Use of fly-ash geopolymer incorporating ground granulated slag for stabilisation of kaolin clay cured at ambient temperature

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ABSTRACT: This paper focuses on stabilisation of kaolin clay at ambient temperature using fly-ash based geopolymer incorporating ground granulated blast-furnace slag (GGBFS). Comprehensive experimental programme was conducted including soil plasticity, compaction, unconfined compressive strength, durability and leaching. These tests were followed by a microstructural analysis using scanning electron microscopy (SEM) technique. An optimisation study using several combinations of geopolymer ingredients was performed, and the role of GGBFS in enhancing the geopolymer-stabilised clay was evaluated. The results indicated that introducing partial replacement of class (F) fly-ash by GGBFS assists, when synthesised in certain ratios, in achieving strength properties of geopolymer-stabilised clay comparable to those of cement stabilised clay. Although a small percentage of geopolymer can improve the soil strength, a larger amount was essential to enhance the wetting-drying durability performance. Under freezing-thawing conditions, low durability performance was detected indicating retardation in the geopolymer reaction at low temperature. For simulated water infiltration, leaching of the activator from geopolymer-stabilised clay was a minor concern in relation to the gel formation and long-term strength gain. Finally, SEM results clearly demonstrated a clay fabric modification attributed to the inter-particle contacts and the corresponding bonding due to the gel formation and hardening.

Keywords: Geopolymer; Fly-ash; Ground granulated blast-furnace slag; Kaolin clay, Soil stabilisation; Ground improvement.

1. Introduction

Soft soils are problematic in nature and pose serious challenges to the service life of infrastructure projects due to their high compressibility and low load-carrying capacity. Chemical stabilisation, using ordinary Portland cement (OPC), has been widely employed as a traditional solution for ground improvement, where the properties of problematic soils are altered through hydration and pozzolanic reactions (Karol 2003; Das 2010; Kirsch and Bell 2012; Han 2015). However, the use of OPC and the associated carbon footprint raised serious environmental issues in the last decades. For example, manufacturing of 1 tonne of OPC has been usually found to release about 0.8−1.0 tonne of carbon dioxide (CO_2) to the atmosphere; the OPC manufacturing is estimated to account for about 7% of the total artificial CO_2 emission (Garcia-Lodeiro et al. 2014). Considering such an emission problem along with some other environmental detrimental effects related to the sourcing of non-renewable raw materials, an enormous motivation exists for finding more environmentally-friendly and cost-effective alternative binders to replace OPC (Roy 1999; Hardjito 2005; Komnitsas and Zaharaki 2007; Davidovits 2008; Siddique et al. 2011; Pacheco-Torgal 2014).

It has been found in the literature that the bonding characteristics offered by the alkaline activation of some abended pre-calcined by-products, such as geopolymers, can introduce an effective alternative binder to OPC (Roy 1999; Davidovits 2008; Pacheco-Torgal et al. 2008; Shi et al. 2011). Geopolymer is a low-calcium alkali aluminosilicate gel that is usually synthesised from two main components including fly-ash or metakaolin plus potassium or sodium liquid-based activator (Provis and Bernal 2014). The use of fly-ash based geopolymers contribute to a considerable reduction in the energy consumption and CO_2 emission (Siddique et al. 2011). In brief, the geopolymerisation process involves the following four main steps: (1) leaching by which a dissolution of solid aluminosilicate oxides from source materials in an alkaline environment provided by solution activator with high pH value; (2) diffusion (migration) of the dissolved Al and Si complexes; and (3) gel formation through chemical condensation (polycondensation) between the added solution and Al and Si complexes before the final step of gel hardening (Komnitsas and Zaharaki 2007). Depending on the synthesised conditions, geopolymers can possess good mechanical properties such as low permeability, high compressive strength, high durability and low volumetric changes (Xu and Van Deventer 2000; Gianoncelli et al. 2013; Horpibulsuk et al. 2015). However, several factors may control the mechanical properties of geopolymer including properties of source materials, chemical composition of activator, curing time and treatment temperature (Sukmak et al. 2013; Zhang et al. 2013). Among these factors, the curing temperature is the most challenging for field implementation (Xu and Van Deventer 2000). Geopolymers are usually cured at temperatures ranging from 60–90^{o}C (Liew et al. 2012); hence, most geopolymers have been limited in use to steamed or dry heat-cured concrete (Gianoncelli et al. 2013). For geotechnical engineering applications, geopolymers have to be utilised at ambient temperature as it is not practically applicable to be treated at elevated heat. However, the use of geopolymers at ambient temperature maintains slow rate of geopolymerisation; hence, geopolymer-stabilised soils usually take long time for strength enhancement. A curing time of 90 days is normally required for geopolymer-stabilised soils treated at ambient temperature to gain equivalent strength to that obtained from OPC treated soils at 28 days (Cristelo et al. 2012b). Therefore, to increase the feasibility of using geopolymers for soil stabilisation at ambient temperature and to make it more comparable to OPC treated soils, low water-to-binder ratio and high contents of activator and binder are required to overpass the delay in the setting time and strength development (Bernal and Provis 2014). However, water is essential for soil to achieve proper compaction and the use of high content of geopolymer with low water content might involve mixing difficulties; this is a salient feature that is investigated in the current study.

Considering the nature of the cementitious components of different source materials used in alkaline binders, three alkaline activation models can be derived, as follows (Garcia-Lodeiro et al. 2014). *Model-I* is usually derived from low calcium high aluminosilicate materials such as fly-ash or metakaolin, which when activated forms a gel of bonding characteristics of three-dimensional framework (i.e. geopolymer). This model is represented by the chemical structure Sodium Aluminate Silicate Hydrate (N-A-S-H), and the literature includes several studies that have used this model for soil stabilisation (e.g. Markou and Atmatzidis 2002; Wilkinson et al. 2010b; Cristelo et al. 2011; Cristelo et al. 2013a; Zhang et al. 2013; Liu et al. 2016). *Model-II* produces a fundamental Calcium Aluminate Silicate Hydrate (C-A-S-H) gel similar to the gel obtained during the OPC hydration. It is important to emphasise that the activation of by-product source materials of this model with high calcium content > 70% (e.g. blast furnace slag) usually leads to a reaction output different from that of geopolymer. Consequently, there is a debate in the literature of whether or not this model may be classified as geopolymer. Examples of previous studies carried out using this model for soil stabilisation include the work done by Hughes and Glendinning (2004), Wilkinson et al. (2010a), Sargent et al. (2013) and Yi et al. (2014). *Model-III* is comprised of the two preceding models (hybrid), which consists of activated fly-ash and slag, where a combination of the N-A-S-H and C-A-S-H gels is introduced in the reaction process, to enhance the effectiveness of the geopolymer at ambient temperature. This process assists in bringing the strength of geopolymer-treated soils to the economical boundary. Limited studies are available in the literature on the use of this model for soil stabilisation (e.g., Sargent et al. 2013; Singhi et al. 2017); hence, there is an immense need for further studies on this model and the current work will fill out this gap.

It is observed that most studies found in the literature in relation to geopolymer-stabilised soils focus mainly on improving the compressive strength of treated soils (Verdolotti et al. 2008;

Cristelo et al. 2011; Cristelo et al. 2012b; Cristelo et al. 2013a; Zhang et al. 2013; Zhang et al. 2015; Liu et al. 2016; Phummiphan et al. 2016; Singhi et al. 2017). However, the long-term performance of geopolymer-stabilised soils in terms of durability and leaching have not been considered extensively. There is currently no specific designation in the literature for the optimum amount of geopolymer that can attain durability as specified to OPC treated soils. In fact, the lack of detailed investigation on the durability performance of geopolymer-stabilised soils is one of the main reasons restricting the extensive use of this promising technique for ground improvement. In the current study, the durability of geopolymer-stabilised clay will be investigated in detail under different weathering conditions, including wetting-drying and freezing-thawing. In addition, the water infiltration (rainfall or groundwater) will be investigated through leaching tests.

2. Materials and Methodology

2.1 Soil used

In this study, kaolin clay was selected due to its well-defined characteristics and availability. Table 1 shows the chemical composition of the clay used, which is Prestige NY clay commercially available in the form of white coloured kaolin produced in Western Australia. The chemical composition of other materials used in the current study are also shown in Table 1 and will be discussed later. The percentage of fines of the clay used is 79.4% passing 2 μm 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 1289.3.2.1 (2009) and AS 1289.3.9.1 (2015), and found to be equal to 27.1% and 53.6%, respectively. The compaction properties (i.e. the maximum dry unit weight and the corresponding optimum moisture content) are measured using the standard Proctor test in accordance with the Australian Standards AS 1289.5.1.1 (2003) and found to be equal to 14.95 kN/m^3 and 25.2%, respectively.

Table 1. Chemical compositions of materials used.

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	14.30
Fly-ash	51.11	25.56	12.48	4.30	1.45	0.70	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 Geopolymer ingredients

The geopolymer binder used in this research is a mixture of low calcium (class F) fly-ash (FA), ground granulated blast furnace slag GGBFS (denoted herein as S) and liquid-based sodium activator (denoted herein as A). The fly-ash is used as a reactive material to produce the N-A-S-H gel, whereas the GGBFS is introduced to produce the C-A-S-H gel after activation. As mentioned by Yip et al. (2005), the coexistence of the N-A-S-H and C-A-S-H gels through a hybrid alkaline cementation model offers an enhancement to the mechanical properties and setting time of geopolymer-stabilised soils at ambient temperature. The chemical activator is essential to launch the reaction and to form the geopolymer. In preparation of geopolymers, the combination of fly-ash and slag is denoted herein as the source material (i.e. SM = FA + S).

The fly-ash (FA) used in this study is a coal fly-ash obtained from a pulverised coal combustion, known as low calcium Gladstone fly-ash, which was supplied from Gladstone power station by Cement Australia Limited. This type of fly-ash conforms to the Australian Standards AS 3582.1 (1998) and its chemical characteristics are given in Table 1. The availability of this fly-ash as a waste material promotes its use as an economic option compared to metakaolin for better alkaline activation and geopolymer production. Low calcium fly-ash contains higher silica and alumina, which puts low calcium (class F) fly-ash in favour as a source material to high calcium (class C) fly-ash (Hardjito 2005; Duxson 2009; Garcia-Lodeiro et al. 2014).

The Ground granulated blast furnace slag (GGBFS) used in this study is a calcium-rich aluminosilicate material produced from the steel industry waste and is considered to be one of the most commonly used materials in alkali-activated binders (Provis and Bernal 2014). The slag used was supplied by Independent Cement & Lime Ltd and complies with the Australian Standards AS 3582.2 (2001). The chemical composition of this type of slag is given in Table 1.

For soil stabilisation and geotechnical applications, activators based on sodium hydroxide and sodium silicate were recommended by most researchers to synthesise geopolymers (Verdolotti et al. 2008; Cristelo et al. 2011; Cristelo et al. 2012a; Cristelo et al. 2012b; Cristelo et al. 2013a; Cristelo et al. 2013b; Sargent et al. 2013; Zhang et al. 2013; Zhang et al. 2015; Phummiphan et al. 2016; Rios et al. 2016). The activator used in this study consists of Grade D sodium silicate and 14M concentrated sodium hydroxide in a fixed weight ratio of 70:30. This ratio was selected because it was recommended in the geopolymer literature to maximise the strength gain, as reported by Hardjito (2005). 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 (NaOH) was prepared in a fume cabinet by dissolving sodium hydroxide pellets in deionised water for at least one day prior to mixing.

2.3 Samples preparation

The source material (i.e. SM = FA + S) was initially mixed with dry kaolin to ensure mixture uniformity and to form the total dry material, which is denoted herein as (DM). To form the ultimate moisture for the optimum compaction, the liquid activator was diluted with additional free water before use, and was then mixed with the DM. Table 2 summarises details of the mixtures used. A code was used to identify the different mixtures involved, as follows: M(SM/DM-S/SM-A/SM). The letter M before the bracket is an abbreviation of the word “Mixture” followed by three ratios: SM/DM, S/SM and A/SM, indicated inside a bracket and separated by hyphens.

Directly after mixing, the effect of additives on the compaction parameters was determined through a series of standard Proctor compaction tests according to the Australian Standards AS 1289.5.1.1 (2003). Having obtained the compaction parameters, the geopolymer-treated soil mixtures were remoulded in designated specimen moulds. The specimens used for the UCS and leaching tests were prepared using cylindrical polyvinyl chloride (PVC) tubes of 42 mm in diameter and 84 mm in height so that an aspect ratio of height-to-diameter of 2:1 is attained. The durability specimens were prepared in accordance with the ASTM D559-03 (2003) and ASTM D560-15 (2015). For each specimen, the compaction was performed in layers of controlled weight/thickness to replicate similar maximum dry unit weight to that obtained from the Proctor test. After compaction, the end of the PVC tubes was sealed with plastic lid to avoid any moisture loss, and the specimens were left to cure for 24 hours at 60% humidity and temperature of 20-25°C. The specimens were then demoulded and covered again with plastic bags before curing was continued at the same conditions until the samples were tested. Additional samples were prepared and stabilised by adding 3%, 6% and 9% OPC (denoted herein as OPC3, OPC6 and OPC9, respectively), as shown in Table 2. These samples were tested for the purpose of comparison with the geopolymer-stabilised samples.

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

Mixture no.	SM/DM (%)	S/SM (%)	A/SM (%)	OPC (%)
M(0-0-0)	0	0	0	−
M(10-20-0)	10	20	0	−
M(20-20-0)	20	20	0	−
M(30-20-0)	30	20	0	−
M(10-0-40)	10	0	40	−
M(10-0.1-40)	10	10	40	−
M(10-20-40)	10	20	40	−
M(20-0-40)	20	0	40	−
M(20-0.1-40)	20	10	40	−
M(20-20-40)	20	20	40	−
M(30-0-40)	30	0	40	−
M(30-0.1-40)	30	10	40	−
M(30-20-40)	30	20	40	−
M(10-20-80)	10	20	80	−
M(20-20-80)	20	20	80	−
M(30-20-80)	30	20	80	−
OPC3	−	−	−	3
OPC6	−	−	−	6
OPC9	−	−	−	9

2.4 Tests conducted

2.4.1 Unconfined compressive strength

To investigate the samples strength development, unconfined compressive strength (UCS) tests were performed at curing time of 7, 28 and 90 days. The average of two tests was reported for each mixture, and all UCS tests were performed according to the Australian Standards AS 5101.4 (2008). The tests were performed on specimens of an aspect ratio of diameter-to-height equal to 1:2 using a strain rate of 1% per minute. For soil samples stabilised with either geopolymer or OPC, care was taken to complete the sampling within 30 minutes after mixing so as to avoid any binder hardening interaction. In order to verify homogeneity and uniformity, the maximum dry unit weights and the corresponding optimum moisture contents were maintained for all tested UCS samples.

2.4.2 Durability

The durability tests were conducted in accordance with ASTM D559-03 (2003) and ASTM D560-15 (2015). The tests were performed for many cycles of wetting-drying and freezing-thawing, to examine the water content and volume changes due to repeated weathering conditions. In brief, after completing the curing period of 7 days, standard moulded specimens were completely immersed in water for 5 hrs to start the wetting-drying cycles. Then the samples were dried in the oven at a temperature of 70 °C for 43 hrs. After each stage, the samples weight and dimensions were measured and recorded. This process represented one cycle of wetting-drying, which requires 48 hrs. For the freezing-thawing cycles, freezing was performed at a temperature of –18 °C for 24 hrs. Following the freezing stage, the specimens were placed in the moist room having a temperature of 21°C and relative humidity of 100% for 24 hrs. Care was taken to provide water-saturated felt pads between the specimens and container in all stages. Similar to the wetting-drying tests, the freezing-thawing procedure was designed to continue until the specimen reaches 12 cycles.

To investigate the residual strength under the effect of durability, a set of specimens with aspect ratio of height-to-diameter of 2:1 was examined for the UCS tests after completing 3, 6, 9 and 12 durability cycles. To bring the samples to moisture contents close to their optimum values, the samples passed the desired wetting-drying cycles were submerged in water for 1 hr and were then air-dried for 15 minutes. For the freezing-thawing samples, the UCS tests were directly performed after thawing.

2.4.3 Leaching

The leaching tests were carried out using a triaxial cell based on the procedure recommended by McCallister and Petry (1992). The cell was assembled to hold a sample of an aspect ratio of height-to-diameter of 2:1. A rubber membrane was extended to the full length of the sample for isolation and to form a barrier that allows the water confining cell pressure to be applied to prevent water from percolating through the sides of the specimen. Pressurised water was then leached by flowing over a porous stone through the sample from the bottom to allow uniform water distribution. Another porous stone was used on top of the sample to prevent solids from washing-out. Sufficient leachate for one cycle was achieved in 24 hrs, which is equivalent to leaching out a collection of one pore volume change presented in the compacted soil samples. A number of 3, 6 and 9 cycles of leaching were conducted to monitor the strength performance and the pH values of the geopolymer-stabilised soil. After a designated number of leaching cycles, the leached stabilised samples were tested for the UCS residual strength determination and were then broken down and tested for the pH determination. The leachate liquid was also collected for each cycle and was analysed for the pH value. The pH determination was carried out in accordance with the Australian Standards AS 1289.4.3.1 (1997) in which a 30 gm of geopolymer-stabilised soil was sieved and stirred with 75 mL distilled water to form a suspension that cured for 1 hr before testing. The pH value was measured for the leached liquid and soil suspension using an electronic pH metre, and a comparison between the pH values before and after leaching was then possible.

2.4.4 Microstructural analysis

To investigate the microstructural development of geopolymer gel and to examine the change in clay fabric after stabilisation, scanning electron microscopy (SEM) was performed using a fully PC controlled MIRA3 XMU equipment. The SEM was carried out on geopolymer-stabilised specimens of optimum geopolymer-clay mixture at curing time 7 and 28 days. The SEM was also performed on samples in which only fly-ash and slag were mixed with clay at the optimum moisture content without activator. Additional images were necessary to distinguish the different shapes of dry particles involved before mixing.

3. Discussion of Results

3.1 Physical properties of geopolymer-treated clay

Fig. 1 presents the compaction properties of geopolymer-stabilised clay for different mixtures in terms of the maximum dry unit weight (MDD) and the corresponding optimum water content (OMC). It should be noted that the results of compaction parameters of clay samples after treatment with geopolymer, denoted herein as $MDD_{(T)}$ and $OMC_{(T)}$, respectively, were normalised with the corresponding values of untreated kaolin clay (i.e. $MDD_{(U)} = 14.95kN/m^3$ and $OMC_{(U)} = 25.2\%$).

Generally speaking, the ratios A/SM and SM/DM were expected to control the compaction parameters and are thus presented in Fig. 1. As mentioned earlier, the GGBFS (denoted as S), was used as a partial replacement of fly-ash (FA) to form the geopolymer dry source material, which is denoted as SM (i.e. SM = FA + S). Also, (DM) refers to the total dry material (i.e. dry component of geopolymer and dry clay) and (A) is the alkaline activator (i.e. fixed weight ratio of 70:30 of sodium silicate to 14M sodium hydroxide solution). It can be seen from Fig. 1(a) that the ratio ($MDD_{(T)}/MDD_{(U)}$) increases with the increase of the ratio SM/DM, for all ratios of A/SM. Also, it can 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 instance, an increase in the activator amount of 80% of SM (i.e. A/SM = 80%) increases the ratio $MDD_{(T)}/MDD_{(U)}$ by about 17% at SM/DM = 30%. In contrast, it can be seen from Fig. 1(b) that the ratio OMC_{KG}/OMC_K decreases with the increase of 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 to 80% of SM (i.e. A/SM = 80%) decreases the ratio $OMC_{(T)}/OMC_{(U)}$ by 33% at SM/DM = 30%. This suggests that the alkaline chemicals presented in the activator play a positive role in the compaction results, by partially reducing some of the moisture needed to reach the optimum compaction. It is of interest to mention that the role of activator was detected earlier in this research through an attempt to compact the geopolymer samples in a state corresponding to MDD and OMC for un-activated soil at A/SM = 0. This indicates a significant volume of air pockets and poor compaction at higher ratio of SM/DM and activator content. It should be noted that while the results presented in Fig. 1 are for S/SM = 20%, similar results were obtained for S/SM = 0 and 10% but are not presented for brevity.

Fig. 1 Compaction characteristics of geopolymer-stabilised clay for S/SM = 20%: (a) maximum dry unit weight; and (b) optimum moisture content.

The Atterberg limits, including Liquid Limit (LL) and Plastic Limit (PL), are essential indices to quantify the response of soil to moisture. The effect of SM/DM and A/SM ratios on LL and PL were examined and the results are shown in Fig. 2, for two types of mixtures (i.e. activated with A/SM = 40% and un-activated with A/SM = 0), with all mixtures having the same S/SM ratio of 20%. It can be seen that the addition of SM tends to reduce both the LL and PL of geopolymer-stabilised mixtures, regardless of whether the mixture was activated or not. The reduction in LL and PL was mainly controlled by the role of the non-plastic fly-ash and slag particles introduced into the SM content as a partial replacement of the kaolin clay. It may also be attributed to the role of chemicals involved in the activator before the geopolymer gel formation, which tends to assist in the sliding between the dry particles. In an attempt to track the effect of geopolymer stabilisation on soil plasticity, the values of plasticity index (PI = LL−PL) of stabilised activated and un-activated mixtures were calculated at different SM/DM concentrations, and it was found that the PI values were reduced and thus 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 geopolymer-stabilised clay for samples with S/SM = 20% and A/SM = 40%.

3.2 Strength performance of geopolymer-stabilised clay

Using the UCS results, a strength development index (SDI) was suggested as a non-dimensional parameter to reflect the effect of the controlling factors (i.e. fly-ash, activator and slag). The SDI is defined as $[(UCS_{(T)}–UCS_{(U)})/UCS_{(U)}]$, where $UCS_{(T)}$ refers to the UCS of geopolymer-treated clay, whereas $UCS_{(U)}$ refers to the UCS of untreated clay.

3.2.1 Effect of fly-ash

Using different ratios of SM/DM = 10%, 20% and 30%, as well as a fixed combination of S/SM = 0 and A/SM = 40%, the effect of various fly-ash percentages as a main source material on the strength improvement of geopolymer-stabilised clay was examined and the results are presented as in Fig. 3. It can be seen that the increase in fly-ash percentage (i.e. SM/DM) proved to give enhanced UCS values for the geopolymer-treated clay, for all mixtures at both 7 and 28 curing days. In terms of the strength development index (SDI), it was found to increase by 1.2 and 2 when the percentage of fly-ash was added to the clay by only 10%, for curing time of 7 days and 28 days, respectively. When the percentage of fly-ash was further increased to 20%, a higher increment in the SDI was detected up to 2.1 and 6.5 for curing time of 7 days and 28 days, respectively. It is observed that the increase in SDI is more pronounced at higher fly-ah content and late curing period. However, such findings were found to be similar to those reported in the literature (e.g. Cristelo et al. 2013a; Sargent et al. 2013), which are mainly related to the cementitious characteristics of the activated fly-ash through the formed N-A-S-H geopolymer gel.

Fig. 3 Strength gain of fly-ash based geopolymer for different mixtures and curing time, with S/SM = 0 and A/SM = 40%.

3.2.2 Effect of GGBFS

The effect of various slag percentages on the strength improvement of geopolymer-stabilised clay was examined and the results are presented in Fig. 4, for different ratios of S/SM = 0%, 10% and 20%, and a fixed ratio of A/SM = 40%. It can be seen that the UCS values increases substantially with the increase in S/SM ratio, for all mixtures at both 7 and 28 curing days. For instance, at S/SM = 20% (i.e. replacing 20% of fly-ash with slag) the UCS value of M(20-S/SM-40) increased from 609 kPa to 1377 kPa (at 7 days curing time) with a corresponding SDI increase from 2.1 to 6. For 28 days of curing, the SDI improvement was detected to be increase from 6.5 at zero slag to 9.7 with slag. Such an increase in the SDI is mainly related to the role of the C-A-S-H gel produced from the slag activation within the fly-ash based geopolymer, which enhanced the strength performance at ambient temperature and curing time of up to 28 days. However, for all samples incorporating GGBFS, the SDI was found to range between 1.8-7.6 for 7 curing days, and between 2.5-17.3 for 28 curing days in which the S/SM ratio = 20% has achieved the highest value and thus was selected for further investigation.

Fig. 4 Effect of slag on strength gain of fly-ash based geopolymer for different mixtures and curing time.

3.2.3 Effect of activator

Based on a set of geopolymer-stabilised clay specimens of different mixtures cured at 7 and 28 days and different A/SM ratios, the effect of activator was investigated and compared, as shown in Fig. 5. It can be seen that at zero activation (i.e. A/SM = 0) no UCS improvement copared to untreated clay was detected for all mixtures at various source material contents, and this can be attributed to the weak pozzolanic reaction (i.e. self-cementitious characteristics) of the source material. On the contrary, for A/SM > 0 (i.e. at 40% and 80%), a substantial increase in strength gain was detected for all mixtures and curing periods. As explained by Cristelo et al. (2012a), this can be attributed to the increase in the Na_2O to fly-ash concentration resulted from the increase in the activator content and in turn the increase in the geopolymer reaction.

Fig. 5 Effect of activator on UCS of geopolymer-stabilised clay for different mixtures and A/SM ratios.

For mixture M(10-20-A/SM), it can be seen that an increase in the activator concentration (A/SM) above 40% did not enhance the UCS values, for both 7 and 28 curing days. This may be attributed to the consumption of most of the source material in the mixture. It is worthwhile noting that a low development of strength at this stage may also confirm a low reactivity of kaolin clay for any short-term reaction of the activator. For mixture M(20-20-A/SM), an increase of 12% in the UCS value was detected from A/SM = 40% to A/SM = 80% for 7 curing days, whereas an increase of 47% in the UCS value was detected from A/SM = 40% to A/SM = 80% for 28 curing days. Mixture M(30-20-A/SM) proved to give an increase of 23% from A/SM = 40% to A/SM = 80% for 7 curing days, and an increase of 33% for 28 curing days.

3.2.4 Correlations of strength and stiffness

In this section, the long-term strength of geopolymer-stabilised clay was correlated with the early strength and curing time. It is evident from the results presented in Figs. 3 and 4 that the average UCS values at different curing time and different SM/DM ratios are dependent on the initial strength at a curing time = 7 days (i.e. $UCS_{(7)}$). As such, the normalised ratio $UCS_{(t)}/ UCS_{(7)}$ versus curing time (t) in days was plotted and presented in Fig. 6, for M(10-20-40), M(20-20-40) and M(30-20-40) up to 90 curing days. As can be seen, the strength curve for A/SM = 40% is unique and its trend can be nicely represented by a power function.

Fig. 6 Relationship between $UCS_{(t)}/UCS_{(7)}$ and curing time for geopolymer-stabilised clay.

It was found in the cement-soil literature that the variation of stiffness (i.e. secant modulus at 50% of peak strength, E_{50}) can be correlated as an approximate value of the corresponding UCS (e.g. Porbaha et al. 2000; Lorenzo and Bergado 2006). For geopolymer-stabilised clay, the results demonstrate a clear correlation with a best fitting logarithmic relationship, as shown in Fig. 7, which presents the E_{50} against UCS values for SM/DM = 10%, 20% and 30% tested at 7, 28 and 90 curing days.

Fig. 7 Relationship between E_{50} and unconfined compressive strength for geopolymer-stabilised clay.

3.2.5 Strength comparison of geopolymer-treated clay with OPC treated clay

Out of the geopolymer-stabilised clay mixtures used in the current study, two mixtures [i.e. M(10-20-40) and M(20-20-40)] were found to give a strength range between 1000−2000 kPa, which fulfils most ground improvement applications and were thus recommended for comparison with the strength results of the OPC treated soil. Fig. 8 shows the results of such a comparison in terms of the UCS values, SDI and the corresponding curing time. It can be seen that at curing time = 7 days, the strength of geopolymer-stabilised clay mixture M(10-20-40) is equivalent to that of OPC3 (SDI = 2.6), whereas the strength of geopolymer-stabilised clay mixture M(20-20-40) is comparable to OPC9 (SDI = 6). At 28 and 90 curing days, the strength of geopolymer-stabilised clay mixture M(10-20-40) is almost equivalent to that of OPC6, confirming a higher rate of strength development in geopolymer-stabilised clay mixtures compared to that at 7 curing days. On the contrary, it can be seen that the geopolymer-stabilised clay mixture M(20-20-40) shows superior development in strength gain compared to all OPC treated mixtures. For example, M(20-20-40) was found to achieve SDI values of 9.7 and 16.5 at 7 and 28 curing days, respectively, representing an improvement of SDI of 30% and 101% more than those of OPC 9.

Fig. 8 Strength of geopolymer-stabilised clay samples for S/SM = 20% and S/M = 40% against OPC treated clay samples.

Fig. 9 shows UCS stress-strain curves for M(20-20-40) and OPC9 mixtures cured at 7 and 28 days. It can be seen that the addition of geopolymer increases the strength and stiffness of treated clay, for both curing periods. At 7 days of curing, a more comparable stiffness behaviour is evident to that of OPC additive. However, as the curing period is increased, the geopolymer-stabilised mixture shows more stiff behaviour than OPC treated clay. The reason behind the difference in stiffness between the different mixtures may be attributed to the competition between the higher rate of geopolymerisation reaction in geopolymer-stabilised clay compared to the hydration reaction in OPC treated clay.

Fig. 9 Typical stress-strain curves of geopolymer-stabilised clay and OPC treated clay.

3.3 Durability performance of geopolymer-stabilised clay

3.3.1 Wetting-drying and freezing-thawing

After bracketing the optimum dosages of geopolymer ingredients that attained the optimal strength, further evaluation of the durability performance is presented herein through the wetting-drying and freezing-thawing durability tests. Fig. 10 presents the durability cycles of different treated mixtures. It can be seen that increasing the binder percentage minimises the degradation performance of geopolymer-stabilised clay. For example, increasing the binder dosage to 20% for M(20-20-40) proved to provide much better wetting-drying durability performance than lower dosage of 10% binder for M(10-40-20). It can also be seen that M(20-20-40) lasted all 12 wetting-drying cycles successfully, whereas M(10-20-40), as the lowest geopolymer content mixture, showed a considerable distress and collapsed completely during the wetting stage of the first wetting-drying cycle. An additional mixture, i.e. M(15-20-40), was examined and found to suffer from a significant material loss during the first 3 cycles of wetting-drying, as evidenced by the slight performance enhancement in Fig. 10. The results of wetting-drying tests clearly indicate that higher geopolymer dosage is necessary to improve the durability performance of geopolymer-stabilised clay than that needed for strength improvement. Under the test conditions introduced by successive freezing and thawing cycles, Fig. 10 also shows an earlier failure at low cycles indicating lower resistance to temperature and moisture changes.

Fig. 10 Durability performance of different geopolymer-stabilised clay mixtures compared to OPC9 treated clay.

Figs. 11 and 12 demonstrate the pictorial representation of the durability performance mentioned above for the geopolymer-stabilised clay concerning the wetting/drying cycles. In general, the degradation detected at low geopolymer concentration can be attributed to the permanency of the geopolymer stabiliser against weather effects. The concentration of activator involved in the geopolymerisation reaction seems to be affected by the water movement in and out the specimen during the different test conditions, causing unstable geopolymerisation rate in the specimens and thereby influencing the binder durability. Moreover, a high temperature of 70 ^{o}C for 43 hrs of drying also seems to draw a considerable amount of moisture out of the treated specimens, which may compromise the geopolymerisation process.

Fig. 11 Images of geopolymer-stabilised clay samples subjected to different wetting/drying cycles: (a) M(10-20-40) 1st cycle; (b) M(15-20-40) 2rd cycle; (c) M(20-20-40) 3rd cycle; and (d) M(20-20-40) 12th cycle.

Fig. 12 Images of geopolymer-stabilised clay samples subjected to different wetting/drying cycles: (a) M(10-20-40) vs M(20-20-40), i.e. samples (1-8) vs samples (9-16); and (b) M(15-20-40).

During the durability tests, the voids are expected to experience capillary pressure as a result of the moisture and temperature changes, which may affect the clay structure and residual strength level causing physical changes in terms of the soil volume and moisture content. To investigate this point, M(20-20-40) mixture was examined to determine the corresponding volumetric and moisture content changes associated with the wetting-drying durability cycles and the results are shown in Fig. 13. It can be seen that the influence of the wetting-drying durability cycles on the volume and moisture content changes is not significant, the volume change was almost constant along the 12 cycles of wetting-drying durability testing.

Fig. 13 indicates that the response of the geopolymer clay mixtures to freezing-thawing conditions is higher than that to the wetting-drying conditions, indicating an earlier failure for the freezing-thawing conditions. In addition, the results show that the geopolymer-stabilised clay seems to exhibit less stable performance in the freezing climate than the tropical climate, which can be explained by the retardation of the geopolymerisation reaction at low temperature and the acceleration of such reaction in temperature above the ambient.

Fig. 13 Volume and moisture changes versus durability cycles for geopolymer-stabilised clay mixture M(20-20-40).

3.3.2 Durability performance comparison with OPC treated clay

Fig. 14 presents the durability performance of OPC treated clay at 9% dosage of cement. Through a direct comparison of Fig. 13 with Fig. 14, it can be seen that a comparable wetting-drying durability performance for geopolymer-treated clay mixture M(20-20-40) with that of OPC9 treated mixture. Both treated clay mixtures lasted the 12 wetting-drying cycles successfully with almost identical volumetric and moisture changes. However, this was not the case for the freezing-thawing cycles in which mixture M(20-20-40) shows a rapid degradation at the 6th cycle with high volumetric change of up to 20% against a more stable performance for OPC9 treated clay along the 12 designated cycles.

Fig. 14 Volume and moisture changes versus durability cycles for OPC9 treated mixture.

To investigate the expected degradation in strength gain under the accelerated weathering conditions, Fig. 15 shows the residual strength of geopolymer-stabilised mixtures in terms of the UCS values after 3, 6, 9 and 12 cycles of wetting-drying or freezing-thawing. Fig. 15 also includes the impact of durability conditions on strength gain of OPC treated clay with 9% cement. As can be seen from Fig. 15(a), the strength degradation of geopolymer-stabilised clay increases with the successive wetting-drying cycles, and the complete degradation in strength is observed for M(10-20-40) and M(15-20-40) mixtures after 1 and 3 wetting-drying cycles, respectively. It can also be seen that the strength degradation of M(20-20-40) with the number of wetting-drying cycles is not as severe as the two other geopolymer mixtures, and the residual strength of this mixture was found to be 67% of the initial strength at zero cycle. The behaviour of OPC treated clay shows a strength development at the first 3 wetting-drying cycles, after which a slight decrease in the UCS values is observed at furfur cycles. Such a difference in behaviour between the geopolymer-stabilised clay and OPC treated clay towards the wetting-drying durability can be attributed to the continuous hydration in the OPC treated mixture against the geopolymerisation degradation due to the activator leaching in the geopolymer-stabilised mixtures, especially in the first 3 cycles of the successive wetting-drying periods. For the freezing-thawing conditions (Fig. 15b), it can be seen that the residual strength is sharply affected by the increase of the freezing-thawing cycles, for all mixtures including the geopolymer and OPC treated soils, and a significant degradation is observed after 6 cycles, indicating a destructive impact towards the freezing-thawing conditions.

Fig. 15 Influence of durability cycles on UCS values for geopolymer-stabilised clay and OPC9 treated clay: (a) wetting-drying condition; and (b) freezing-thawing condition.

To quantify the strength performance against durability, the results of the wetting-drying durability tests for M(20-20-40) were used to correlate the residual average strength at any cycle ($UCS_{(c)}$) with the initial compressive strength at cycle 0 (i.e. $UCS_{(0)}$), and the strength index (i.e. $UCS_{(c)}/ UCS_{(0)}$) was then plotted against the number of wetting-drying durability cycles (*c*), as presented in Fig. 16. The relationship between the strength index and durability cycles shows an exponential trend.

Fig. 16 Relationship between $UCS_{(c)}/UCS_{(0)}$ and wetting-drying cycles for geopolymer-stabilised clay.

3.4 Leaching performance of geopolymer-stabilised clay

Compacted specimens for M(20-20-40) mixture cured for 7 days were leached with pressurised water in the specially leaching cell described earlier for a number of cycles between 1–9. During the test, the leachate was continuously collected and monitored for measuring the pH value using the digital pH meter. The pH of leachate was used as an indicator of the degree of leaching out of alkali from the stabilised clay specimens. After a designated number of cycles (i.e. 3, 6 and 9), the corresponding residual pH values and the residual unconfined compressive strength were determined for the stabilised clay. Fig. 17 shows the leachate pH, soil pH and soil UCS values against leaching cycles. It can be seen that the leachate pH and soil pH values decrease at the earlier leaching cycles. For example, the leachate pH at 3 cycles decreased from 13.53 to 12.85, while the residual soil pH decreased from 12.95 to 12.03, representing a total reduction of 5% and 7%, respectively. This is in agreement with the work done by McCallister and Petry (1992) on lime treated expansive clay in which it was found that the leachate pH decreased linearly during the leaching cycles and that leaching does have a detrimental impact on the stabilised soil when a low lime dosage was utilised. However, the pH value remained approximately constant for both the leachate and soil after 6 cycles indicating a minimum change in the alkalinity concentration inside the stabilised sample due to water infiltration.

Fig. 17 Residual strength and pH against leaching cycles of geopolymer-stabilised clay.

As can be seen in Fig. 17, the strength degradation of geopolymer-stabilised clay against number of leaching cycles is not significant, and the residual strength after 9 cycles was found to be 90% of the initial strength at zero cycle. This is in agreement with the findings by Chittoori and Puppala (2013) for different leached clay types treated with lime and cement. Interestingly, a continuous development do exist up to the third cycle and the degradation of strength occurs between the third and sixth cycles before remaining approximately constant at further cycles. This can be related to the effect of leaching on the clay structure associated with the change in the solubility rate for the amorphous silica and alumina of the fly-ash particles along the different leach cycles caused by the alkalinity concentration reduction due to water infiltration. In light of this, the activator leaching might be a minor concern in geopolymer clay stabilisation during the initial curing period, which might disturb the gel formation, and in turn, the targeted strength gain rate. To avoid any activator loss, field protection from water infiltration (e.g. rainfall or groundwater) may be needed, for curing time of up to 28 days.

3.5 Geopolymer composition molarity

To attain strength and durability criteria for high binder performance, the geopolymer literature usually recommends certain composition molarity ratios. Based on a set of geopolymer-treated clay specimens of different mixtures, the synthesised geopolymer concentrations and the corresponding molarity compositions were investigated and compared against the UCS and durability performance, as shown in Table 3. The chemical molarity ratios at higher activator-to-source material (A/SM = 80%) were found to comply with the range limits predefined in the geopolymer literature for binder execution (Khale and Chaudhary 2007; Pacheco-Torgal et al. 2008). However, these morality ratios were also found to gain higher strength exceeding the needed levels when presented in kaolin stabilisation compared to OPC control mixtures. Utilising a more optimum activator ratio of A/SM = 40% with SM/DM = 20% attained strength and durability close to those of OPC treated clay with 9% cement. This suggests minimum molarity limits of: $SiO_2/Al_2O_3 = 4.08$, $Na_2O/SiO_2 = 0.14$ and $Na_2O/Al_2O_3 = 0.57$, and maximum limits of $H_2O/Na_2O = 44.45$ and $H_2O/SiO_2 = 6.24$. The ratio of Si/Al was found to comply with the minimum range limit of 2.04 for all mixtures. However, these mentioned limits achieved a compressive strength of 2101 kPa for the geopolymer-stabilised clay cured at 28 days, which was also found to survive the 12 cycles of the wetting-drying durability test.

Table 3. Geopolymer composition molarity ratios against strength-durability performance.

Mixture	**Si:Al**	**SiO_2 :Al2O_3**	**Na_2O :SiO_2**	**Na_2O: Al2O_3**	**H_2O :Na_2O**	**H_2O : SiO_2**	**UCS 7 days**	**UCS 28 days**	**Durability cycles**
M(10-20-40)	2.04	4.08	0.14	0.57	101.96	14.30	709	1103	1
M(20-20-40))					44.45	6.24	1378	2101	12
M(30-20-40))					25.71	3.61	3442	6191	–
M(10-20-80)	2.34	4.68	0.24	1.12	52.94	12.7	764	1121	–
M(20-20-80)					23.43	5.62	1544	3087	–
M(30-20-80)					13.75	3.30	4240	8260	–
Literature range	2.04 – 5.57	3.3 – 4.5	0.2 – 0.48	0.8 – 1.6	10 – 25	2 – 12	–	–	–

As a step towards evaluating the effect of water on the mechanical performance of geopolymer-stabilised clay, the H_2O/Na_2O and H_2O/SiO_2 molarity ratios were found to have a dominant role in the durability and strength performance, as shown in Fig. 18. For example, at molarity ratios of $H_2O/Na_2O = 101.96$ and $H_2O/SiO_2 = 14.3$ for mixture M(10-20-40), the SDI increased by approximately 5 folds at the end of 28 curing days compared to that before stabilisation but this was also associated with an earlier failure in terms of the wetting-drying durability test. Decreasing the above two molarity ratios by approximately 56%, as suggested by the maximum limits, for M(20-20-40) achieved a total gain in compressive strength equal to 10 folds compared to that before stabilisation. More importantly, in such circumstances, the specimens survived the full 12 cycles of the wetting-drying durability test. It seems that when the defined molarity limits are exceeded, the addition of free water needed to achieve the moisture content requirement for the optimum compaction can result in a dramatic decrease in both the durability and strength of geopolymer-stabilised clay. Consequently, the quantity of free water in the geopolymer-stabilised clay is more relevant to the amount needed for reaction than for compaction. It can be concluded that the synthesised geopolymer binder using the abovementioned molarity limits promotes more an economical and efficient performance for geopolymer-stabilised clay cured at ambient temperature.

Fig. 18 Influence of composition molarity on strength and durability of geopolymer-stabilised clay: (a) H_2O/Na_2O vs UCS; and (b) H_2O/SiO_2 vs UCS.

3.6 SEM characterisation of optimum mixture of geopolymer-stabilised clay

The microstructure fabric of geopolymer-stabilised clay was examined using scanning electron microscopy (SEM). Fig. 19 shows the microstructure of two mixtures, i.e. M(20-20-0) and M(20-

20-40), cured at 7 and 28 days, respectively, and representing the early stage and advanced stage of geopolymerisation at ambient temperature. Generally speaking, the homogeneity of the clay fabric was enhanced with the increase of geopolymer binder and curing time. It can be seen from Fig. 19(a) that significant discontinuities and voids in the soil fabric are indicated for wet mixing (without activation). On the contrary, it can also be seen from Fig. 19(b, c) that the activation of fly-ash and slag within the stabilised clay mixture resulted in more closely linked clay particles and fewer voids due to the initial compaction enhancement and gel formation/hardening with the curing time. The clay fabric enhancement is believed to produce a durable higher strength clay structure, and these findings are in agreement with those observed in the earlier geopolymer-soil studies carried out by different researchers (Cristelo et al. 2012b; Zhang et al. 2013; Liu et al. 2016).

Although an enhancement of the clay fabric was achieved at 7 days, Fig.19(e) shows the presence of spherical fly-ash particles that are still unreacted. The silica and alumina of the fly-ash seem to be partially leached at this stage under the activator concentration. This is in agreement with the findings by Phummiphan et al. (2016) who confirmed the gradual improvement of the stabilised soil properties with time due to the gradual reaction of fly-ash with the activator at certain concentrations. Interestingly, the reactivity of the fly-ash used in the geopolymer binder seemed to be related more to its particle size. For example, the distribution of the fly-ash particle size within the clay mixture before and after activation at 7 days [see Fig. 19(d, e)] confirms the reaction of the smallest fly-ash particles in comparison to the larger particles, which remained intact. Obviously, the reaction of the smallest particles are responsible for the short-term enhancement, whereas the larger particles are the main reason for the advanced long-term improvement. It is worthwhile noting that at higher magnification of 2 µm [see Fig. 19(f)], a cementitious geopolymer gel was detected in the activated mixture cured for 28 days.

Fig.19 SEM results of geopolymer-stabilised clay for: (a) un-activated mixture-10µm; (b) activated-7days-10µm; (c) activated-28days-10µm; (d) un-activated-5µm; (e) activated-7days-5µm; and (f) activated-28 days-2µm.

4. Conclusions

In this paper, the use of ground granulated blast-furnace (GGBFS) slag blended fly-ash geopolymer binder for kaolin clay stabilisation at ambient temperature was investigated. The compaction characteristics and strength development of geopolymer-stabilised clay for curing time 7, 28 and 90 days were evaluated. Further examination was made to address the durability performance and the effect of activator leaching on the geopolymer-stabilised clay. The microstructure of the optimum geopolymer-treated clay mixture was also investigated by SEM analysis. A set of geopolymer-stabilised clay specimens containing the following mixtures: ratios of source material (i.e. fly-ash + slag) to dry material equal to 10%, 20% and 30%; slag-to-source material = 0%, 10% and 20%; and activator-to-source material = 40% and 80%, were investigated and compared. The results of the geopolymer-clay mixtures were also compared with un-activated clay mixtures containing only fly-ash and GGBFS without activator, as well as soil stabilised with ordinary Portland cement (OPC). The following conclusions are drawn from this study:

- Higher percentage of source material (i.e. fly-ash + slag) and the corresponding activator quantity offers an early enhancement to geopolymer-stabilised clay through an increase in the maximum dry unit weight and a decrease in the corresponding optimum moisture content required for compaction.
- The unconfined compressive strength of geopolymer-stabilised clay increases with the addition of GGBFS as a partial replacement of fly-ash for curing time up to 90 days. However, at low concentration of slag-to-source material = 10%, little strength gain was offered

compared to slag-to-source material = 20%. A mixture that contains source material-to-dry material = 20%; slag-to-source material = 20%; and activator-to-source material = 40% resulted in soil strength development index to increase to 6 and 9.7 at 7 and 28 days, respectively, compared to 2.1 and 6.5 for soil stabilised without slag. This mixture was also found to give soil strength equivalent to that obtained from soil stabilised with 9% OPC at curing time = 7 days. Interestingly, at curing time ≥ 28 days, the mixture provided superior strength improvement over soil stabilised with 9% OPC.

- The geopolymer mixtures suggested in this research can effectively modify and stabilise clay soil for field conditions when the binder proportioned in the mixtures applied properly. Low dosage of geopolymer was found to produce strength enhancement of treated clay but may not necessarily enhance the durability performance against accelerated weathering conditions. The durability of geopolymer-stabilised clay seems to exhibit less stable performance in the freezing climate than the tropical climate, confirming the retardation of the geopolymerisation reaction at very low temperature.
- During curing and under an extreme field wetting condition, leaching of the activator was found to be a minor concern for geopolymer clay stabilisation in terms of the residual strength. The field protection against water infiltration may be recommended during the initial curing time to maintain a long-term reaction and to attain good strength and durability performance.
- The molarity ratios of geopolymer binder in terms of $SiO_2/Al2O_3$, Na_2O/SiO_2 and Na_2O/Al_2O_3 were found to comply with the ranges recommended in the literature (i.e. $SiO_2/Al2O_3 = 3.3–4.5$, $Na_2O/SiO_2 = 0.2 – 0.48$ and $Na_2O/Al_2O_3 = 0.8 –1.6$) for higher strength performance. On the contrary, the reduction of H_2O/Na_2O and H_2O/SiO_2 to the predefined suggested limits of 44.45 and 6.24, respectively, was found to have a significant role in the strength gain. This also showed a crucial influence on the durability performance against the wetting-drying

weather conditions. For economic and practical utilisation, the following molarity limits are suggested: $SiO_2/Al_2O_3 \geq 4.08$, $Na_2O/SiO_2 \geq 0.14$, $Na_2O/Al_2O_3 \geq 0.57$, $H_2O/Na_2O \leq 44.45$ and $H_2O/SiO_2 \leq 6.24$.

- The SEM analysis carried out on the geopolymer-stabilised clay provided an evidence of a gradual homogeneity improvement in the clay fabric due to the geopolymer gel formation, leading to development of an increased rate of compressive strength gain with the increase in curing time.

The results obtained in this study clearly promote the potential use of geopolymer as an effective and environmentally-friendly alternative binder to traditional OPC for soil stabilisation. However, the results presented in the current study focussed mainly on kaolin clay and further studies are needed for other soils.

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References

American Society for Testing and Materials ASTM 559 (2003) Standard test methods for wetting and drying compacted soil-cement mixtures. West Conshohcken, PA

American Society for Testing and Materials ASTM D560 (2015) Standard test methods for freezing and thawing compacted soil-cement mixtures. West Conshohcken, PA

Bernal SA, Provis JL (2014) Durability of alkali-activated materials: progress and perspectives. Journal of the American Ceramic Society 97:997-1008. doi:10.1111/jace.12831

Chittoori BC, Puppala AJ, Wejrungsikul T, Hoyos LR (2013) Experimental studies on stabilized clays at various leaching cycles. Journal of Geotechnical and Geoenvironmental Engineering 139:1665-1675. doi:DOI: 10.1061/(ASCE)GT.1943-5606.0000920

Cristelo N, Glendinning S, Fernandes L, Pinto AT (2013a) Effects of alkaline-activated fly ash and Portland cement on soft soil stabilisation. Acta Geotechnica 8:395-405. doi:10.1007/s11440-012-0200-9

Cristelo N, Glendinning S, Miranda T, Oliveira D, Silva R (2012a) Soil stabilisation using alkaline activation of fly ash for self compacting rammed earth construction. Construction and Building Materials 36:727-735. doi:10.1016/j.conbuildmat.2012.06.037

Cristelo N, Glendinning S, Pintio A, Fernandes L (2012b) Effect of calcium content on soil stabilisation with alkaline activation. Construction and Building Materials 29:167-174. doi:10.1016/j.conbuildmat.2011.10.049

Cristelo N, Glendinning S, Pinto AT (2011) Deep soft soil improvement by alkaline activation. Proceedings of the Institution of Civil Engineers-Ground Improvement 164:73-82. doi:10.1680/grim.900032

Cristelo N, Soares E, Rosa I, Miranda T, Oliveira D, Silva R, Chaves A (2013b) Rheological properties of alkaline activated fly ash used in jet grouting applications. Construction and Building Materials 48:925-933. doi:10.1016/j.conbuildmat.2013.07.063

Das BM (2010) Geotechnical engineering handbook. J. Ross Publishing, Florida

Davidovits J (2008) Geopolymer chemistry and applications. 2nd ed. edn. Saint-Quentin, France: Institut Géopolymère,

Duxson P (2009) Geopolymer precursor design. In: Deventer JLP, Jannie SJv (eds) Geopolymers: Structures, Processing, Properties and Industrial Applications. Woodhead Publishing, Abingdon UK, pp 37-49. doi:10.1533/9781845696382.1.37

Garcia-Lodeiro I, Palomo A, Ernandez-Jimenez AF (2014) An overview of the chemistry of alkali-activated cement-based binders. In: Pacheco-Torgal F, Labrincha J, Leonelli C, Sargent P (eds) Handbook of alkali-activated cements, mortars and concretes. Elsevier Science, Instituto Eduardo Torroja (IETcc-CSIC), Madrid, Spain, pp 47-47. doi:10.1533/9781782422884.1.19

Gianoncelli A, Zacco A, Struis RP, Borgese L, Depero LE, Bontempi E (2013) Fly ash pollutants, treatment and recycling. In: Pollutant diseases, remediation and recycling, vol 4.

Environmental Chemistry for a Sustainable World. Springer, pp 103-213. doi:10.1007/978-3-319-02387-8_3

Han J (2015) Principles and practice of ground improvement. John Wiley & Sons, New Jersey

Hardjito D (2005) Studies on fly ash-based geopolymer concrete. Ph.D. Thesis, Curtin University of Technology

Horpibulsuk S, Suksiripattanapong C, Samingthong W, Rachan R, Arulrajah A (2015) Durability against wetting-drying cycles of water treatment sludge-fly ash geopolymer and water treatment sludge-cement and silty clay-cement systems. Journal of Materials in Civil Engineering 28:04015078. doi:10.1061/(ASCE)MT.1943-5533.0001351

Hughes P, Glendinning S (2004) Deep dry mix ground improvement of a soft peaty clay using blast furnace slag and red gypsum. Quarterly Journal of Engineering Geology and Hydrogeology 37:205-216

Karol RH (2003) Chemical grouting and soil stabilization, 3rd Ed. vol 12. Marcel Dekker, New jersey

Khale D, Chaudhary R (2007) Mechanism of geopolymerization and factors influencing its development: a review. Journal of Materials Science 42:729-746. doi:10.1007/s10853-006-0401-4

Kirsch K, Bell A (2012) Ground improvement, 3rd Ed. CRC Press, New York

Komnitsas K, Zaharaki D (2007) Geopolymerisation: A review and prospects for the minerals industry. Minerals Engineering 20:1261–1277. doi:10.1016/j.mineng.2007.07.011

Liew YM et al. (2012) Optimization of solids-to-liquid and alkali activator ratios of calcined kaolin geopolymeric powder. Construction and Building Materials 37:440-451. doi:10.1016/j.conbuildmat.2012.07.075

Liu Z, Cai C, Liu F, Fan F (2016) Feasibility study of loess stabilization with fly ash–based geopolymer. Journal of Materials in Civil Engineering 28. doi:10.1061/(ASCE)MT.1943-5533.0001490

Lorenzo GA, Bergado DT (2006) Fundamental characteristics of cement-admixed clay in deep mixing. Journal of Materials in Civil Engineering 18:161-174. doi:10.1061/(ASCE)0899-1561(2006)18:2(161)

Markou I, Atmatzidis D (2002) Development of a pulverized fly ash suspension grout. Geotechnical and Geological Engineering 20:123-147

McCallister LD, Petry TM (1992) Leach tests on lime-treated clays. Geotechnical Testing Journal 15:106-114. doi:10.1520/GTJ10232J

Pacheco-Torgal F (2014) Introduction to handbook of alkali-activated cements, mortars and concretes. In: Handbook of Alkali-activated Cements, Mortars and Concretes. Elsevier,

Pacheco-Torgal F, Castro-Gomes J, Jalali S (2008) Alkali-activated binders: A review. Part 2. About materials and binders manufacture. Construction and Building Materials 22:1315-1322. doi:10.1016/j.conbuildmat.2007.03.019

Phummiphan I, Horpibulsuk S, Sukmak P, Chinkulkijniwat A, Arulrajah A, Shen S-L (2016) Stabilisation of marginal lateritic soil using high calcium fly ash-based geopolymer. Road Materials and Pavement Design 0629:1-15. doi:10.1080/14680629.2015.1132632

Porbaha A, Shibuya S, Kishida T (2000) State of the art in deep mixing technology. Part III: Geomaterial characterization. Proceedings of the Institution of Civil Engineers-Ground Improvement 4:91-110

Provis JL, Bernal SA (2014) Geopolymers and related alkali-activated materials. Annual Review of Materials Research 44:299-327. doi:10.1146/annurev-matsci-070813-113515

Rios S, Cristelo N, Viana Da Fonseca A, Ferreira C (2016) Structural performance of alkali-activated soil ash versus soil cement. Journal of Materials in Civil Engineering 28. doi:10.1061/(ASCE)MT.1943-5533.0001398

Roy DM (1999) Alkali-activated cements Opportunities and challenges. Cement and Concrete Research 29:249-254. doi:10.1016/S0008-8846(98)00093-3

Sargent P, Hughes PN, Rouainia M, White ML (2013) The use of alkali activated waste binders in enhancing the mechanical properties and durability of soft alluvial soils. Engineering Geology 152:96-108. doi:10.1016/j.enggeo.2012.10.013

Shi C, Jiménez AF, Palomo A (2011) New cements for the 21st century: the pursuit of an alternative to Portland cement. Cement and concrete research 41:750-763

Siddique R, Iqbal Khan M, Chandra S, Berntsson L (2011) Fly Ash vol 37. Supplementary cementing materials. Springer Berlin Heidelberg. doi:10.1007/978-3-642-17866-5_1

Singhi B, Laskar AI, Ahmed MA (2017) Mechanical behavior and sulfate resistance of alkali activated stabilized clayey soil. Geotechnical and Geological Engineering 35:1907-1920. doi:DOI 10.1007/s10706-017-0216-x

Standards Australia AS 1289.4.3.1 (1997) Methods of testing soils for engineering purposes-Method 4.3.1: soil chemical tests-determination of the pH value of a soil-electrometric method. Sydney, NSW

Standards Australia AS 3582.1 (1998) Supplementary cementitious materials for use with portland and blended cement-Part 1: fly ash. Sydney, NSW

Standards Australia AS 3582.2 (2001) Supplementary cementitious materials for use with portland and blended cement-Part 2: slag-ground granulated iron blast-furnace. Sydney, NSW

Standards Australia AS 1289.5.1.1 (2003) Method 5.1.1: soil compaction and density tests-determination of the dry density/moisture content relation of a soil using standard compactive effort. Sydney, NSW

Standards Australia AS 5101.4 (2008) Methods for preparation and testing of stabilized materials -Method 4: unconfined compressive strength of compacted materials. Sydney, NSW

Standards Australia AS 1289.3.2.1 (2009) Method 3.2.1: soil classification tests-determination of the plastic limit of a soil-standard method. Sydney, NSW

Standards Australia AS 1289.3.1.1 (2015) Method 3.9.1: soil classification tests-determination of the liquid limit of a soil. Sydney, NSW

Sukmak P, Horpibulsuk S, Shen S-L, Chindaprasirt P, Suksiripattanapong C (2013) Factors influencing strength development in clay–fly ash geopolymer. Construction and Building Materials 47:1125-1136. doi:10.1016/j.conbuildmat.2013.05.104

Verdolotti L, Iannace S, Lavorgna M, Lamanna R (2008) Geopolymerization reaction to consolidate incoherent pozzolanic soil. Journal of Materials Science 43:865-873. doi:10.1007/s10853-007-2201-x

Wilkinson A, Haque A, Kodikara J (2010a) Stabilisation of clayey soils with industrial by-products: Part A. Proceedings of the Institution of Civil Engineers-Ground Improvement 163:149-163. doi:10.1680/grim.2010.163.3.149

Wilkinson A, Haque A, Kodikara J (2010b) Stabilisation of clayey soils with industrial by-products: Part B. Proceedings of the Institution of Civil Engineers-Ground Improvement 163:165-172. doi:10.1680/grim.2010.163.3.165

Xu H, Van Deventer J (2000) The geopolymerisation of alumino-silicate minerals. International Journal of Mineral Processing 59:247-266. doi:10.1016/S0301-7516(99)00074-5

Yi Y, Li C, Liu S (2014) Alkali-activated ground-granulated blast furnace slag for stabilization of marine soft clay. Journal of Materials in Civil Engineering 27:04014146. doi:10.1061/(ASCE)MT.1943-5533.0001100

Yip CK, Lukey G, Van Deventer J (2005) The coexistence of geopolymeric gel and calcium silicate hydrate at the early stage of alkaline activation. Cement and Concrete Research 35:1688-1697

Zhang M, Guo H, El-Korchi T, Zhang G, Tao M (2013) Experimental feasibility study of geopolymer as the next-generation soil stabilizer. Construction and Building Materials 47:1468-1478. doi:10.1016/j.conbuildmat.2013.06.017

Zhang M, Zhao M, Zhang G, Nowak P, Coen A, Tao M (2015) Calcium-free geopolymer as a stabilizer for sulfate-rich soils. Applied Clay Science 108:199-207. doi:10.1016/j.clay.2015.02.029

Fig. 1

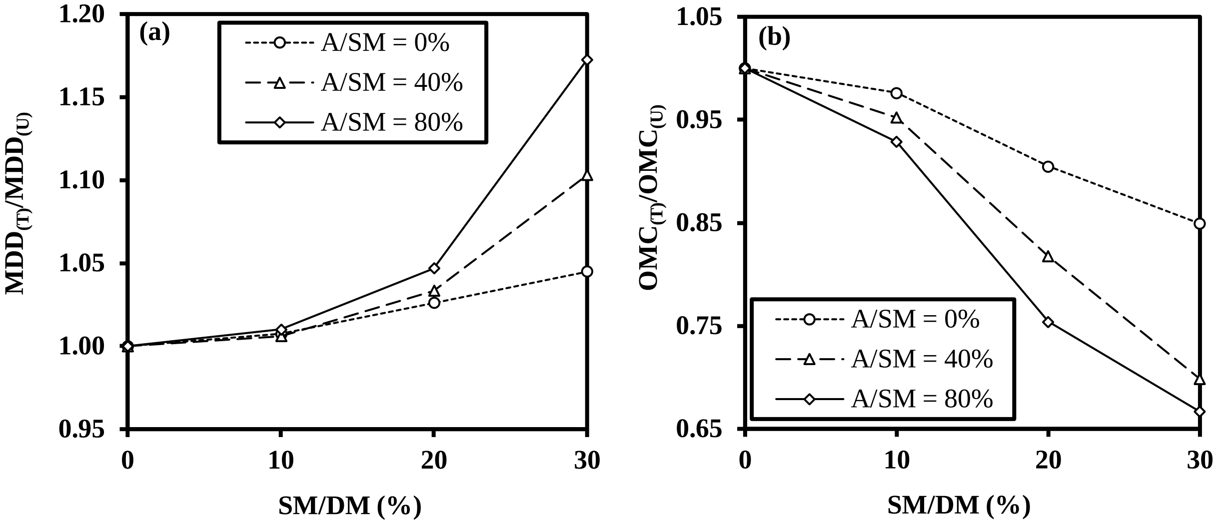
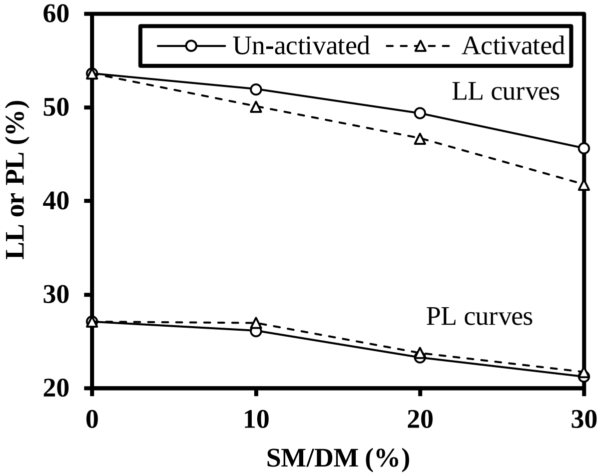


Fig. 2



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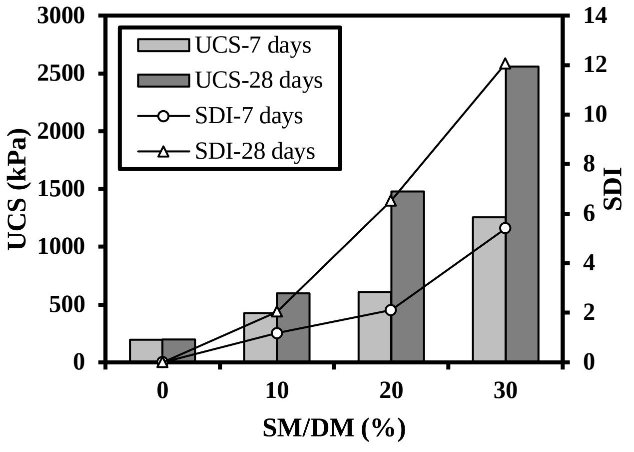

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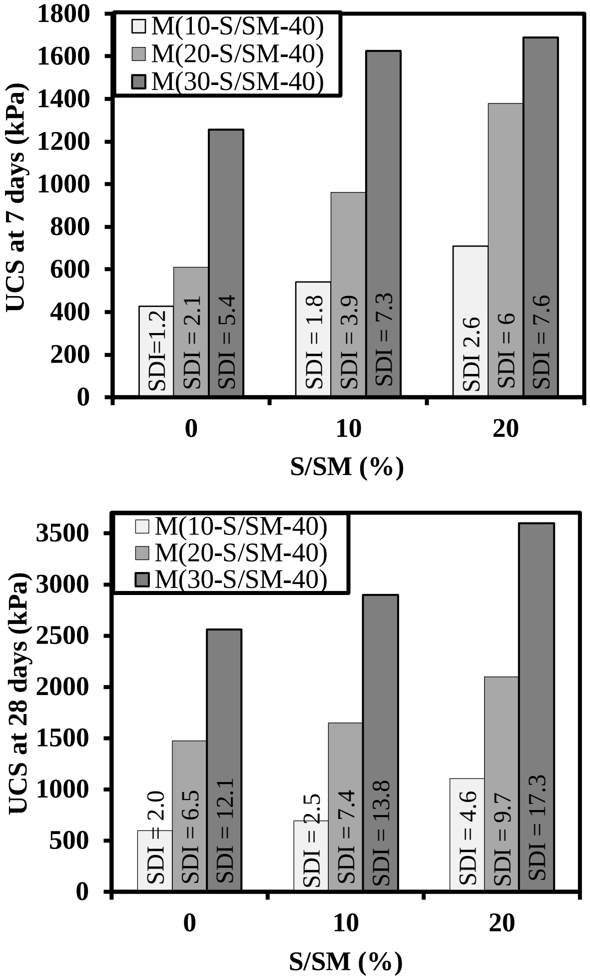


M(10-S/SM-40)
M(20-S/SM-40)
M(30-S/SM-40)
UCS at 7 days (kPa)
1800
1600
1400
1200
1000
800
600
400
200
0
SDI=1.2
SDI = 2.1
SDI = 5.4
SDI = 1.8
SDI = 3.9
SDI = 7.3
SDI 2.6
SDI = 6
SDI = 7.6
0
10
20
S/SM (%)
M(10-S/SM-40)
M(20-S/SM-40)
M(30-S/SM-40)
UCS at 28 days (kPa)
3500
3000
2500
2000
1500
1000
500
0
SDI = 2.0
SDI = 6.5
SDI = 12.1
SDI = 2.5
SDI = 7.4
SDI = 13.8
SDI = 4.6
SDI = 9.7
SDI = 17.3
0
10
20
S/SM (%)

Fig. 5

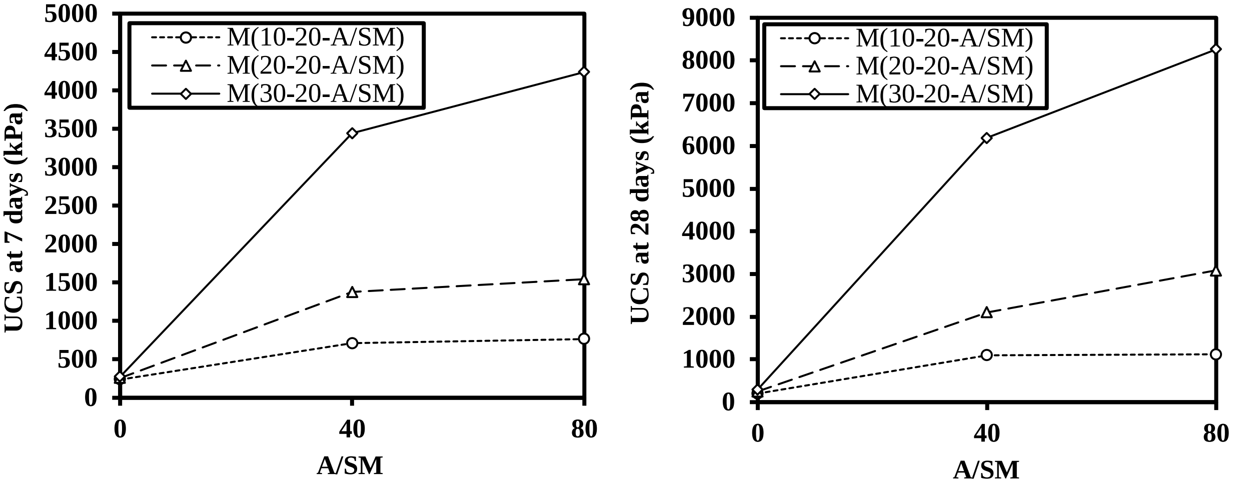


Fig. 6

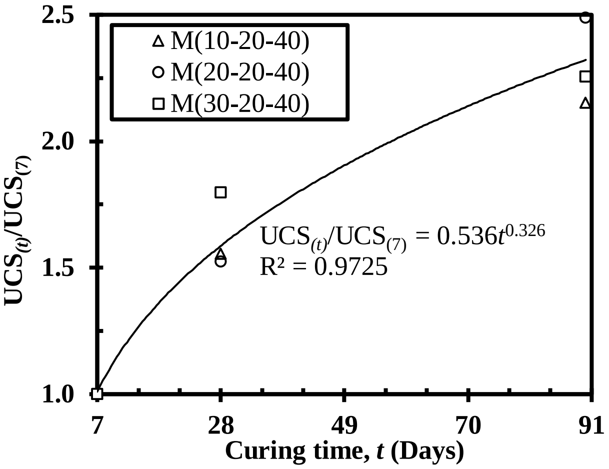


Fig. 7

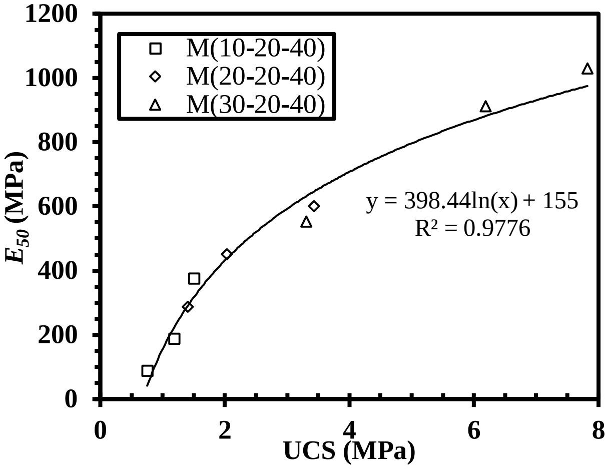


Fig. 8

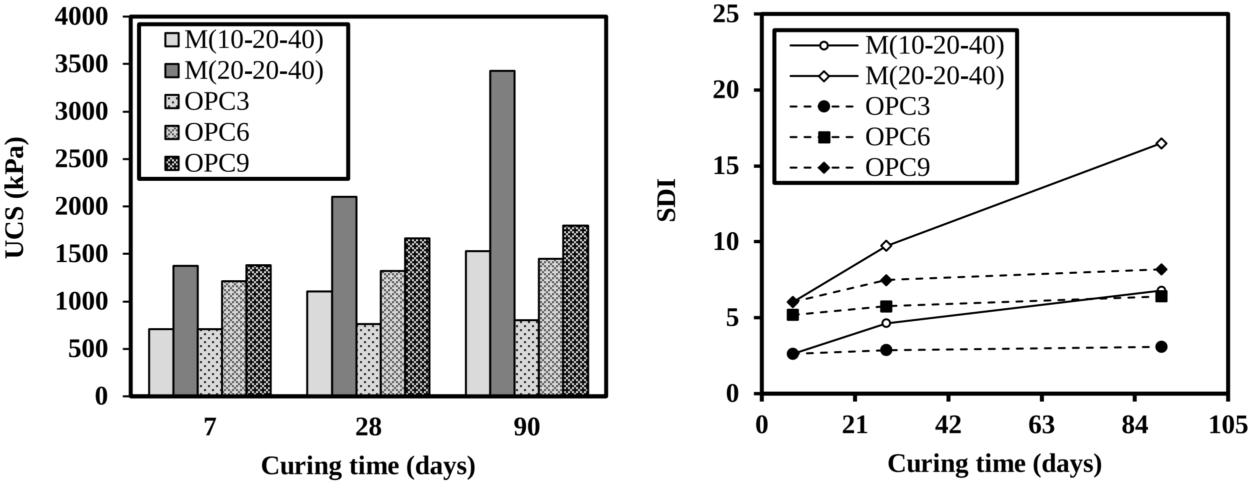


Fig. 9

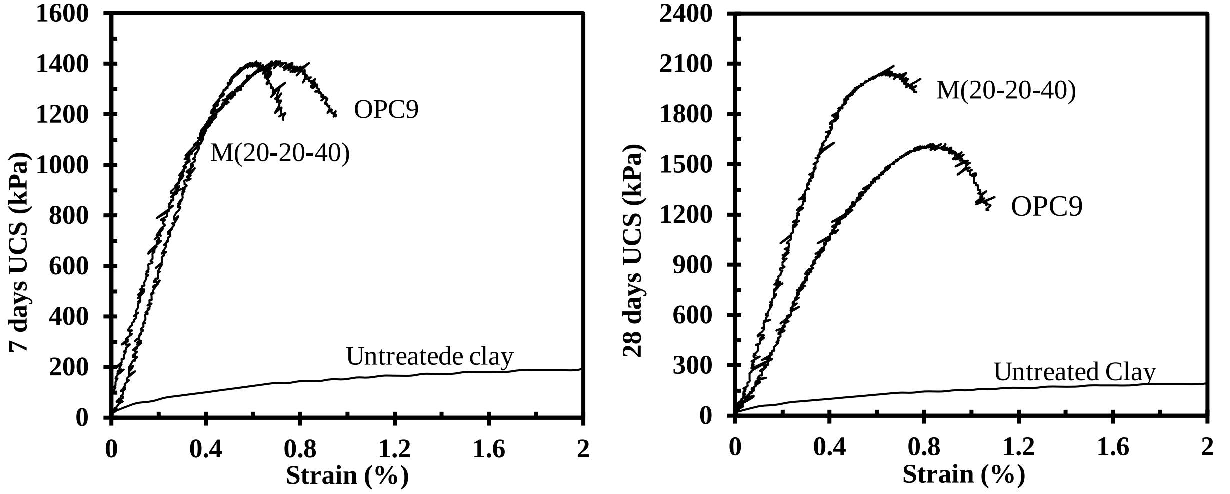


Fig. 10

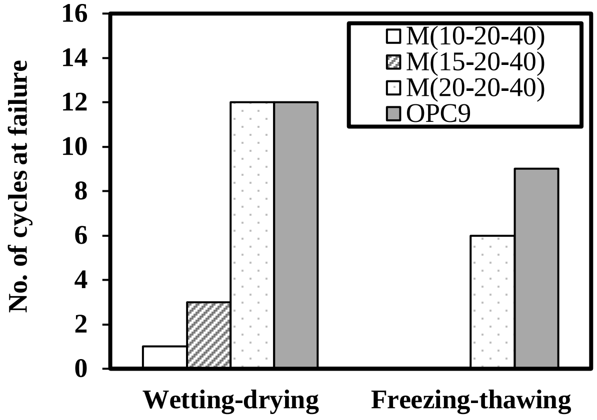


Fig. 11

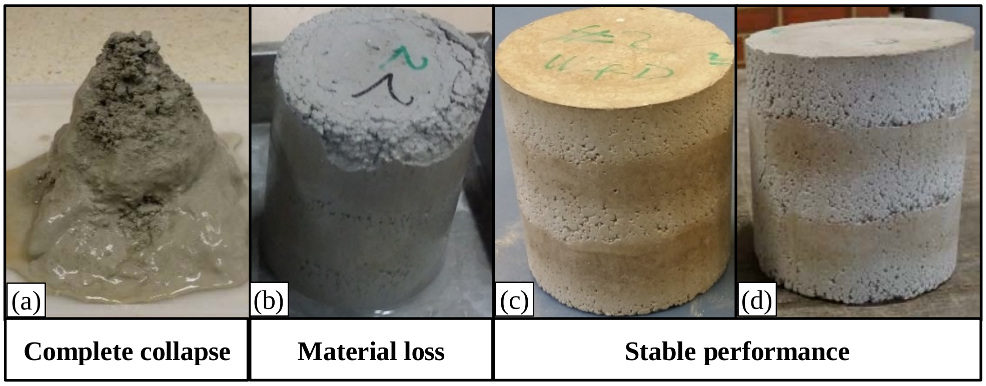

(a)
(b)
(c)
(d)
Complete collapse
Material loss
Stable performance

Fig. 12

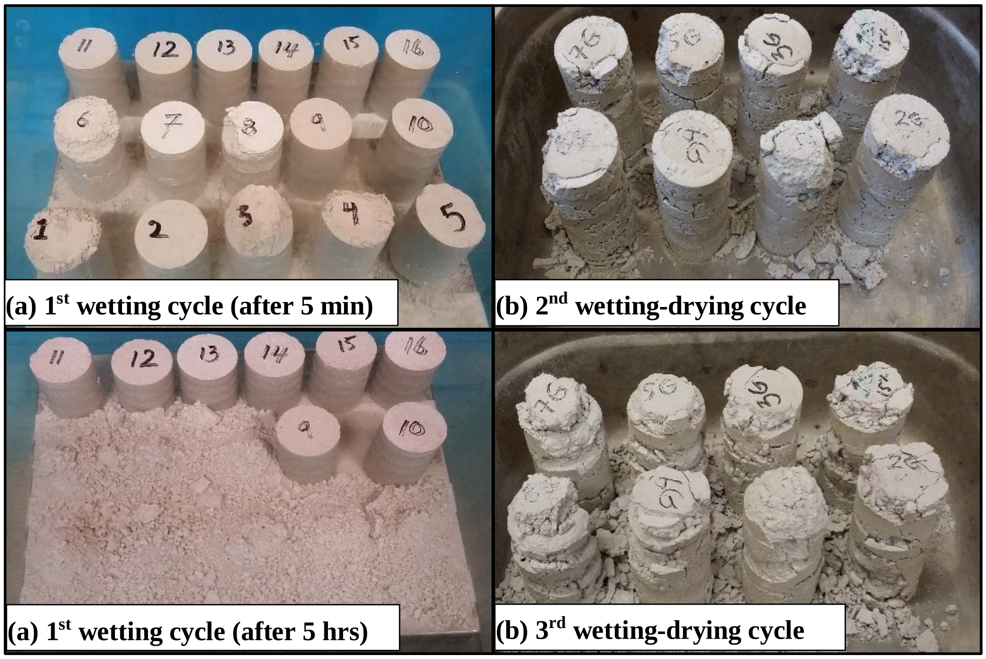

(a) 1st wetting cycle (after 5 min)
(b) 2nd wetting-drying cycle
(a) 1st wetting cycle (after 5 hrs)
(b) 3rd wetting-drying cycle

Fig. 13

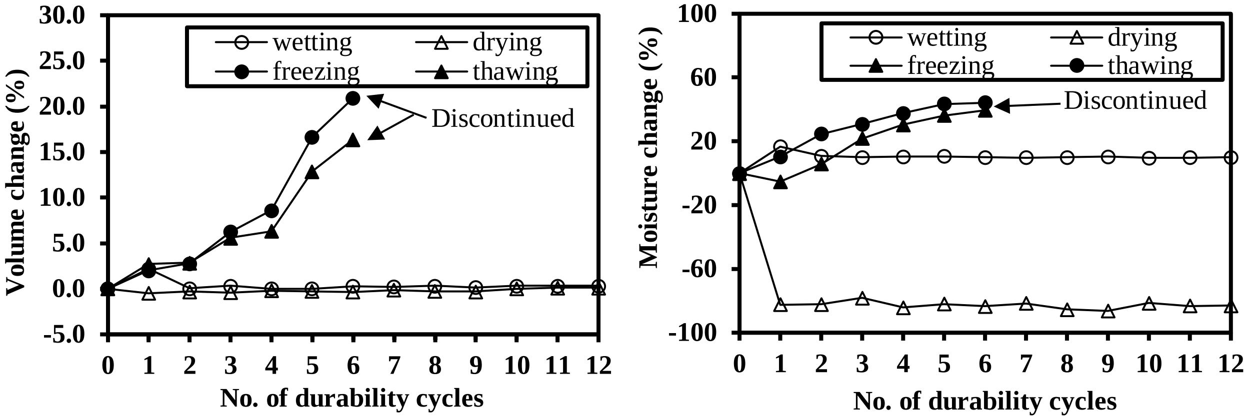


Fig. 14

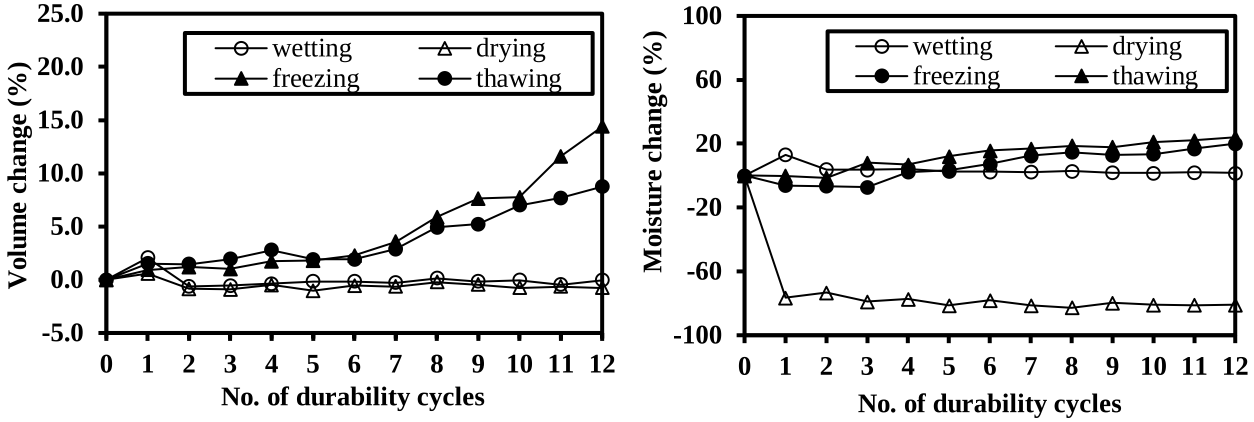


Fig. 15

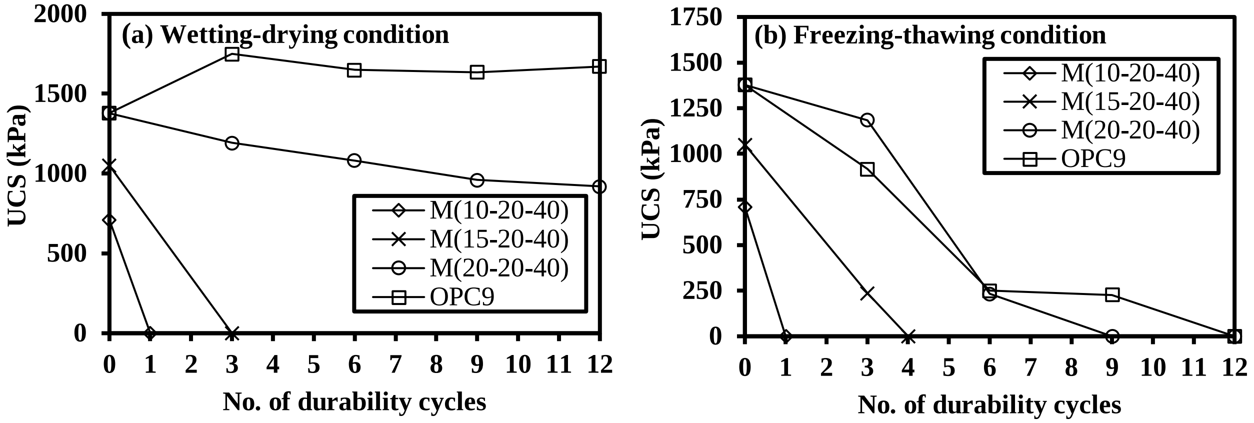


Fig. 16

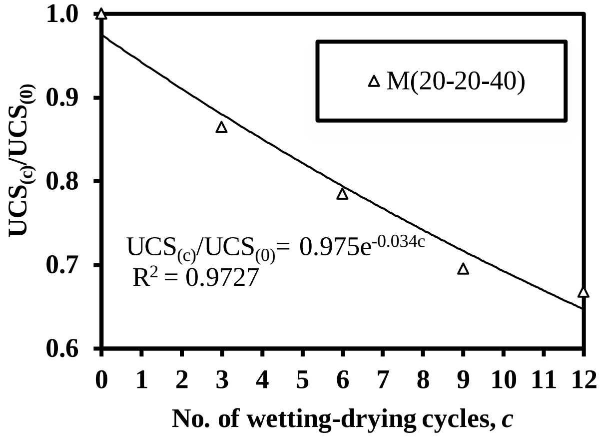


Fig. 17

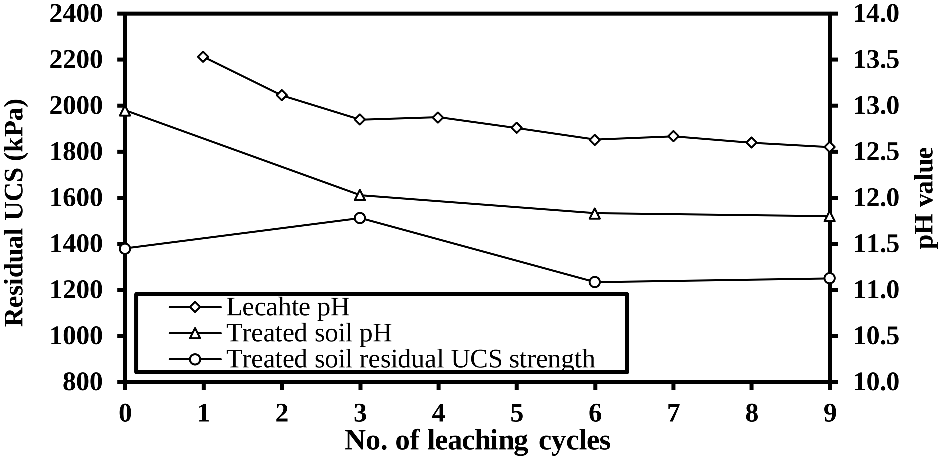


Fig. 18

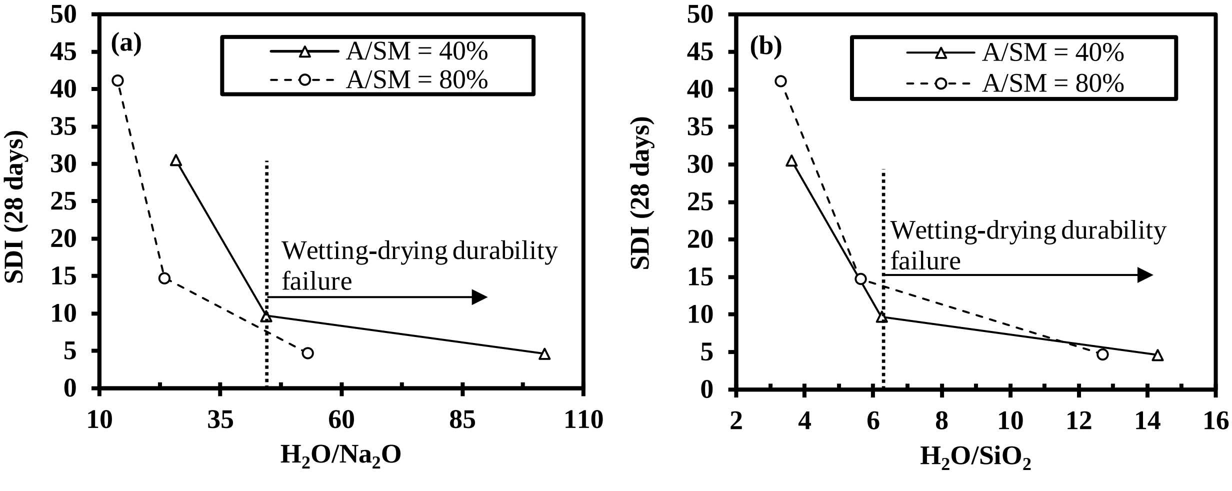
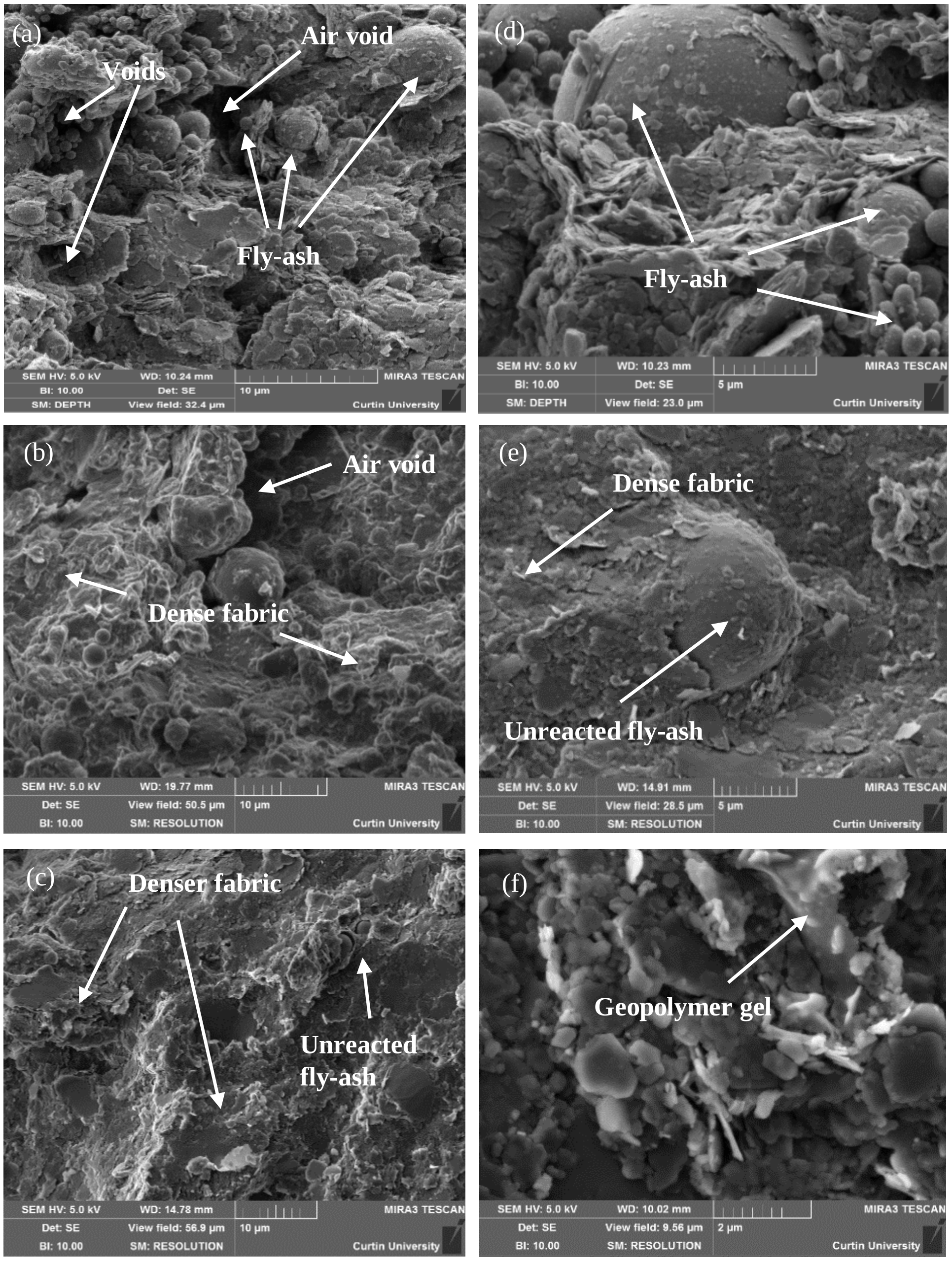


Fig.19


(a)
Air void
Voids
Fly-ash
SEM HV: 5.0 kV
WD: 10.24 mm
MIRA3 TESCAN
BI: 10.00
Det: SE
10 µm
SM: DEPTH
View field: 32.4 µm
Curtin University
(d)
Fly-ash
SEM HV: 5.0 kV
WD: 10.23 mm
MIRA3 TESCAN
BI: 10.00
Det: SE
5 µm
SM: DEPTH
View field: 23.0 µm
Curtin University
(b)
Air void
Dense fabric
SEM HV: 5.0 kV
WD: 19.77 mm
MIRA3 TESCAN
Det: SE
View field: 50.5 µm
10 µm
BI: 10.00
SM: RESOLUTION
Curtin University
(e)
Dense fabric
Unreacted fly-ash
SEM HV: 5.0 kV
WD: 14.91 mm
MIRA3 TESCAN
Det: SE
View field: 28.5 µm
5 µm
BI: 10.00
SM: RESOLUTION
Curtin University
(c)
Denser fabric
Unreacted
fly-ash
SEM HV: 5.0 kV
WD: 14.78 mm
MIRA3 TESCAN
Det: SE
View field: 56.9 µm
10 µm
BI: 10.00
SM: RESOLUTION
Curtin University
(f)
Geopolymer gel
SEM HV: 5.0 kV
WD: 10.02 mm
MIRA3 TESCAN
Det: SE
View field: 9.56 µm
2 µm
BI: 10.00
SM: RESOLUTION
Curtin University