

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.

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

29 **1. Introduction**

30 Soft soils are problematic in nature and pose serious challenges to the service life of infrastructure
31 projects due to their high compressibility and low load-carrying capacity. Chemical stabilisation,
32 using ordinary Portland cement (OPC), has been widely employed as a traditional solution for
33 ground improvement, where the properties of problematic soils are altered through hydration and
34 pozzolanic reactions (Karol 2003; Das 2010; Kirsch and Bell 2012; Han 2015). However, the use
35 of OPC and the associated carbon footprint raised serious environmental issues in the last decades.
36 For example, manufacturing of 1 tonne of OPC has been usually found to release about 0.8–1.0
37 tonne of carbon dioxide (CO₂) to the atmosphere; the OPC manufacturing is estimated to account
38 for about 7% of the total artificial CO₂ emission (Garcia-Lodeiro et al. 2014). Considering such an
39 emission problem along with some other environmental detrimental effects related to the sourcing
40 of non-renewable raw materials, an enormous motivation exists for finding more environmentally-
41 friendly and cost-effective alternative binders to replace OPC (Roy 1999; Hardjito 2005;
42 Komnitsas and Zaharaki 2007; Davidovits 2008; Siddique et al. 2011; Pacheco-Torgal 2014).

43 It has been found in the literature that the bonding characteristics offered by the alkaline
44 activation of some abended pre-calcined by-products, such as geopolymers, can introduce an
45 effective alternative binder to OPC (Roy 1999; Davidovits 2008; Pacheco-Torgal et al. 2008; Shi
46 et al. 2011). Geopolymer is a low-calcium alkali aluminosilicate gel that is usually synthesised
47 from two main components including fly-ash or metakaolin plus potassium or sodium liquid-based
48 activator (Provis and Bernal 2014). The use of fly-ash based geopolymers contribute to a
49 considerable reduction in the energy consumption and CO₂ emission (Siddique et al. 2011). In
50 brief, the geopolymerisation process involves the following four main steps: (1) leaching by which
51 a dissolution of solid aluminosilicate oxides from source materials in an alkaline environment
52 provided by solution activator with high pH value; (2) diffusion (migration) of the dissolved Al

53 and Si complexes; and (3) gel formation through chemical condensation (polycondensation)
54 between the added solution and Al and Si complexes before the final step of gel hardening
55 (Komnitsas and Zaharaki 2007). Depending on the synthesised conditions, geopolymers can
56 possess good mechanical properties such as low permeability, high compressive strength, high
57 durability and low volumetric changes (Xu and Van Deventer 2000; Gianoncelli et al. 2013;
58 Horpibulsuk et al. 2015). However, several factors may control the mechanical properties of
59 geopolymer including properties of source materials, chemical composition of activator, curing
60 time and treatment temperature (Sukmak et al. 2013; Zhang et al. 2013). Among these factors, the
61 curing temperature is the most challenging for field implementation (Xu and Van Deventer 2000).
62 Geopolymers are usually cured at temperatures ranging from 60–90°C (Liew et al. 2012); hence,
63 most geopolymers have been limited in use to steamed or dry heat-cured concrete (Gianoncelli et
64 al. 2013). For geotechnical engineering applications, geopolymers have to be utilised at ambient
65 temperature as it is not practically applicable to be treated at elevated heat. However, the use of
66 geopolymers at ambient temperature maintains slow rate of geopolymerisation; hence,
67 geopolymer-stabilised soils usually take long time for strength enhancement. A curing time of 90
68 days is normally required for geopolymer-stabilised soils treated at ambient temperature to gain
69 equivalent strength to that obtained from OPC treated soils at 28 days (Cristelo et al. 2012b).
70 Therefore, to increase the feasibility of using geopolymers for soil stabilisation at ambient
71 temperature and to make it more comparable to OPC treated soils, low water-to-binder ratio and
72 high contents of activator and binder are required to overpass the delay in the setting time and
73 strength development (Bernal and Provis 2014). However, water is essential for soil to achieve
74 proper compaction and the use of high content of geopolymer with low water content might
75 involve mixing difficulties; this is a salient feature that is investigated in the current study.

76 Considering the nature of the cementitious components of different source materials used in
77 alkaline binders, three alkaline activation models can be derived, as follows (Garcia-Lodeiro et al.
78 2014). *Model-I* is usually derived from low calcium high aluminosilicate materials such as fly-ash
79 or metakaolin, which when activated forms a gel of bonding characteristics of three-dimensional
80 framework (i.e. geopolymer). This model is represented by the chemical structure Sodium
81 Aluminate Silicate Hydrate (N-A-S-H), and the literature includes several studies that have used
82 this model for soil stabilisation (e.g. Markou and Atmatzidis 2002; Wilkinson et al. 2010b; Cristelo
83 et al. 2011; Cristelo et al. 2013a; Zhang et al. 2013; Liu et al. 2016). *Model-II* produces a
84 fundamental Calcium Aluminate Silicate Hydrate (C-A-S-H) gel similar to the gel obtained during
85 the OPC hydration. It is important to emphasise that the activation of by-product source materials
86 of this model with high calcium content > 70% (e.g. blast furnace slag) usually leads to a reaction
87 output different from that of geopolymer. Consequently, there is a debate in the literature of
88 whether or not this model may be classified as geopolymer. Examples of previous studies carried
89 out using this model for soil stabilisation include the work done by Hughes and Glendinning
90 (2004), Wilkinson et al. (2010a), Sargent et al. (2013) and Yi et al. (2014). *Model-III* is comprised
91 of the two preceding models (hybrid), which consists of activated fly-ash and slag, where a
92 combination of the N-A-S-H and C-A-S-H gels is introduced in the reaction process, to enhance
93 the effectiveness of the geopolymer at ambient temperature. This process assists in bringing the
94 strength of geopolymer-treated soils to the economical boundary. Limited studies are available in
95 the literature on the use of this model for soil stabilisation (e.g., Sargent et al. 2013; Singhi et al.
96 2017); hence, there is an immense need for further studies on this model and the current work will
97 fill out this gap.

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

100 Cristelo et al. 2011; Cristelo et al. 2012b; Cristelo et al. 2013a; Zhang et al. 2013; Zhang et al.
101 2015; Liu et al. 2016; Phummiphan et al. 2016; Singhi et al. 2017). However, the long-term
102 performance of geopolymer-stabilised soils in terms of durability and leaching have not been
103 considered extensively. There is currently no specific designation in the literature for the optimum
104 amount of geopolymer that can attain durability as specified to OPC treated soils. In fact, the lack
105 of detailed investigation on the durability performance of geopolymer-stabilised soils is one of the
106 main reasons restricting the extensive use of this promising technique for ground improvement. In
107 the current study, the durability of geopolymer-stabilised clay will be investigated in detail under
108 different weathering conditions, including wetting-drying and freezing-thawing. In addition, the
109 water infiltration (rainfall or groundwater) will be investigated through leaching tests.

110

111 **2. Materials and Methodology**

112 **2.1 Soil used**

113 In this study, kaolin clay was selected due to its well-defined characteristics and availability. Table
114 1 shows the chemical composition of the clay used, which is Prestige NY clay commercially
115 available in the form of white coloured kaolin produced in Western Australia. The chemical
116 composition of other materials used in the current study are also shown in Table 1 and will be
117 discussed later. The percentage of fines of the clay used is 79.4% passing 2 μm and its specific
118 gravity is 2.62. The plastic limit (PL) and liquid limit (LL) of this clay are determined using the
119 Australian Standards AS 1289.3.2.1 (2009) and AS 1289.3.9.1 (2015), and found to be equal to
120 27.1% and 53.6%, respectively. The compaction properties (i.e. the maximum dry unit weight and
121 the corresponding optimum moisture content) are measured using the standard Proctor test in
122 accordance with the Australian Standards AS 1289.5.1.1 (2003) and found to be equal to 14.95
123 kN/m^3 and 25.2%, respectively.

124

Table 1. Chemical compositions of materials used.

Material	Chemical composition (%)								
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	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

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126

127 2.2 Geopolymer ingredients

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

137 The fly-ash (FA) used in this study is a coal fly-ash obtained from a pulverised coal
 138 combustion, known as low calcium Gladstone fly-ash, which was supplied from Gladstone power
 139 station by Cement Australia Limited. This type of fly-ash conforms to the Australian Standards
 140 AS 3582.1 (1998) and its chemical characteristics are given in Table 1. The availability of this fly-
 141 ash as a waste material promotes its use as an economic option compared to metakaolin for better
 142 alkaline activation and geopolymer production. Low calcium fly-ash contains higher silica and

143 alumina, which puts low calcium (class F) fly-ash in favour as a source material to high calcium
144 (class C) fly-ash (Hardjito 2005; Duxson 2009; Garcia-Lodeiro et al. 2014).

145 The Ground granulated blast furnace slag (GGBFS) used in this study is a calcium-rich
146 aluminosilicate material produced from the steel industry waste and is considered to be one of the
147 most commonly used materials in alkali-activated binders (Provis and Bernal 2014). The slag used
148 was supplied by Independent Cement & Lime Ltd and complies with the Australian Standards AS
149 3582.2 (2001). The chemical composition of this type of slag is given in Table 1.

150 For soil stabilisation and geotechnical applications, activators based on sodium hydroxide
151 and sodium silicate were recommended by most researchers to synthesise geopolymers (Verdolotti
152 et al. 2008; Cristelo et al. 2011; Cristelo et al. 2012a; Cristelo et al. 2012b; Cristelo et al. 2013a;
153 Cristelo et al. 2013b; Sargent et al. 2013; Zhang et al. 2013; Zhang et al. 2015; Phummiphan et al.
154 2016; Rios et al. 2016). The activator used in this study consists of Grade D sodium silicate and
155 14M concentrated sodium hydroxide in a fixed weight ratio of 70:30. This ratio was selected
156 because it was recommended in the geopolymer literature to maximise the strength gain, as
157 reported by Hardjito (2005). Grade D sodium silicate (Na_2SiO_3) was supplied by PQ Australia and
158 contains weight dosages of $\text{Na}_2\text{O} = 14.7\%$ and $\text{SiO}_2/\text{Na}_2\text{O} = 2$. The 14M concentrated sodium
159 hydroxide (NaOH) was prepared in a fume cabinet by dissolving sodium hydroxide pellets in
160 deionised water for at least one day prior to mixing.

161

162 **2.3 Samples preparation**

163 The source material (i.e. $\text{SM} = \text{FA} + \text{S}$) was initially mixed with dry kaolin to ensure mixture
164 uniformity and to form the total dry material, which is denoted herein as (DM). To form the
165 ultimate moisture for the optimum compaction, the liquid activator was diluted with additional
166 free water before use, and was then mixed with the DM. Table 2 summarises details of the mixtures

167 used. A code was used to identify the different mixtures involved, as follows: M(SM/DM-S/SM-
168 A/SM). The letter M before the bracket is an abbreviation of the word “Mixture” followed by three
169 ratios: SM/DM, S/SM and A/SM, indicated inside a bracket and separated by hyphens.

170 Directly after mixing, the effect of additives on the compaction parameters was determined
171 through a series of standard Proctor compaction tests according to the Australian Standards AS
172 1289.5.1.1 (2003). Having obtained the compaction parameters, the geopolymer-treated soil
173 mixtures were remoulded in designated specimen moulds. The specimens used for the UCS and
174 leaching tests were prepared using cylindrical polyvinyl chloride (PVC) tubes of 42 mm in
175 diameter and 84 mm in height so that an aspect ratio of height-to-diameter of 2:1 is attained. The
176 durability specimens were prepared in accordance with the ASTM D559-03 (2003) and ASTM
177 D560-15 (2015). For each specimen, the compaction was performed in layers of controlled
178 weight/thickness to replicate similar maximum dry unit weight to that obtained from the Proctor
179 test. After compaction, the end of the PVC tubes was sealed with plastic lid to avoid any moisture
180 loss, and the specimens were left to cure for 24 hours at 60% humidity and temperature of 20-25°C.
181 The specimens were then demoulded and covered again with plastic bags before curing was
182 continued at the same conditions until the samples were tested. Additional samples were prepared
183 and stabilised by adding 3%, 6% and 9% OPC (denoted herein as OPC3, OPC6 and OPC9,
184 respectively), as shown in Table 2. These samples were tested for the purpose of comparison with
185 the geopolymer-stabilised samples.

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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

192

193

194 **2.4 Tests conducted**

195 **2.4.1 Unconfined compressive strength**

196 To investigate the samples strength development, unconfined compressive strength (UCS) tests
 197 were performed at curing time of 7, 28 and 90 days. The average of two tests was reported for each
 198 mixture, and all UCS tests were performed according to the Australian Standards AS 5101.4
 199 (2008). The tests were performed on specimens of an aspect ratio of diameter-to-height equal to
 200 1:2 using a strain rate of 1% per minute. For soil samples stabilised with either geopolymer or
 201 OPC, care was taken to complete the sampling within 30 minutes after mixing so as to avoid any
 202 binder hardening interaction. In order to verify homogeneity and uniformity, the maximum dry
 203 unit weights and the corresponding optimum moisture contents were maintained for all tested UCS
 204 samples.

205 **2.4.2 Durability**

206 The durability tests were conducted in accordance with ASTM D559-03 (2003) and ASTM D560-
207 15 (2015). The tests were performed for many cycles of wetting-drying and freezing-thawing, to
208 examine the water content and volume changes due to repeated weathering conditions. In brief,
209 after completing the curing period of 7 days, standard moulded specimens were completely
210 immersed in water for 5 hrs to start the wetting-drying cycles. Then the samples were dried in the
211 oven at a temperature of 70 °C for 43 hrs. After each stage, the samples weight and dimensions
212 were measured and recorded. This process represented one cycle of wetting-drying, which requires
213 48 hrs. For the freezing-thawing cycles, freezing was performed at a temperature of -18 °C for 24
214 hrs. Following the freezing stage, the specimens were placed in the moist room having a
215 temperature of 21°C and relative humidity of 100% for 24 hrs. Care was taken to provide water-
216 saturated felt pads between the specimens and container in all stages. Similar to the wetting-drying
217 tests, the freezing-thawing procedure was designed to continue until the specimen reaches 12
218 cycles.

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

225

226 **2.4.3 Leaching**

227 The leaching tests were carried out using a triaxial cell based on the procedure recommended by
228 McCallister and Petry (1992). The cell was assembled to hold a sample of an aspect ratio of height-

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

245

246 **2.4.4 Microstructural analysis**

247 To investigate the microstructural development of geopolymer gel and to examine the change in
248 clay fabric after stabilisation, scanning electron microscopy (SEM) was performed using a fully
249 PC controlled MIRA3 XMU equipment. The SEM was carried out on geopolymer-stabilised
250 specimens of optimum geopolymer-clay mixture at curing time 7 and 28 days. The SEM was also
251 performed on samples in which only fly-ash and slag were mixed with clay at the optimum

252 moisture content without activator. Additional images were necessary to distinguish the different
253 shapes of dry particles involved before mixing.

254

255 **3. Discussion of Results**

256 **3.1 Physical properties of geopolymer-treated clay**

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

262 Generally speaking, the ratios A/SM and SM/DM were expected to control the compaction
263 parameters and are thus presented in Fig. 1. As mentioned earlier, the GGBFS (denoted as S), was
264 used as a partial replacement of fly-ash (FA) to form the geopolymer dry source material, which
265 is denoted as SM (i.e. $SM = FA + S$). Also, (DM) refers to the total dry material (i.e. dry component
266 of geopolymer and dry clay) and (A) is the alkaline activator (i.e. fixed weight ratio of 70:30 of
267 sodium silicate to 14M sodium hydroxide solution). It can be seen from Fig. 1(a) that the ratio
268 ($MDD_{(T)}/MDD_{(U)}$) increases with the increase of the ratio SM/DM, for all ratios of A/SM. Also, it
269 can be seen that activating the source material using $A/SM > 0$ confirms the significant role of the
270 activator on the MDD stabilised mixtures, especially at high SM/DM percentages. For instance,
271 an increase in the activator amount of 80% of SM (i.e. $A/SM = 80\%$) increases the ratio
272 $MDD_{(T)}/MDD_{(U)}$ by about 17% at $SM/DM = 30\%$. In contrast, it can be seen from Fig. 1(b) that
273 the ratio OMC_{KG}/OMC_K decreases with the increase of SM/DM percentages, for all ratios of
274 A/SM. Again, it can be concluded that activating the source material using $A/SM > 0$ confirms the
275 significant role of the activator on the OMC stabilised mixtures, especially at high SM/DM

276 percentages. For example, an increase in the activator amount to 80% of SM (i.e. $A/SM = 80\%$)
277 decreases the ratio $OMC_{(T)}/OMC_{(U)}$ by 33% at $SM/DM = 30\%$. This suggests that the alkaline
278 chemicals presented in the activator play a positive role in the compaction results, by partially
279 reducing some of the moisture needed to reach the optimum compaction. It is of interest to mention
280 that the role of activator was detected earlier in this research through an attempt to compact the
281 geopolymer samples in a state corresponding to MDD and OMC for un-activated soil at $A/SM =$
282 0. This indicates a significant volume of air pockets and poor compaction at higher ratio of SM/DM
283 and activator content. It should be noted that while the results presented in Fig. 1 are for $S/SM =$
284 20%, similar results were obtained for $S/SM = 0$ and 10% but are not presented for brevity.

285

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

288

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

300 activated mixtures were calculated at different SM/DM concentrations, and it was found that the
301 PI values were reduced and thus changed the initial high plasticity state of the clay used towards
302 the low plasticity state, for SM/DM ratio > 10%.

303

304 **Fig. 2** Plasticity characteristics of geopolymer-stabilised clay for samples with S/SM =
305 20% and A/SM = 40%.

306

307 **3.2 Strength performance of geopolymer-stabilised clay**

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

312

313 **3.2.1 Effect of fly-ash**

314 Using different ratios of SM/DM = 10%, 20% and 30%, as well as a fixed combination of S/SM
315 = 0 and A/SM = 40%, the effect of various fly-ash percentages as a main source material on the
316 strength improvement of geopolymer-stabilised clay was examined and the results are presented
317 as in Fig. 3. It can be seen that the increase in fly-ash percentage (i.e. SM/DM) proved to give
318 enhanced UCS values for the geopolymer-treated clay, for all mixtures at both 7 and 28 curing
319 days. In terms of the strength development index (SDI), it was found to increase by 1.2 and 2 when
320 the percentage of fly-ash was added to the clay by only 10%, for curing time of 7 days and 28
321 days, respectively. When the percentage of fly-ash was further increased to 20%, a higher
322 increment in the SDI was detected up to 2.1 and 6.5 for curing time of 7 days and 28 days,
323 respectively. It is observed that the increase in SDI is more pronounced at higher fly-ah content

324 and late curing period. However, such findings were found to be similar to those reported in the
325 literature (e.g. Cristelo et al. 2013a; Sargent et al. 2013), which are mainly related to the
326 cementitious characteristics of the activated fly-ash through the formed N-A-S-H geopolymer gel.

327

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

330

331 **3.2.2 Effect of GGBFS**

332 The effect of various slag percentages on the strength improvement of geopolymer-stabilised clay
333 was examined and the results are presented in Fig. 4, for different ratios of S/SM = 0%, 10% and
334 20%, and a fixed ratio of A/SM = 40%. It can be seen that the UCS values increases substantially
335 with the increase in S/SM ratio, for all mixtures at both 7 and 28 curing days. For instance, at S/SM
336 = 20% (i.e. replacing 20% of fly-ash with slag) the UCS value of M(20-S/SM-40) increased from
337 609 kPa to 1377 kPa (at 7 days curing time) with a corresponding SDI increase from 2.1 to 6. For
338 28 days of curing, the SDI improvement was detected to be increase from 6.5 at zero slag to 9.7
339 with slag. Such an increase in the SDI is mainly related to the role of the C-A-S-H gel produced
340 from the slag activation within the fly-ash based geopolymer, which enhanced the strength
341 performance at ambient temperature and curing time of up to 28 days. However, for all samples
342 incorporating GGBFS, the SDI was found to range between 1.8-7.6 for 7 curing days, and between
343 2.5-17.3 for 28 curing days in which the S/SM ratio = 20% has achieved the highest value and thus
344 was selected for further investigation.

345

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

348

349 3.2.3 Effect of activator

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

359

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

362

363 For mixture M(10-20-A/SM), it can be seen that an increase in the activator concentration
364 (A/SM) above 40% did not enhance the UCS values, for both 7 and 28 curing days. This may be
365 attributed to the consumption of most of the source material in the mixture. It is worthwhile noting
366 that a low development of strength at this stage may also confirm a low reactivity of kaolin clay
367 for any short-term reaction of the activator. For mixture M(20-20-A/SM), an increase of 12% in
368 the UCS value was detected from $A/SM = 40\%$ to $A/SM = 80\%$ for 7 curing days, whereas an
369 increase of 47% in the UCS value was detected from $A/SM = 40\%$ to $A/SM = 80\%$ for 28 curing
370 days. Mixture M(30-20-A/SM) proved to give an increase of 23% from $A/SM = 40\%$ to $A/SM =$
371 80% for 7 curing days, and an increase of 33% for 28 curing days.

372

373 **3.2.4 Correlations of strength and stiffness**

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

381

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

383

384 It was found in the cement-soil literature that the variation of stiffness (i.e. secant modulus
385 at 50% of peak strength, E_{50}) can be correlated as an approximate value of the corresponding UCS
386 (e.g. Porbaha et al. 2000; Lorenzo and Bergado 2006). For geopolymer-stabilised clay, the results
387 demonstrate a clear correlation with a best fitting logarithmic relationship, as shown in Fig. 7,
388 which presents the E_{50} against UCS values for SM/DM = 10%, 20% and 30% tested at 7, 28 and
389 90 curing days.

390

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

393

394 **3.2.5 Strength comparison of geopolymer-treated clay with OPC treated clay**

395 Out of the geopolymer-stabilised clay mixtures used in the current study, two mixtures [i.e. M(10-
396 20-40) and M(20-20-40)] were found to give a strength range between 1000–2000 kPa, which
397 fulfils most ground improvement applications and were thus recommended for comparison with

398 the strength results of the OPC treated soil. Fig. 8 shows the results of such a comparison in terms
399 of the UCS values, SDI and the corresponding curing time. It can be seen that at curing time = 7
400 days, the strength of geopolymer-stabilised clay mixture M(10-20-40) is equivalent to that of
401 OPC3 (SDI = 2.6), whereas the strength of geopolymer-stabilised clay mixture M(20-20-40) is
402 comparable to OPC9 (SDI = 6). At 28 and 90 curing days, the strength of geopolymer-stabilised
403 clay mixture M(10-20-40) is almost equivalent to that of OPC6, confirming a higher rate of
404 strength development in geopolymer-stabilised clay mixtures compared to that at 7 curing days.
405 On the contrary, it can be seen that the geopolymer-stabilised clay mixture M(20-20-40) shows
406 superior development in strength gain compared to all OPC treated mixtures. For example, M(20-
407 20-40) was found to achieve SDI values of 9.7 and 16.5 at 7 and 28 curing days, respectively,
408 representing an improvement of SDI of 30% and 101% more than those of OPC 9.

409

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

412

413 Fig. 9 shows UCS stress-strain curves for M(20-20-40) and OPC9 mixtures cured at 7 and
414 28 days. It can be seen that the addition of geopolymer increases the strength and stiffness of
415 treated clay, for both curing periods. At 7 days of curing, a more comparable stiffness behaviour
416 is evident to that of OPC additive. However, as the curing period is increased, the geopolymer-
417 stabilised mixture shows more stiff behaviour than OPC treated clay. The reason behind the
418 difference in stiffness between the different mixtures may be attributed to the competition between
419 the higher rate of geopolymerisation reaction in geopolymer-stabilised clay compared to the
420 hydration reaction in OPC treated clay.

421

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

423

424 **3.3 Durability performance of geopolymer-stabilised clay**

425 **3.3.1 Wetting-drying and freezing-thawing**

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

442

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

445

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

455

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

459

460 **Fig. 12** Images of geopolymer-stabilised clay samples subjected to different wetting/drying
461 cycles: (a) M(10-20-40) vs M(20-20-40), i.e. samples (1-8) vs samples (9-16); and (b) M(15-
462 20-40).

463

464 During the durability tests, the voids are expected to experience capillary pressure as a result
465 of the moisture and temperature changes, which may affect the clay structure and residual strength
466 level causing physical changes in terms of the soil volume and moisture content. To investigate
467 this point, M(20-20-40) mixture was examined to determine the corresponding volumetric and
468 moisture content changes associated with the wetting-drying durability cycles and the results are
469 shown in Fig. 13. It can be seen that the influence of the wetting-drying durability cycles on the

470 volume and moisture content changes is not significant, the volume change was almost
471 constant along the 12 cycles of wetting-drying durability testing.

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

478

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

481

482 **3.3.2 Durability performance comparison with OPC treated clay**

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

491

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

493

494 To investigate the expected degradation in strength gain under the accelerated weathering
495 conditions, Fig. 15 shows the residual strength of geopolymer-stabilised mixtures in terms of the
496 UCS values after 3, 6, 9 and 12 cycles of wetting-drying or freezing-thawing. Fig. 15 also includes
497 the impact of durability conditions on strength gain of OPC treated clay with 9% cement. As can
498 be seen from Fig. 15(a), the strength degradation of geopolymer-stabilised clay increases with the
499 successive wetting-drying cycles, and the complete degradation in strength is observed for M(10-
500 20-40) and M(15-20-40) mixtures after 1 and 3 wetting-drying cycles, respectively. It can also be
501 seen that the strength degradation of M(20-20-40) with the number of wetting-drying cycles is not
502 as severe as the two other geopolymer mixtures, and the residual strength of this mixture was found
503 to be 67% of the initial strength at zero cycle. The behaviour of OPC treated clay shows a strength
504 development at the first 3 wetting-drying cycles, after which a slight decrease in the UCS values
505 is observed at further cycles. Such a difference in behaviour between the geopolymer-stabilised
506 clay and OPC treated clay towards the wetting-drying durability can be attributed to the continuous
507 hydration in the OPC treated mixture against the geopolymerisation degradation due to the
508 activator leaching in the geopolymer-stabilised mixtures, especially in the first 3 cycles of the
509 successive wetting-drying periods. For the freezing-thawing conditions (Fig. 15b), it can be seen
510 that the residual strength is sharply affected by the increase of the freezing-thawing cycles, for all
511 mixtures including the geopolymer and OPC treated soils, and a significant degradation is
512 observed after 6 cycles, indicating a destructive impact towards the freezing-thawing conditions.

513

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

516

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

523

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

526

527 **3.4 Leaching performance of geopolymer-stabilised clay**

528 Compacted specimens for M(20-20-40) mixture cured for 7 days were leached with pressurised
529 water in the specially leaching cell described earlier for a number of cycles between 1–9. During
530 the test, the leachate was continuously collected and monitored for measuring the pH value using
531 the digital pH meter. The pH of leachate was used as an indicator of the degree of leaching out of
532 alkali from the stabilised clay specimens. After a designated number of cycles (i.e. 3, 6 and 9), the
533 corresponding residual pH values and the residual unconfined compressive strength were
534 determined for the stabilised clay. Fig. 17 shows the leachate pH, soil pH and soil UCS values
535 against leaching cycles. It can be seen that the leachate pH and soil pH values decrease at the
536 earlier leaching cycles. For example, the leachate pH at 3 cycles decreased from 13.53 to 12.85,
537 while the residual soil pH decreased from 12.95 to 12.03, representing a total reduction of 5% and
538 7%, respectively. This is in agreement with the work done by McCallister and Petry (1992) on
539 lime treated expansive clay in which it was found that the leachate pH decreased linearly during
540 the leaching cycles and that leaching does have a detrimental impact on the stabilised soil when a

541 low lime dosage was utilised. However, the pH value remained approximately constant for both
542 the leachate and soil after 6 cycles indicating a minimum change in the alkalinity concentration
543 inside the stabilised sample due to water infiltration.

544

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

546

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

560

561 **3.5 Geopolymer composition molarity**

562 To attain strength and durability criteria for high binder performance, the geopolymer literature
563 usually recommends certain composition molarity ratios. Based on a set of geopolymer-treated
564 clay specimens of different mixtures, the synthesised geopolymer concentrations and the

565 corresponding molarity compositions were investigated and compared against the UCS and
 566 durability performance, as shown in Table 3. The chemical molarity ratios at higher activator-to-
 567 source material ($A/SM = 80\%$) were found to comply with the range limits predefined in the
 568 geopolymer literature for binder execution (Khale and Chaudhary 2007; Pacheco-Torgal et al.
 569 2008). However, these molarity ratios were also found to gain higher strength exceeding the
 570 needed levels when presented in kaolin stabilisation compared to OPC control mixtures. Utilising
 571 a more optimum activator ratio of $A/SM = 40\%$ with $SM/DM = 20\%$ attained strength and
 572 durability close to those of OPC treated clay with 9% cement. This suggests minimum molarity
 573 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
 574 $H_2O/Na_2O = 44.45$ and $H_2O/SiO_2 = 6.24$. The ratio of Si/Al was found to comply with the
 575 minimum range limit of 2.04 for all mixtures. However, these mentioned limits achieved a
 576 compressive strength of 2101 kPa for the geopolymer-stabilised clay cured at 28 days, which was
 577 also found to survive the 12 cycles of the wetting-drying durability test.

578

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

Mixture	Si:Al	SiO ₂ :Al ₂ O ₃	Na ₂ O:SiO ₂	Na ₂ O:Al ₂ O ₃	H ₂ O:Na ₂ O	H ₂ O:SiO ₂	UCS 7 days	UCS 28 days	Durability cycles
M(10-20-40)					101.96	14.30	709	1103	1
M(20-20-40))	2.04	4.08	0.14	0.57	44.45	6.24	1378	2101	12
M(30-20-40))					25.71	3.61	3442	6191	–
M(10-20-80)					52.94	12.7	764	1121	–
M(20-20-80)	2.34	4.68	0.24	1.12	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	–	–	–

580

581

582 As a step towards evaluating the effect of water on the mechanical performance of
583 geopolymer-stabilised clay, the $\text{H}_2\text{O}/\text{Na}_2\text{O}$ and $\text{H}_2\text{O}/\text{SiO}_2$ molarity ratios were found to have a
584 dominant role in the durability and strength performance, as shown in Fig. 18. For example, at
585 molarity ratios of $\text{H}_2\text{O}/\text{Na}_2\text{O} = 101.96$ and $\text{H}_2\text{O}/\text{SiO}_2 = 14.3$ for mixture M(10-20-40), the SDI
586 increased by approximately 5 folds at the end of 28 curing days compared to that before
587 stabilisation but this was also associated with an earlier failure in terms of the wetting-drying
588 durability test. Decreasing the above two molarity ratios by approximately 56%, as suggested by
589 the maximum limits, for M(20-20-40) achieved a total gain in compressive strength equal to 10
590 folds compared to that before stabilisation. More importantly, in such circumstances, the
591 specimens survived the full 12 cycles of the wetting-drying durability test. It seems that when the
592 defined molarity limits are exceeded, the addition of free water needed to achieve the moisture
593 content requirement for the optimum compaction can result in a dramatic decrease in both the
594 durability and strength of geopolymer-stabilised clay. Consequently, the quantity of free water in
595 the geopolymer-stabilised clay is more relevant to the amount needed for reaction than for
596 compaction. It can be concluded that the synthesised geopolymer binder using the abovementioned
597 molarity limits promotes more an economical and efficient performance for geopolymer-stabilised
598 clay cured at ambient temperature.

599

600 **Fig. 18** Influence of composition molarity on strength and durability of geopolymer-stabilised
601 clay: (a) $\text{H}_2\text{O}/\text{Na}_2\text{O}$ vs UCS; and (b) $\text{H}_2\text{O}/\text{SiO}_2$ vs UCS.

602

603 **3.6 SEM characterisation of optimum mixture of geopolymer-stabilised clay**

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

606 20-40), cured at 7 and 28 days, respectively, and representing the early stage and advanced stage
607 of geopolymerisation at ambient temperature. Generally speaking, the homogeneity of the clay
608 fabric was enhanced with the increase of geopolymer binder and curing time. It can be seen from
609 Fig. 19(a) that significant discontinuities and voids in the soil fabric are indicated for wet mixing
610 (without activation). On the contrary, it can also be seen from Fig. 19(b, c) that the activation of
611 fly-ash and slag within the stabilised clay mixture resulted in more closely linked clay particles
612 and fewer voids due to the initial compaction enhancement and gel formation/hardening with the
613 curing time. The clay fabric enhancement is believed to produce a durable higher strength clay
614 structure, and these findings are in agreement with those observed in the earlier geopolymer-soil
615 studies carried out by different researchers (Cristelo et al. 2012b; Zhang et al. 2013; Liu et al.
616 2016).

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

630 **Fig.19** SEM results of geopolymer-stabilised clay for: (a) un-activated mixture-10 μ m; (b)
631 activated-7days-10 μ m; (c) activated-28days-10 μ m; (d) un-activated-5 μ m; (e) activated-7days-
632 5 μ m; and (f) activated-28 days-2 μ m.

633

634 **4. Conclusions**

635 In this paper, the use of ground granulated blast-furnace (GGBFS) slag blended fly-ash
636 geopolymer binder for kaolin clay stabilisation at ambient temperature was investigated. The
637 compaction characteristics and strength development of geopolymer-stabilised clay for curing time
638 7, 28 and 90 days were evaluated. Further examination was made to address the durability
639 performance and the effect of activator leaching on the geopolymer-stabilised clay. The
640 microstructure of the optimum geopolymer-treated clay mixture was also investigated by SEM
641 analysis. A set of geopolymer-stabilised clay specimens containing the following mixtures: ratios
642 of source material (i.e. fly-ash + slag) to dry material equal to 10%, 20% and 30%; slag-to-source
643 material = 0%, 10% and 20%; and activator-to-source material = 40% and 80%, were investigated
644 and compared. The results of the geopolymer-clay mixtures were also compared with un-activated
645 clay mixtures containing only fly-ash and GGBFS without activator, as well as soil stabilised with
646 ordinary Portland cement (OPC). The following conclusions are drawn from this study:

647

648 • Higher percentage of source material (i.e. fly-ash + slag) and the corresponding activator
649 quantity offers an early enhancement to geopolymer-stabilised clay through an increase in the
650 maximum dry unit weight and a decrease in the corresponding optimum moisture content
651 required for compaction.

652 • The unconfined compressive strength of geopolymer-stabilised clay increases with the
653 addition of GGBFS as a partial replacement of fly-ash for curing time up to 90 days. However,
654 at low concentration of slag-to-source material = 10%, little strength gain was offered

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

662 • The geopolymer mixtures suggested in this research can effectively modify and stabilise clay
663 soil for field conditions when the binder proportioned in the mixtures applied properly. Low
664 dosage of geopolymer was found to produce strength enhancement of treated clay but may
665 not necessarily enhance the durability performance against accelerated weathering conditions.
666 The durability of geopolymer-stabilised clay seems to exhibit less stable performance in the
667 freezing climate than the tropical climate, confirming the retardation of the geopolymerisation
668 reaction at very low temperature.

669 • During curing and under an extreme field wetting condition, leaching of the activator was
670 found to be a minor concern for geopolymer clay stabilisation in terms of the residual strength.
671 The field protection against water infiltration may be recommended during the initial curing
672 time to maintain a long-term reaction and to attain good strength and durability performance.

673 • The molarity ratios of geopolymer binder in terms of $\text{SiO}_2/\text{Al}_2\text{O}_3$, $\text{Na}_2\text{O}/\text{SiO}_2$ and $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$
674 were found to comply with the ranges recommended in the literature (i.e. $\text{SiO}_2/\text{Al}_2\text{O}_3 = 3.3\text{--}$
675 4.5 , $\text{Na}_2\text{O}/\text{SiO}_2 = 0.2\text{--}0.48$ and $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3 = 0.8\text{--}1.6$) for higher strength performance. On
676 the contrary, the reduction of $\text{H}_2\text{O}/\text{Na}_2\text{O}$ and $\text{H}_2\text{O}/\text{SiO}_2$ to the predefined suggested limits of
677 44.45 and 6.24, respectively, was found to have a significant role in the strength gain. This
678 also showed a crucial influence on the durability performance against the wetting-drying

679 weather conditions. For economic and practical utilisation, the following molarity limits are
680 suggested: $\text{SiO}_2/\text{Al}_2\text{O}_3 \geq 4.08$, $\text{Na}_2\text{O}/\text{SiO}_2 \geq 0.14$, $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3 \geq 0.57$, $\text{H}_2\text{O}/\text{Na}_2\text{O} \leq 44.45$ and
681 $\text{H}_2\text{O}/\text{SiO}_2 \leq 6.24$.

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

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

690

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694

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Fig. 1

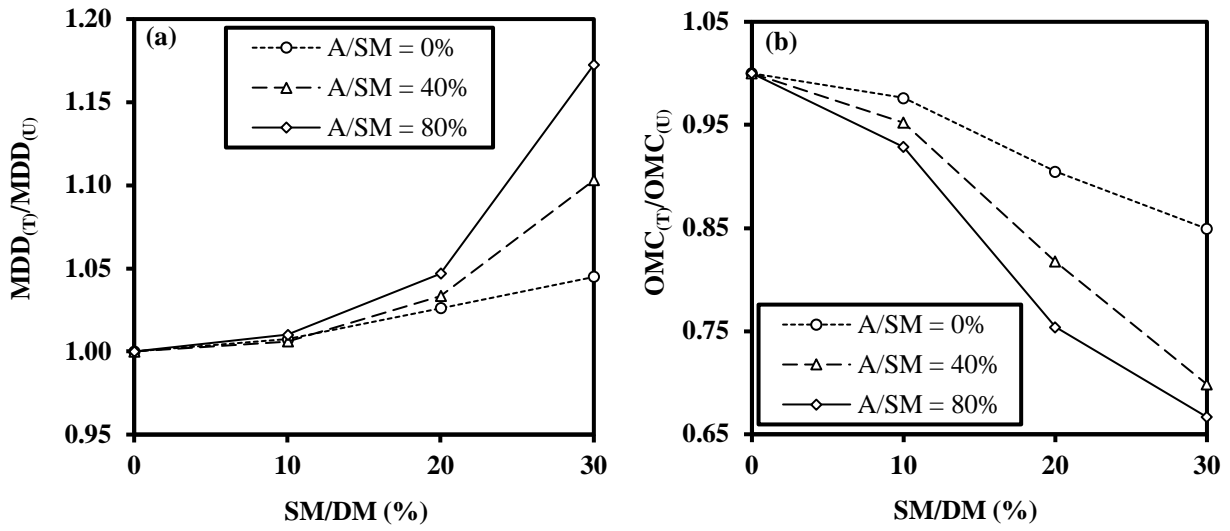


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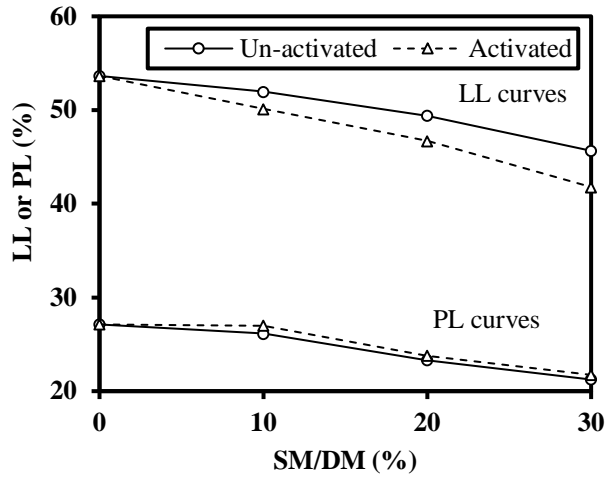


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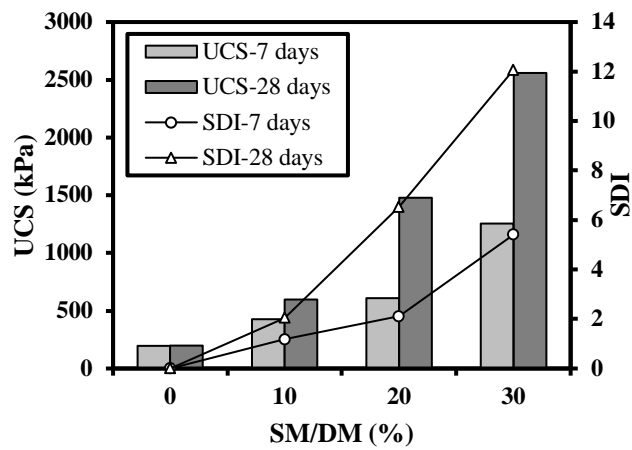


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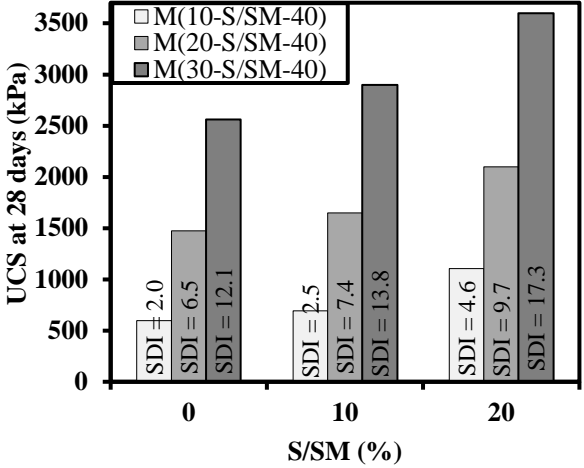
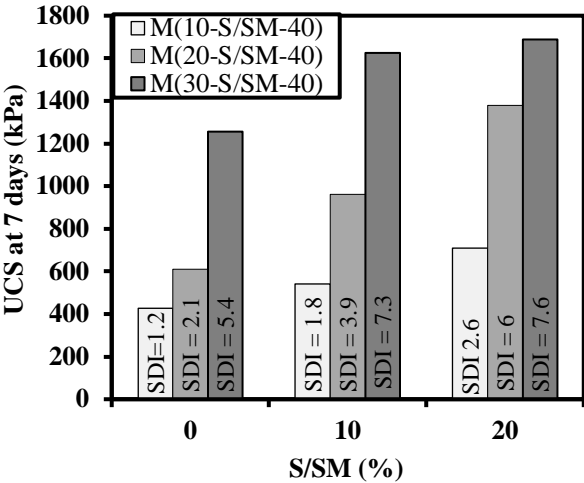


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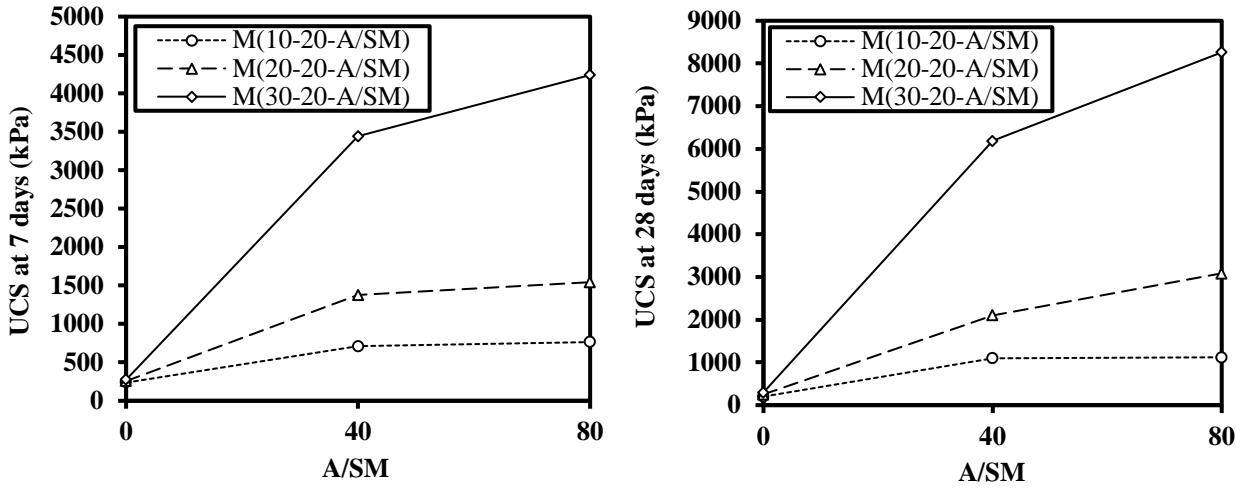


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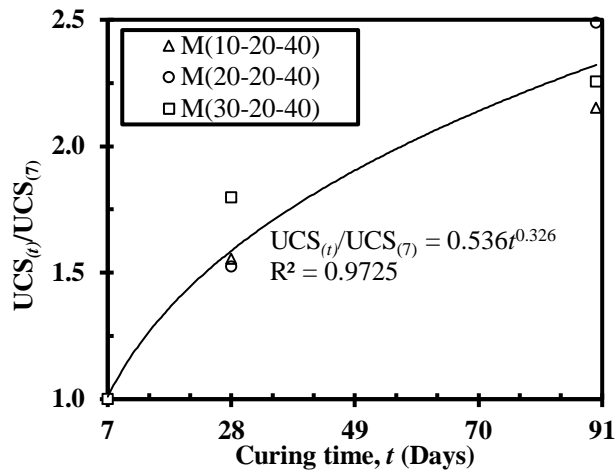


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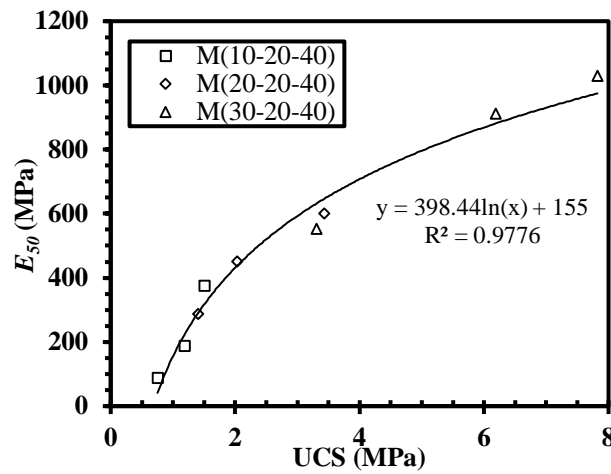


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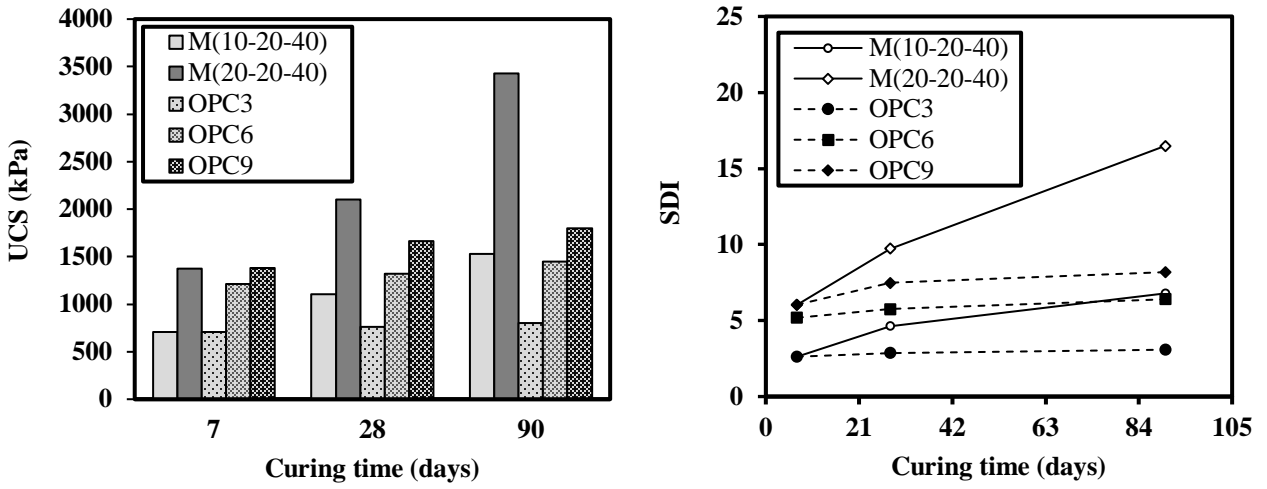


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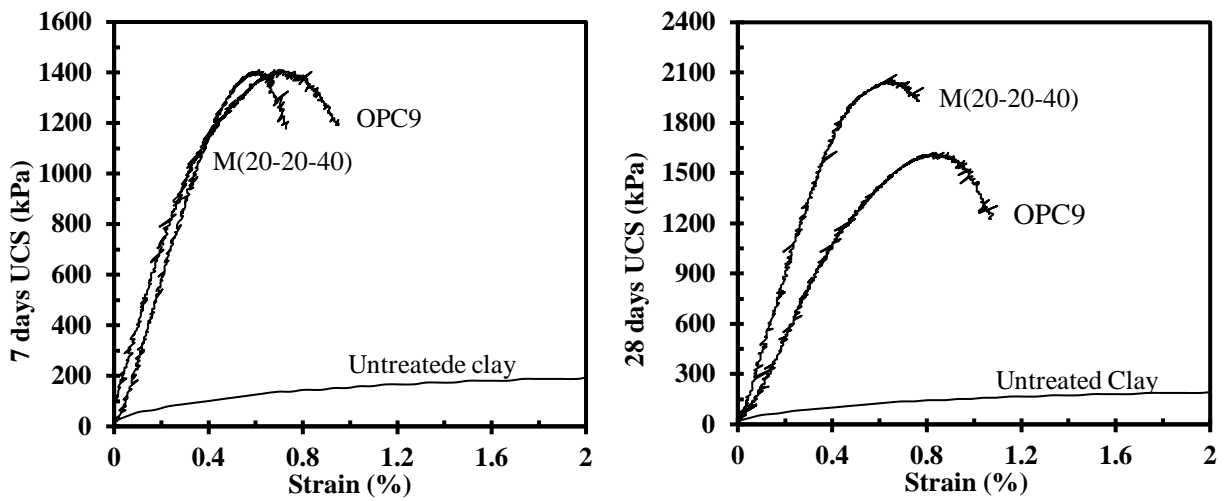


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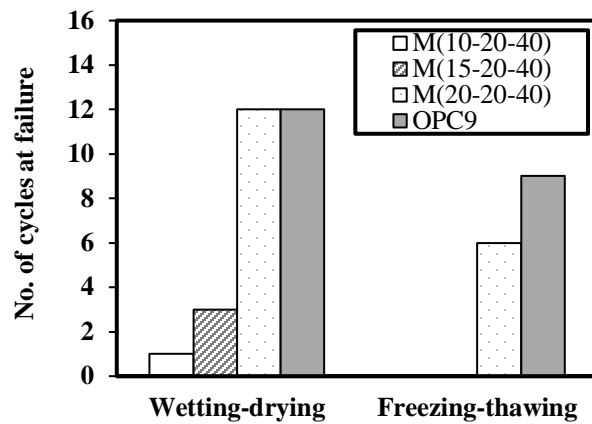


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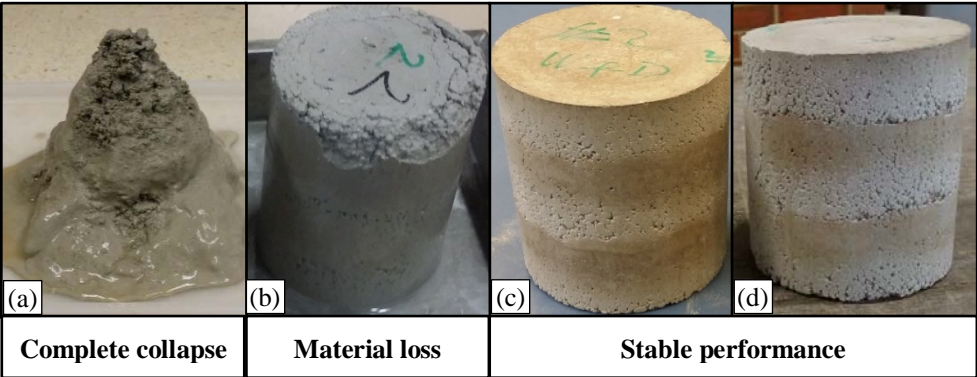


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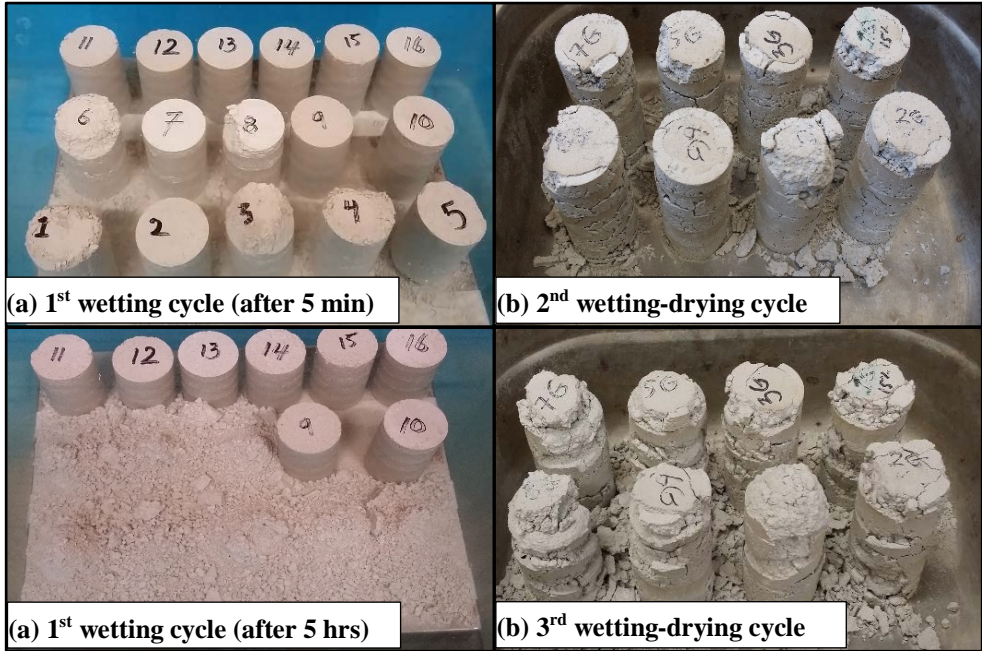


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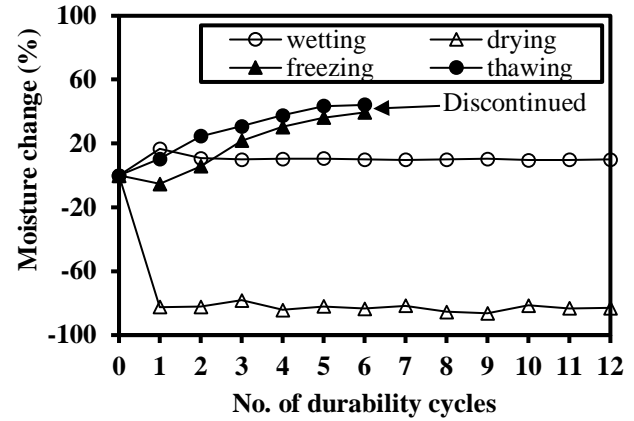
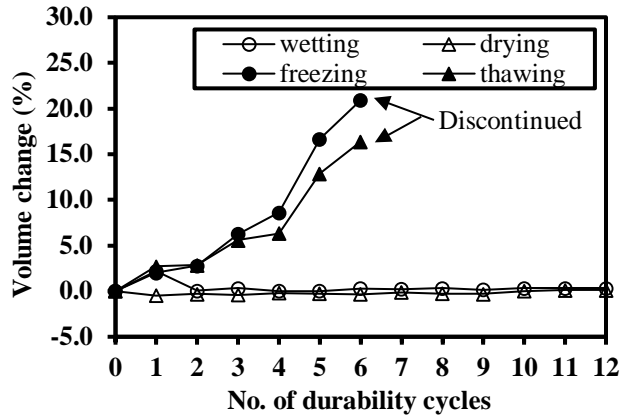


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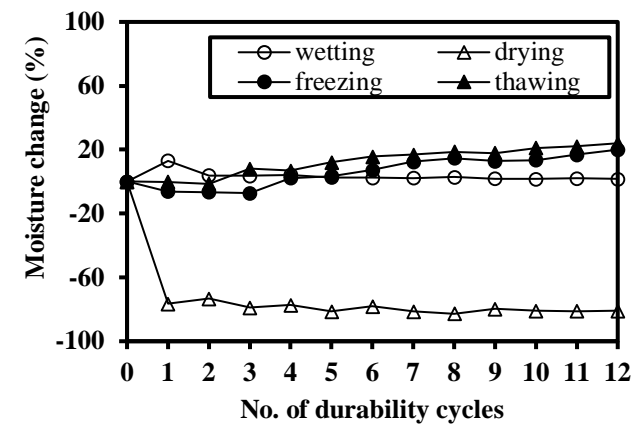
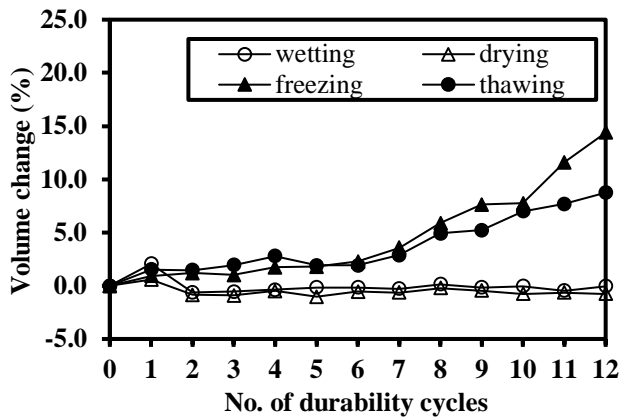


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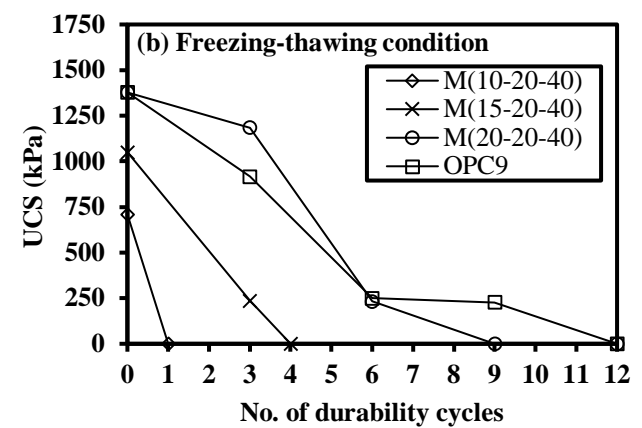
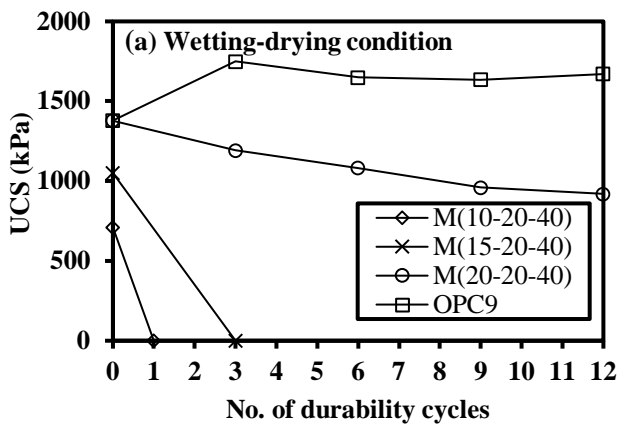


Fig. 16

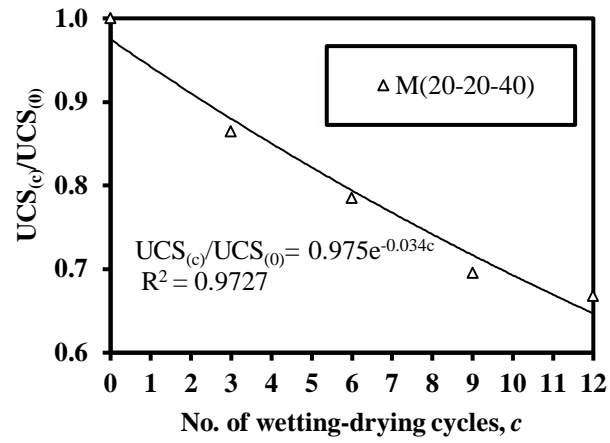


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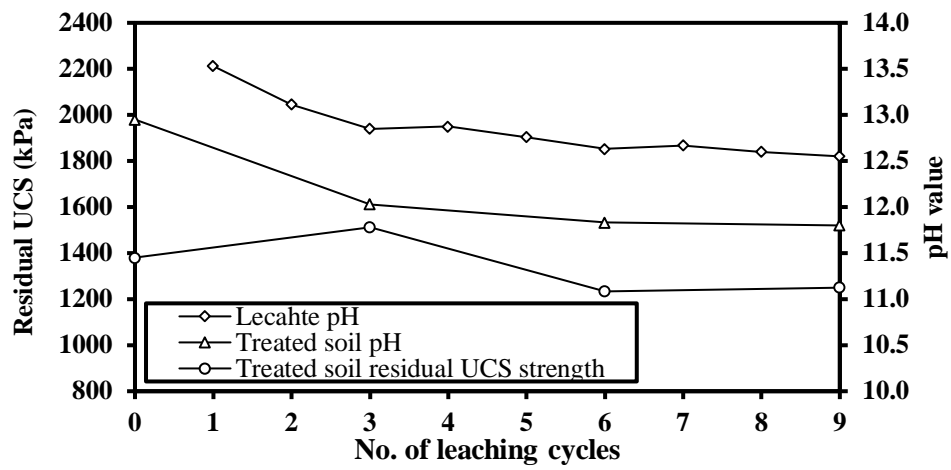


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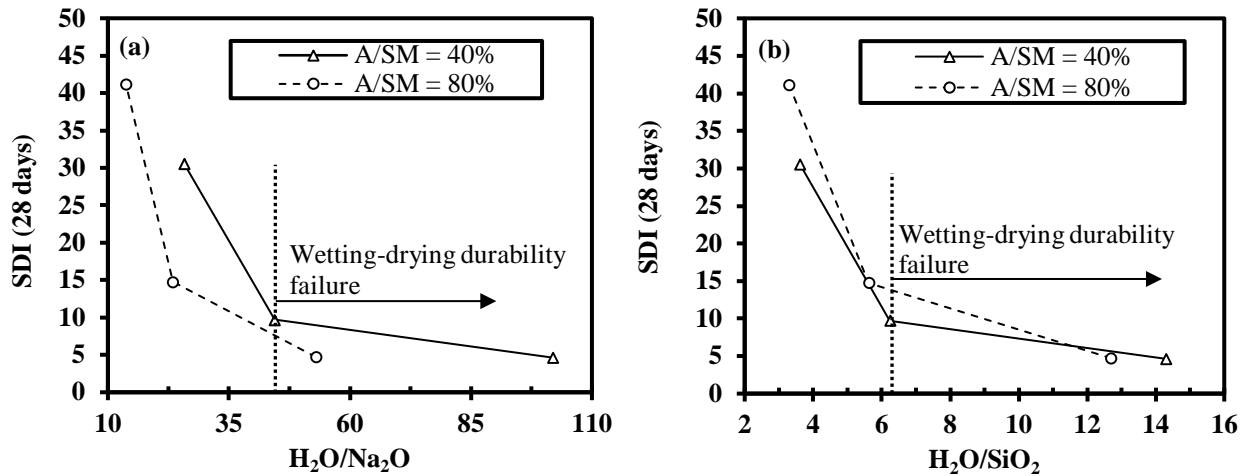


Fig.19

