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# **A new low carbon cementitious binder for stabilising weak ground conditions through deep soil mixing**

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28 **Abstract**

29 Soft alluvial soils present unfavourable conditions for engineering developments, due to their poor bearing  
30 capacities and high potential for experiencing shrinkage and swelling. This paper focusses on deep dry soil mixing  
31 (DDSM), which introduces cementitious binders to soft soils via a rotating auger drill; thereby producing soil-  
32 cement columns. Ordinary Portland cement (CEM-I) is globally used across the construction industry and is the  
33 most commonly used binder for DDSM applications, due to its high strength performances. However, CEM-I  
34 production is one of the world's most energy intensive and expensive industrial processes; contributing 5-7% of the  
35 world's total CO<sub>2</sub>. There is now significant pressure on the cement and construction industries to greatly reduce  
36 their CO<sub>2</sub> emissions by developing "greener" alternatives to CEM-I, which are both more environmentally and  
37 financially sustainable in the long-term. Alkali activated industrial by-products (IBP's) such as ground granulated  
38 blast furnace slag (GGBS), known as geopolymers have been identified as potential alternatives. These are  
39 advantageous due to negating the need to transfer IBP's to landfill, their abundance, negligible or zero production  
40 costs. Geopolymers are capable of reducing greenhouse gas emissions by up to 64%. Calcium-bearing slags have  
41 also been found to possess potential for carbon capture and storage (CCS). Comparisons with the strength and  
42 durability of untreated and stabilised soils have been made in this study. Results indicate that stabilising an alluvial  
43 soil with sodium hydroxide (NaOH) activated GGBS produced significant strength and durability improvements  
44 surpassing CEM-I. The addition of NaOH allowed pozzolanic reactions to occur, leading to improved mechanical  
45 properties with time; primarily strength.

46  
47 **Keywords**

48 Deep dry soil mixing, sustainability, low carbon, alkali activation, performance.

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## 51 **1.0 Introduction**

52 Soft soils including alluvium present problematic ground conditions, given their poor bearing capacity,  
53 shrinkage/swelling, settlement and durability properties. Various ground improvement techniques may be adopted  
54 to enhance the engineering performance of such soils, whereby the most appropriate technique depends on the  
55 physico-chemical properties of the soil in question. Deep dry soil mixing (DDSM) is becoming an increasingly  
56 popular and effective ground improvement technique in the UK for treating such soils by creating cemented soil  
57 columns via auger mixing. Since the development of the DDSM technique, lime and Ordinary Portland Cement  
58 (CEM-I) have traditionally been used as the binders, given their abilities to produce impressive strengths -  
59 particularly for CEM-I. The presence of soil water and calcium silicates/aluminates within the cementitious binders  
60 injected into the soil during mixing react to form hydration products including calcium silica hydroxide (C-S-H)  
61 and calcium aluminate hydroxide (C-A-H) gels. For DDSM, the physico-chemical properties of a soil to be  
62 considered in selecting the most appropriate cementitious binder include particle size distribution, plasticity, pH,  
63 moisture content, cation exchange capacity (CEC), specific surface area, organic and sulphate contents. For lime  
64 and cement stabilisation to work effectively; low organic contents (<1%), low sulphate contents (<0.3%) and clay  
65 contents of 10 – 50% are required (Tutumluer, 2012).

66 Unfavourable environmental and financial issues are associated with utilising CEM-I as a binder. Cement  
67 production contributes 5 – 7% of global CO<sub>2</sub> emissions (McLellan et al., 2011). Increases in such emissions are  
68 anticipated to have long term adverse warming effects on the global climate; the consequences of which include  
69 changing weather patterns, melting polar ice caps, rising sea levels and ocean acidification (EPA, 2015). These  
70 effects will have potentially major impacts on marine and land based life. Therefore, it has become extremely  
71 important for the construction industry to become more sustainable by using materials with lower values of  
72 embodied CO<sub>2</sub>. The continued use of CEM-I is also financially unsustainable, whereby its manufacture is energy  
73 intensive and expensive. The electrical energy consumed per ton of CEM-I produced is 75 kWh (Madlool et al.,  
74 2011). The UK's price indices of electricity and coal as fuels rose by 75 and 63% respectively between 2005 and  
75 2011. Similar trends were observed during the same period in the United States, whereby electricity and coal prices  
76 increased by 19 and 47%, respectively (Imbabi et al., 2012). Since the Fukushima nuclear disaster in 2011, global  
77 coal prices have reduced by half to approximately \$70 per ton (Reuters, 2015), as have oil prices from \$120 to  
78 approximately \$45 per barrel (LSE, 2015). However, according to DECC (2015) and EIA (2015), electricity prices  
79 in the UK and US have remained relatively constant since 2011.

80 Hence, there is a need to identify more environmentally and financially sustainable replacement binders. These  
81 binders should satisfy the following criteria in that they: 1) provide engineering performances comparable to or  
82 surpass those of CEM-I within similar curing times, 2) be commercially available at comparable/lower prices than  
83 CEM-I, 3) produced in such a way that fuel costs are markedly lower than those affiliated with CEM-I production  
84 whilst incurring lower CO<sub>2</sub> emissions. A modern popular route for selecting new binders has been to recycle  
85 alumino-silicate based pozzolanic industrial by-products (IBP's) such as ground granulated blastfurnace slag  
86 (GGBS) and pulverised fly ash (PFA). Such materials are already being used as additives to cement mixtures;  
87 namely CEM-II for PFA and CEM-II/III for GGBS. Per Hanson (2014), GGBS is preferred over PFA in the UK as  
88 a replacement for CEM-I in cement mixtures due to its higher levels of replacement and ability to produce higher  
89 strengths compared with PFA. However, the aim of this research area is to design new low carbon cementitious  
90 binder mixtures which negate the need to use any lime or CEM-I.

91 Laboratory and field-based research by workers including Hughes and Glendinning (2004) and Sargent et al.  
92 (2013) have demonstrated that GGBS has significant potential as a sustainable replacement for lime and CEM-I;  
93 whereby Hughes and Glendinning (2004) implemented GGBS for stabilising peaty soils through DDSM along the  
94 Channel Tunnel Rail Link. However, there are instances when soil pH is too acidic and moisture contents are too  
95 high for strength gains to develop when just using GGBS. The hydraulicity of the GGBS is latent - i.e. confined  
96 within its glassy structure (Newman and Choo, 2003). Hence, the addition alkali-activators aims to release the  
97 GGBS reactivity by raising soil pH and ultimately increase rates at which the mechanical properties of stabilised  
98 soils are improved (Palomo et al., 1999). Once the stabilised soil's pH reaches 10.5 (Davidson et al., 1965), the  
99 GGBS reactivity has been triggered and will start to react over long periods of time with the soil water via  
100 pozzolanic reactions to produce cementitious gels. Such materials are known as "Geopolymers".

101 The continued use of lime as an alkali activator is environmentally unfavourable due to their high carbon costs.  
102 According to Shi et al. (2006), solid NaOH flakes/pellets and Na<sub>2</sub>SiO<sub>3</sub> solution are becoming two of the most  
103 widely available and popular activators for use in concretes and cements. Cristello et al. (2011) used NaOH and  
104 Na<sub>2</sub>SiO<sub>3</sub> to activate IBP's (class F PFA) for use in DDSM treatment of a low plasticity sandy clay. Field testing  
105 results demonstrated that the activated geopolymer produced higher strengths compared with CEM-I.

106 Per Habert et al. (2011) lower financial and environmental costs are associated with their production over lime and  
107 CEM-I. However, NaOH flake/pellet production has lower environmental impacts (3.71 x 10<sup>-1</sup> kg CO<sub>2</sub> eq, human  
108 toxicity level of 15.84 kg 1,4-DB eq and a freshwater ecotoxicity of 3.98 kg 1,4-DB eq) compared with Na<sub>2</sub>SiO<sub>3</sub>

109 solution, which has a high global warming potential of 117.8 kg CO<sub>2</sub> eq, high human toxicity level of 82.75 kg 1,4-  
110 DB eq and a high freshwater ecotoxicity of 21.84 kg 1,4-DB eq.

111 Further justification behind using NaOH over Na<sub>2</sub>SiO<sub>3</sub> as an activator is that the latter has a higher accelerated  
112 carbonation depth when used within geopolymer pastes, which has been attributed to the composition and structure  
113 of the C-S-H gels formed; whereby NaOH activated slags have a higher Ca/Si ratio (1.2) compared with Na<sub>2</sub>SiO<sub>3</sub>  
114 activated slags (Bernal, 2014). However, with NaOH activated slags possessing such a higher Ca/Si ratio and  
115 reduced silicate chain length, these properties may consequently favour the precipitation of increasing quantities of  
116 carbonates to fill pore spaces. The MgO content of slags has been identified to have a significant role in the  
117 mechanism and extent of carbonation; whereby slags with higher MgO content are more likely to be less effected  
118 by carbonation. Thus, on this basis and the typical MgO contents of various slag types per Sanna et al. (2012), the  
119 extent to which carbonation extends within GGBS-based geopolymers is anticipated to be lower compared with  
120 steel slags, argon-oxygen decarburisation (AOD) process slag and most ash wastes (e.g. PFA).

121 Under accelerated carbonation testing (i.e. >1%), if alkali-activated slag pastes show similar carbonation depths as  
122 CEM-I pastes, it is considered likely by Bernal (2014) that the alkali-activated slag will be much more durable  
123 under natural (atmospheric) carbonation conditions. C-S-H gels within alkali-activated slag mixtures are known to  
124 be prone to turning into amorphous silicate gels post-carbonation, which consequently reduces the strength of the  
125 material (Song et al., 2014). Whilst using higher dosages of alkali-activated slag binders significantly reduces the  
126 carbonation depth (Bernal, 2014), simply adjusting the slag/alkali activator ratio of the binder in favour of the  
127 activator causes an increased rate of reaction, produces more C-S-H and therefore increases strength and  
128 carbonation resistance (Song et al., 2014). Experiments undertaken by Song et al. (2014) demonstrated that by  
129 changing the GGBS/alkali activator ratio from 94/6 to 86/14, this increased 28 day compressive strengths (no  
130 carbonation) from 14.9 to 42.5MPa, increased 21 day carbonated compressive strengths from 7.6 to 28.9MPa and  
131 reduced carbonation depth from 25 to 10mm – which is typical for pastes using CEM-I.

132 This paper investigates whether NaOH can successfully activate GGBS to ultimately produce engineering  
133 performances similar to CEM-I and lime when incorporated within a soft alluvial soil whilst minimising  
134 carbonation potential, and whether the binder is suitable for use in DDSM treatment.

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138 **2.0 Soil and Binder Materials**

139 2.1 Lanton Alluvium

140 For this paper, an alluvial soil was sourced from the flood plain of the River Glen in Lanton, 4km north west of  
141 Wooler in Northumberland, UK. Disturbed and undisturbed U100 samples from depths of 1.5 – 2.4m were  
142 obtained.

143  
144 2.2 Cementitious Binder

145 The IBP binder used for this research was ground granulated blast-furnace slag (GGBS) supplied by Hanson  
146 Cements Ltd. A particle size distribution (PSD) curve for the GGBS is provided within Figure 1. For comparison  
147 purposes, non-activated GGBS, CEM-I (supplied by Lafarge) and lime (supplied by Fisher Scientific UK Ltd) were  
148 also used. To ensure that the binder to be utilised for stabilising Lanton alluvium in this paper had low embodied  
149 carbon in terms of energy and production costs, lower financial cost and reduced potential carbonation depth, the  
150 Na<sub>2</sub>SiO<sub>3</sub> solution activator was not used. Thus, solid NaOH pellets were used as an activator, which was supplied  
151 by Fisher Scientific UK Ltd.

152

153 **Table 1:** Summary of the GGBS properties. Courtesy of Hanson (2016)

Property	Value
Granulated grain size (mm)	0-5
Colour	Light grey
Odour	N/A
pH (DEV-S4-eluate according EN 12457-4)	10 - 12
Density at 20°C (Mg/m <sup>3</sup> )	2.4-3.0
Water solubility (g/l)	<1
Melting/freezing point (°C)	>1000
Flash point	N/A (inorganic)
<u>Composition:</u>	
EG-Nr.	266-002-0
CAS-Nr.	65996-69-2
CaO (%)	40
SiO <sub>2</sub> (%)	35
Al <sub>2</sub> O <sub>3</sub> (%)	12
MgO (%)	10
Fe <sub>2</sub> O <sub>3</sub> (%)	0.2

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155 **3.0 Methodologies**

156 3.1 Soil Index Properties

157 A series of geotechnical index tests were conducted according to BS 1377 (BSI, 1990). These included PSD  
158 through wet sieving and sedimentation (Figure 1), Atterberg limits (LL = 35.7%, PL = 20.7%, PI = 15.0), particle  
159 density (2.61Mg/m<sup>3</sup>), natural in-situ moisture contents (25%) and compaction testing to determine the soil's  
160 optimum moisture contents (14.7%), bulk (2.0Mg/m<sup>3</sup>) and dry (1.74Mg/m<sup>3</sup>) densities. According to BS 5930

161 (2015), Lanton alluvium may be categorised as a silty SAND in terms of dry density. A summary of these  
162 geotechnical index properties is provided within Table 2.

163 Modern day loadings imposed on geotechnical structures and foundation soils are generally complex, comprising a  
164 mixture of monotonic, cyclic and dynamic loadings occurring at different magnitudes over various timescales. With  
165 reference to the cyclic and dynamic loads, these may be imposed by human-related activities such as high-speed  
166 trains and highway loads and/or natural phenomena such as earthquakes. Depending on the soil type, moisture  
167 content and loading conditions, both human-related activities and earthquakes can cause soil liquefaction, which if  
168 occurs can severely compromise the integrity of geotechnical structures, along with any other surrounding  
169 infrastructure. Thus, the potential of the Lanton alluvium to undergo liquefaction upon cyclic/dynamic loading was  
170 assessed according to Japanese criteria defined by Tsuchida (1970) for port and airport design. This criteria was  
171 selected on the basis that Japan is a seismically active region with a well established background into understanding  
172 the liquefaction behaviour of soils and the remediation measures available. Additionally, the UK does not currently  
173 have any such comparable British Standards whereas ASTM only has a standard which evaluates a soil's  
174 liquefaction potential through the normalisation of penetration resistance specifically for sands.

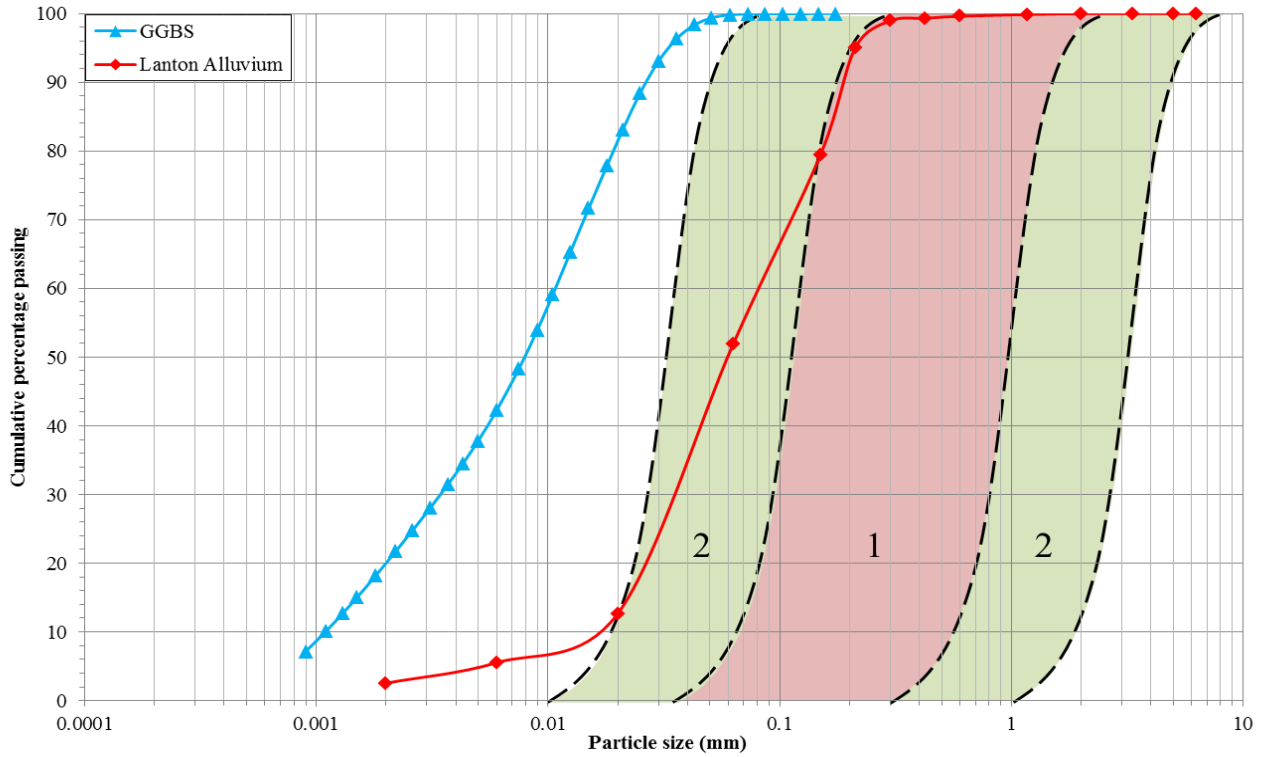
175 According to Tsuchida's (1970) soil grading criteria, the Lanton alluvium's PSD curve (Figure 1) lies within the  
176 zone for soils which may potentially liquefy. This raises concerns about the soil's strength, thereby emphasising the  
177 need for treatment to ensure that the ground conditions are suitable for future engineering developments,  
178 particularly those involving variable cyclic and dynamic loadings.

179 The soil was also subjected to physico-chemical tests to understand their capacities to react with binders and  
180 produce cementitious gels. The pH of the soil in its untreated and stabilised states after various curing periods were  
181 measured per BS 1377 part 3 (BSI, 1990). CEC and specific surface area testing were also conducted. The former  
182 provides an estimate of the number of sites on clay minerals where cation exchange may occur. Soils with high  
183 surface area values (i.e. higher clay contents) result in higher CEC values. These properties provide insights into  
184 the soil's potential for undergoing cementitious reactions. The method used for CEC analysis was BS 7755 (1995).  
185 The CEC-related charge density ( $\sigma_{CEC}$ ) for the soil was obtained as follows:

186 
$$\sigma_{CEC} = \frac{e (CEC \times 10^{-2})}{2 ab}$$

187 where  $e$  is the elementary charge ( $1.6022 \times 10^{-2}$  C),  $a$  and  $b$  are unit cell parameters for clay minerals in the x-y  
188 plane (Meunier, 2005). The soil had an average CEC of 11.45cmol/kg and  $\sigma_{CEC}$  of 0.0019.

189



190

191 **Figure 1:** PSD curves for Lanton alluvium soil (red) and GGBS (blue) with Tsuchida (1970) liquefaction criteria superimposed  
 192 (red area “1” denotes zone for most liquefiable soils, green area “2” denotes zone for potentially liquefiable soils).

193

194 The Brunauer Emmett Teller (BET) nitrogen absorption method (Brunauer et al., 1938) was adopted to determine  
 195 the surface area of the Lanton alluvium by using a Micromeritics Tristar 300. An average surface area of  $6.45\text{m}^2/\text{g}$   
 196 was recorded for the soil. Total organic carbon (TOC) and total organic matter (TOM) testing revealed low values  
 197 of 0.42% and 0.76%, respectively. Per Nair and Little (2009), sulphates within soils can have detrimental effects on  
 198 their engineering performances when stabilised with cementitious binders. This arises from the likely formation of  
 199 ettringite and/or thaumasite, which swell upon contact with water. The sulphate content of the soil was determined  
 200 through the use of a Dionex Ion-Chromatography ICS-1000, which revealed a low sulphate content of 49 mg per  
 201 kg. Finally, 100 mm diameter remoulded and undisturbed samples of Lanton alluvium were placed within a triaxial  
 202 cell under isotropically consolidated conditions to determine their coefficients of vertical permeability ( $k_v$ ), per BS  
 203 1377 (BSI, 1990). At  $22^\circ\text{C}$ , the  $k_v$  values obtained for the soil in its undisturbed and remoulded states were  $1.41 \times$   
 204  $10^{-8}$  m/s and  $5.58 \times 10^{-9}$  m/s, respectively.

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**Table 2:** Summary of the soil's index properties.

Property	Value
In-situ moisture content (%)	25.0
Plasticity Index	14.95
Liquid Limit (%)	35.66
Saturated unit weight (kN/m <sup>3</sup> )	18.44
Bulk Density (Mg/m <sup>3</sup> )	1.99
Dry density (Mg/m <sup>3</sup> )	1.74
Cation exchange capacity (cmol/kg)	11.45
Specific surface area (m <sup>2</sup> /g)	6.45
Total organic content (%)	0.76
Sulphate content (mg/kg soil)	49.0
BS 5930 classification <sup>[15]</sup>	Silty SAND

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## 3.2 Engineering Performance Testing

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### 3.2.1 Preparation of Testing Samples

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Numerous binder combinations were added to the soil at dosages of 2.5 – 10% by dry weight to identify the most effective binder and corresponding dosage. Once soil samples were obtained from the field, they were oven dried at 110°C for 24 hours and crushed into a fine powder (particle size  $\leq 1$ mm). This provided a starting point for achieving a specific moisture content of 25%, made experiments repeatable and also increased practicality when mixing the dry powdered binders within the soil in the laboratory. Stabilised samples were mixed via a rotary mixer for 10 minutes to maximise homogeneity and therefore the number of reactive sites for cementitious bond formation. Water was then added to the mixtures to achieve the required pre-treatment (in-situ) soil moisture content.

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Samples were created by tamping and compressing the samples into split-sample moulds, which were then placed into a hydraulic press to compact the material to the required dimensions and the compacted conditions induced upon DDSM. For compressive strength tests, samples 38mm in diameter and 76mm long were formed. For oedometer testing, separate samples with dimensions of 76mm in diameter and 18mm in thickness were prepared. Finally, samples 105mm in diameter and 115mm in length were produced and cured for durability testing. All stabilised samples for each type of test were prepared with a bulk density of 1.9Mg/m<sup>3</sup>, based on optimum compaction criteria and a moisture content of 25%. Table 3 summarises the soil-binder mixtures examined and their respective concentrations.

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235 **Table 3:** Summary of the binder compositions used for the laboratory stabilisation of Lanton alluvium.

Soil – Binder Mixture	Composition
Lanton	Lanton (25% grav. water)
Lanton + 5% Lime	Lanton (25% grav. water) + 5% lime
Lanton + 10% Lime	Lanton (25% grav. water) + 10% lime
Lanton + 5% CEM-1	Lanton (25% grav. water) + 5% CEM-I
Lanton + 10% CEM-1	Lanton (25% grav. water) + 10% CEM-I
Lanton + 5% GGBS	Lanton (25% grav. water) + 5% GGBS
Lanton + 10% GGBS	Lanton (25% grav. water) + 10% GGBS
Lanton + 2.5% GGBS-NaOH	Lanton (25% grav. water) + 1.67% GGBS + 0.83% NaOH
Lanton + 5% GGBS-NaOH	Lanton (25% grav. water) + 3.33% GGBS+ 1.67% NaOH
Lanton + 7.5% GGBS-NaOH	Lanton (25% grav. water) + 5% GGBS + 2.5% NaOH
Lanton + 10% GGBS-NaOH	Lanton (25% grav. water) + 6.67% GGBS + 3.33% NaOH

236

237 For all compressive strength, durability, pH and moisture content testing, samples were cured within wax-sealed  
 238 PVC sample moulds for periods of 0, 7, 14, 21, 28, 35, 42, 49 and 56 days and stored within a temperature  
 239 controlled room (55% relative humidity, 20°C ambient air temperature). Whereas for compressibility testing,  
 240 samples were prepared and cured within oedometer rings and tightly sealed using three layers of cling film. For  
 241 compressibility and durability testing, samples were cured for 28 days before testing based on construction  
 242 specifications by Hansson et al. (2001). Once cured, all samples were extruded, trimmed and tested.

243

### 244 3.2.2 Laboratory Tests

245 A suite of laboratory tests was conducted according to BS 1377 (BSI, 1990) to assess the performance of the  
 246 various binders. Strength and stiffness were assessed via unconfined compressive strength (UCS). Samples were  
 247 tested either to failure or a maximum axial strain of 15%. The compressibility of samples was assessed by  
 248 oedometer testing, involving a series of load-unload-reload loops up to vertical stresses of 1600kPa. Per Davidson  
 249 et al. (1965), pozzolanic reactions require a minimum soil pH of 10.5. Thus, the pH of all the stabilised mixtures  
 250 was tested prior to and after each curing period. The durability of the stabilised mixtures was assessed by wetting-  
 251 drying and freeze-thaw tests according to ASTM D559/559M and D560/560M (ASTM, 2015a,b), especially given  
 252 that frequent wetting-drying can be expected in the UK's temperate maritime climate.

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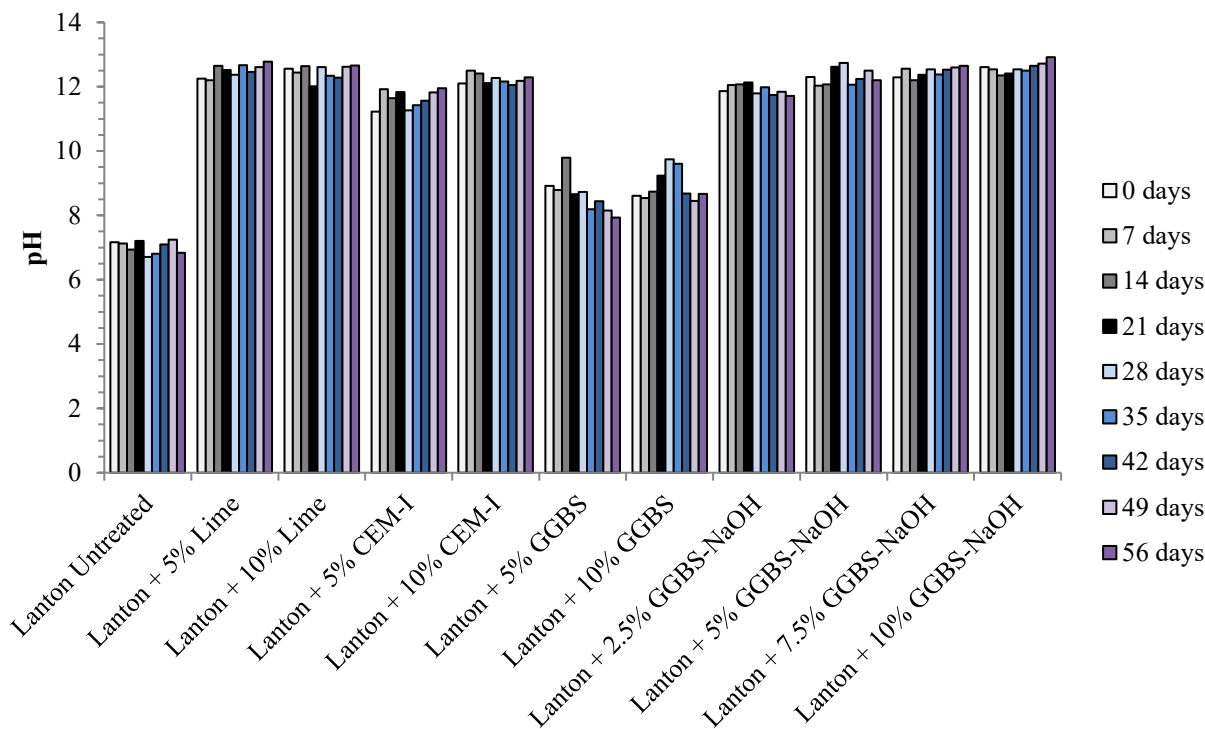
## 254 4.0 Results and Discussion

### 255 4.1 pH

256 Strength development of stabilised soils can be greatly influenced by their pH; whereby alkali activation may be  
 257 required to raise soil pH to  $\geq 10.5$  to promote pozzolanic conditions. pH values recorded for Lanton alluvium and  
 258 non-activated GGBS samples were all  $< 10$ , highlighting the need for activation (Figure 2). For GGBS-NaOH  
 259 specimens, all four dosages successfully raised soil pH to at least 11.7. The maximum pH values recorded ranged  
 260 between 12.6 for the 7.5% dosage and 12.9 for 10%. These values were comparable with those recorded for

261 samples stabilised with 10% lime or 10% CEM-I; confirming that pH conditions were ideal for pozzolanic  
 262 reactions.

263 Whilst stabilisation using lime and CEM-I at 5% raised and maintained a pH >10.5 for 56 days, poor strength and  
 264 durability performances were recorded. A similar observation was made for 2.5% GGBS-NaOH samples, which  
 265 may be attributed to: 1) insufficient binder dosage; 2) insufficient curing time for cementitious gels to form, 3) the  
 266 soil's high water content and therefore low calcium concentration. Should oxidising reactions and subsequent pH  
 267 reductions occur within stabilised samples, hydration and pozzolanic reactions may become inhibited and result in  
 268 poor or severely delayed strength developments. Thus, it is essential to assess the quantities of activator required  
 269 within samples to ensure that pH values >10.5 are maintained for the long-term.



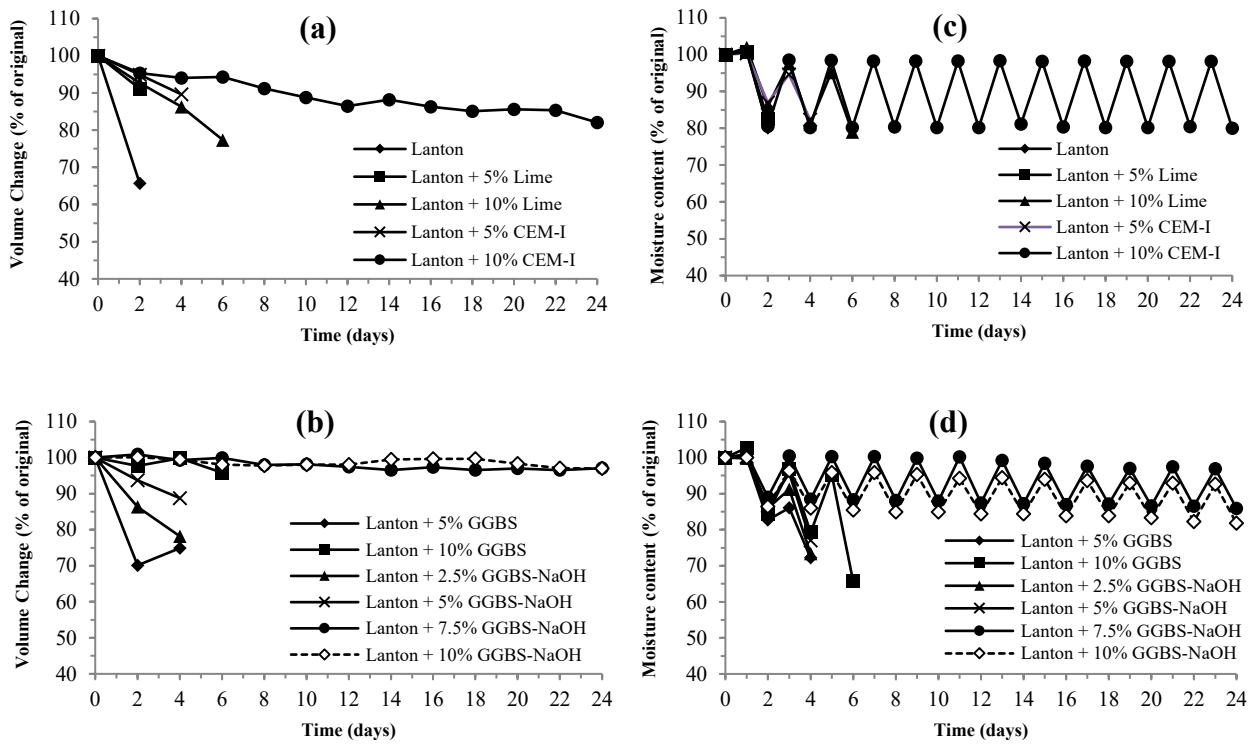
270  
 271 **Figure 2:** pH for all binder mixtures and dosages used to stabilise Lanton alluvium over 56 days.

272  
 273 **4.2 Durability**

274 **4.2.1 Wetting-drying**

275 All sample mixtures were subjected to wetting-drying durability testing to determine soil-cement loss and changes  
 276 in moisture content and sample volume. Testing results are displayed in Figure 3. For the purposes of this study,  
 277 samples are considered to have failed in wetting-drying and freezing-thawing testing upon splitting and/or complete  
 278 disaggregation. In addition, samples may be discontinued should volume measurements become inaccurate due to  
 279 soil-cement loss (ASTM D559-559M, 2015). For the traditional binders, a minimum dosage of 10% was required

280 to maximise the chances of samples surviving all 12 testing cycles. Samples stabilised with CEM-I survived the 12  
 281 cycle testing period with a gradual reduction in volume, whereas 10% lime samples only survived 3 cycles  
 282 exhibiting larger volumetric losses. According to Sargent et al. (2013), most non-activated geopolymers fail after  
 283 the first cycle. However, the 5 and 10% GGBS samples survived 2 and 3 cycles respectively.  
 284 GGBS-NaOH dosages of 2.5 and 5% displayed similar disappointing performances to those observed for non-  
 285 activated GGBS samples. However, impressive performances were recorded for specimens containing a dosage of  
 286 7.5 or 10%, as they displayed negligible changes in volume or moisture content over the 12 cycles. Whilst the  
 287 Lanton + 7.5% and 10% GGBS-NaOH samples demonstrate higher levels of durability against wetting-drying  
 288 compared with Lanton + 10% GGBS samples, the decreasing water content of such non-activated samples after  
 289 developing latent hydraulicity inhibits the hydration of cementitious gels and therefore long-term strength  
 290 development.



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293 **Figure 3:** Volumetric (a-b) and moisture content (c-d) changes experienced by all stabilised Lanton alluvium mixtures during  
 294 wetting-drying testing.

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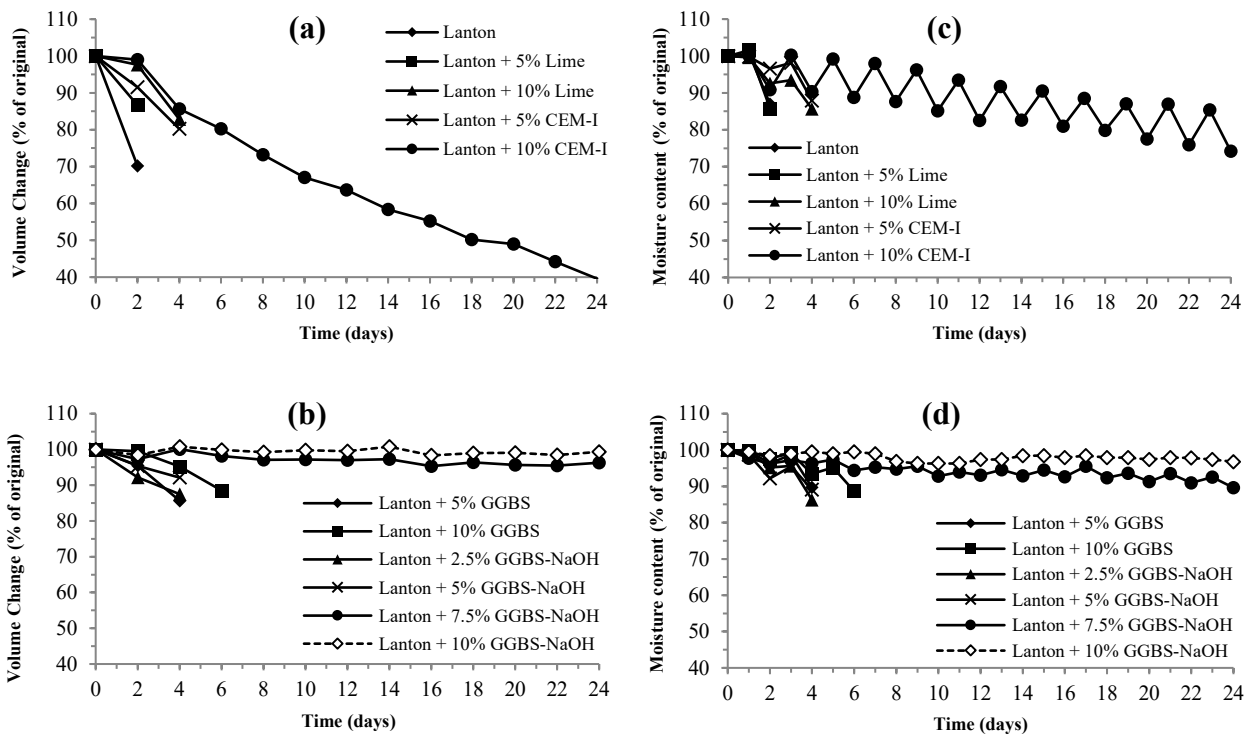
296 **4.2.2 Freezing-thawing**

297 Freezing-thawing testing was conducted to assess the ability of the binder mixtures to resist repeated freezing-  
 298 thawing cycles by measuring changes in sample volume, moisture content and soil-cement losses. In the UK,  
 299 freeze-thaw occurs up to depths of 2m, subject to variations between locations due to in-situ soil and vegetation  
 300 conditions (Clarke and Smethurst, 2010). Given the grading of Lanton alluvium and that water may easily percolate  
 301 through the soil; shrinkage, swelling and physical weathering are likely to occur within the shallow sub-surface.

302 This raises concerns as the binder within DDSM columns must resist such processes. Albeit the ASTM  
 303 D560/560M procedure may be considered extreme for simulating typical freeze-thaw conditions in the UK, the  
 304 results are conservative and will prove useful when assessing similar alluvial soils in other countries with harsher  
 305 winters. Results from the freezing-thawing testing are presented in Figure 4.

306 Using a dosage of 5% for lime and CEM-I was too low to produce any marked strength or durability enhancements,  
 307 as samples failed after their first cycle of testing. Although the 10% lime specimens only survived 2 cycles with a  
 308 significant volumetric reduction, the 10% CEM-I samples survived all 12 cycles. However, the samples did  
 309 experience a volumetric reduction of up to 60%. NaOH activation of GGBS was essential to promote pozzolanic  
 310 conditions and ultimately ensure that samples survived beyond 3 – 10 cycles. The 10% GGBS-NaOH mixture was  
 311 the most effective binder tested, followed by the 7.5 % dosage, as they provided high levels of resistance to harsh  
 312 freezing-thawing cycles. This was confirmed by specimens surviving all testing cycles and the negligible changes  
 313 in volume or moisture content.

314



316

317 **Figure 4:** Volumetric (a-b) and moisture content (c-d) changes experienced by all stabilised Lanton alluvium mixtures during  
 318 freezing-thawing testing.

319

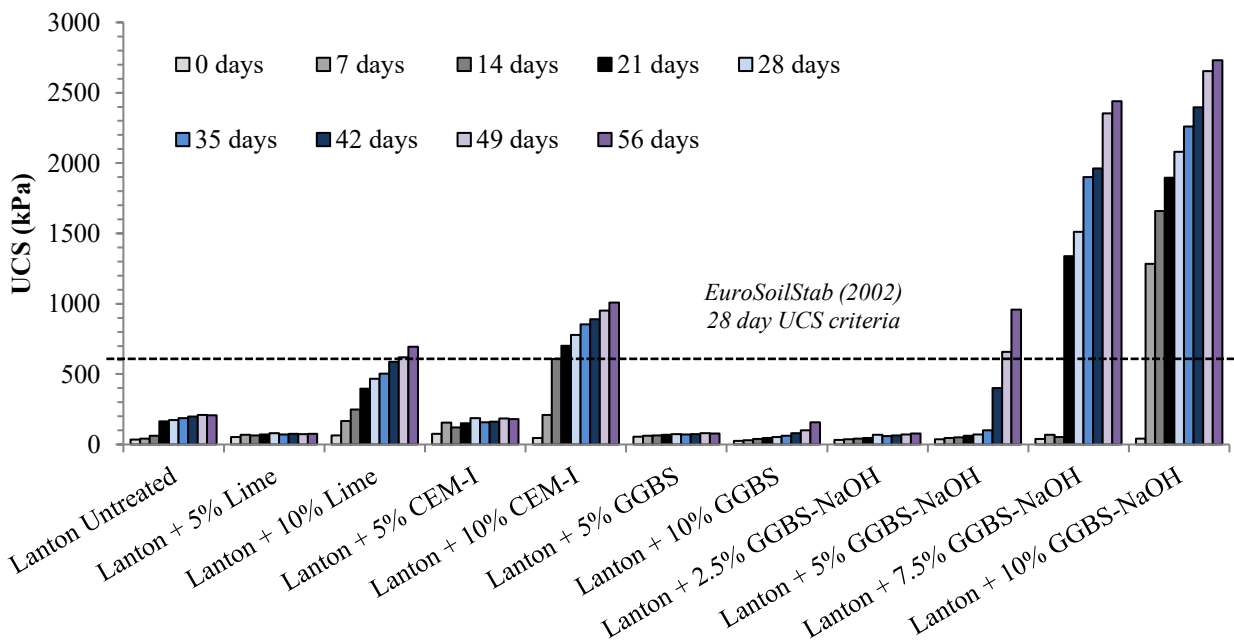
320 To summarise, GGBS-NaOH at dosages >7.5% (particularly 10%) produced the best durability performances for  
 321 both wetting-drying and freezing-thawing, surpassing that of 10% CEM-I. NaOH activation proved very effective  
 322 in producing dense high strength samples, which possessed low permeabilities and were thereby deemed less likely

323 to experience water absorption and subsequent sample deterioration through shrinkage, swelling and physical  
 324 weathering.

325  
 326 4.3 Compressive strength

327 A summary of the average maximum compressive strengths achieved by the various stabilised mixtures is  
 328 presented in Figure 5. With a few exceptions, sample strengths increased over the 28 day curing period for all  
 329 mixtures. However, the degree of strength development observed within samples varies significantly between  
 330 binder dosages. Using 2.5 or 5% for any binder type proved unsuccessful in producing 28 day UCS values of  
 331 300kPa required by EuroSoilStab (2002).

332 The strengths recorded for 5 and 10% GGBS were also low, reaching 56 day strengths of 77kPa and 157kPa  
 333 respectively; both failing to match the strengths achieved by either lime or CEM-I at equivalent dosages and curing  
 334 periods. These samples were characterised by highly ductile behaviour at failure. Hence, alkali activation was  
 335 necessary to produce any considerable strength development. Four dosages (2.5, 5, 7.5 and 10%) of NaOH  
 336 activated GGBS were assessed to identify the most sustainable and optimum dosage in terms of strength gain.  
 337 There was no advantage in using either the 2.5 or 5% dosages due to the strengths achieved for each curing period  
 338 (70kPa after 28 days) closely resembling the performance of untreated Lanton alluvium. The 10% GGBS-NaOH  
 339 samples exhibited the highest and most rapid strength enhancements with curing, with the effects of NaOH  
 340 activation first being seen after 14 days curing. After 28 and 56 days curing, impressive UCS values of 2.08 and  
 341 2.73MPa were recorded, respectively.



342  
 343 **Figure 5:** UCS performances for all binder mixtures and dosages used to stabilise Lanton alluvium after all curing periods.

345 Although the 7.5% GGBS-NaOH binder dosage produced lower strengths than the 10% dosage after 7 and 14 days;  
346 significant strength enhancements initiated after 21 days curing, producing UCS values of 1.3 – 1.4MPa which  
347 exceed strengths for samples stabilised with 10% lime or CEM-I by factors of 3 and 2, respectively. The strengths  
348 also met EuroSoilStab (2002) 28 day 300kPa requirement. The behaviour of the 7.5 and 10% GGBS-NaOH  
349 samples after 28 days was brittle upon failure. The 10% GGBS-NaOH samples exhibited higher levels of brittle  
350 behaviour due to their higher strength, even after 7 days curing. This contrasts with the more ductile behaviour  
351 observed for the other mixtures tested after 7 days.

352 Using NaOH with GGBS at dosages  $\geq 7.5\%$  was necessary to produce significant strength gains. For the 5%  
353 dosage, strength development commenced after 42 days – reaching comparable 56 day strengths to 10% CEM-I.  
354 However, such delayed strength gains are unacceptable, as construction specifications require strength  
355 enhancements after 28 days (Hansson et al., 2001).

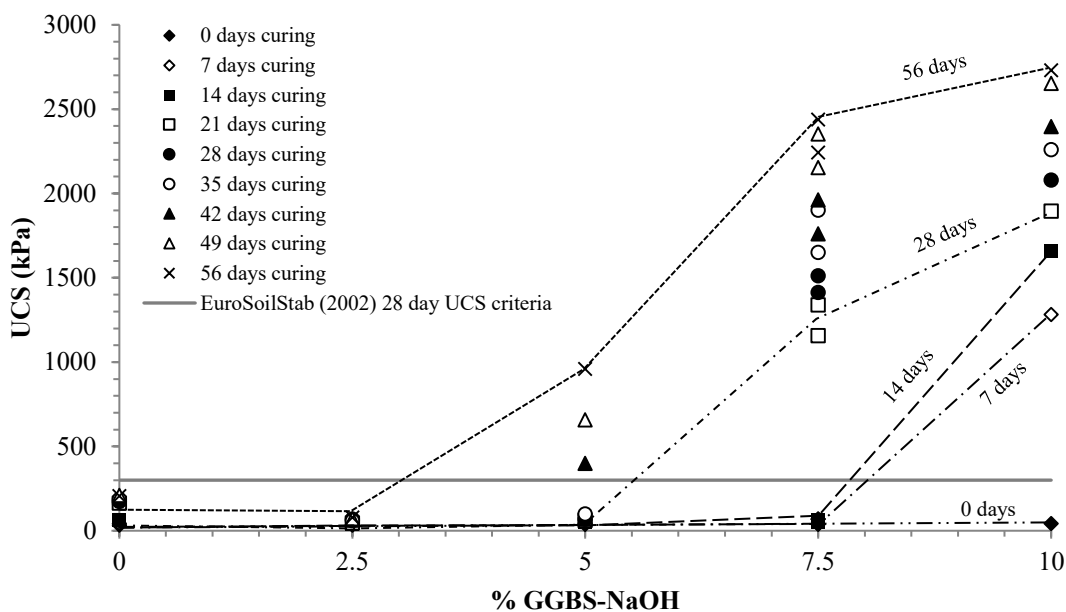
356 Given the Lanton alluvium's low permeability, there are two factors which may explain why such impressive  
357 strength gains were achieved within stabilised samples. Firstly, the activated GGBS binder was thoroughly mixed  
358 into the soil to achieve a high level of homogeneity; thereby allowing hydration and pozzolanic reactions to occur  
359 throughout samples and produce a wide distribution of cementitious gels. The second factor may be attributed to  
360 the even distribution of water throughout samples, which is partly owed to the thorough sample mixing and the  
361 soil's particle size distribution. The soil's sand and silt fractions provide hydration reactions with better access to  
362 water for cementitious gel formation compared with soils containing higher clay contents.

363 GGBS-NaOH dosage influences strength development as can clearly be seen on Figure 6. Whilst further testing is  
364 required to more definitively identify the most optimum dosage for use in stabilising Lanton alluvium, Figure 6  
365 uses the strength results achieved with increasing curing time for the four GGBS-NaOH dosages in an attempt to  
366 approximate an optimum dosage. The performance of this new binder also surpassed that for the CEM-I and lime  
367 binders. According to the 28 day strength development trend line presented in Figure 6, there is an indication that  
368 the GGBS-NaOH dosage which satisfies the EuroSoilStab (2002) strength criterion would be approximately 5.5%.  
369 However, this dosage would be insufficient to produce the 28 day strength of 778kPa recorded for 10% CEM-I;  
370 whereby an approximate GGBS-NaOH dosage of 6.5% would be required. Thus, to satisfy both strength criteria, an  
371 optimum GGBS-NaOH dosage of 6.5% would be envisaged for inclusion within the Lanton alluvium.

372 Moisture content and porosity also influence strength development, whereby mixtures with higher moisture  
373 contents have lower calcium concentrations (pertaining to GGBS) for cement formation; resulting in lower

374 strengths. Consoli et al. (2011) suggested porosity also influences strength by modifying the number of contact  
 375 points between soil particles; whereby delayed strength gains are anticipated within soils of higher porosities and  
 376 those which contain less cement and therefore a less dense network of cementitious gels.

377



378

379 **Figure 6:** Relationship between unconfined compressive strength and GGBS-NaOH dosage, with trend lines shown for 0, 7,  
 380 14, 28 and 56 days curing.

381

382 Suctions may have been generated within UCS samples during their preparation, which may have resulted in higher  
 383 sample strengths than anticipated. DDSM treatment of sands using CEM-I has been adopted successfully world  
 384 wide for many years; whereby high strengths are generally achieved early (within 14 days) with very limited long-  
 385 term (months-years) strength development. For more clayey soils, these are generally required to have 10 – 50 %  
 386 clay content to have sufficiently adequate CEC and surface area characteristics to promote conditions required for  
 387 long-term strength improvements through DDSM (Tutumluer, 2012). Conversely, higher clay contents reduce the  
 388 soil's permeability; as does the addition of GGBS. Stabilising soils with clay contents >30% may not be as  
 389 successful compared with soils containing <30% clay, as it would reduce the volume of water which hydration and  
 390 long-term pozzolanic reactions could utilise to form C-S-H/C-A-H gels (Hughes et al., 2011).

391

#### 392 4.4 Moisture content

393 To assess whether samples contained adequate supplies of water to allow for continued hydration and cementitious  
 394 bond formation, water content was determined according to BS 1377: Part 2 (BSI, 1990). Most samples had water



395 contents of 22 – 25%. According to Table 4, each mixture showed slight reductions in moisture content over 28  
 396 days. Negligible reductions were recorded within all non-activated samples. For GGBS-NaOH samples, moisture  
 397 content reduced by 1 – 1.8%; whereby reductions >1.4% were observed for those containing dosages >7.5%. The  
 398 most significant reductions (up to 5.25%) were observed in samples stabilised with a 10% lime and CEM-I.  
 399 Sub-samples were retained after UCS testing at 28 days and tested according to BS 1377: Part 3 (BSI, 1990).  
 400 Average pH values recorded for Lanton alluvium ranged between 6.7 – 7.2 over 56 days; thereby indicating the  
 401 need for an alkali activator or a high alkaline binder. Stabilisation using 5 – 10% CEM-I or lime produced pH  
 402 values >11.2 and were sustained for the 56 day testing period.

403

404 **Table 4:** Average changes in water content observed over 28 days for all untreated and stabilised mixtures.

Soil – Binder Mixture	Water content (%) with increasing curing time		Reduction in water content (%)
	0 days	28 days	
Lanton	24.6	23.9	0.7
Lanton + 5% Lime	24.1	23.3	0.8
Lanton + 10% Lime	25.1	21.6	3.5
Lanton + 5% CEM-I	24.2	22.7	1.5
Lanton + 10% CEM-I	24.5	19.3	5.3
Lanton + 5% GGBS	24.8	24.1	0.7
Lanton + 10% GGBS	24.9	24.6	0.4
Lanton + 2.5% GGBS-NaOH	24.6	23.5	1.0
Lanton + 5% GGBS-NaOH	25.6	24.5	1.1
Lanton + 7.5% GGBS-NaOH	25.1	23.6	1.5
Lanton + 10% GGBS-NaOH	24.7	22.9	1.8

405

406 Moisture content reductions 1 – 1.8% correspond with samples which achieved high UCS values and durability  
 407 performances; (e.g. 7.5 – 10 % GGBS-NaOH) suggesting that cementitious bonds formed through hydration and  
 408 pozzolanic reactions. This implies that all sample mixtures contained sufficient volumes of water for cementitious  
 409 bonding reactions during and beyond 56 days.

410 In line with Duxson et al. (2007), a relationship may exist between decreasing moisture content and strength  
 411 enhancement when Lanton alluvium is stabilised with lime or GGBS-NaOH. As soil water is consumed during the  
 412 dissolution of geopolymetric reactions and the breakdown of solid aluminosilicates to give silicate and aluminate  
 413 species through alkaline hydrolysis (Duxson et al. (2007)); it is unsurprising that GGBS-NaOH samples showed  
 414 greater reductions in water content compared with non-activated GGBS. By increasing the GGBS-NaOH dosage  
 415 within the alluvium, this inherently increases the calcium concentration within the stabilised material due to the  
 416 GGBS. This would result in water within the soil being utilised at an accelerated rate to form cementitious gels and  
 417 therefore achieving higher strength gains over 28 days compared with using lower GGBS-NaOH dosages (i.e.

418 <5%). This corroborates with the strength results presented in Figure 5 and the degrees of moisture content  
419 reduction within the four GGBS-NaOH dosage sample mixtures.

420 Considering that Lanton alluvium has a natural water content of 25%, there is potentially scope for further  
421 hydration and pozzolanic reactions beyond 56 days, and therefore further water consumption and cementitious gel  
422 development. In the long term, Lanton alluvium stabilised with binder dosages <7.5% may outperform the  
423 performances of stabilised soils containing water contents of <25%. Locat et al. (1990) attributed such behaviour to  
424 solutes being able to migrate through the soil's pore spaces more easily. This may be apparent for the 5% GGBS-  
425 NaOH sample, which started to display encouraging strengths after 42 days.

426 Locat et al.'s (1990) research implies that stabilising Lanton alluvium with 10% GGBS-NaOH closely resembles  
427 rapid strength gain behaviour for soils with low water contents. Using 7.5% GGBS-NaOH showed slower rates of  
428 strength development, with 28 day strengths of 1.3MPa. Comparing this behaviour with Locat et al.'s (1990)  
429 model, it corresponds well with slower rates of strength development typically observed for soils with high water  
430 contents. For 5% GGBS-NaOH, negligible strength developments were observed until 42 days. These findings  
431 prove that further study is required over a longer time period to gain a better understanding of the progressive  
432 strength development of GGBS-NaOH stabilised Lanton alluvium at various dosages.

433

#### 434 4.5 Compressibility and stiffness

435 Based on the relatively high strength and durability performances of the GGBS-NaOH binder, compressibility  
436 testing was focussed on the Lanton alluvium when untreated and stabilised with GGBS-NaOH. In the UK, Network  
437 Rail standard RT/CE/S/065 Issue 4 2014 "Examination of Earthworks" Risk Matrix (Network Rail, 2014) considers  
438 railway embankment height ranges of: a) <3m b) 3 – 6m and c) 6 – 10m. Most failures occur 3 – 6m high  
439 embankments with slope angles >25 degrees. On the UK's railway network, embankment heights are known to  
440 typically vary between 3 and 10m. However, there are locations where embankment heights are known to exceed  
441 the aforementioned height range, whereby embankments reach up to 30m high. Vertical effective stresses  
442 associated with 30m high embankments, assuming embankment fill unit weight of 20kN/m<sup>3</sup> and worst case shallow  
443 groundwater levels (5mbgl) may be as high as 300 – 400kPa. Hence,  $m_v$  values recorded for each sample mixture  
444 under vertical stresses up to 400kPa during compressibility testing were considered. It is under the vertical stresses  
445 of less than or equal to 400kPa where specimens also experience the most compressional strain during testing;  
446 hence why  $m_v$  values obtained for vertical stresses ( $\sigma_v$ ) of 800 – 1600kPa have not been included.

447 Compression curves for the soil in its untreated and GGBS-NaOH stabilised states after 0 and 28 days curing are  
448 displayed in Figure 7. The coefficients of compressibility ( $m_v$ ) values obtained for each sample after 0 and 28 days  
449 curing are given in Table 5.

450 The compression curves in Figure 7a illustrate a reduction of 0.23 in the initial void ratio for the remoulded Lanton  
451 alluvium, compared with its undisturbed counterpart. This reduction can be attributed to the removal of the soil's  
452 natural structure, which provides a degree of additional strength to the material due to fabric and/or inter-particle  
453 bonding as a result of the soil's geological history – i.e. depositional and post-depositional processes (Gasparre and  
454 Coop, 2007). A more significant reduction in initial void ratio can be seen in Figure 7a for all 28 day cured  
455 stabilised samples compared with the undisturbed (untreated) Lanton alluvium. This is an inherent result of  
456 densification due to the nature of the DDSM process; whereby the orientation of the auger mixer blades provides a  
457 degree of compaction. Additionally, by introducing a fine grained (silty) cementitious GGBS binder into the  
458 alluvium, this alters the PSD curve for the material and infills void spaces within the soil – thereby having the  
459 effect of reducing its initial void ratio. However, the increase in material stiffness due to void ratio reduction is  
460 small compared with that provided by the formation of cementitious gels.

461 After 0 days, all stabilised mixtures experienced void ratio reductions of 0.1, which contrasts with untreated  
462 samples whose void ratios decreased by 0.25 and 0.4 for remoulded and undisturbed samples, respectively. Given  
463 that introducing a binder via DDSM disturbs the soil, it is unsurprising that the initial void ratios of stabilised  
464 samples were similar to the remoulded soil. After 28 days curing, samples containing 2.5 and 5% GGBS-NaOH  
465 exhibited slightly improved consolidation behaviour compared with that observed after 0 days curing, as proven by  
466 the compression indices ( $C_c$ ) and swelling indices ( $C_s$ ) values in Table 5. Figure 6b shows samples containing 7.5  
467 or 10% GGBS-NaOH displayed a significantly stiffer response after 28 days.  $C_c$  values for these mixtures  
468 decreased considerably compared with their 0 day values.  $C_s$  values for all four dosages were almost identical.  $C_c$   
469 values for 7.5 and 10% dosage samples are at least one third of the values obtained for samples containing 2.5 or  
470 5% binder, 9 and 20 times smaller than the  $C_c$  values obtained for the remoulded and undisturbed soil, respectively.

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473  
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**Table 5:**  $m_v$ ,  $C_c$  and  $C_s$  values for treated and untreated Lanton alluvium after 0 and 28 days.

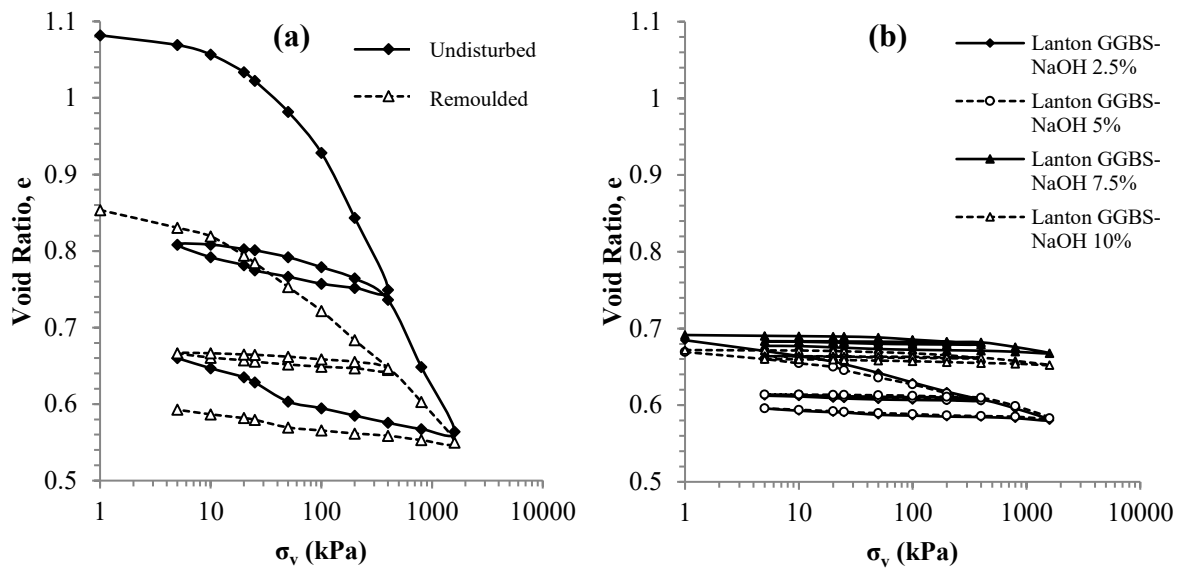
Soil – Binder Mixture	Coefficient of Compressibility ( $m_v$ ), $m^2/MN$								Compression index ( $C_c$ )		Swelling index ( $C_s$ )	
	0 days				28 days				0 days	28 days	0 days	28 days
	50kPa	100kPa	200kPa	400kPa	50kPa	100kPa	200kPa	400kPa				
Lanton remoulded	0.703	0.359	0.221	0.116	0.703	0.359	0.221	0.116	0.132 0.309	0.013 0.030	0.015	0.004
Lanton undisturbed	0.799	0.542	0.440	0.255	0.799	0.542	0.440	0.255				
Lanton + 2.5% GGBS-NaOH	0.238	0.074	0.098	0.055	0.276	0.153	0.073	0.036	0.065	0.039	0.015	0.004
Lanton + 5% GGBS-NaOH	0.231	0.150	0.071	0.058	0.230	0.109	0.070	0.029	0.087	0.034	0.011	0.004
Lanton + 7.5% GGBS-NaOH	0.222	0.142	0.071	0.046	0.025	0.035	0.016	0.011	0.077	0.016	0.011	0.004
Lanton + 10% GGBS-NaOH	0.214	0.133	0.071	0.034	0.025	0.019	0.015	0.012	0.055	0.014	0.009	0.003

480

481 The  $m_v$  results complement the compression curves, whereby all of the binder dosages reduced the compressibility  
482 of the untreated Lanton alluvium. The initial  $m_v$  values of the untreated undisturbed and disturbed alluvium ranged  
483 between 0.7 – 0.8 $m^2/MN$ , which is typical of normally consolidated alluvium and therefore highly compressible  
484 (Tomlinson, 2001). The 0 day  $m_v$  values for each dosage ranged between 0.21  $m^2/MN$  for vertical stresses ( $\sigma_v$ ) of  
485 50kPa and 0.03 $m^2/MN$  for  $\sigma_v=400kPa$ . These values indicate that each mixture had a medium to very low  
486 compressibility. For dosages of 2.5 and 5%, negligible changes in  $m_v$  values were achieved after 0 and 28 days  
487 curing. However, there was a significant reduction in  $m_v$  values after 28 days for samples containing 7.5 or 10%  
488 GGBS-NaOH, where the effect of cementation is apparent. Considerably lower  $m_v$  values of 0.01 – 0.03 $m^2/MN$   
489 and 0.01 – 0.02 $m^2/MN$  were calculated for samples containing 7.5 and 10% binder dosages, respectively; and are  
490 deemed to be of very low compressibility.

491 These results suggest that the most effective dosage of the GGBS-NaOH binder in reducing the initially high  
492 compressibility of untreated Lanton alluvium was 10%. However, the 7.5% dosage was equally as effective when  
493 samples were subjected to  $\sigma_v > 200kPa$ . Hence, there is little benefit in using a dosage of 10% over 7.5%, given their  
494 similarly small reductions in void ratio after two loading-unloading cycles.

495



496  
497 **Figure 7:** Oedometer compression curves of Lanton alluvium in (a) its untreated remoulded and undisturbed state, and (b)  
498 treated with 2.5-10% GGBS-NaOH after 28 days curing. Note: the curves are based on averages taken from triplicate testing.

499  
500 The undisturbed soil possessed a fairly high level of sedimentation structure. Slight disturbance or increase in  
501 loading up to 100kPa resulted in a sudden and considerable reduction in void ratio, and therefore significant  
502 structural collapse. This highlights treatment is required to improve the soil's high levels of compressibility.

503 In summary, a significant improvement in compressibility and therefore stiffness was observed after 28 days for 7.5  
504 and 10% GGBS-NaOH specimens; whereby  $m_v$  values decreased to  $<0.03\text{m}^2/\text{MN}$  with increasing  $\sigma_v$ , indicating  
505 very low levels of compressibility. Using  $>7.5\%$  GGBS-NaOH within Lanton alluvium produced brittle failures.  
506 This behaviour could be unfavourable under dynamic loading conditions due to passing rail traffic and earthquakes.  
507 However, the strengths achieved were lower and more favourable than those recorded by Sargent et al. (2013) for a  
508 GGBS-NaOH- $\text{Na}_2\text{SiO}_3$  stabilised artificial alluvium.

## 510 5.0 Sustainability assessment

511 New geopolymers must demonstrate commercial and practical viability as alternatives to CEM-I and lime. Per  
512 Global Cement (2011), demonstrating GGBS-NaOH for use in DDSM on an industrial field scale is essential to  
513 proving its practicality and for developing knowledge regarding the cost implications of non-equitable economies  
514 of scale. Assurance of this binder's potential for commercialisation should be taken from the commercialisation of  
515 similar alkali-activated GGBS-based geopolymer concretes ("E-Crete") in Australia (Global Cement, 2011).

### 517 5.1 Environmental impact

518 Although the use and practicality of cement and lime as binders is well proven in DDSM, their continued usage is  
519 environmentally unsustainable. Cement and lime production have high carbon costs. Cement production

520 contributes up to 7% of the world's CO<sub>2</sub> emissions (McLellan et al., 2011), whereby for every ton of cement  
521 produced 900 – 1100kg of CO<sub>2</sub> is emitted (EPA, 2005). An estimated 4,100 million tonnes of cement was produced  
522 in 2015 (Statista, 2016). The cement and civil engineering industries are under significant pressure to reduce CO<sub>2</sub>  
523 emissions and contribute towards atmospheric carbon capture storage (CCS).

524 Using IBP's as alternatives or partial replacements to CEM-I or lime has real potential for reducing the  
525 environmental impact of using cements and lime. According to Hanson (2014), GGBS has impressive  
526 environmental sustainability credentials. Compared with the production of lime and CEM-I, it reduces embodied  
527 CO<sub>2</sub> emissions by 2 million tonnes per annum, reduces primary energy usage during manufacture/processing by  
528 2000 million kWh, saves 3 million tonnes of quarrying and reduces landfill by almost 2 million tonnes. GGBS has  
529 advantages over other IBP's due to the quantity of CEM-I which it can replace within a given concrete or stabilised  
530 soil, whilst achieving engineering performances comparable with pure CEM-I (Connell, 2014). 50 – 70% of CEM-I  
531 may be replaced by GGBS whereas only 20 – 25% may be replaced by PFA. Whilst approximately 75% of CaO  
532 within the CEM-I component of concretes is able to sequester atmospheric CO<sub>2</sub> via carbonation (DTI, 2005),  
533 mixing other high-calcium binders including GGBS and steel slag within urban soils has recently proved to have  
534 excellent atmospheric CO<sub>2</sub> sequestration potential in the UK (Sanna et al., 2012). GGBS and steel slag have a  
535 theoretical global CO<sub>2</sub> potential uptake of approximately 80 million tonnes per year (Yan, 2015). CCS within urban  
536 soils through the incorporation of such slag materials has recently been demonstrated by Washbourne et al. (2012)  
537 on the Science Central site in Newcastle upon Tyne, UK. Washbourne et al. (2012) demonstrated that the top metre  
538 of soil for the 10 hectare site has the potential to capture and store 64,000 Mg of atmospheric CO<sub>2</sub> in the form of  
539 carbonate minerals, half of which was captured within 3 years at an annual rate of 325 Mg C ha<sup>-1</sup>. Similar figures  
540 were also calculated for similarly mixed quarry soils (Barrasford, UK); namely 300 Mg C ha<sup>-1</sup>, which was observed  
541 down to depths of three metres over ten years (Manning et al., 2013). Such differences in sequestration rates were  
542 attributed to differing soil mineralogies; whereby urban soils at Science Central contained cementitious rubble  
543 material (calcium silicates and calcium hydroxide) which produce greater rates of carbonation compared with  
544 Barrasford quarry soil (Manning et al., 2013). Globally, construction and development site soils are considered able  
545 to capture and store 290 million Mg of atmospheric carbon within soil matrices per year (Renforth et al., 2009).

546 However, strength gains within GGBS-stabilised soft alluvial soils require alkali activation. Most alkali materials  
547 for industrial purposes are synthetically sourced with high costs and negative environmental impacts. Although the  
548 use of NaOH in this paper promoted pozzolanic conditions and high strength gains within stabilised samples, its  
549 production involves the electrolysis of brine, which is energy intensive and produces considerable CO<sub>2</sub> emissions.

550 During its production, there is also the risk of contaminating local aquatic environments. A more sustainable NaOH  
551 source could be the by-product from existing chlor-alkali plants (Kumar et al., 2012).

552 Significant CO<sub>2</sub> emission reductions of up to 64% are estimated for Australian geopolymers compared with CEM-I  
553 (McLellan et al., 2011). There are carbon footprint implications associated with the brine electrolysis (membrane)  
554 technique used to produce NaOH. However, the quantities of NaOH required in this research were small (0.83 –  
555 3.3% by dry weight or 12.4 – 49.4kg m<sup>-3</sup>) compared with the quantities of CEM-I typically used in more traditional  
556 binder mixtures for DDSM treatment of soft soils. According to Topolnicki (2004), cement dosages of 120 – 300  
557 kg m<sup>-3</sup> may be used within most soils, with the exception of sludges, peats and organic silts/clays where dosages of  
558 250 – 400kg m<sup>-3</sup> are recommended.

559 The GGBS CO<sub>2</sub> reductions far outweigh the carbon footprint produced by the NaOH's manufacture. There is also  
560 potential for GGBS-NaOH to sequester atmospheric carbon within the stabilised soil, which assists in driving the  
561 binder towards commercialisation. Further work is required on the effects of carbonation on the long-term  
562 durability, strength and mineralogical development of stabilised soft alluvial soils and how much atmospheric CO<sub>2</sub>  
563 such mixtures can capture.

## 564 5.2 Financial costs

565 Although the engineering performances observed for GGBS-NaOH meet EuroSoilStab (2002) strength criteria and  
566 surpass those exhibited by CEM-I and lime, it is also crucial to demonstrate that its overall cost is financially  
567 competitive. There are considerable stockpiles of GGBS in the UK, given the country's active pig iron and steel  
568 manufacturing industry. This makes GGBS sustainable in the UK for use in geopolymers as stockpiles are  
569 continuously replenished and thus avoids expensive overseas sourcing. GGBS also requires little post-production  
570 processing (i.e. ground granulation) to make it suitable for mixing.

571 Solid NaOH is available as flakes, pellets or pearls and is commercially available in raw bulk production and  
572 scientific forms, the difference being that the latter has been purified. Hence, whilst the cost of scientific NaOH is  
573 much higher, its effectiveness as an alkali activator is equal to that of industrial grade. For laboratory studies  
574 involving various chemicals, scientific NaOH is recommended as it is in a much purer form. For large scale  
575 applications, raw bulk production NaOH is more financially feasible. Additionally, the electrical energy consumed  
576 per ton of NaOH produced is 1.285 kWh, which is almost 60 times lower than that required per ton of CEM-I  
577 (Madloul et al., 2011).

579 The international market prices of these materials at the time of writing (July 2014 US\$:£ currency exchange rates)  
580 were £25 – 60 per ton of GGBS and £175 per ton of NaOH (Alibaba, 2014). By taking the lowest available prices,  
581 this produces a significantly lower price of £75 per ton for the GGBS-NaOH binder when using the 2/3 GGBS : 1/3  
582 NaOH ratio as used in this paper. Whilst this price is more expensive than the international market price of CEM-I  
583 (£50 per ton), it is only marginally more expensive compared with the UK price of £70 per ton. In order to make  
584 the GGBS-NaOH break even with CEM-I in the UK, its price would only need reducing by 7% which would  
585 equate to a binder dosage of 5.5% within Lanton alluvium. This advocates that GGBS-NaOH is potentially a  
586 financially more sustainable alternative to CEM-I. McLellan et al.'s (2011) study demonstrated that for a number of  
587 NaOH-bearing geopolymers developed in Australia, the total financial cost of these mixtures was not much greater  
588 than that for CEM-I. However their transportation costs were considerably higher than those associated with CEM-  
589 I, due to the significant transportation distances between binder source and the treatment site.

590 Turner and Collins (2013) stated that for an Australian geopolymer concrete comprising PFA, NaOH, sodium  
591 silicate and a superplasticiser, a carbon foot print reduction of 9% was measured against a comparable strength  
592 CEM-I concrete. There is a confliction between the reduced carbon footprint estimates provided by McLellan et al.  
593 (2011) and Turner and Collins (2013). However, the geopolymers assessed by Turner and Collins (2013) contained  
594 considerable quantities of sodium silicate, which is expensive and has significant negative environmental impacts  
595 (Habert et al., 2011). Thus, the reductions in the GGBS-NaOH carbon footprint compared with CEM-I is more  
596 comparable with estimates provided by McLellan et al. (2011). Based on the available evidence, GGBS-NaOH has  
597 a smaller carbon footprint and lower financial cost compared with CEM-I; thereby highlighting its potential as a  
598 commercially viable alternative to CEM-I.

599

## 600 **6.0 Engineering Practicality**

601 A key factor to consider in assessing the potential for the GGBS-NaOH binder to be used instead of lime or CEM-I  
602 for future DDSM projects is engineering practicality. The application of chemical treatment in stabilising soft soils  
603 is generally limited to those characterised by low organic and sulphate contents and relatively high clay contents.  
604 These criteria have been defined to ensure that cation exchange and long term cementitious reactions occur within  
605 the stabilised material. Although the Lanton alluvium possessed unfavourably high moisture and silt-sand contents,  
606 using a GGBS-NaOH binder dosage  $\geq 7.5\%$  proved effective in producing high levels of strength and durability  
607 within the soil post 21 days curing. The enhanced mechanical performances of the GGBS-NaOH stabilised Lanton



608 soil were at least 2 – 3 times better than those observed for samples mixed with traditional binders, whilst meeting  
609 strength criteria defined by EuroSoilStab (2002).

610 Another component which needs to be considered in assessing the engineering practicality of the GGBS-NaOH  
611 binder for use in DDSM is whether any modifications to existing plant and equipment would be required. GGBS  
612 comes in the form of a dried fine powder and that NaOH pellets/flakes are solid particulates. Hence, it is  
613 anticipated that the GGBS-NaOH binder could be substituted for CEM-I and lime with relative ease; whereby only  
614 minimal plant and equipment modifications would be required to ensure that the efficiency of binder delivery  
615 during deep mixing is maintained. However, the use of NaOH on site can pose some health and safety risks for  
616 DDSM operatives such as skin irritation (dermatitis) and eye damage. Thus, operatives should wear the appropriate  
617 personal protective equipment including disposable rubber gloves, safety goggles/glasses, disposable overalls and  
618 dust masks.

619 Based on the aforementioned factors, the GGBS-NaOH binder potentially has an impressive level of engineering  
620 practicality, exceeding that of lime, CEM-I and other waste-based binders. In addition to being used as a binder to  
621 stabilise soils, it may also be used as a partial/total substitute to CEM-I in concrete mixtures. However, the binder's  
622 engineering practicality in terms of soil stabilisation requires further research; whereby the performance of the  
623 GGBS-NaOH binder needs to be assessed when incorporated within soils characterised by higher organic and  
624 sulphate contents compared with Lanton alluvium.

## 625 **7.0 Conclusions**

627 Alkali-activated IBP's show great potential for use as replacements for CEM-I and lime in stabilising alluvial soils.  
628 The strengths and stiffnesses achieved by GGBS-NaOH significantly improved with curing, particularly when  
629 using dosages >7.5% by dry weight (>107kg m<sup>-3</sup>), which comfortably met or surpassed those exhibited by samples  
630 stabilised with equivalent quantities of lime/CEM-I and met criteria defined by EuroSoilStab (2002). For any of the  
631 binder mixtures tested, a dosage <7.5% is not recommended given the natural chemical and geotechnical properties  
632 of Lanton alluvium, along with the aggressiveness of the ASTM's durability testing programmes, which may occur  
633 regularly in some countries.

634 Some engineering specifications require high strengths and stiffnesses and such cases, using GGBS-NaOH would  
635 be the most logical replacement for CEM-I or lime. However, in addition to engineering scenarios characterised by  
636 static loads, there are those such as high-speed rail lines where the high-frequency dynamic loading of the ground  
637 requires slightly lower stiffnesses to prevent brittle failures. In such cases, using GGBS-NaOH at lower dosages

638 would be preferred. NaOH is very effective in activating GGBS and producing long term high strength gains,  
639 which proved to be equally as effective as the sodium silicate-sodium hydroxide activator used by Sargent et al.  
640 (2013) in raising soil pH, promoting pozzolanic conditions and long term strength gains. The GGBS based binders  
641 and solid NaOH activator pellets could be substituted for CEM-I and lime in DDSM with minimal modification to  
642 pre-existing plant and equipment, or a reduction in the efficiency of mixing.

643 The dosage of GGBS-NaOH for use within soils will differ between DDSM projects. For soils more problematic  
644 than Lanton alluvium, higher dosages would be required to achieve high strengths. Additionally, the ratio between  
645 GGBS and NaOH within the binder will also require customisation, whereby higher NaOH concentrations would  
646 be required to stabilise soils with a low pH. Care must be taken in designing the GGBS-NaOH binder mixture, as  
647 high NaOH concentrations would result in the binder becoming less environmentally and financially sustainable.  
648 The use of GGBS-NaOH has the potential of becoming a more sustainable alternative than the continued use of  
649 lime and CEM-I; thereby promoting its commercialisation potential. Although the current UK and international  
650 market prices for the GGBS-NaOH binder mixture are higher than CEM-I, the financial costs in terms of raw  
651 materials, energy consumption, transport and the associated CO<sub>2</sub> emissions incurred by CEM-I production far  
652 outweigh those incurred by GGBS-NaOH. Ultimately, this new binder aims to achieve a balance between the desire  
653 for making cost savings and a desire for a binder with low embodied carbon.

654 The cost of any DDSM project involving alkali-activated mixtures can be quite high. It is common for geopolymers  
655 components to come from various locations. The distances between sourcing plants and stabilisation sites can be  
656 considerable. As modern transportation costs are high, careful planning must be conducted to minimise delivery  
657 distances, helping geopolymers become more sustainable and competitive than lime or CEM-I.

658

## 659 **References**

660 Alibaba, 2014. International market prices for sodium hydroxide. [online]. Available at:  
661 <[http://www.alibaba.com/premium/sodium\\_hydroxide.html?uptime=20140708&ptid=1012000053229821&crea=475012239](http://www.alibaba.com/premium/sodium_hydroxide.html?uptime=20140708&ptid=1012000053229821&crea=47501223981&plac=&netw=s&device=c&ptscode=0110202010030001)  
662 81&plac=&netw=s&device=c&ptscode=0110202010030001>. Last accessed: 19<sup>th</sup> July 2014.

663 American Society for Testing and Materials (ASTM), 2015. Designation: D 559/D559M – 15 Standard Test Methods for  
664 Wetting and Drying Compacted Soil-Cement Mixtures. Annual Book of ASTM Standards. 4.08, West Conshocken: Pa.

665 American Society for Testing and Materials (ASTM), 2015. Designation: D 560/560M – 15 Standard Test Methods for  
666 Freezing and Thawing Compacted Soil-Cement Mixtures. Annual Book of ASTM Standards. 4.08, West Conshocken: Pa.

667 Bernal, S. A., 2014. The resistance of alkali-activated cement-based binders to carbonation. in Pacheco-Torgal, F., Labrincha,  
668 J., Leonelli, C., Palomo, A. and Chindaprasit, P. (Eds.), Handbook of alkali activated cements, mortars and concretes.  
669 Woodhead Publishing.

670 Brunauer, S., Emmett, P. H. and Teller, E., 1938. Adsorption of gases in multimolecular layers. *Journal of the American*  
671 *Chemical Society*. 60, 309-319.

672 BSI, 1990. BS: 1377 Incorporating Amendment No. 1, Methods of test for Soils for Civil Engineering Purposes. British  
673 Standards Institution, Milton Keynes.

674 BSI, 1996. BS: 7755-3.12, ISO 13536:1995. Soil Quality. Chemical methods. Determination of the potential cation exchange  
675 capacity and exchangeable cations using barium chloride solution buffered at pH = 8.1. British Standards Institution, Milton  
676 Keynes.

677 BSI, 2015. BS: 5930, Incorporating Amendment No. 1, Code of Practice for Site Investigations. British Standards Institution,  
678 Milton Keynes.

679 Bye, G., 2011. Portland Cement. Third edition. Institute of Civil Engineers Publishing. ISBN: 978-0-7277-3611-6.

680 Clarke, D. and Smethurst, J. A., 2010. Effects of climate change on cycles of wetting and drying in engineered clay slopes in  
681 England. *Quarterly Journal of Engineering Geology and Hydrology*. 43, 473-486.

682 Connell, M., 2014. Hanson Cements, UK. Personal communication.

683 Consoli, N. C., Rosa, D. A., Cruz, R. C. and Rosa, A. D., 2011. Water content, porosity and cement content as parameters  
684 controlling strength of artificially cemented silty soil. *Engineering Geology*. 122, 328-333. Doi: 10.1016/j.enggeo.2011.05.017.

685 Davidson, L. K., Demirel, T. and Handy, R. I., 1965. Soil Pulverization and Lime Migration in Soil Lime Stabilisation.  
686 *Highway Research Record*. 92, 103-126.

687 DECC – Department of Energy & Climate Change, 2015. Statistical press release: UK Energy Statistics, Q1 2015, ref:  
688 2015/020. [online]. Available at: <[https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/437747/](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/437747/Press_Notice_June_15.pdf)  
689 [Press\\_Notice\\_June\\_15.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/437747/Press_Notice_June_15.pdf)>. Last accessed 2<sup>nd</sup> August 2015.

690 DTI – Danish Technical Institute, 2005. Nordic Innovation Centre Project: NI-project 03018 “CO<sub>2</sub> uptake during the concrete  
691 life cycle”. Guidelines: Uptake of carbon dioxide in the life cycle inventory of concrete. October 2005. Prepared by Pommer,  
692 K. and Pade, C. ISBN: 87-7756-757-9.

693 Duxson, P., Fernandez-Jimenez, A., Provis, J. L., Lukey, G. C., Palomo, A. and Deventer, J. S. J., 2007. Geopolymer  
694 technology: the current state of the art. *Journal of Materials Science, Advances in Geopolymer Science and Technology*. 42,  
695 2917-2933. Doi: 10.1007/s10853-006-0637-z.

696 EIA – Energy Information Administration, 2015. Growth in residential electricity prices highest in 6 years, but expected to  
697 slow in 2015. [online]. Available at: <<http://www.eia.gov/todayinenergy/detail.cfm?id=20372>>. Last accessed 2<sup>nd</sup> August 2015.

698 EPA – United States Environmental Protection Agency, 2005. AP 42 – Compilation of Air Pollutant Emission Factors,  
699 Volume 1: Stationary Point and Area Sources. Environmental Protection Agency, Washington DC, 2005.

700 EPA - United States Environmental Protection Agency, 2015. Increasing greenhouse gas concentrations will have many  
701 effects. [online]. Available at: <<http://www.epa.gov/climatechange/science/future.html>>. Last accessed: 1st June 2015.

702 EuroSoilStab, 2002. Development of design and construction methods to stabilise soft organic soils: Design guide soft soil  
703 stabilisation. CT97-0351. Project No.: BE 96-3177.

704 Fraay, A. L. A., Bijen, J. M. and Haan, D. Y. M., 1989. The reaction of fly ash in concrete: a critical examination. *Cement and*  
705 *Concrete Research*. 19, 235-246.

706 Global Cement, 2011. Geopolymer concrete – A commercial reality (2<sup>nd</sup> February 2011). [online]. Available at: <[http://](http://www.globalcement.com/magazine/articles/316-geopolymer-concrete-a-commercial-reality)  
707 [www.globalcement.com/magazine/articles/316-geopolymer-concrete-a-commercial-reality](http://www.globalcement.com/magazine/articles/316-geopolymer-concrete-a-commercial-reality)>. Last accessed: 10th July 2014.

708 Habert, G., d'Espinose de Lacaillerie, J. B. and Roussel, N., 2011. An environmental evaluation of geopolymer based concrete  
709 production: reviewing current research trends. *Journal of Cleaner Production*. 19, 1229-1238. Doi:  
710 10.1016/j.clepro.2011.03.012.

711 Hanson Cements (Heidelberg Cement Group), 2014. Regen GGBS. [online]. Available at:  
712 <[http://www.heidelbergcement.com/uk/en/hanson/products/cements/ggbs\\_and\\_related\\_products/regen\\_ggbs.htm](http://www.heidelbergcement.com/uk/en/hanson/products/cements/ggbs_and_related_products/regen_ggbs.htm)>. Last  
713 accessed: 10<sup>th</sup> July 2014.

714 Hanson Cements (Heidelberg Cement Group), 2016. GGBS Material Safety Data Sheet (MSDS), updated May 2015.  
715 Available at: <<http://www.hanson.co.uk/en/products/regen-ggbs>>. Last accessed: 8<sup>th</sup> July 2016.

716 Hansson, T., Parry, L., Graham, M., Troughton, V. and Eriksson, H., 2001. Limix: a deep dry mixing system used at Channel  
717 Tunnel Rail Contract 440. *Proceedings of Underground Construction 2001 Symposium and Exhibition*, London. Institute of  
718 Materials, Minerals and Mining, London.

719 Hughes, P. N., Glendinning, S., Manning, D. A. C. and White, M. L., 2011. Use of red gypsum in soil mixing engineering  
720 applications. *Proceedings of the Institution of Civil Engineers, Geotechnical Engineering*. 164, 223-234. Doi:  
721 10.1680/geng.10.00061.

722 Imbabi, M. S., Carrigan, C. and McKenna, S., 2012. Trends and developments in green cement and concrete technology.  
723 *International Journal of Sustainable Built Environment*. 1, 194-216. Doi: 10.1016/j.ijbsbe.2013.05.001.

724 Jegandan, S., Liska, M., Osman, A. A-M. and Al-Tabbaa, A., 2010. Sustainable binders for soil stabilisation. *Proceedings of*  
725 *the Institution of Civil Engineers, Ground Improvement*. 163, 53-61. Doi: 10.1680/grim.2010.163.1.53.

726 Kumar, S., Drozd, V. and Saxena, S. K., 2012. Catalytic studies of sodium hydroxide and carbon monoxide reaction. *Catalysts*.  
727 2, 532-543. Doi: 10.3390/catal2040532.

728 Locat, J., Berube, M. A. and Choquette, M., 1990. Laboratory investigations on the lime stabilization of sensitive clays: shear  
729 strength development. *Canadian Geotechnical Journal*. 27, 294-304.

730 LSE – London School of Economics, 2015. EUROPP – Falling oil prices should help Europe's ailing economies, but the wider  
731 implications of the price drop remain to be seen, by Bert Scholtens. [online]. Available at  
732 <[http://blogs.lse.ac.uk/europpblog/2015/01/21/falling-oil-prices-should-help-europes-ailing-economies-but-the-wider-](http://blogs.lse.ac.uk/europpblog/2015/01/21/falling-oil-prices-should-help-europes-ailing-economies-but-the-wider-implications-of-the-price-drop-remain-to-be-seen/)  
733 [implications-of-the-price-drop-remain-to-be-seen/](http://blogs.lse.ac.uk/europpblog/2015/01/21/falling-oil-prices-should-help-europes-ailing-economies-but-the-wider-implications-of-the-price-drop-remain-to-be-seen/)>. Last accessed: 2<sup>nd</sup> August 2015.

734 Madlool, N. A., Saidur, R., Hossain, M. S. and Rahim, N. A., 2011. A critical review on energy use and savings in the cement  
735 industries. *Renewable and Sustainable Energy Reviews*. 15, 2042-2060. Doi: 10.1016/j.rser.2011.01.005.

736 Manning, D. A. C., Renforth, P., Lopez-Capel, E., Robertson, S. and Ghazireh, N., 2013. Carbonate precipitation in artificial  
737 soils produced from basaltic quarry fines and composts: An opportunity for passive carbon sequestration. *International Journal*  
738 *of Greenhouse Gas Control*. 17, 309-317. Doi: 10.1016/j.ijggc.2013.05.012.

739 McLellan, B. C., Williams, R. P., Lay, J., van Riessen, A. and Corder, G. D., 2011. Costs and carbon emissions for geopolymer  
740 pastes in comparison to ordinary portland cement. *Journal of Cleaner Production*. 19, 1080-1090. Doi:  
741 10.1016/j.jclepro.2011.02.010.

742 Meunier, A., 2005. *Clays*, Springer Publishing - Berlin Heidelberg New York, ISBN 3-540-21667-7.

743 Nair, S. and Little, D. N., 2009. Water as the Key to Expansion of Ettringite in Cementitious Materials. *Transportation*  
744 *Research Record: Journal of the Transportation Research Board*, No. 2104, Transportation Research Board of the National  
745 Academies, Washington D.C., 55-62. Doi: 10.3141/2104-06.

746 Network Rail (UK), 2014. Network Rail standard RT/CE/S/065 Issue 4 2014 "Examination of Earthworks".

747 Newman, J. and Choo, B. S., 2003. *Advanced Concrete Technology*. Elsevier Butterworth Heinemann publishing. ISBN 0-  
748 7506-5103-2.

749 Palomo, A., Grutzeck, M. W. and Blanco, M. T., 1999. Alkali-activated fly ashes. A cement for the future. *Cement and*  
750 *Concrete Research*. 29, 1323-1329.

751 Renforth, P., Manning, D. A. C. and Lopez-Capel, E., 2009. Carbonate precipitation in artificial soils as a sink for atmospheric  
752 carbon dioxide. *Applied Geochemistry*. 24 (2009), 1757-1764.

753 Reuters, 2015. Is coal's decline permanent? By Mike Coronas – 6<sup>th</sup> January 2015. [online]. Available at  
754 <<http://blogs.reuters.com/data-dive/2015/01/06/is-coals-decline-permanent/>>. Last accessed 2<sup>nd</sup> August 2015.

755 Sanna, A., Dri, M., Hall, M. R. and Maroto-Valer, M., 2012. Waste materials for carbon capture and storage by mineralisation  
756 (CCSM) – A UK perspective. *Applied Energy*. 99 (2012), 545-554.

757 Sargent, P., Hughes, P. N., Rouainia, M. and White, M., 2013. The use of alkali activated waste binders in enhancing the  
758 mechanical properties and durability of soft alluvial soils. *Engineering Geology* 152, 96-108.

759 Shi, C., Krivenko, P. V. and Roy, D., 2006. *Alkali-Activated Cements and Concretes*. Taylor & Francis Publishing. ISBN 0-  
760 415-70004-3.

761 Song, K-I., Song, J-K., Yeon Lee, B. and Yang, K-H., 2014. Carbonation characteristics of alkali-activated blast-furnace slag  
762 mortar. *Advances in Materials Science and Engineering*. Volume 2014, Article ID 326458. Hindawi Publishing Corporation.  
763 Doi: 10.1155/2014/326458.

764 Statista, 2016. United States and world cement production in 2010-2015. [online]. Available at:  
765 <<http://www.statista.com/statistics/219343/cement-production-worldwide/>>. Last accessed 14<sup>th</sup> February 2016.

766 Tomlinson, M. J., 2001. *Foundation Design and Construction*. Seventh Edition. Pearson Education, Prentice Hall, ISBN 0-13-  
767 031180-4.

768 Topolnicki, M., 2004. In situ soil mixing. 331-428, within “Ground Improvement” 2<sup>nd</sup> edition, edited by Moseley, M. P. and  
769 Kirsch, K., Spon Press, ISBN 0-415-27455-9.

770 Tsuchida, H., 1970. Prediction and countermeasure against the liquefaction in sand deposits. Abstract of the seminar in the Port  
771 and Harbor Research Institute (in Japanese).

772 Turner, L. K. and Collins, F. G., 2013. Carbon dioxide equivalent (CO<sub>2</sub>-e) emissions: A comparison between geopolymers and  
773 OPC cement concrete. *Construction and Building Materials*. 43, 125-130. Doi: 10.1016/j.conbuildmat.2013.01.023.

774 Tutumluer, E., 2012. Short course notes for Geotechnical Aspects of Pavement Design and Construction – ASCE GeoCongress  
775 2012 “State of the Art and Practice in Geotechnical Engineering”, 25 – 29th March 2012, Oakland, CA, USA.

776 Washbourne, C.-L., Renforth, P. and Manning, D. A. C., 2012. Investigating carbonate formation in urban soils as a method  
777 for capture and storage of atmospheric carbon. *Science of the Total Environment*. 431 (2012), 166-175.

778 Yan, J., 2015. *Handbook of Clean Energy Systems: Volume 5 – Energy Storage*. John Wiley & Sons Publishing Ltd. ISBN:  
779 978-1-118-38858-7.s