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

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Abstract

Soft alluvial soils present unfavourable conditions for engineering developments, due to their poor bearing capacities and high potential for experiencing shrinkage and swelling. This paper focusses on deep dry soil mixing (DDSM), which introduces cementitious binders to soft soils via a rotating auger drill; thereby producing soil-cement columns. Ordinary Portland cement (CEM-I) is globally used across the construction industry and is the most commonly used binder for DDSM applications, due to its high strength performances. However, CEM-I production is one of the world's most energy intensive and expensive industrial processes; contributing 5-7% of the world's total CO_2. There is now significant pressure on the cement and construction industries to greatly reduce their CO_2 emissions by developing "greener" alternatives to CEM-I, which are both more environmentally and financially sustainable in the long-term. Alkali activated industrial by-products (IBP's) such as ground granulated blast furnace slag (GGBS), known as geopolymers have been identified as potential alternatives. These are advantageous due to negating the need to transfer IBP's to landfill, their abundance, negligible or zero production costs. Geopolymers are capable of reducing greenhouse gas emissions by up to 64%. Calcium-bearing slags have also been found to possess potential for carbon capture and storage (CCS). Comparisons with the strength and durability of untreated and stabilised soils have been made in this study. Results indicate that stabilising an alluvial soil with sodium hydroxide (NaOH) activated GGBS produced significant strength and durability improvements surpassing CEM-I. The addition of NaOH allowed pozzolanic reactions to occur, leading to improved mechanical properties with time; primarily strength.

Keywords

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

1.0 Introduction

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

Unfavourable environmental and financial issues are associated with utilising CEM-I as a binder. Cement production contributes 5 – 7% of global CO_2 emissions (McLellan et al., 2011). Increases in such emissions are anticipated to have long term adverse warming effects on the global climate; the consequences of which include changing weather patterns, melting polar ice caps, rising sea levels and ocean acidification (EPA, 2015). These effects will have potentially major impacts on marine and land based life. Therefore, it has become extremely important for the construction industry to become more sustainable by using materials with lower values of embodied CO_2. The continued use of CEM-I is also financially unsustainable, whereby its manufacture is energy intensive and expensive. The electrical energy consumed per ton of CEM-I produced is 75 kWh (Madlool et al., 2011). The UK's price indices of electricity and coal as fuels rose by 75 and 63% respectively between 2005 and 2011. Similar trends were observed during the same period in the United States, whereby electricity and coal prices increased by 19 and 47%, respectively (Imbabi et al., 2012). Since the Fukushima nuclear disaster in 2011, global coal prices have reduced by half to approximately $70 per ton (Reuters, 2015), as have oil prices from $120 to approximately $45 per barrel (LSE, 2015). However, according to DECC (2015) and EIA (2015), electricity prices in the UK and US have remained relatively constant since 2011.

Hence, there is a need to identify more environmentally and financially sustainable replacement binders. These binders should satisfy the following criteria in that they: 1) provide engineering performances comparable to or surpass those of CEM-I within similar curing times, 2) be commercially available at comparable/lower prices than CEM-I, 3) produced in such a way that fuel costs are markedly lower than those affiliated with CEM-I production whilst incurring lower CO_2 emissions. A modern popular route for selecting new binders has been to recycle alumino-silicate based pozzolanic industrial by-products (IBP's) such as ground granulated blastfurnace slag (GGBS) and pulverised fly ash (PFA). Such materials are already being used as additives to cement mixtures; namely CEM-II for PFA and CEM-II/III for GGBS. Per Hanson (2014), GGBS is preferred over PFA in the UK as a replacement for CEM-I in cement mixtures due to its higher levels of replacement and ability to produce higher strengths compared with PFA. However, the aim of this research area is to design new low carbon cementitious binder mixtures which negate the need to use any lime or CEM-I.

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

The continued use of lime as an alkali activator is environmentally unfavourable due to their high carbon costs. According to Shi et al. (2006), solid NaOH flakes/pellets and Na_2SiO_3 solution are becoming two of the most widely available and popular activators for use in concretes and cements. Cristello et al. (2011) used NaOH and Na_2SiO_3 to activate IBP's (class F PFA) for use in DDSM treatment of a low plasticity sandy clay. Field testing results demonstrated that the activated geopolymer produced higher strengths compared with CEM-I.

Per Habert et al. (2011) lower financial and environmental costs are associated with their production over lime and CEM-I. However, NaOH flake/pellet production has lower environmental impacts (3.71×10^{-1} kg CO_2 eq, human 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_2SiO_3

solution, which has a high global warming potential of 117.8 kg CO_2 eq, high human toxicity level of 82.75 kg 1,4-DB eq and a high freshwater ecotoxicity of 21.84 kg 1,4-DB eq.

Further justification behind using NaOH over Na_2SiO_3 as an activator is that the latter has a higher accelerated carbonation depth when used within geopolymer pastes, which has been attributed to the composition and structure of the C-S-H gels formed; whereby NaOH activated slags have a higher Ca/Si ratio (1.2) compared with Na_2SiO_3 activated slags (Bernal, 2014). However, with NaOH activated slags possessing such a higher Ca/Si ratio and reduced silicate chain length, these properties may consequently favour the precipitation of increasing quantities of carbonates to fill pore spaces. The MgO content of slags has been identified to have a significant role in the mechanism and extent of carbonation; whereby slags with higher MgO content are more likely to be less effected by carbonation. Thus, on this basis and the typical MgO contents of various slag types per Sanna et al. (2012), the extent to which carbonation extends within GGBS-based geopolymers is anticipated to be lower compared with steel slags, argon-oxygen decarburisation (AOD) process slag and most ash wastes (e.g. PFA).

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

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

2.0 Soil and Binder Materials

2.1 Lanton Alluvium

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

2.2 Cementitious Binder

The IBP binder used for this research was ground granulated blast-furnace slag (GGBS) supplied by Hanson Cements Ltd. A particle size distribution (PSD) curve for the GGBS is provided within Figure 1. For comparison purposes, non-activated GGBS, CEM-I (supplied by Lafarge) and lime (supplied by Fisher Scientific UK Ltd) were also used. To ensure that the binder to be utilised for stabilising Lanton alluvium in this paper had low embodied carbon in terms of energy and production costs, lower financial cost and reduced potential carbonation depth, the Na_2SiO_3 solution activator was not used. Thus, solid NaOH pellets were used as an activator, which was supplied by Fisher Scientific UK Ltd.

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^3)	2.4-3.0
Water solubility (g/l)	<1
Melting/freezing point (°C)	>1000
Flash point	N/A (inorganic)
Composition:	
EG-Nr.	266-002-0
CAS-Nr.	65996-69-2
CaO (%)	40
SiO_2 (%)	35
Al_2O_3 (%)	12
MgO (%)	10
Fe_2O_3 (%)	0.2

3.0 Methodologies

3.1 Soil Index Properties

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

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

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

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

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

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

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

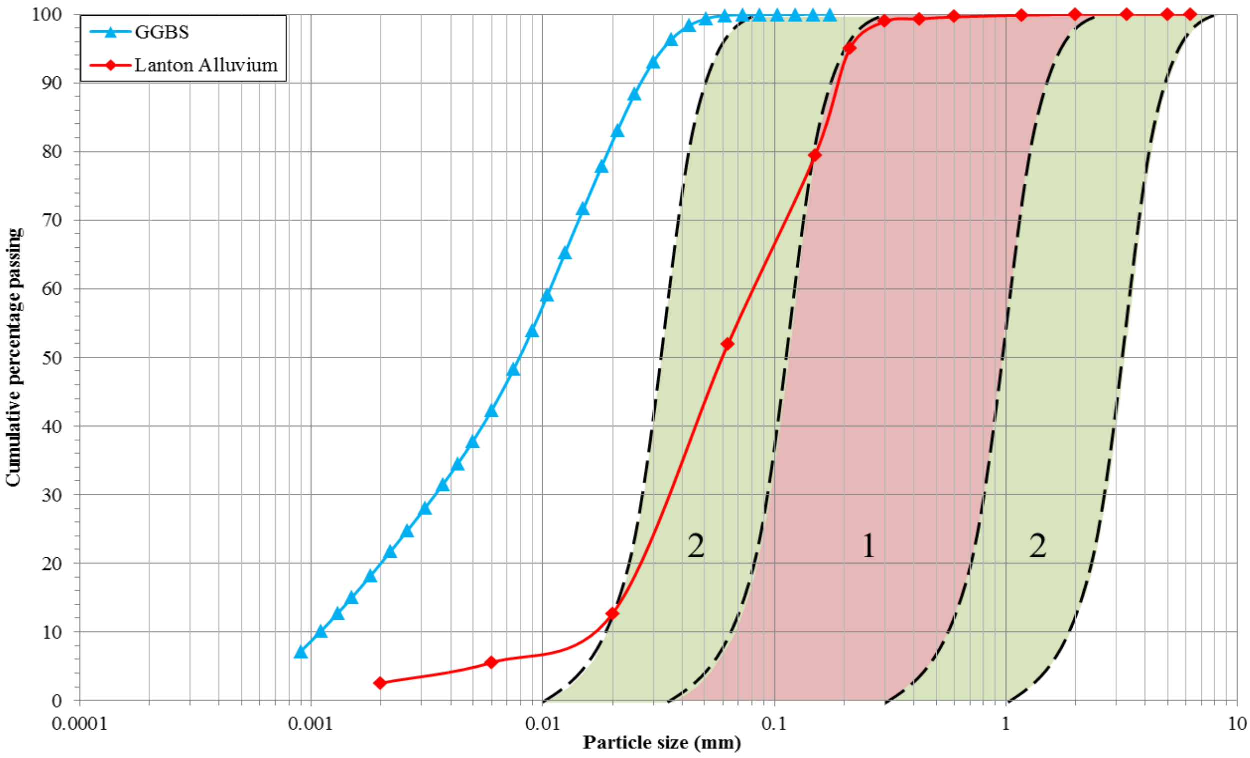

Figure 1: PSD curves for Lanton alluvium soil (red) and GGBS (blue) with Tsuchida (1970) liquefaction criteria superimposed (red area "1" denotes zone for most liquefiable soils, green area "2" denotes zone for potentially liquefiable soils).

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

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^3)	18.44
Bulk Density (Mg/m^3)	1.99
Dry density (Mg/m^3)	1.74
Cation exchange capacity (cmol/kg)	11.45
Specific surface area (m^2/g)	6.45
Total organic content (%)	0.76
Sulphate content (mg/kg soil)	49.0
BS 5930 classification[15]	Silty SAND

3.2 Engineering Performance Testing

3.2.1 Preparation of Testing Samples

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^{o}C for 24 hours and crushed into a fine powder (particle size ≤1mm). 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.

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^3, based on optimum compaction criteria and a moisture content of 25%. Table 3 summarises the soil-binder mixtures examined and their respective concentrations.

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

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

3.2.2 Laboratory Tests

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

4.0 Results and Discussion

4.1 pH

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

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

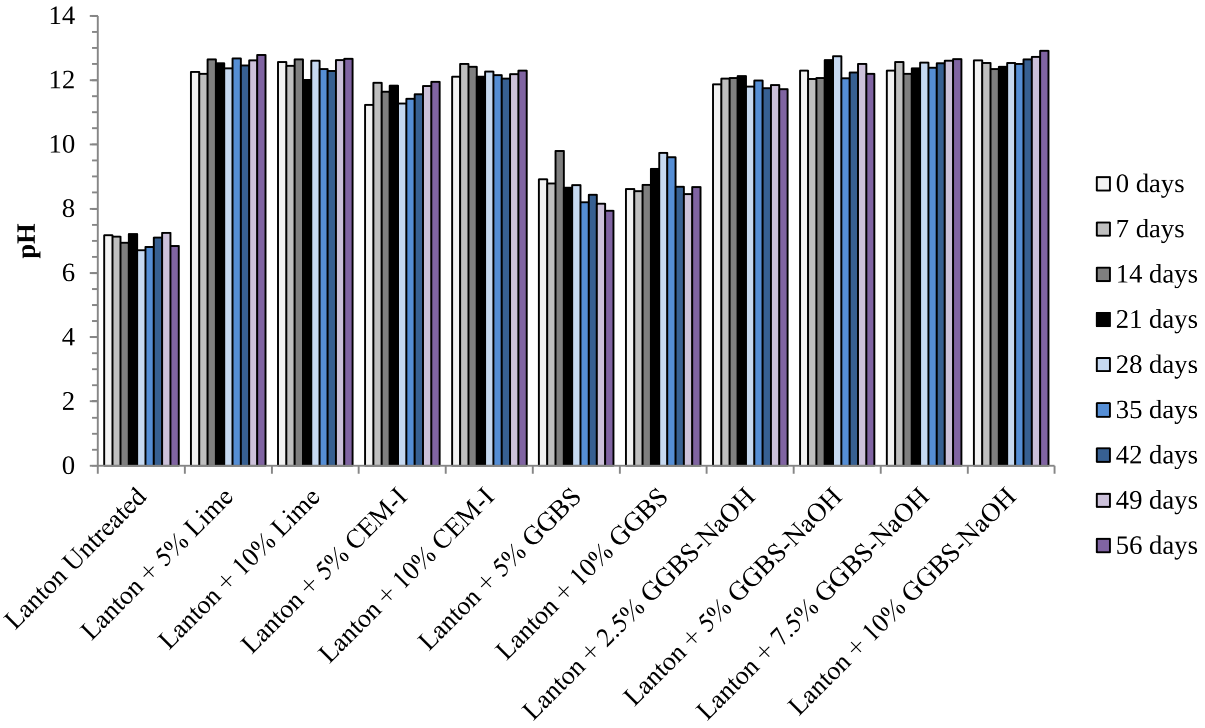

Figure 2: pH for all binder mixtures and dosages used to stabilise Lanton alluvium over 56 days.

4.2 Durability

4.2.1 Wetting-drying

All sample mixtures were subjected to wetting-drying durability testing to determine soil-cement loss and changes in moisture content and sample volume. Testing results are displayed in Figure 3. For the purposes of this study, samples are considered to have failed in wetting-drying and freezing-thawing testing upon splitting and/or complete disaggregation. In addition, samples may be discontinued should volume measurements become inaccurate due to soil-cement loss (ASTM D559-559M, 2015). For the traditional binders, a minimum dosage of 10% was required to maximise the chances of samples surviving all 12 testing cycles. Samples stabilised with CEM-I survived the 12 cycle testing period with a gradual reduction in volume, whereas 10% lime samples only survived 3 cycles exhibiting larger volumetric losses. According to Sargent et al. (2013), most non-activated geopolymers fail after the first cycle. However, the 5 and 10% GGBS samples survived 2 and 3 cycles respectively.

GGBS-NaOH dosages of 2.5 and 5% displayed similar disappointing performances to those observed for non-activated GGBS samples. However, impressive performances were recorded for specimens containing a dosage of 7.5 or 10%, as they displayed negligible changes in volume or moisture content over the 12 cycles. Whilst the Lanton + 7.5% and 10% GGBS-NaOH samples demonstrate higher levels of durability against wetting-drying compared with Lanton + 10% GGBS samples, the decreasing water content of such non-activated samples after developing latent hydraulicity inhibits the hydration of cementitious gels and therefore long-term strength development.

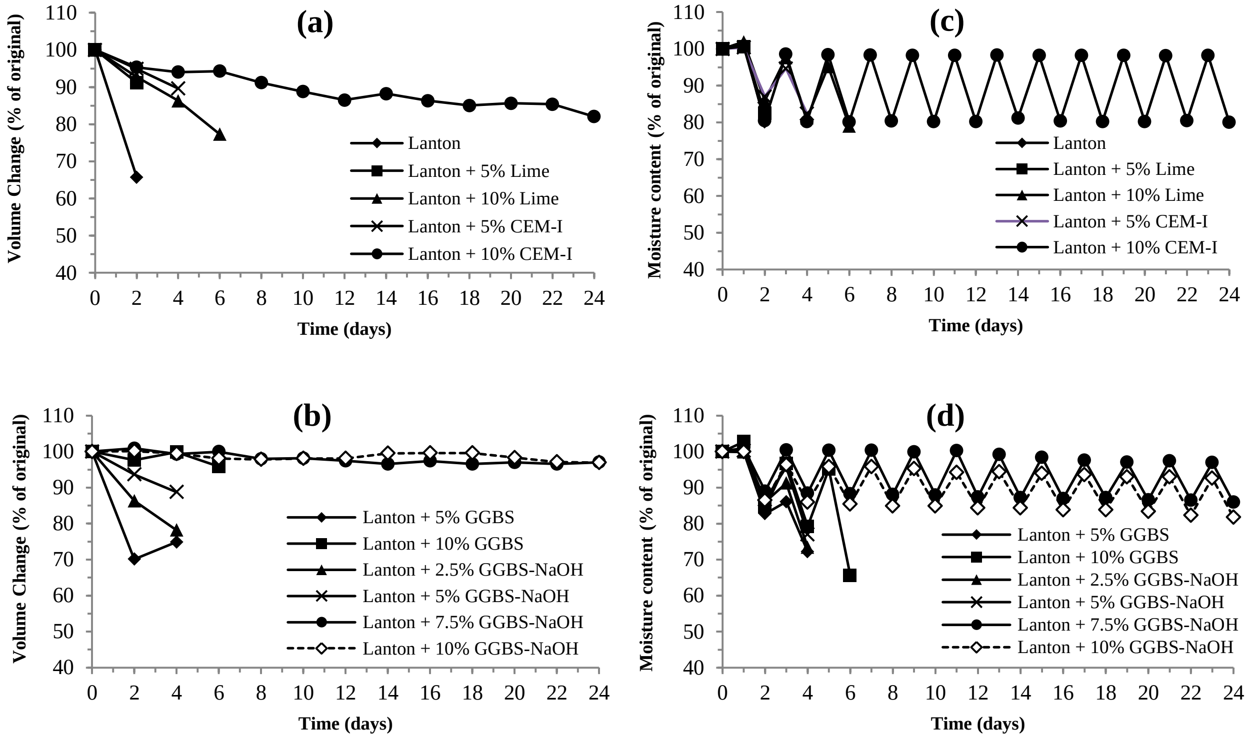

Figure 3: Volumetric (a-b) and moisture content (c-d) changes experienced by all stabilised Lanton alluvium mixtures during wetting-drying testing.

4.2.2 Freezing-thawing

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

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

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

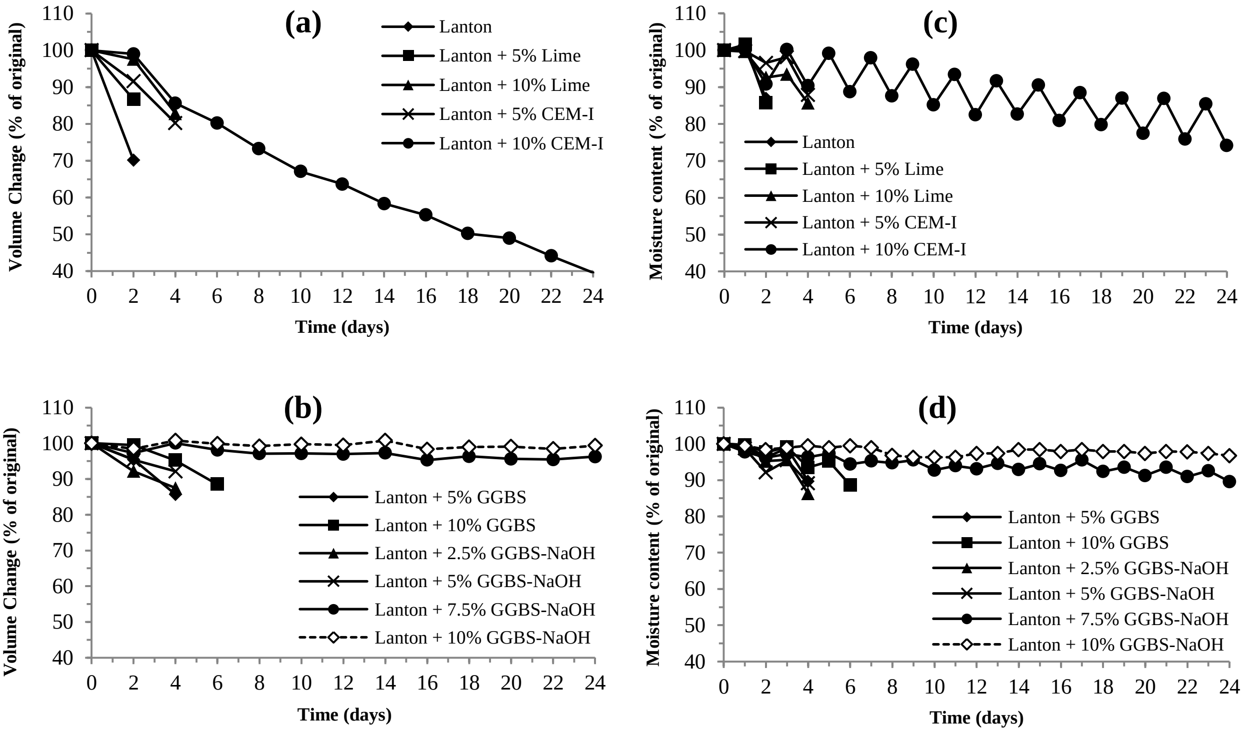

Figure 4: Volumetric (a-b) and moisture content (c-d) changes experienced by all stabilised Lanton alluvium mixtures during freezing-thawing testing.

To summarise, GGBS-NaOH at dosages >7.5% (particularly 10%) produced the best durability performances for both wetting-drying and freezing-thawing, surpassing that of 10% CEM-I. NaOH activation proved very effective in producing dense high strength samples, which possessed low permeabilities and were thereby deemed less likely to experience water absorption and subsequent sample deterioration through shrinkage, swelling and physical weathering.

4.3 Compressive strength

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

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

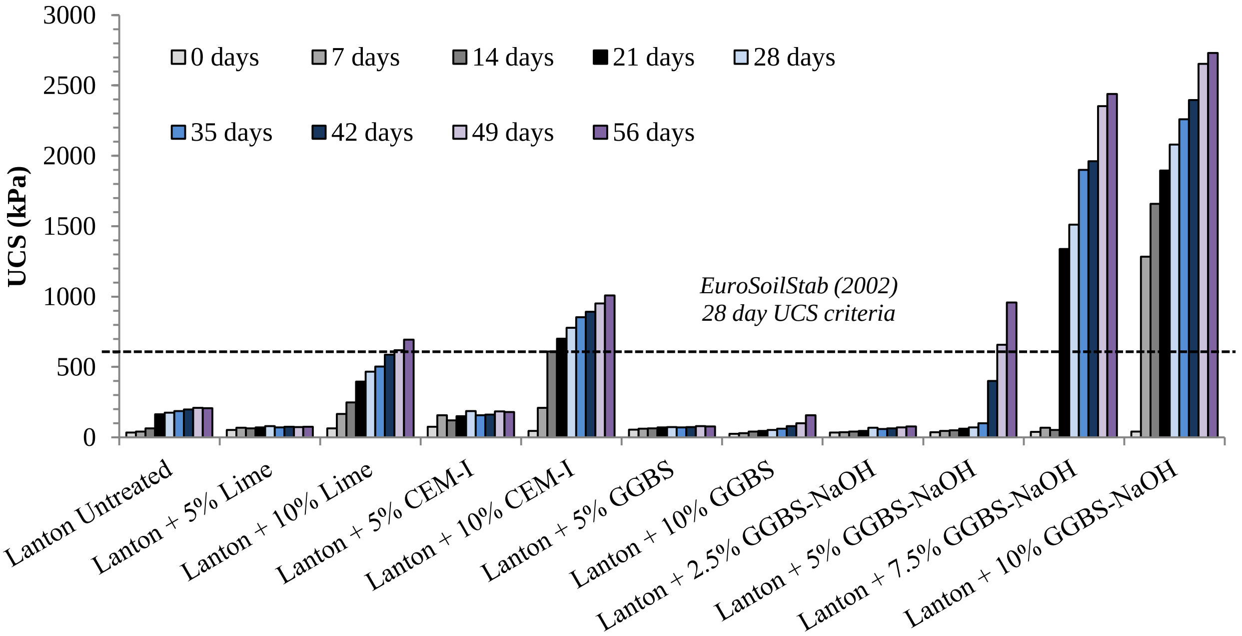

Figure 5: UCS performances for all binder mixtures and dosages used to stabilise Lanton alluvium after all curing periods.

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

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

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

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

Moisture content and porosity also influence strength development, whereby mixtures with higher moisture contents have lower calcium concentrations (pertaining to GGBS) for cement formation; resulting in lower strengths. Consoli et al. (2011) suggested porosity also influences strength by modifying the number of contact points between soil particles; whereby delayed strength gains are anticipated within soils of higher porosities and those which contain less cement and therefore a less dense network of cementitious gels.

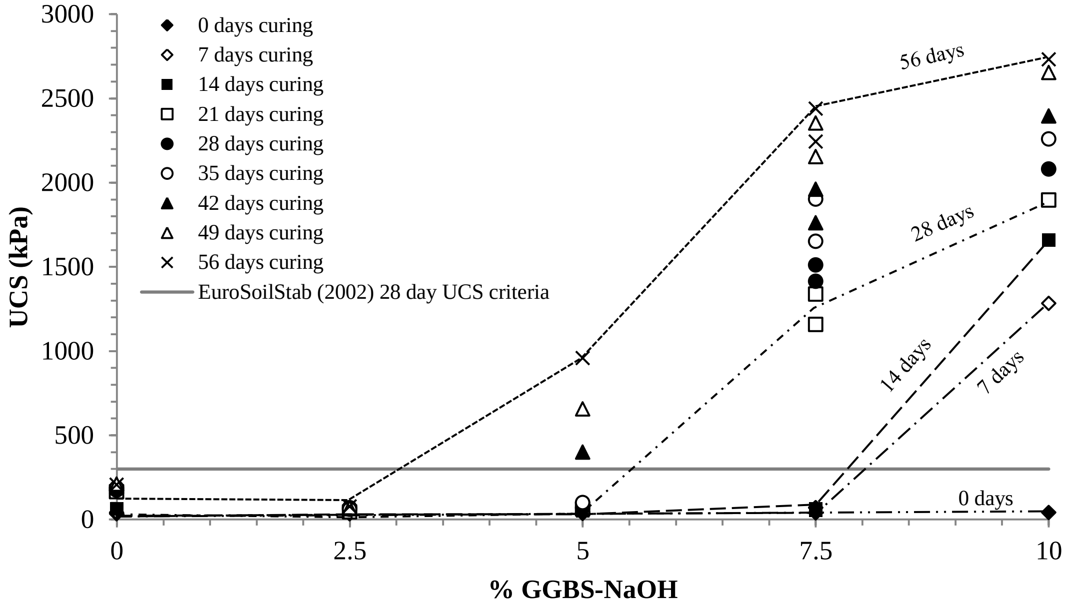

Figure 6: Relationship between unconfined compressive strength and GGBS-NaOH dosage, with trend lines shown for 0, 7, 14, 28 and 56 days curing.

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

4.4 Moisture content

To assess whether samples contained adequate supplies of water to allow for continued hydration and cementitious bond formation, water content was determined according to BS 1377: Part 2 (BSI, 1990). Most samples had water contents of 22 – 25%. According to Table 4, each mixture showed slight reductions in moisture content over 28 days. Negligible reductions were recorded within all non-activated samples. For GGBS-NaOH samples, moisture content reduced by 1 – 1.8%; whereby reductions >1.4% were observed for those containing dosages >7.5%. The most significant reductions (up to 5.25%) were observed in samples stabilised with a 10% lime and CEM-I.

Sub-samples were retained after UCS testing at 28 days and tested according to BS 1377: Part 3 (BSI, 1990). Average pH values recorded for Lanton alluvium ranged between 6.7 – 7.2 over 56 days; thereby indicating the need for an alkali activator or a high alkaline binder. Stabilisation using 5 – 10% CEM-I or lime produced pH values >11.2 and were sustained for the 56 day testing period.

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

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

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

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

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

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

4.5 Compressibility and stiffness

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

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

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

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

Table 5: m_v, Cc and Cs 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 (Cc)**		**Swelling index (Cs)**	
	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		0.013	
Lanton undisturbed	0.799	0.542	0.440	0.255	0.799	0.542	0.440	0.255	0.309		0.030	
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

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

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

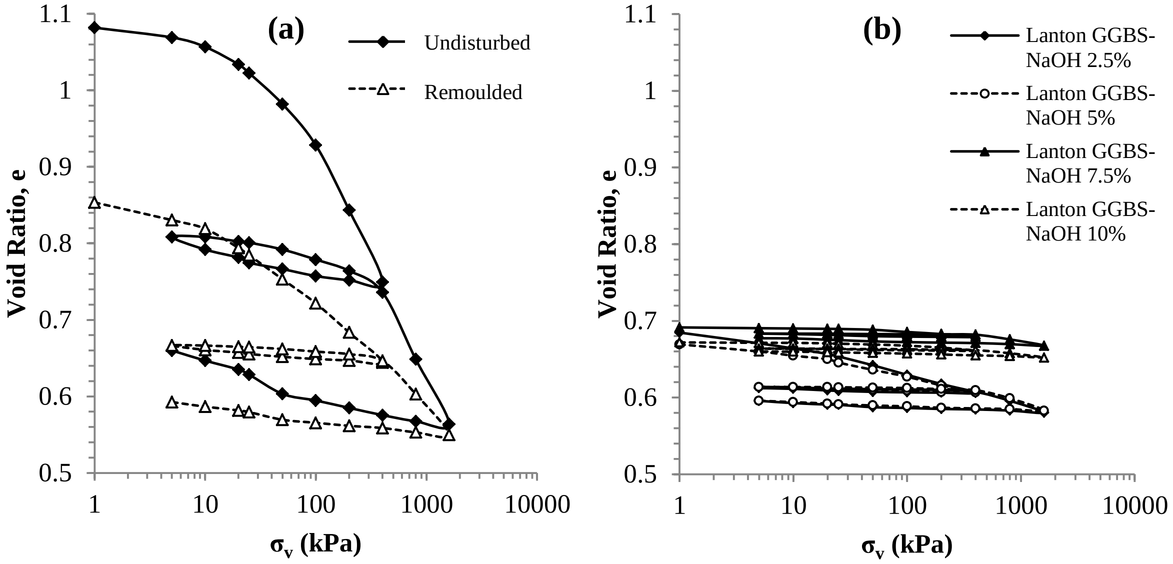

Figure 7: Oedometer compression curves of Lanton alluvium in (a) its untreated remoulded and undisturbed state, and (b) treated with 2.5-10% GGBS-NaOH after 28 days curing. Note: the curves are based on averages taken from triplicate testing.

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

In summary, a significant improvement in compressibility and therefore stiffness was observed after 28 days for 7.5 and 10% GGBS-NaOH specimens; whereby m_v values decreased to <0.03m^2/MN with increasing σ_v, indicating very low levels of compressibility. Using >7.5% GGBS-NaOH within Lanton alluvium produced brittle failures. This behaviour could be unfavourable under dynamic loading conditions due to passing rail traffic and earthquakes. However, the strengths achieved were lower and more favourable than those recorded by Sargent et al. (2013) for a GGBS-NaOH-Na_2SiO_3 stabilised artificial alluvium.

5.0 Sustainability assessment

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

5.1 Environmental impact

Although the use and practicality of cement and lime as binders is well proven in DDSM, their continued usage is environmentally unsustainable. Cement and lime production have high carbon costs. Cement production contributes up to 7% of the world's CO_2 emissions (McLellan et al., 2011), whereby for every ton of cement produced 900 – 1100kg of CO_2 is emitted (EPA, 2005). An estimated 4,100 million tonnes of cement was produced in 2015 (Statista, 2016). The cement and civil engineering industries are under significant pressure to reduce CO_2 permissions and contribute towards atmospheric carbon capture storage (CCS).

Using IBP's as alternatives or partial replacements to CEM-I or lime has real potential for reducing the environmental impact of using cements and lime. According to Hanson (2014), GGBS has impressive environmental sustainability credentials. Compared with the production of lime and CEM-I, it reduces embodied CO_2 emissions by 2 million tonnes per annum, reduces primary energy usage during manufacture/processing by 2000 million kWh, saves 3 million tonnes of quarrying and reduces landfill by almost 2 million tonnes. GGBS has advantages over other IBP's due to the quantity of CEM-I which it can replace within a given concrete or stabilised soil, whilst achieving engineering performances comparable with pure CEM-I (Connell, 2014). 50 – 70% of CEM-I may be replaced by GGBS whereas only 20 – 25% may be replaced by PFA. Whilst approximately 75% of CaO within the CEM-I component of concretes is able to sequester atmospheric CO_2 via carbonation (DTI, 2005), mixing other high-calcium binders including GGBS and steel slag within urban soils has recently proved to have excellent atmospheric CO_2 sequestration potential in the UK (Sanna et al., 2012). GGBS and steel slag have a theoretical global CO_2 potential uptake of approximately 80 million tonnes per year (Yan, 2015). CCS within urban soils through the incorporation of such slag materials has recently been demonstrated by Washbourne et al. (2012) on the Science Central site in Newcastle upon Tyne, UK. Washbourne et al. (2012) demonstrated that the top metre of soil for the 10 hectare site has the potential to capture and store 64,000 Mg of atmospheric CO_2 in the form of carbonate minerals, half of which was captured within 3 years at an annual rate of 325 Mg C ha^{-1}. Similar figures were also calculated for similarly mixed quarry soils (Barrasford, UK); namely 300 Mg C ha^{-1}, which was observed down to depths of three metres over ten years (Manning et al., 2013). Such differences in sequestration rates were attributed to differing soil mineralogies; whereby urban soils at Science Central contained cementitious rubble material (calcium silicates and calcium hydroxide) which produce greater rates of carbonation compared with Barrasford quarry soil (Manning et al., 2013). Globally, construction and development site soils are considered able to capture and store 290 million Mg of atmospheric carbon within soil matrices per year (Renforth et al., 2009).

However, strength gains within GGBS-stabilised soft alluvial soils require alkali activation. Most alkali materials for industrial purposes are synthetically sourced with high costs and negative environmental impacts. Although the use of NaOH in this paper promoted pozzolanic conditions and high strength gains within stabilised samples, its production involves the electrolysis of brine, which is energy intensive and produces considerable CO_2 emissions.

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

Significant CO_2 emission reductions of up to 64% are estimated for Australian geopolymers compared with CEM-I (McLellan et al., 2011). There are carbon footprint implications associated with the brine electrolysis (membrane) technique used to produce NaOH. However, the quantities of NaOH required in this research were small (0.83 – 3.3% by dry weight or 12.4 – 49.4kg m^{-3}) compared with the quantities of CEM-I typically used in more traditional binder mixtures for DDSM treatment of soft soils. According to Topolnicki (2004), cement dosages of 120 – 300 kg m^{-3} may be used within most soils, with the exception of sludges, peats and organic silts/clays where dosages of 250 – 400kg m^{-3} are recommended.

The GGBS CO_2 reductions far outweigh the carbon footprint produced by the NaOH's manufacture. There is also potential for GGBS-NaOH to sequester atmospheric carbon within the stabilised soil, which assists in driving the binder towards commercialisation. Further work is required on the effects of carbonation on the long-term durability, strength and mineralogical development of stabilised soft alluvial soils and how much atmospheric CO_2 such mixtures can capture.

5.2 Financial costs

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

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

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

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

6.0 Engineering Practicality

A key factor to consider in assessing the potential for the GGBS-NaOH binder to be used instead of lime or CEM-I for future DDSM projects is engineering practicality. The application of chemical treatment in stabilising soft soils is generally limited to those characterised by low organic and sulphate contents and relatively high clay contents. These criteria have been defined to ensure that cation exchange and long term cementitious reactions occur within the stabilised material. Although the Lanton alluvium possessed unfavourably high moisture and silt-sand contents, using a GGBS-NaOH binder dosage ≥7.5% proved effective in producing high levels of strength and durability within the soil post 21 days curing. The enhanced mechanical performances of the GGBS-NaOH stabilised Lanton soil were at least 2 – 3 times better than those observed for samples mixed with traditional binders, whilst meeting strength criteria defined by EuroSoilStab (2002).

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

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

7.0 Conclusions

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

Some engineering specifications require high strengths and stiffnesses and such cases, using GGBS-NaOH would be the most logical replacement for CEM-I or lime. However, in addition to engineering scenarios characterised by static loads, there are those such as high-speed rail lines where the high-frequency dynamic loading of the ground requires slightly lower stiffnesses to prevent brittle failures. In such cases, using GGBS-NaOH at lower dosages would be preferred. NaOH is very effective in activating GGBS and producing long term high strength gains, which proved to be equally as effective as the sodium silicate-sodium hydroxide activator used by Sargent et al. (2013) in raising soil pH, promoting pozzolanic conditions and long term strength gains. The GGBS based binders and solid NaOH activator pellets could be substituted for CEM-I and lime in DDSM with minimal modification to pre-existing plant and equipment, or a reduction in the efficiency of mixing.

The dosage of GGBS-NaOH for use within soils will differ between DDSM projects. For soils more problematic than Lanton alluvium, higher dosages would be required to achieve high strengths. Additionally, the ratio between GGBS and NaOH within the binder will also require customisation, whereby higher NaOH concentrations would be required to stabilise soils with a low pH. Care must be taken in designing the GGBS-NaOH binder mixture, as high NaOH concentrations would result in the binder becoming less environmentally and financially sustainable. The use of GGBS-NaOH has the potential of becoming a more sustainable alternative than the continued use of lime and CEM-I; thereby promoting its commercialisation potential. Although the current UK and international market prices for the GGBS-NaOH binder mixture are higher than CEM-I, the financial costs in terms of raw materials, energy consumption, transport and the associated CO_2 emissions incurred by CEM-I production far outweigh those incurred by GGBS-NaOH. Ultimately, this new binder aims to achieve a balance between the desire for making cost savings and a desire for a binder with low embodied carbon.

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

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