Proceedings of the 24th European Young Geotechnical Engineers Conference (EYGEC), Durham, UK
Osman, A.S. & Toll, D.G. (Eds.) 2015
ISBN 978-0-9933836-01

Development of a Low Carbon Geopolymer for High Speed Rail

P. Sargent [1]

[1] AECOM, First Floor One Trinity Gardens, Broad Chare, Quayside, Newcastle upon Tyne, UK
E-mail: paul.sargent@aecom.com

ABSTRACT Portland cement and lime are commonly used binders in deep dry soil mixing (DDSM). However, their production is energy intensive, expensive and environmentally unfriendly. Pressure is mounting to develop more sustainable alternatives, such as geopolymers. DDSM has previously proved effective in treating sections of high-speed railways with poor ground conditions. Traditionally, monotonic properties of geopolymers have been used to assess their suitability for stabilising railway embankments. However, their dynamic properties require investigation to provide better estimates of their response to high-frequency train traffic. A new GGBS-NaOH binder significantly reduced axial displacements within a soft alluvium after the simulated passage of a high-speed train (HST); and has great potential for using GGBS-NaOH as a more sustainable binder for future UK DDSM projects, including HS2.

1 INTRODUCTION

Soft soils including alluvium present challenging ground conditions; given their high settlement and poor bearing capacities. DDSM is becoming popular in the UK for treating such soils by creating cement-soil columns via auger mixing. Portland cement (CEM-I) and lime have long been utilised as binders, though CEM-I usually provides higher strengths[1,2]. Soil water and calcium silicates/aluminates within the binders hydrate to form calcium silica hydroxide (C-S-H) and/or calcium aluminate hydroxide (C-A-H). These continue forming over long time-periods via pozzolanic reactions when soil pH ≥10.5[3], producing stronger “Geopolymers”[4].

CEM-I production contributes ~7% of global CO_2 emissions[5]. Its continued use in DDSM is unsustainable; placing pressure on the construction industry to find sustainable binders with comparable engineering performances. Recent efforts have focussed on recycling alumina-silicate industrial by-products (IBP’s)[6,7,8]. Adding alkali activators to IBP’s can increase rates at which geopolymers’ mechanical properties improve by raising pH[9].

The UK government has outlined plans for HS2 to better connect major northern cities to southern England and European railway networks by 2026[10]. Soft ground conditions are abundant in the UK and can be expected along the proposed route. DDSM could treat such ground conditions, given its success in stabilising Sweden’s Vastkustbanan[11] and the Channel Tunnel Rail Link[7]. Investigating geopolymers’ monotonic behaviour is insufficient in assessing their suitability for stabilising high-speed railway embankments, given the associated high-frequency dynamic loadings. This paper explores using dynamic and monotonic triaxial tests to more accurately simulate and understand the behaviour of untreated and geopolymerised soils when subjected to HST loadings.

2 ENGINEERING PERFORMANCE OF A GEOPOLYMER

The suitability of NaOH activated ground granulated blast furnace slag (GGBS) to stabilise a soft alluvium from Lanton near Wooler, Northumberland (UK) was examined, along with determining any mineralogical/microstructural changes. Table 1 summarises the soil’s index properties, which are unlikely to interfere with cementitious reactions. The soil’s PSD suggests it is potentially liquefiable[13], thereby emphasising the need for treatment.

The engineering properties considered in assessing GGBS-NaOH's suitability include compressive strength (UCS), pH and durability. Samples were cured within wax-sealed PVC tubes and tested every 7 days to 56 days[14,15,16]. 2.5, 5, 7.5 and 10% dosages by dry weight (6.7:3.3 GGBS-NaOH ratio) were added to determine the most effective dosage. For comparison, tests were also conducted on the alluvium when untreated; and stabilised with lime/CEM-I/GGBS at 5-10%.

Table 1. Geotechnical and physico-chemical index properties of Lanton alluvium.

Property	Value
In-situ moisture content (%)	25
Plasticity Index (%)	14.95
Liquid Limit (%)	35.66
Saturated unit weight (kN/m^3)	18.44
Bulk Density (Mg/m^3)	2.0
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
BS 5930 (BSI, 1990) classification	Silty SAND

2.1 *Strength*

56 day strengths recorded for 5-10% GGBS were poor (77-157kPa) (Figure 1); and under-performed untreated (206kPa), 5-10% lime (75-695kPa) or 5-10% CEM-I (179-1009kPa) samples. The higher strengths of untreated samples may be attributed to structure[17]. Hence, NaOH activation was necessary to increase strength.

2.5-5% GGBS-NaOH achieved poor strengths, similar to 5% lime/CEM-I. 10% GGBS-NaOH samples exhibited the highest and most rapid strength enhancements (2.73MPa after 56 days). Although 7.5% GGBS-NaOH samples produced lower initial strengths, values of 1.4MPa initiated after 21 days; with 28 day strengths exceeding those of 10% lime/CEM-I by factors of 2-3, thereby meeting [18] criteria.

2.2 *pH*

The untreated alluvium's pH ranged between 6.7–7.2. 5-10% CEM-I/lime produced pH >11.2 for 56 days. pH for GGBS samples were <10, highlighting the need for activation. For GGBS-NaOH specimens, all dosages raised pH to ≥11.7. Values of 12.6-12.9 were recorded for 7.5 and 10% samples, confirming pH conditions were ideal for pozzolanic reactions.

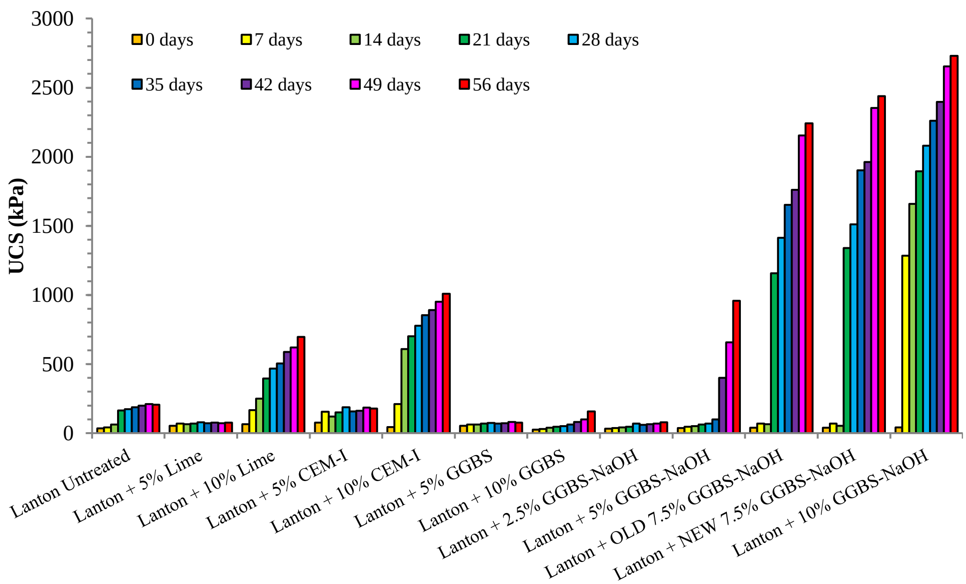

Figure 1. Unconfined compressive strength development for all binder mixtures and dosages used to stabilise Lanton alluvium.

2.3 *Durability*

Given the silty/sandy nature of the alluvium, surface water will percolate through the soil and potentially cause shrinkage/swelling during wetting-drying and freezing-thawing periods. GGBS-NaOH must be able to contend with such aggressive cycles to prevent DDSM column disintegration.

2.3.1 *Wetting-drying*

10% CEM-I samples were the only traditional mixtures to survive the testing period. Large volumetric losses were observed for 5% CEM-I, 5-10% lime and 5-10% GGBS samples; each surviving 2-3 cycles. 2.5-5% GGBS-NaOH displayed similar performances. However, 7.5-10% GGBS-NaOH displayed impressive performances (Figure 2c) and experienced negligible volume/moisture content variations.

2.3.2 *Freezing-thawing*

5% lime/CEM-I samples failed after first immersions. 10% CEM-I survived 12 cycles but experienced 60% volumetric reduction. GGBS activation was essential to ensure samples survived >3 cycles. 10% GGBS-NaOH was the most effective binder, followed by 7.5% GGBS-NaOH; recording negligible volumetric or moisture content variations (Figure 2f).

3 MINERALOGICAL AND MICROSTRUCTURAL ASSESSMENT

The 7.5% GGBS-NaOH mixture was selected for further study, given its similar performances to 10% GGBS-NaOH and improved sustainability. Quantitative XRD and SEM-EDX analyses were conducted on the untreated and 56 day 7.5% GGBS-NaOH samples. The soil contained Quartz, Orthoclase/Albite Feldspars, Dolomite, Chlorite, Illite, Vermiculite and Na-Montmorillonite. Chlorite and Dolomite were not detected within the stabilised soil; implying their Ca/Al/Si contents were consumed to form cement minerals. SEM analyses of the stabilised soil showed cementitious growths infilling void spaces (Figure 3a). GGBS particles also displayed cementitious surface coatings. Point element analyses (Figure 3b) revealed that the cementitious gels are probably C-(N)-A-S-H.

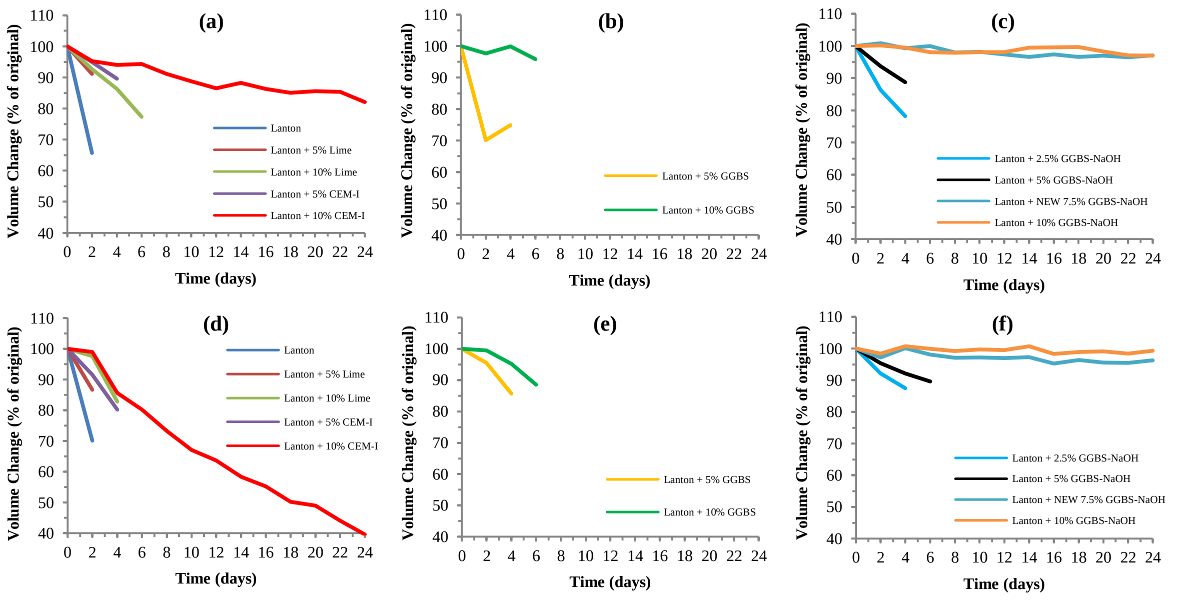

Figure 2. Volumetric changes experienced by samples during: (a-c) wetting-drying and (d-f) freezing-thawing testing.

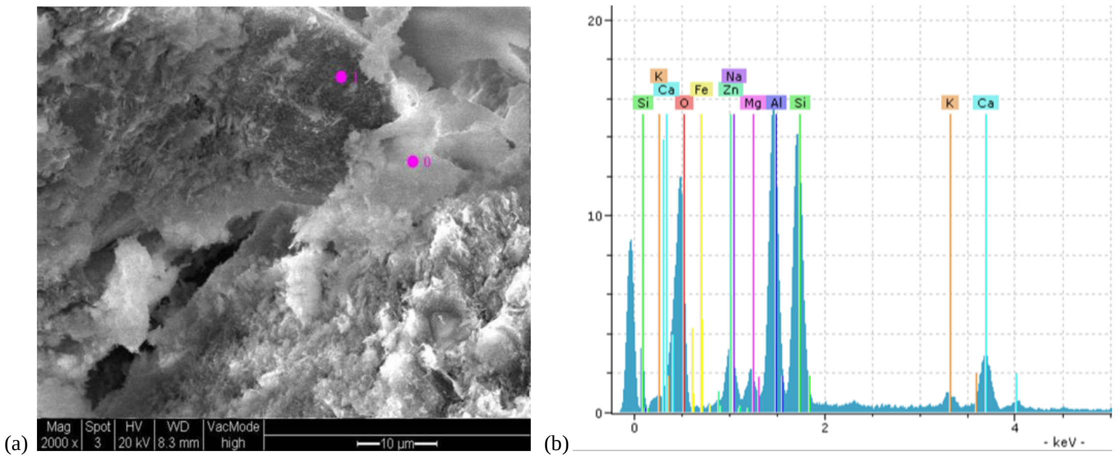

Figure 3. (a) SEM micrograph showing cement development within GGBS-NaOH stabilised alluvium after 56 days curing; (b) EDX spectra for point "0" on Figure 3a.

4 STATIC AND DYNAMIC BEHAVIOUR

4.1 Static behaviour

Undisturbed-untreated (Undis) and 28 day cured 7.5% GGBS-NaOH stabilised (28d) alluvium underwent isotropically consolidated triaxial testing under drained (CID) and undrained (CIU) conditions. Effective confining stresses (p'_0) of 50, 150 and 250kPa were used for Undis samples; and 200, 400 and 600kPa for 28d samples.

4.1.1 Untreated alluvium

All samples displayed work hardening under p'_0=50-150kPa. However, for p'_0=250kPa, softening occurred at axial strains (ε_a) >7%. Strain-localisation, shear plane development and dilation occurred within all samples, with minor contraction at small strains. In effective Cambridge stress space, the soil's failure envelope coincides with its critical state line (CSL_{Undis}) (Figure 4). An M value of 1.37 was derived from CSL_{Undis}, giving $\varphi'=33.87^o$ and c'=6.68kPa.

4.1.2 28 day cured 7.5% GGBS-NaOH

Increasing p'_0 only influenced samples' deviatoric stress (q)–ε_a behaviour for p'_0>200kPa, similar to [19]. Samples experienced strain-localisation and dilation; the latter becoming more pronounced when p'_0=200kPa. Strain softening occurred upon cementitious bond degradation. The measured effective shear strength parameters were $\varphi'=37.25^o$ and c'=360.5kPa. When CIU samples reached advanced yielding and touched their failure envelope, a phase transformation occurred (Figure 5). The stress paths then dropped towards the $CSL_{28dayCement}$. Hence, the non-linear $CSL_{28dayCement}$ and failure envelope do not coincide. For simplicity, an average M value of 1.22 was obtained.

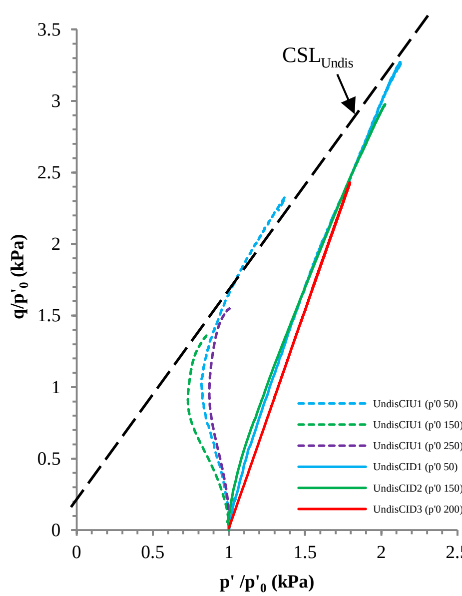

Figure 4. p'_0 normalised effective Cambridge stress paths, CSL's and yield loci for undisturbed alluvium.

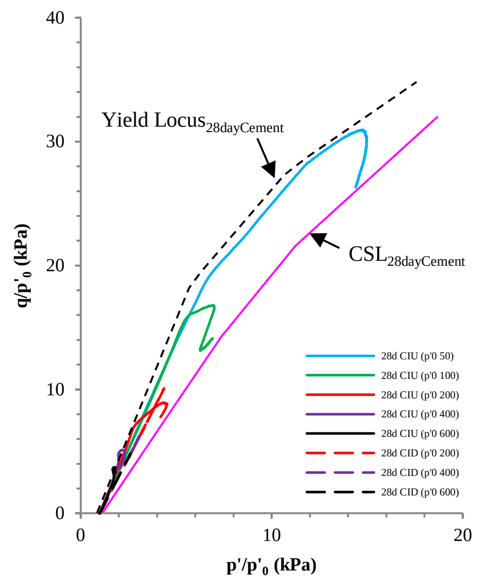

Figure 5. p'_0 normalised effective Cambridge stress paths, CSL's and yield locus for 28d 7.5% GGBS-NaOH alluvium.

4.2 Dynamic behaviour

Undrained one-way-dynamic tests were conducted under p'_0=60kPa, simulating 3m depth beneath a railway embankment, assuming embankment fill unit weight is 20 kN/m^3. The loading conditions simulated an InterCity-125 HST travelling at 125mph. Due to equipment limitations, the true loading frequency (27.94Hz) could not be applied. Thus, a frequency of 2.794Hz was used.

4.2.1 Untreated alluvium

Pore water pressures (PWP) and ε_a ratcheted with loading. Total plastic ε_a accumulations of 1.4% were recorded, which could cause unfavourable surface displacements; confirming the soil's sensitivity to dynamic disturbances. Excess pore pressure ratios (R_u) also increased with loading, ranging between 0.3-0.4. Hence, liquefaction was not observed[20]. The peak cyclic q exceeded the peak monotonic q (Figure 6a), due to the soil's viscous response to the high loading frequency[21], which dictates q and plastic ε_a accumulations.

4.2.2 28 day cured 7.5% GGBS-NaOH

Samples accumulated 0.055% plastic ε_a. Excess PWP of 1.5kPa was generated, with negligible ratcheting. R_u values were <0.08 and cyclic q-ε_a stress paths are located beneath the monotonic q-ε_a line (Figure 6b); indicating minimal liquefaction risk. Whilst the ε_a experienced falls outside the small strain range, it is within the material's elastic zone. No long-term PWP reductions were observed, suggesting cementitious bonds had not degraded. Visual inspections of samples post-testing showed no fracturing.

5 CONCLUSIONS

GGBS-NaOH-based geopolymers show great potential as CEM-I/lime replacements in DDSM. The performances met or surpassed [18] criteria. Whilst 10% dosage produced the most impressive performances, some engineering scenarios (i.e. DDSM-stabilised railway embankments) require lower stiffnesses to prevent brittle failures and hence, a lower dosage (7.5%). This successfully increased soil stiffness, minimised ε_a/PWP ratcheting and liquefaction risk during HST loading. GGBS-NaOH showed comparably small axial displacements to those for lime/CEM-I columns used to stabilise the Vastkustbanan. Thus, GGBS-NaOH may be suitable for stabilising problematic soils along the proposed HS2 route. Its impressive performances were attributed to C-(N)-A-S-H gels. No unfavourable minerals such as ettringite were observed, given the hydration kinetics of GGBS-NaOH systems and low sulphate content[22]. Given high transportation costs, careful planning is needed to minimise distances between source plants and site to ensure that geopolymers remain sustainable and competitive. The current market price of CEM-I is £70/tonne[23]. Per world market prices and exchange rates from July 2014[24], the cost of 7.5% GGBS-NaOH would be £75/tonne. Hence, this price would only need reducing by 7% to breakeven with the price of CEM-I. This warrants further investigation to determine the engineering performance of a lower dosage when used to treat Lanton alluvium amongst other problematic soils. If successful, the binder's commercial value would be significant.

ACKNOWLEDGEMENTS

Thanks go to my PhD supervisors from Newcastle University, Dr P Hughes and Dr M Rouainia and to AECOM geotechnics who supported this submission.

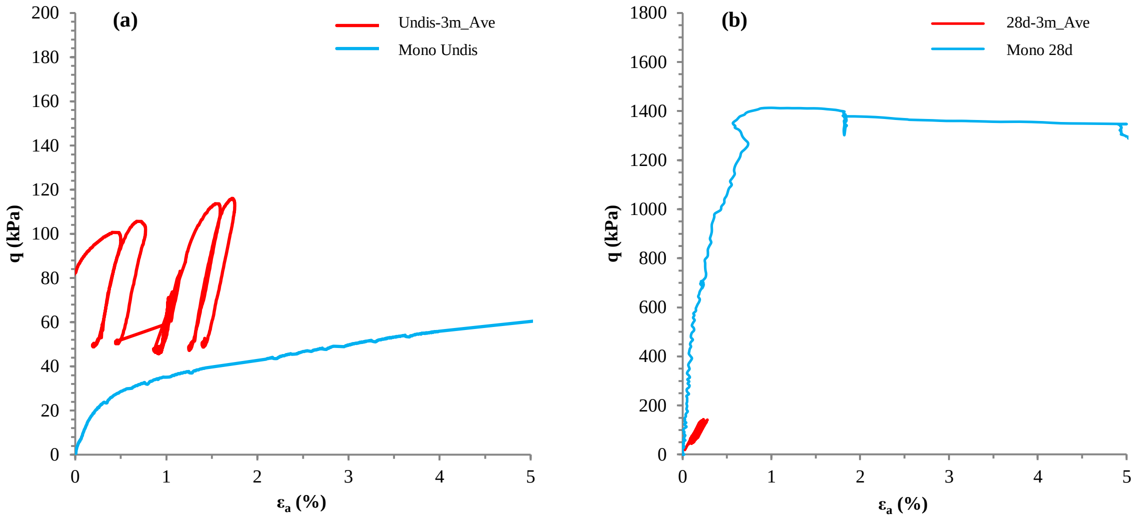

Figure 6. Cyclic (red) and respective monotonic (blue) deviatoric strengths at p'_0 = 60kPa for: (a) Undis and (b) 28d samples.

REFERENCES

[1] Rogers, C. D. F., Glendinning, S. and Holt, C. C., 2000. Slope stabilisation using lime piles – a case study. P I Civil Eng - Gr Impv. 4, 165-176.

[2] Jegandan, S., Liska, M., Osman, A. A-M. and Al-Tabbaa, A., 2010. Sustainable binders for soil stabilisation. P I Civil Eng - Gr Impv. 163, 53-61.

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

[4] Sherwood, P. T., 1993. Soil stabilisation with cement and lime – state of the art review. Transport Research Laboratory, Department of Transport. HMSO publications, ISBN 0-11-551171-7.

[5] McLellan, B. C., Williams, R. P., Lay, J., van Riessen, A. and Corder, G. D., 2011. Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. J Clean Prod. 19, 1080-1090.

[6] Al-Tabbaa, A. and Evans, C. W., 1998. Pilot in situ auger mixing treatment of a contaminated site – Part 1: treatability study. P I Civil Eng - Geotec. 131 Jan, 52-59.

[7] Hughes, P. N. and Glendinning, S., 2004. Deep dry mix ground improvement of a soft peaty clay using blast furnace slag and red gypsum. Q J Eng Geol Hydroge. 37, 205-216.

[8] Sargent, P., Hughes, P. N., Rouainia, M. and White, M. L., 2013. The use of alkali activated waste binders in enhancing the mechanical properties and durability of soft soils. Eng Geol. 152, 96-108.

[9] Palomo, A., Grutzeck, M. W. and Blanco, M. T., 1999. Alkali-activated fly ashes. A cement for the future. Cement Concrete Res. 29, 1323-1329.

[10] HS2, 2014. [online]. Available at:< http://www.hs2.org.uk>. Last accessed: 10th July 2014.

[11] Holm, G., Andreasson, B., Bengtsson, P-E., Bodare, A. and Eriksson, H., 2002. Mitigation of track and ground vibrations by high speed trains at Ledsgard, Sweden. Svensk Djupstabilisering: Swedish Deep Stabilization Research Centre – Report 10.

[12] BSI, 1999. BS: 5930 Inc A1, Code of Practice for Site Investigations. British Standards Institution, Milton Keynes.

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

[14] ASTM, 1996. D 559 – 89 Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures. Annual Book of ASTM Standards. 4.08, West Conshocken: Pa.

[15] ASTM, 1996. D 560 – 96 Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures. Annual Book of ASTM Standards. 4.08, West Conshocken: Pa.

[16] BSI, 1990. BS: 1377 Inc A1, Methods of test for Soils for Civil Engineering Purposes. British Standards Institution, Milton Keynes.

[17] Rouainia, M. and Muir-Wood, D., 2000. A kinematic hardening constitutive model for natural clays with loss of structure. Geotechnique. 50 (2), 153-164.

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

[19] Ahnberg, H., 2006. Strength of stabilised soils – A laboratory study on clays and organic soils stabilised with different types of binder. Doctoral Thesis. Svensk Djupstabilisering: Swedish Deep Stabilization Research Centre – Report 16.

[20] Ishihara, K., 1993. Liquefaction and flow failure during earthquake. Geotechnique. 106 (3), 351-415.

[21] Yilmaz, M. T., Pekcan, O. and Bakir, B. S., 2004. Undrained cyclic shear and deformation behaviour of silt-clay mixtures of Adapazari, Turkey. Soil Dyn Earthq Eng. 24, 497-507.

[22] Haha, M. B., Le Saout, G., Winnefeld, F. and Lothenbach, B., 2011. Influence of activator type on hydration kinetics, hydrate assemblage and microstructural development of alkali activated blast-furnace slags. Cement Concrete Res. 41, 301-310.

[23] Connell, M., 2014. Hanson Cements. Personal communication.

[24] Alibaba, 2014. International market prices for sodium hydroxide. [online]. Available at: <http://www.alibaba.com/premium/sodium_hydroxide.html>. Last accessed: 19th July 2014.