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The use of alkali activated waste binders in enhancing the mechanical properties and durability of soft alluvial soils

Paul Sargent [a,*], Paul N. Hughes [a], Mohamed Rouainia [a], Maggie L. White [b]

[a] School of Civil Engineering and Geosciences, Drummond Building, Newcastle University, Newcastle upon Tyne, Tyne and Wear, NE1 7RU, UK
[b] Materials Analysis Group, School of Chemical Engineering and Advanced Materials, Herschel Building, Newcastle University, Newcastle upon Tyne, Tyne and Wear, NE1 7RU, UK

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ABSTRACT

This paper presents recent work in utilising industrial by-products as sustainable binders for use in deep soil mixing, to enhance the geotechnical properties of soft soils. The study has used geotechnical and mineralogical tests to determine the performance of the binders when incorporated into an artificial silty sand soil. Comparisons with the strength and durability of untreated and stabilised soils have been made. The study indicates that from the by-products tested, soils stabilised with alkali activated blast furnace slag resulted in the greatest strength and durability improvements; with other materials tested showing smaller improvements. The addition of alkali activators has been observed to allow pozzolanic reactions to occur, which has led to improved mechanical properties; primarily strength, which increased with time. The durability of the soil was improved by the additions of by-products, though alkali activation did not cause significant additional increase in durability.

1. Introduction

In many countries, large areas of the ground surface are covered by soft soils (e.g. alluvium and peats). These can be problematic when built upon, due to their unfavourable bearing capacity, shrink/swell, settlement and durability characteristics. To improve such conditions, a number of stabilisation techniques are available for use, including compaction/consolidation, mechanical stabilisation and soil mixing with cementitious binders (Sherwood, 1993). This paper focuses on soil mixing, specifically deep dry soil mixing.

Deep soil mixing has used lime and cement as the primary binder since the 1970s, which have been extensively used internationally. Techniques commonly utilised include column installation and slurry pressure injection. These decrease soil moisture contents; thereby reducing their likelihood of shrinkage/swelling and enhancing strength and compaction properties (Glendinning and Rogers, 1996; Threadgold, 1996; Rogers et al., 2000; Ahnberg et al., 2003). Deep dry mixing started in the UK during the 1990s (Al-Tabbaa, 2003); whereby it creates stabilised soil columns through injecting a binding agent (Figure. 1). To introduce binders into the ground, a rotary mixing auger is drilled to the treatment depth. The drill's rotation direction is then reversed and retrieved whilst a binder is pumped through the auger drill bit and mixes the binder and soil. The drill bit's fins are orientated so compaction occurs along the column during mixing.

Portland Cement (CEM-I according to BS EN: 197-1; BSI, 2000) and lime have long been utilised as binders; whereby the former is considered more favourable in providing rapid strength enhancements (Rogers et al., 2000; Hossain, 2010; Jegandan et al., 2010). Deep mixed soils typically have binder contents of 5–15% by mass, although the dosage used depends upon numerous factors including the soil's organic content, mineralogy and water content. The presence of soil water and calcium silicates/aluminates within binders reacts to form hydration products such as calcium silica hydroxide (C-S-H) and calcium aluminate hydroxide (C-A-H) gels. Such cementitious gels continue to form over long periods of time via pozzolanic reactions, which occur when soil pH levels are ≥10.5 (Davidson et al., 1965). The soil-binder mixtures progressively cure and produce stronger, cementitious soil matrices known as "Geopolymers" (Sherwood, 1993). Should any further water percolate around or through the deep mixed columns, through curing the cementitious gels will be able to resist dissolution and therefore soil erosion. Deep mixing has a wide number of applications, such as providing supporting walls for excavations, foundation engineering, hydraulic cut-off walls, liquefaction mitigation and environmental remediation. Japan extensively uses deep mixing for numerous applications, one of which was the construction of the 15 km long Trans-Tokyo Bay Highway; whereby the soft alluvial clay foundation soil was treated using a cement slurry to safeguard the tunnels. UCS values after 28 days curing reached up to 2 MPa (CDIT, 2002). Elsewhere, deep mixed soil columns have been used for stabilising failed levees and floodwalls along Orleans Avenue Canal in New Orleans, USA after Hurricane Katrina in 2005. By using a high strength cement binder, deep mixed shear panels were extended through the levee fill into the underlying beach sands (McGuire et al., 2012). For the purpose of this

* Corresponding author. Tel.: +44 7815 714237; fax: +44 191 222 5322.
E-mail addresses: paul.sargent@newcastle.ac.uk (P. Sargent), p.n.hughes@newcastle.ac.uk (P.N. Hughes), m.rouainia@newcastle.ac.uk (M. Rouainia), maggie.white@newcastle.ac.uk (M.L. White).

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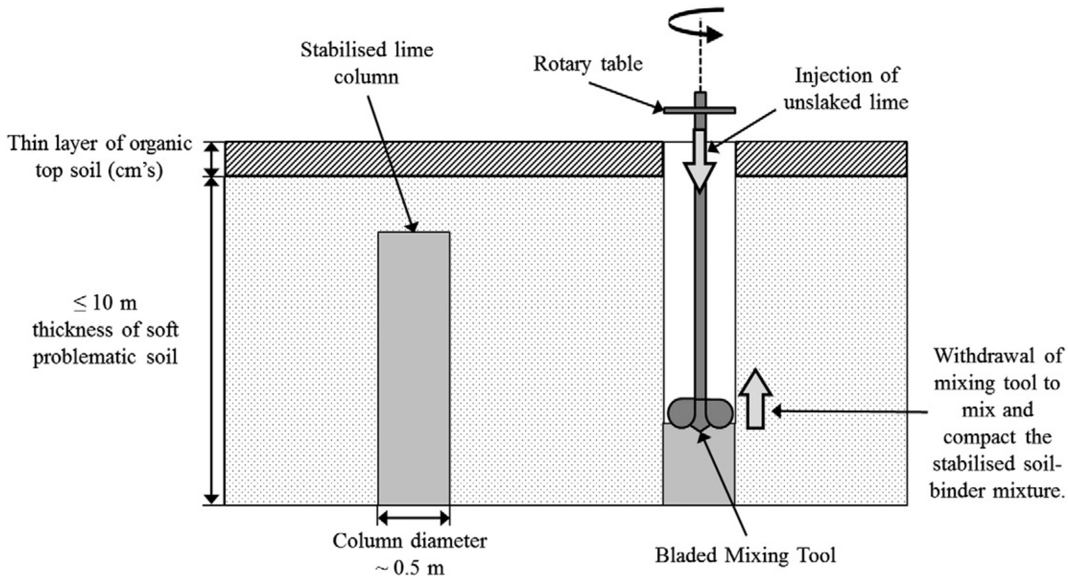

Fig. 1. Schematic of the deep dry soil mixing technique.

paper, the intended application of deep mixing using the new IBP-based binders is to stabilise soft foundation soils beneath road or railway embankments.

Negative environmental and financial issues are associated with utilising CEM-I and lime as binders. McLellan et al. (2011) recently conducted a sustainability comparison study between CEM-I and geopolymer cements in terms of their costs and carbon emissions; whereby the three main factors considered were energy (direct fuel and electricity consumption), greenhouse gas emissions and financial cost. Also considered in the study were factors including technical performance, leaching, water usage, hazardous material content and the volume of waste produced. A number of previous works were considered by McLellan et al. (2011); notably that of Weil et al. (2009) who assessed the financial cost and CO_2 emissions (kg $CO_{2\text{-eq}}/m^3$) produced for feedstock and transport. Weil et al. (2009) determined that for a geopolymer comprising 78% gravelly soil and 22% binder (9.6% GGBS, 2.4% PFA, 3.5% reactive waste, 1.4% Na_2SiO_3, 1% NaOH and 4% deionised water), a reduction of 131 kg $CO_{2\text{-eq}}/m^3$ was observed for the combined feedstock and transport of the binder compared with that produced for CEM-I. Thus, McLellan et al. (2011) concluded that geopolymers have high potential for reducing the environmental impacts of cement production. Based on a proposed Australian geopolymer mix, McLellan et al. (2011) estimated a significant greenhouse gas emission reduction of 44–64% compared with CEM-I.

Hence, there becomes a need for identifying more sustainable binders to replace CEM-I and lime; specifically in terms of lower energy consumption, greenhouse gas emissions, production and transport costs. These binders should provide strength and durability performances that are either comparable or surpass those of CEM-I and lime within similar curing times. A popular route for selecting new binders has been to recycle industrial by-products (IBP's); preferably those which are alumino-silicate based (i.e. pozzolanic). Based on findings by Palomo et al. (1999), the introduction of alternative alkalis such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) to these IBP's, can potentially further enhance the rate at which the mechanical properties of stabilised soils are improved by increasing soil pH; thereby allowing pozzolanic reactions and cementitious bonding to occur.

2. Materials

This paper presents results from a laboratory study, which investigates the mechanical strength and durability of alkali activated IBP-stabilised soil. For consistency an artificial silty sand was produced in the laboratory. This soil type was chosen for study as alluvial soils containing large quantities of silt present difficult ground conditions for construction purposes; whereby in both wet and dry conditions it has low levels of cohesion which can cause wall collapses within excavations and slope instability. These soils can also have low strength and stiffness leading to bearing capacity problems. Alluvial soils are found in abundance across the UK, especially on floodplains within river valleys which tend to be where housing and industrial developments are concentrated.

The IBP binders used in the study were pulverised fly ash (PFA), ground granulated blast furnace slag (GGBS) and red gypsum (RG). PFA is a synthetic pozzolanic material that is produced from combustion processes occurring within coal-fired power stations, which for this study was supplied by ScotAsh Ltd. GGBS is a latent hydraulic cement produced during pig iron manufacture, whose chemical composition partly resembles that of CEM-I cement (GGBS used in this study was supplied by Frodingham Cement Ltd). RG is a by-product of Titanium Dioxide manufacture (an extensively used white pigment), which occurs in a filter cake form during sulphuric acid neutralisation, this is produced in the UK by Huntsman Tioxide Europe Ltd. The chemical composition of RG can be seen in Table 1.

Previous studies (Hughes et al., 2010, 2011) have investigated the use of lime as an alkali activator in a range of similar soils/IBP binders. In these studies, whilst some soil/binder combinations exhibited significant mechanical improvement not all IBP's investigated could be seen to improve the strength of all the soils investigated. The low strength development could at least be partially attributed to insufficiently high pH being generated by the lime activator. Durability was also

Table 1
Summary of the chemical composition of red gypsum.
After Hughes et al. (2011).

Component	Content (% dry weight)	Component	Content (mg/kg)
Gypsum ($CaSO_4.2H_2O$)	58.5–59.3	Chromium (Cr)	500–800
Iron Oxide (Fe_2O_3)	32.9–36.6	Zinc (Zn)	200–400
Titanium (Ti)	1.0–1.3	Strontium (Sr)	100–300
Aluminium (Al)	0.1–0.8	Nickel (Ni)	50–60
Magnesium (Mg)	0.5–0.6	Cobalt (Co)	20–30
Manganese (Mn)	0.2–0.5	Barium (Ba)	1–3
Silicon (Si)	0–0.5	Lead (Pb)	1–2
Chlorine (Cl)	0.002–0.2		