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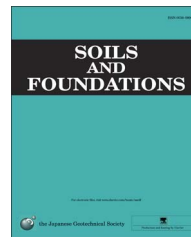


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# A new low carbon cementitious binder for stabilising weak ground conditions through deep soil mixing

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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 performance. 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<sub>2</sub>. There is now significant pressure on the cement and construction industries to greatly reduce their CO<sub>2</sub> 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, with a particularly marked improvement in strength.

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**Keywords:** Deep dry soil mixing; Sustainability; Low carbon; Alkali activation; Performance

## 1. Introduction

Soft soils, including alluvium, present problematic ground condition, as a result of their poor bearing capacity, shrinkage/

swelling, settlement and durability properties. Various ground improvement techniques can 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 been used as the binders

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because of their ability to produce impressive strength, particularly in 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 the 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, a low organic content (<1%), a low sulphate content (<0.3%) and a 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<sub>2</sub> 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 potentially have 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<sub>2</sub>. The continued use of CEM-I is also financially unsustainable, since 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, with electricity and coal prices having 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), and oil prices have fallen 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: 1) they should provide engineering performances comparable to or surpass those of CEM-I within similar curing times, 2) they should be commercially available at comparable/lower prices than CEM-I, and 3) they should be produced in such a way that fuel costs are markedly lower than those affiliated with CEM-I production whilst incurring lower CO<sub>2</sub> 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: CEM-II is used in the production of PFA, and CEM-II/III is being used in GGBS. According to 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 for the use of any lime or CEM-I.

Laboratory and field-based research by workers including Hughes and Glendinning (2004) and Sargent et al. (2013) has demonstrated that GGBS has significant potential as a sustainable replacement for lime and CEM-I, 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 the moisture content is too high for strength gains to develop when just using GGBS. The hydraulicity of the GGBS is latent; i.e. it is 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 increasing rates at which the mechanical properties of stabilised soils are improved (Palomo et al., 1999). Once the pH of the stabilised soil reaches 10.5 (Davidson et al., 1965), the GGBS reactivity will be triggered and the reaction will start and continue 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<sub>2</sub>SiO<sub>3</sub> solution are becoming two of the most widely available and popular activators for use in concretes and cements. Cristelo et al. (2011) used NaOH and 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 results demonstrated that the activated geopolymer produced higher strengths than CEM-I.

Habert et al. (2011) reported that lower financial and environmental costs are associated with the production of Na<sub>2</sub>SiO<sub>3</sub> rather than lime and CEM-I. However, NaOH flake/pellet production has a lower environmental impact (3.71 × 10<sup>-1</sup> kg CO<sub>2</sub> eq, human toxicity level of 15.84 kg 1,4-DB eq and a freshwater ecotoxicity of 3.98 kg 1,4-DB eq) than Na<sub>2</sub>SiO<sub>3</sub> solution, which has a high global warming potential of 117.8 kg CO<sub>2</sub> eq, a 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<sub>2</sub>SiO<sub>3</sub> as an activator is that the latter has a higher accelerated carbonation depth when used within geopolymer pastes. This has been attributed to the composition and structure of the C-S-H gels formed. The NaOH activated slags have been reported to have a higher Ca/Si ratio (1.2) than Na<sub>2</sub>SiO<sub>3</sub> activated slags (Bernal, 2014). However, since the Ca/Si ratio and reduced silicate chain length of NaOH activated slags is so much higher, 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, and slags with higher MgO content are more likely to be less affected by

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