Alternative calcium-based chemical stabilisers for ground improvement: Paper Sludge Ash treatment of London Clay

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Abstract Due to the recent focus on promoting sustainable construction practices, chemical ground improvement of problematic soils for construction has been increasingly used worldwide. However conventional soil stabilisers such as cement or lime still suffer from the use of non-renewable natural resources, high energy consumption and CO_2 emissions for their production. Consequently alternative stabilisers are intensively sought; these would be linked to lower or even zero CO_2 emissions if these come from waste. The paper studies the effect of waste paper sludge ash (PSA) as an alternative to lime for the treatment of London clay (a moderately expansive soil). The effectiveness of the treatment is assessed comparing a number of PSA-treated soil properties (plasticity characteristics, unconfined compressive strength and stiffness) to those of the same soil treated with lime. In most cases the PSA-treated soil specimens are shown to have a better performance than the lime-treated ones. The findings on the macroscopic properties are complemented by microstructural analysis.

Keywords: Solid waste management, paper sludge ash, chemical soil stabilisation, geotechnical properties

1. Introduction

The increase in the earth's population is bringing about the need to build on sites and subsoil conditions that are inadequate for construction in their present state. This need is exacerbated by the gradual depletion of natural aggregate resources. It is therefore becoming increasingly important to improve in situ soil rather than replacing it with imported, more suitable natural aggregate. Established methods include chemical stabilisation techniques using cement or lime to improve the hydromechanical properties of unsuitable soils. However the production of conventional soil stabilisers such as cement and lime is linked to high CO_2 emissions. In addition, it was reported that about half of the cost of deep soil stabilization works is related to the cost of binder materials (Bujulu *et al*, 2007). For these reasons there has been a lot of interest in the use of other binders such as Pulverised Fuel Ash (PFA) or Ground Granulated Blast Furnace Slag (GGBS), which are waste or industrial byproduct materials. Paper sludge is becoming abundant in the UK, as paper recycling rates increase, with recent statistics reporting an annual production of approximately 1 million tonnes (Dunster, 2007). A large amount of this sludge is incinerated to waste paper sludge ash (PSA) in combined heat and power (CHP) plants at approximately 800ºC and disposed of in landfills. There is therefore a lot of interest in finding outlets for this ash as alternative routes to landfilling, which is the most usual method for its disposal, causing high expenses to the factories. PSA contains reactive silica and alumina (in the form of metakaolin) as well as lime (CaO); it could therefore be a suitable cementitious material, also providing a source of additional silica and alumina. An advantage of PSA is that it is a fairly consistent material due to high controls in the combined heat and power (CHP) plants (Dunster, 2007). The potential use of this ash (PSA) for soil stabilisation was recently suggested in a limited amount of works (e.g. Bujulu *et al*, 2007; Kumara and Tani, 2011; Rahmat and Kinuthia, 2011; Khalid *et al*, 2012) but needs further investigation for the material to be used with confidence in industrial production. The possibility of using this ash as a soil stabiliser alternative to lime is further investigated in this paper. To this effect, a series of tests were performed to determine salient properties of PSA-stabilised soil in comparison to those of the same soil treated with lime. The testing details and selected results follow below.

2. Materials and methods

The soil used in this study was London Clay taken from an excavation near Westminster Bridge in central London. X-ray diffraction (XRD) tests showed 50% Illite, 26% Montomorillonite, 15% Kaolinite and 9% Chlorite (relative percentages with respect to the clay fraction). The main physico-chemical characteristics of this soil determined in a related research from our group are shown in Table 1 (Zhang *et al*, 2017). The two soil stabilisers comparatively used were waste paper sludge ash PSA from non-hazardous paper sludge, provided by Aylesford Newsprint Ltd. (Kent, UK) and a commercially available hydrated lime. Chemical analysis on the lime sample carried out in duplicate showed that the relative proportion of calcium hydroxide to calcium oxide was 4.88:1.00. Table 2 shows the chemical composition of this PSA (in terms of ranges of main oxide %) according to information from the supplier and a number of sources from the literature studying the same PSA (e.g. Bernal *et al*, 2014; Rahmat and Kinuthia, 2011; Mozaffari *et al*, 2009). It can be seen that PSA is mainly a calcium aluminosilicate, as its principal compounds are lime (CaO) and silica (SiO_2). The PSA used in this study is richer in CaO and SiO_2 compared to the PSA used elsewhere (e.g. Gluth *et al*. or Frías *et al*.). The PSA was not milled; in this form it has an average particle size (d_{50}) of 96.1 μm (Bernal *et al*, 2014). As the total content of the three major oxides in the PSA (namely silicon dioxide, aluminum oxide and ferric oxides) does not exceed 50%, the material is not strictly speaking a pozzolan. On the other hand, due to the high CaO content (much higher than that usually found in type C fly ash), the material is likely to have cementitious properties. Based on Initial Consumption of Lime tests (ICL) (Eades and Grim, 1966), the minimum necessary lime and PSA percentage (per dry soil mass) to treat this soil was about 4 % and 14% respectively. Specimens were therefore prepared at these respective lime and PSA contents; in addition specimens with 6% lime and 17% PSA were also prepared, as any lime in excess of the ICL, can lead to long term pozzolanic reactions. The lime or PSA at these respective binder percentages was mixed with air-dried pulverised clay passing the 425 μm sieve. The particle size distribution of the sieved clay soil is shown in Figure 1. The resulting plasticity characteristics of the different soil-stabiliser mixes after 24 hours of mellowing are shown in Table 3. Both stabilisers changed the plasticity characteristics and structure of the soil (to a more aggregate structure); interestingly, the plasticity index appears to first considerably increase (mostly due to the lowering of the plastic limit) to then reduce drastically to that of a non-plastic coarser grained soil. PSA has also considerably changed the texture of the soil to a much coarser /granular one as it is evidenced in Figure 2. After mellowing for 24 hours cylindrical specimens of 50mm diameter and 100mm were prepared by static compaction in five equal layers; the lime or PSA treated specimens were then left to cure as required. Compaction dry densities above and below the maximum compaction dry densities and water contents above and below the Proctor optimum of the untreated soil were used to investigate the respective effects on soil properties. Two different curing methods were used, namely water and air curing, which correspond to different curing conditions in-situ. For the latter curing method the specimens were extracted from the moulds, wrapped in cling film and stored in an insulated cabinet for the specified curing period. During the water-curing method, curing was performed in parallel with water saturation using porous stones, so that water moved into the specimen by capillary action. To assess the effect of confinement during saturation/water curing, which would be representative of soil at depth, (conditions usually ignored in the chemical soil stabilisation literature), some specimens were water-cured at constant volume (i.e. kept in moulds with top and bottom caps, so that any expansion during saturation from as compacted state is prevented). The stiffness evolution of the specimens with curing was recorded based on Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT) measurements at different curing times. At the end of the required curing periods (7, 28, 56 and 84 days respectively), the specimens were extracted from the moulds, measured for length and diameter, weighed and then subjected to uniaxial compression at a constant rate of strain of 1mm/min, to determine their Unconfined Compressive Strength (UCS).

Table 1. Properties of London Clay used in this study

Clay content	51(%)
Sand content	4(%)
Silt content	45(%)
Liquid limit	64(%)
Plastic limit	26(%)
Plasticity index	38(%)
Activity Index	0.75 (normal activity)
Specific gravity, G_s	2.75
Proctor w_{opt} (%)	25.5
Proctor ρ_{dmax} (g/cm^3)	1.43
pH	7.2
Soluble sulphate content	<0.1(%)
Total sulphate content	<0.1 (%)

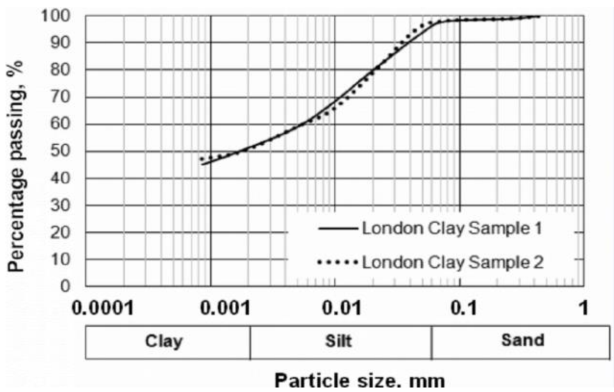

Figure 1. Particle size distribution of London clay

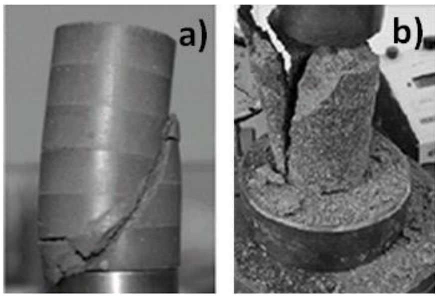

Figure 2. UCS samples a) lime-treated; b) PSA-treated

Table 2. Oxide composition of PSA used in this study

Compound (wt. % as oxide)	
CaO	61.2-36.82
SiO_2	33.9-16.43
Al_2O_3	18.86-2.8
MgO	5.44-0.9
Fe_2O_3	0.96-0.4
Na_2O	1.56-0.07
K_2O	1.31-0.22
SO_3	1.05-0.2

Table 3. Plasticity characteristics of treated soils

	4% lime	6% lime	14% PSA	17% PSA
w_L (%)	89	88	92	44
w_P (%)	54	54	28	40
I_P (%)	35	34	64	4

3. Results

Indicative SEM pictures of UCS specimens of the untreated soil, 4% lime treated and 14% PSA treated (7 days air curing) show the clear differences in the structure of the samples: namely compared to the untreated soil the lime-treated one has a more open structure where flocculation and aggregation of the particles can be observed, leading to larger pore radii compared with the untreated soil; converesly, disordered, needle-like crystals are observed in the PSA-treated samples. Indicative UCS testing results are shown in Figures 4-6. In Figure 4 the labels of the x-axis show respectively: binder content; compaction dry density (symbol 'dd') and compaction water content (symbol 'w'). It is evident that all PSA-treated samples exhibit much higher unconfined compressive strengths than the respective ones of lime-treated soils at similar compaction characteristics (see Fig. 4). It is important that this is also the case for the water cured results (saturated samples, Fig. 5) which confirms that the effects are due to the stabiliser used and not to possible degree of saturation differences. The UCS results are also consistent with the indicative stiffness evolution based on ultrasonic pulse velocity measurements (which is directly proportional to the sample stiffness): it can be seen that the stiffness of the air-cured lime-treated samples at the lime content corresponding to the ICL is lower than that of air-cured PSA samples treated with the PSA content corresponding to the ICL for the PSA binder (i.e. 4% for lime and 14% for PSA respectively). Regarding the effects of the investigated parameters (curing time and conditions, stabiliser content, compaction density and compaction water content), in addition to the higher strengths with higher stabiliser content (expected, unless the stabiliser percentage becomes too high) a number of observations can be made: (a) as shown in Fig 4 and 5(b), although in untreated soils the higher water content would implies lower strength, the strength evolution with curing times is facilitated by higher water contents (beyond the Proctor compaction optima of the two soils: e.g. for the 17% PSA treated soil this was found to be 23%); (b) the confined samples are stronger than the unconfined ones (although the state of stress in the sample is unknown in this instance, this reflects the higher effective stress effects upon confinement) (Fig 5a); (c) both the 14% and 17% PSA cured samples keep developing higher strengths for all measured curing times (Fig 6), which is reflected by the evolution of pH in the samples (note the small anomaly of +0.1 units in the average pH results of the 84 days measurement of the 17% treated sample which could be within the accuracy level of the pH metre measurements). This is important as it is believed that binder contents corresponding to the ICL (here, 14% PSA) would normally have immediate modification effects on the soil but no longer term effects on the strengths. A note should be made on the UCS testing results accuracy and repeatability. Although most average values of duplicate samples reported were within 1-5% of difference, two values had 11% and 19% differences respectively between duplicate samples. The trends are however clear in particular regarding the higher effectiveness of the PSA compared to lime at an equivalent calcium content; this is likely to be because of the additional sources of aluminosilicates supplied by PSA and also, due to the change in the consistency of the clay soil when mixed with a high percentage of a coarser grained material.

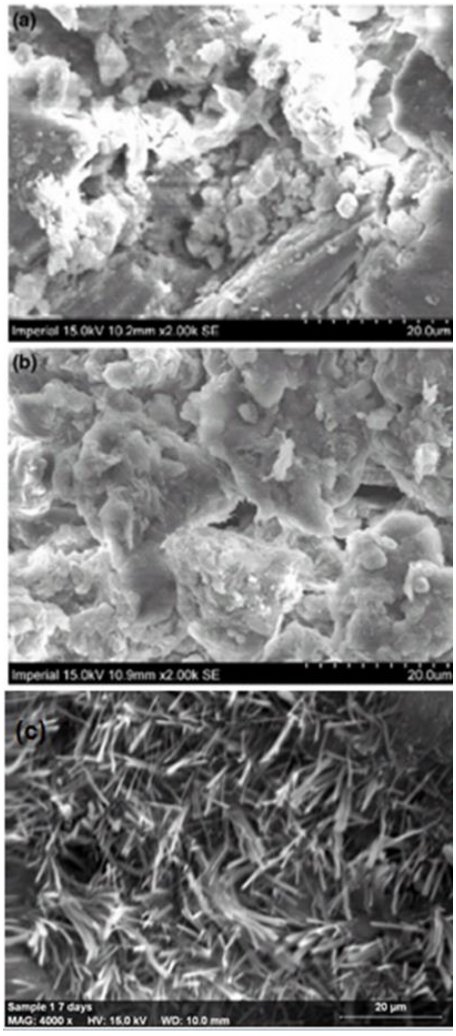

Figure 3. Indicative SEM results: (a) untreated soil; (b) 4% lime-treated soil; (c) 14% PSA-treated soil

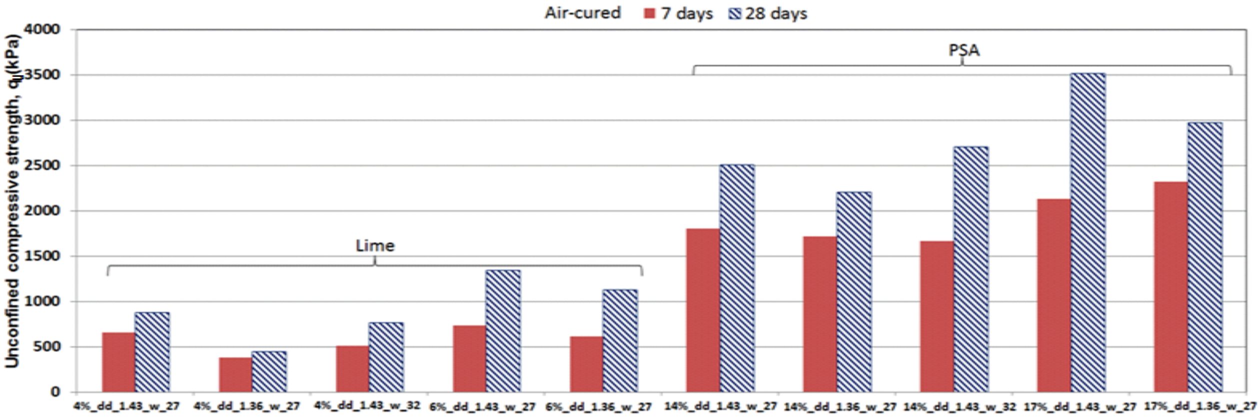

Figure 4. Indicative comparative results of 28-day cured lime-treated vs. PSA-treated specimens

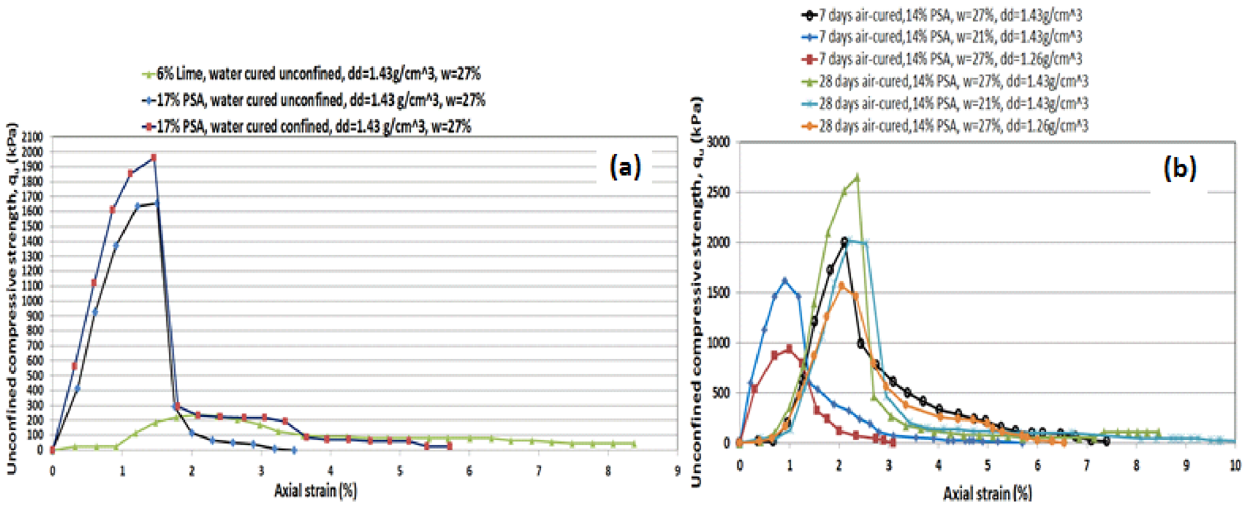

Figure 5. Indicative comparative results of 28-day specimens (a) water-cured specimens; (b) air-cured specimens

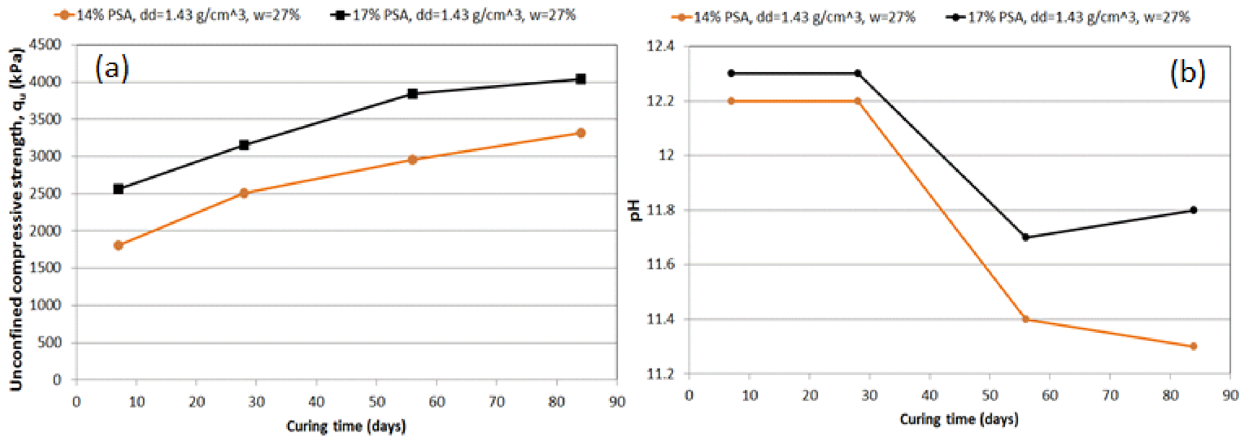

Figure 6. Indicative UCS sample results: (a) evolution of UCS with time; (b) pH of UCS specimens

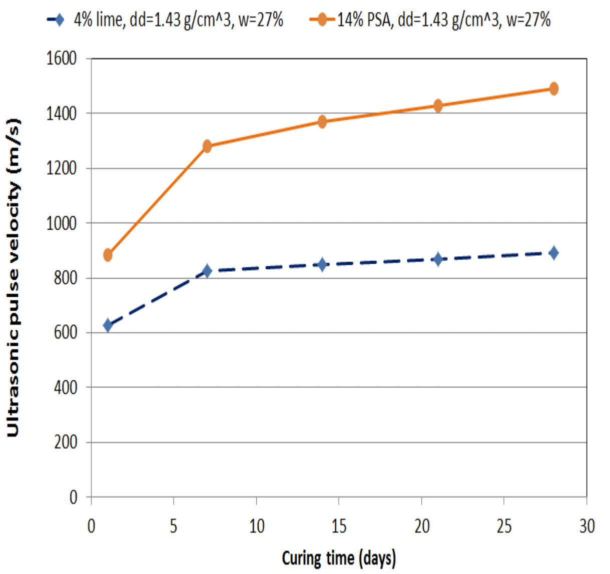

Figure 7. Indicative PUNDIT results (air-cured samples)

4. Conclusions

The results showed the effectiveness of PSA for clay stabilisation, as an alternative to commonly used commercial lime. This was proven in terms of treated soil properties (plasticity characteristics, unconfined compressive strength, stiffness). These were found to be superior for the PSA-treated soils compared to lime treated soils for all cases studied. This shows promise for an alternative disposal route to PSA landfilling.

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