Use of waste paper sludge ash as a calcium-based stabiliser for clay soils

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Abstract

Chemical ground improvement of soils of poor quality for construction has been increasingly used as a means of promoting sustainable construction practices. The production of conventional soil stabilisers such as cement or lime involves non-renewable natural resource and energy consumption and high carbon dioxide emissions; therefore, alternative stabilisers are sought. This study used waste paper sludge ash (PSA) to treat three different clays. The aim was to assess PSA effectiveness as an alternative to lime or cement for clay stabilisation based on plasticity characteristics, unconfined compressive strength (UCS), water retention and volumetric stability. PSA-treated soil specimens were shown to perform well compared to lime-treated or cement-treated ones: (a) PSA considerably lowered the plasticity indices of the two expansive clays, in a similar way as lime; (b) in most cases PSA dosages equal to or greater than the initial consumption of lime gave UCS at least twice as high compared to those obtained using commercial limes at equivalent dosages (> 1 MPa for the two expansive soils after 7 or 28 days of curing) and in the inspected cases also higher UCS than cement; and (c) consistently with the plasticity results PSA-treated specimens swelled less during wetting and had lower volumetric strains upon drying (better volumetric stability) compared to lime-treated or cement-treated soils. Overall the results give promise for a valorisation route of this waste material in the field of ground improvement.

Keywords

Solid waste management, waste paper sludge ash, chemical soil stabilisation, geotechnical properties, clay soils

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Introduction

Engineers must provide infrastructure making better use of resources to minimise waste generation and the consumption of primary materials. Thus, it is becoming increasingly common to improve the hydromechanical properties of unsuitable for construction ground rather than landfilling it and replacing it with transported, more suitable natural aggregate. Established methods of ground improvement include chemical stabilisation with cement or lime, whose production involves high energy consumption, carbon dioxide emissions, the depletion of natural raw materials, and high costs – for instance, binder materials incur about half of the costs of deep soil stabilisation works (Bujulu et al., 2007). Consequently, there is interest in finding alternative stabilisers from waste that can be used as a source of the required chemicals. Examples of such alternatives to commercially supplied cement or lime include cement or lime kiln dust (Petry and Little, 2002) and other forms of by-product lime, for example, calcium carbide residue (Kampala and Horpibulsuk, 2013) or lime extracted from eggshells (Zaman et al., 2018). This short communication assesses waste paper sludge ash (PSA) as a calcium-based clay stabiliser alternative to lime or cement. PSA is produced by the incineration of paper sludge (a semi-solid slurry collected in the effluent treatment units), which is the main waste stream of the paper recycling industry. Combustion is primarily used to reduce the volume of sludge waste for landfilling (80–90% reduction) and partly to recover energy through co-combustion with biomass

(although mechanically dewatered paper sludge has a low calorific value of 2.5–6.0 MJ/kg; Spathi, 2015). PSA is subsequently disposed of in landfills in a large part. With an annual paper production of approximately 4.5 million tonnes in the UK and an increase in paper recycling rates, abundant volumes of waste paper sludge are produced, leading to steadily increasing amounts of PSA (in the UK 4 out of 40 paper mills generate 140 kilotonnes of PSA annually; Spathi, 2015). This has caused environmental concerns and high costs to industry due to UK landfill tax. There is thus a lot of interest in finding alternative routes to landfilling and the valorisation of PSA, currently classified as waste. PSA is a fairly consistent material due to high controls in the combined heat and power plants. It contains reactive silica as well as lime (CaO) and calcium silicate/aluminate/alumino-silicate phases; it could thus be a suitable calcium-based soil stabiliser alternative to lime or cement, possibly also providing additional aluminosilicates. The potential use of PSA as a soil stabiliser was studied in a limited amount of works, for example, Bujulu et al. (2007), who found that 18-month old field samples from lime–cement–PSA columns in a quick Scandinavian clay were about five

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times stronger and fifty times less permeable than the corresponding lime–cement column samples; Khalid et al. (2012), who found that 10% PSA (identified as the optimum content) approximately doubled the unconfined compressive strength (UCS) of a high plasticity slightly sandy clay from Malaysia and increased its California bearing ratio (CBR) value by about 1.5 to 3.6 times depending on the curing condition; Rahmat and Kinuthia (2011), who showed that specimens of sulphate-bearing Oxford clay treated with stabiliser blends containing PSA had generally higher strengths than quicklime-treated ones; and Kumara and Tani (2011) who, referring to the shear strength improvement of a PSA-treated dredged clay, produced charts of the required PSA content to achieve appropriate slope stability safety factors for embankments with PSA-treated dredged clay fill material. Although these findings are promising, further studies are needed for PSA to be widely used with confidence in industrial applications. In this context, this short communication makes a synthesis of ongoing work at London South Bank University, assessing the use of PSA to improve properties of clay soils.

Materials and methods

The clays used in this study were: (a) London Clay from Westminster Bridge in central London, a moderately expansive high plasticity clay with a typical mineral composition (percentages of the clay fraction) of 50% illite, 26% montmorillonite, 15% kaolinite, and 9% chlorite (Zhang et al., 2017); (b) a non-expansive kaolin clay from the South West of England (supplied by Imerys); (c) a mix of 70% of this kaolin with 30% sodium activated bentonite marketed as Bentonex SB (expansive clay). Tests for the total and water-soluble sulphate content based on the gravimetric method of BS 1377-3:1990 (British Standards Institution, 1990a) showed no evidence of sulphates in the soils; this allows for the use of calcium-based stabilisers, without the risk of clay–sulphate reactions. The soil stabilisers used were: (a) a hydrated lime with a relative $Ca(OH)_2/CaO$ ratio of 4.88/1.00; (b) a highly reactive quicklime of particle size < 2 mm and pH = 12.3; (c) CEM I (52.5N strength) cement; (d) CEM II/A-L: 6–20% limestone cement (42.5 strength); and (e) PSA from Aylesford Newsprint Ltd. (Kent, UK). Free lime contents vary according to feedstock and combustion conditions: Mozaffari et al. (2009) reported free CaO of 5% for this PSA, that is, higher than in commercial cements (typically 1–2%; Paige-Green and Netterberg, 2004) but elsewhere 10% free CaO in PSA is typical (Tagnit-Hamou et al., 2015). Free CaO > 20% has also been reported (Doudart de la Grée, 2012). Due to high free lime contents PSA is corrosive (pH = 12.3–12.4). It is thus classified as hazardous waste (EU Directive 2008/98/EC Annex III, criterion H8; European Commission, 2008), although in terms of hazardous substance leaching it could have generally been classified as inert waste (Dunster, 2007) according to solid waste disposal criteria of 2003/33/EC Decision (European Commission, 2003). On the other hand, cement or lime are also caustic: the minimum required lime content is that raising the pH of the soil to 12.4. Therefore, using PSA as an alternative to lime would not be different in terms of soil pH. According to supplier's information and literature (Bernal et al., 2014; Rahmat and Kinuthia, 2011; Spathi,

2015) the major crystalline phases of this PSA are calcite ($CaCO_3$), lime (CaO), gehlenite ($Ca_2Al(AlSiO_7)$), belite (Ca_2SiO_4), and mayenite ($Ca_{12}Al_{14}O_{33}$) with traces of calcium hydroxide ($Ca(OH)_2$) and quartz (SiO_2), and the oxide content (%) is: CaO = 61.2–43.51; SiO_2 = 25.7–16.43; Al_2O_3 = 18.86–9.05; MgO = 5.15–2.72; Fe_2O_3 = 0.9–0.41; K_2O = 1.31–0.22; Na_2O = 1.56–0.07; SO_3 = 1.05–0.2; TiO_2 = 0.68–0.3; and P_2O_5 = 0.52–0.1. It is thus a cementitious material, richer in CaO and SiO_2 compared to PSA used elsewhere (e.g., in Frías et al., 2008 or Gluth et al., 2014). Its average particle size (d_{50}) when unmilled is approximately 90 μm (Spathi, 2015), that is, larger than clay size particles (of < 2 μm). It is thus coarser than the average particle size d_{50} of the tested soils, that is, 4.5 μm and 1.5 μm for kaolin and London Clay, respectively (based on hydrometer testing according to BS 1377-2:1990; British Standards Institution, 1990b). Bentonite is even finer, consisting of 92% montmorillonite clay with only 5% of the particles > 150 μm (based on supplier's data). The minimum required stabiliser dosage (per dry soil mass) for each soil was determined from initial consumption of lime (ICL) tests (Eades and Grim, 1966). Specimens were thus prepared at stabiliser contents corresponding to ICL except for kaolin: 8% PSA was its ICL but all tested quicklime dosages gave pH just above 12.4; 4% lime was thus used as a typical *in situ* dosage (higher than in laboratory) for better uniformity of treatment (Bhattacharja et al., 2003). 10% CEM I was also used as a typical dosage (Andrews, 1955; Paige-Green and Netterberg, 2004). For the two expansive clays, dosages above ICL were also used (typically an additional 2–3%; see, e.g., Highways Agency, 2007), as lime content at ICL is sufficient for immediate clay modification reactions (to address shrinkage–swelling behaviour) but for long term strength gain (pozzolanic reactions) lime in excess of ICL is needed. Thus, for London Clay (with PSA and lime having very different ICL), the two sets of results to compare are 14% PSA versus 4% lime (ICL) (Figure 1c) and 17% PSA versus 6% lime (above ICL) (Figure 1b). The dry powder stabilisers were mixed with clays in dry powder form (the natural London Clay was also air-dried and pulverised to pass the 425 μm sieve). After mellowing the PSA/lime treated samples for 24 hours (1 hour mellowing for cement treated samples) cylindrical specimens of 50 mm diameter/100 mm height and 75 mm diameter/20 mm height were compacted in equal layers of 10 mm height for the UCS and filter paper tests, respectively. The specimens were then left to cure as required using two different curing methods, corresponding to different curing conditions *in situ*, that is: (a) air curing (constant moisture curing): specimens were extracted from moulds, wrapped in cling film and stored in an insulated cabinet to cure as required; and (b) water-curing: specimens were subject to capillary soak. At the end of curing the dimensions and masses of the specimens were measured before testing, which included: (a) uniaxial compression at a constant strain rate of 1 mm/minute, to determine the UCS; and (b) the contact filter paper method (Whatman 42 paper) following procedures and calibrations developed at Imperial College, London (e.g., Dineen, 1997) to assess the water retention and volumetric behaviour of the expansive clay mix (soil c) as a function of matric suction. The filter paper specimens (with similar compaction water contents and compaction dry density of 1.43 g/
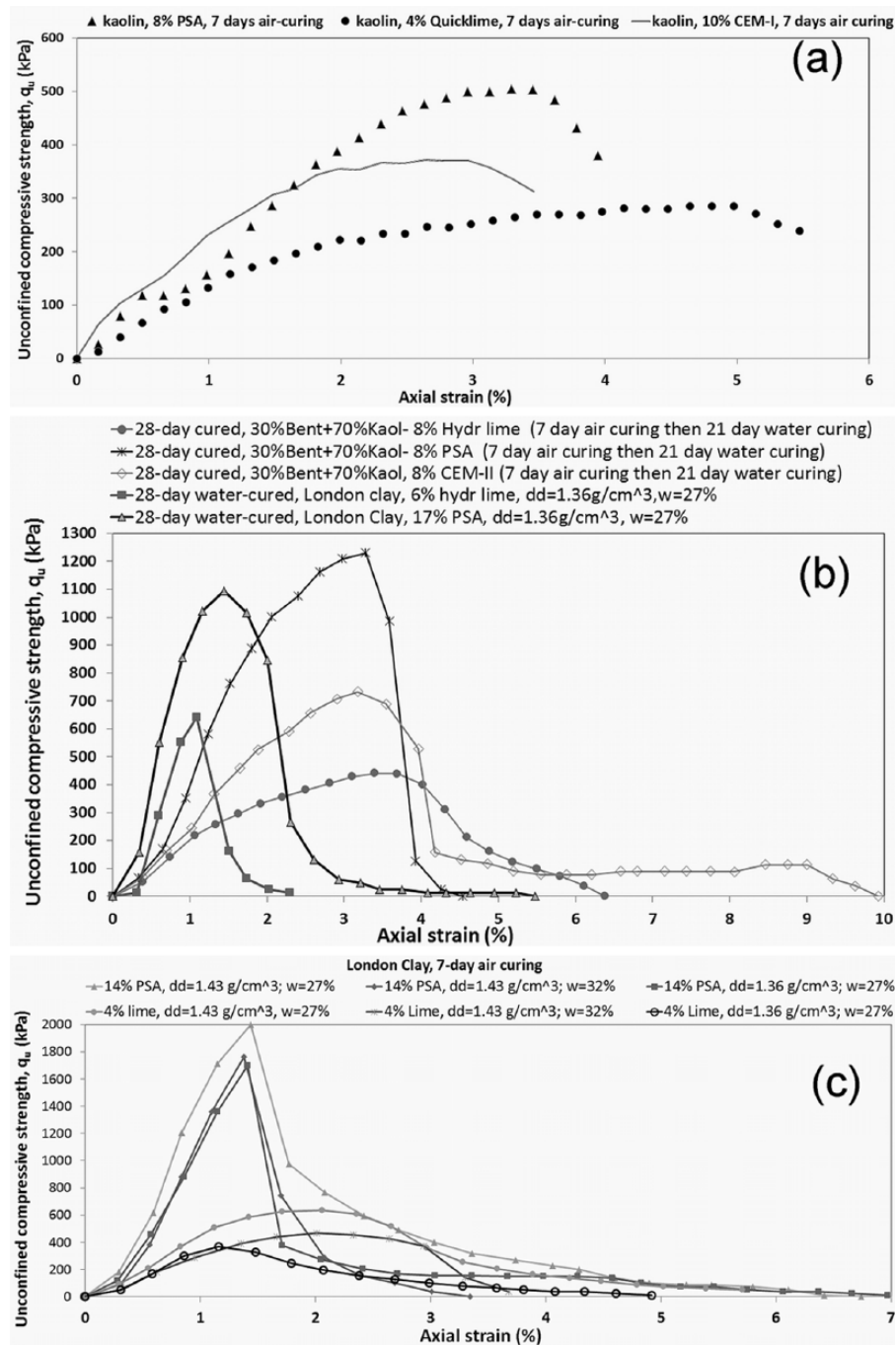
Figure 1. Indicative unconfined compressive strength results: (a) air-cured kaolin; (b) water-cured London Clay and 30% bentonite + 70% kaolin; and (c) air-cured London Clay with different compaction characteristics.

cm³ for all stabilisers) were air-cured for 7 days, and then water-cured for another 7 days; their initial void ratio before the start of drying thus reflects the tendency for swelling of each stabilised soil, after exposure in water for the same period.
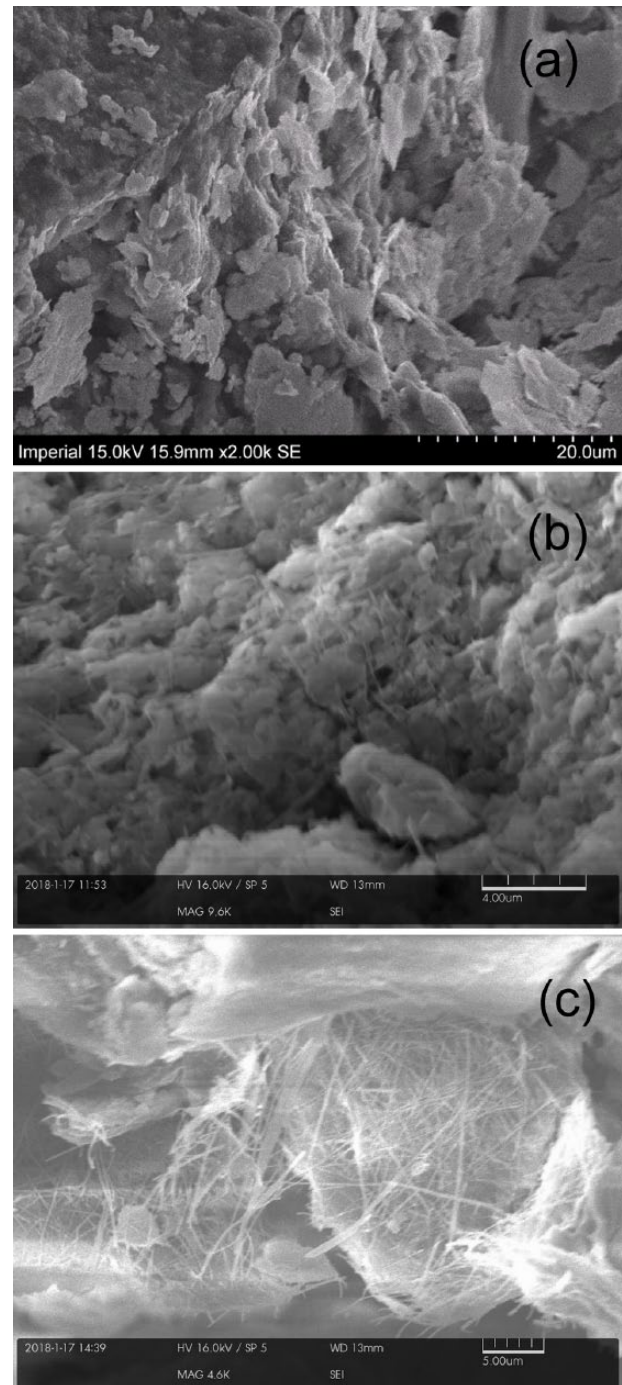
Results and discussion

Table 1 shows the plasticity characteristics of the soils before and after treatment following 24 hours of mellowing (1 hour for cement). All stabilisers affected the plasticity characteristics; in particular lime and PSA favourably changed the plasticity characteristics of all clays (lower plasticity index (PI) showing a

reduced tendency of the soil to swell) mainly due to the higher plastic limit (PL) (especially for PSA-treated soils); the liquid limit (LL) of each soil was in most cases consistent between lime and PSA; conversely for the expansive clay mixture (bentonite/kaolin) cement increased both LL and PI. PSA also considerably changed the texture of the soil to a much coarser/granular one (Mavroulidou et al., 2017). Figure 1(a)–(b) shows indicative UCS testing results based on specimens with fixed water contents and the same compaction dry densities regardless of stabiliser type to assess the effect of the stabiliser only. PSA-treated specimens are shown to have much higher UCSs compared to cement-treated or, in particular, lime-treated ones for all soils.

Table 1. Plasticity characteristics of soils before and after treatment.

London Clay

	Liquid limit (LL [%])	Plastic limit (PL [%])	Plasticity index (PI [%])
Untreated soil	64	26	38
Soil + 4% hydrated lime	89	54	35
Soil + 6% hydrated lime	88	54	34
Soil + 17% paper sludge ash (PSA)	89	62	27

kaolin

	LL [%]	PL [%]	PI [%]
Untreated	61	32	29
Soil + 4% quicklime	70	36	34
Soil + 8% PSA	69	42	27
Soil + 10% CEM I	70	29	41

30% bentonite + 70% kaolin

	LL [%]	PL [%]	PI [%]
Untreated	130	43	87
Soil + 6% hydrated lime	109	41	68
Soil + 8% hydrated lime	108	49	59
Soil + 6% PSA	138	56	82
Soil + 8% PSA	111	51	60
Soil + 6% CEM II	200	52	148
Soil + 8% CEM II	185	56	129

Figure 2. Indicative scanning electron microscopy results: (a) untreated London Clay; (b) 6% hydrated lime-treated London Clay (28-day curing); and (c) 17% paper sludge ash-treated London Clay (28-day curing).

This is also the case for any curing conditions or compaction characteristics used for the London Clay soil, for which extensive investigation with compaction dry densities and water contents above and below the Proctor optimum of the untreated soil was performed in Mavroulidou et al. (2017) to assess the respective effects (see indicative results in Figure 1c). However, PSA-treated specimens were in all cases, but one, more brittle than the corresponding lime-treated ones, that is, closer to the very brittle behaviour of the cement- treated soils (see Figure 1a and Figure
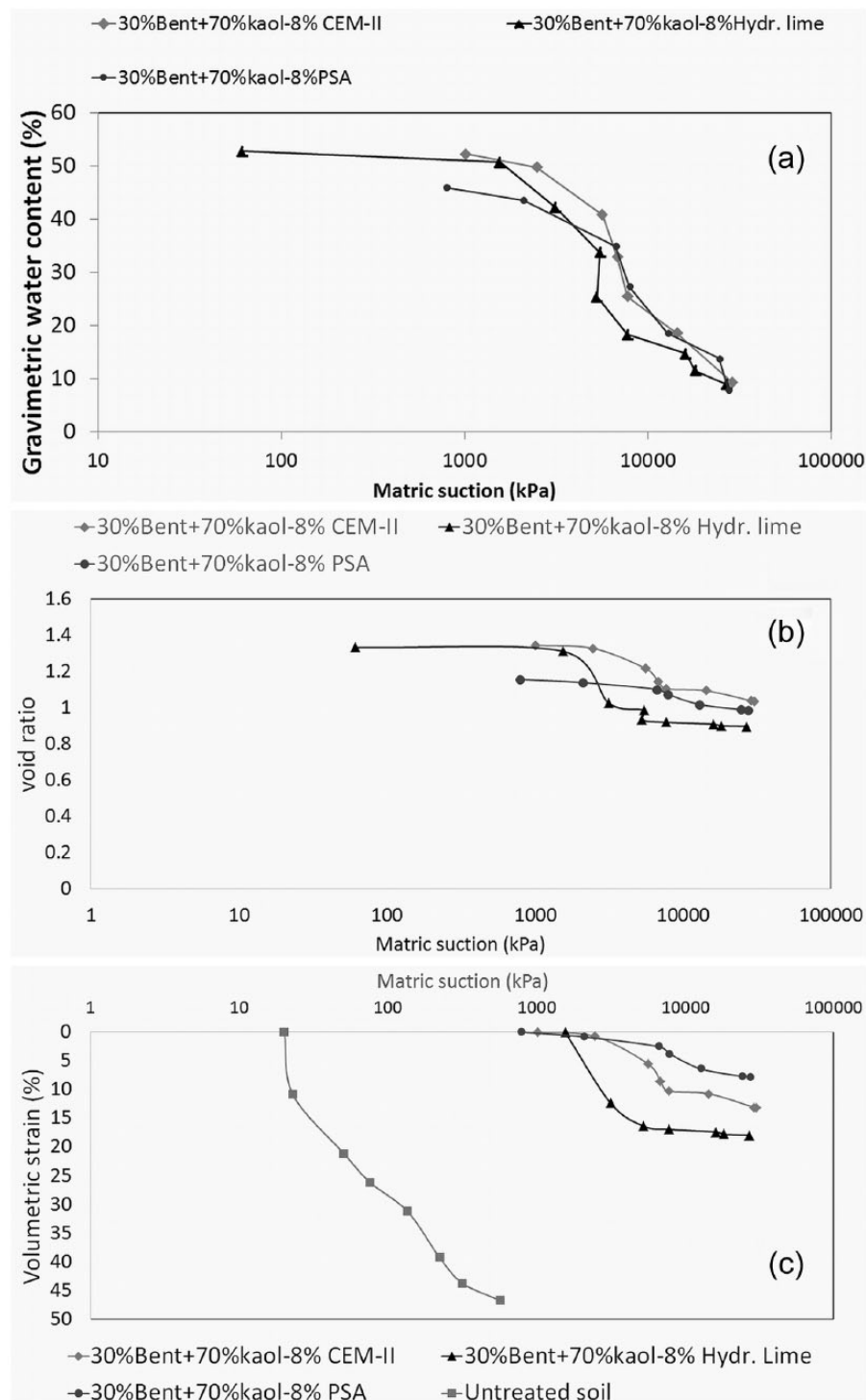
Figure 3. Indicative filter paper results: (a) gravimetric water content versus matric suction; (b) void ratio versus matric suction; and (c) volumetric strain versus matric suction.

1b). Overall, the trends are consistent regarding the effectiveness of the PSA. Its comparatively better performance can be attributed to the additional aluminosilicates supplied by PSA and the physical changes in the consistency and grading of the clay soil when mixed with the high percentages of the coarser-grained material (PSA) that are required for sufficient lime contents for stabilisation. Indicative scanning electron microscopy pictures of London Clay specimens (Figure 2): (a) untreated soil; (b) 6%

lime treated; and (c) 17% PSA-treated soil (28 days of water-curing), show the latter two specimens to have developed reaction products/hydration coatings (disordered, fibrous-like crystals are wrapping the particles of PSA-treated specimen) consistent with the high strengths of the stabilised soils. Figure 3 shows indicative filter paper results (drying curves) in terms of water retention and volumetric behaviour of the soil. The volumetric behaviour is consistent with the plasticity results, as PSA-treated

specimens swelled less during water-curing (see the lower initial void ratios at the start of filter paper testing) and then had lower volumetric strains upon drying (i.e., better volumetric stability) compared to lime-treated or cement-treated soil. The rates of drying of the PSA-treated soil are similar to that of lime or CEM II (see water content–suction curve gradient) but for the same suction different water contents than in the lime-treated soil are retained (closer to CEM II treated soil). Finally, another positive finding based on London Clay testing, reported in Mavroulidou et al (2017) was that when London Clay was treated with PSA its Proctor optimum water content was considerably lower than when treated with lime (23% versus 32%, respectively, for 17% PSA and 6% lime, that is, the stabiliser contents above the respective ICLs). The need for less water to achieve optimum dry densities would lead to savings in the use of water and lower costs.

Conclusions

The results showed the effectiveness of PSA for clay stabilisation, as an alternative to commonly used commercial limes or cements. This was proven in terms of treated soil properties (plasticity characteristics, UCS, water retention, and volumetric stability). These were found to be in most cases superior for the PSA-treated soils compared to lime-treated or cement-treated clays. PSA-stabilised clays could thus be used as fill materials with clear environmental and economic benefits: PSA has zero costs (other than transportation) as the paper sludge is anyway incinerated at the factory to reduce paper sludge waste volume and requires less water for treated soil compaction. The positive findings give promise for the potential of commercial exploitation of PSA in the ground engineering/construction industry, as an alternative route to landfilling. In addition to the savings for the construction industry in terms of stabilisers, this would also help the paper-making industry to meet current and emerging sustainability targets by significantly reducing the costs of landfilling.

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