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Geotechnical properties of paper recycling waste streams

Propriétés géotechniques des déchets de désencrage des papiers usés

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ABSTRACT: This paper studies two waste streams of the paper recycling industry for potential use in geotechnical applications. Namely, de-inking paper sludge from the secondary treatment stage, and paper sludge ash (PSA) obtained from the incineration of this sludge. Salient geotechnical properties of the statically compacted sludge before and after stabilisation with lime or PSA are presented. Tests include shear box testing, uniaxial compressive strength (UCS) testing, 1-D swelling and compression in oedometric conditions, p-wave velocity measurements using a Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT), and filter paper testing to determine water retention characteristics. The volume changes of the untreated sludge were found to be considerable in all above tests; however its shear strength at a highly compacted state was overall adequate. Chemical stabilization of the sludge was effective in reducing volume changes. The PSA was also assessed as a silt soil stabiliser. As geomaterial stabiliser, PSA was found to have a similar or better performance than lime. Overall the results are encouraging and indicate that it is possible to use paper industry waste in geotechnical applications.

RÉSUMÉ: Nous étudions les propriétés géotechniques de boues de désencrage secondaires (BDDS) suite au recyclage des papiers usés, avant et après traitement soit à la chaux, soit aux cendres d'incinération des BDDS. Dans ce but nous effectuons des essais de cisaillement direct, de compression uniaxiale, de gonflement et de compression unidimensionnelle en condition oedométrique, des essais ultrasoniques de la vitesse d'impulsion (UPV), ainsi que des essais de papier filtre pour obtenir les courbes de drainage des matériaux concernés. Les cendres d'incinération des BDDS sont aussi employées pour la stabilisation d'un limon. Les boues de désencrage secondaires ont manifesté des changements volumiques importants, qui sont cependant reduits suite du traitement chimique; leur résistance au cisaillement était pourtant adéquate. Les cendres d'incinération des BDDS employées comme agents stabilisants, avaient des effets comparables ou meilleurs que ceux de la chaux. Les résultats sont encourageants et indiquent qu'il est possible d'employer ces matériaux–déchets en génie géotechnique.

Keywords: solid waste management; paper sludge; paper sludge ash; chemical soil stabilisation

1 INTRODUCTION

Recycled paper has been increasingly used worldwide as a raw material for the production of paper-based products. For instance, in the UK 4.5 million tonnes of various types of paper are produced annually; 73 % of the fibre used for this production comes from recovered paper (Spathi, 2015). As paper recycling rates increase, a considerable amount of waste is generated from the de-inking and water treatment stages in the papermaking process.

The main waste stream of the deinking and repulping of paper is paper mill sludge; this is the semi-solid slurry collected in the effluent treatment units. The large volumes of sludge produced at the mill create serious waste management challenges. The sludge is thus incinerated in controlled heat and power (CHP) plants according to EU Waste Incineration Directive (EC 2000), primarily to reduce the volume of paper sludge waste (80-90% reduction), as well as to recover some energy in the factory. Incineration produces paper sludge ash (PSA), another waste stream of the paper industry. This waste stream is also becoming abundant. For instance, in the UK 40 paper mills generate 140 ktonnes of PSA annually (Spathi, 2015). Currently, both paper sludge and PSA are predominantly landfilled. This has caused environmental concerns and high costs to industry upon landfilling (e.g. in the UK landfill tax is £84.40/t and £2.65/t for active and inactive waste respectively). Therefore there is a pressing need to find more sustainable alternative management options and uses for these materials.

Alternative management options for paper sludge waste include its use as fuel (Class 2 - liquid alternative fuel) and as agricultural fertiliser through land-spreading. The latter is regulated through the Environmental Permitting Regime (EPR) and Duty of Care with respect to the transport and transfer of the sludges (CPI, 2014). Landspreading requires great space capacity, is restricted to certain periods (to achieve optimum biological action) and is viewed with caution due to reliability issues in case of lack of proper treatment. Using sludge in cement-based construction materials was also suggested, however it is only feasible at low sludge contents. This means that further options are required for the large volumes of sludge generated by paper industry worldwide.

In the context of geotechnical engineering the main suggested application for paper sludge has been its use in landfill cover /barrier systems (e.g. Moo-Young & Zimmie 1996 or Inazumi, 2003 amongst many others). Most of the literature on such applications present data from very wet sludges of high organic content. At this state the sludges can be problematic in view of the large associated settlements. For sludges of high water content landfill slope stability issues were also observed (e.g. wastewater sludge from Georgia-Pacific linerboard paper mill Big Island, Virginia, caused stability and operational problems at the mill landfill, with displace-ment of 15-30 m after placement in the land-fill, Hinshelwood and Moore, 2002). Stabili-sation of the sludges was thus proposed.

This paper investigates salient geotechnical properties of a highly dewatered paper sludge from the secondary stage of paper recycling. The sludge was tested both untreated and after chemical treatment. The purpose of chemical treatment would be to neutralise some potentially harmful micro-organisms, stabilise the sludge, and enhance its properties. In addition, PSA, the waste stream resulting from the incineration of this sludge, is studied as a stabiliser of the sludge and other soils.

2 MATERIALS AND METHODS

The dewatered paper sludge (paper crumble) and its ash used in this study came from a newspaper recycling company in the South-East of England, with an annual production of ca. 400,000 tonnes of recycled paper newsprint. The fibre recovery process consists in mechanical cleaning and deinking. The sludge used in this study comes from the latter process. A series of screening and cleaning operations are used to separate fibrous material from impurities and contaminants with the aid of warm water and chemical additives. The two main stages of the recycling of the paper which yield this sludge are shown in Figure 1. Namely in the primary stage the old newspaper material goes into the fibre separation plant; it is fed onto conveyor belts and enters two large rotating drums where it is mixed with water to swell and separate the fibres to become a pulp. Screening separates the fibres and water from large contaminates (e.g. cans, plastic bottles etc.), which are ejected onto a conveyor belt for disposal, while the fibre and water mixture (pulp) is put through a series of cyclone screens, which remove small unwanted fragments (e.g. staples). It is then moved to two flotation tanks, where soap is added. In the secondary stage (which yields the dewatered sludge used in this study) the recycled fibre is cleaned with 85º C water; it is then bleached so that any unwanted ink is removed. The good fibres are then moved to the next stage for recycled paper production, whereas the unwanted residues i.e. small fibres unsuitable for reuse, clays, inks etc. (forming the paper sludge) are removed from the paper and stored in a silo.

According to the suppliers' Material Safety Data, the sludge from the secondary treatment phase is non-hazardous and stable under the effects of temperature. Its main components are water, cellulosic fibre, kaolinite, printing ink, and calcium carbonate (see Table 1); its $CaCO_3$ equivalent is 58.42%. The material is of grey colour (Figure 2), it has a mild organic smell and is slightly alkaline in aqueous solution (pH=7.6).

Table 1. Main components of the dewatered sludge

Component	Concentration (%)
Clay/calcium carbonate	< 78.0
Carbon black	<15.0
Lignin	< 10.0

Figure 1. Newsprint recycling process

In this study, the sludge was ground using a rubber pestle, in order to pass the 2mm sieve. This portion was then subject to physico-chemical and plasticity testing (see Table 2). ASTM D 2974-14 (ASTM, 2014) was used to determine its organic content; its specific gravity

G_s was determined using the small pycnometer test according to BS 1377-2:1990 (BSI, 1990a); plasticity characteristics were obtained using BS 1377-2:1990 (BSI, 1990b). Three different batches of paper sludge were used for this study: the first one was found to be of a water content of 57%; the other two were of a water content of 30-32% which is consistent with the suppliers' product datasheet. The presented tests on the geotechnical properties of the material are based on the latter two batches.

The chemical stabilisers used were: (a) A commercially available hydrated lime; (b) Paper sludge ash (PSA) from the same sludge, a calcium aluminosilicate ash whose three main oxide components (in terms of % of total oxides) are: CaO (60.7%), SiO_2 (19.2%) and Al_2O_3 (8.7%). These values are according to suppliers' information and represent a typical composition; however the composition can vary according to batches. Based on the Initial Consumption of Lime tests (ICL) (Eades & Grim, 1966), the minimum required lime and PSA percentage to treat the sludge were found to be about 11 % and 13.5% respectively (% of the dry sludge mass). An additional 2% of stabiliser was added in the mixes to provide lime above the ICL, as required for long-term stabilisation reactions.

The stabilisers were mixed in powder form with the sieved sludge samples at as received water contents. After mellowing the PSA/lime treated samples for 24 hours, statically compacted cylindrical specimens of 50mm diameter/100mm height, and 75mm diameter/20mm height were prepared for the UCS and filter paper tests respectively. In addition, 60mmx60mm compacted shear box specimens were prepared (specimen height 20m); these specimens were also used for 1-D swelling and consolidation measurements. The highest achievable dry density for this material i.e. 1.3 g/cm^3 was used as the target compaction dry density of all specimens (this dry density was also used for the treated specimens). Compaction was carried out in layers of 10mm height. The compacted specimens were then wrapped in multiple layers of cling film and left to cure in a controlled humidity and temperature cabinet to prevent moisture losses. The stiffness evolution of the UCS specimens with curing was monitored with a Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT).

Filter paper testing was used to determine the water retention curve (SWRC) of both untreated and treated sludge. SWRC provides the constitutive relationship between suction and the moisture content of a soil. It is thus essential in characterising the hydro-mechanical behaviour of a partially saturated soil (in this case the sludge, which is a soil-like material), as the behaviour is highly dependent on the magnitude of soil suction. The filter paper procedure and calibrations were those developed at Imperial College, London (see e.g. Dineen 1997). During filter paper testing volume measurements were performed using Vernier callipers.


(a) *(b)*

Figure 2. Paper waste streams used in this study (a) Dewatered paper sludge; (b) PSA

Table 2. Basic properties of the sludge

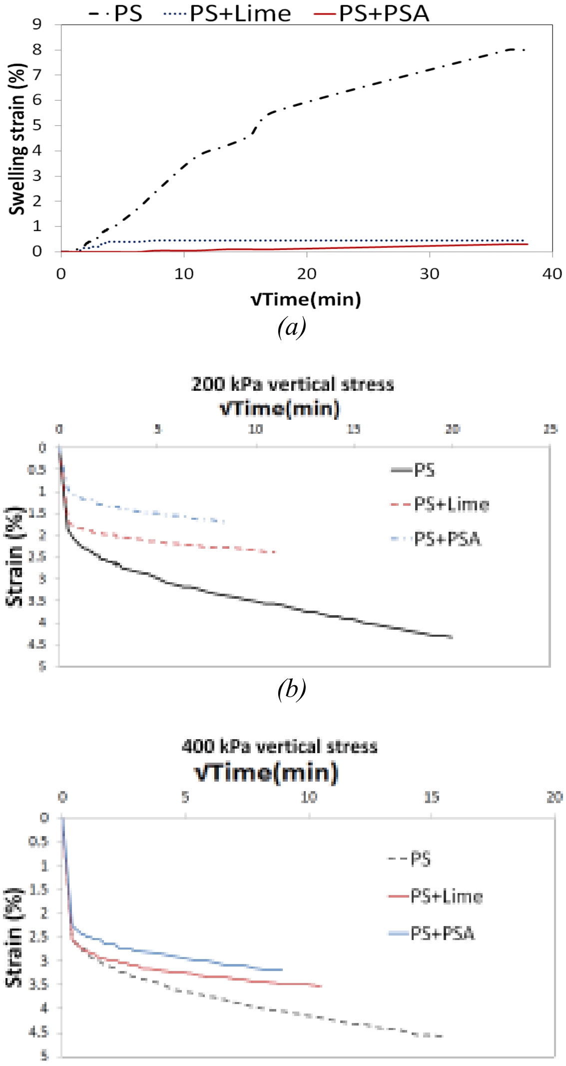
pH	**Organic content %**	**w_L %**	**w_P %**	**I_P %**	**G_s**
7.6	24	100	57	43	1.61

3 RESULTS

3.1 Paper sludge

3.1.1 1-D volume change

Figure 3(a)-(c) shows 1-D testing results in terms of free swelling strain (Fig 3(a)) and compressive strains of the same specimens subjected to 1-D compression at two different confinement stresses (after swelling) (Fig 3 (b) and (c)). Note that 'PS' in the graph labels refers to paper sludge. It can be seen that the untreated sludge had a propensity for expansion which was reduced to almost nil when chemical stabilisers were used (after 14 day curing at constant moisture content).

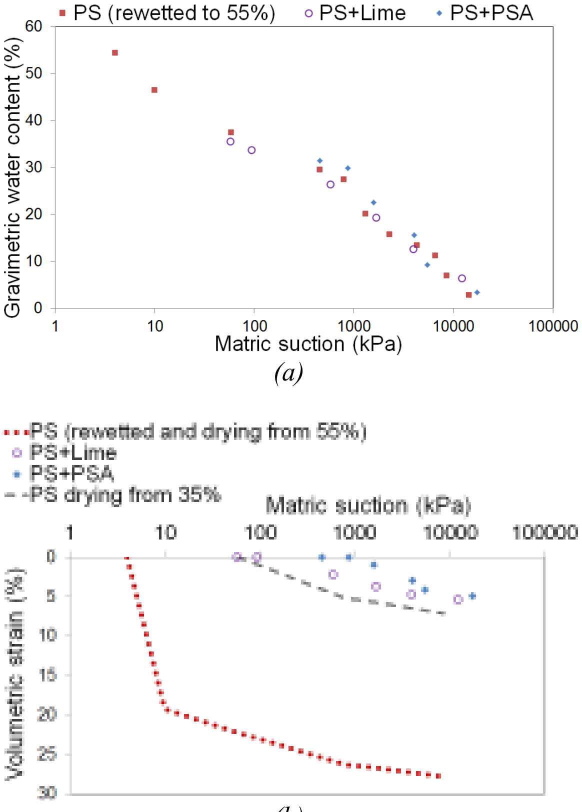


(c)

Figure 3 (a)-(c). 1-D strains upon free swelling and 1-D compression

According to Figure 3(b) and (c) the settlement of untreated sludge was still ongoing at the end of the test, with strains 1.5-3 times higher than those of the stabilised soils; thus the use of stabilisers (in particular PSA) drastically reduced the compressive strains of the sludge and led to faster consolidation (primary consolidation appears to have been completed within approximately half the displayed times in Figure 3(b) and (c), as opposed to untreated sludge whose consolidation is still ongoing).

3.1.2 Filter paper testing results



(b)

Figure 4 (a)-(b). Filter paper testing results (drying curves): (a) water content vs. matric suction;(b) volumetric strain upon drying vs. matric suction

Figure 4 (a) and (b) shows results of filter paper testing of specimens subjected to drying. Before filter paper testing, these specimens were allowed to imbibe water through capillary action until no further mass change was observed. Gravimetric water content vs. suction plots show the sludge to be able to retain water at high suctions in a similar fashion as a clay soil. The addition of stabilisers (with a 7 day curing period before filter paper testing) does not appear to have affected the overall water retention characteristics as the gravimetric water content vs. suction curves of treated and untreated specimens are very close. On the other hand, the untreated sludge showed very considerable drying shrinkage; this was substantially reduced when stabilisers were used. Note that the untreated sludge started drying from a higher water content, as it had absorbed more water than the treated specimens during the imbibition period. Thus we also plotted the drying strain results starting from an initial water content similar to that of the stabilised sludge specimens; despite this, the strains of the untreated sludge upon drying were still higher than those of the stabilised sludge specimens.

3.1.3 Shear strength testing results

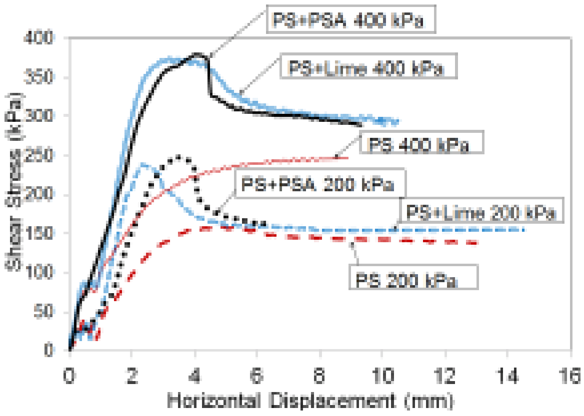


Figure 5. Indicative shear box results

Figure 5 shows indicative shearbox testing results at two different normal stress levels (200kPa and 400 kPa, as marked on the graph labels); the tests were carried out at a rate of shearing of 0.04mm/min. Note that all shearbox specimens were first left to imbibe water until no further swelling was recorded. They were then subjected to stepwise consolidation prior to theshearing stage. The shear stress-horizontal displacement graphs indicate an improvement in strength with the addition of stabilisers (after 14 day curing); when the data is fitted using Mohr-Coulomb criterion this improvement is manifested by the presence of intercepts of 60-130 kPa in the shear vs. normal stress graph for 'peak' conditions in the range of 2-4 mm displacements. The ultimate angle of friction increased by approximately 2-3 degrees for either stabiliser compared to that of the untreated sludge (33-34 degrees, which is higher than typical values for clays and closer to those of sands).

UCS testing showed a considerable increase in the unconfined compressive strength when stabilisers were used, with the PSA outperforming lime. Note however that the unconfined compressive strength of the compacted untreated sludge at the as received water content was not low.

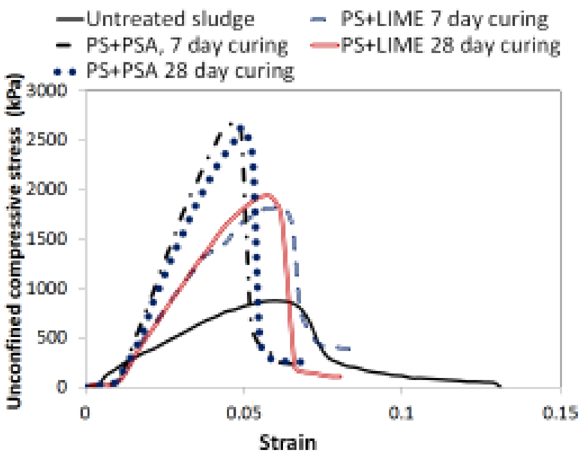


Figure 6. Indicative UCS results

3.1.4 P-wave velocity results

Figure 7 shows ultrasonic pulse velocity (p-wave velocity) results obtained using PUNDIT equipment. The p-wave velocity can be expressed as the square root of the stiffness/density ratio; therefore for a constant specimen density, the higher the ultrasonic pulse velocity, the higher the stiffness. Figure 7 results are overall consistent with those of UCS testing, with the stabilised specimens showing higher stiffness, and with PSA outperforming lime.

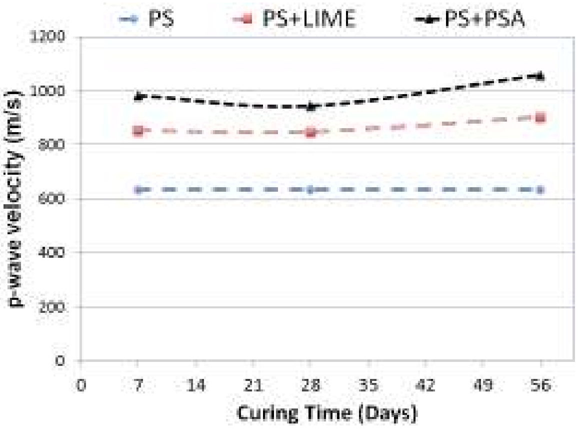


Figure 7. p-wave velocity at different curing times

3.2 PSA used as silt and clay soil stabiliser

In addition to the above study showing the effect of PSA on the sludge, the use of PSA as a clay stabiliser was extensively assessed in Mavroulidou (2018) and Mavroulidou et al (2017), who found that for the clays studied in these papers PSA was a very effective stabiliser and outperformed lime or cement.

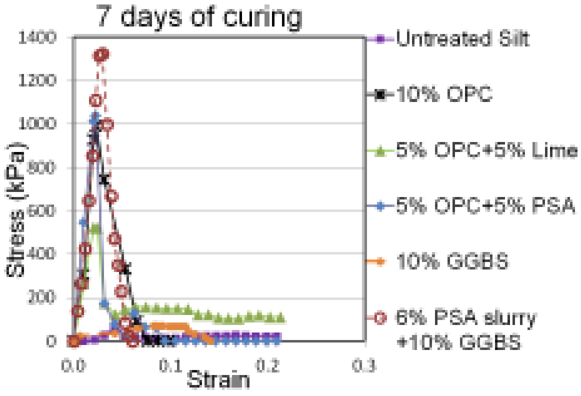


Figure 8. Indicative UCS results of PSA used as silt stabiliser compared to other stabilisers

PSA was also studied as a stabiliser of a silt soil. Figure 8 shows some indicative UCS results with PSA used on its own or in conjunction with other chemical stabilisers; it can be seen that in all instances PSA was very succesful in increasing the strength of the silt. The use of PSA as GGBS activator in alkali-activated cement mixes (as e.g. in the 6% slurry+10% GGBS mix shown in Figure 8) is studied further in Mavroulidou et al (2019), a paper submitted to this conference.

4 CONCLUSIONS

The paper investigated geotechnical properties of a highly dewatered paper sludge from the secondary stage of paper recycling. This sludge had a relatively lower organic content than other sludges studied elsewhere. Both untreated and chemically treated sludge were studied. In addition, paper sludge ash (PSA), a waste material derived from this sludge, was studied as a stabiliser of the sludge (mainly) as well as two other soils. The untreated sludge showed considerable volumetric strains both upon wetting and drying but had adequate shear strengths and angles of friction matching those of a sand soil. Chemical stabilisation of the sludge with lime or PSA improved its volumetric stability. As geomaterial stabiliser, PSA was found to generally outperform lime for the treatment of the sludge; this was also observed for the treatments of clays in other works by the authors. Presented results also showed the potential of PSA to be used as a silt stabiliser. Overall the results showed promise for the use of recycling paper industry waste streams in geotechnical applications, provided that the hazardous substance contents (tested on an individual basis) are below prescribed limits, as in the case of the materials used in this study.

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