Geomechanics and Engineering, *Vol. 41, No. 2 (2025) 307-318*
https://doi.org/10.12989/gae.2025.41.2.307

Utilization of paper sludge ash in geotechnical engineering – Review

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(*Received December 7, 2024, Revised March 16, 2025, Accepted March 18, 2025*)

Abstract. The pulp and paper industry has grown and created tremendous volumes of byproducts (e.g., fly ash) via combustion process. Unfortunately, most of them are being landfilled; in the meantime, environmental regulations restrict the disposal in landfill because of high disposal cost and reduced land due to urbanization. Therefore, the pulp and paper industries urgently seek for its beneficial reuse and one of the most cost-effective applications is a building and construction sector, particularly its reuse as geomaterials such as stabilizing soils. This paper provides a comprehensive review of the beneficial use of the paper sludge ash (PSA) in geotechnical engineering applications. Specifically, the paper explored the state-of-the-art knowledge in the areas of physical, chemical, and mineralogical properties of PSA, geotechnical engineering properties (e.g., strength, stiffness, shear strength parameters, etc.) and field applications of the PSA. In addition, the paper looks into geo-environmental applications such as PSA's water absorption and retention performance and its performance as adsorbent for environmental contaminants.

Keywords: incineration; paper sludge ash; soil stabilization; strength

1. Introduction

A survey of all industrial industries revealed that the paper industry is responsible for 17% of all worldwide waste (Karak *et al.* 2012; Sakai *et al.* 1996). Around 26% of solid municipal garbage is made up of paper and paperboard trash, and pulp and paper factories are a major source of air, water, and land pollution (Pati *et al.* 2008). While this is going on, there is a sharp rise in the annual production of wastepaper sludge, with 11 million tonnes generated in Europe (Monte *et al.* 2009), 5.1 million tonnes produced in Japan (Kinoshita *et al*. 2017), and 26 million tonnes produced in Korea (Jang *et al.* 2018), to mention a few. Additionally, 80 tonnes of paper sludge ash were produced daily in Malaysia (Sharipudin and Mohd Ridzuan 2012). In 2004, Italy generated about 600,000 tonnes of trash from paper mills (Asquini *et al*. 2008). In recycling factories, about one-third of the wastepaper that is processed becomes sludge and rejects, according to Göttsching *et al.* (1996).

The paper industry faces a challenge in disposing of remaining paper sludge, which is made more difficult by the rising popularity of recycling old, used papers. The amount of recycled-paper sludge produced has significantly increased as a result of increasing recycling, which is almost counterintuitive. In addition, as landfilling becomes more expensive and less practical in many nations, interest in energy recovery from paper sludge is developing. In response to this, paper mill sludge is frequently burned in order to recover heat and reduce the volume for disposal. These factors have spurred interest in using paper sludge for electricity production as a practical and environmentally friendly form of disposal (Anthony *et al.* 1993). Burning wastepaper sludge from the paper industry produces a by-product called waste paper sludge ash (Fig. 1).

Only 10 to 15 kg of ash are produced for every ton of paper produced, which is the main benefit of incineration's 90% reduction in the amount of waste that must be landfilled (Monte *et al*. 2009). The two processes that make up the volume/weight reduction process are dewatering (i.e., mechanical methods and/or evaporation) at low temperature (200°C) and incineration at high temperature (> 800°C). Organic compounds burn during incineration at temperatures of approximately 350 to 500°C, whereas mineral fillers and inorganic salts are transformed into the corresponding oxides at higher temperatures (> 800°C). In paper ash the most prevalent oxides are CaO, Al2O3, MgO, and SiO2. Instead of the usable product, the resulting paper ash is categorized as waste in its current state (Naik and Kraus 2003). This is why it is currently primarily disposed of in landfills at great expense to the environment. For the sake of the ecology and paper manufacturers, recycling paper ash is essential.

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http://www.techno-press.org/?journal=gae&subpage=7
ISSN: 2005-307X (Print), 2092-6219 (Online)

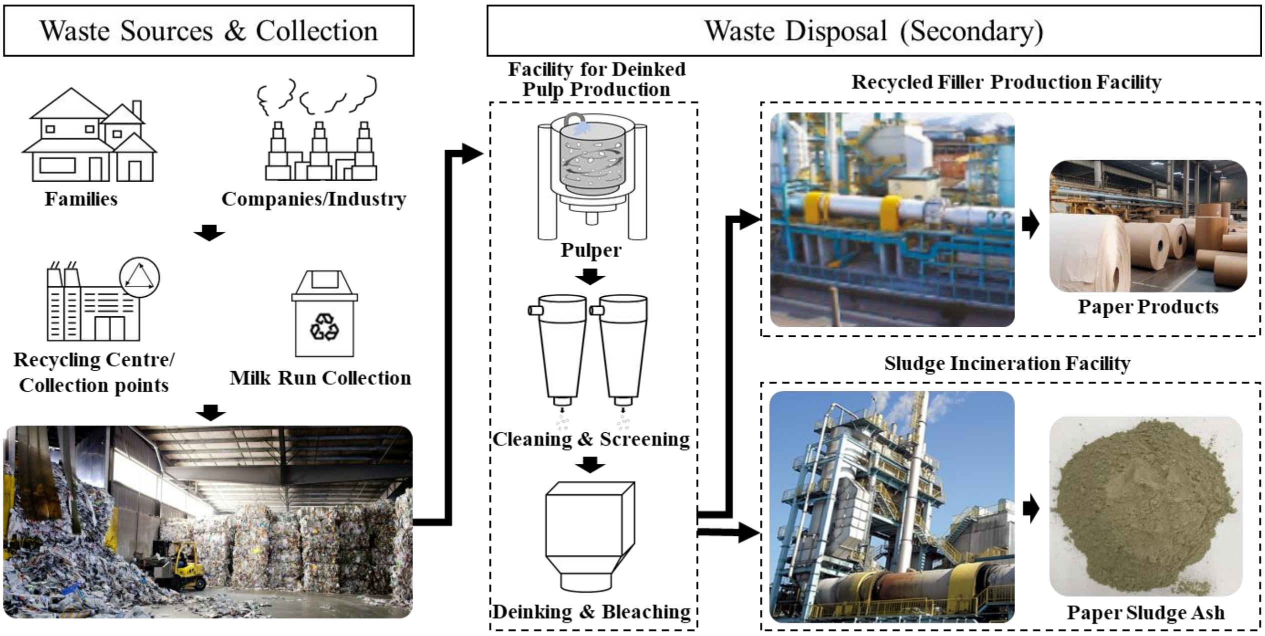


Fig. 1 Process of paper sludge ash

Recent studies have examined the usefulness of paper sludge ash (PSA) in the civil engineering sector of the construction industry. A cementitious property in the ash from paper waste may cause it to react with water, settle, and eventually solidify (Wong *et al*. 2015). Further, the combination of lime with rice husk ash has shown to improve the geotechnical properties of loess soils, as demonstrated in studies conducted in Golestan province, Iran (Zivari *et al*. 2023). Additionally, PSA behaved differently based on the combustion temperature (Ferrandiz-Mas *et al.* 2014). In order to stabilize subgrades and other areas, PSA.

In this paper, we have conducted a comprehensive review on the beneficial use of waste paper sludge ash. In particular, the review has focused on its use as geomaterials such as stabilizing poor soils; thus, we looked into physical and chemical properties, geotechnical engineering properties and field applications of the paper sludge ash. Similarly, the utilization of bottom ash for producing controlled low strength materials with high fillability, highlighting the critical role of optimal mixing proportions in achieving desired material properties and functionalities in geotechnical engineering (Lee *et al*. 2024). Please note that there are multiple different names of the paper sludge ash, for instance, waste paper sludge ash (WPSA), pulp and paper mill fly ash (PPFA), paper fly ash (PFA), etc., but since the chemical composition and their geotechnical applications are similar, the authors united the terms as paper sludge ash (PSA) from now on.

2. Physical properties

Paper mill sludge is a mixture of water, inorganic salts, organic materials, mineral fillers, and cellulose fibers. Paper sludge ash (PSA) is produced through the incineration of waste paper sludge from the paper-making process. Among the solid byproducts of wood combustion, paper fly ash (PFA) has a specific gravity ranging from 2.4 to 2.8 (Grau *et al*. 2015, Etiégni and Campbell 1991). The pH of PSA varies significantly depending on its composition, ranging from near neutral to approximately 12 (Mochizuki et al., 2019).

The density characteristics of PSA also vary. The maximum dry density ranges from 0.65 to 0.95 g/cm³, and the particle density is 2.2 to 2.9 g/cm³. Its bulk density ranges from 150 to 1300 kg/m³, with an average of 500 kg/m³, and tends to decrease as carbon content increases (Grau *et al.* 2015). Several studies have reported different bulk density values for PSA. Monosi *et al.* (2012) determined a bulk density of 1200 kg/m³, which is lower than conventional binders such as cement (2100-3100 kg/m³) and sand (2500-2600 kg/m³). Tay (1987) reported an average specific gravity of 2.81, while Ahmad *et al*. (2013) found it to be 2.6. Conversely, Khanbilvardi *et al*. (1995) identified PSA as an inorganic material with a specific gravity of 1.83 and a water content of approximately 28%. Corinaldesi *et al.* (2010) reported that PSA has a bulk density of 1720 kg/m³ under saturated surface drying (SSD) conditions. In addition, paper sludge composition consists of 60% water and 40% solids, with 30% of the solid content being ash and the remainder subject to ignition loss (Ishimoto *et al.* 2000).

Table 1 summarizes the bulk density and specific gravity variations of PSA. The bulk density ranges from 1200 to 1720 kg/m³, making PSA lighter than conventional binders and suitable for soil stabilization without excessive weight addition. Additionally, the specific gravity of PSA varies from 1.83 to 2.81, depending on its source and processing conditions, which may influence its performance as a soil stabilizer in geotechnical applications.

Table 1 Density and specific gravity of the PSA

Reference	Bulk density	Specific gravity	Note
Grau *et al*. (2015)	-	2.4 – 2.8	
Kato *et al.* (2005)	1300 kg/m^3	-	
Monosi *et al*. (2012)	1200 kg/m^3	-	
Tay (1987)	-	2.81	
Ahmad *et al*. (2013)	-	2.6	
Khanbilvardi *et al.* (1995)	-	1.83	
Corinaldesi *et al*. (2010)	1720 kg/m^3	-	SSD condition

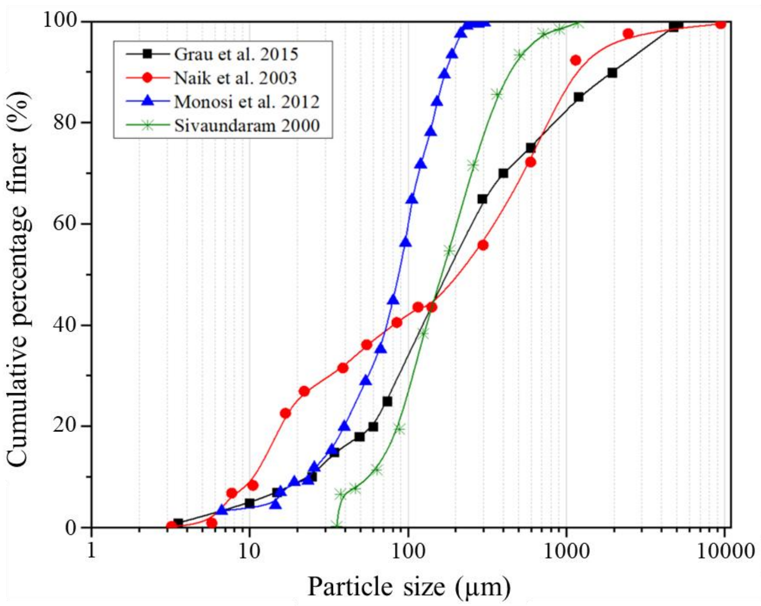


Fig. 2 Pulp and paper mill fly ash particle size distribution

Table 2 summarizes the chemical composition of PSA from various sources. The high calcium oxide (CaO) content (up to 66%) suggests that PSA exhibits cementitious properties, making it effective in soil stabilization applications. Additionally, the presence of silica (SiO_2) and alumina (Al_2O_3) indicates pozzolanic reactivity, which contributes to long-term strength development in treated soils. However, the variability in PSA composition highlights the importance of source-specific assessments before field application.

The fluctuation in particle size is strongly influenced by the degree of biomass combustion. At 150 to 250 µm, the typical particle size is comparable to high-calcium coal fly ash (Sivasundaram 2000). Fig. 2 illustrates the wide particle size distribution of PSA, ranging from 1 to 10,000 µm (Monosi *et al*. 2012, Sivasundaram 2000, Grau *et al.* 2015). The variation in particle size is strongly influenced by the combustion process. Finer PSA particles, similar to high-calcium fly ash, provide better pozzolanic activity, which can enhance soil stabilization performance. Conversely, coarser PSA particles may contribute to improved drainage properties in engineering applications.

The surface area ranges from 4200 to 100,600 m^2/kg and is more than 200 times larger than that of class C coal fly ash (Cheah and Ramli 2011). The fineness of the particles, their high degree of irregularity, and their more porous makeup are all factors in PSA's large surface area. According to Pöykiö *et al.* (2005), these characteristics also result in improved adsorption capacities as well as higher leaching rates. Due to its hydrophilic nature, PSA has a high moisture holding capacity, and the particles also have a propensity to aggregate (Pitman 2006).

According to Corinaldesi *et al*. (2010), it can absorb around 25% of its weight in water, and 80% of the paper sludge ash passes through a 75 µm sieve. The average moisture content of paper sludge is 75.40%, the ignition loss is 70.11%, and the ignition loss drops to 19.63% after the co-generation of ashes, according to Liao *et al*. (2010). Corinaldesi *et al.* (2010) estimated its water absorption capability to be about 25%.

3. Chemical properties

Wood residues used as fuel in the combustion process significantly influence the chemistry of paper sludge ash. Factors including the type of wood such as hardwood or softwood, combustion temperature, and furnace conditions

Table 2 Summary of the typical oxide compositions of pulp and paper fly ash (N/P = not provided)

Reference	Composition of Major and Minor Oxides (%)										
	SiO_2	Al_2O_3	FeO_3	CaO	MgO	Na_2O	K_2O	TiO_2	SO_3	MnO	P_2O_5
Muse and Mitchell (1995)	N/P	1.25	0.63	12.0	0.77	0.14	1.33	N/P	N/P	N/P	N/P
Pitman (2006)	N/P	9.1	5.1	1.66	0.11	0.01	0.26	N/P	20	N/P	N/P
Naik *et al*. (2003)	26.5	9.0	5.4	16.0	3.0	1.7	5.0	0.51	4.8	N/P	N/P
Vassilev *et al*. (2013)	31.6	13.2	5.12	28.9	5.4	1.42	13.2	N/P	2.67	2.77	2.64
Serafimova *et al*. (2011)	N/P	N/P	N/P	52	1.32	N/P	2.39	N/P	N/P	N/P	0.72
Ohno and Eric (1993)	N/P	8.21	1.43	9.49	0.65	0.67	1.03	N/P	N/P	N/P	N/P
Abdulahi (2006)	31.8	28	2.34	10.53	9.32	6.5	10.38	N/P	N/P	N/P	N/P
Chowdhury *et al*. (2015)	50.7	8.2	2.1	19.6	6.5	2.1	2.8	N/P	N/P	N/P	N/P
Johakimu *et al*. (2016)	0.68 - 52.78	0.12 - 28.30	0.37 - 3.69	1.59 - 4.88	0.35 - 83.58	N/P	1.43 - 1.97	0.01 - 1.68	4.23 - 62.62	N/P	N/P
Phan (2021)	19.0	5.9	2.9	66.2	1.2	N/P	N/P	N/P	4.0	N/P	0.8 (w/others)

critically determine the ash's properties (Pitman 2006). The chemical mechanisms underlying stabilization, such as the pozzolanic reactions observed in lime-stabilized kaolinite, are crucial for understanding the strength development in treated soils (Ahmadullah and Chrysochoou 2024). The amount and chemical composition of ash produced are significantly influenced by the combustion temperature. According to Scheepers *et al*. (2016) and Etiégni *et al.* (1991), the combustion temperature is also correlated with the amount of organic matter and heavy metals in the ash. Their concentration in PSA is typically modest because carbon and nitrogen molecules undergo oxidation during burning, resulting in gaseous chemicals (Demeyer *et al*. 2001). The sporadic presence of charcoal in PSA can result in an overestimation of organic carbon, even though it does not always contribute to the nutritious contents (Guerrini *et al.* 2000, Park *et al.* 2005). The combustion of free organic carbon and inorganic carbonate species is a factor in how Fmuch total carbon is expressed as loss on ignition (LOI) in PSA. LOI is used to determine the amount of carbon that is still present in the ash, although to a certain extent, sulfur, salt, potassium, and other components can also contribute to mass loss during ignition (Vassilev *et al*. 2013). Depending on the type of wood and combustion conditions, the value varies between 5% and 60%, with the average LOI of PSA being between 20% and 30%. (Naik 2003, Malhotra 1994, Serafimova *et al.* (2011).

Elemental composition study shows that alumina (Al_2O_3), silica (SiO_2), and iron oxide make up the majority of PSA (Fe_2O_3). There are varying amounts of other metal oxides such MgO, K_2O, CaO, TiO_2, Na_2O, and SO_3. Calcium content in PSA can vary significantly depending on the different source materials, and may even be the most prevalent element, claim Scheepers and du Toit (Scheepers *et al*. 2016). For instance, fly ash derived from coniferous trees has a much lower K and S content compared to hardwood species and a greater Si and Ca content. Furthermore, at greater combustion temperatures, the concentrations of K, Na, and carbonate (CO_3^{2-}) decrease while those of other metal ions rise or remain constant (Etiégni *et al.* 1991, Pitman 2006, Misra 1993). It is crucial to determine the entire elemental composition because it sheds light on how fly ash leaches (Naik 2003). According to the pertinent literature, Table 2 lists the amounts of various metal oxides that were found in paper fly ash during X-ray fluorescence (XRF) investigation.

The majority of the literature reports that the fly ash has an average pH value of 11, with the range falling between 8 and 13. (Patterson 2001, Camberato *et al*. 2011). Ash with a high calcium oxide content has pH values of 12 or higher. The introduction of lime as a causticizing component during the pulping process is the primary source of the excessive alkalinity (Camberato *et al*. 2011). However, the sulfates in PSA may occasionally cause an initial acidic pH, a phenomenon known as a masking effect (Sear *et al.* 2003). Additionally, it has a strong acid-neutralizing (pH buffering) capacity, which results in a liming action (Etiégni 1991, Demeyer 2001).

The PSA's component makeup is identical to that of regular Portland cement, according to Kawai *et al*. (2018).'s research. Rahmat and Kinuthia (2011) and Segui et al. (2012) reported similar calcium oxide (CaO) concentrations, which account for 40.6% of its weight. Kawai *et al*. (2018) showed that the PSA alone can start a hydration response when combined with water. In this instance, the porous PSA particles physically absorbed the extra water in the muds before the hydrated compound ettringite during curing chemically absorbed it. However, PSA's hydration reaction is weaker than cement's. Kawai *et al.* (2018) investigated the effects of PSA treatment on various clay mixture conditions using X-ray diffraction. It was discovered that at 110°C, the hydrated chemical ettringite produced via PSA absorption totally decomposes. The PSA does not solidify, and the alkalinity is not as high as cement or lime, as stated in Mochizuki (2016, 2019).

4. Mineralogical composition

Paper sludge contains extremely small amounts of the minerals used as coating agents to produce a smooth paper surface, such as kaolinite and calcium carbonate.

(a) (b)

Fig. 3 SEM observations of PSA particles, (a) 50micrometers (b) 10 micrometers (Sherian and Siddiqua 2019)

Depending on the type of paper, the amount of coating agents varies, but is typically between 5 g/m^2 and 20 g/m^2. Gehlenite ($Ca_2Al_2SiO_7$), lime (CaO), calcite ($CaCO_3$), quartz (SiO_2), merwinite ($Ca_3Mg(SiO_4)_2$), and α'-Ca_2SiO_4 were the minerals found in the WSA. The primary mineral, glenite, is mixed with lime to give the strongest diffraction pattern, according to Bai *et al.* (2003). Additionally, it was believed that bredigite ($Ca_{14}Mg_2(\text{-}SiO_4)_8$) might be present but that it would be difficult to identify from α-Ca_2SiO_4 due to their extremely similar XRD patterns (Baloochi *et al.* 2022, Wang *et al.* 2024, Jeremiah *et al*. 2023). The value of Waste Paper Sludge Ash (PSA) as a hydraulic binder is greatly influenced by the results of the XRD examination. Lime (CaO), mayenite ($C1_2Al1_4O_{33}$), and α'-Ca_2SiO_4 are three potentially reactive minerals found in PSA. There is no reason for the PSA under research to have pozzolanic qualities, in contrast to other calcined paper sludges that do so because of the presence of metakaolin.

Images of a PSA sample taken using a scanning electron microscope (SEM) are shown in Fig. 3. The images depict asymmetrical, angular-looking inorganic particles with thin layers of crystalline formations. These amorphous particles are fundamentally hydrophilic in nature and simultaneously hydrate oxides by absorbing water into their pores through capillary action (Etiégni *et al*. 1991, Grau *et al*. 2015, Sivasundaram 2000). There are several agglomerated particles as well as a few spherical ones. Some particles are made of porous cells and are made of unburned or only partially burned wood (Naik *et al*. 2003).

PSA is an amorphous glassy substance made primarily of iron oxide, alumina, and silica (SiO_2) (Fe_2O_3). Various amounts of the different crystalline phases, such as tricalcium silicate (Ca_3SiO_5), tricalcium aluminate ($Ca_3Al_2O_6$), portlandite ($Ca(OH)_2$), lime (CaO), and quartz (SiO_2), may be found (Pitman 2006, Serafimova *et al.* 2011). The crystalline calcium oxide, amorphous components (SiO_2, Al_2O_3, and Fe_2O_3), and sulfates are the main factors in PSA's mechanical and cementing capabilities. Consequently, due to its high calcite and aluminosilicate content, it is suitable for use as a cement alternative in the building industry as well as an aggregate or binder in the construction of roads. A high sulfate content is undesirable for concrete applications because it may promote the formation of ettringite crystals, which may result in expansion cracking (Pitman 2006, Gu *et al*. 1995).

5. Geotechnical engineering properties

The engineering performance of expansive soils, road subgrades and subbase layers, hydraulic layers, etc. can be improved by fly ash when used as a stabilizer in general (Rios *et al.* 2018, Rani *et al.* 2016, Jhariya *et al.* 2018, James 2018). Similar benefits have been observed with wood pellet fly ash in enhancing the strength and modifying the microstructure of weathered granite soils (Balagosa *et al.* 2024). Municipal solid incineration ash and other solid waste have been extensively studied in the construction industry over the past few decades. Examples include road foundation (Kim *et al.* 2016, Cho *et al.* 2020), aggregate replacement in concrete (An *et al.* 2014, An *et al*. 2017), aggregate replacement in asphalt concrete (An *et al*. 2015), cementitious supplementary materials (Kim *et al*. 2015), leaching potential (Tasneem *et al*. 2017, An *et al.* 2021). Agricultural wastes have also been reviewed for their effectiveness in stabilizing expansive soils (Gidebo *et al.* 2023).

Field monitoring revealed considerable stiffness increases and permeability decreases over time, which were due to ash hydration. The high calcium and aluminosilicate content of PSA also gives rise to its self-cementitious property, which can significantly enhance strength and volume change characteristics of expansive subgrade soils. After learning about the potential benefits of using PSA in geotechnical engineering, many studies have tried to use it as a soil stabilizer. Mavroulidou (2018) also highlighted PSA as an alternative to commonly used lime treatment or cements stabilization for poor clayey soil. According to Bujulu *et al*. (2007), lime-cement-PSA mixtures are compared to traditional lime-cement mixtures for deep stabilization of quick clay. The equal proportions of lime and PSA yield higher compressive strength and lower

Table 3 Summary of the unconfined compression strength on clayey soil with paper ash

Study	Soil type	PSA Contents (%)	Unconfined Compressive strength (kPa)					
			0-day	3-day	5-day	7-day	14-day	28-day
Lee *et al*. (2002)	Silty clay	3	16	17	-	24	21	21
		7	53	56	-	64	64	58
		10	87	111	-	86	87	94
		15	202	231	-	211	246	302
Bawa *et al*. (2017)	Silty, clayey peat, and organic soil	0	316	318	314	300	-	284
		2	377	389	445	445	-	537
		4	390	406	444	481	-	565
		5	423	433	474	497	-	591
		6	368	408	432	462	-	544
		7	354	416	486	458	-	507
		10	321	385	409	418	-	473
Onyelowe *et al*. (2017)	Silty, clayey soil	0	-	-	-	194	219	231
		3	-	-	-	198	201	245
		6	-	-	-	244	212	245
		9	-	-	-	244	245	246
		12	-	-	-	243	247	247
		15	-	-	-	202	233	242
Shin *et al*. (2018)	Low-compressibility clay	0	-	1	-	1	3	9
		2	-	4	-	4	6	120
		4	-	8	-	20	44	217
		6	-	24	-	103	429	399
		8	-	24	-	103	150	420
		10	-	24	-	134	163	461
Khalid *et al*. (2012)	Clayey soil	2	-	-	-	-	-	392
		4	-	-	-	-	-	427
		6	-	-	-	-	-	518
		8	-	-	-	-	-	685
		10	-	-	-	-	-	737
		12	-	-	-	-	-	656
		14	-	-	-	-	-	407
		16	-	-	-	-	-	366

permeability. Field test revealed that the lime-cement-PSA mixture cured for 18 months exhibited significant long-term strength and impermeability compared to lime-cement mixture. Rahmat and Kinuthia (2011) found that when PSA was used in place of quicklime, the strength of sulfate-bearing stabilized clays increased, leading to the swelling qualities reduced. With the right ratios of PSA and quicklime, it is possible to increase the strength of the treated soils without significantly altering their swelling characteristics. The usage of PSA as a component of hydraulic binder was examined by Segui *et al.* (2012).

Lee *et al.* (2002) found the strength increases in all cases. Based on the strength of specimens cured for 28 days, it is observed that more than 75% to 90% of the final strength develops within the first three days of mixing. In all instances, strength improves with an increase in the mixing ratio. The optimal efficiency for strength increase is attained at a soil mixing ratio of approximately 9%.This indicates that while strength increases with higher mixing ratios, the rate of strength enhancement decreases after a specific threshold. Bawa *et al.* (2017) found that after 28 days of curing, the change in UCS (uniaxial compressive strength) was significant up to 5% PSA content. Nevertheless, when the PSA content surpassed 5%, no further enhancement in UCS was noted. The UCS value rose by approximately 40% with the incorporation of 5% PAS based on dry soil weight. The mixtures were prepared with different ratios of PSA for attaining maximal UCS. The minimal WPS content was 2%, yielding a 7-day UCS of 445.2 kPa and a 28-day UCS of 537.2 kPa. The optimal

Table 4 The shear strength result of soft soil and soft stabilized with 10% PSA

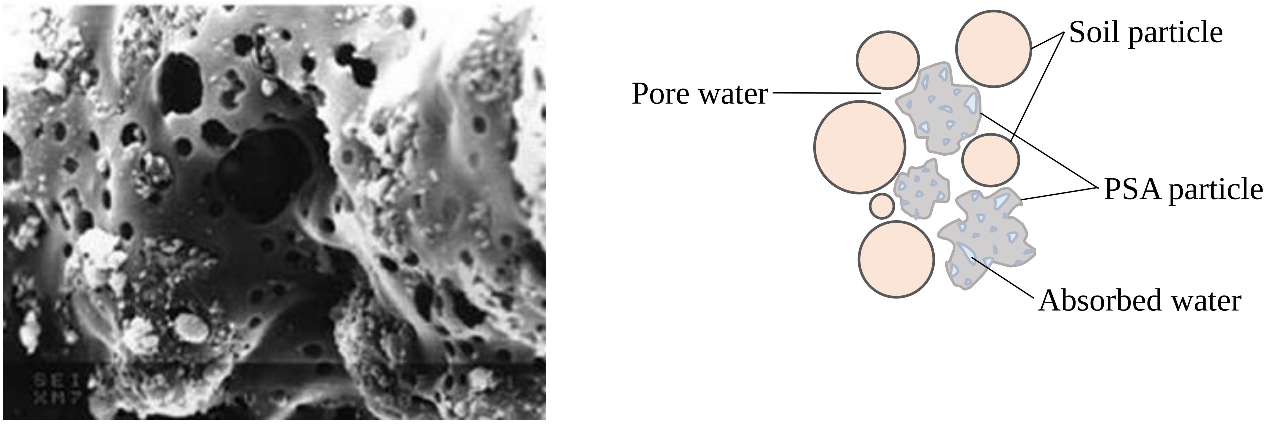
Samples	Consolidated undrained test		Consolidated drained test	
	Total strength		Effective strength	
	Cohesion, c_u (kPa)	Friction, φ_u (°)	Cohesion, c′ (kPa)	Drained friction, φ′ (°)
Soft soil (control)	29	5	0	26
Soft soil + 10% PSA	40	5	0	35

WPS content was 5%, with a 7-day UCS of 496.9 kPa and a 28-day UCS of 590.8 kPa, meeting the criteria for stabilized subgrade. While the addition of PSA enhanced the strength and stiffness modulus of the original soil, it reduced the soil's ductility or cohesiveness, making. Onyelowe *et al.* (2017) demonstrated that the incorporation of PSA into Umuntu Olokoro soil, which was stabilized using PSA as an additive, improved the strength of the samples during different curing durations. The soil mixed with PSA demonstrated continuous strength improvement; however, when the PSA content reached 15%, the strength began to decline. This suggests that further increases in PSA content could lead to a reduction in the strength of the stabilized soil. Cepria and Orejana (2022) investigated the unconfined compressive strength test at various curing durations. Specimens were prepared and tested at various curing time in accordance with EN 13285 standards (Unbound mixtures. Specifications) after being cured in a damp room with 95% humidity at 20°C in order to analyze the evolution of the strength of mixtures of soils and PSA or cement. The results indicate that both stabilized soils with PSA and cement were able to attain a compressive strength higher than 1.5 MPa after 7 days, taking into account the mechanical property needed by the Spanish Specification. The compressive resistance was not significantly affected by the curing period in the case of PSA stabilization. The soils utilized in this study lacked flexibility, however it's crucial to note that the stabilized soil had a high level of organic matter, which might pose a challenge to the strength improvement. Table 3 indicate the summary of unconfined compression test on the paper ash with clayey soil.

Shin *et al*. (2018) investigated the soil-ash mixture's unconfined compressive strength across curing intervals of up to 28 days as the PSA content increases from 0% to 10%. The results show the maximum strength at 10% ash, which is about 450 kPa. Additionally, they performed a frost heave test and measured the heave at different PSA content. The results of the frost heave test are presented in this study. As the ash increases in the mixture, the amount of heave decreases; less than 1 mm when the ash of Finally, due to their extremely low permeability, geopolymers based on PSA can also be used as hydraulic barriers, especially as landfill covers (Slim *et al.* 2016, Moo-Young and Zimmie 1997). Additionally, PSA could replace currently utilized materials as a drainage material in a layer covering landfills (Sathia *et al.* 2008, Rani *et al*. 2016).

Elias (2015) talked on how waste paper sludge affects soft clayey soil's plasticity, free swell index, compaction, unconfined compressive strength, and California Bearing Ratio (CBR). Over 7 and 28 days of curing, adding 5% PSA increased the compressive strength from 314 kPa to 496 kPa and from 284 kPa to 590 kPa, respectively. Using 5% of PSA in a 28-day curing process also resulted in an increase in UCS values of 107.9%. In addition, Barani Dharan (2016) found that the addition of PSA at the suggested PSA level of 8% might raise the values of UCSs and CBR values for treated black cotton soils by 2.5 and 5 times, respectively. PSA can enhance the strength and compression characteristics of soils based on a number of compaction tests, CBR testing, and unconfined compression tests. It was discovered that 8% of PSA is the optimal dose. Jhariya and Parte (2018) found that 10% of PSA added to black cotton soil offered the best stabilization for the soil after conducting a series of unconfined compression tests and CBR testing. Khalid *et al*. (2012) found that adding up to 16% PSA increased CBR values in soaked and unsoaked conditions by 1.5 times and 3.6 times, respectively, while increasing UCS of treated soil by about 2 times. The findings showed that the strength of soft soil stabilized with waste paper sludge ash (PSA) was enhanced from 392 to 737 kPa with additions of PSA ranging from 2 to 10%, respectively. Additionally, the compressive strength development is showed in a soil mixture treated with PSA over time, showing that compressive strength peaks at a PSA content of approximately 10%. This trend underlines PSA's optimal performance at specific dosages, supporting its use in geotechnical stabilization applications where both strength and stability are critical.

Table 4 compares the shear strength parameters of untreated soft soil and PSA-stabilized soil. The results show a 38% increase in total shear strength and a rise in undrained cohesion from 29 kPa to 40 kPa, indicating improved resistance to deformation. The increase in effective friction angle from 26° to 35° suggests enhanced interparticle bonding, which can improve slope stability and reduce settlement in construction applications. Additionally, they investigated the differences in total shear strength and effective shear strength through consolidated undrained and consolidated drained tests, respectively, between soft soil and soft soil stabilized with 10% PSA. It shows that soft soil stabilized with 10% PSA has an increase in effective shear strength of about 35% as compared to unstabilized soft soil with an increase in draining friction (φ′) from 26° to 35°. Soft soil stabilized with 10% PSA shows the best results in terms of effective strength because of the significant internal locking of friction between the particles. The total shear strength of saturated soil increases by about 38% while the undrained cohesion (c_u) rises from 29 to 40 kPa as a result of the cohesion between the soft soil and 10% PSA particles acting as glue and the electrostatic attraction between the ions of the soft soil and the ions of the 10% PSA. An experimental investigation was conducted



(a) (b)

Fig. 4 PSA's capacity to absorb water is shown in (a) the scanning electron microscope image of the substance and (b) a schematic illustration of a PSA particle absorbing water (modified from Phan 2021).

(a)

(b)

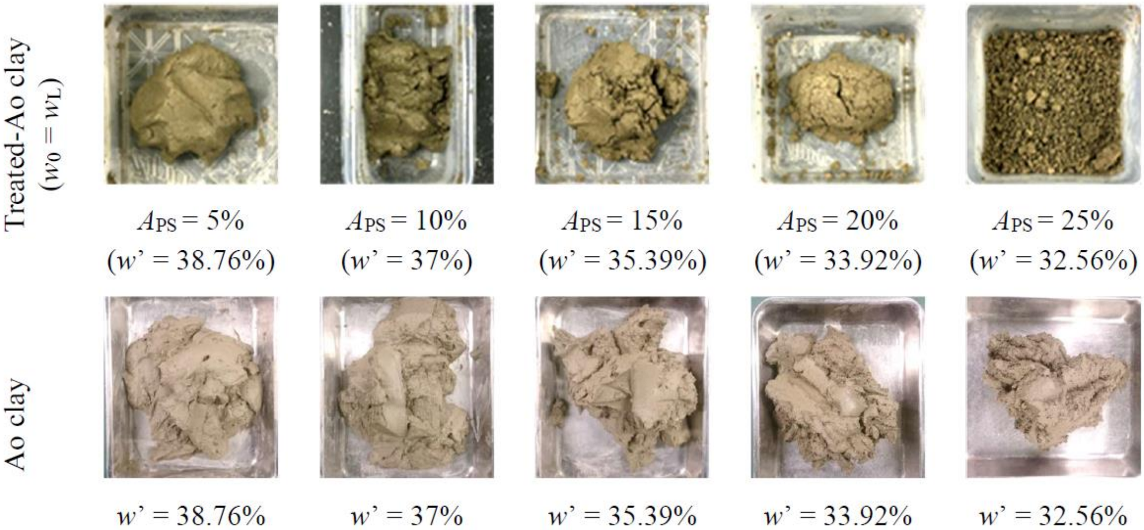


Fig. 5 Appearance of (a) treated clay just after mixing A_o clay with APS (amount of paper sludge ash) and (b) A_o clay at corresponding total water content, w' (Kawai *et al*. 2018).

by Phan *et al*. in 2021 to determine how well cement and paper sludge ash combined to stabilize dredged clay. It was discovered that the waster-cement (w/c) ratio controls how strongly hybrid-treated clay develops. For high-water-content clay, the combination of cement and PSA provided treatment results even better than those of cement alone.

6. Other engineering properties

6.1 Water absorption and retention performance

The PAS-based stabilizer has a great absorption capability (Phan *et al*. 2021). According to Fig. 4, PSA has the surface morphology of porous structures with multiple intricate flaws and spaces, which allows it to absorb and hold onto more water in soft soil.

It has been discovered that adding PSA to mud and sludge immediately increases their stability. The state of the treated clay immediately following the mixing of PSA and A_o clay (initial water content: $w_0 = w_L$) and the resultant total water content of the mixture, w', is illustrated (Fig. 5(a)). The treated clay displayed much less fluidity than the untreated clay when compared to the appearance of A_o clay mixes at the same w' (Fig. 5(b)). This demonstrates that after combining the clay and water, the PSA immediately absorbed them, reducing the water in the voids and the fluidity of the treated clay.

In an effort to assess the water absorption and retention capacities of PSA, Kato *et al*. (2005) proposed a method known as the "cylinder approach." The quantity of water that is absorbed and retained per 1 g of dry PSA mass is known as the water absorption and retention rate, or W_{ab}, and it may be calculated using the equation below

$$W_{ab} = \frac{V_w - A(H_1 - H_2)}{m_{ps}} \times \rho_w \times 100 \quad (1)$$

Where W_{ab} represents the water absorption and retention rate. V_w is the volume of water initially added. A denotes the cross-sectional area of the cylinder used in the test. H_1 and H_2 are the initial and final heights of the water column, respectively. m_{ps} is the mass of the paper sludge ash, and ρ_w is the density of water.

The water absorption and retention rate for the PSA-mixed clay exhibits over 160% while that of A_o clay is about 80%, which is a half of the PSA-clay mixture.

6.2 Adsorbent for remediation of contaminated environments

Because of its superior absorption and retention capabilities, PSA can be used as a low-cost material to remove heavy metals from municipal and industrial effluents, acid mine drainage, etc (Malakootian *et al*. 2008, Laohaprapanon *et al*. 2010; Sahoo *et al.* 2013). The numerous metal oxides included in PSA combine to generate metal hydroxides under excessively alkaline conditions. Domestic laundry wastewater and other dissolved and suspended organic pollutants can be effectively adsorbed by these hydroxides (Laohaprapanon *et al.* 2010, Sahoo *et al*. 2013). PSA is better adapted to eliminate quantities of harmful metals due to its greater ability for adsorption as carbon content increases (Tewari *et al.* 2006, Ahmed *et al*. 2012). Furthermore, PSA has key inherent properties like fineness, surface area, porosity, and ion exchange capacity (Li *et al*. 2016, Tewari *et al.* 2016). Aside from pH, temperature, adsorbent dosage, and contact time, there are other crucial variables that affect efficacy (Singh *et al.* 2016). Ash can be processed by being heated to a high temperature (calcination), which produces a material that is highly porous and has superior ability to remove pollutants (Kimura *et al.* 2017). For the many field applications mentioned above, PSA is difficult to transport and disseminate due to its small particle size and fine texture. Direct application of PSA in powder form may have negative effects on ground plants, including the potential for overliming, and may be hazardous to users' health (Jacobson 2003). These problems have been addressed and PSA has been employed more successfully by using granulation techniques (Väätäinen *et al.* 2011). Additionally, the likelihood of unintentionally flushing high-magnitude alkaline chemicals into the environment is reduced by the granular form's slower chemical element release. Additionally, by producing molecules that are more stable and environmentally safe, geo-polymerization of PSA significantly minimizes handling issues (Ohno *et al.* 1993).

7. Conclusions

This study provides a comprehensive review of the geotechnical and geo-environmental properties of PSA-mixed soil, focusing on its physical, chemical, mineralogical, and mechanical characteristics. The findings indicate that PSA-treated soils exhibit superior performance compared to lime- or cement-treated clays, offering enhanced strength, stability, and sustainability. Given that PSA is a byproduct of the paper industry and is already incinerated, its reuse in geotechnical applications presents a cost-effective and environmentally responsible alternative to conventional soil stabilizers. Moreover, PSA requires less water for compaction, making it a practical solution for soil stabilization, foundation improvement, and fill material applications.

Beyond its geotechnical benefits, PSA's high absorption capacity enhances its effectiveness in soft clay treatment, while its adsorbent properties allow for applications in environmental remediation, particularly for heavy metal contamination. These advantages position PSA as a sustainable material that supports waste reduction, circular economy principles, and eco-friendly engineering practices.

Acknowledgments

This work was also supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (RS-2024-00340187).

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