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Article

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Recycling and utilization of paper sludge ash -current status review and future perspectives

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ABSTRACT

Paper sludge ash (PSA) is a type of industrial waste produced by the pulp and paper industry that poses both environmental and financial difficulties. However, in recent years, scientists and engineers have looked into its potential as a green and sustainable material for a variety of technical applications. With a focus on PSA's appropriateness, advantages, and drawbacks, this in-depth research intends to shed light on the numerous applications of PSA in engineering. The paper starts by going through PSA's composition and physical and chemical properties to shed light on them. After that, it looks at the various engineering fields where PSA has been used, such as geotechnical engineering, and building materials. To further explain the uses of PSA, a variety of experimental results are presented. In the field of construction engineering, PSA has been used as an additional cementitious component in the creation of concrete. Its pozzolanic qualities increase the strength and durability of concrete while lessening the negative environmental effects of cement manufacture. Additionally, PSA has been used as a soil stabilizer in geotechnical engineering to improve soil qualities and lower the risk of soil erosion. Its use is challenged by questions of durability, uniformity, and potential environmental dangers, among other challenges and worries. The positive potential of PSA as a resourceful and sustainable material in engineering applications is highlighted by this review, in its conclusion. It emphasizes the need for further research, standardization, and widespread adoption of PSA-based products to harness its full benefits.

1. Introduction

A key contributor to greenhouse emissions and global warming is cement. 8 to 10% of the global CO_2 emissions are caused by the manufacture of cement [1]. It is predicted that from 2017 to the end of 2050, the yearly output of OPC will rise by almost 50% [2]. A ton of carbon dioxide (CO_2) is predicted to be released during the production of one ton of OPC [1,2]. Industrialization, urbanization, the global economy, consumerism and market, and population growth are the main forces behind social and economic developments. In general, these elements clearly cause dangerous problems for humans, which in turn lead to climate change [3,4]. Construction of new buildings has risen as a result of the rapid expansion of population growth and globalization. The demand for building supplies, particularly cement, is rising as the construction industry expands tremendously. One of the major environmental repercussions of modern human activity is the construction sector [5,6]. Researchers have been motivated to find a workable solution for lowering the demand for cement due to the detrimental environmental effects connected to cement's widespread use. Numerous research studies have been investigated to identify workable substitutes for cement in concrete binders as such measure represents the efficient approach for reducing CO_2 emissions. In place of some of the cement, supplementary cementitious materials (SCMs) such as metakaolin, rice husk ash, powdered granulated blast furnace slag, silica fume, and fly

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ash can be used [6–9].

Paper sludge ash (PSA) is a by-product resulting from the incineration of waste paper sludge generated by the paper industry. Incineration serves a dual purpose: it substantially mitigates the volume of sludge waste for disposal, typically achieving an 80–90% reduction, and it partially harnesses energy by biomass co-combustion. It's important to note that mechanically dewatered paper sludge has a relatively low calorific value, ranging from 2.5 to 6.0 MJ/kg [10,11]. Every year, hundreds of tons of PSA ash are produced together with thousands of tons of paper sludge globally. Worldwide, the quantity of waste paper sludge is increasing quickly each year; for example, in Europe, 11 million tonnes are produced. PSA disposal landfills have serious environmental consequences. After that, a significant portion of PSA gets dumped in landfills. Due to the landfill charge, this has raised environmental concerns and increased industry expenses [10,12]. Finding alternatives to landfilling is therefore of great importance. According to Wong et al. [13], PSA may possess a cementitious characteristic that reacts with water, settles, and subsequently hardens. Various methods have been explored for the potential recycling of PSA, including its use as soil amendments, soil stabilization, incorporation into road sublayers, and as a partial cement replacement in the concrete industry [10,14,15]. Nevertheless, a significant portion of WSA continues to be disposed of in landfills.

In order to have a through apprehension about the available research studies for the use of PSA in engineering applications, the Scopus database was used as it represents a main international and prominent peer-reviewed database [16]. The used keywords included “paper sludge ash” And “pozzolanic” or “cement, applied to probe articles, titles, abstracts, and keywords. The analysis identified >300 papers from the period 1974 to 2023. Figs. 1 and 2 illustrate the Scopus database and their authorship countries respectively. It can be seen that the period of 2006, and 2010 onwards provided growth in PSA research, and 2021 noticed the greatest growth. Fig. 2 shows the distribution of publications across the globe, with India having the highest authorship of >58 publications. Next came China with 50 publications, followed by the United Kingdom, Spain, Malaysia, and Japan with >25 publications.

As far as the authors are aware, there isn't any thorough review material about PSA use. They take a unique approach to resolving the inconsistent findings seen in the body of current literature. In addition, recently released findings have not been covered in earlier review publications. A systematic literature review strategy was used to review and assemble a significant body of literature that was published in the previous two decades (2010−2023). There were several research databases used for this, including Google Scholar, Web of Science, and Scopus. As a result, this study provides a current assessment of recent and cutting-edge research on the incorporation of PSA in engineering fields. The goal of this comprehensive assessment is to give experts, engineers, and researchers in the building and materials fields an in-depth understanding of PSA application in engineering. The study ends with suggestions and ideas for additional research.

2. Production and characteristics of PSA

The primary source of fiber used in paper production is wood, which can come from both coniferous and deciduous trees. There are also secondary sources of fiber, including seed fibers, leaves, hemp, linen, woody bamboo stems, sugarcane (like bagasse), rice, rye, wheat straw, and barks, such as those from sisal, abaca, and cotton. The paper manufacturing process starts with the extraction of cellulose. During the drying process, cellulose has the capacity to generate hydrogen bonds, which causes the pulp to transform into a sheet of paper. For this reason, recycling old paper is advantageous because the cellulose fibers and lignin have already been separated. Nevertheless, due to the eventual breaking of cellulose fibers, the recycling process for producing new paper or cardboard can only be repeated for a limited number of cycles, typically ranging from 3 to 8 cycles. Afterwards, the residue produced is considered waste and must be disposed of [17,18]. Waste paper sludge is burned to minimize its volume and then dumped in landfills because practical reuse has not been actively advocated. PSA is generated during the burning of paper [6]. The main purpose of burning the sludge is to reduce the amount of paper sludge waste (by between 80 and 90%) as well as recover some energy for use in manufacturing by co-combusting with biomass. Ash, which is then produced by incinerating waste, is appearing more frequently. For every tonne of paper produced, this results in the production of 10–15 kg of PSA [18,19].

Due to its pozzolanic characteristics and cementitious characteristics, PSA could be added to cement mixes as an additional cementitious ingredient. The final composition significantly relies on the feedstock and composition circumstances, although it mostly consists of lime (CaO), silica (SiO_2) and alumina (Al_2O_3) [6,20]. Paper sludge comprises a significant amount of cellulose, an organic material, and inorganic substances including calcium carbonate and clays. The temperature of combustion affects the mineralogical makeup of PSA. When combustion occurs between 700 and 750 °C, clay minerals like kaolinite in the paper

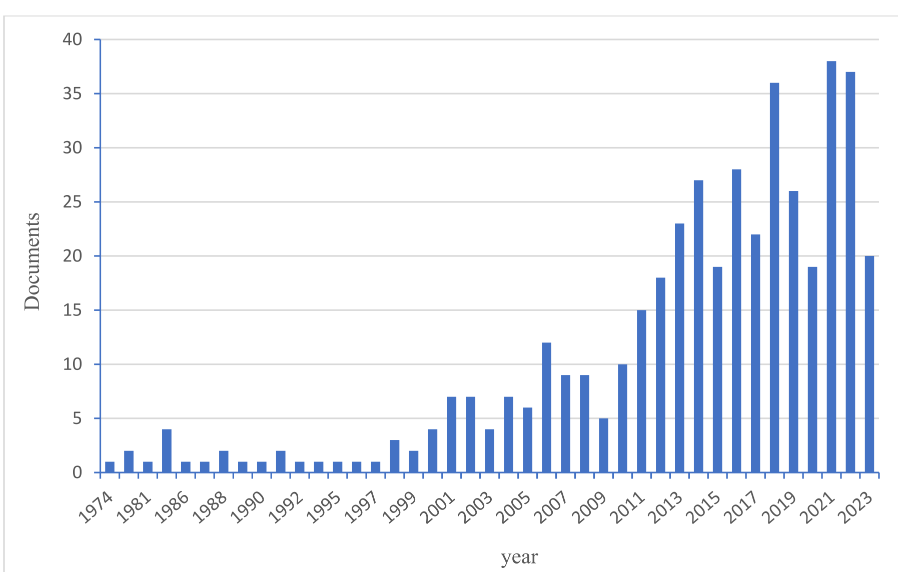

Fig. 1. Number of scientific publications per year from Scopus.

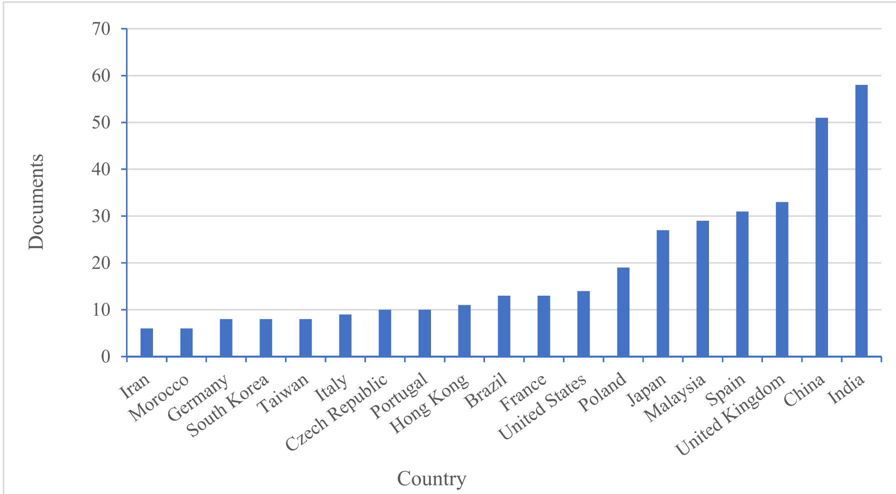

Fig. 2. Number of scientific publications per country from Scopus.

sludge transform into metakaolinite (MK), which is combustible, and the PSA behaves as a pozzolanic material. However, the PSA acts more like a hydraulic material when it is produced at temperatures between 850 and 1200 °C. It has no discernible MK [21]. The raw sludge (waste paper sludge) does not exhibit pozzolanic properties. Although calcination might raise initial processing costs, it frequently results in better performance and wider application in different building materials, such as concrete. Better strength development, durability, and other desired qualities in concrete mixes can be obtained from the increased reactivity of calcined PSA, possibly outweighing the initial cost increase [22,23]. Depending on the mill and the type of paper sludge to be burned, different thermal treatment techniques may be used. In one instance, ash from mills that just burn paper sludge has a high calcium oxide concentration (> 10%), while PSA with a somewhat high chlorine level is also produced by mills that burn plastic [24].

Paper sludge ash is described as a fine powder with extremely high pH between 12 and 13, limited content of moisture of about 0.2 wt%, and organic content between 0.05 and 2.39 wt%. chemical composition of PSA from various research are summarized in Table 1. Aluminum, silicon, and calcium are present in large levels; MgO is the only additional element present in significant proportions. The durability of cement-based materials may be affected by the presence of magnesium oxide (MgO) in paper sludge ash (PSA). Excess MgO can result in the creation of expansive phases like magnesium hydroxide (brucite), although minor levels of MgO can also aid in the formation of stable hydration products. However, research in this area is rare and further research would be beneficial to state such an effect. The mineralogical characterisation indicates that Gehlenite, the primary mineral present in waste paper sludge ash, seems to be inert when exposed to water. The waste paper sludge ash particles are porous, as demonstrated by the SEM observation, allowing for the possibility of PSA as a hydraulic mineral admixture [25,26]. Due to the high porosity and numerous open zones, the PSA has coagulated particles with uneven morphologies that may make them less workable, as shown in Fig. 3. The agglomeration of particles justifies the industrial incineration process. The OPC has angular and flaky-shaped particles.

Table 1
Chemical composition of PSA.

Composite	[6]	[10]	[21]	[27]	[28]	[29]
CaO, %	65.03	44.55	54.20	66.2	49,84	70.276
SiO_2, %	24.58	27.80	20.46	19.0	26.44	24.671
Al_2O_3, %	2.15	13.79	12.10	5.9	15.36	2.209
Fe_2O_3, %	–	4.94	0.82	2.9	1.16	0
MgO, %	2.60	3.92	3.38	1.2	2.16	2.721
Na_2O, %	1.71	0.33	0.21	–	–	1.811
K_2O %	0.27	0.28	0.42	–	–	0.335
SO_3, %	0.36		0.40	4.0	0.45	0.342
TiO_2, %	0.46	0.73	0.32	–	–	–
LOI, %	4.5	–	–	–	4.59	–
pH	12.86	–	–	–	–	–

3. Applications of PSA

3.1. Replacement of cement in concrete, mortar, and paste

According to the majority of studies, There are two ways to recover PSA: either by replacing some of the cement in mortars or concrete or by integrating it into regular Portland cement (OPC). PSAs are utilized in mortars for masonry in particular to support green technology because there is less cement production involved, which reduces carbon dioxide emissions. According to the most recent experiments stated above, PSA can be recycled up to 100% of the time, with very high levels of cement added up to 50% of the time. When conducting such research, a microstructure analysis is typically combined with mechanical and environmental parameters [12,30–32]. The greatest technical challenges to the PSA recovery, however, are caused by the presence of free lime, which in excess leads to issues with swelling and their activation. Seifi et al. [33] found that very few research specifically address PSA activation, despite the fact that this technology is frequently employed for coal fly ash [34].

Pozzolanic materials and sludge from waste paper were used to partially replace the cement. Ahmad et al. [35] studied the properties of concrete that had some cement replaced with waste paper sludge ash. They demonstrated that concrete could benefit from the addition of up to 5% waste paper sludge ash. Wong et al. [13] studied hydrophobic concrete. The durability characteristics of concrete might be improved by 12% by utilizing waste paper sludge ash, according to their research. Meko and Ighalo [36] studied the characteristics of fresh and cured concrete. 0%, 5%, 10%, 15%, and 20% of waste paper sludge ash were utilized to substitute the cement. According to the findings, concrete with PSA became less workable as the content rose. To explain the connection between a material's characteristics and its physico-chemical structure, advanced analytical characterisation is necessary for the development and manufacture of new materials. It has been discovered that highly integrated microelectronic structural evaluation of surfaces with X-ray fluorescence-assisted and laser beam tools is useful in providing important data, such as correlations between the mechanical, chemical, and durability of the newly developed products. Most of the time, multiple strategies need to be applied at once since no one method can supply all the information required. Sadique et al. [37] used FTIR

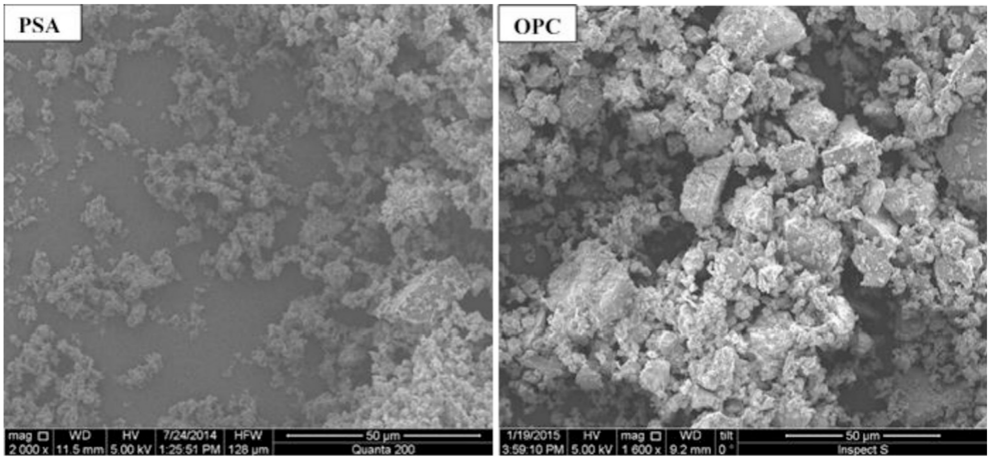

Fig. 3. SEM images of PSA and OPC [6].

and TG/DTA to analyze the hydration, characterize, and assess a new non-Portland binder including PSA. The non-Portland binder had hydration products that were gradually forming, and their microstructural traits were examined. After 365 days of curing, secondary ettringite formation's stable and non-expansive characteristics were also discovered. Expanded polystyrene (EPS) and PSA were utilized by Ferrándiz-Mas et al. [21] to create lightweight cement mortars with good thermal-insulation qualities. In comparison to control samples, the mortars produced showed minimal bulk density and thermal conductivity. In comparion with EPS powder, ground EPS yielded samples with decreased thermal conductivity. The use of resource-efficient mortars in plastering and rendering applications is thought to be appropriate when they include up to 20% PSA and 60% EPS.

Additionally, The use of PSA in blended cement for concrete and mortars is not widely discussed in the international literature. In order to reduce the excessive water consumption of wood-wool composite boards, upgraded (processed) PSA was examined as a partial cement replacement [38]. Controlled self-compacted low-strength cementitious materials and low-strength self-compacted concrete were the focus of the majority of research using blended cement with WPSA [39,40]. There is a significant scientific knowledge gap because of the behaviour of the ternary Portland cement matrix against sulfate attack. Early studies on ternary and quaternary blended cement blends have been documented in the literature. The initial studies conducted by Frias et al. [41] and Goñi et al. [42] examined the combined effects of thermally activated paper sludge (APS) and coal fly ash (FA). These pozzolanic by-products were found in ternary cement pastes, and their mechanical properties, durability, and reaction kinetics were investigated. Based on the nature of the APS, the acquired data showed that the primary hydrates originating from the system APS + FA/$Ca(OH)_2$ were hemi-carboaluminate, hydrotalcite like structures, CSH gel, and C_4AH_{13}. Furthermore, when juxtaposed with traditional Portland cement pastes, those ternary cement pastes showed improved resistance to corrosive media like Cl, sulfates, and seawater. However, it is not well understood how to use PSA in structural concrete that has higher strengths (above 40/50 MPa), and in particular how to combine PSA with other supplemental cementitious elements to potentially increase the sustainability of the concrete. The use of PSA for structural concrete was investigated by Mavroulidou et al. [18] in ternary and binary mixtures with high-strength cement and the industrial by-products (ground granulated blast-furnace slag (GGBS) and pulverised fuel ash (PFA)). Table 2 presents the outcomes. The best binary blends for strength and longevity while maintaining pumpability often contained 15% PSA. These mixtures produced greater early strength improvements but less workability. Even while ternary GGBS and PFA mixes had lower strengths than binary PSA mixtures, the addition of PSA increased their ability to resist carbonation. Further mix optimization can produce alternative strong, long-lasting high-strength cement systems with PSA that allow greater strength cement substitutions in structural concrete for a more favorable environmental impact.

Table 2
Testing results on binary and ternary mixes with PSA [18].

Binder	E_c (GPa) (measured)	Flexural strength, f_r (MoR) (MPa)	ft/fc	Tensile splitting strength, f_t (MPa)
OPC (ref.)	35.0	4.3	5.84	3.00
90%OPC-10% PSA	35.0	4.1	6.04	3.20
85%OPC-15% PSA	35.0	4.9	6.02	3.10
80%OPC-20% PSA	35.0	4.4	5.70	2.85
70%OPC-30% PSA–	35.0	4.1	5.52	2.65
50%OPC-25% PFA-25%PSA	34.0	N/A	6.16	2.15
60%OPC-20% PFA-20%PSA	32.0	4.3	6.44	2.50
65%OPC-20% PFA-15%PSA	34.0	4.6	6.38	2.80
70%OPC-20% PFA-10%PSA	34.0	4.7	5.97	2.50
70%OPC-15% PFA-15%PSA	33.0	4.5	6.22	2.75
50%OPC-25% GGBS-25% PSA	34.0	N/A	6.12	2.55
60%OPC-20% GGBS-20% PSA	30.0	3.9	7.45	2.55
65%OPC-20% GGBS-15% PSA	32.0	4	7.14	2.65
70%OPC-20% GGBS-10% PSA	32.5	4	6.06	2.45
70%OPC-15% GGBS-15% PSA	32.5	4.3	5.90	2.35
75%OPC-15% GGBS-10% PSA	32.0	4.3	5.83	2.55
80%OPC-10% GGBS-10% PSA	32.0	4.5	6.95	2.95

Keerthana Devi et al. [17] employed PSA to partially replace cement in M25 grade concrete, with varying proportions (2.5%, 5%, and 7.5%). The objective was to assess its impact on flexural strength, splitting tensile strength, compressive strength, and durability after 28 days of curing. Based on the outcomes, Up to 5% of the cement's weight can be successfully replaced by PSA. The test findings unmistakably show that integrating PSA as a partial cement substitute improves the concrete's performance, especially in terms of its strength. The impact of the PSA replacement level (up to 50%) and grinding time on the mortar's compressive strength and surface electrical resistivity was studied by Shubbar et al. [6]. Two replacement levels, three testing ages, and three grinding times (in addition to no grinding) were taken into account. The findings showed that after 28 days of curing, Portland synthetic aggregate (PSA) ground for 10 min and used to substitute up to 50% of the amount of cement performed similarly to ordinary Portland cement in terms of mechanical and durability. Additionally, the cost of building materials and CO2 emissions can be significantly reduced by this novel binder.

On the other hand, the amount of waste generated by building and demolition projects (also known as CDW) has been increasing rapidly globally; 40 countries produce >3 billion tonnes of CDW annually [43]. One of the alluring ideas is using recycled concrete aggregate (RCA), also known as CDW, as aggregate in concrete. Tam et al. [44] claimed that the global trend toward incorporating RCA in concrete is making the construction sector more cost-effective and environmentally friendly. However, the adherent mortar in RCA limits its ability to perform as well as natural aggregate concrete (NAC) [45,46], particularly if the concrete has over 30 % coarse RCA. Only 100% coarse RCA in concrete results in subpar performance and inability to meet safety standards for concrete structures. Nonetheless, research is increasingly employing 100% coarse RCA for concrete, and numerous ways to improve the effectiveness of RAC have been put forth in recent years [47,48]. Although there have been various attempts to use 100% coarse RCA in concrete, some of them are expensive or require intricate procedures. The use of more cement is one outstanding way to enhance the effectiveness of RAC. A crucial component for raising RAC quality is the use of Mineral Admixtures (MAs) in concrete. Compared to MAs in NAC, MAs in RAC performed the following additional roles: Pores and fissures in adherent mortar are filled, As CH in both old and new mortars is transformed into CSH in RAC depending on the pozzolanic reaction, ITZ is produced, strengthening the link between cement paste and RAC. Fly ash, metakaolin, and silica fume are the MAs that are most frequently utilized as pozzolanic ingredients for concrete. To increase the usage of by-products and waste materials in RAC, such as paper sludge, replacements for the current pozzolanic materials are required [10,49]. In concrete using 25% or 50% RCA, Fauzi et al. [50] explored 5%, 10%, and 15% PSA to replace the cement. A study examining the characteristics of concrete with 100% coarse RCA and PSA is not, however, currently accessible. If RAC contains PSA instead of NAC, it might operate differently. The toughness and mechanical characteristics of RAC with industrial by-products and 100% coarse RCA were examined by Bui et al. [10]. The by-products, which were used in RAC in two separate approaches (replacement and addition), included PSA, FA, SF, and MK in various quantities (5%, 10%, 15%). The addition strategy outperformed the replacement method and the use of more cement in terms of durability and strength for RAC using mineral admixtures, according to the results. Notably, PSA greatly enhanced RAC resistance to sulfate and acid attacks, as well as its mechanical capabilities at an early age. At 90 days, FA and MK considerably improved the mechanical properties of RAC in contrast to SF and PSA. The combinations that yielded the best results for RAC using 100% coarse RCA are those with by-product proportions of 15% FA, 15% MK, 10% SF, and 5% PSA. As shown in Fig. 4, the addition of PSA to RAC increased its capacity to

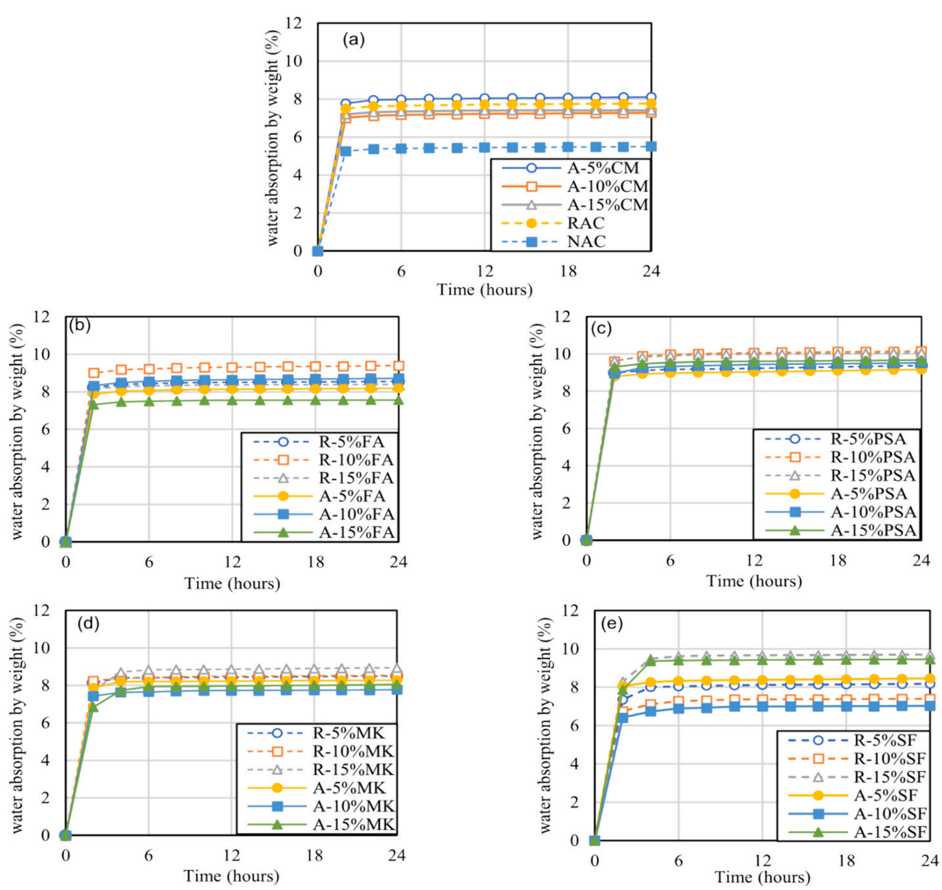

Fig. 4. Water absorption results [10].

absorb water in comparison with the other materials. It may be because PSA has less SiO2 in its chemical makeup than others, which has reduced the pozzolanic reaction. Furthermore, PSA concrete may absorb more water than others due to its high porosity.

The effects of utilizing fine recycled concrete aggregate (FRCA) and PSA on the characteristics of lightweight foam concrete (LWC) with densities ranging from 1400 to 1800 kg/m3 were investigated by Sharipudin et al. [51]. The PSA replacement percentages were 5% to 30%. The compressive strength of LWC was found to be decreased by PSA, according to the results. A few research combined PSA with CEMII and aggregates derived from waste streams, such as glass cullet [52,53], or foundry sand [54]. The results are not comparable because the PSA in [54] was found to consist of only 8.69% CaO, in contrast to the majority of the PSA in other studies. With no significant negative effects on hydration, strength, or density, concrete has been successfully coated with 12% hydrophobic PSA powder as a water-repellent surface addition [13].

Some of the above studies are summarized in Table 3. As is generally known, the C-S-H gel plays a major role in determining the mechanical qualities by keeping the cement paste cohesive. This can be attributed to the inherent qualities of the gel texture, wherein the engineering features are largely dependent on factors such as nanoparticles and assembly possibilities. When pozzolanic additives like crushed granulated furnace slags, fly ash from burning coal, or metakaolin are added, a different kind of C-S-H gel is created that has a lower Ca/Si ratio and a higher Al content. According to earlier research by Largo et al. [55], the APS pozzolanic reaction results in the creation of layered double hydroxide (LDH) compounds like hydrotalcite (HT) and calcium-aluminates hydrates like C_4AH_{13}. The minerals lime (CaO), mayenite ($C_{12}Al_{14}O_{33}$), and α'-Ca_2SiO_4 are present in PSA and have the ability to ignite. The strong pozzolanic activity of the APS(L)–FA–OPC system was also confirmed when such pozzolanic by-products were combined with regular Portland cement (OPC). This also showed significant direct linear quantitative connections between the textural parameters, nanoporosity, and mechanical compressive strength for the C-S-H gel generated during the hydration reaction. An analysis of research on waste paper sludge ash reveals that these substances can be utilized in place of some cement. When WSA reacts with water, sets, and hardens, its properties can be made similar to those of cement. However, because of its high porosity, the WSA has a very high water requirement. Additionally, it has been claimed that swelling and expansion in alkali conditions are caused by the presence of Al in the WSA. Another possible issue is shrinkage-related cracking. In order to determine its appropriate use, it is therefore observed that the reactive features in WSA provide useful information. Based on specific investigations, it has been shown that a particular degree of WSA may achieve the specimen's compressive strength, making WSA a potential material for usage in civil engineering construction applications. Many researchers have reported positive outcomes regarding its use as an SCM in concrete. The effectiveness of PSA depends on its chemical composition, fineness, reactivity, and the proportion at which it is incorporated into concrete mixtures. Proper processing and quality control measures are crucial to ensure the optimal utilization of PSA in concrete applications.

Table 3
Previous studies on cement-based materials with PSA.

Ref.	Replacement level	Usage	Results
[18]	10–30%	Concrete	Increasing PSA content decreased workability. The mechanical strength is equivalent or superior to OPC samples.
[35]	5–10%	Cement	Increasing PSA content decreased workability. The optimum replacement was 5%.
[17]	2.5%, 5%, and 7.5%	Concrete	Up to 5% of the cement's weight can be successfully replaced by PSA.
[10]	5–15%	RAC	PSA increased water absorption capacity. 5% PSA yielded the best results.
[51]	5–30%	LWC	PSA decreased the mechanical strength of LWC.

3.2. Soil stabilization

For many years, geotechnical engineers have employed construction-generated and soft soils as a possible recycling resource to address ecological and financial issues. For instance, they have been utilized in re-cultivation, backfilling, and road building. However, recycling and stabilization of such soils with a high-water content using standard treatment techniques that use cement or lime frequently has a detrimental impact on the environment and raises construction costs [56–58]. Studies have looked into using sustainable material substitutes produced by industrial processes to solve these issues. Additionally, the possibility of PSA as a stabilizer for clayey soil has been researched [11,59,60]. Mavroulidou [11] treated three different kinds of clays using PSA. With an emphasis on properties like volumetric stability, water retention, unconfined compressive strength (UCS), and plasticity. The objective was to evaluate PSA effectiveness as a clay stabilization substitute for cement or lime. The results demonstrated that PSA-treated soil specimens performed better than cement or lime-treated soil specimens in the following ways: a) Similar to lime, PSA significantly reduced the plasticity indices of the two expanding clays., b) After seven or twenty-eight days of curing, PSA dosages that were equal to or higher than Initial Consumption of Lime (ICL) produced UCS values that were at least twice as high as those obtained with commercial limes at equivalent dosages (>1 MPa for both soils), and in certain cases, even higher than cement, and c) PSA-treated materials displayed less swelling while wet and less volumetric strain when dry (better volumetric stability) than soils treated with cement or lime, in line with the plasticity results. Overall, these results point to the waste product's potential utility in the field of ground augmentation.

Sand backfilling is typically needed for manholes, pipelines, waste collection systems, and building public water supplies. However, big natural occurrences like earthquakes usually cause backfilled sand to become fragile. The liquefaction phenomenon is referred to as a weakness in this situation. A survey found that the liquefaction of backfilled sand causes road surface subsidences, pipe sags, and manhole uplifts, which interfere with drainage operations and traffic movement [56,61]. Backfilling sand needs to be strengthened or stabilised with additional minerals to prevent liquefaction. It has been proposed recently to stabilize the soil by using paper sludge ash-based stabilizers (PSAS) [27,62]. In order to develop PSASs, heavy metals in the initial PSA particles should be insolubilized. The manufacture of stabilizers based on cement or lime creates more CO_2 than the production of PSASs from PS ash as PS ash is produced as an industrial byproduct rather than as a finished product. Because PS ash surface is porous, it can absorb and retain more water from the soil which has numerous intricate imperfections and voids. When combined with PS ash, PSASs can concurrently increase the stability of sludge and mud [56,63]. As a result, there is now a greater need for PSASs for stabilizing muds in construction projects such as digging pits and tunnels below ground or dredging in lakes, rivers, and harbours. To make sure they can be used effectively in mud treatment, researchers have looked into the water retention and absorption capabilities of PSASs. The “cylinder method” was created to calculate the water retention and absorption rate, or Wab, of a PSAS, which is calculated as how much water is retained and absorbed by a PSAS in relation to its dry mass [64]. Nevertheless, it was shown that the Water Absorption by PSAS (Wab) stayed consistent when the cylinder approach was used. According to Phan et al. [65], this discrepancy could be explained by mistakes made when estimating Wab as a result of the cylinder method drawbacks. In order to tackle these constraints, Phan et al. [65] introduced a new technique known as the ‘sieve method,’ which offers a more rapid and accurate estimation of Wab over a specified curing period. In an effort to guarantee a specific cone index, Mochizuki [66] suggested a mixture design strategy for treating muds with PSASs. For instance, the following equation suggested the PS ash addition ratio, APS, needed to guarantee a cone index qc of 200 kN/m^2:

$$APS = a\{(w - wL) + 37.8 logIp - 33.5$$

APS is the mass relationship between a PSAS to a mud, while wL and Ip are the mud's liquid limit and plasticity index, respectively. "a" is a parameter that in Eq. (1) represents how well the PSAS absorbs and retains water. The parameter "a" reflects the Wab of the PSAS. The aforementioned investigations were limited to treating muds like dredging clays or sludge that contained a lot of small particles. As a result, Eq. (1) only applies to muds that have more water than the liquid limit, wL, and cannot be used for construction-related soils where the coarse fraction predominates. Nguyen Phan et al. [64] conducted experiments to explore how a PSAS affects the mechanical and physical characteristics of stabilised clay. Fig. 5 depicts the experimental principle in detail. Each PSAS was cured in a sealed environment for a period of time ranging from 10 min to 72 h, then passed through a stainless-steel 53-m sieve after being soaked in distilled water with a PSAS to water ratio of 0.25. The PSAS particles that had absorbed and retained the free water in the PSAS solution were separated using three-dimensional vibrations produced by an electromagnetic sieve shaker. The PSAS particles moved in the direction of each other due to the vibration, and as the free water flowed through the sieve, these particles were trapped. Water absorption and retention, or Wab, is the ratio of the water mass absorbed and retained by PSAS to its dry mass. The outcomes showed that Wab values were influenced by the kind of PSAS utilized and that Wab rose with longer curing durations. Through experimentation, Depending on the particle sizes of both the PSAS and untreated clays and the Wab values of PSAS, it was possible to predict the liquid and plastic limits of clays treated with PSAS that were measured at various curing periods. Furthermore, both treated and untreated clays showed a distinct association between the liquidity index (IL) and cone index (qc). A fresh method for combination design was put out in light of these findings. Investigation into the viability of this strategy revealed that when clay was treated with PSAS, the measured qc values closely matched the intended qc values. Generally, the measured qc exceeded the desired qc by 1.1 times. A maximum of 30% difference existed between measured and target qc values.

The use of PSASs in sandy soils has not been the subject of many investigations. According to a recent study, PSASs alone are predicted to cause a hydration reaction when coupled with water, however the reaction won't be as strong as cement [63]. On the application of PSASs to coarse-grained soils, limited research has been done. As was previously indicated, even while such coarse-grained soils can meet the needed range of particle sizes, they find it challenging to achieve the necessary degree of compaction when they contain a lot of water. The strong absorption and retention capabilities of PSASs in this scenario might help to lower the quantity of free water in coarse-grained soils with high water contents. The reduction in free water is anticipated to help with compaction efforts during embankment and filling buildings as well as with preventing segregation issues [27]. Furthermore, scientists [67,68] have shown that extra moisture in muds is absorbed chemically during the curing process after initially being physically absorbed by PS ash particle pores. Considering these conclusions, it may be concluded that PSAS-treated sand won't harden too much when used as a backfill around an underground pipeline and won't become as alkaline as backfill stabilised with cement or lime, which has been observed in some cases. Otieboame Djandjieme et al. [56] explored the potential use of a stabilizer derived from PSAS to enhance the qualities of sand intended for usage around underground pipers as backfill materials. Swelling tests have shown that when the PSAS-treated sand is completely dry, it undergoes significant expansion upon soaking, similar to sand treated with ordinary Portland cement (OPC). According to the results, however, depending on how long the PSAS-treated sand would be temporarily placed at the building site, maintaining the ideal moisture level can reduce its propensity to expand. Despite the fact that PSAS and OPC have very comparable chemical compositions, unconfined compression experiments have shown that under the same mixing conditions, the compressive strength of the sand treated with PSAS is noticeably lower than that of the sand treated with OPC. Additionally, sand treated with PSAS had a more progressive increase in compressive strength with curing time than sand treated with OPC, suggesting that the former is simpler to excavate again. Because of the presence of berlinite, the PSAS-treated sand may have improved long-term strength. X-ray diffraction study has shown that the sand mostly produces calcite.

Watanabe et al. [27] assessed the effects of a PSAS on the mechanical characteristics and compaction of coarse-grained soils with the goal of employing them as building materials for irrigation earth dams. The

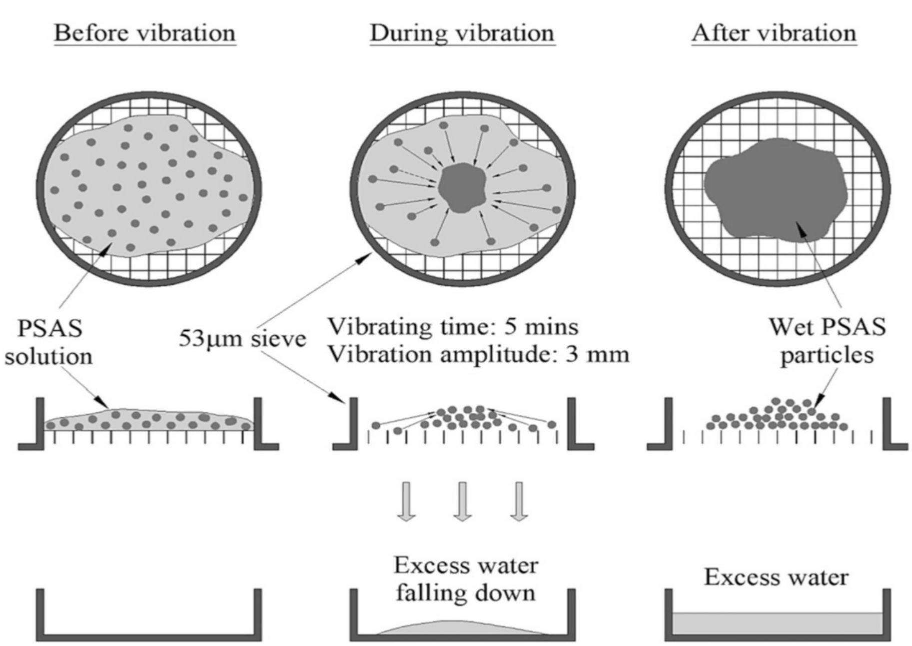

Fig. 5. Experimental principle for water retention and absorption rate of PSAS, Wab [27].

study found that the treated samples modified optimal water content (w*opt), which was calculated by taking into account the quantity of water not absorbed or retained by the PSAS, was remarkably similar to that of the untreated samples. In light of these compaction features, a unique mixture design strategy was consequently suggested. The outcomes of this method showed that by measuring the Wab of the PSAS at a particular curing period and the compaction curve of an untreated sample, it was possible to estimate the required amount of PSAS to achieve the desired compaction level (Dc) for that curing period, eliminating the need for compaction tests on treated samples. The performance of water absorption and retention is illustrated in Fig. 6. Particles of PS ash physically absorb clay-water at an early stage (Fig. 6(b)), as the cement is hydrating. As the process progresses (Fig. 6(c)), PS ash particles enlarge the space while also absorbing water both physically and chemically. In the clay that has undergone hybrid treatment, the cement paste may consequently become more concentrated. PS ash may also be hydrated to create calcium silicates, which add to strength, just like cement can. When the quantity of unretained and unabsorbed clay-water is adequate for the hydration of cement, this mechanism aids in the formation of bond strength in the hybrid-treated clay.

3.3. Asphalt

The careful selection of a filler fraction with a fine grind and a particle size of <0.063 mm is essential for the creation of a high-quality hot asphalt concrete mix. Due to its substantial specific surface area, this component of asphalt concrete performs a number of essential tasks. As a result, the asphalt binder-mastic bond is formed, which improves the connections between the structural elements of asphalt concrete, fills in any small spaces between larger particles, and makes it easier for bitumen to change from a bulk state to a film. Among the various filler aggregates utilized worldwide for these purposes, mineral powder (MP) extracted from primary carbonate sedimentary rocks such as dolomitized limestone, dolomites, limestone, and their derivatives emerge as the predominant choice. The filler type choice that is composed of >90%, 80%, or 70% calcium carbonate is challenging. It is also affected by several external factors, including noise emissions, surface texture, climate, pavement load, and traffic volume. Moreover, the specific composition of the asphalt concrete mix employed plays a crucial role in determining the optimal filler category for achieving desired performance characteristics and longevity [67–69]. As an alternative fuel, flammable residue-containing industrial by-products are used. They also include wastes from paper sludge (PSA). In earlier studies [69–71], the use of PSA as an alternative to conventional limestone mineral powder (LMP) in the manufacture of hot mix asphalt (HMA) was examined. The ability of this material to fully or partially replace conventional LMP for HMA has been demonstrated [69]. The features of the asphalt concrete produced using LMP without foreign inclusions are not considerably worse as a result of replacing 50% of the LMP with PSA. It was therefore necessary to bring PSA to the required composition so that LMP could be completely replaced in hot asphalt concrete without suffering any loss of quality, and potentially even seeing an enhancement in the latter's qualities. The authors recommended activating WSA to accomplish this. As is common knowledge, there are three different types of activation: physico-chemical, chemical, and physical (mechanical activation). These categories are determined by the method by which new active centres grow on the surface of the filler aggregate.

A novel filler aggregate variant, PSA, along with a chemical activator called acid tar (a waste product from the oil-refining industry, AT), was suggested by Gunka et al. [28]. When utilizing wastepaper sludge ash and limestone mineral powder that has been activated by acid tar, stone mastic asphalt (SMA) may undergo probable chemical changes, according to the research. They established the viability of using industrial wastepaper sludge ash in place of standard limestone mineral powder and the efficiency of activating filler aggregates with acid tar. Interestingly, neutralisation is not necessary when acid tar is employed as an activator for filler aggregates, as SMA exhibits improved properties compared to when acid tar is neutralized. Using mineral powder (MP) that has been activated by AT, Fig. 7 depicts potential chemical changes in SMA. When a strong link between AT and MP, or chemical activation, occurs, AT can be immediately neutralized in MP (waste paper sludge ash (WSA) or limestone mineral powder (LMP)). It was established by

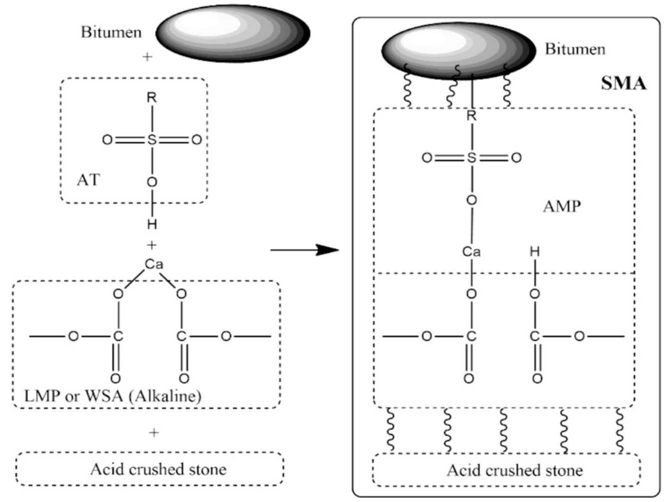

Fig. 7. Possible chemical transformations [28].

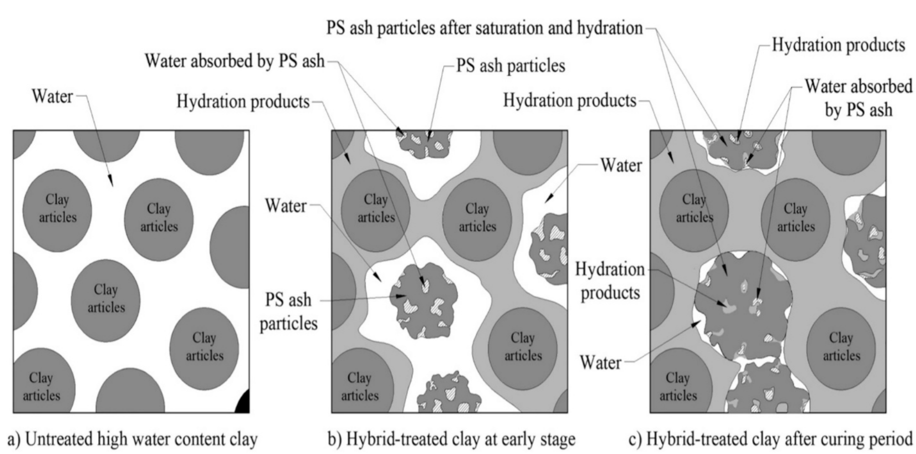

Fig. 6. The effectiveness of PSA in hybrid-treated soil [27].

FTIR spectroscopy that AT included acids (R-O-SO2-OH; H2SO4). Investigations have shown that PSA can work well as a filler material for stone mastic asphalt. When activating wastepaper sludge ash, it is advised to utilise 5 wt% acid tar to get improved stone mastic asphalt properties.

One or more of the following drawbacks of using hot mix asphalt (HMA) could have been: it would have been difficult to maintain temperature over long distances (logistical issues), the release of hazardous gases into the environment (environmental issues), and significant energy requirements for preparation and material laying (economic and practical issues). In an attempt to address the aforementioned problems, Dulaimi et al. [29] developed fast-curing emulsified asphalt cold mixes (EACM), which include a cementitious filler derived from industrial waste materials. Conventional mineral filler was replaced with PSA as the active filler for the EACM. As an additional activator, incinerated sewage ash (ISA) was used at a concentration of 0%–4% by mass of the aggregates to boost the hydraulic activity of PSA. The indirect tensile stiffness modulus (ITSM) after two days was approximately ten times higher when waste PSA was used than when standard emulsified asphalt cold mixes were used, as indicated by the results shown in Fig. 8. Furthermore, the ITSM improvement was around 65% and 30% for the 6%PSA + 4%ISA and 6%PSA + 1%ISA mixtures, respectively. Additionally, the rutting for the 6%PSA + 4%ISA and 6%PSA + 1%ISA mixtures decreased to roughly 11% and 19%, respectively, in comparison to the standard 131-pen HMA. The reason for the higher rutting resistance and ITSM is the quick demulsification of asphalt emulsion as well as the development of hydration products, causing the mixtures to bind. As a consequence, environmental problems are reduced and energy conservation might still be possible.

As an alternative to conventional mineral filler, paper sludge ash has been used in a limited number of studies to produce cold bituminous emulsion mixtures. In order to create cold emulsion mixtures with mechanical qualities akin to conventional hot mix asphalt, he intends to investigate the prospective use of waste and by-product materials as fillers. Consequently, in order to replace traditional mineral filler, cold mix asphalt was made by Dulaimi et al. [72] with percentages ranging from 0 to 6% and 0–4% for PSA and cement kiln dust (CKD). Based on test results, the stiffness and strength evolution of the mixture significantly improved with the addition of such waste materials. In addition to the residual binder produced during the PSA's hydraulic reaction, a new binder is also formed, which explains this improvement. A significant factor in the mixture's fragility was also the hydration's absorption of the stored water. Moreover, a noteworthy rise in the stiffness modulus was seen when including PSA with CBEM. The outcomes of Al-Busaltan et al. [73] are consistent with our findings. It is evidently demonstrated that the PSA is activated by the CKD. Hydration is accelerated by the high potassium content of CKD, which enhances the process. It is evident that adding an activator raised the level of hydration may surpass the target value for all HMA mixtures.

3.4. Other applications

3.4.1. Geopolymer

Geopolymers are artificial compounds created from natural or discarded materials using chemical reactions involving either alkaline or acidic activation processes. Geopolymers have the ability to incorporate hazardous waste into new cement, resulting in the development of sustainable construction materials [74]. Research into geopolymers spans various technological and scientific domains, encompassing inorganic chemistry, physical chemistry, and mineralogy. Geopolymers are composed of both pure inorganic and organic substances, as well as synthetic equivalents of natural macromolecules [75]. There are two primary methods for their synthesis: one involving alkaline conditions and the other acidic conditions [76]. The outcome of this process is the creation of a tetrahedral framework consisting of SiO_4 and AlO_4, with the specific structure determined by the SiO_2/Al_2O_3 ratio [77]. Geopolymerization results in the formation of a network held together by covalent bonds, leading to the development of aluminosilicate frameworks reminiscent of minerals found in rocks. Alkaline substances such as KOH, NaOH, and K_2SiO_3 are employed as activators to initiate these aluminosilicate reactions using precursor materials [78].

Three areas of application can be served by geopolymerization technology. The initial step involves creating nanoscale silicates with reduced alkali contamination at temperatures as low as 800 °C [79]. Secondly, monolithic materials are prepared, which may substitute Portland cement, and different wastes or by-products are recycled [80]. One application that dates back to 1988 is the third, which is the immobilisation of radioisotopes or toxic heavy metals polluted in sludgy solid wastes. However, another kind of radioisotope-contaminated liquid waste is out there and needs to be addressed [81]. Liquor/filler ratio (L/F) must increase to immobilize this kind of waste through geopolymerization. Hazardous elements would, however, escape from the geopolymer as a result of a greater L/F if the geopolymer is formed from ordinary aluminosilicate powder (such as metakaolin and fly ash). For example, coal fly ash cenospheres or porous glass ceramics might be used to tackle this issue [81,82], but their production or collection in

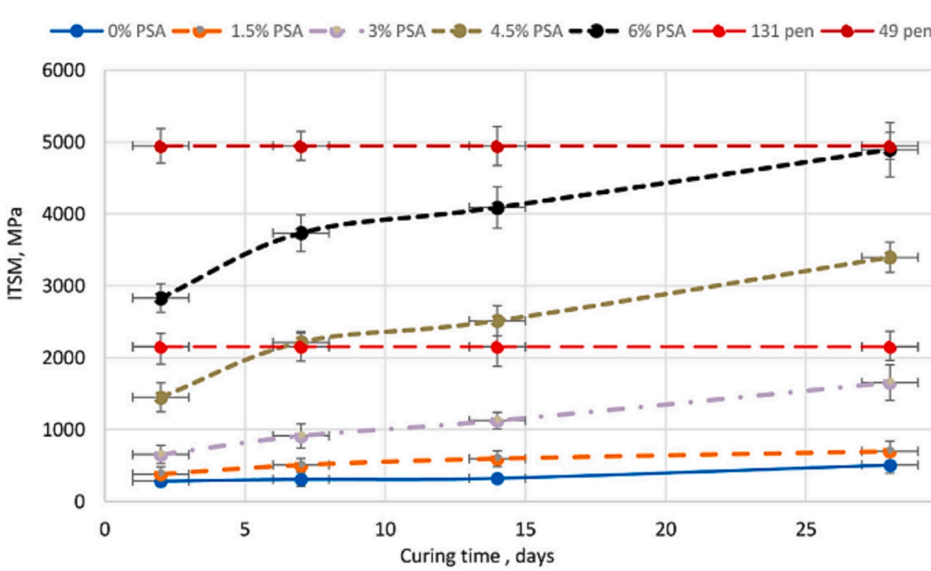

Fig. 8. ITSM results [29].

large amounts is very expensive and complicated. A few years back, the authors discovered that PS-ash might be utilized to make geopolymers, which needed to have an L/F >1.0 because of PS-ash's strong water absorption capacity. The radioactively contaminated water can be disposed of using PS-ash-based geopolymer due to this property [83].

SEM, X-ray diffraction, and plasma atomic emission spectrometry coupled with X-ray absorption near edge structure (XANES) were used by Li et al. [82] to study the ambient temperature geopolymerization of PSA discharged from paper mills. The ash based geopolymers were made with two different types of alkaline liquors, which correspond to aqueous Na-metasilicate and Na-disilicate compositions. A lot of alcohol can be absorbed by PSA due to its semi-crystalline structure and porous characteristics. Depending on the PS-ashes and liquors employed, the flexural strengths of PSA-based geopolymers with liquor/filler ratios (L/F) of 1.0–1.5 varied from 0.82 to 1.51 MPa at 4 weeks of age. The reactions between the minerals that make up PSA were described in detail. In line with these, 1% doses of non-radioactive cesium and strontium nitrates were added to the geopolymers. High immobilisation ratios of up to 99.89% for Sr2+ and 98.77% for Cs+, respectively, were often attained, depending on the PSA source, the alkaline liquors, and the material ages. The causes of the instability of the created geopolymer gels were further examined using XANES spectra, however in certain instances, inadequate immobilisation ratios were noted.

Antunes Boca Santa et al. [84] focused on the creation of geopolymers made from aluminosilicate-containing industrial waste. Geopolymers are inorganic polymers produced by a very alkaline method that activates amorphous aluminosilicates ($Al_2O_3.SiO_2$). They used sodium hydroxide (NaOH) at concentrations of 5, 10, and 15 M and sodium silicate (Na_2SiO_3, with a SiO_2/Na_2O ratio of 1.58) as the alkaline medium, with bottom ash serving as the aluminosilicate source (SiO_2/Al_2O_3 ratio of around 3.3 to 4.5). The partially solidified bottom ash was made more reactive by adding PSA. The solid waste was characterized using XRF and XRD, whereas the geopolymer samples were characterized using SEM, FTIR, compressive strength testing, and XRF and XRD. Fig. 9 displays the compressive strength findings for 24 h, 7-, 28-, and 90-day setting intervals. Only samples with a sodium hydroxide content of 15 mol/l showed low resistance. The compressive strength resistances of samples synthesized with 5 and 10 mol/l sodium hydroxide were equal. The gradual rise in resistance that geopolymers exhibit over time is another feature. The outcomes used sodium silicate, a 15 M NaOH solution, and a 2:1 PSA to bottom ash mixture demonstrated the most promise.

Geopolymerization in a very alkaline atmosphere is how PSA-based geopolymer gets its strength. Given that CaO makes up a larger portion of PSA's chemical composition than SiO_2, it is the cause of the strength development in FA-PSA geopolymer. The binding system of FA-PSA geopolymer was changed from silica–aluminum (Si + Al) to silica–calcium (Si + Ca) due to this reason, unlike FA-geopolymer. Depending on

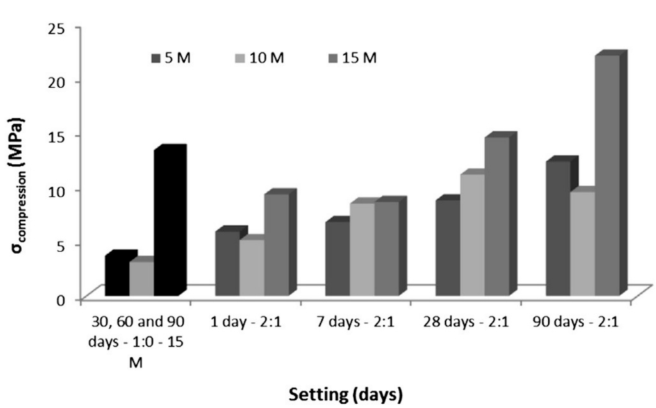

Fig. 9. Results for the compressive strength of geopolymeric samples made with an ash/calcined paper sludge ratio of 2:1 [84].

whether calcium is present in the geopolymer mixture, the reaction mechanism of geopolymerization changes dramatically [85]. The calcium aluminate hydrate gel phase and calcium silica hydrate occur as a result of calcium's reaction with the soluble silicate and aluminate species. When the calcium aluminate hydrate gel or calcium silica hydrate gel coexist, the compressive strength increases [86]. There are some unreacted or partially reacted fly ash particles visible in the mechanical characteristics, which diminish after 10% replacement of fly ash by PSA [87]. The compressive, tensile, and flexural strengths improve with a rise in PSA from 0% to 10% under various curing conditions.

3.4.2. Synthesis of zeolites

"Zeolites" are a class of over 40 hydrated, crystalline aluminosilicate minerals that contain exchangeable alkali or alkaline earth cations and three-dimensional networks of (Al, Si)O4 tetrahedra. Zeolites are frequently linked to the modification of glassy volcanic rocks and can be synthesized from a range of high-Si and Al starting materials or discovered in naturally occurring deposits. Similar to volcanic ash, paper sludge ash is composed of both crystalline and amorphous phases as a result of burning. In light of this, zeolites can be produced from ash. Formerly employed as a filler in paper, clay minerals like kaolinite have been replaced more and more lately by calcite. Anorthite ($CaAl_2Si_2O_8$) and gehlenite ($Ca_2Al_2SiO_7$) are two minerals that are more abundant in burned ash as a result of this. Si concentrations in the ash have also decreased as a result of the declining usage of silicate minerals as paper fillers. The Si/Ca ratio decreases in line with this. It is challenging to transform ash into zeolites, or at least into more attractive zeolite phases, because of its low Si content [88–91]. In order to create zeolite, Rojas-Valencia et al. [92] employed PSA. Using calcination and HCl solutions, the chosen sludge was leached and then utilized in the manufacture of zeolites. Zeolites A and P (the calcium and sodium forms) are formed when sludge is leached with a 1 M HCl solution. There will be less pollution connected to these wastes if the paper industry's sludge is effectively used in the synthesis of zeolites. Compared with other comparable methods that use very pure commercial raw materials, this offers significant advantages in terms of technology, economy, and the environment.

PSA was largely converted into zeolites in a study by Wajima and Munakata [93] by reacting it with a 3 M NaOH solution at 90 °C for 24 h. In order to create zeolites with a high capacity for cation exchange (CEC), diatomite, which contains amorphous silica and dissolves easily in alkali solution, was combined with the ash and added to the NaOH solution to raise its Si content during the alkali reaction. Without the incorporation of diatomite, the original ash generated hydroxysodalite with an approximate CEC of 50 cmol kg-1. Na—P1 (zeolite-P), which had a greater CEC (approximately 100 cmol kg −1), was produced when diatomite was incorporated into the ash. The reported concentrations of Si and Al in the solution through the procedure are what account for the crystallisation of these two phases. The authors looked at the capacity of the reaction products to adsorb K^+, NH_4^+, and PO_4^{3-} from liquid fertiliser. The product comprises zeolite-P, which is excellent for use in soil development since it has a strong ability to adsorb almost all of the nutrients from fertiliser.

Wajima [94] examined producing a zeolitic product with a high CEC, Ca interference was lessened during zeolite production using ethylenediaminetetraacetic acid (EDTA). With the use of EDTA and an alkali reaction, PSA can be converted into zeolite-A, tobermorite, hydroxycancrinite, zeolite-P, and hydroxysodalite as \shown in Fig. 10. The amount of zeolitic crystals with low Si/Al (Si/Al = 1), zeolite-A, increased as a result of the addition of EDTA, which helped the synthesis reaction by trapping and chelating calcium ions in the solution. It was possible to produce a material with a high CEC and high zeolite-A concentration. By Ca-masking, the chelating agent can prevent Ca from interfering with the synthesis of zeolites, and by utilizing EDTA to extract PSA, a high zeolite-A content product can be made.

When using industrial waste as a raw material for zeolite synthesis,

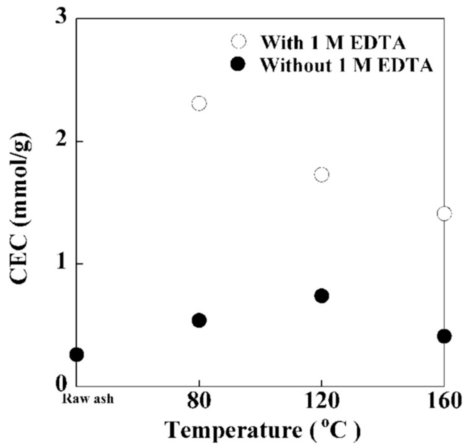

Fig. 10. CECs of PSA and the products produced from PSA at various temperatures with and without 1 M EDTA (3 M NaOH, 24 h of reaction time) [94].

as opposed to natural zeolite, there are significant environmental implications involved. Because paper sludge ash has a high silica/alumina content, it can be utilized as a raw material for the manufacture of zeolites. Yet, it was discovered that the most promising materials were those that could be made from glass, coal fly ash, waste pearlite, rice husk ash, and clay (kaolin) [95].

3.4.3. Super-hydrophobic powder

The self-cleaning process used by super-hydrophobic leaves is just one example of how hydrophobicity is frequently utilized in biological systems. Water droplets clean the leaf of debris and germs, making it more resistant to chemical and biological harm. In many engineering applications, this effect could offer significant benefits. Examples of inexpensive hydrophobic coatings that generate self-cleaning building facades with advantages include resistance to general soiling, biodeterioration, and algae development. Hydrophobic coatings are also useful for marine infrastructure, biofouling-resistant ship hulls, corrosion-resistance applications, and anti-icing surfaces [13,96]. In order to learn more about PSA's potential role as a bloating agent in sintered glass products, investigations involving dry milling have been conducted in the presence of stearic acid [97]. As a result, a hydrophobic powder was created that couldn't be combined with water to form pellets. In order to maximize this impact, it was found that the water contact angle (WCA) was used to measure hydrophobicity with the investigation of the intreation between stearic acid and PSA using Fourier transform infrared spectroscopy (FTIR).

In a study by Spathi et al. [32], a fatty acid surface functionalizing agent was added to PSA before it was dry milled to create hydrophobic powders. The results in Fig. 11 show that, under ideal laboratory conditions, a super-hydrophobic powder with a 153° water contact angle was created after dry milling for 8 h with a 4-wt% stearic acid addition. It was found that stearic acid had the highest hydrophobicity among the fatty acids with different chain lengths that were investigated. Synthesising surface monolayers of calcium stearate that self-assembled and adhered chemically to fracture surfaces, together with the dry milling-induced micro-particulate texture, is what gives PSA its super-hydrophobicity.

3.4.4. Sulphate environment

Construction of coastal fortifications is needed to protect the people living close to the shore from the anticipated sea level rise caused by global warming. As greenhouse gas emissions rise steadily, more concrete will be needed, necessitating the use of cements other than OPC, which is why OPC cements are no longer sufficient. Alkali-activated cements, that additionally contain waste products or by-products from industry, may offer viable prospective substitutes [98]. In a study by Mengasini et al. [99], GGBS was alkali-activated and combined PSA to create concrete mixtures. Additionally, the usage of seawater for mixing and curing purposes was looked into. Alkali-activated mixes' compressive strength as well as a number of durability-related characteristics in a maritime environment were examined and contrasted with OPC systems. The cements were more durable against chloride ion attack in mixes with freshwater and more resistant to sulphate attack when coupled with seawater thanks to the addition of paper sludge ash. Other results included high initial strengths, a drop in the actual porosity of alkali-activated slag concretes, and generally lower water absorption. While using seawater to mix and cure OPC concretes produced unfavorable outcomes, the inclusion of seawater in the mixes boosted the alkali-activated systems' durability against sulphate attack and compressive strength.

By combining PSA (60%) with gypsum-assisted grinding, silica fume (20%), and another alkali sulphate-rich bio material fly ash (20%), a new innovative non-portland binder (NPB) was created by Sadique et al. [37]. It was shown that the ionic species of alkali sulphate (K^+, Na^+, and SO_4^{2-}) had an impact on the activation and subsequent hydration. The higher SO_4^{2-} concentration during activation reacts with the PSA alumina phase to produce aluminosulphate, which combines with Ca^{2+} to form ettringite. This reaction is caused by the presence of gypsum and fly ash rich in alkali sulphate. This ettringite gives strength at first. After NPB paste was allowed to cure for 28 days, TG analysis revealed that the key strength-generating phase, C-S-H, had a lower concentration. This finding was consistent with the slower rate of growth in strength in NPB mortar. Nevertheless, TG/DTA results, in Table 4, confirmed that the C—H phase in the ternary blend had a lower density following long-term curing for further Pozzolanic reactions than it did in the control cement.

3.4.5. Composite & blocks

To develop composite materials for indoor wall systems, Kizinievic et al. [100] produced three different types of composite materials: paper sludge (80 wt%) + clay (20 wt% and 40 wt%), paper sludge (60 wt%), and paper sludge (100 wt%). This study took into account two different types of paper sludge granulometric composition: the S type and the S* type. S-type composite materials (paper sludge particles smaller than 8 mm) performed better in terms of thermal conductivity; however S* type composite materials (paper sludge particles smaller than 4 mm) fared worse in terms of compressive stress at 10% relative deformation. Rhizopus oryzae mold biological susceptibility decreased with clay content (20% and 40%, S* type composite materials), although density, shrinkage, and compressive stress rose at a 10% relative deformation. The data showed that the bulk densities of all composite materials ranged between 0.65 and 1.12 g/cm3, shrinkage ranged between 1.7 and 6.0%, compressive stress at 10% relative deformation ranged between 0.95 and 7.0 MPa, and thermal conductivity ranged between 0.07 and 0.154 W/(mK). Additionally, water erosion is a problem for very few composite materials. Pulp and paper sludge can be recycled to create medium-density fiberboard, according to Migneault et al. [101]. With 25–75% paper sludge, authors characterized the features of medium-density fiberboard. This study revealed that medium-density fiberboard only complied with standards when it contained 25% paper sludge.

According to Azevedo et al. [102], a mixture of cement (10 %), soil (fifty-two to 90 %), sand (zero to 27 %), and pulp and paper industry waste sludge can be recycled and utilized to form locking blocks for construction. The Brazilian standards were found to be met by blocks with a 5–10% waste addition. The blocks' density ranges from 2.48 to 2.53 g/m3, their compressive strength ranges from 2.5 to 3.5 MPa, and they absorb water at a rate of 14 to 18%. Muñoz et al. [103] conducted a comprehensive analysis to decide whether it would be feasible to use paper/pulp waste (between 2.5% and 20%) in the making of unfired clay bricks. Their findings indicated that the thermal conductivity of unfired clay bricks might be reduced by 50% by replacing 10% of the clay raw materials with paper/pulp waste. The compressive strength of

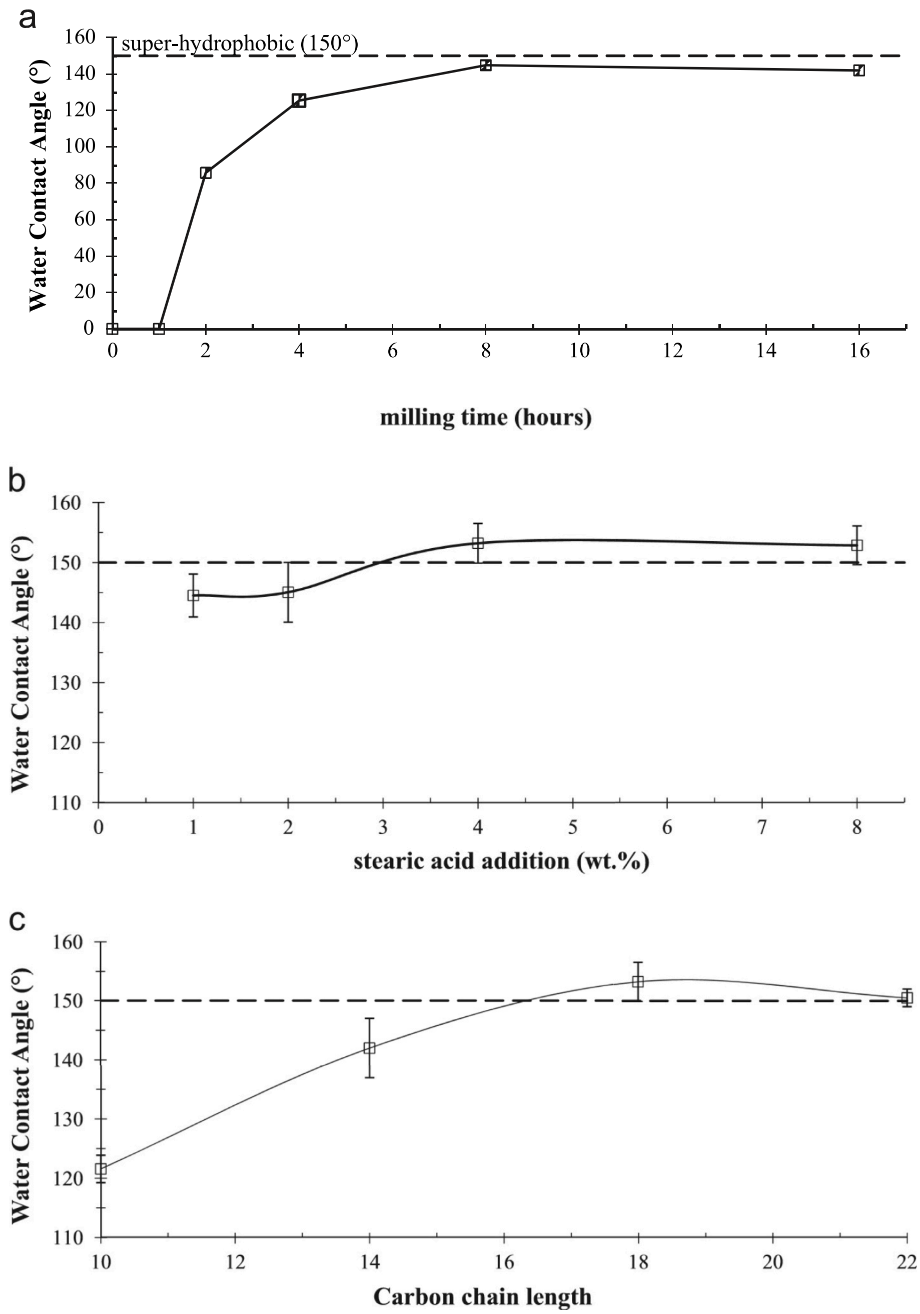

Fig. 11. Processing impact on PSA's WCA: A) the amount of stearic acid added at 1 wt% during the milling process, B) the amount of stearic acid dry milled for eight hours, and C) the use of various chain length fatty acids as surface functionalizing agents [32].

unfired clay bricks is nonetheless decreased by 25% addition of paper/pulp waste. Muñoz et al. [104] investigated how paper pulp (in concentrations ranging from 5.0% to 20%) affected the characteristics of burnt clay brick. The authors noted that adding more paper pulp to clay bricks improved their thermal characteristics. Thus, it can be claimed that adding paper pulp to clay bricks reduces their bulk density, which in turn results in a reduction in their thermal conductivity. With 900 °C burned temperature, however, they also discovered higher shrinkage and porosity and lower compressive strength.

4. Comparison of PSA to other volcanic ash materials

Table 5 presents a detailed analysis of the attributes and features of Paper Sludge Ash (PSA) in relation to other frequently utilized supplemental cementitious materials, such as fly ash, metakaolin, and silica fume. In conclusion, PSA provides a versatile, affordable, and sustainable substitute for conventional supplemental cementitious ingredients, potentially improving the sustainability and performance of concrete mixtures.

5. Conclusion

In conclusion, paper sludge ash (PSA) offers several promising opportunities for use in various engineering applications, primarily as a sustainable alternative to traditional materials. Its utilization can help reduce waste, conserve natural resources, and contribute to environmental sustainability. Some key findings regarding the use of PSA in engineering applications are:

Table 4
Results of TG/DTA curves [37].

Temperature	% Mass loss					Comments
	7 day	14 day	28 day	90 day	365 day	
0–150° C	6.17	22.43	25.49	23.30	14.6	de-hydroxylation of CSH phase
150–170° C	0.63	0.76	0.78	0.95	1.5	dehydroxylation of Ettringite (AFm) phase
400–500 °C	1.0	0.78	0.98	1.6	1.3	dehydration of Ca $(OH)_2$ or portlandite (C—H)
Absolute mass loss (%)	20	35	37	35	32	

1. Generally, PSA contains pozzolanic materials, such as silica and alumina, which can react with calcium hydroxide ($Ca(OH)_2$) in the presence of water to form pozzolanic compounds.
2. In mortar and concrete mixtures, PSA can be used to partially replace cement, boosting the durability and strength of the concrete while minimising the environmental damage caused by cement manufacture. The strength development of concrete containing PSA may be slower initially.
3. PSA can be used to stabilize soil, improving its strength and reduce its susceptibility to erosion. The addition of paper sludge ash can enhance soil structure, especially in clayey soils, by improving their water absorption and plasticity properties.
4. Road Infrastructure: In road construction, PSA can serve as a filler material in asphalt mixes, contributing to better road surfaces while reducing the use of virgin materials.
5. PSA can serve as a valuable source in various engineering applications such as geopolymers, creating bricks and blocks, in sulphate environments, etc.. However, the exact enhancement depends on factors like the reactivity of the PSA. To minimize the negative impact of PSA, it's crucial to carefully design mixes that consider the specific properties of the PSA. Also, the research in such areas is in progression and requires further investigation.

5.1. Future perspectives

There are several research areas that can be investigated for the use of PSA in engineering applications including:

1. Examine how paper sludge ash-based materials behave in particular environmental situations, such as corrosive or high-temperature settings.
2. To verify that structures containing paper sludge ash are durable and up to industry standards, evaluate their long-term performance, especially in hard environmental circumstances.
3. The application of PSA in engineering cannot be accomplished without issues, despite its potential. There are a number of problems that need to be resolved, including the variability in PSA content, the absence of established standards, and issues about long-term durability.
4. Applying PSA to engineering can help reduce landfill trash and preserve natural resources. However, the effects on the environment, particularly any potential leaking of toxins, need to be carefully assessed and reduced.
5. The cost of transportation, the type of application, and the availability of PSA all affect how economically viable it is to use PSA in engineering projects. Cost-effectiveness research is crucial.

In conclusion, utilizing paper sludge ash in engineering is a potential option that supports sustainability objectives and resource efficiency. To fully realize the advantages of PSA while resolving its problems, more research, industry-academia collaboration, and adherence to best practices and standards are essential. PSA's importance in engineering applications is projected to increase as technology develops and public awareness of environmental issues rises, making it a crucial component of sustainable engineering methods.

CRediT authorship contribution statement

Zahraa Jwaida: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anmar Dulaimi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Wajde Alyhya:** Writing – review & editing, Writing – original draft, Resources, Methodology, Formal analysis, Conceptualization. **Hayder Algretawee:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Conceptualization. **Shakir Al-Busaltan:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Conceptualization.

Declaration of competing interest

None.

Table 5
Comparison of PSA to ash materials [18,105–108].

Properties	Paper Sludge Ash (PSA)	Silica Fume	Metakaolin	Fly Ash
Availability	Abundant in paper-producing regions	Depends on silicon or ferrosilicon production	Generally available	Depends on coal-fired power plants
Source	By-product of paper industry	By-product of silicon or ferrosilicon alloy production	Calcined kaolin clay	By-product of coal combustion in power plants
Chemical Composition	Rich in silica and alumina, may contain calcium oxide and magnesium oxide	Consists of mostly amorphous silica	Consists mainly of amorphous silica	Variable composition depending on coal source
Strength Development	Enhances strength development and durability	Improves compressive strength and durability	Improves early-age and long-term strength	Contributes to strength gain over time
Pozzolanic Activity	High silica content contributes to pozzolanic reactions	High surface area enhances pozzolanic activity	High reactivity with calcium hydroxide	High pozzolanic activity
Durability	Reduces permeability, enhances durability	Enhances resistance to chloride ingress and carbonation	Improves resistance to chemical attack and corrosion	Enhances resistance to sulphate attack and alkali-silica reaction
Environmental Impact	Converts waste into resource, reduces landfilling	Reduces waste from industrial processes	Low environmental impact	Reduces coal ash disposal, but potential for environmental contamination
Cost	Generally cost-effective due to availability	Can be expensive due to production process	Typically more expensive	Cost can vary based on supply and demand

Data availability

No data was used for the research described in the article.

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