



# Recovering acidic solid residues from wet chemical phosphorus recovery of sewage sludge ash in the production of cementitious composites

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## ABSTRACT

Phosphorus (P) recovery from sewage sludge ash (SSA) represents a promising solution to P supply concerns, with a key challenge being the management of the acidic solid residues (ASR) generated by wet chemical P recovery processes. This work explores the integration of ASR, obtained by SSA leaching with different extractants, as a partial substitute of sand in cementitious mortars. ASR samples were first physically and chemically characterized, and their disposability in landfills as non-hazardous or inert waste was assessed. Fe, Si and Ca were the main components identified in H<sub>2</sub>SO<sub>4</sub>- and HCl-based ASR (ASR/H<sub>2</sub>SO<sub>4</sub> and ASR/HCl, respectively), while Zn and Cu were the principal detected heavy metals. Slight exceedances of Cu and Zn thresholds for ASR disposability in non-hazardous landfills were observed, with further optimisation of the leaching process potentially ensuring legal compliance. The residues were then ground and employed as a 25% volumetric sand replacement in cementitious mortars. Tailored water content adjustment need to be made to ensure workable mixes and cast the specimens. The mechanical performance of mortars was evaluated through flexural and compressive strength tests. By properly adjusting the water content, the reduction in compressive strength was maintained within acceptable levels when using ASR/HCl. Specifically, while the use of ASR/H<sub>2</sub>SO<sub>4</sub> led to a minimum 42% decrease in 28th-day compressive strength and 47% decrease in 28th-day flexural strength, sand substitution with ASR/HCl limited the reduction to 12% for compressive strength and 26% for flexural strength, paving the way for effective use of these residues in the production of cement-based construction materials.

## 1. Introduction

Phosphorus (P) is an essential nutrient for all living organisms and plays a pivotal role in human society. Around 89% of the global P production is dedicated to agricultural applications, primarily for fertilizers manufacturing (Desmidt et al., 2015; Jupp et al., 2021; Meng et al., 2019). Currently, P is commonly extracted from phosphate rocks (PR), with major reserves located in Morocco, Russia, China, and US (Ryszko et al., 2023). However, the rising demand for PR, driven by intensive agriculture practices, population growth and rapid urbanization, has led to overexploitation and decline in the quality of available reserves (Bacelo et al., 2020; Ryszko et al., 2023). Considering this scenario, recovering P from alternative and, in case, renewable sources has become crucial to address the future demand and face the aforesaid more and more demanding social and environmental challenges (Esposito et al., 2024).

Sewage sludge (SS) has emerged as promising secondary source of P, with a content ranging between 1.4% and 3% by dry weight (Meng et al.,

2019; Ottosen et al., 2013; Zheng et al., 2023). The direct use of SS as a fertilizer is still widely adopted in agriculture, due to its richness in organic matter and macro-nutrients (Meng et al., 2019). However, increasing restrictions are being placed on this practice due to growing concerns over land and groundwater contamination by heavy metals, microplastics, parasites, pathogens and pharmaceuticals (Meng et al., 2019; Witek-Krowiak et al., 2022). Moreover, Al- and Fe-phosphates from P chemical removal in wastewater treatment plants exhibit solubility and bioavailability under typical soil pH conditions (Meng et al., 2019; Zheng et al., 2023). Therefore, the rising cost and environmental concerns related to SS conventional management routes, such as land application, landfilling and co-composting, are promoting the implementation of thermal treatments including incineration, pyrolysis and hydrothermal carbonization (Kwapinski et al., 2021; Zhu et al., 2022). Among these, mono-incineration has proved to be particularly favourable for P recovery, producing sewage sludge ashes (SSA) with a P content (4% – 15.7%) comparable to medium- to low-grade PR (5% – 13%) (Esposito et al., 2024). In addition, this approach enables efficient

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energy recovery from the generated hot flue gases, while achieving a waste volume reduction up to 90%, high Hg removal rates and the complete destruction of organic matter and organic pollutants, such as polychlorinated biphenyls and dioxins (Jupp et al., 2021; Meng et al., 2019). Several European countries are actively supporting SS incineration and P recovery from SSA. Switzerland made P recovery from SS mandatory from 2026 (ADWO, 2015), Austria targeted to achieve a P recovery rate from the municipal SS between 65% and 85% by 2030 (BAWP, 2017) and, starting from 2029, Germany will mandate P recovery for wastewater treatment plants (WWTPs) serving more than 100,000 population equivalent (PE) and a P content in SS exceeding 20 g/kg of dry sludge (BMUV, 2017). Among the existing P recovery processes from SSA, thermochemical treatment and wet chemical leaching have gained significant attention in the last years. While thermochemical treatment guarantees a significant volatilisation of heavy metals (e.g.: Zn, Cr, Ni) and an increase in P bioavailability in SSA, wet chemical leaching is generally preferred due to its flexibility, low energy consumption and similarity to the established P extraction methods from PR (Canziani et al., 2023; Fang et al., 2018, 2021; Liu et al., 2021; Luyckx & Van Caneghem, 2021; Meng et al., 2019). The process involves a first P extraction from SSA by means of an extractant, which can be an inorganic acid, an organic acid, an alkali, or a chelating agent. The resulting P-enriched solution, named as leachate, is then separated from the acidic solid residues (ASR) by filtration. Finally, a base is added to the leachate to precipitate P, typically as Ca- and/or Mg-phosphates (e.g., hydroxyapatite, magnesium phosphate) (Bonardi et al., 2021, 2024; Canziani et al., 2023).

A key challenge of the adopted wet chemical P recovery process consists in managing the generated ASR. These residues can account for up to 87% of the initial SSA mass when leaching by H<sub>2</sub>SO<sub>4</sub> (Esposito et al., 2024). Without any reuse alternative, ASR should be disposed by landfilling, with involved operations accounting for up to 75% of process operating costs in some recovery configurations (Esposito et al., 2024). Moreover, leaching by H<sub>2</sub>SO<sub>4</sub> significantly increases the leachability of Cu and Zn in ASR, raising potential environmental concerns in case of improper disposal (Li et al., 2018). Therefore, to enhance the economic and environmental sustainability of wet chemical P recovery, alternative applications for ASR must be explored. These efforts could reduce landfill dependency, lower process costs, and potentially open new circular economy perspectives.

A possible application of ASR, well-documented in the literature, is its use in the production of concrete and cementitious composites, either as a partial substitute of sand or as a supplementary cementitious material (Donatello et al., 2010; Li et al., 2018; Liang et al., 2021; Ottosen et al., 2022). However, while the use of SSA in cement-based materials has been widely studied in the literature and resulted in promising outcomes, research on ASR remains limited.

According to Danish and Ozbakkaloglu (2022), the workability of cement-based materials is expected to reduce when adding SSA. Prabhakar et al. (2022) used ball-milled SSA as cement replacement (2% and 5% by volume) and raw SSA for sand replacement (20%, 30%, 40% 70%, and 100% by volume), also investigating combined mix replacements. While a reduction in compressive strength was observed with 5% cement replacement, there were no significant changes at 2%. For sand replacement, compressive strength decreased notably at 40% and higher replacement ratios. Similarly, Motisariya et al. (2023) studied the microfine SSA as cement substitute at replacement levels of 5%, 10%, 15%, 20%, and 25% without specifying whether these percentages were based on volume or mass. In their study, the highest compressive strength was observed at 10% replacement, whereas a sharp decrease was reported at 20%. According to Danish and Ozbakkaloglu (2022), research on the flexural and tensile strength of SSA-modified cement-based materials is limited. Specifically, the available studies typically report a less pronounced reduction in flexural and tensile strength compared to compressive strength when integrating SSA in cement-based materials. Tipraj and Shanmugapriya, 2022)

reported that 10% SSA cement replacement resulted in similar or slightly lower flexural strength compared to reference mortar.

In contrast to the aforementioned studies, Ottosen et al. (2022) investigated the use of SSA as both a sand and cement replacement, emphasizing the need to consider SSA not only as a secondary phosphorus source but also as an alternative raw material for cement-based composites – an aspect largely overlooked in the existing literature. In the study, 56.3 g of additional water was needed to obtain mouldable mortars and continue with the mechanical tests when replacing 10% by weight of sand with ASR from SSA leached with HCl. Moreover, the authors identified the 10% by weight cement replacement with ground ASR as a promising configuration for ASR integration in mortars, with a similar 28th-day compressive strength and an approximately 7% higher 42nd-day compressive strength (+ 5 MPa) compared to the reference mortar. Similarly, Liang et al. (2021) found that cement mortar obtained by 15% by weight cement replacement with ASR from SSA leached with oxalic acid resulted in 28th-day compressive and flexural strengths comparable to those of the reference mortar. These investigated percentages may not fully utilize the available waste material. This research gap was also addressed in the present study.

While the use of ASR as cement replacement was deeply explored, research on its use as a sand replacement was limited. Indeed, Ottosen et al. (2022) limited their investigation to a 10% sand replacement and did not examine higher ASR replacement ratios or the mix design adjustments required to compensate for the increased water demand and reduced workability. Exploring the use of ASR as a sand replacement at higher proportions could enable the utilization of larger quantities of waste residues, as sand and aggregates constitute the majority of concrete mixes. In contrast, the replacement levels investigated for cement are relatively low, limiting their potential impact. Reducing sand demand can contribute to mitigate raw material depletion. Moreover, given the origin of the studied residues, their integration could also support local supply chains by enabling distribution through existing networks.

To address this gap, this work has explored the 25% (by volume) sand replacement with ASR in cement mortars, accompanied by a carefully designed procedure for optimizing the water content. Moreover, despite different acid extractants result in ASR-based mortars with different mechanical properties, no studies have systematically compared their performances. Building upon this gap, this study hence aims to evaluate the influence of different mineral acid extractants (H<sub>2</sub>SO<sub>4</sub> and HCl) on the mechanical properties of ASR-containing mortars, combining the P recovery and material reuse perspectives.

ASR samples were sourced from a pilot-scale wet chemical P recovery processes described in Bonardi et al. (2024). The residues were first chemically and physically characterised, integrating X-Ray Diffraction (XRD) data from Bonardi et al. (2024) and assessing their disposability in landfills for different waste categories. Successively, the feasibility of sand replacement in cement-based composites was tested, evaluating the effect of ASR origin and mix design on mortar mechanical properties. By contributing the current state of art on ASR reuse from P recovery processes, this study aims to promote sustainable management of industrial residues and cleaner practices in the concrete construction industry.

## 2. Materials and methods

### 2.1. Pilot-scale experiments of P recovery from SSA

This study builds upon the wet chemical P recovery process outlined in Bonardi et al. (2024). This process used fly ash sampled from the electro-filters of the Werdhölzli mono-incineration full-scale plant (Zurich, Switzerland), which burns around 100,000 tonne/y of dewatered SS from the Zürich canton's WWTPs in a fluidized bed kiln.

The employed SSA sample corresponds to sample S5, as reported in Bonardi et al. (2021). This sample exhibits pH of 8.8, particle size

distribution in the range of 20 – 400  $\mu\text{m}$  and irregular morphology with rough surfaces. SSA main elemental components are summarised in **Table A.1** (Annex 1), where Ca (11.1%), P (8.6%) and Fe (5.2%) are the most abundant elements, while Zn (2024 mg/kg) and Cu (783 mg/kg) are the most present heavy metals. Major crystalline phases include quartz ( $\text{SiO}_2$ ) and hematite ( $\text{Fe}_2\text{O}_3$ ), with minor traces of calcium hydrogen iron phosphate ( $\text{Ca}_9\text{FeH}(\text{PO}_4)_7$ ) and anhydrite ( $\text{CaSO}_4$ ).

P was extracted from SSA by means of 0.5 mol/L  $\text{H}_2\text{SO}_4$  or 1 mol/L HCl solutions at liquid-to-solid ratio of 10 L<sub>acid solution</sub>/kg<sub>SSA</sub> and contact time of 0.5 h. ASR were removed from the leachate via a pilot-scale filter-press designed by Tecnoidea Impianti S.r.l. (Italy). P precipitation was performed by adding alkaline solutions of 300 g/L  $\text{Ca}(\text{OH})_2$  or 800 g/L LG-MgO to the leachate till pH 7 was reached, with LG-MgO consisting in a low-grade MgO by-product of magnesite calcination (LG-MgO) provided by Magnesitas Navarras (Spain). Both SSA and ASR samples were stored in hermetically sealed HDPE bottles under controlled temperature and humidity conditions, to minimise any possible change in their physio-chemical properties. A summary of the available characterisation parameters for the analysed materials, together with the corresponding literature sources, is reported in **Table A.2** (Annex 1). More details about testing procedures and leachate and precipitate samples analyses are reported in [Bonardi et al. \(2024\)](#).

## 2.2. ASR samples characterization

$\text{H}_2\text{SO}_4$ -based (ASR/ $\text{H}_2\text{SO}_4$ ) and HCl-based (ASR/HCl) ASR samples were collected from the space between filter-press plates and subsequently dried at 60 °C in a laboratory standard oven. A physical and chemical characterization of the residues was performed in accordance with the assigned CER code 19.03.07 (“Solidified wastes other than those mentioned in 19.03.06”), integrating XRD data reported in [Bonardi et al. \(2024\)](#). The main analysed parameters and corresponding standard measurement methods are summarised in **Table 1**.

None of the tested ASR samples was classified as “hazardous” according to the criteria set by European Directive [EC 98 \(2008, Annex III\)](#) and subsequent updates – European regulations [ER 1357 \(2014\)](#) and [ER 997 \(2017\)](#). Given this classification, different potential pathways for the management of ASR samples were explored. First, the suitability of ASR disposal in landfills for non-hazardous or inert wastes was assessed according to the Italian Decree [D.Lgs. 36, 2003 \(Annex IV, Table 2 and 5\)](#). This assessment included a leaching test and an eluate analysis based on [BS EN 12457–2 \(2002\)](#) and [BS EN 16192 \(2011\)](#) methods. Moreover, ASR were investigated for their possible use as sand replacement in cement-composites. Experimental procedures included ASR grinding to a finer grain size with a steel ball grinding machine. Different grinding times were checked according to particle size analysis. Sieve analyses were performed for different grinding time and conditions. While direct grinding for 90 s was identified as the optimum condition for ASR/HCl, additional drying at 110 °C for 24 h was required for ASR/ $\text{H}_2\text{SO}_4$  to achieve 90% of the material with a particle size below 600  $\mu\text{m}$ , as discussed in detail in the relevant results section. This requirement was attributed to an increase in the material’s moisture content during the waiting period associated with the grinding of ASR/HCl. The resulting

**Table 1**

Main parameters for physical and chemical characterization of ASR samples collected from the P recovery process described in [Bonardi et al. \(2024\)](#).

Parameters	Standard measurement methods
Colour, odour, physical state	ASTM D 4979 (2019)
pH	CNR IRSA 1 Q 64 Vol 3 (1985)
Al, Fe, P, Mg, Ca, K, Ba, Cd, Cr, Pb, Cu, Zn, As, Hg, Se, Ni, Sb, Te, Tl	BS EN 13657 (2002); EPA 6010D (2018)
Cr(VI)	CNR IRSA 1 Q 64 Vol 3, (1985)
Si	EPA 3052 (1996); EPA 6010D (2018)

ground ASR were then used for sand replacement in this study. After grinding, the material was tested for water absorption in accordance with [BS-EN 1097–6 \(2022\)](#), adopting the procedure described in Annex D. Based on this approach, the water absorption values were calculated as 97.73% for ASR/ $\text{H}_2\text{SO}_4$  and 59.03% for ASR/HCl, respectively. It should be noted that this standard is intended for sand and is not specifically designed for ASR specimens.

## 2.3. Material characterisation for cementitious mortar production

The reference mortar mix (later called REF) consisted of cement, water, fine aggregate, and a superplasticizer (SP). The water-to-cement (w/c) ratio was set at 0.40, while the volumetric ratio of the aggregate was set to 0.57. CEM II A-LL 42.5 R cement (Italcementi S.p.A.) was used in this study, and the particle size distribution of the natural sand employed in the experiments is presented in **Table A.3** (Annex 1). To enhance workability, the Dynamon NRG 1030® superplasticizer from Mapei, which is based on a modified acrylic polymer, was used.

## 2.4. Mix designs of cement-based mortars

Both types of ASR, obtained through P extraction from SSA with two different acidic extractants ( $\text{H}_2\text{SO}_4$  and HCl), were used as a 25% volumetric replacement for sand. A 25% volumetric replacement ratio was selected based on two main considerations. Previous studies on ASR as a sand replacement have mostly been limited to 10% replacement levels [Ottosen et al. \(2022\)](#). Meanwhile, [Prabhakar et al. \(2022\)](#) investigated SSA as a sand replacement at 20%, 30%, 40%, 70%, and 100% volume replacement levels. The best performance was observed at 30%; however, intermediate ratios such as 25% and 35% were not examined. Higher replacement ratios are expected to require higher amounts of additional water. To minimize the need for extra water while examining intermediate ratios close to the highest performance reported in the literature (30%), a 25% replacement ratio was selected, also considering the amount of material available for present investigation. This ratio was chosen to ensure a lower water demand compared with the 35% replacement level and to enable the investigation of the promising interval (25%–30%) while targeting the minimum additional water requirement within this range. Therefore, a 25% replacement ratio was chosen to explore this potentially promising range while also minimising additional water demand. All calculations were based on the specific gravity values of 3.20 g/cm<sup>3</sup> for cement, 2.60 g/cm<sup>3</sup> for sand, 2.90 g/cm<sup>3</sup> for ASR/HCl, and 2.83 g/cm<sup>3</sup> for ASR/ $\text{H}_2\text{SO}_4$ . REF was prepared with a 0.4 w/c ratio, a volumetric paste ratio of 0.43 and a volumetric ratio of sand of 0.57 with respect to the total volume. During the initial trials with 25% volume sand replacement, most of the mixing water was absorbed by ASR, making the mortar unsuitable for moulding due to its excessively dry consistency. As illustrated in Figure A.1.a in Annex 1, the mixture was too dry to permit moulding or to conduct any workability test, such as the slump test.

To achieve a mouldable mix with fresh-state properties comparable to the REF mix, the superplasticiser (SP) dosage was initially increased. However, it was observed that this increase had no significant effect. The inability of the SP to activate in the absence of sufficient water prevented the formation of a workable mix. To resolve this issue additional water was introduced (**Figure A.1.b**, Annex 1). While improving workability, this strategy also increased the total mix volume, thereby reducing the relative cement content per unit volume. Consequently, the total water-to-cement (w/c) ratio was raised to 0.84 while the theoretical effective w/c was calculated as 0.18 for ASR/ $\text{H}_2\text{SO}_4$ -1 and 0.43 for ASR/HCl-1, respectively. The volumetric paste content increased to 0.55, and the sand content was reduced to 0.45 (Mix Design 1).

Knowing that part of the added water could be reduced by optimising the mixing procedure, a second mix design was developed. With sufficient water now available to activate the SP, a lower SP dosage was effective. Moreover, the cement content was restored to the same level

as in the REF mix. These modifications resulted in a decreased total w/c ratio of 0.6, while the theoretical effective w/c was calculated as 0.09 and 0.29 for ASR/H<sub>2</sub>SO<sub>4</sub>-2 and ASR/HCl-2, respectively, and the paste volume remained at 0.55 (Mix Design 2). It should be noted that the theoretically effective w/c ratio was calculated considering materials' full absorption capacity. However, previous studies shown that aggregates do not instantaneously absorb water up to their full absorption capacity (Ferrara et al., 2007, 2015). According to Ferrara et al. (2015), more than 600 h are required to reach the total absorption capacity, after which desorption is expected to start. In the context of this work, if an instantaneous absorption ratio of 50% could be assumed, as adopted by Ferrara et al. (2007). In that case, the effective w/c ratios would be recalculated as 0.51 (ASR/H<sub>2</sub>SO<sub>4</sub>-1), 0.64 (ASR/HCl-1), 0.35 (ASR/H<sub>2</sub>SO<sub>4</sub>-2), and 0.45 (ASR/HCl-2), indicating that an adequate amount of free water would still be available for cement hydration.

Based on the aforesaid mix-design adjustment process, the final compositions for REF and ASR-based mortars tested in this work are reported in Table 2. It is worth remarking, as it will also be elucidated in the forthcoming sections, that these mix proportions were obtained with the goal of achieving a workability of the investigated ASR-based mixes comparable to the REF one.

### 2.5. Mixing procedures

Different mixing procedures were applied for different mix designs. For Mix Design 1 samples, cement, sand, and ASR were first placed in the mixing bowl and dry-mixed for 30 s. Water and SP were then added to the dry mixture, followed by 120 s of mixing. For Mix Design 2 samples, cement, water, and SP were initially placed in the mixing bowl and mixed for 30 s. Sand was then added, and the mixture was blended for additional 30 s. Finally, ASR was introduced in two equal portions, with 30 s of mixing after each addition. With the aforesaid change in the mixing procedure a better workability was achieved. The proposed approach, which involved modifications of the mixing procedure, had two primary objectives. The first objective was to allow sufficient time for cement and sand to interact with water before the introduced water was largely absorbed by ASR. The second objective was to establish a time interval between the completion of mixing and the end of casting, during which the absorption of free water by ASR and the resulting reduction in workability could be delayed. Upon completion of mixing, 4 × 4 × 16 cm specimens were prepared in accordance with the BS EN 196-1 (2016) standard. For REF and each Mix Design 1, 9 specimens were produced for mechanical testing at 7, 28, and 56 days. For each Mix Design 2, 6 specimens were prepared to conduct mechanical testing only at 7 and 28 days.

### 2.6. Flow table tests

The fresh state performance of the investigated mixes was evaluated using a flow table test (Figure A.2.a, Annex 1), conducted in accordance with the BS EN 1015-3 (1999) standard. The mortar was placed into the cone-frustum mould in two layers, with each layer compacted using 10 strokes. After filling the mould and removing any excess mortar or remaining material from the table, a waiting period of 15 s was observed. Subsequently, the mould was slowly and vertically lifted, and

the mortar was spread by jolting the flow 15 times at a constant frequency over approximately 15 s. The final diameter of the mortar spread was then measured in two perpendicular directions. Only one test was performed for different mixes due to the limited ASR sample availability.

### 2.7. Mechanical tests on mortar

The setup for the compression test is presented in Figure A.2.b (Annex 1). Compressive strength measurements were conducted in accordance with the BS EN 196-1 (2016) standard. For REF and Mix Design 1, tests were performed on the 7th, 28th, and 56th days, while for Mix Design 2, measurements were taken on the 7th and 28th days. The reason for not conducting tests on Mix Design 2 at the 56th day was the limited availability of the material. Additionally, the three-point bending test setup is shown in Figure A.2.c (Annex 1). Specimens were prepared in accordance with the BS EN 196-1 (2016) standard and notched to a depth of 6 mm at midspan. The loading rate for the three-point bending test was determined according to the BS EN 14651 (2007) standard and tests were performed at the 7th and 56th days for the REF and Mix Design 1, and at the 28th day for Mix Design 2. For the 28th-day tests of REF and Mix Design 1, as well as the 7th-day tests of Mix Design 2, the specimens were tested under load control following the BS EN 196-1 (2016) standard. The reason for testing some specimens under load control was due to a malfunctioning of the testing machine, which prevented testing under CMOD control.

## 3. Results

### 3.1. ASR physical and chemical characterization

The physical and chemical properties of ASR samples are summarized in Table 3. Both samples featured a red colour, absence of odours and a non-dusty physical state. The pH values were acidic, ranging from 2.8 (ASR/H<sub>2</sub>SO<sub>4</sub>) to 4 (ASR/HCl).

The main components identified in ASR/H<sub>2</sub>SO<sub>4</sub> and ASR/HCl were Fe (13 and 22%), Si (8 and 15%), Ca (10 and 2%), Al (1 and 2%) and P (1 and 2%). Si and Fe contents were significant because quartz (SiO<sub>2</sub>) and hematite (Fe<sub>2</sub>O<sub>3</sub>), identified through XRD analyses described in Boniardi et al. (2024), are almost insoluble in an acidic environment. The high Fe content aligns with the low Fe extraction efficiency (4%) reported by Boniardi et al. (2024) for both the employed acids. Similarly, Donatello et al. (2010) found that Fe extraction was always below 10% in all the leaching tests performed, and also Biswas et al. (2009) observed that Fe-based compounds in the SSA require high energy to dissolve, either in terms of temperature or acid concentration. The high Ca content in ASR/H<sub>2</sub>SO<sub>4</sub> may be explained by the precipitation of Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup> ions as bassanite (Ca<sub>5</sub>O<sub>4</sub>•0.5 H<sub>2</sub>O) on the ASR surface, as indicated by XRD analyses, rather than an actual lower Ca dissolution from SSA (Boniardi et al., 2024).

The principal detected heavy metals were Zn (1090 and 1530 mg/kg) and Cu (390 and 760 mg/kg), while other heavy metals/metalloids (As, Cd, Cr, Cr (VI), Hg, Ni, Pb, Ba, Se, Sb, Te, Tl) were either present in negligible amounts or below the limit of detection (LOD). These outcomes are consistent with findings by Sun et al. (2018), which highlighted the limited mobility of Zn and Cu in SSA due to their

**Table 2**

Mix designs for the reference (REF) and ASR-based mortars tested in this work. ASR-based mortars are named as "ASR - Mix Design number".

Mortar	Cement [g/L]	Water [g/L]	Sand [g/L]	ASR/H <sub>2</sub> SO <sub>4</sub> [g/L]	ASR/HCl [g/L]	SP [g/L]	Theoretical Effective w/c [g/g]
REF	600.0	240.0	1483.0	0.0	0.0	3.3	0.40
ASR/H <sub>2</sub> SO <sub>4</sub> - 1	475.8	399.0	882.0	320.0	0.0	5.2	0.18
ASR/HCl - 1	475.8	399.0	882.0	0.0	327.9	5.2	0.43
ASR/H <sub>2</sub> SO <sub>4</sub> - 2	600.0	365.3	872.0	316.4	0.0	4.5	0.09
ASR/HCl - 2	600.0	365.3	872.0	0.0	324.2	4.5	0.29

**Table 3**

Physical and chemical characteristics of ASR samples resulting from SSA leaching by H<sub>2</sub>SO<sub>4</sub> or HCl. Measurement standard deviations ( $\pm$ ) are provided where available. Values below the respective LOD are indicated with “<”.

Parameter	U.M.	ASR/H <sub>2</sub> SO <sub>4</sub>	ASR/HCl
Colour	[-]	Red	Red
Odour	[-]	Absent	Absent
Physical state	[-]	Non-dusty solid	Non-dusty solid
pH	[-]	2.8 $\pm$ 0.2	4 $\pm$ 0.2
P	[%]	1.4	1.7
Al	[%]	1.1	1.6
Fe	[%]	12.7 $\pm$ 2.1	21.6 $\pm$ 3.6
Mg	[%]	0.3 $\pm$ 0.04	0.4 $\pm$ 0.06
Ca	[%]	10.2 $\pm$ 1.3	2.03 $\pm$ 0.3
K	[%]	0.2	0.3
As	[mg/kg]	< 20	< 20
Cd	[mg/kg]	< 2	< 2
Cr	[mg/kg]	58 $\pm$ 11	129 $\pm$ 24
Hg	[mg/kg]	5.7 $\pm$ 1.6	< 0.5
Ni	[mg/kg]	< 40	75 $\pm$ 17
Pb	[mg/kg]	61 $\pm$ 13	65 $\pm$ 14
Cu	[mg/kg]	390 $\pm$ 79	760 $\pm$ 160
Zn	[mg/kg]	1090 $\pm$ 210	1530 $\pm$ 290
Ba	[mg/kg]	48.3 $\pm$ 8.2	1250 $\pm$ 200
Se	[mg/kg]	< 5	< 5
Sb	[mg/kg]	9.8 $\pm$ 4	22.4 $\pm$ 6.2
Te	[mg/kg]	< 10	< 10
Tl	[mg/kg]	< 4	< 4
Cr (VI)	[mg/kg]	< 30	< 30
Si	[%]	8.0	15.1

incorporation into stable oxide and co-crystal aluminosilicate under high incineration temperature.

Comparing SSA to ASR/H<sub>2</sub>SO<sub>4</sub> and ASR/HCl, significant differences were observed for Ca (-1% and -9%), P (-7% for both), Mg (-1% for both) and Fe (+8% and +16%). The increased Fe content is likely due to the simultaneous leaching of other major elements, as detailed in [Bonardi et al. \(2024\)](#), and the limited solubility of hematite in acidic environment, as introduced before, which could have resulted in an apparent Fe enrichment. Similarly, XRD analyses from [Li et al. \(2018\)](#) indicated that hematite and quartz intensities remained stable or even increased in ASR compared to SSA, underlining the chemical stability of Fe and Si during the extraction phase.

It should be noted that the low pH values obtained for ASR are considered indicative of residual acid. Therefore, the chloride and sulfate concentrations of ASR should be quantified in future studies. Chloride presence is known to have an accelerating effect on cement hydration reactions ([Aydoğan et al., 2025](#)). According to the study conducted by [Aydoğan et al. \(2025\)](#), the presence of chloride increased compressive strength during the first three months as a result of accelerated hydration. It is important to emphasize that the mortar investigated in this study may not intended for use with reinforcement, the chloride content should be carefully evaluated whenever the presence of a steel reinforcement or a sensitivity to chloride crystallization e.g. in masonry may be of concern. In addition, the presence of sulfate ions may promote gypsum formation ([Aydoğan et al., 2025](#)), and an increased gypsum content may lead to a delayed setting time ([Mohammed & Safiullah, 2018](#)) or unintended disruptive expansion. For future studies, the concentrations of residual sulfate and chloride ions should be determined, and their potential effects on the hydration behaviour and mechanical performance should be systematically evaluated.

### 3.2. Sample characterization: disposability

**Table 4** displays the results from the leaching test performed to determine ASR disposability. The eluates from both the ASR samples exceeded the thresholds for disposability in inert landfills due to elevated concentrations of Cd, Cu, Ni, Zn, fluorides, sulphates and total dissolved solids (TDS). Additional exceedances were observed for Se in

**Table 4**

Eluate analyses from ASR leaching ([BS EN 12457-2, 2002](#); [BS EN 16192, 2011](#)). Measurement standard deviations ( $\pm$ ) are provided where available. Values below the respective LOD are indicated with “<”. “DOC”: Dissolved Organic Carbon. “TDS”: Total Dissolved Solids. Parameters exceeding regulatory limits for inert or inert and non-hazardous wastes are underlined or bolded, respectively.

Element/U. M.	ASR		D.Lgs 36 (2003)	
	H <sub>2</sub> SO <sub>4</sub>	HCl	Non-hazardous	Inert
	[mg/L]	[mg/L]	[mg/L]	[mg/L]
As	0.016 $\pm$ 0.002	0.002 $\pm$ 0.001	0.2	0.05
Ba	0.105 $\pm$ 0.011	0.155 $\pm$ 0.019	10	2
Cd	<u>0.022 <math>\pm</math> 0.005</u>	<u>0.023 <math>\pm</math> 0.006</u>	0.1	0.004
Cr	0.039 $\pm$ 0.007	< 0.02	1	0.05
<b>Cu</b>	<b>10.1 <math>\pm</math> 2.6</b>	<b>7.1 <math>\pm</math> 1.8</b>	5	<b>0.2</b>
Hg	< 0.0002	< 0.0002	0.02	0.001
Mo	< 0.005	< 0.005	1	0.05
Ni	<u>0.45 <math>\pm</math> 0.10</u>	<u>0.48 <math>\pm</math> 0.11</u>	1	0.04
Pb	0.048 $\pm$ 0.009	< 0.02	1	0.05
Sb	0.0008 $\pm$ 0.0002	0.0006 $\pm$ 0.0002	0.07	0.006
Se	<u>0.013 <math>\pm</math> 0.003</u>	0.006 $\pm$ 0.001	0.05	0.01
<b>Zn</b>	<b>61 <math>\pm</math> 15</b>	<b>14.8 <math>\pm</math> 3.7</b>	5	<b>0.4</b>
Chlorides	53 $\pm$ 11	<u>2170 <math>\pm</math> 390</u>	2500	80
Fluorides	<u>2.1 <math>\pm</math> 0.7</u>	<u>1.62 <math>\pm</math> 0.55</u>	15	1
Sulphates	<u>2500 <math>\pm</math> 870</u>	<u>1150 <math>\pm</math> 400</u>	5000	100
Phenol index	0.0235	0.0354	-	0.1
DOC	< 25	< 25	100	50
TDS	<u>2360 <math>\pm</math> 410</u>	<u>4120 <math>\pm</math> 710</u>	10000	400

ASR/H<sub>2</sub>SO<sub>4</sub> and chlorides in ASR/HCl.

Concerning disposability in non-hazardous landfills, slight exceedances were observed for Cu and Zn (+ 2.1 – 9.8 mg/L) in the eluates from both ASR samples, with only ASR/H<sub>2</sub>SO<sub>4</sub> exhibiting a pronounced exceedance for Zn thresholds (+ 56 mg/L). While the latter could be explained by a possible contamination from the filter-press equipment, as reported in [Bonardi et al. \(2024\)](#), minor exceedances can be avoided through process optimizations, including, e.g. refining the filter-press selection and maintenance to ensure resistance to the highly acidic conditions achieved during SSA leaching (pH  $\leq$  1). These findings are consistent with previous literature on ASR characterisation. [Li et al. \(2018\)](#) reported that SSA leaching with H<sub>2</sub>SO<sub>4</sub> increased the mobility of Zn and Cu in ASR compared to untreated SSA, attributing this effect to possible weak electrostatic interactions between dissolved metals and ASR particle surfaces. Similarly, [Li et al. \(2017\)](#) found that SSA leaching with H<sub>2</sub>SO<sub>4</sub> significantly increased the exchangeable fraction and, therefore, the leachability and mobility, of several heavy metals in ASR (Zn, Cu, Pb, Ni, Cd, Ba, Cr and As). The enhancement of exchangeability was attributed to the potential destabilization and transformation of heavy metals into weakly bound forms that were readily mobile and leachable.

The significant leachability of Cu and Zn from ASR raises serious concerns about the potential environmental and health risks related to both conventional (i.e., landfilling) and innovative (e.g. recovery) ASR management strategies. These risks have been extensively documented in available literature on waste landfilling, highlighting that landfill leachates rich in heavy metals can migrate through soil and groundwater, potentially altering soil composition, structure and function, inhibiting crop root development and, ultimately, reducing crop yields ([Adu and Aneke, 2025](#); [Ahmad et al., 2023](#); [Bhupal et al., 2020](#); [Ngole and Ekosse, 2012](#); [Vaverková, 2019](#)). Furthermore, the build-up of heavy metals in the food chain could lead to bioaccumulation phenomena, posing long-term risks to human health. For example, excessive intake of Cu was associated to vascular disease, angiosarcoma, skin cancer, cutaneous lesions and peripheral neuropathy ([Jia et al., 2018](#)). Although different technologies are currently available for treating landfill leachate – including biological processes, physical-chemical

processes, membrane filtration, advanced oxidative treatments and natural systems (Vaverková, 2019) – future ASR management strategies need to integrate a comprehensive assessment of heavy metal leachability and speciation based on standardized procedures, such as Toxic Characteristic Leaching Procedure (TCLP; EPA 1311, 1992).

### 3.3. Sieve analysis results and optimization of grinding procedure

To achieve a particle size smaller than 600  $\mu\text{m}$  for over 90% of the material, the grinding process was performed at a first attempt for 60 s on ASR/HCl. However, since the target particle size was not achieved within this duration, the grinding time was increased to 90 s, successfully meeting the target. To evaluate the effects of prolonged grinding, the process duration was extended to 300 s. Although a higher percentage of particles passed through the 600  $\mu\text{m}$  sieve with prolonged grinding, the fraction of finer particles was significantly reduced according to sieve analysis results, as shown in Figure A.3 (Annex 1). All grinding processes were carried out under ambient humidity conditions. It was later observed that the material's rapid moisture absorption, especially at longer grinding durations, led to clumping, which hindered effective sieving. Based on these results, the optimum grinding time for ASR/HCl was determined to be 90 s, the minimum duration required to achieve the targeted particle size distribution.

For ASR/H<sub>2</sub>SO<sub>4</sub>, the target sieve test result could not be achieved even after 210 s of grinding in environmental humidity. Further investigation revealed that the actual particle size of the material was much smaller than indicated by the sieve analysis. This discrepancy was attributed to the material tendency to absorb humidity, causing particles to clump together. To address this issue, the material was preliminarily dried at 110 °C for 24 h and then ground for 90 s. Sieve analysis of the dried sample confirmed that 90 s of grinding was sufficient to meet the predetermined target (Figure A.4, Annex 1). Therefore, a grinding time of 90 s was also selected for ASR/H<sub>2</sub>SO<sub>4</sub>.

### 3.4. Fresh state performance

The flow table test results are shown in Figure A.5 (Annex 1). Mix design 1 was prepared by adding water to the 25% sand replacement from REF, to ensure similar flow table results. Mix design 2 was prepared by using about three quarters of the additional water introduced in Mix Design 1, while adjusting the SP dosage to achieve comparable flow table results. Due to the absorbent nature of both ASR samples, additional water was necessary in all cases, as evident from the mix compositions in Table 2.

### 3.5. Compressive strength

Figure A.6 (Annex 1) presents the compressive strength results at 7th, 28th, and 56th days, normalized to the 28th-day values, while the average values for each mix and age are shown in Fig. 1. All ASR-based mixtures exhibited lower compressive strength compared to REF. Mix design 1, which was characterized by the lowest cement content (475.8 g/dm<sup>3</sup>) and highest total w/c ratio (0.84), demonstrated the weakest performance. In contrast, Mix Design 2, which maintained the same cement content as the REF mix (600 g/dm<sup>3</sup>) and lower total w/c ratio (0.6), showed improved strength compared to Mix Design 1. As shown in Table 2, Mix Design 1 exhibits higher water content, than Mix Design 2. Consistent with expectations, compressive strength decreased as water content increased. Additionally, the improved performance of Mix Design 2 relative to Mix Design 1 can be attributed to the adjusted cement content following the water addition.

The theoretical effective w/c ratios were 0.18 and 0.09 for ASR/H<sub>2</sub>SO<sub>4</sub>-1 and ASR/H<sub>2</sub>SO<sub>4</sub>-2, respectively, whereas values of 0.43 and 0.29 were obtained for ASR/HCl-1 and ASR/HCl-2 after accounting for ASR water absorption capacity. It is well established that a theoretical effective w/c ratio of approximately 0.23 is required to sustain cement hydration reactions (Neville, 2002). However, given that aggregates require more than 600 h to reach their full water absorption capacity (Ferrara et al., 2015), and that only partial absorption is expected at early ages, the effective w/c ratios were reassessed by assuming an instantaneous absorption equal to 50% of the total capacity, as proposed by Ferrara et al. (2007). Under this assumption, the effective w/c ratios were determined as 0.51 (ASR/H<sub>2</sub>SO<sub>4</sub>-1), 0.64 (ASR/HCl-1), 0.35 (ASR/H<sub>2</sub>SO<sub>4</sub>-2), and 0.45 (ASR/HCl-2), indicating that sufficient water was available to sustain hydration reactions. In addition, those results indicate that ASR/HCl mixtures exhibited better compressive strength performance compared with ASR/H<sub>2</sub>SO<sub>4</sub> mixtures. This behaviour may be attributed to the higher Si content of ASR/HCl, which is nearly twice that of ASR/H<sub>2</sub>SO<sub>4</sub> (Table 3). Specifically, for ASR/HCl-2, a 12% reduction in 28th-day compressive strength was observed at a 25% sand replacement level. Furthermore, for all specimens tested up to 56 days, the development of compressive strength followed a trend similar to that of the REF mixture.

Prabhakar et al. (2022) reported a compressive strength decrease with 5% cement replacement, while no significant changes were observed for 2% cement replacement. For sand replacement, a decrease in compressive strength was observed starting with 40% replacement, with a sudden drop at 20% replacement ratio, which is similar to the ratio studied in this research. Comparing the decrease in strength, this work revealed a 12% decrease in compressive strength at the 28th day

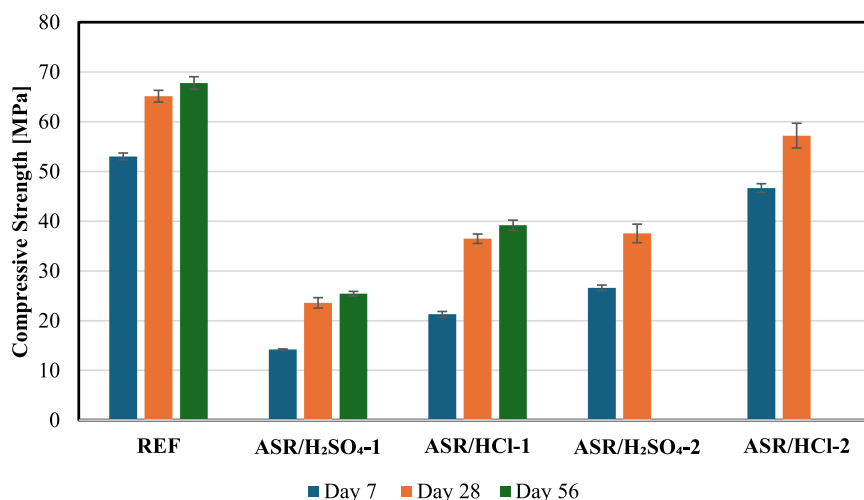


Fig. 1. Compressive strength for the 7th-, 28th- and 56th-day tests.

with 25% sand replacement, whereas Prabhakar et al. (2022) reported a 15% decrease with 20% sand replacement.

Motisariya et al. (2023) reported a strong decrease in compressive strength with 20% cement replacement, while the highest compressive strength was achieved with 10% replacement. In the study by Ottosen et al. (2022), compressive strength could only be measured when additional water was introduced for sand replacement, as other mixtures could not be moulded or crumbled under the load. For 10% sand replacement, an average strength of 46 MPa was obtained, compared to 70 MPa for the reference mix. Concerning cement replacement, ground ASR showed better performance than raw ASR but further grinding time did not significantly affect the results. Specifically, while raw ASR showed the lowest performance with 20% replacement (the only investigated replacement ratio for it), ground ASR exhibited similar performance to the reference mix at 10% replacement. Moreover, a decrease in strength was observed for 20% and 30% replacement ratios, regardless of grinding time.

As observed in previous studies, an increase in the replacement ratio generally leads to a decrease in compressive strength, as shown in Fig. 2. Based on the data presented in Fig. 3, this study demonstrated promising performance compared to the limited research on using ASR as a sand replacement in mortar. Specifically, it highlighted that by properly selecting the P extractant and adjusting the mix design, especially in terms of water content, acceptable mechanical properties can be achieved for ASR-based mortars.

### 3.6. Flexural strength

Figure A.7 (Annex 1) presents the flexural strength results at 7th, 28th, and 56th days, normalized to the 28th-day value, while Fig. 4

shows the average values for every mix and age. The slightly higher flexural strength results observed for Mix Design 2 at 7th day and for REF and Mix Design 1 at 28th day, compared to their later-age results, can be attributed to the use of a different testing machine and variations in the loading method due to the malfunction of the primary testing equipment. Mix design 1 exhibited lower flexural strength compared to both REF and Mix Design 2 for all the ASR samples, similarly to the compressive strength. Overall, Mix Design 2 performed better than the Mix Design 1, regardless of the employed ASR sample. Similar to compressive strength, the decrease in flexural strength is mainly due to the increased water content caused by ASR's high absorption capacity, which weakens the internal bonding within the cementitious matrix and reduces resistance to tensile stresses. Furthermore, the ASR/HCl-based mortars exhibited superior flexural performance compared to ASR/H<sub>2</sub>SO<sub>4</sub>-based ones, regardless of the applied mix designs consistent with the trends observed in compressive strength. Specifically, for ASR/HCl-2, a 26% reduction in the 28th-day strength was observed with 25% sand replacement, as can be seen in Fig. 4. These findings align with those reported by Danish & Ozbakkaloglu (2022), who identified similar decreasing trends in flexural strength in the available limited literature.

### 4. Conclusions and further studies

This study has explored the potential use of acidic solid residues (ASR) derived from phosphorus (P) recovery from sewage sludge ash (SSA) as a partial sand replacement in cement-based composites. ASR samples obtained from SSA leached with H<sub>2</sub>SO<sub>4</sub> and HCl were investigated. Various mix-design protocols were explored to develop a suitable ASR-based mortar, and, once a feasible mix was validated, its mechanical properties were assessed.

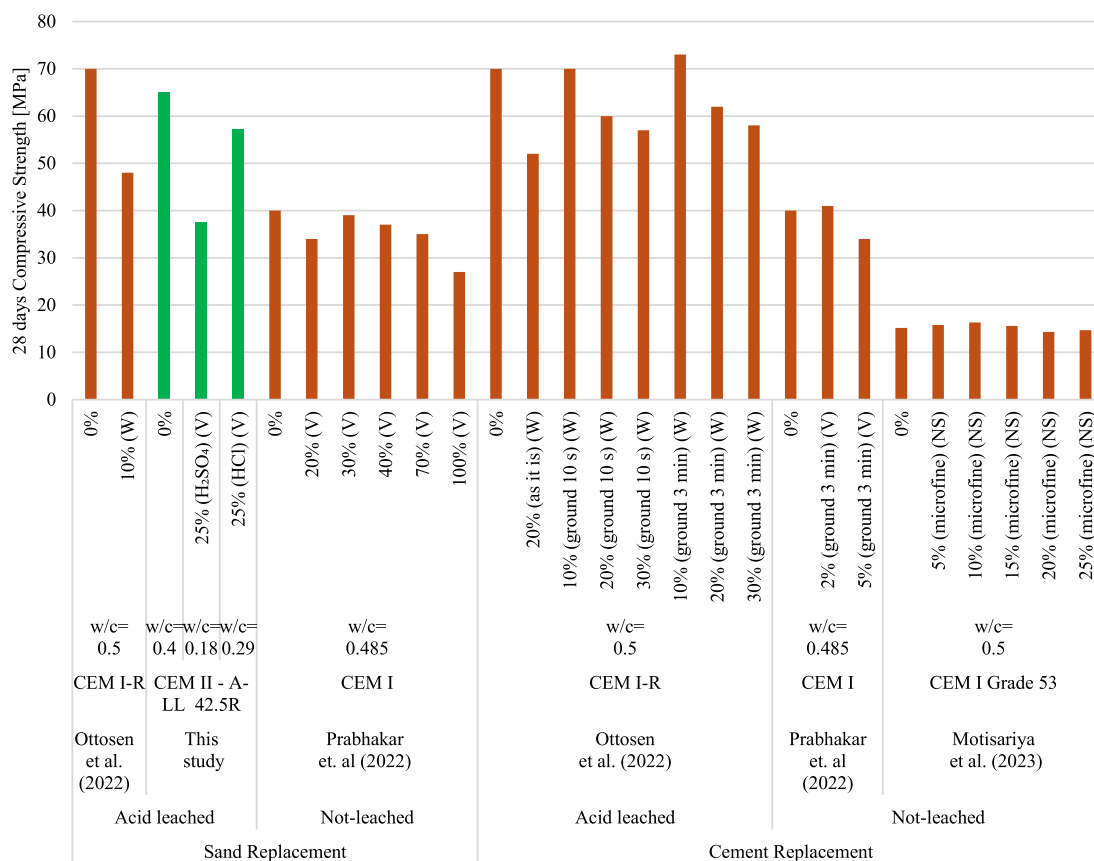


Fig. 2. 28th-day compressive strength results for SSA use in mortar (Motisariya et al., 2023; Ottosen et al., 2022; Prabhakar et al., 2022). (V) stands for volumetric replacement, while (W) stands for by weight replacement, and (NS) stands for non-specified in the paper.

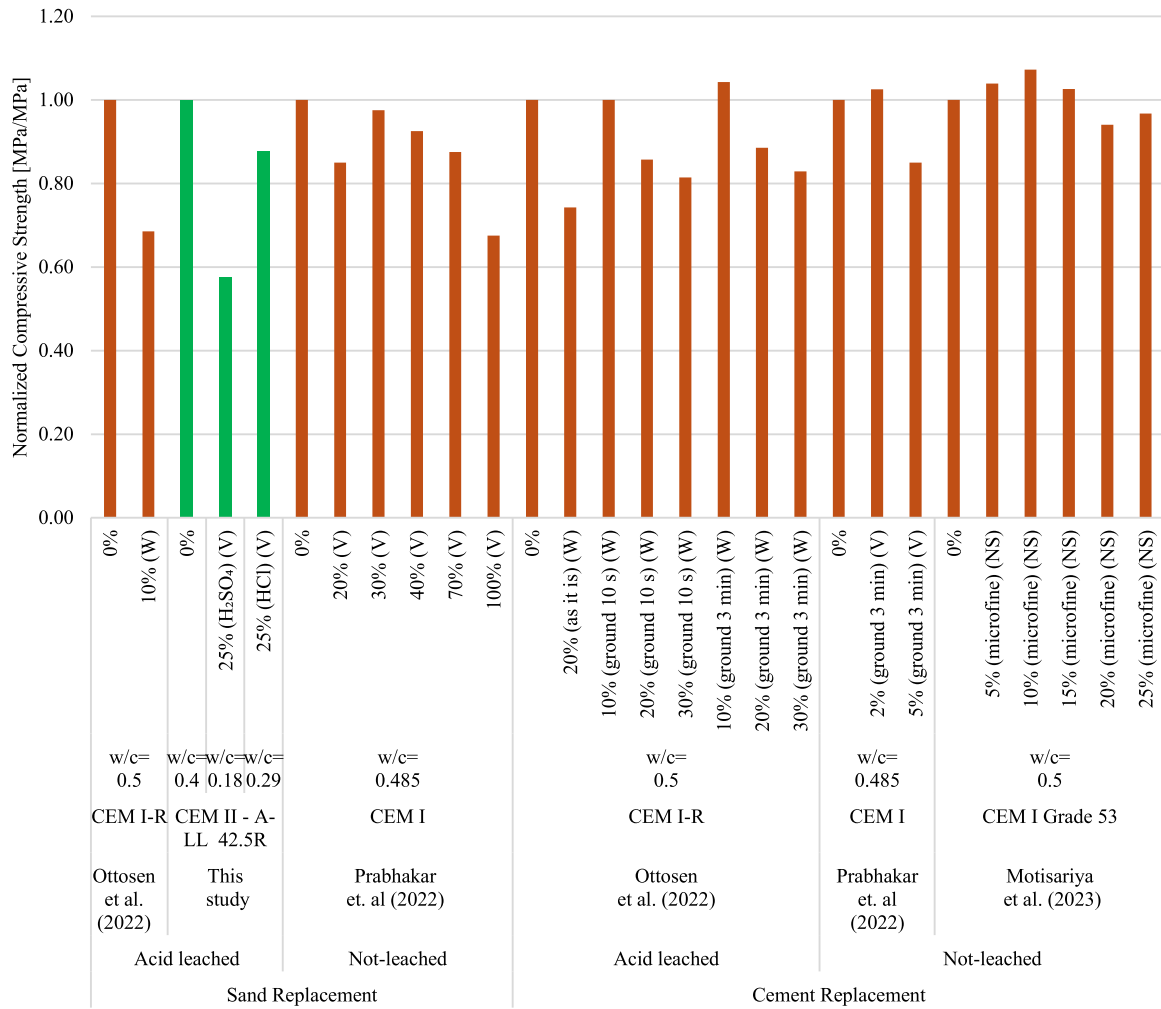


Fig. 3. 28th-day compressive strength results for SSA use in mortar, normalized to the relative reference mixes (Motisariya et al., 2023; Ottosen et al., 2022; Prabhakar et al., 2022). (V) stands for volumetric replacement, while (W) stands for by weight replacement, and (NS) stands for non-specified in the paper.

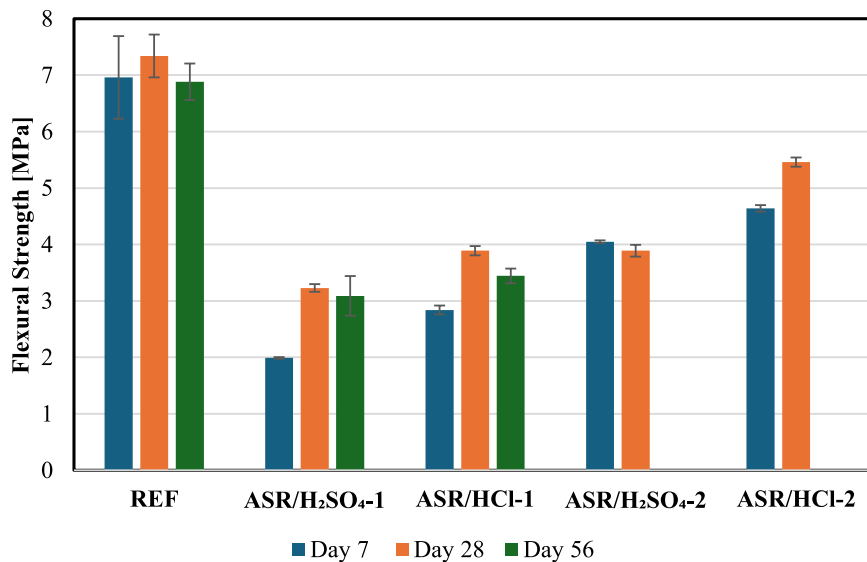


Fig. 4. Flexural strength for the 7th-, 28th- and 56th-day tests.

Key findings

- The main components identified in ASR/H<sub>2</sub>SO<sub>4</sub> and ASR/HCl were Fe (13% and 22%), Si (8% and 15%) and Ca (10% and 2%), while the

principal detected heavy metals were Zn (1090 mg/kg and 1530 mg/kg) and Cu (390 mg/kg and 760 mg/kg), respectively.

- Slight exceedances (< 10 mg/L) of Cu and Zn leaching limits were observed in ASR eluates, which may hinder disposal in non-hazardous landfills. However, technical improvements in the recovery process (e.g., optimized filter-press selection and maintenance) could allow compliance with regulatory thresholds.
- Due to the high water absorption of ASR, adjustment of water content was essential when using ASR as a partial sand replacement. After water optimization, the reduction in compressive strength could be contained within acceptable levels.
- The acid extractant used for P recovery significantly influenced ASR characteristics and, consequently, mortar performance.
- ASR/HCl-based mortars exhibited higher compressive strength than ASR/H<sub>2</sub>SO<sub>4</sub>-based mortars. Under the tested conditions, ASR/H<sub>2</sub>SO<sub>4</sub> led to a 42% reduction in compressive strength, whereas ASR/HCl limited the reduction to 12%.
- Based solely on compressive strength results under the tested conditions, the developed mix designs achieved values suitable for masonry mortars in accordance with BS EN 196-1, 2016. Accordingly, ASR/H<sub>2</sub>SO<sub>4</sub>-1 and ASR/HCl-1 could be classified as M35 and M20, respectively, while ASR/H<sub>2</sub>SO<sub>4</sub>-2 and ASR/HCl-2 corresponded to M35 and M55.

#### Future developments

- Further investigations are required to assess additional performance criteria specified in EN 998-2, including bond strength, thermal conductivity and durability, to fully validate the use of ASR as a sand replacement.
- Future investigations employing a larger and more representative set of ASR samples are essential for a thorough assessment of the hydration products and microstructural characteristics of mortars containing ASR.
- Optimization of water content adjustment should be further developed to achieve a fixed w/c ratio between REF and the ASR-based mortars, with the aim of establishing a robust mix-design protocol tailored to the specific characteristics of the parent ASR.
- Future studies should quantify residual chloride and sulphate in ASR and evaluate their effects on cement hydration behaviour and long-term mechanical performance.
- Comparative leaching studies on raw ASR and ASR-based mortars are needed to assess the potential immobilisation of Cu and Zn in cementitious matrices.
- From a broader perspective, establishing a viable market for ASR in cement-based materials would support End-of-Waste classification and foster its integration into circular-economy strategies.

Overall, this study demonstrates that ASR from P recovery processes can be valorised as a partial sand replacement in cementitious mortars, achieving adequate compressive strength under the tested conditions and highlighting promising pathways for sustainable material recovery and reuse.

#### CRedit authorship contribution statement

**Elifsu Balci:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andrea Turolla:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Roberto Canziani:** Writing – review & editing, Supervision, Resources, Project administration. **Liberato Ferrara:** Writing – review & editing, Supervision, Resources, Project administration. **Lorenzo Esposito:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization.

#### Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used correction tools based on generative AI to improve text fluency. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

#### Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Andrea Turolla reports financial support was provided by Italian Ministry of University and Research. Elifsu Balci reports financial support was provided by Italian Ministry of University and Research. Elifsu Balci reports financial support was provided by Resilco srl - Società Benefit. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.clwas.2026.100496](https://doi.org/10.1016/j.clwas.2026.100496).

#### Data availability

Data will be made available on request.

#### References

- Adu, J.T., Aneke, F.I., 2025. Evaluation of heavy metal contamination in landfills from e-waste disposal and its potential as a pollution source for surface water bodies. *Results Eng.* 25, 104431. <https://doi.org/10.1016/J.RINENG.2025.104431>.
- ADWO. (2015). (<https://www.fedlex.admin.ch/eli/cc/2015/891/en>).
- Ahmad, W., Zubair, M., Ahmed, M., Ahmad, M., Latif, S., Hameed, A., Kanwal, Q., Iqbal, D.N., 2023. Assessment of potentially toxic metal(loid)s contamination in soil

- near the industrial landfill and impact on human health: an evaluation of risk. *Environ. Geochem. Health* 45 (7), 4353–4369. <https://doi.org/10.1007/S10653-023-01499-7/TABLES/6>.
- ASTM D 4979. (2019). Standard Practice for Physical Description Screening Analysis in Waste. (<https://img.antpedia.com/standard/files/pdfs/ora/20221211/astm/ASTM%20D4979-19.pdf>).
- Aydoğan, O.G., Dilber, A.A., Özyurt, N., 2025. Friedel's salt stability and sulfate durability of seawater mixed cement-based materials. *J. Build. Eng.* 110. <https://doi.org/10.1016/j.jobte.2025.113124>.
- Aydoğan, O.G., Dilber, A.A., Sepetçi, A., Tarhan, M., Özyurt, N., 2025. Effect of Ion Concentration in the Mixing Water on Performance and Hydration Kinetics of Cement-Based Materials. In: *RILEM Bookseries*, 56. Springer Science and Business Media B.V., pp. 408–415. [https://doi.org/10.1007/978-3-031-70281-5\\_46](https://doi.org/10.1007/978-3-031-70281-5_46).
- Bacelo, H., Pintor, A.M.A., Santos, S.C.R., Boaventura, R.A.R., Botelho, C.M.S., 2020. Performance and prospects of different adsorbents for phosphorus uptake and recovery from water. *Chem. Eng. J.* 381, 122566. <https://doi.org/10.1016/J.CEJ.2019.122566>.
- BAWP. (2017). (<https://www.bmk.gv.at/en/topics/climate-environment/waste-resource-management/waste-management/fed-waste-mgt-plan.html>).
- Bhupal, R., Donthi, R., Ramannagari, B., Mohd-Salleh, S.N.A., Shaylinda, Z.N., Irvanian, A., Ravari, S.O., 2020. Types of Contamination in Landfills and Effects on The Environment: A Review Study. *IOP Conf. Ser. Earth Environ. Sci.* 614 (1), 012083. <https://doi.org/10.1088/1755-1315/614/1/012083>.
- Biswas, B., Inoue, K., Harada, H., Ohto, K., Kawakita, H., 2009. Leaching of phosphorus from incinerated sewage sludge ash by means of acid extraction followed by adsorption on orange waste gel. *J. Environ. Sci.* 21, 1753–1760. [https://doi.org/10.1016/S1001-0742\(08\)62484-5](https://doi.org/10.1016/S1001-0742(08)62484-5).
- BMUV. (2017). (<https://www.bmuv.de/en/law/sewage-sludge-ordinance>).
- Boniardi, G., Paini, E., Seljak, T., Azzellino, A., Volonteri, A., Canziani, R., Turolla, A., 2024. Optimization of phosphorus wet acid extraction from sewage sludge ashes: detailed process insight via multi-variate statistical techniques. *J. Clean. Prod.* 458, 142491. <https://doi.org/10.1016/J.JCLEPRO.2024.142491>.
- Boniardi, G., Turolla, A., Fiameni, L., Gelmi, E., Malpei, F., Bontempi, E., Canziani, R., 2021. Assessment of a simple and replicable procedure for selective phosphorus recovery from sewage sludge ashes by wet chemical extraction and precipitation. *Chemosphere* 285. <https://doi.org/10.1016/j.chemosphere.2021.131476>.
- BS EN 196-1. (2016). Methods of Testing Cement. Determination of Strength. (<https://sol.bsigroup.com/Bibliographic/BibliographicInfoData/00000000030291447>).
- BS EN 1015-3. 1999. Methods of Test for Mortar for Masonry. Determ. Consistence Fresh Mortar (Flow. Table). (<https://bsol.bsigroup.com/Bibliographic/BibliographicInfoData/00000000030151075>).
- BS EN 12457-2. (2002). Characterisation of Waste. Leaching. Compliance Test for Leaching of Granular Waste Materials and Sludges. One Stage Batch Test at a Liquid to Solid Ratio of 10 L/Kg for Materials with Particle Size below 4 Mm (without or with Size Reduction). (<https://bsol.bsigroup.com/Bibliographic/BibliographicInfoData/00000000030017799>).
- BS EN 13657. (2002). Characterization of Waste. Digestion for Subsequent Determination of Aqua Regia Soluble Portion of Elements. (<https://bsol.bsigroup.com/Bibliographic/BibliographicInfoData/00000000030007878>).
- BS EN 14651. (2007). *In Test method for metallic fibre concrete. Measuring the flexural tensile strength (limit of proportionality (LOP), residual)*. (<https://bsol.bsigroup.com/Bibliographic/BibliographicInfoData/00000000030160504>).
- BS EN 16192. (2011). Characterization of Waste. Analysis of Eluates. (<https://bsol.bsigroup.com/Bibliographic/BibliographicInfoData/00000000030233989>).
- BS-EN 1097-6, 2022. Tests for mechanical and physical properties of aggregates. Part 6, Determination of particle density and water absorption. *British Standards Institution*.
- Canziani, R., Boniardi, G., Turolla, A., 2023. Phosphorus recovery—recent developments and case studies. *Sustain. Circ. Manag. Resour. Waste Towards a Green. Deal* 269–281. <https://doi.org/10.1016/B978-0-323-95278-1.00007-3>.
- CNR IRSA 1 Q 64 Vol 3. (1985). *Metodi Analitici per Le Acque*. ([https://www.irsa.cnr.it/wp/?page\\_id=5435](https://www.irsa.cnr.it/wp/?page_id=5435)).
- Danish, A., Ozbakkaloglu, T., 2022. Greener cementitious composites incorporating sewage sludge ash as cement replacement: A review of progress, potentials, and future prospects. In: *Journal of Cleaner Production*, 371. Elsevier Ltd. <https://doi.org/10.1016/j.jclepro.2022.133364>.
- Desmidt, E., Ghyselbrecht, K., Zhang, Y., Pinoy, L., Van der Bruggen, B., Verstraete, W., Rabaey, K., Meesschaert, B., 2015. Global Phosphorus Scarcity and Full-Scale P-Recovery Techniques: A Review. *Crit. Rev. Environ. Sci. Technol.* 45 (4), 336–384. <https://doi.org/10.1080/10643389.2013.866531>.
- D.Lgs. 36. (2003). Decreto Legislativo 13 Gennaio 2003, n. 36. Attuazione Della Direttiva 1999/31/CE Relativa Alle Discariche Di Rifiuti. (<https://www.normattiva.it/uri-res/N2Ls?urn:nir:stato:decreto.legislativo:2003;36#>).
- Donatello, S., Freeman-Pask, A., Tyrer, M., Cheeseman, C.R., 2010. Effect of milling and acid washing on the pzoalanic activity of incinerator sewage sludge ash. *Cem. Concr. Compos.* 32 (1), 54–61. <https://doi.org/10.1016/j.cemconcomp.2009.09.002>.
- EC 98. (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives. (<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32008L0098#d1e32-25-1>).
- EPA 1311. (1992). Toxicity Characteristic Leaching Procedure (SW-846). (<https://www.epa.gov/hw-sw846/sw-846-test-method-1311-toxicity-characteristic-leaching-procedure>).
- EPA 3052. (1996). Microwave Assisted Acid Digestion of Siliceous and Organically Based Matrices (SW-846). (<https://www.epa.gov/hw-sw846/sw-846-test-method-3052-microwave-assisted-acid-digestion-siliceous-and-organically-based>).
- EPA 6010D. (2018). Inductively Coupled Plasma - Atomic Emission Spectrometry (SW-846). (<https://www.epa.gov/esam/epa-method-6010d-sw-846-inductively-coupled-plasma-atomic-emission-spectrometry>).
- ER 997. (2017). Council Regulation (EU) 2017/997 of 8 June 2017 Amending Annex III to Directive 2008/98/EC of the European Parliament and of the Council as Regards the Hazardous Property HP 14 'Ecotoxic'. (<https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32017R0997>).
- ER 1357. (2014). Commission Regulation (EU) No 1357/2014 of 18 December 2014 Replacing Annex III to Directive 2008/98/EC of the European Parliament and of the Council on Waste and Repealing Certain Directives. (<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014R1357>).
- Esposito, L., Boniardi, G., Frigerio, M., Guembe, M., García-Zubiri, Í.X., El Chami, D., Canziani, R., Turolla, A., 2024. Development of a multi-objective support tool for optimizing phosphorus recovery from sewage sludge ash: A step towards process feasibility. *J. Clean. Prod.* 485, 144378. <https://doi.org/10.1016/J.JCLEPRO.2024.144378>.
- Fang, L., Li, J. shan, Guo, M.Z., Cheeseman, C.R., Tsang, D.C.W., Donatello, S., Poon, C. S., 2018. Phosphorus recovery and leaching of trace elements from incinerated sewage sludge ash (ISSA). *Chemosphere* 193, 278–287. <https://doi.org/10.1016/J.CHEMOSPHERE.2017.11.023>.
- Fang, L., Wang, Q., Li, J. shan, Poon, C.S., Cheeseman, C.R., Donatello, S., Tsang, D.C.W., 2021. Feasibility of wet-extraction of phosphorus from incinerated sewage sludge ash (ISSA) for phosphate fertilizer production: A critical review. *Crit. Rev. Environ. Sci. Technol.* 51 (9), 939–971. <https://doi.org/10.1080/10643389.2020.1740545>.
- Ferrara, L., Cortesi, L., Ligabue, O., 2015. Internal curing of concrete with presaturated LWA: a preliminary investigation, 12.1-12.12 Acids Symp Publ. 305. <https://doi.org/10.14359/51688572>.
- Ferrara, L., Park, Y.D., Shah, S.P., 2007. A method for mix-design of fiber-reinforced self-compacting concrete. *Cem. Concr. Res.* 37 (6), 957–971. <https://doi.org/10.1016/j.cemconres.2007.03.014>.
- Jia, Z., Li, S., Wang, L., 2018. Assessment of soil heavy metals for eco-environment and human health in a rapidly urbanization area of the upper Yangtze Basin. *Sci. Rep.* 8 (1), 1–14. <https://doi.org/10.1038/S41598-018-21569-6;TECHMETA=141;SUBJMETA=172,4081,685,704,844;KWRD=ENVIRONMENTAL+IMPACT,SUSTAINABILITY>.
- Jupp, A.R., Beijer, S., Narain, G.C., Schipper, W., Slootweg, J.C., 2021. Phosphorus recovery and recycling-closing the loop. In: *Chemical Society Reviews*, 50. Royal Society of Chemistry, pp. 87–101. <https://doi.org/10.1039/D0cs01150a>.
- Kwapinski, W., Kolinovic, I., Leahy, J.J., 2021. Sewage Sludge Thermal Treatment Technologies with a Focus on Phosphorus Recovery: A Review. 2021 12:11 Waste Biomass. *Valoriz.* 12 (11), 5837–5852. <https://doi.org/10.1007/S12649-020-01280-2>.
- Li, J. shan, Chen, Z., Wang, Q. ming, Fang, L., Xue, Q., Cheeseman, C.R., Donatello, S., Liu, L., Poon, C.S., 2018. Change in re-use value of incinerated sewage sludge ash due to chemical extraction of phosphorus. *Waste Manag.* 74, 404–412. <https://doi.org/10.1016/j.wasman.2018.01.007>.
- Li, J. shan, Tsang, D.C.W., Wang, Q. ming, Fang, L., Xue, Q., Poon, C.S., 2017. Fate of metals before and after chemical extraction of incinerated sewage sludge ash. *Chemosphere* 186, 350–359. <https://doi.org/10.1016/j.chemosphere.2017.08.012>.
- Liang, S., Yang, L., Chen, H., Yu, W., Tao, S., Yuan, S., Xiao, K., Hu, J., Hou, H., Liu, B., Yang, J., 2021. Phosphorus recovery from incinerated sewage sludge ash (ISSA) and reutilization of residues for sludge pretreated by different conditioners. *Resour. Conserv. Recycl.* 169. <https://doi.org/10.1016/j.resconrec.2021.105524>.
- Liu, H., Hu, G., Basar, I.A., Li, J., Lyczko, N., Nzihou, A., Eskicioglu, C., 2021. Phosphorus recovery from municipal sludge-derived ash and hydrochar through wet-chemical technology: A review towards sustainable waste management. In: *In Chemical Engineering Journal*, 417. Elsevier B.V. <https://doi.org/10.1016/j.cej.2021.129300>.
- Luyckx, L., Van Caneghem, J., 2021. Recovery of phosphorus from sewage sludge ash: Influence of incineration temperature on ash mineralogy and related phosphorus and heavy metal extraction. *J. Environ. Chem. Eng.* 9 (6). <https://doi.org/10.1016/j.jece.2021.106471>.
- Meng, X., Huang, Q., Xu, J., Gao, H., Yan, J., 2019. A review of phosphorus recovery from different thermal treatment products of sewage sludge. In: *Waste Disposal and Sustainable Energy*, 1. Springer, pp. 99–115. <https://doi.org/10.1007/s42768-019-00007-x>.
- Mohammed, S., Safullah, O., 2018. Optimization of the SO3 content of an Algerian Portland cement: Study on the effect of various amounts of gypsum on cement properties. *Constr. Build. Mater.* 164, 362–370. <https://doi.org/10.1016/j.conbuildmat.2017.12.218>.
- Motisariya, K., Agrawal, G., Baria, M., Srivastava, V., Dave, D.N., 2023. Experimental analysis of strength and durability properties of cement binders and mortars with addition of microfine sewage sludge ash (SSA) particles. *Mater. Today. Proc.* 85, 24–28. <https://doi.org/10.1016/j.matpr.2023.05.248>.
- Neville, A.M., 2002. *Properties of Concrete*, 4th ed. Pearson Education Limited.
- Ngole, V.M., Ekosse, G.I.E., 2012. Copper, nickel and zinc contamination in soils within the precincts of mining and landfilling environments. *Int. J. Environ. Sci. Technol.* 9 (3), 485–494. <https://doi.org/10.1007/S13762-012-0055-5/FIGURES/5>.
- Ottosen, L.M., Kirkegaard, G.M., Jensen, P.E., 2013. Extracting phosphorus from incinerated sewage sludge ash rich in iron or aluminum. *Chemosphere* 91 (7), 963–969. <https://doi.org/10.1016/J.CHEMOSPHERE.2013.01.101>.
- Ottosen, L.M., Thornberg, D., Cohen, Y., Stjernström, S., 2022. Utilization of acid-washed sewage sludge ash as sand or cement replacement in concrete. *Resour. Conserv. Recycl.* 176. <https://doi.org/10.1016/j.resconrec.2021.105943>.
- Prabhakar, A.K., Krishnan, P., Lee, S.S.C., Lim, C.S., Dixit, A., Mohan, B.C., Teoh, J.H., Pang, S.D., Tsang, D.C.W., Teo, S.L.M., Wang, C.H., 2022. Sewage sludge ash-based

- mortar as construction material: Mechanical studies, macrofouling, and marine toxicity. *Sci. Total Environ.* 824. <https://doi.org/10.1016/j.scitotenv.2022.153768>.
- Ryszko, U., Rusek, P., Kolodyńska, D., 2023. Quality of Phosphate Rocks from Various Deposits Used in Wet Phosphoric Acid and P-Fertilizer Production. *2023, Vol. 16, Page 793 Materials* 16 (2), 793. <https://doi.org/10.3390/MA16020793>.
- Sun, S., Huang, X., Lin, J., Ma, R., Fang, L., Zhang, P., Qu, J., Zhang, X., Liu, Y., 2018. Study on the effects of catalysts on the immobilization efficiency and mechanism of heavy metals during the microwave pyrolysis of sludge. *Waste Manag.* 77, 131–139. <https://doi.org/10.1016/J.WASMAN.2018.04.046>.
- Tipraj, Shanmugapriya, T., 2022. A comprehensive analysis on optimization of Sewage sludge ash as a binding material for a sustainable construction practice: A state of the art review. *Mater. Today. Proc.* 64, 1094–1101. <https://doi.org/10.1016/j.matpr.2022.05.479>.
- Vaverková, M.D., 2019. Landfill Impacts on the Environment—Review. *2019, Vol. 9, Page 431 Geosciences* 9 (10), 431. <https://doi.org/10.3390/GEOSCIENCES9100431>.
- Witek-Krowiak, A., Gorazda, K., Szopa, D., Trzaska, K., Moustakas, K., Chojnacka, K., 2022. Phosphorus recovery from wastewater and bio-based waste: an overview. In: *Bioengineered*, 13. Taylor and Francis Ltd, pp. 13474–13506. <https://doi.org/10.1080/21655979.2022.2077894>.
- Zheng, Y., Wan, Y., Zhang, Y., Huang, J., Yang, Y., Tsang, D.C.W., Wang, H., Chen, H., Gao, B., 2023. Recovery of phosphorus from wastewater: A review based on current phosphorous removal technologies. *Crit. Rev. Environ. Sci. Technol.* 53 (11), 1148–1172. <https://doi.org/10.1080/10643389.2022.2128194>.
- Zhu, Ya, Zhai, Y., Li, S., Liu, Xiangmin, Wang, B., Liu, Xiaoping, Fan, Y., Shi, H., Li, C., Zhu, Yun, 2022. Thermal treatment of sewage sludge: a comparative review of the conversion principle, recovery methods and bioavailability-predicting of phosphorus. *Chemosphere* 291, 133053. <https://doi.org/10.1016/J.CHEMOSPHERE.2021.133053>.