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MICROSTRUCTURAL CHARACTERISATION OF ADSORBENT ASH WITH POTENTIALLY TOXIC ELEMENTS IN A MORTAR

Abstract: Potentially toxic elements (PTEs) in ecosystems and construction materials pose a significant environmental concern. Various qualitative and quantitative techniques are employed to analyse PTEs in a sample. This study explores an innovative approach that incorporates PTE (Cd, Zn, Cu, Pb) adsorbent ash, specifically adsorbed paper ash (APA) and adsorbed mulch ash (AMA), into mortar composites. This approach offers several advantages, including reduced reliance on waste landfills, energy recovery during the ashing process, and immobilisation of PTEs within a cement matrix. This study evaluated the elemental and microstructural characteristics of mortar composites incorporated with adsorbed ash by using a scanning electron microscope (SEM) equipped with energy-dispersive X-ray spectroscopy (EDS), followed by analysing the elemental maps with ImageJ software version 1.8.0. Parallel experiments were conducted to measure the leaching of mortar composites. The total elemental content of PTEs in the leachate solutions was quantified using an inductively coupled plasma-optical emission spectrometer (ICP-OES). The differences in adsorption capacity and leaching of PTEs observed between paper and mulch can be ascribed to their distinct affinities, which are influenced by the recorded pH levels. The examined elemental mapping revealed a consistent distribution across the APA and AMA mortar matrix structures, with greater intensity than the blank mortar sample. Furthermore, there is a reverse correlation between the order of percentage area coverage of the immobilised elements and the order of leaching, indicating that the PTEs were successfully immobilised. The percentage of PTE area coverage within AMA mortar composites followed the subsequent order: Pb > Cd > Zn > Cu, constituting 32.1 %, 28.6 %, 13.8 %, and 12.4 %, respectively. This order was also observed in the blank mortar composite, with percentages of 12.5 %, 8.6 %, 4.5 %, and 4.2 %, respectively. In the case of the APA mortar composite, the percentage of area coverage followed a different sequence: Cd > Pb > Zn > Cu, representing 27.7 %, 26.6 %, 14.5 %, and 14.1 %, respectively. The results also demonstrated notable improvements in the microstructure of the mortar when AMA and APA are incorporated, which is attributed to the ash additives' micro-filling capacity. The findings contribute to advancing environmentally sound construction practices, with implications for sustainable waste management and pollution mitigation.

Keywords: potential toxic elements, mortar, elemental mapping, adsorbent ash

Introduction

Recently, the generation of ash from various sources, including wood biomass and paper waste, mainly waste ash containing potentially toxic elements, has garnered significant attention due to its environmental and economic implications. The European Union (EU) alone produced an estimated 7.3 million tonnes ([t] = tonne = 10^6 g = Mg) of wood biomass ash (WBA) in 2015 [1], reflecting the increasing utilisation of wood biomass

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as an energy source. For example, Croatia annually consumes 37,900 t of wood biomass in a single biomass plant, contributing to WBA production at a rate of 3.1 % relative to the initial biomass input [2]. Similarly, Hungary generates 30,000 t of wood ash each year, primarily managing it as waste, with disposal methods ranging from filling former mineshafts to traditional landfilling [3]. On a global scale, the paper industry produces over 450 million t annually, with projections indicating a rise to 500 million t by the end of 2020 [4]. Notably, Canada, a significant contributor to paper waste, annually produces more than 1 million t of wood ash from pulp and paper mills and wood and forest biomass ashes. However, this trend is expected to decline due to increasing disposal costs, stringent regulations, and limited landfill capacity, prompting the reduction or discontinuation of landfilling as a viable disposal method [5, 6].

In response to the mounting challenges posed by the disposal of these ashes, researchers have explored innovative solutions. A notable solution has been the incorporation of industrial by-products such as fly ash and bottom ash, as well as waste wood ash and other cellulose-based material ashes, into cementitious composites, including mortar [7-9]. The use of mortar as a binding agent in masonry work units has been well-established to fill gaps, seal surfaces, and enhance the aesthetic appeal of masonry structures [10]. By utilising waste wood ash and similar materials in cementitious composites, there is the potential to address two pressing issues simultaneously. First, it reduces the volume of discarded ash, mitigating its adverse environmental impacts and minimising the waste sent to landfills. Second, it provides a valuable and eco-friendly way to improve the performance and longevity of construction materials. However, it is important to note that the elemental composition and structural characteristics of ash can vary significantly depending on its source, necessitating thorough assessments through leaching and microstructural tests to ensure the suitability of these materials for practical applications [9].

Researchers have explored various aspects of incorporating waste ash into construction materials. Awolusi et al. [11] investigated the microstructure features of conventional Portland cement mortar incorporating waste wood ash from sawdust. The SEM image revealed more considerable interstitial distances between sawdust ash particles compared to cement particles, indicating a more compact arrangement of the latter. Similarly, Gabrijel et al. [1] conducted a microstructural study and observed that the addition of wood ash to concrete increased particle sphericity, leading to improved packing and enhanced workability when combined with smaller particle sizes. The microstructure investigation of incorporating paper waste ash into mortar composites has received limited attention in the existing literature. However, Wong et al. [12] conducted a study in which waste newspaper ash was employed as a partial replacement for cement in treated concrete cylinders. The study utilised SEM analysis to examine the microstructure of the incorporated newspaper ash concrete composite sample compared to a reference sample. After 28 days of curing, the SEM analysis of the micrograph of the newspaper ash concrete composite sample showed a dense surface with fewer voids. This shows that the sample is more compact and has less porosity than the reference sample. Additional investigations conducted by researchers have explored the chemical composition of the added ash. These studies have substantiated that incorporating ash derived from wood and various other waste sources enhances the compressive strength and durability of the composite material. These improvements are attributed to oxides such as SiO_2, Al_2O_3, and Fe_2O_3 within wood ash. These oxides can generate calcium silicate hydrate (C-S-H) gel, providing secondary binding properties to the composite material [13, 14]. Additionally, studies of paper ash chemical composition showed that paper ashes consist mainly of Ca, Si, Al, Mg, and K as oxides, generally present in Portland cement and typical supplementary cementitious materials [15, 16].

This research addresses a significant gap in the study of mortar composites containing cellulose-based adsorbent ash, particularly when loaded with potentially toxic elements. While existing studies have primarily focused on mechanical strength and leaching behaviour, there is limited research on their microstructural properties linked to leaching properties. The primary objectives of this research are to examine and quantify the dispersion of PTEs within various cellulose adsorbent ashes immobilised within hardened mortar matrices, specifically adsorbed paper ash (APA) and adsorbed mulch ash (AMA). Additionally, the study aims to explore the relationship between the leaching behaviour of these composites and the effective immobilisation of PTEs.

Several steps were included in the research process. Initially, mortar-adsorbent ash mixes were prepared. Images and elemental maps were then captured using scanning electron microscopy with energy-dispersive X-ray spectroscopy. ImageJ software was used to quantify the dispersion of potentially toxic elements in these images. Finally, the concentrations of the leached PTEs were determined using an inductively coupled plasma-optical emission spectrometer (ICP-OES).

This study aims to better understand the elemental and microstructural properties of mortar composites containing adsorbed paper ash (APA) and mulch ash (AMA). The findings of this study will aid in the development, improvement, and performance evaluation of sustainable construction materials, as well as provide insights into the immobilisation and distribution of PTEs within mortar composites, advancing our knowledge of these materials.

Materials and methods

Adsorption method

This study used two cellulose-based adsorbents shown in Supplementary Materials (Fig. S1). The first is a wastepaper obtained from a local store in Godollo, Hungary. The second adsorbent is mulch obtained from oak trees. The adsorbent was applied at a concentration of 10 g L^{-1}, and triplicate aqueous solutions of PTEs were prepared with concentrations of 50 mg L^{-1} for the adsorption experiments. The prepared PTEs solution included lead, zinc, cadmium, and copper from chemical grade salts [$Pb(NO_3)_2$, $CdCl_2 \cdot 21/2H_2O$, $Cu(NO_3)_2 \cdot 3H_2O$, $Zn(CH_3CO_2)_2 \cdot 2H_2O$]. The samples were shaken for four hours at 24 rpm. After adsorption, samples were filtered using ashless MN 640 m Ø90 mm filter paper.

The removed fluid's pH was measured using the Jenway 3510 pH meter and acidified with concentrated nitric acid to below pH two before testing. The total elemental content of PTEs filtrate was determined by a Horiba Jobin Yvon Activa M Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES). The adsorption capacity, q [mg g^{-1}] of PTEs was calculated using the following equation:

$$q = \frac{V(C_0 - C_e)}{m} \tag{1}$$

where q is the uptake [mg g^{-1}], C_0 and C_e are the liquid phase concentrations of PTEs at initial and equilibrium [mg L^{-1}], V is the volume [L], and m is the amount of adsorbent [g].

Adsorbent ash preparation

In this study, two kinds of PTE-contaminated ash shown in supplementary materials (Fig. 2). were produced in the laboratory after the adsorption experiments. The remaining adsorbents on filter paper were compressed to separate the adsorbed fraction; this procedure was followed by oven drying at 105 °C. Finally, samples were burned in the furnace at 450 °C for four hours.

Mortar adsorbent ash mixture preparation

Preparing mortar-adsorbed ash composite samples for the microstructure and elemental mapping study. Ash mortar mixture preparation involved weighing various constituents of the mixture. Mix proportions are 1:3:0.5:0.03. In this study, the weight ratio of APA and AMA added to mortar was 3 %.

The preparation steps are summarised as follows: The sand was added to (AMA) and (APA) ash and mixed to improve the homogenisation of the mortar. Cement was added with additional dry mixing. Finally, the water addition had a fixed ratio of water/binder (w/b). The ordinary Portland cement used was of commercial origin and supplied by Baumit Building Materials Manufacturer and Trade Limited. The cement compressive strength (28 days) is 40 N/mm^2, and the setting time is approximately 230 minutes. The specimens in Figure S2 (Supplementary Materials) were left for 28 days under temperature-controlled conditions in the laboratory at (20 ± 2) °C. The procedure also included the preparation of blank mortar samples. For each analysed parameter, three repetitions were made to ensure the accuracy of the work.

Leaching method

The mortar composite leaching concentrations were studied following the CEN/TS 14429 : 2005 test method [17]. The mortar samples were crushed and sieved through a 1 mm sieve. The HNO_3 reagent was prepared in concentrations of 0.43 M. The crushed sample was weighed, and the reagent was added to a PE bottle at a weight/volume ratio of 1/10. The sealed PE bottles were placed on a rotary agitator and rotated at 24 rpm for four hours. After mixing, the elute was filtered using an MN 640 m ashless filter paper. The removed fluid's pH was measured using the JENWAY 3510 pH meter and acidified with concentrated nitric acid to below pH two before testing. The total elemental content of PTEs leachate solutions was determined by a Horiba Jobin Yvon Activa M Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES).

Scanning electron microscopy (SEM)

The microstructure and elemental mapping study of the mortar ash composite samples were performed using scanning electron microscopy (SEM). The SEM analysis shows the structural differences between mortar before and after incorporating (APA) and (AMA) into mortar composites. Additionally, SEM images provide a better analysis of the morphology and the porosity and identify the core-shell structure of the samples. The instrument used for SEM analysis was a Hitachi S-4700 field emission scanning electron microscope combined with a Bruker (former Röntec) QX2 energy dispersive X-ray fluorescence spectrometer. Before analysis to enable the user to gather high-quality information from SEM. An extra step involved coating the sample with an additional thin layer (~10 nm) of a conductive material; the sputter coater used to coat the samples was gold. The elemental mapping of the studied elements (Cu, Pb, Zn, Cd, Si, Ca, Al) was carried out at 20 kV acceleration voltage and 9 µA beam current. The acquisition time of the individual samples was at least 1 hour.

Image analysis procedure

The elemental mapping covered the adsorbed elements (Cd, Zn, Cu, Pb) and others (Si, Ca, and Al). The working method of image analysis of the elemental maps of each of the seven elements in AMA, APA, and blank mortar composites was carried out using ImageJ software V 1.8.0. ImageJ is one of the first tools for analysing digital images. The National Institutes of Health produced the initial version in 1997. This program’s open-source code, made accessible under a BSD-2 license, is a significant benefit. It can be used for image analysis and other purposes [18].

Results and discussion

Influence of adsorbent type on PTEs adsorption

Cellulose-based adsorbents have a strong affinity for PTEs and dyes due to the presence of cellulose, which contains oxygen and hydroxyl functional groups. These characteristics enhance their capacity for effective adsorption of PTEs [19]. The adsorption capacities of potentially toxic elements, namely lead, copper, cadmium, and zinc, within mulch were investigated. The competitive adsorption capacities among these metal cations exhibited a slightly descending order: Pb > Cu > Cd > Zn, with respective capacities of 0.496 mg g^{-1}, 0.495 mg g^{-1} , 0.491 mg g^{-1} and 0.482 mg g^{-1}. This trend is in accordance with prior findings reported by Chirenje et al. [20], which suggested that wood ash effectively immobilised these four metals. The quantities of metals retained by the wood ash also followed the Pb > Cu > Cd > Zn sequence. Similarly, modified coated wood mulches follow the same order for Pb, Cu, and Zn [21, 22]. Furthermore, an intriguing consistency emerged between adsorption affinity and electronegativity, suggesting that electronegativity provided a compelling explanation for our experimental observations. Electronegativity values, as presented in Table 1, for the four PTEs are ranked in decreasing order: Pb^{2+} (2.33) > Cu^{2+} (1.90) > Cd^{2+} (1.69) > Zn^{2+} (1.65). Electronegativity plays a significant role in PTE adsorption, as metals with higher electronegativity tend to form stronger covalent bonds with oxygen atoms on the adsorbent surface. Consequently, Pb^{2+}, possessing the highest electronegativity value, exhibited the most substantial biosorption capacity, whereas Zn^{2+}, characterised by the lowest electronegativity value, displayed the least biosorption capacity, as supported by research conducted by Pham et al. [23] and Han et al. [24].

In contrast, when examining the adsorption capacities of these same metal cations within the paper, the competitive adsorption capacities followed a descending order of Pb > Cu > Zn > Cd, with respective capacities of 1.48 mg g^{-1}, 1.26 mg g^{-1}, 0.81 mg g^{-1} and 0.77 mg g^{-1}. This outcome is consistent with the study by Ding et al. [25], which looked at the adsorption capacity of carbonised paper packaging boxes for aqueous Pb, Zn, and Cd. Their study revealed high aqueous Pb, Zn, and Cd sorption capacities, with Langmuir maximum sorption capacities of 458 mg g^{-1}, 146 mg g^{-1} and 10.7 mg g^{-1}, respectively.

Notably, cadmium exhibited the lowest adsorption among these elements. Furthermore, it was observed that the paper showed a superior adsorption capacity compared to mulch for all the investigated PTEs.

The varying affinities of mulch and paper adsorbents for PTE adsorption could be attributed to differences in the pH levels of the solutions. After the adsorption process, the average pH for mulch was measured at 4.69, while for paper, it registered at 5.58. Lower pH levels were associated with reduced adsorption of metal ions due to competition with H^+ ions for active adsorption sites [26-28]. Conversely, at higher pH levels, the presence of H^+ ions decreased on the adsorbent surface, resulting in increased adsorption of metal ions, as supported by Kushwaha et al. [29].

Table 1

Basic physical and chemical properties of potentially toxic elements [30]

Ion species	**Ion radius [pm]**	**Electronegativity [-]**	**Hydrolysis constant [-]**	**Water and ion radius [nm]**	**Charge-to-diameter ratio [eÅ^{-1}]**
Pb^{2+}	119	2.33	7.80	0.40	1.68
Cu^{2+}	73	1.90	7.34	0.42	2.74
Zn^{2+}	74	1.65	8.96	0.43	2.10
Cd^{2+}	95	1.69	9.20	0.43	2.70

Influence of adsorbent ash type on PTEs leaching from mortar composites

The leaching results from the AMA mortar composite followed the order Cu > Zn > Cd > Pb, with respective values of 1.25 mg kg^{-1}, 1.01 mg kg^{-1}, 0.50 mg kg^{-1}, and 0.14 mg kg^{-1} at 0.43 M HNO_3. This observation could be attributed inversely to the ionic radius of PTEs, as indicated in Table 1. While APA leaching test results followed the order Cu > Zn > Pb > Cd with leaching amounts of 1.96 mg kg^{-1}, 1.81 mg kg^{-1}, 1.69 mg kg^{-1}, and 0.41 mg kg^{-1}, respectively. These results highlight how adsorption affinity also played a pivotal role in determining the resulting leachate concentrations of PTEs. For instance, cadmium exhibited consistently low adsorption capacity when paper was used as the adsorbent. Additionally, pH, as noted by Kinniburgh et al. [31], is another influencing factor in adsorption and leaching behaviour in hydrous oxide gels composed of iron and aluminium. After the leaching process with 0.43 M HNO_3, the measured pH values were 5.25 for (AMA) mortar and 7.22 for (APA) mortar. These results align with the idea that variations in pH contribute to the differing affinities for PTE adsorption, with (AMA) mortar being more acidic than (APA) mortar, which aligns with their respective adsorption preferences due to the pivotal role of acidity in this phenomenon.

Table 2

Compared leaching results with leaching limit values [mg kg^{-1}], L/S = 10 [32]

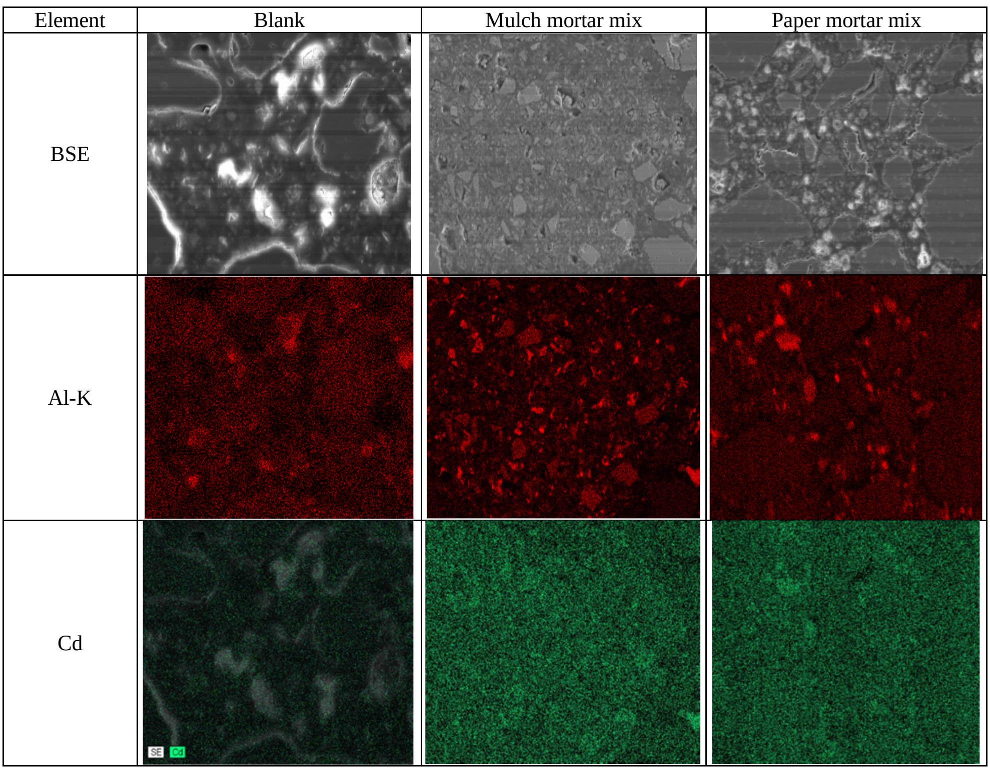
Element	**AMA leaching**	**APA leaching**	**Inert waste limit**	**Non-hazardous waste**	**Hazardous waste**
Cd	0.50	0.41	0.04	1	5
Pb	0.14	1.69	0.5	10	50
Cu	1.25	1.96	2	50	100
Zn	1.01	1.81	4	50	200

The leaching quantities from both AMA and APA were evaluated against the leaching threshold values specified in accordance with the waste acceptance criteria outlined in EU directive 1999/31/EC, as illustrated in Table 2. The findings reveal that for all the investigated PTEs, the leaching levels were below the hazardous limits, thus confirming that these utilised adsorbents can be safely employed in construction applications without posing any environmental risks.

Elemental mapping

Research findings on elemental mapping are presented in Figure 1. The elemental distribution of Al, Cd, Zn, Pb, Cu, Si, and Ca in the AMA, APA, and blank mortar composites was examined using SEM-EDS. The analysis revealed that the adsorbed PTEs - Cd, Zn, Cu, and Pb - exhibited a uniform distribution throughout the APA and AMA mortar matrix structure. However, their distribution intensity was higher than that of the blank mortar sample, indicating evidence of PTE immobilisation.

Several steps were performed to conduct an in-depth analysis of the elemental maps. Each image was cropped, filtered, adjusted, and transformed to 8-bit using ImageJ software V 1.8.0 [33].



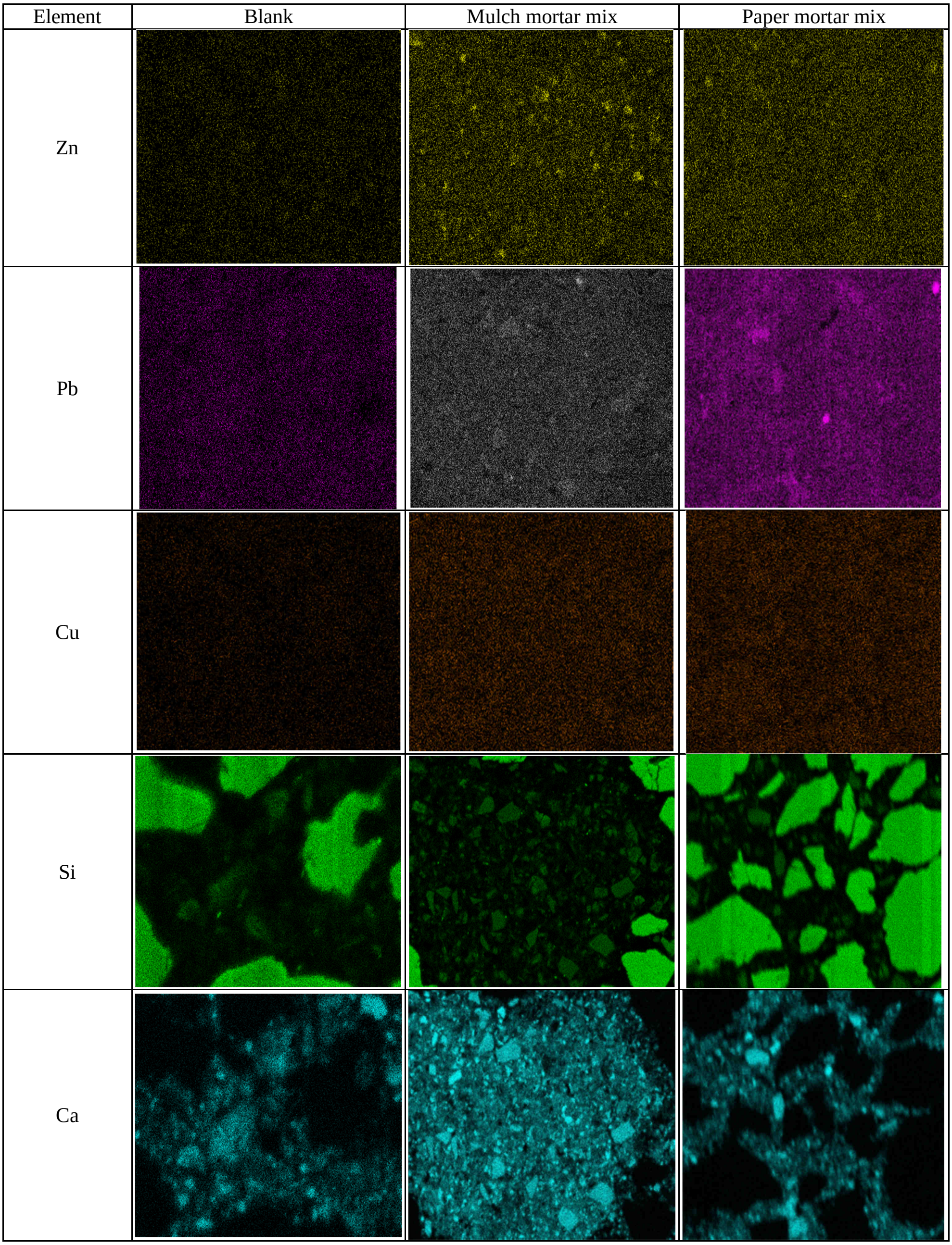


Fig. 1. Elemental mapping of APA, AMA, and blank mortar samples

The analysed elemental maps provided information on the estimated area coverage percentage [%] for the adsorbed PTEs and other major elemental content in the studied mortar composites. Figure 2 displays the estimated percentage of the area coverage for each element of the adsorbed PTEs within AMA, APA, and blank mortar composites. The percentage of area coverage of PTEs within AMA mortar composites followed the following order: Pb > Cd > Zn > Cu, accounting for (32.1, 28.6, 13.8 and 12.4) %, respectively. This order was also followed by the blank mortar composite, accounting for 12.5 %, 8.6 %, 4.5 % and 4.2 %, respectively.

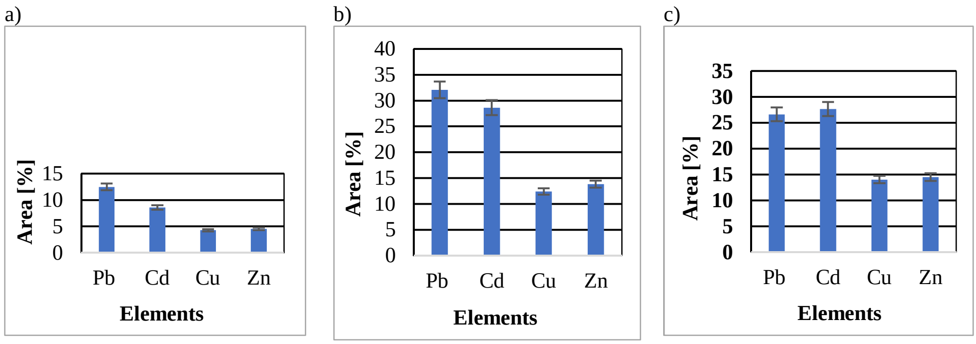


Fig. 2. Area coverage percentage for adsorbed elements estimated using ImageJ software V 1.8.0 for: a) blank mortar, b) AMA, and c) APA composites

In the APA mortar composite, the percentage of area coverage followed the following order: Cd > Pb > Zn > Cu, accounting for 27.7 %, 26.6 %, 14.5 %, and 14.1 %, respectively. The highest percentage of area coverage was observed for Pb, accounting for 32.1 %, followed by Cd at 28.6 % within the AMA mortar composite. In contrast, the APA mortar composite exhibited slightly lower percentages of area coverage for Pb and Cd, with values of 26.6 % and 27.7 %, respectively. The Cd behaviour in APA mortar composites could be attributed to the results of pH, which shows that APA composites tend to shift towards a more basic environment than AMA composites. This behaviour aligns with the findings of Singh et al. [34], which demonstrate that Cd has a higher adsorption capacity than Pb when the media is basic. In all the tested mortar composites, the area coverage percentage for Zn was consistently observed to be slightly higher than that for Cu.

An inverse correlation between the estimated percentage of area coverage for adsorbed PTEs and the leaching results from the mortar composites was observed, suggesting valuable insights into the immobilisation mechanisms for these PTEs. Specifically, the immobilisation mechanisms for Pb, Cd, and Zn in cementitious materials can be explained as follows: Lead: The predominant immobilisation mechanism for Pb in cementitious materials involves precipitation as insoluble lead silicates (e.g., $PbSiO_3$, Pb_2SiO_4, Pb_3SiO_5, and Pb_4SiO_6) [35, 36]. Cadmium: In cement hydration systems, Cd is primarily immobilised through the precipitation of hydroxides. These insoluble phases are subsequently adsorbed onto the C-S-H surface or fill the pore structure of cement pastes. [37, 38]. Zinc: precipitation as hydroxides or carbonates may be the major mechanism for immobilising Zn in solidification/stabilisation systems [39]. Zinc, being amphoteric, is soluble in a highly alkaline environment provided by cement hydration and exists as hydroxyl complexes ($[Zn(OH)_4]^{2-}$ and $[Zn(OH)_3]^-$). These hydroxyl complexes are less prone to adsorption onto the surface of C-S-H due to their negative charge [36].

Zn immobilised less than Pb and Cd because of its mechanism of immobilisation. It is an amphoteric metal that is soluble in highly alkaline environments and hardly adsorbs onto C-S-H, while Pb and Cd precipitate as hydroxides, filling the pore structure of cement pastes. This comprehensive understanding of the immobilisation mechanisms helps explain the observed order of PTEs and provides insights into how these mechanisms influence leaching behaviour in mortar composites.

The percentage of area coverage of the major elements within AMA, APA, and blank mortar composites compared are presented in Figure 3. The results showed that the percentage coverage of the major elements within the AMA mortar composite followed the following descending order: Pb > Ca > Cd > Al > Fe > Si > Zn > Cu. In contrast, the order in APA mortar composite was Si > Cd > Pb > Al > Ca > Fe > Zn > Cu. Silicon in APA mortar samples has the highest area coverage percentage because calcium silicate is usually used as paper filler to improve the paper bulk, one of the most critical properties in papermaking [40]. In AMA mortar composite, the calcium area coverage percentage was higher than APA mortar composite; this result is consistent with the findings of the researchers [41] who studied the chemical composition of oak mulch ash and other wood ashes and found that calcium was the element with the highest elemental content in these ashes.

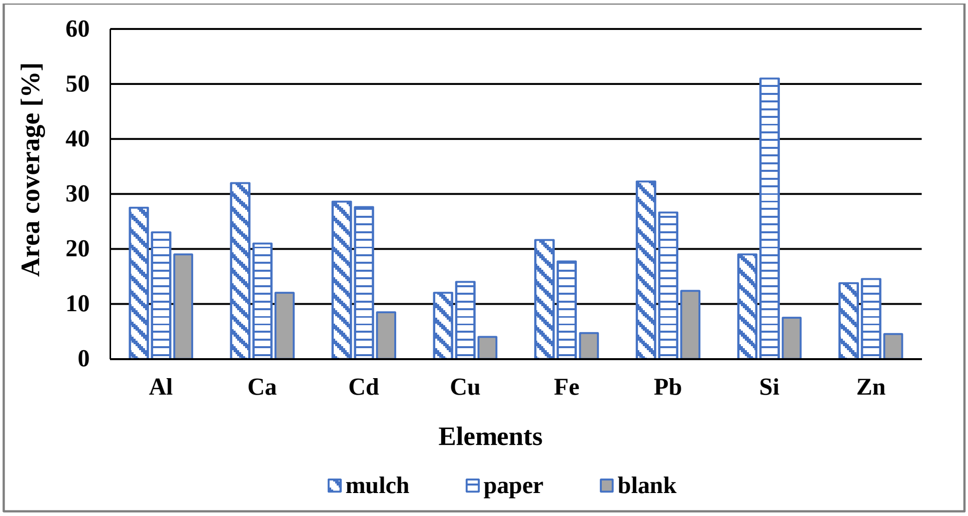


Fig. 3. Compared area coverage percentage for major elements estimated using ImageJ software V 1.8

SEM analysis

Scanning Electron Microscopy (SEM) has emerged as a powerful tool for the characterisation and analysis of materials, particularly in the field of construction materials. In the context of mortar composites, SEM analysis allows for the investigation of microstructure features, providing valuable insights into the arrangement and distribution of different components within the composite material.

The SEM examination in this study revealed differences in the microstructure of APA, AMA, and blank samples, referring to Figure 4 of the SEM images. The results showed that, unlike APA mortar, blank mortar has the most microcracks and porosity, while AMA mortar has the least. The microstructure of AMA mortar is significantly denser than that of APA and blank mortar. According to SEM examination, the inclusion of AMA and APA enhanced the microstructure of the mortar due to its micro-filling capabilities. The hydration phase was aluminate-ferrite, monosubstituted (AFm), a well-developed yet very thin hexagonal plate, indicating late formation for all composites [42]. Another apparent colour difference appeared in SEM images where the adsorbed paper ash and mulch ash, when incorporated in the mortar, led to a darker colour than the blank mortar. This finding is consistent with the results of Lessard et al. [6] when using fly and bottom ash of paper waste in a concrete composite.

The results of this study suggest that further studies should examine the mechanical strength and durability of the PTEs adsorbed paper ash mortar composite and the adsorbed mulch ash mortar composites to ensure that PTEs do not affect these properties. It is also recommended to investigate the usage of AMA and APA in other applications in civil engineering, including use in bricks, panels, geopolymers, and other alkali-activated materials, concrete, and other green building materials. Finally, a long-term study for aged samples of APA and AMA mortar composites is recommended to see the effect of age on microstructure; further research involving more extensive analysis will help to ensure better use of this waste material.

a) b) c)

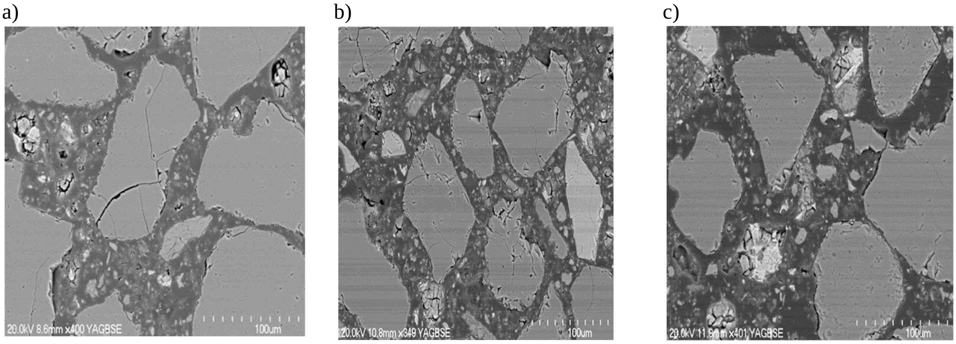


Fig. 4. The microstructure of: a) blank, b) APA, and c) AMA mortar composites

Conclusion

This research addresses the utilisation of cellulose-based adsorbent ashes, specifically adsorbed paper ash (APA) and mulch ash (AMA), in mortar composites. The study investigates their affinity for potentially toxic elements (PTEs), their immobilisation mechanisms, leaching behaviour, and microstructure. Key findings include:

- Adsorption and leaching: APA and AMA effectively adsorb PTEs due to their unique chemical properties. The pH of the solution affects adsorption, with higher pH fevering more significant adsorption. Notably, both ashes immobilise PTEs effectively, reducing leaching potential.
- Low environmental risk: Leaching tests reveal that PTEs leached from these mortar composites are well below hazardous limits, suggesting that APA and AMA can be safely used in construction materials without posing significant environmental risks.

- Elemental mapping and microstructure: According to Scanning Electron Microscopy (SEM) analysis, the AMA mortar has a denser microstructure than APA mortar and blank mortar, lending credence to the idea that the addition of AMA and APA improved the mortar’s microstructure thanks to their micro-filling capabilities. Elemental mapping results show that adsorbed Cd, Zn, Cu, and Pb are distributed reasonably uniformly throughout the APA and AMA mortar matrices, with a greater intensity of dispersion than the blank mortar sample, indicating evidence of immobilisation of the PTEs.
- Future research: Future studies should examine these composites’ mechanical strength and durability and explore their use in various civil engineering applications. Long-term investigations on aged samples will provide insights into the effects of aging on microstructure and performance.

This research contributes to sustainable construction materials by offering valuable insights into using cellulose-based adsorbent ashes in mortar composites, reducing waste and environmental impact while enhancing material performance.

Acknowledgements

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