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Leachability of metals from sludge-based artificial lightweight aggregate

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Abstract

Metal sludge from industrial wastewater treatment plants was mixed with mining residues to be recycled into lightweight aggregate (LWA) through sintering at different temperatures. The physical properties of the LWA thus obtained were examined by scanning electron microscopy analyzer (SEM) coupled with an energy dispersive X-ray analyzer (EDX). The sequential extraction method combined with inductively coupled plasma atomic emission spectrometry (ICP-AES) was employed to determine the concentration and distribution of hazardous toxic elements in the metal sludge-based artificial LWA. The results show that the leaching concentrations of Cd, Cr, Cu, and Pb present in the non-sintered raw aggregate pellets reached 7.4, 68.0, 96.0, and 61.4 mg/l, respectively, far exceeding the regulatory threshold. Sintering at 1150 °C for 15 min results in stronger chemical bonds being formed between the elements. Hence, after the first three steps of sequential extraction, the concentrations of Cr, Cu, and Pb reached 2.69, 1.50, and 1.88 mg/l at 1150 °C, while the final residues had total concentrations of 96.1, 88.4, and 60.6 mg/kg, respectively, with Cd undetected in both phases. The concentration levels fell within the regulatory threshold, indicating that the LWA fabricated from recycled metal sludge contains elements that are toxic and hazardous but not leached. Having no harmful effect on the environment, the metal sludge-based artificial LWA is not only safe but also practical with good physical properties.

Keywords: Artificial lightweight aggregate; Metal sludge; Sequential extraction method; ICP-AES; SEM/EDX

1. Introduction

Lightweight aggregate (LWA) is not only light and fire resistant, but also have good insulation against heat and sound. Its good engineering properties make it an ideal construction material [1–3]. The flourishing electronic industry in Taiwan has resulted in a huge accumulation of industrial waste, mainly metal sludge. Metal sludge produced in Taiwan in 2004 amounted to 580,000 tonnes [4]. The sludge contains various metals such as Zn, Cr, Ni, Cu, Pb, and Ag originating from different industries involved in surface polishing, electroplating, as well as the production of printed circuit boards (PCB), batteries, electric wires, and cables. Studies have been done in recent years on the manufacturing of artificial LWA using recycled resources such as non-hazardous dredged silt and waste sludge. Research on metal sludge focuses mainly on its proper treatment without harmful effect on the environment, while little effort has been made on exploring the possibility and environmental impact of its recycling for resource recovery.

The most frequently used LWA is manufactured using bentonite, shale, perlite, vermiculite, expanded polystyrene, and different kinds of pelleted or sintered waste, including sintered glass. Under high-temperature heating, certain elements present in the raw materials expand, thus forming a hard vitrified layer on the surface [2]. Ramamurthy and Harikrishnan [5] observed that (i) properties of sintered aggregates vary with the type and amount of binder used and (ii) sintered aggregates show significant improvement in strength and reduction in water absorption when bentonite is added. Bhatty and Reidt [3] investigated the properties of lightweight sludge ash aggregate and reported that lightweight aggregate made from pelletized or slabbed sludge ash incinerated at between 1050 and 1110 °C could produce concrete of moderate strength. Ducman et al. [6,7] explored the

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possibility of producing LWA in a rotary kiln at 1100 °C using waste glass. Pioro and Pioro [8] employed non-selfbloating clays to produce aggregate for lightweight concrete with bulk density ranging between 160 and 850 kg/m^3 and cylindrical compressive strength within the range of 0.7–14.4 MPa. In addition, sewage sludge ash (SSA) [9–11] and clay-blended sludge [12] have also been recycled into LWA through sintering.

In this study, LWA is produced by sintering recycled mining residues and metal sludge from electronic industries in a tunnel kiln. The raw materials are fed at around 800 °C causing rapid vitrification of the raw aggregate pellet surface. The physical properties of the LWA thus obtained were examined by scanning electron microscopy (SEM) coupled with an energy dispersive X-ray (EDX). The sequential extraction method combined with inductively coupled plasma atomic emission spectrometry (ICP-AES) was employed to determine the concentration and distribution of hazardous toxic elements in the non-sintered raw aggregate pellets and the sintered metal sludge-based LWA. This method has previously been used to measure the toxic metal content in fly ash [13]. Sequential extraction involves the addition of different reagents of increasing acidities in a series of steps to extract different elements, thus characterizing the chemical composition of the sample examined [14]. When used in the pre-treatment process, this method can provide information on the chemical composition distribution and the potential mobility of metal present in the waste to be recycled. Previous studies have mainly applied sequential extraction to analysis of toxic waste raw materials for recycling and rarely to that of recycled products, in this study the metal sludge-based LWA. Such analysis can contribute to a better understanding of whether the recycled LWA, which contains toxic elements, poses any harmful effect for the environment.

2. Materials and method

2.1. Raw materials

2.1.1. Metal sludge

Table 1 shows the analysis data of the total concentrations [15] and the TCLP leaching test [16] of the sludge cake obtained from electronic factories. As can be seen, copper (Cu) constitutes the highest proportion in the sludge (3050 mg/kg), followed by chromium (Cr), lead (Pb), cadmium (Cd), and other hazardous metal wastes. The leaching concentration was much higher than the regulatory threshold [17]. The chemical composition of metal sludge is shown in Table 2.

Table 1
Total concentrations and leaching concentrations of metal sludge

Element	Total concentrations (mg/kg)	Leaching concentrations (mg/l)[a]	TCLP limits (mg/l) [17]
Lead (Pb)	2452 ± 22	61.4 ± 1.7	5.0
Cadmium (Cd)	275 ± 15	7.4 ± 0.3	1.0
Copper (Cu)	3050 ± 41	96.0 ± 2.5	15.0
Zinc (Zn)	118 ± 9	BDL[b]	No limit
Total Chromium (Cr)	2492 ± 39	68.0 ± 1.4	5.0
Chromium (Cr^{+6})	34 ± 2	3.6 ± 0.2	2.5
Arsenic (As)	BDL	BDL	5.0
Mercury (Hg)	BDL	BDL	0.2

[a] Extraction fluid #1: pH 4.93 ± 0.05.
[b] BDL: below detection limit (<0.002 mg/l).

Table 2
Chemical composition of mining residues, metal sludge, and raw aggregate pellets before sintering

Composition	Mining residues (%)	Metal sludge (%)	Raw aggregate pellets before sintering (%)
SiO_2	56.3 ± 2.5	59.4 ± 3.3	58.3 ± 2.8
Al_2O_3	14.4 ± 0.9	19.5 ± 1.0	17.1 ± 0.9
Fe_2O_3	6.8 ± 0.3	6.0 ± 0.4	6.5 ± 0.3
CaO	5.1 ± 0.2	3.1 ± 0.1	4.3 ± 0.2
MgO	4.2 ± 0.2	1.5 ± 0.1	3.1 ± 0.2
Na_2O	1.4 ± 0.1	2.9 ± 0.1	2.0 ± 0.1
K_2O	1.6 ± 0.1	2.0 ± 0.1	1.8 ± 0.1
P_2O_5	–	1.1 ± 0.1	0.5 ± 0.0
Others	10.2 ± 0.7	4.5 ± 0.2	6.5 ± 0.5

2.1.2. Mining residues

Table 2 shows the composition of the residues (by XRF, as oxides) from a mine producing mainly shale, bentonite and kaolin. As can be seen, the residues comprise mainly silicon dioxide (SiO_2), followed by aluminum oxide (Al_2O_3) and iron oxide (Fe_2O_3), as well as the amounts of calcium oxide (CaO), manganese oxide (MgO), potassium oxide (K_2O), and sodium oxide (Na_2O). No hazardous metal was detected.

2.2. Experimental procedure

2.2.1. LWA preparation

The waste raw materials collected were oven dried at 105 °C until constant weight was obtained. After sifting through the size of 75 μm, the metal sludge and mining residues were evenly mixed at a weight ratio of 40%:60% into raw aggregate pellets of 3–5 mm diameter and then dried to contain 15% water [18]. Table 2 shows the chemical composition of the raw aggregate pellets before sintering. As seen in the compositional analysis, the pellets comprise mainly SiO_2, followed by Al_2O_3, Fe_2O_3, and Flux, which matches the chemical composition of expandable LWA [19,20].

The raw aggregate pellets were then sintered at temperatures of 850, 950, 1050, 1150, and 1250 °C for 15 min [20] and cooled under ambient air. The sintered LWA thus obtained was then subjected to further examination as follows.

2.2.2. Physical properties of sintered LWA

The hydration rate was examined according to ASTM C12 [21], the apparent specific density was analyzed according to ASTM C127 [22] and the compressive strength was assessed using the method proposed by Yashima et al. [23].

2.2.3. SEM/EDX investigation

Morphological investigations of the LWA at different sintered temperatures were carried out by scanning electron microscopy

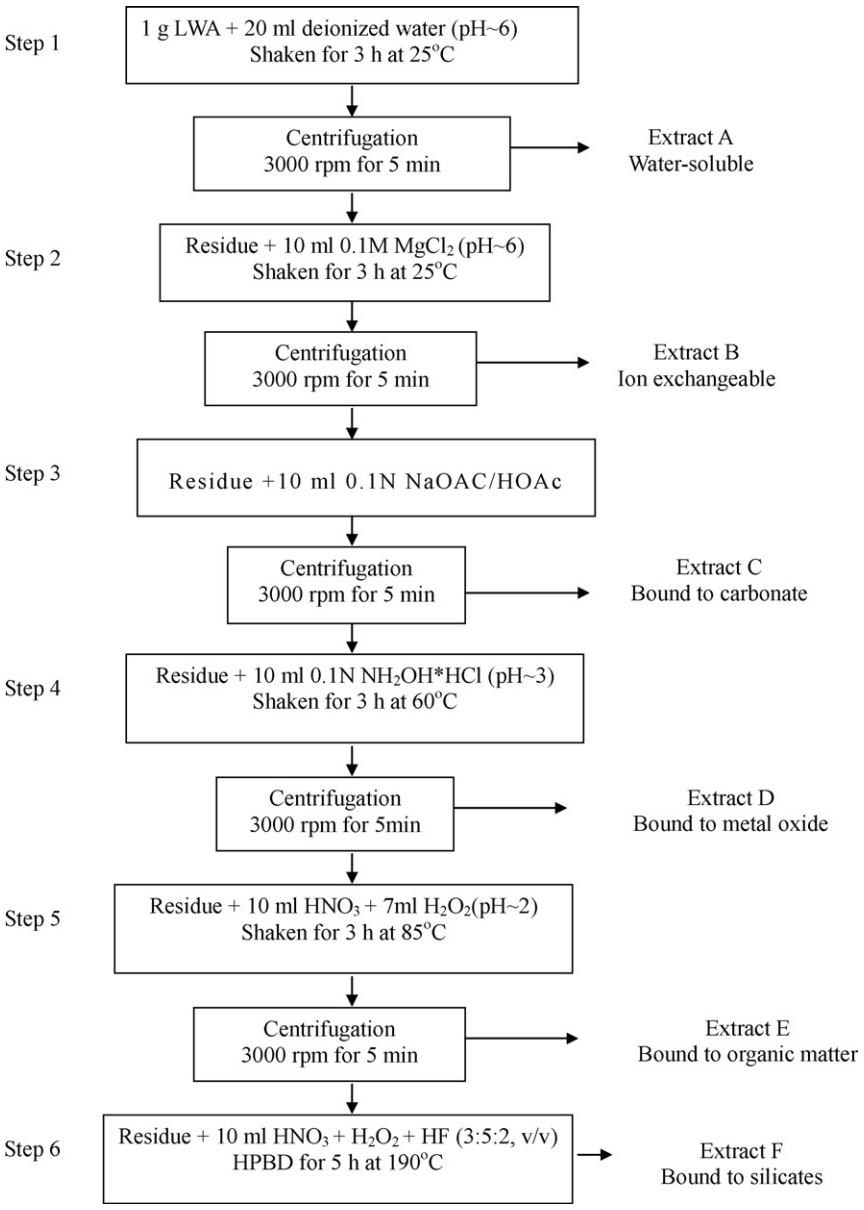

Fig. 1. Flowchart of sequential extraction procedure.

analyzer (SEM, JEOL JSM-6300F), coupled with an energy dispersive X-ray analyzer (EDX, Oxford Inca Energy 400). The typical accelerating voltage of SEM was 30 kV. The EDX detector used was a Si (Li) detector at a resolution of 133 eV.

2.2.4. *Sequential extraction procedure*

Following Chang et al. [13], we modified the original Tessier et al. [14] five-step sequential extraction scheme to examine the composition of toxic metal elements in the metal sludge-based LWA before sintering and after being sintered at different temperatures. Fig. 1 is the flowchart summarizing the six-step sequential extraction method basically modified from the method proposed by Tessier et al. [14], but the residual fraction was particularly digested by HNO_3/H_2O_2/HF acid mixture. Steps 1–5 were conducted in the same 15-ml polyethylene centrifuge tube with the same extraction process by shaking at a speed of 150 rpm for 3 h at different temperatures. The extract was then separated from the solid residue by centrifugation for 5 min. The supernatant was removed with the pipette and stored in a polyethylene tube at 4 °C for analysis. Solid residue obtained after solid–liquid separation was to be used in the subsequent extraction process, thus, between each step, care had to be taken not to discard any such residue. In Step 6, after high-pressure bomb digestion, the sample solution was transferred into a PTFE beaker and heated gently (<90 °C) on a hot plate to allow the residual acid to evaporate. The final residue was diluted to 50 ml for instrumental analysis.

The morphological and mineralogical phases after extraction were examined by SEM. The concentrations of major components (such as Cd, Cr, Cu, and Pb) in the different extracts were measured by inductively coupled plasma atomic emission spectrometry (ICP-AES).

To evaluate the reproducibility of the results, all experiments were triplicated and the averaged results were presented.

3. Results and discussion

3.1. Effect of sintering temperature on sludge-based LWA

Fig. 2 shows the SEM surface images of sludge-based LWA sintered at different temperatures for 15 min. As seen in Fig. 2(a), there are abundant pores present in the center, which are even and with thin boundary, while away from the center toward the vitrified surface, the pores becomes smaller and denser. Comparing the images in Fig. 2(b and c) reveals that higher sintering temperatures result in smaller and fewer pores on the LWA surface.

Fig. 3 shows pore formation inside the LWA sintered at different temperatures for 15 min. As can be seen, the higher the temperature, the fewer and denser the pores formed inside the LWA.

The above results indicate that LWA sintered at higher temperature will be more densified and have lower porosity, which results in higher strength and lower hydration rate. Characteristics of LWA microstructure including particle size, shape and distribution of pores, extent of vitrification, and unit weight are all affected by sintering temperature [11,20]. For raw aggregate pellets fed at ambient temperature, their small size with diameter below 10 mm causes the temperature at the center to rise together with the kiln temperature. The pellet surface becomes rapidly vitrified under sintering and envelops the internal gas produced. As a result, pores are formed and the LWA thus obtained shows an expanded and porous structure.

3.2. Toxic metal elements in sludge-based LWA

Table 3 shows the concentration of toxic metal elements present in the sludge-based LWA before sintering and after being sintered at different temperatures. The results, expressed as a recovery (mg/kg) of the element determined in each step, correspond to the mean obtained in Steps 1–6 in the sequential extraction method. As can be seen, the metals extracted by Steps 1–6 include Cd, Cr, Cu, and Pb with total concentrations of 108.4, 990.3, 1175.4, and 976.0 mg/kg, respectively, all of which exceed the standard specified by the US EPA [17] and are thus classified as hazardous wastes. After three steps of sequential extraction, the concentrations of Cd, Cr, Cu, and Pb reached the levels of 3.8, 146.0, 88.8, and 68.6 mg/kg, which are close to the natural environmental leached levels. This is because metals in the water-soluble and ion exchangeable phases (Steps 1 and 2) are leachable under neutral conditions, while those bound to carbonates (Step 3) are leachable only under acidic conditions (pH ≈ 5). Most metals bound to Fe–Mn oxides and organic matters (Step 4) are potentially leachable under reducing conditions; while those bound to silicates can hardly leach under natural conditions. It would thus be interesting to know whether toxic elements contained in the sludge-based LWA would be readily released into the environment or not. The real danger of sludge-based LWA is the amount of readily soluble constituents which is best represented by the first three extraction fractions in the experiment. Table 4 shows the sum of the first three extraction fractions for these elemental concentrations in the sludge-based LWA before sintering and after being sintered at different temperatures to indicate their availability in the environment. It was found that the extracted concentrations of Cd, Cu, and

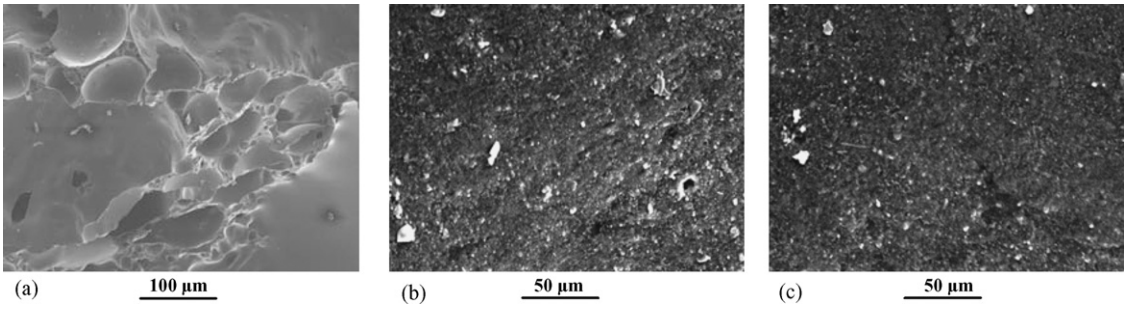

Fig. 2. SEM image of pores formed on surface of LWA sintered at different temperatures. (a) SEM image of LWA; (b) LWA sintered at 1050 °C; (c) LWA sintered at 1250 °C.

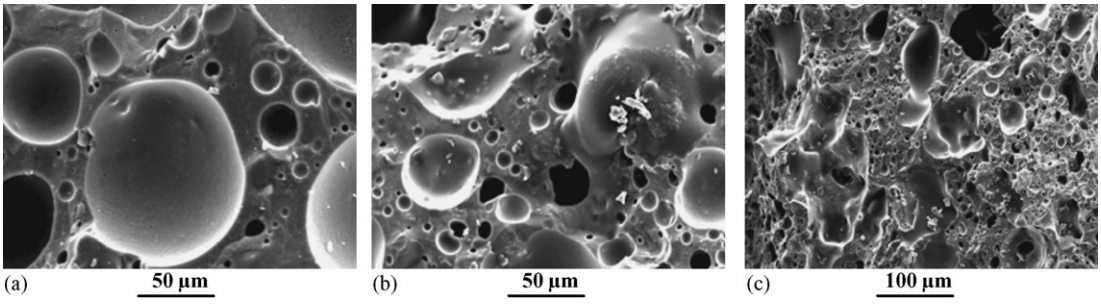

Fig. 3. SEM image of pores formed inside LWA sintered at different temperatures. (a) LWA sintered at 1050 °C; (b) LWA sintered at 1150 °C; (c) LWA sintered at 1250 °C.

Table 3
Concentration of toxic elements in metal sludge-based LWA before and after sintering at different temperatures (unit: mg/kg)

Sample	Non-sintered	850 °C	950 °C	1050 °C	1150 °C	1250 °C
Extract A						
Cd	BDL[a]	BDL	BDL	BDL	BDL	BDL
Cr	5.4 ± 0.6	75.6 ± 5.8	89.6 ± 7.4	81.6 ± 9.1	29.8 ± 1.5	2.0 ± 0.1
Cu	4.6 ± 0.4	5.4 ± 0.5	5.6 ± 0.6	5.8 ± 0.4	7.0 ± 0.4	11.2 ± 0.8
Pb	BDL	4.0 ± 0.2	7.0 ± 0.8	18.0 ± 0.7	10.0 ± 0.7	11.6 ± 1.2
Extract B						
Cd	BDL	BDL	BDL	BDL	BDL	BDL
Cr	3.0 ± 0.2	89.0 ± 10.1	103.4 ± 9.2	21.4 ± 1.3	19.4 ± 1.0	1.6 ± 0.1
Cu	8.0 ± 0.8	9.6 ± 0.6	7.0 ± 0.6	2.4 ± 0.5	7.0 ± 0.6	11.2 ± 1.0
Pb	34.2 ± 3.6	10.0 ± 0.9	11.0 ± 1.1	12.0 ± 0.9	14.0 ± 0.7	12.6 ± 0.9
Extract C						
Cd	3.8 ± 0.1	BDL	BDL	BDL	BDL	BDL
Cr	137.6 ± 8.4	58.0 ± 3.4	25.0 ± 1.3	9.0 ± 0.6	4.6 ± 0.2	1.6 ± 0.1
Cu	76.2 ± 6.2	88.6 ± 6.1	17.0 ± 0.9	16.2 ± 1.2	16.0 ± 0.8	10.0 ± 0.8
Pb	34.2 ± 4.2	10.0 ± 1.0	9.0 ± 0.5	22.0 ± 1.8	13.6 ± 0.6	0.6 ± 0.0
Extract D						
Cd	19.0 ± 1.0	BDL	BDL	BDL	BDL	BDL
Cr	168.4 ± 9.2	30.2 ± 2.3	19.0 ± 1.0	8.4 ± 0.5	7.0 ± 0.3	3.4 ± 0.2
Cu	168.8 ± 11.4	141.2 ± 9.9	20.0 ± 1.4	16.2 ± 1.4	7.2 ± 0.3	10.6 ± 0.9
Pb	222.8 ± 18.2	16.0 ± 1.2	17.0 ± 0.7	18.0 ± 1.0	11.2 ± 0.9	0.6 ± 0.0
Extract E						
Cd	83.8 ± 3.6	BDL	BDL	BDL	BDL	BDL
Cr	396.2 ± 28.6	95.2 ± 6.5	75.2 ± 8.6	50.6 ± 2.5	11.0 ± 0.5	5.6 ± 0.3
Cu	624.8 ± 53.0	110.0 ± 9.6	30.4 ± 1.5	22.8 ± 1.7	15.8 ± 1.1	11.8 ± 1.3
Pb	249.6 ± 34.4	18.0 ± 1.9	12.0 ± 1.0	4.0 ± 0.2	12.0 ± 0.6	15.6 ± 1.5
Extract F						
Cd	1.6 ± 0.1	9.6 ± 0.7	4.6 ± 0.3	BDL	BDL	BDL
Cr	279.8 ± 25.8	150.8 ± 14.6	111.8 ± 10.4	82.6 ± 6.3	24.4 ± 1.5	1.6 ± 0.1
Cu	293.0 ± 31.8	241.6 ± 12.9	83.8 ± 7.2	64.8 ± 4.9	35.8 ± 2.0	21.0 ± 1.4
Pb	435.0 ± 48.8	113.2 ± 7.3	61.8 ± 5.5	9.8 ± 0.7	0.2 ± 0.0	BDL

[a] BDL: below detection limit (<0.002 mg/l).

Pb in the sludge-based LWA after being sintered at different temperatures through the first three steps are much lower than their regulated TCLP limits. However, the Cr concentrations for sintering temperatures between 850 and 1050 °C exceed the regulated TCLP limits, with a much weaker set of reagents. This is because the Cr compounds were converted into more soluble or more extractable forms after sintering. Hazardous metals will be encapsulated in the silicate matrix structure when sintered at high temperature (>1150 °C), making them non-volatile vitrified residues with low leachability. Hence, high-temperature sintering can be an effective treatment approach for volatile metals. Moreover, the longer the sintering and the higher temperature, the lower the leachability of hazardous metals.

Table 5 shows the recovery of metals in each sequential extraction step for non-sintered LWA pellets. As can be seen, 77.3%, 40.0%, 53.2%, and 25.6% of Cd, Cr, Cu, and Pb, respectively, were bound to organic matter, while 28.3%, 24.9%, and 44.6% of Cr, Cu, and Pb, respectively, were bound to silicates. In addition, 3.5%, 14.7%, 7.6%, and 7.0% of Cd, Cr, Cu, and Pb, respectively, were dissolved after Steps 1–3. In the presence of microorganisms, metals bound to organic matter might be decomposed and become a potential pollutant, implying that small amounts of Cd, Cr, Cu, and Pb are leached in the natural environment. Since these four elements are all toxic, their release during storage will have a potentially negative impact on environmental quality, human health, as well as surface-

Table 4
Comparisons between the sums of first three extraction fractions for toxic elements in metal sludge-based LWA and the TCLP limits (unit: mg/l)

Sample	Non-sintered	850 °C	950 °C	1050 °C	1150 °C	1250 °C	TCLP limits
Cd	0.19 ± 0.01	BDL[a]	BDL	BDL	BDL	BDL	1.0
Cr	7.30 ± 0.46	11.12 ± 0.97	10.91 ± 0.90	5.60 ± 0.55	2.69 ± 0.14	0.25 ± 0.02	5.0
Cu	4.44 ± 0.37	5.17 ± 0.36	1.47 ± 0.09	1.22 ± 0.11	1.50 ± 0.09	1.63 ± 0.13	15.0
Pb	3.43 ± 0.39	1.19 ± 0.11	1.34 ± 0.12	2.59 ± 0.17	1.88 ± 0.10	1.25 ± 0.11	5.0

[a] BDL: below detection limit (<0.002 mg/l).

Table 5
Recovery (%) of metals in each sequential extraction step for non-sintered LWA pellets ($n = 3$)

Element	Recovery (%)					
	A[a]	B	C	D	E	F
Cd	–	–	3.5 (0.1)	17.5 (0.9)	77.3 (3.3)	1.6(0.1)
Cr	0.5 (0.1)[b]	0.3 (0.0)	13.9 (0.8)	17.0 (0.9)	40.0 (2.9)	28.3 (2.5)
Cu	0.4 (0.0)	0.7 (0.1)	6.5 (0.5)	14.4 (1.0)	53.2(4.5)	24.9 (2.7)
Pb	–	3.5 (0.4)	3.5 (0.4)	22.8 (1.9)	25.6(3.5)	44.6 (5.0)

[a] Extracts: (A) water-soluble, (B) ion-exchangeable, (C) bound to carbonates, (D) bound to Fe–Mn oxides, (E) bound to organic matter and (F) silicates.
[b] Values presented in parentheses are the relative standard deviations.

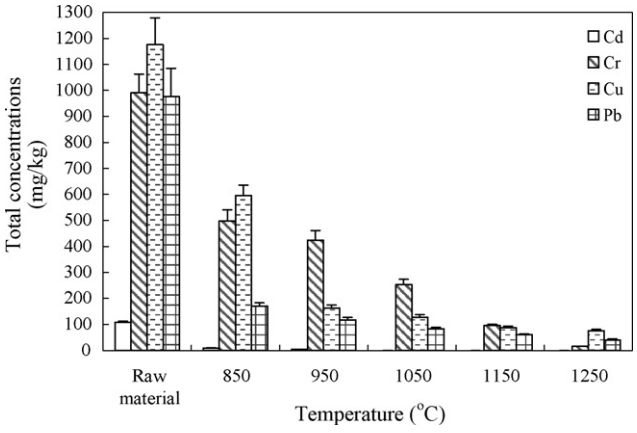

Fig. 4. Total metal concentrations at different sintering temperatures.

and ground-water resources; pretreatment is thus needed before utilization.

Fig. 4 shows the total metal concentration at different sintering temperatures. As can be seen, the concentration of Cd, Cr, Cu, and Pb in raw LWA pellets amount to 108.4, 990.3, 1175.4, and 976.0 mg/kg, respectively. With increasing sintering temperatures, the amounts of metals leached decreased, resulting in a falling trend in the total concentrations. At sintering temperature of 1150 °C, the concentrations of Cr, Cu, and Pb leached dropped to 96.2, 88.4, and 60.6 mg/kg, respectively, with Cd undetected. Concentrations of metals leached from LWA sintered at this temperature were much lower than the regulatory threshold [17]. Sintering at higher temperature of 1250 °C further reduced the concentrations of Cr, Cu, and Pb to 15.8, 75.8, and 41.0 mg/kg, respectively.

3.3. Morphology analysis with SEM/EDX

Fig. 5 shows the SEM and EDX images of the non-sintered raw aggregate pellets for manufacturing LWA. A fragmented structure can be seen in the SEM image while elemental analysis performed by EDX revealed that the pellets contained Si, O, Al, Ca, and Fe. Hence, the crystals formed were compounds of SiO_2 and Al_2O_3. Owing to the agglomeration of the particles, accurate quantitative measurement could not be made by surface analysis.

Step 3 of the sequential extraction method uses NaOAc/HOAc (pH ~ 5) as reagent, simulating leaching under acid rain. Fig. 6 shows the SEM/EDX image of NaOAc/HOAc-leached LWA. As can be seen, the shape of the sphere surface had turned irregular, indicating that some of the matters on the sphere surface had been extracted in this step. Elemental analysis performed by EDX revealed that the residue contained SiO_2 with Al, Ca, K, Cd, and S being leached in the process. This implies that only weak physical bonds are formed between these elements and the compounds on the residue surface, and thus they are leached easily, posing a detrimental impact on the environment.

Further extraction using reagents $NH_2OH^{\bullet}$ HCl (Step 4) and $HNO_3 + H_2O_2$ (Step 5) simulated the leaching of toxic metals under reducing and oxidizing conditions. Fig. 7 depicts the SEM/EDX image of LWA at the final step of extraction using $HNO_3 + H_2O_2 + HF$. As can be seen, under strong reducing condition, some of the oxidized metals were extracted and small particles were formed. The broken sphere was filled with many smaller spheres composed of Al, Mg, and Si oxides as seen in the EDX image. Elemental analysis performed by EDX revealed that the residue contained mainly SiO_2 and other metal oxides with Fe, Mn, As, Pb, Cu, and Zn being leached in the

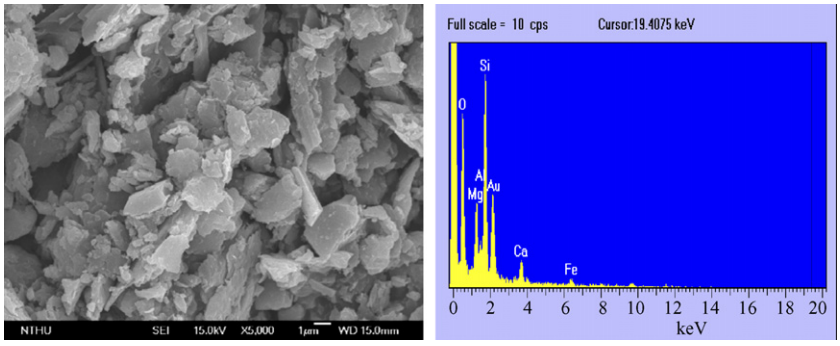

Fig. 5. SEM/EDX analysis of non-sintered raw aggregate pellets.

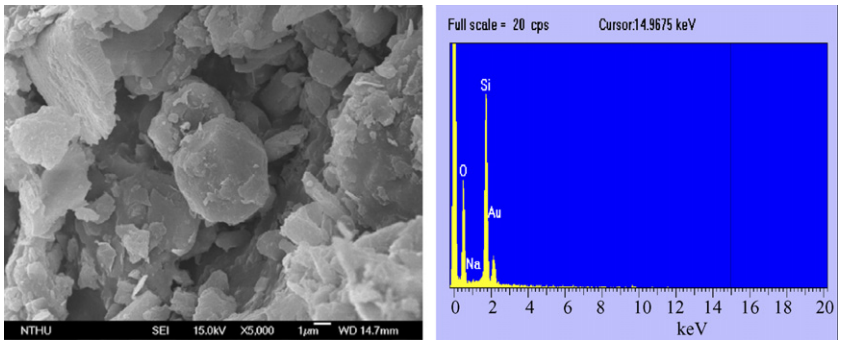

Fig. 6. SEM/EDX analysis of NaOAc/HO Ac-leached LWA.

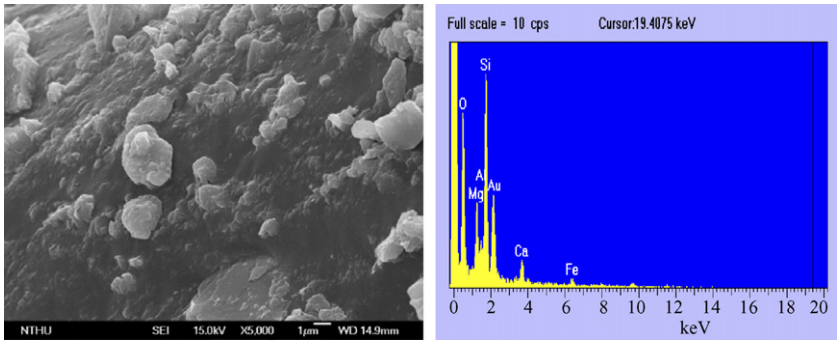

Fig. 7. SEM/EDX analysis of $HNO_3 + H_2O_2 + HF$-leached LWA.

process. This implies that stronger chemical bonds are formed between these elements and the compounds on the residue surface, making it difficult for them to be leached even under acid rain condition. In other words, the toxic metals present in the LWA cannot be easily leached and pose no harmful impact on the environment.

3.4. Physical properties of metal sludge-based LWA

Table 6 lists the physical properties of metal sludge-based LWA sintered at different temperatures. As can be seen, the higher the sintering temperature, the lower the hydration rate. Beyond 1050 °C, the hydration rate drops below 5%. It can be attributed to more complete vitrification of the LWA surface at higher sintering temperature. As mentioned above, LWA has a porous structure; thus, the hydration rate is directly related with the number of open pores on the surface. On the other hand, the porosity also affects the compressive strength of the LWA. Higher compressive strength can be obtained using more densified aggregates with spherical shape, good surface polish, higher density, low hydration rate, and small pores. In this study, the main concern is to achieve better expansion and low weight and density of obtained LWA. As seen in Table 6, the lowest density of 0.74 g/cm^3 can be obtained at sintering temperature of 1150 °C. Below 1150 °C, the sintering temperature is too low to achieve complete vitrification of the raw pellet surface. On the other hand, sintering beyond this temperature will melt all crystals, thus reducing the pore ratio, which in turn increases the density to 1.18 g/cm^3. Compressive strength was found to increase with increasing sintering temperature and reached its first peak of 7.55 MPa at 1050 °C. The reduction in compressive strength at 1150 °C can be attributed to the lower density as a result of an increase in porosity. Finally, with increasing density at 1250 °C, the compressive strength rises again to its highest degree of 8.04 MPa.

Table 6
Physical properties of metal sludge-based LWA

Sintering temperature (°C)	Hydration rate (%)	Apparent specific density (g/cm^3)	Compressive strength (MPa)
850	22.15 ± 2.11	1.11 ± 0.06	3.33 ± 0.25
950	12.03 ± 0.87	1.07 ± 0.03	5.49 ± 0.18
1050	7.56 ± 0.46	0.89 ± 0.02	7.55 ± 0.31
1150	4.51 ± 0.33	0.74 ± 0.02	4.41 ± 0.26
1250	4.20 ± 0.19	1.18 ± 0.07	8.04 ± 0.35

4. Conclusion

Great care should be taken when using recycled resources to manufacture LWA because of the different leachability of toxic elements present in the waste materials. Knowledge of the chemicals and physical properties of metal sludge-based artificial lightweight aggregate is needed to assess the risk of potential environmental mobility of the trace toxic metals.

The findings of this study reveal that sintering of metal sludge-based artificial lightweight aggregate in a tunnel kiln can promote rapid vitrification of the raw pellet surface, thus facilitating the expansion of the LWA, which is best achieved at 1150 °C. The concentrations of metals leached tend to decrease with increasing sintering temperature. Results obtained by

sequential extraction show that concentrations of Cd, Cr, Cu, and Pb in LWA sintered at 1150 °C for 15 min dropped significantly to the regulatory threshold. This gives evidence that metal sludge-based LWA not only possesses good physical properties, but also poses no harmful effect on the environment.

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