Journal of Hazardous Materials 159 (2008) 499–504

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Study on the characteristics of building bricks produced from reservoir sediment

Kung-Yuh Chiang*, Kuang-Li Chien, Sue-Jean Hwang

Department of Environmental Engineering and Science, Feng-Chia University, Tai-Chung 407, Taiwan

ARTICLE INFO

Article history:
Received 18 May 2007
Received in revised form 3 December 2007
Accepted 18 February 2008
Available online 23 February 2008

Keywords:
Sintering
Reservoir sediment
Building brick

ABSTRACT

This research investigates the feasibility of building bricks produced from reservoir sediment sintering using various sintering temperatures and clay additions. The experimental results indicate that sintered specimen densification occurred at sintering temperatures of 1050–1100 °C. Increasing the sintering temperature decreases the water absorption and increases the shrinkage, density and compressive strength of sintered specimens. The experiments were conducted at a temperature ranged from 1050 to 1150 °C with clay addition contents varying from 0% to 20%. All sintered specimens made from reservoir sediment were in compliance with Taiwan building bricks criteria. This means that raw materials for producing building bricks can be replaced with reservoir sediment. The metals concentrations of the leachate from the toxicity characteristics leaching procedure (TCLP) test are all complying with the current regulatory limits. These results confirm the feasibility of using reservoir sediment to produce sintered construction brick.

1. Introduction

Poor soil conservation, frequent typhoons and the unique geography of Taiwan cause drinking water shortages, increased reservoir sediment quantity and reduced reservoir storage capacity. According to the annual report on reservoir operation and maintenance in 2006, the average quantity of reservoir sediment was approximately 23% of the reservoir storage capacity. This is a serious deposition problem in Taiwan's reservoirs. The total storage capacity of Taiwan's reservoirs was nearly 2000 million tons per year [1]. It was estimated that the quantities of reservoir sediment produced annually is approximately 460 million tons per year. This is expected to continue to increase in the future. Sanitary landfills are normally used for reservoir sediment disposal. The Taiwan Government has a waste management strategy that aims to reduce landfill disposal and increase beneficial reservoir sediment reuse. Waste treatment, disposal and resourcification have recently become important public concerns and environmental issues. To implement and meet the goal of zero waste, the Taiwan government has established many strategies for waste recovery and recycling. Among these strategies, non-hazardous inorganic wastes or residues can serve as raw materials for the manufacture of bricks, aggregates, and other reusable products using thermal treatment technologies.

Sintering treatment technology is becoming more attractive as an alternative method for the recovery and recycling of inorganic wastes and residues in Taiwan. Over the last decade many researches have successfully developed suitable products made from various wastes or residues by sintering. Numerous wastes or residues, such as pulverized fuel ash (PFA), bottom ash and air pollution control (APC) residues from municipal solid waste (MSW) incinerators, sewage sludge ash, water treatment sludge, dam sediment, slag from steel production, molten slag from incinerator residues, or various inorganic mixtures have been studied for "materials from waste" (MfW) applications. It is important for the MfW application that the physical–chemical, mechanical, and hazardous characteristics of the different MfW manufactured are widely discussed. The MfW potential applications include lightweight aggregate, bricks, tiles and other construction products [2–12].

In recognition of the trend toward increased use of reservoir sediment as construction materials, the objective of this study was to investigate the properties of sintered specimens manufactured using reservoir sediment with added clay at different sintering temperatures. The added clay effects and sintering temperature on the physical–chemical characteristics, mineralogy and micro-structure of the sintered specimens are also discussed.

2. Experimental

2.1. Materials

Representative reservoir sediment samples were collected from the drying beds at Shi-Men Dam in Tao-Yuan County, Taiwan. This dam, which began operation in 1964, is a typical water supply and agricultural irrigation water system capable of storing

* Corresponding author. Tel.: +886 4 24517250x5216; fax: +886 4 24517686.
E-mail address: kychiang@fcu.edu.tw (K.-Y. Chiang).

0304-3894/$ – see front matter
doi:10.1016/j.jhazmat.2008.02.046

approximately 300 million tons. The field sampling procedure has evolved for determining composition based on the quartered and random sampling techniques. To ensure that the samples obtained are representative, a sufficiently large sample weight must be correctly collected for quartering until a sample weight of about 100 kg was obtained. The collected reservoir sediment had agglomerated and was therefore mechanically shredded and sieved to produce particles between 74 and 300 μm. The shredded reservoir sediments were homogenized, then placed into a pan and laboratory combustor dried at 105 °C for 48 h. After the samples were dried and cooled, they were sealed in the plastic box until they were tested. Reagent grade clay was purchased from a chemical company. Due to the chemical composition of selected clay was similar to the reservoir sediments, the selected clay was used to compare the different materials effect on characteristics of sintered products. The clay was also sieved before use in subsequent experiments.

2.2. Characterization of reservoir sediment

The moisture content of the reservoir sediment samples was determined by heating to 105 °C for 48 h. The combustible fraction of the samples was determined in triplicate using American Public Health Association (APHA) standard methods [13]. Inductively coupled plasma optima optical emission spectroscopy (ICP-OES, PerkinElmer, Optima 2000DV, plasma: 15 l/min, 1300 W) was used to determine the chemical composition of the reservoir sediment and clay. Crystalline minerals were identified by X-ray diffraction (XRD, MAC Science, MXP3) using 30 mA, 40 kV Cu Kα radiation. The pH was determined in triplicate using dried sample aqueous extracts at a 1:10 solid: distilled water ratio (w/v).

The Pb, Cd, Cu, Cr, and Zn concentrations were determined using nitric acid (HNO_3)/hydrogen peroxide (H_2O_2) digestion followed by flame atomic absorption spectroscopy (FAAS, Hitachi, Z-8200, wavelengths were between 213.9 and 357.87 nm). The toxicity characteristic leaching procedure (TCLP) test was conducted according to the Environmental Protection Administration (EPA) of Taiwan (NIEA R201.10T) [14]. This involves the addition of an acetic acid solution (0.57%, v/v) to the samples at a ratio of 2 l of leachant to 100 g of dried sample. After 18 h the leachate was filtered off and analyzed using FAAS for Pb, Cd, Cu, Cr, and Zn.

2.3. Preparation of reservoir sediment specimen and sintering operation procedure

Dried reservoir sediment samples and clay with particle sizes between 74 and 300 μm were blended to produce homogenous mixes with clay additions of 0%, 5%, 10%, and 20% (by dry weight). Uniaxially pressed 'green' compacted samples were prepared by adding water (20% weight) to the dry powder and pressing at 60 kgf/cm^2 (800 psi). This formed cylindrical specimens sized approximately 55 mm in height and 20 mm diameter. The green specimens were sintered at different sintering temperatures and analyzed for determining their characteristics, respectively.

The heating profile used in the sintering experiments is shown in Fig. 1. The temperature was increased at 10 °C/min in an electric furnace (DENGYNG, DF-404). The first dwell was at 105 °C for 60 min to evaporate moisture. The temperature was then increased to the sintering temperature, which ranged between 1000 and 1150 °C and held for 60 min dwell.

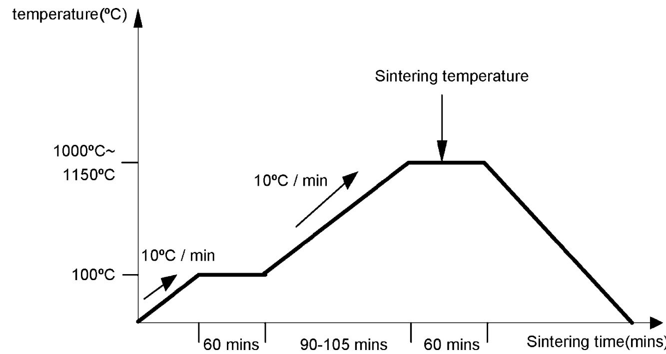

Fig. 1. The temperature profile used to sinter samples.

2.4. Characterization of sintered samples

The density, water absorption, and linear shrinkage of the sintered specimens were calculated from their weights and dimensions in terms of ASTM C373 standard [15]. The density of the sintered specimens was determined using the dry mass to volume ratio. The volume was determined using Archimedes method [16]. Water absorption was determined by weighing (W_1) the sintered samples, immersing them in water for 24 h, wiping the samples dry and re-weighing (W_2). Water absorption was calculated from the ratio between W_2–W_1 and W_1. Open porosity was also calculated from the ratio between W_2–W_1 and external volume of sintered specimen. The change in specimen volume during sintering was determined using:

$$V_0 = \pi \left(\frac{d_0}{2}\right)^2 \times l_0$$

where V_0 is the volume of green specimens; d_0 the diameter of green specimens; l_0 is the length of green specimens.

$$V_1 = \pi \left(\frac{d_1}{2}\right)^2 \times l_1$$

where V_1 is the volume of sintered specimens; d_1 the diameter of sintered specimens; l_1 is the length of sintered specimens.

$$\text{Dimensional change}\,(\%) = \frac{V_1 - V_0}{V_0} \times 100$$

Unconfined compressive strength was measured using the Taiwan Environmental Protection Administration (EPA) Standard method (NIEA R 206.22C) [17]. Strengths were obtained in triplicate using a loading rate of 6 kgf/s. The micro-structures of the sintered samples were examined using scanning electron microscopy (SEM, Hitachi, S3000). The crystalline phases were identified using XRD.

3. Results and discussion

3.1. Properties of reservoir sediment and clay

Table 1 shows the pH, moisture content, combustible fraction, percentage ash and metals content (mg/kg) data for the reservoir sediment and clay. The water content and combustible fraction of the reservoir sediment were 28.04 ± 0.67% and 4.64 ± 0.06%, respectively. The total metal concentrations in the reservoir sediment and clay were relatively low. The Zn concentrations were typically 15.93 ± 1.42 mg/kg for clay and 132.04 ± 10.19 mg/kg for reservoir sediment. Other metal concentrations were less than 30 mg/kg or below detection limits.

TCLP leachate analysis data is also given in Table 1. The concentrations of the selected metals leached from the reservoir sediment were below current Taiwan EPA regulatory thresholds (Pb: 5 mg/l, Cd: 1 mg/l, Cr: 5 mg/l, Zn: 25 mg/l). Meanwhile, Cd and Cr were not detected in the TCLP leachate. Chemical composition data expressed as percentage of major oxides is shown

Table 1
Principal properties and metal contents of the tested materials

Properties	Reservoir sediment	Clay
pH (in H_2O)	6.82 ± 0.16[a]	3.59 ± 0.01
Moisture (%)	28.04 ± 0.67	16.63 ± 0.06
Combustible (%)	4.64 ± 0.06	3.42 ± 0.03
Ash (%)	66.96 ± 0.71	79.95 ± 0.30
Total metal content (mg/kg)		
Zn	132.04 ± 10.19	15.93 ± 1.42
Pb	28.23 ± 0.85	2.72 ± 0.33
Cu	27.04 ± 1.85	0.87 ± 0.08
Cr	16.35 ± 1.33	<0.12
Cd	<0.16	<0.16
TCLP concentration (mg/l)		
Zn	1.15 ± 0.25	1.30 ± 0.05
Pb	0.07 ± 0.02	0.10 ± 0.02
Cu	0.03 ± 0.03	0.07 ± 0.01
Cr	<0.006	<0.006
Cd	<0.008	<0.008
Chemical composition (%)		
SiO_2	70.14	70.40
Al_2O_3	15.45	15.17
Fe_2O_3	5.37	3.15
CaO	0.64	1.17
MgO	1.64	2.13
Na_2O	1.02	0.33
K_2O	5.24	1.26

TCLP regulatory thresholds: Pb: 5 mg/l; Cd: 1 mg/l; Cr: 5 mg/l; Zn: 25 mg/l.
[a] Data obtained from triplicate.

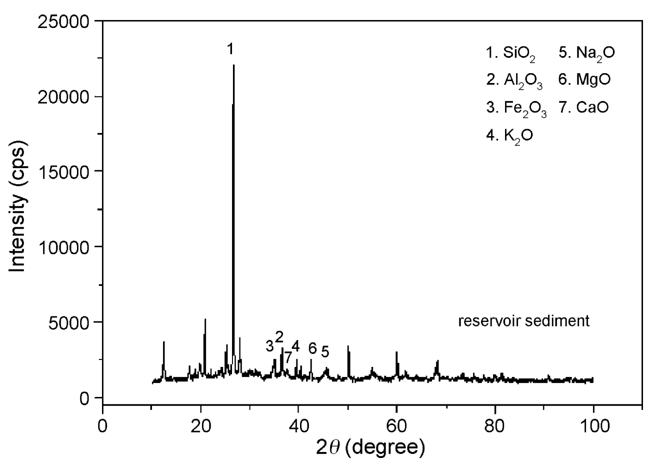

Fig. 2. XRD data for the as-received reservoir sediment.

in Table 2. This indicates that the main reservoir sediment components were SiO_2 (70.14%), Al_2O_3 (15.45%), Fe_2O_3 (5.37%), K_2O (5.24%) and MgO (1.64%). Fig. 2 gives XRD data for the reservoir sediment. This shows that silica (SiO_2) was the major crystalline phase present. Relatively low intensity peaks corresponding to those for Al_2O_3, MgO, K_2O, Na_2O, CaO and Fe_2O_3 were also detected.

Table 2
TCLP metal leachate concentrations of sintered specimens (mg/l)

	Sintering temperature 1100 °C				Sintering temperature 1150 °C			
	0% clay	5% clay	10% clay	20% clay	0% clay	5% clay	10% clay	20% clay
Pb	<0.009	0.02	<0.009	<0.009	<0.009	<0.009	<0.009	0.02
Cd	0.02	<0.008	<0.008	<0.008	0.03	<0.008	<0.008	<0.008
Cr	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
Cu	<0.005	<0.005	<0.005	0.01	<0.005	<0.005	<0.005	<0.005
Zn	0.86	0.44	0.13	0.18	0.98	0.67	0.17	0.11

TCLP regulatory thresholds: Pb: 5 mg/l; Cd: 1 mg/l; Cr: 5 mg/l; Zn: 25 mg/l.

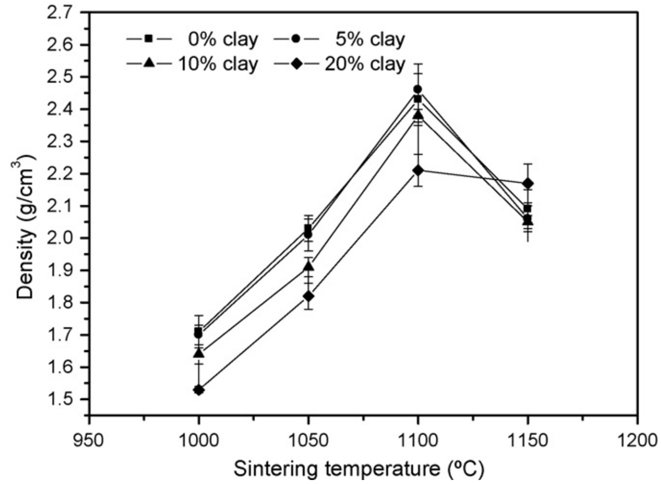

Fig. 3. Effect of sintering temperature on the density of specimens.

3.2. Properties of sintered specimens

3.2.1. Density

The effect of sintering temperature on the sintered density of reservoir sediments is shown in Fig. 3. Sintering temperature is a key factor controlling the characteristics of sintered specimens, with less clay content producing higher densities of sintered specimens. Fig. 3 showed that the density of the sintered specimens ranged from 1.82 to 2.45 g/cm^3 at sintering temperature of 1050 °C and above. Normally, bricks were made from clay had a bulk density of 1.8–2.0 g/cm^3 [18]. In this study, the densities of sintered specimens were higher than that of empirical criteria for building brick, it can concluded that densification of sintered specimens was occurred at sintering temperature of 1050 °C.

The density of sintered specimen increased significantly with increasing sintering temperature (1000–1150 °C) and decreasing clay addition. A maximum density of approximately 2.5 g/cm^3 was obtained at sintering temperature 1100 °C and 0% clay addition (100% reservoir sediment). That is, raw material (clay) for producing building bricks may be replaced with reservoir sediment. In case of 20% clay addition, as sintering temperature increased from 1100 to 1150 °C, the density of sintered specimens was slightly decreased. The density of approximately 2.2 g/cm^3 was obtained at sintering temperature between 1100 and 1150 °C. However, in case of sintering temperature of 1150 °C, the density of sintered specimens decreased significantly with the clay addition decreased. This is due to the thermal expansion of sintered specimens occurred below 20% clay addition and sintering temperature of 1150 °C. In this study, sintering the reservoir sediment that is replaced with different clay addition ratio can produce relatively high density building bricks. The densities of sintered specimens were above Taiwan's empirical criteria, indicating that these ceramic materials are good for construction application.

According to the results of open porosity, the open porosity decreased with increasing the sintering temperature and decreasing clay addition. The open porosity decreased ranging from 40% to 5% when the sintering temperature was increased between 1000 and 1100 °C (as shown in Fig. 4). The less open porosity occurred at 1100 °C and above where the sintered specimens were well densified. The results are in good agreement with previous study results that densification is a pore-filling and shrinkage process [19].

3.2.2. Water absorption

The water absorption is an effective index in evaluating the quality and densification of building brick. Water absorption is based on

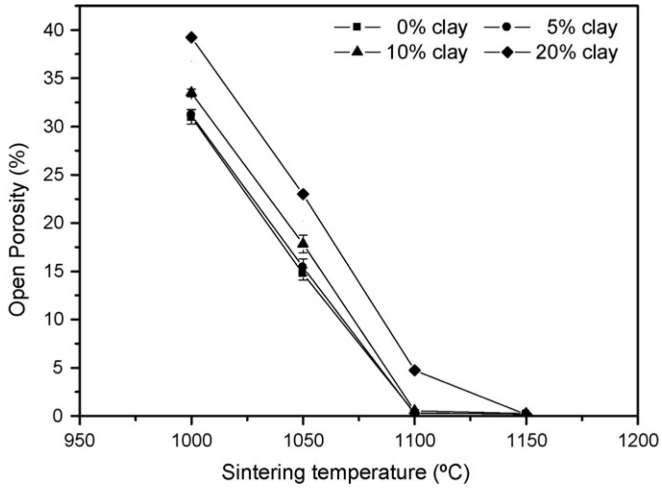

Fig. 4. Effect of sintering temperature on the open porosity of specimens.

the amount of open pore in sintered specimen. This means that the high water absorption indicated that the sintered specimens had a large number of open pores. This is also a function of compressive strength and the density of the sintered specimen. According to the results of previous open pore analysis, the water absorption of sintered specimens decreases significantly with increasing sintering temperature (as shown in Fig. 5). This is due to the open porosity of sintered specimens decreased significantly with increasing sintering temperature. The results also indicated that the water absorption decreased slightly with decreasing clay addition. In this work, water absorption decreases by above 80% when temperature is raised from 1000 to 1100 °C for all tested clay addition. However, with the sintering temperature higher than 1100 °C, the water absorption showed that no further significant variation occurred with an increasing clay addition ratio. The results are in good agreement with previous study results that water absorption decreased from 20% to 5% with increasing sintering temperature from 1000 to 1100 °C [5]. The results also reveals that all water absorption results for the evaluated sintered specimens sintered at 1050 °C and above were in compliance with the Taiwan's building brick criteria (below 15%) [20].

3.2.3. Dimensional change after sintering

The dimensional change in sintered specimens is a prominent indicator for the building brick quality. Controlling shrinkage and densification are both critical in reusing recycled materials for building materials. The densification of sintered specimens occurred through increasing the shrinkage rate of the sintered specimens. Fig. 6 reveals that the shrinkage rate increased significantly with increased sintering temperature. In this study, a maximum of 32% shrinkage occurs at sintering temperature 1150 °C and 20% clay addition. In the case of 0–10% clay addition, the shrinkage of sintered specimen decreased slightly with increasing temperature from 1100 to 1150 °C. Therefore, the density of sintered specimens decreased slightly for sintered at 1150 °C and 0–10% clay addition (as shown in Fig. 3). Although expansion of the sintered specimen occurred under these operating circumstances, the sintered specimens maintained good densification and high shrinkage. The sintered specimens produced a significant densification, resulting in total volume shrinkage. Accordingly, a contrary trend occurred between the dimensional change and water absorption of sintered specimens (as shown in Figs. 3 and 6). The shrinkage rate was increased with water absorption decreased. It can concluded that the better conditions for sintered specimens were higher shrinkage rate and lower water absorption.

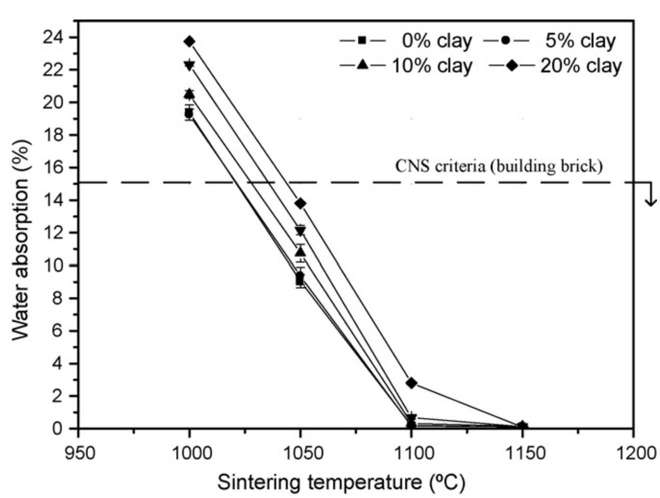

Fig. 5. Effect of sintering temperature on the absorption of water by specimens.

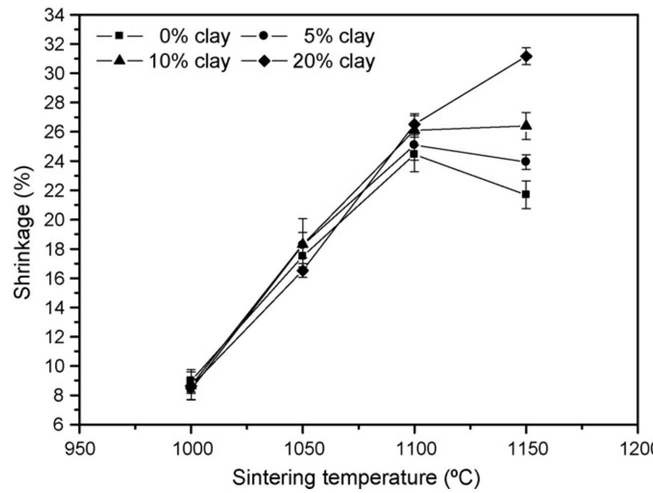

Fig. 6. Effect of sintering temperature on the shrinkage of specimens.

3.2.4. Compressive strength

The compressive strength is an important factor for using recycled material as construction material. As this study shows, the compressive strength was mainly affected by the sintering temperature (as shown in Fig. 7). The sintering temperature

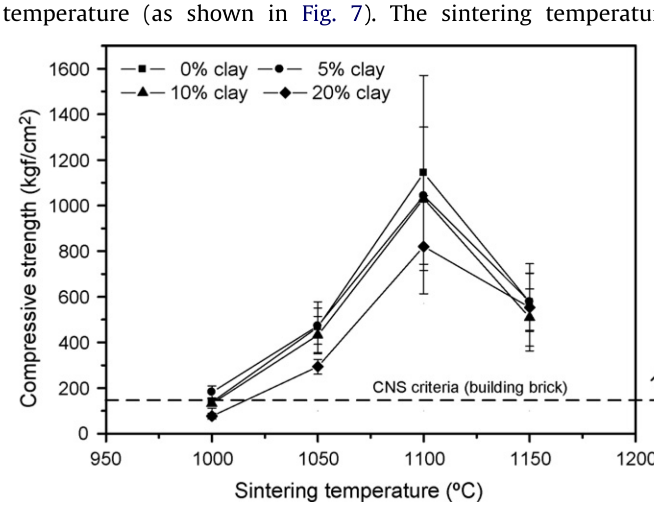

Fig. 7. Effect of sintering temperature on the compressive strength of specimens.

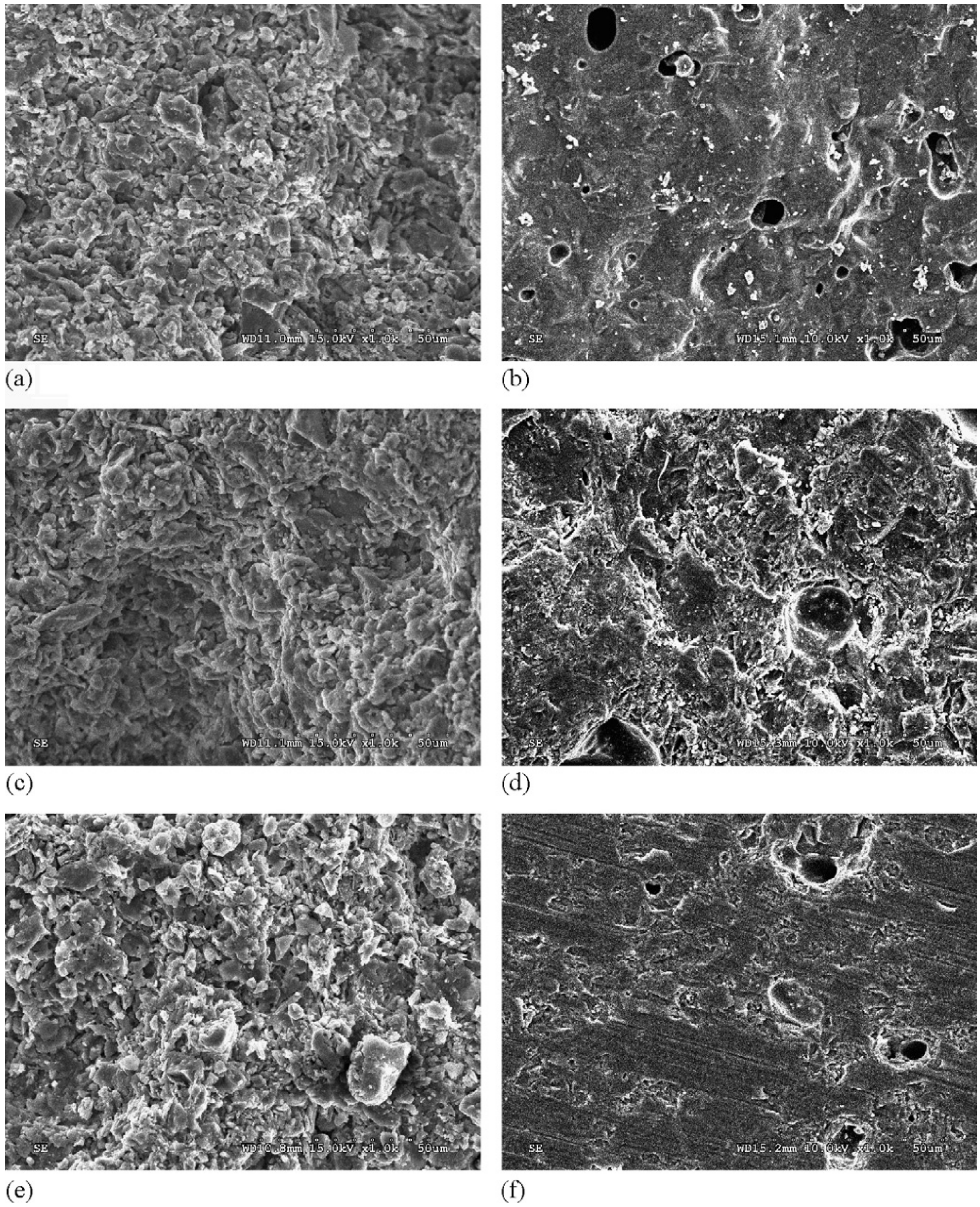

Fig. 8. Scanning electron micrograph images of specimens sintered at 1000 and 1150 °C: (a) 0% clay sintered at 1000 °C (1000×); (b) 0% clay sintered at 1150 °C (1000×); (c) 10% clay sintered at 1000 °C (1000×); (d) 10% clay sintered at 1150 °C (1000×); (e) 20% clay sintered at 1000 °C (1000×); (f) 20% clay sintered at 1150 °C (1000×).

effect increased the compressive strength through densification. Fig. 7 indicates that higher compressive strength developed above 1100 °C sintering temperature and 0–20% clay addition, ranging from approximately 300 to 1200 kgf/cm^2, thereby fulfilling the code requirement (150 kgf/cm^2) for construction building bricks [20]. Maximum compressive strength occurs at 1100 °C sintering temperature with 0% clay addition (as shown in Fig. 7). The compressive strength decreased with increasing temperature from 1100 to 1150 °C. As discussed previously, 0–10% clay addition produced swelling in the sintered specimen and density of sintered specimens decreased at a sintering temperature range of 1100–1150 °C. Therefore, the compressive strength of the sintered specimen decreased resulting in decreasing the sintered specimen density. The compressive strengths of sintered specimens were in compliance with Taiwan's building brick criteria when sintered at temperatures above 1050 °C. The good quality and high compressive strength of building bricks were successfully manufactured from reservoir sediment and clay even if reservoir sediment served as raw material alone.

3.2.5. *Heavy metals characteristics of sintered specimen*

Table 2 summarizes the content of Pb, Cd, Cr, Cu and Zn found in specimens sintered in the 1100 and 1150 °C temperature range. The

Table 3
The XRD peak intensity of the major peak of crystalline phase identified in reservoir sediment and sintered specimens at sintering temperature 1150 °C

	Quartz $2\theta = 26.64^\circ$	Aluminum oxide $2\theta = 35.15^\circ$	Hematite $2\theta = 33.11^\circ$
As-received reservoir sediment	22,113	2226	1393
Sintered specimen (0% clay)	5,940	1490	2120
Sintered specimen (5% clay)	5,423	1386	1730
Sintered specimen (10% clay)	3,190	1160	1436
Sintered specimen (20% clay)	3,116	1160	1390

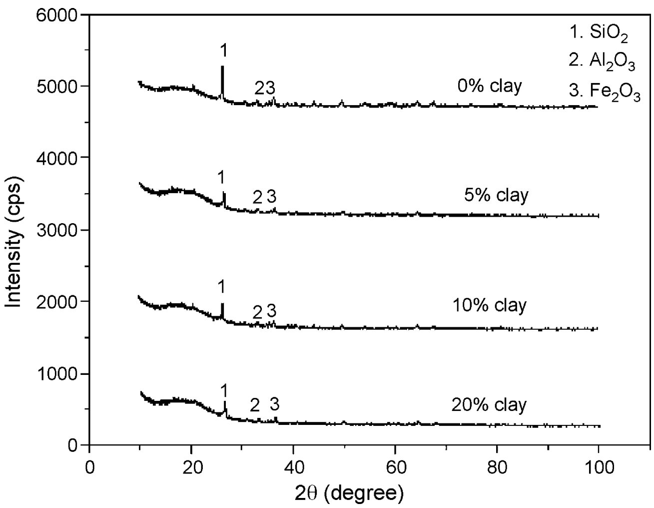

Fig. 9. XRD data for reservoir sediment sintered at 1150 °C.

total TCLP leachate concentrations for all tested metals in the sintered specimens revealed a decreasing tendency compared to the reservoir sediment properties. Based on these analysis results, the TCLP leachate concentrations for the tested metals in all sintered specimens were in compliance with Taiwan EPA regulatory limits (Pb: 5 mg/l, Cd: 1 mg/l, Cr: 5 mg/l, Zn: 25 mg/l).

3.3. Micro-structural analysis of sintered specimens

The SEM results of the sintered specimens at 1000 and 1150 °C and different amounts of added clay are shown in Fig. 8. It is clear that the particles of sintered specimens for sintered at 1150 °C are very closely connected together and have a relatively densified structure. That is, the densified matrix material for sintered at 1150 °C showed better surface characteristics than that for sintered at 1000 °C (as shown in Fig. 8). As previous results indicate, after being sintered at 1150 °C, the sintered specimens have a good quality and higher compressive strength of the building brick than that of specimens sintered at 1000 °C.

Fig. 9 shows the X-ray diffraction pattern of the sintered specimens. XRD result comparisons for the as-received reservoir sediment samples and sintered specimens at sintering temperature 1150 °C with various clay additions indicated that no significant difference was observed. Table 3 shows the XRD intensities of the major identified mineral species peaks. The intensities of the major peaks decrease insignificantly with the amount of added clay increased. XRD analysis results indicated that the major mineral phases of the sintered specimens present were quartz (SiO_2), alumina (Al_2O_3) and hematite (Fe_2O_3).

4. Conclusions

This study examined the characteristics of reservoir sediment sintered under various sintering conditions, considering the sintering temperature and amount of added clay. The conclusions derived from the aforementioned experiments are as follows:

1. The densification of sintered specimens occurred at 1050 °C sintering temperature with reservoir sediment serving as the raw material and with 0–20% clay addition. A maximum density of approximately 2.5 g/cm^3 occurred at 1100 °C and 0% clay (i.e. 100% reservoir sediment) addition.
2. The shrinkage of sintered specimens increased significantly with increased sintering temperature. The shrinkage also improved the compressive strength, density and water absorption of the sintered specimens. The compressive strength and density of the sintered specimens increased as the shrinkage increased. However, the water absorption decreased as the shrinkage increased.
3. The physical and chemical characteristics of the sintered specimens sintered above 1050 °C with 0–20% clay addition were in compliance with Taiwan's relevant criteria for building brick applications. The TCLP leachate concentrations of Pb, Cd, Cr, Cu and Zn also complied with Taiwan EPA regulatory limits. The results of this research confirm the feasibility of using sintered recycled materials for building construction and promote the potential application of reservoir sediment in brick manufacturing.

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