2014 4th International Conference on Future Environment and Energy
IPCBEE vol.61 (2014) © (2014) IACSIT Press, Singapore
DOI: 10.7763/IPCBEE. 2014. V61. 2

Effects of Sintering Temperature on Water Retention Characteristics of Sewage Sludge Ash- Diatomite Based Porous Ceramics

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Abstract. In this investigation, the following operating conditions are applied to developing porous ceramic products; a constant pressure of 5 MPa, a sintering temperature of 1,000-1,270^{o}C, a sintering time of 2 h, and a percentage of sewage sludge ash in waste diatomite of 0-20%. Decrease of the pore size in temperature range between 1100 and 1270 ℃ was associated with a different sintering behaviour between diatomite and sewage sludge ash. The porous ceramic samples contained sewage sludge ash showed low thermal conductivity properties (0.28-0.56 W/mK), probably owing to the more pores than those in the concrete (1.5 W/mK). Water release ($t_{1/2}$ value) by the porous ceramic samples was decelerated by porous ceramic samples contained sewage sludge ash, due to the synergy effect of high water absorption by the sewage sludge ash and better than in the foamed glass material (4 h). In summary, porous ceramic samples contained the sewage sludge ash have excellent mechanical properties, making them feasible for use in water absorption and retention of porous ceramic applications.

Keywords: Diatomite, Sewage sludge ash, Porous ceramics, Compressive strength, Thermal conductivity

1. Introduction

In the Taiwan, the production of sewage sludge ash is currently at slightly over 5 million tonnes (dry solids) per annum. This figure is expected to increase in the future, as wastewater treatment methods become more effective and greater volumes of micro-organisms and solids are removed from the sewage effluent [1]. The disposal of treated sewage sludge requires careful consideration if it is to be managed in an environmentally acceptable and sustainable manner. Increasing demand for natural resources and a scarcity of environmentally acceptable solid waste disposal sites are motivating numerous municipalities in Taiwan to consider resource recovery as an alternative. At present, around 1.8 million tonnes of diatomaceous earth are mined worldwide annually [2]. Clearly, low-grade materials require purification but whether that purification is sufficient as diatomite obtained with a high specific surface area and impurities have an inferior porous micro-structure after sintering. Macroporous ceramics combine high permeability with favorable mechanical, thermal and chemical stability, and are therefore attractive for a wide range of industrial applications [3].

Sintering is a thermal process that transforms a compact powder into a bulk material, and is used in mass-producing complex-shaped components. Sintering is a complex process of microstructural evolution, which involves bond formation, neck growth, pore channel closure, pore shrinkage, densification, coarsening, and grain growth. Porous ceramics with well-defined macroscopic shapes and high mechanical stability can be fabricated using novel processing route, while retaining the intrinsic porosity of the porous powder from which they are manufactured [4]-[8]. Rising temperatures in large cities poses an increasing environmental threat, especially during the summer in Taiwan. This predicament arises from the increasing amount of heat generated by human activity (e.g., vehicles and air conditioners) and the increasing amount of surface areas covered by artificial materials with a high solar absorption capacity. This global warming phenomenon is referred to as the "heat island effect" [9]. Water absorption and retention of porous ceramics as building materials are characterized by their permanence, heat insulation [10] and water retention. Although the utilization of diatomite and sewage sludge ash has economic and environmental advantages, the water absorption, retention and thermal conductivity of this porous ceramic material in terms of service life is still largely unknown. This study demonstrates the feasibility of reuse diatomite and sewage sludge ash produced as water absorption and retention of porous ceramic is also examined by studying their water retention and thermal conductivity properties.

2. Materials and Methods

2.1. Materials

The waste diatomite and sewage sludge ash used were collected from the food-processing industry and refinery plants located in Taipei County, Taiwan. In total, 500 kg of waste diatomite and sewage sludge ash were obtained from the food-processing industry and refinery plants, respectively. The waste diatomite and sewage sludge ash were pulverized using a ball mill until they could pass through a 100 mesh sieve. The resultant pulverized waste diatomite and sewage sludge ash were then stored in a desiccator until testing.

2.2. Preparation of compacted sintered porous ceramics samples

The waste diatomite and the sewage sludge ash samples were oven-dried at 105^{o}C for 24 h and ground in a ball mill to form fine powders suitable for pressing. The powder samples were mixed with each other to prepare a known mass percentage of sewage sludge ash in diatomite in different concentration of sewage sludge ash (0-20% by mass) to produce porous ceramics samples. The content of the sewage sludge ash in the waste diatomite mixture was varied from 0% to 20% by mass. The samples were compacted at 5 MPa to form cylinder specimens (51.8 mm $^{(\Phi)}$×15 mm $^{(H)}$) that were then desiccated before testing. The compacted porous ceramic specimens were placed on a platinum plate and burnt in an electrically heated furnace using a ramp rate of 5^{o}C min^{-1}. The porous ceramic samples were then sintered at temperatures between 1000^{o}C and 1270^{o}C for 120 minutes. The sintered samples were then cooled to room temperature and stored in a desiccator for subsequent physical properties testing and microstructure analyses.

3. Results and Discussion

3.1. Characteristics of waste diatomite and the sewage sludge ash

The densities of the waste diatomite and the sewage sludge ash were 1.26 and 1.88 g cm^{-3}, respectively. The major constituents of the waste diatomite, Al_2O_3 and SiO_2 represent 1.08% and 93.6%, respectively. The major constituents of the sewage sludge ash; SiO_2, Al_2O_3 and Fe_2O_3 represent 59.1%, 16.0% and 4.5%, respectively.

3.2. Mechanical characteristics of porous ceramics

Table 1 shows the open porosity of the pure diatomite specimens that were fired at various temperatures. The porosity declined slowly from 1000^{o}C to 1270^{o}C (from 64.02% to 61.27%). By increasing the sewage sludge ash content, pore size distribution decreased. However, the rate of change was not constant. The high porosity was attributed to the unique porous mineralogical character of diatomite that contained 20% sewage sludge ash, the porosity of which did not change considerably during sintering. First, the open porosity declined gradually from 61.3% at 1000 ^{o}C to 59.2% at 1100 ^{o}C. In the second stage, the porosity decreased from 55.1% at 1200 ^{o}C to 49.7% at 1270 ^{o}C, and the rate of decline was higher than that in the first stage. In this stage, sintering reduced the volume, and most of the pores were closed.

The water absorption rate, which is the weight of the moisture in the pores as a fraction of the weight of the sintered specimen, is an effective index of the quality of porous ceramics. Table 1 shows the results of the water absorption tests on various sewage sludge ash -diatomite mixtures that were heated at four temperatures. Water absorption increased from 81.0% to 93.4%, 74.1% to 91.1%, 67.8% to 87.9%, and 59.7% to 85.2%, with heating temperatures of 1000 ^{o}C, 1100 ^{o}C, 1200 ^{o}C, and 1270 ^{o}C, respectively. The results show that, as the sewage sludge ash content declined, the water absorption of the porous ceramic samples increased. Furthermore, the amount of water absorbed by the porous ceramics decreased with an increase in the heating temperature. The decline in the rate of water absorption with increasing heating temperature (1200 ^{o}C) suggests that local liquid-phase sintering occurred, which contributed to a decrease in pore volume and the water absorption rate.

The compressive strength is the crucial index of the engineering quality of porous ceramic material. Table 1 shows the compressive strength test results for porous ceramics made from diatomite and sewage sludge ash mixtures. The compressive strength of the porous ceramics increased when the heating temperature increased from 1000 ^{o}C to 1270 ^{o}C. The results showed that the optimal heating temperature that maximized the compressive strength was 1270 ^{o}C. The compressive strength of the mixed porous ceramic samples of diatomite that contained the sewage sludge ash decreased slightly when the heating temperature increased above 1200 ^{o}C. The porous diatomite ceramic strength decreased when up to 20% of the sewage sludge ash was added to the porous ceramics that were heated to 1200 ^{o}C. The sewage sludge ash can be converted into porous ceramics by using this method. Consequently, the sewage sludge ash can be blended with diatomite to produce porous ceramics.

Table 1: Mechanical characteristics of porous ceramics

Mechanic Characteristic	Heating Temperature(℃)	Sewage Sludge Ash Replacement Level (%)				
		0	5	10	15	20
Porosity (%)	1000	64.02±0.17	63.05±0.24	62.86±0.20	62.63±0.21	61.37±0.19
	1100	63.41±0.33	62.48±0.19	61.37±0.11	60.18±0.26	59.16±0.22
	1200	62.59±0.20	61.58±0.11	58.98±0.22	56.75±0.23	55.01±0.13
	1270	61.27±0.12	58.48±0.23	55.89±0.28	53.42±0.19	49.57±0.25
Water absorption (%)	1000	93.39±0.24	89.51±0.23	87.08±0.14	84.87±0.85	81.01±0.53
	1100	91.13±0.47	87.17±0.29	82.57±0.20	78.11±0.13	74.09±0.25
	1200	87.85±0.21	83.56±0.33	78.63±0.14	72.59±0.23	67.76±0.16
	1270	85.23±0.12	78.58±0.21	72.49±0.20	66.76±0.13	59.45±0.25
Compressive strength (MPa)	1000	2.48±0.01	3.18±0.03	3.42±0.02	3.77±0.01	4.00±0.01
	1100	4.36±0.03	4.96±0.03	5.71±0.03	6.37±0.05	6.71±0.04
	1200	5.92±0.02	6.35±0.02	7.45±0.02	8.71±0.01	12.2±0.08
	1270	6.10±0.05	7.20±0.02	8.30±0.03	10.64±0.08	15.02±0.07

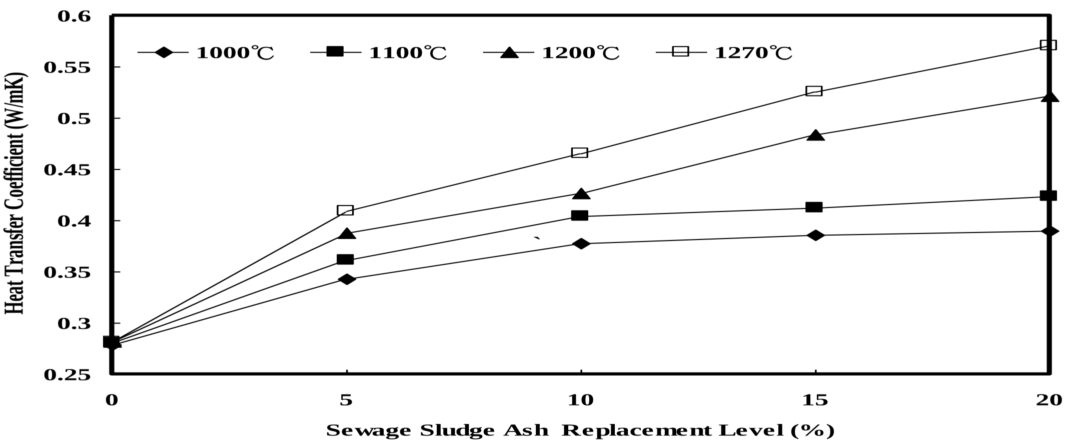


Fig. 1: Thermal conductivity of porous ceramics.

3.3. Thermal conductivity of porous ceramic samples

Fig. 1 shows the variation in thermal conductivity of waste diatomite containing sewage sludge ash sintered porous ceramic samples at various temperatures. When the amount of sewage sludge ash was increased from 5% to 20%, the thermal conductivity of the sintered porous ceramics was 0.342-0.389, 0.361-0.423, 0.388-0.521, and 0.41-0.57 W/ mK. Moreover, the thermal conductivity of the porous ceramic samples increased in conjunction with the sewage sludge ash content. This increase was attributed to the porous structure of sintered porous ceramic samples containing sewage sludge ash, resulting in a denser structure. This confirms the decrease in size of small pores and total porosity with increasing sintering temperature. Few micropores are present in samples sintered at 1000 ℃. They tend to close with increase of temperature and increase of sewage sludge ash content. The samples revealed a correlation between the density and thermal conductivity for sintered porous ceramic samples, in which the thermal conductivity increased with the density. In this study, the porous ceramic samples had a thermal conductivity of approximately 0.28-0.57 W/mK, which was lower than that for the concrete (1.5 W/mK). The porous ceramic samples exhibited properties of low thermal conductivity, which may be attributed to the larger number of pores compared to those in the concrete.

3.4. Water-retention properties of porous ceramic samples

The water-release parameter ($t_{1/2}$) was defined by the time required for half of the amount of water to be released from the samples. Fig. 2 shows the $t_{1/2}$ values as a function of the sewage sludge ash content of the samples. The $t_{1/2}$ values are low, with 50% of the Wa retained for 48 h in the porous ceramic samples containing sewage sludge ash samples at a relative humidity of 55% at 20 ^{o}C; this value is lower than that in pure diatomite porous ceramic samples when the heating temperature reached 1000 ^{o}C. Increasing the heating temperature from 1000 ^{o}C to 1200 ^{o}C decreased the water-retention properties of the resulting porous ceramic samples containing sewage sludge ash samples. When the heating temperature reached 1000 ^{o}C, the porous ceramic samples containing 20% sewage sludge ash had $t_{1/2}$ values of approximately 12 h; these values were larger than those for the porous ceramic samples containing 5% of the sewage sludge ash (7 h). Because the $t_{1/2}$ value of the foamed glass sample was approximately 4 h, the porous ceramic samples containing the sewage sludge ash exhibited excellent slow water-releasing properties, which may be attributed to the smaller pores, compared to those in the foamed glass. The large amounts of sewage sludge ash in the porous ceramic samples also facilitated a slow water release, which yielded acceptable water-retention properties. These properties make the porous ceramic samples containing sewage sludge ash samples promising for use as water-retaining materials to combat ''heat island'' effects.

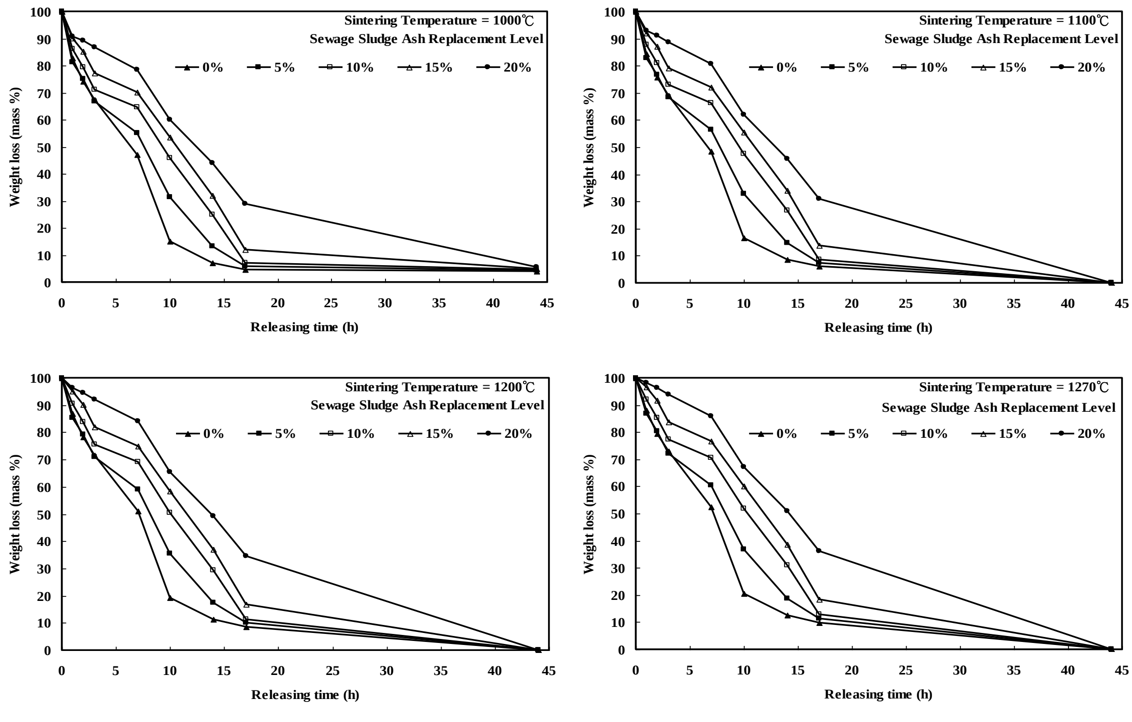
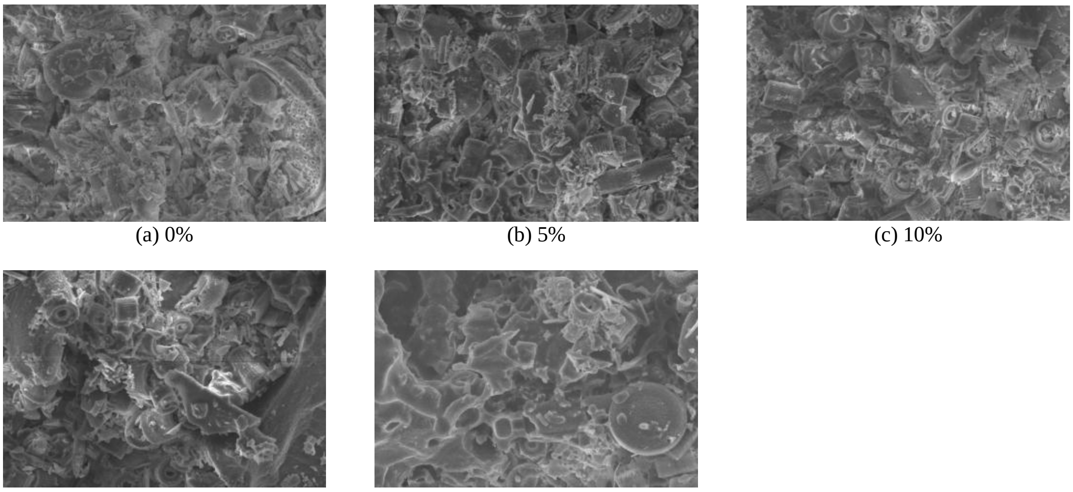


Fig. 2: Water-retention properties of sintered porous ceramics samples at various temperatures.

3.5. Scanning electron microscopic microphotographs of porous ceramics

Fig. 3 shows the SEM microphotographs of porous ceramic samples sintered at 1270 ^{o}C. Fig. 3(a) shows that a small fraction of the diatomite powder began to melt, the liquid phase accumulated in regions with a negative curvature, and the contact points between pairs of particles formed necks. The initially isolated diatomite particles were converted into an integral body, which contained numerous closed pores. A microstructural change was observed during sintering below 1270 ^{o}C. Cylindrical diatomite particles were identified easily, and a number of micropores were distributed. Scanning electron microscopic measurements revealed the sewage sludge ash in various proportions in the microstructures of porous ceramics (Figs. 3(b)-3(e)). The sewage sludge ash bonded the diatomite powder into relatively strong monoliths. However, a melt phase covered the diatomite particles and filled the diatomite pores when the sintering temperature was increased to 1270 ℃. Impurities in diatomite, such as K_2O, Fe_2O_3, and MgO, favor the formation of low-temperature eutectics and the subsequent formation of a melt phase in the silica-rich grains. The internal pore volume of diatomite that contained 20% of the sewage sludge ash was not reduced substantially after heating to 1270 ^{o}C (Fig. 3(e)). Slight fusion occurred at the particle contact points at 1270 ^{o}C. The powder partially melted, and both the interparticle pores and the internal structure collapsed.



(a) 0% (b) 5% (c) 10%

(d) 15% (e) 20%

Fig. 3: SEM microphotographs of porous ceramics samples.

4. Conclusions

The porous ceramics fabricated from waste material exhibited enhanced water absorption and retention capabilities. Moreover, the results of this study also indicated that water absorption and retention are dependent on the pore structures. Heating temperature is the crucial parameter in the controlled densification of porous ceramics and in forming monoliths with a well-defined porosity. The porous ceramic samples containing the sewage sludge ash exhibited low thermal conductivity properties, which may be attributed to the larger number of pores than those in the concrete. Additionally, water release ($t_{1/2}$ value) by the porous ceramic samples was decelerated using porous ceramic samples containing the sewage sludge ash because of the synergy effect of high water absorption by the sewage sludge ash. The $t_{1/2}$ values of the porous ceramic samples were higher than those in the foamed glass material. Porous ceramic samples containing sewage sludge ash is highly promising for use in water absorption and retention applications.

5. Acknowledgements

The authors would like to thank the National Science Council of the Republic of China, Taiwan, for financially supporting this research under Contract No. NSC 101-2221-E-197- 010- MY3.

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