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Article in *Journal of Porous Materials* · June 2018

DOI: 10.1007/s10934-017-0476-0

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Effect of porous properties on self-cooling of fired clay plate by evaporation of absorbed water

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Published online: 3 August 2017
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Abstract Porous ceramic plates were prepared from clay and wood charcoal powder at 900 and 1100 °C and their porous properties, water absorption and the cooling effect of porous plates were investigated to produce eco-friendly porous ceramics for cooling by the evaporation of absorbed water. Porous properties were dependent on the firing temperature, and total pore volume, average pore size and porosity, which were 0.38–0.39 cm³/g, 0.15–0.17 μm and 49–50%, respectively at 900 °C and 0.31–0.33 cm³/g, 2.47–2.59 μm and 43–44%, respectively at 1100 °C. By the addition of wood charcoal powder, the cooling rate of porous plate fired at 1100 °C was 1.7 times faster than that of the plate fired at 900 °C and the cooling temperature difference (ΔT) was around 2.3 °C at 22.5 °C and 52–54% of relative humidity and around 3.2 °C at 29 °C and 77–80% of relative humidity. The porous ceramic plates developed here are potential materials for cooling buildings.

Keywords Raw material · Porous ceramic plate · Water absorption · Evaporative cooling · Self-cooling

1 Introduction

Recently, urban heat island during summer season has become a big global issue as it makes human living condition very difficult. The cooling effect by the evaporation of absorbed water from porous ceramic materials could be used to cool buildings. Building materials that lead to evaporative cooling have been developed by using porous ceramic materials made from several raw materials such as alumina, low grade silica, cordierite, glass and silicate wastes [1–13]. In the above previous studies, it was reported that water absorption and removal of evaporative latent heat could be controlled by changing the particle size of raw materials, using organic additives and changing conditions of firing. Properties of porous ceramics such as pore diameter and porosity were controlled by using the above parameters. Pore diameters of ten to several tens of μm in porous ceramics were found to be effective for the cooling and temperature difference of the wet porous ceramics by the removal of evaporative latent heat during hot summer season. Latent heat of water evaporation gives high potential of cooling capacity. Evapo-transpiration gives cooling effect to the ambient air, i.e. 1 g water evaporation in 1 s can absorb about 2.43 kW heat at a temperature of 30 °C [14].

In developing countries of Africa and Southeast Asia, a simple, eco-friendly and cheap cooling system by using cheap materials and without using electrical energy for cooling is required. The important key to develop this technology is to use locally available cheap clays as raw materials which can be mined in the developing countries [7]. Although evaporative cooling has been used for centuries to cool water in clay pots or vessels, there are few or no papers on the porous ceramics prepared from clay for

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cooling buildings by the removal of heat through evaporative cooling.

In this study, porous plates were prepared from clay and wood charcoal by firing them at 900 and 1100 °C, and the role of porous properties on self-cooling of these porous plates by evaporation of absorbed water was investigated.

2 Experimental procedure

Low grade clay for pottery production [15] was used for making porous plates, and two kinds of commercial wood charcoal powder with different particle sizes were separately mixed with clay to form pores in the plates after firing. Figure 1 shows the morphology of two wood charcoal powders by an optical microscope. The particle sizes of Type A and B wood charcoals were determined to be 1150 μm of length \times 350 μm of width and 1300 μm of

length \times 780 μm of width, respectively (Fig. 1). The content of charcoal powder mixed with clay was 12 mass% and the water content in clay was 19.7 mass%. The wood charcoal powder was well mixed with clay, and then put in the wood mold (70 \times 120 \times 10 mm) and pressed using 0.07 MPa pressure to prepare raw plates of clay and wood charcoal composites. After drying plates at 60 °C for 12 h, samples were fired at 900 or 1100 °C for 1 h to burn off wood charcoal powder. Particle size of clay was analyzed by a particle size analyzer (model; SediGraph III 5120, Micromeritics Instrument Co., USA). Porosity, total pore volume, and pore size distribution were analyzed by a Hg-Porosimeter (model; AutoPore IV, Micromeritics Instrument Co., USA) and the specific surface area was measured by the BET method with nitrogen-gas as the adsorbent (model; TriStar II, Micromeritics Instrument Co., USA). Minerals present in raw clay and fired plates were analyzed by X-ray diffraction (XRD) using an X-ray diffractometer (model: D-Max, 2500, Rigaku Co., Japan). The cooling effect on porous plate surface by evaporation of impregnated water was investigated by measuring the surface temperature of plates using a conventional glass thermometer in contact with porous plates. 5 mm of the lower part of porous plate was dipped in water. Cooling tests were carried out at 22.5 °C with 52–54% of relative humidity and at 29.0 °C with 77–80% of relative humidity in an atmosphere controlled room.

3 Results and discussion

3.1 Porous properties of fired clay plates

The chemical composition of raw clay was determined to be as follows: SiO_2 (70.72%), Al_2O_3 (15.93%), Fe_2O_3 (2.89%), TiO_2 (0.7%), CaO (0.23%), MgO (0.44%), Na_2O (0.85%), K_2O (2.19%) and loss of ignition (5.81 mass%), the latter mainly due to water content of hydroxyls. Average particle diameter of clay was found to be 10.6 μm , and the content of fine particles (below 10 μm) was 49.6 mass% and coarse particles (over 100 μm) was 19.4 mass%. BET surface area and ash content of wood charcoal were 9.7 m^2/g and 3.5 wt%, respectively.

Figure 2 shows XRD patterns of raw clay and fired clays at 900 and 1100 °C. Raw clay was composed of α -quartz, kaolin, Na- and K-feldspar. After firing at 900 °C, Si–Al spinel phase was confirmed ($2\theta = 19.6$ – 19.7°) by the thermal decomposition of kaolin ($2\theta = 12.5^\circ$). At 1100 °C, the plate was composed of α -quartz and mullite ($2\theta = 16.5^\circ$) with a small amount of feldspar.

Table 1 and Figs. 3, 4 and 5 show the porous properties and pore-size distribution of clay plates fired at 900 and 1100 °C. The bulk densities and porosities of clay

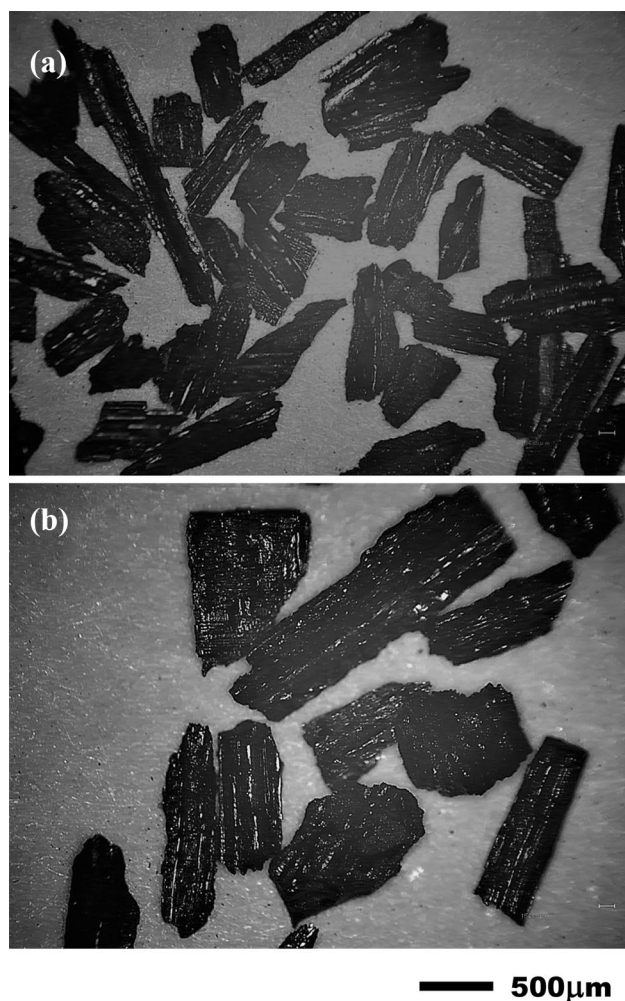


Fig. 1 Morphology of wood charcoal powders. **a** Type A (size: 1150^l \times 350^w μm), **b** Type B (size: 1300^l \times 780^w μm)

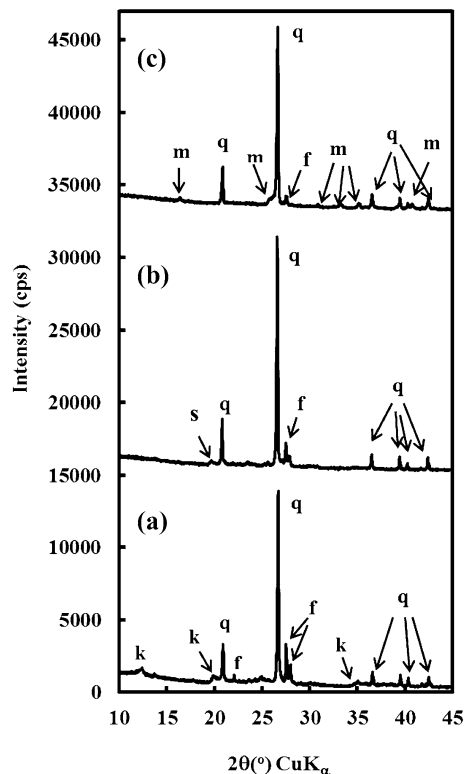


Fig. 2 XRD patterns of **a** original raw clay and **b** fired clays at 900 and **c** at 1100 °C. *q*—quartz, *f*—feldspar, *k*—kaolin, *s*—spinel, and *m*—mullite

plates fired at 900 and 1100 °C without wood charcoal powder were 1.84 and 2.07 g/cm³, and 32.1 and 18.6%, respectively. The density increased and porosity decreased by using a higher firing temperature due to sintering, as expected. Average pore diameters of clay plates without wood charcoal powder fired at 900 and 1100 °C were 0.067 and 0.637 μm, the smaller pores were apparently derived from the decomposition of kaolin at 900 °C but were decreased with firing temperature of 1100 °C (Fig. 4) due to sintering.

By the addition of two kinds of wood charcoal powder, the pore structure was controlled after firing at 900 and 1100 °C, as expected. Total pore volume and porosity of porous plates with two kinds of wood charcoal fired at 900

and 1100 °C decreased with firing temperature. At 1100 °C, porous plates with 2.5–2.6 μm of average pore diameter and 42–44% of porosity were prepared (Table 1). At 900 °C, porous plates with 0.154–0.166 μm of average pore diameter and 49.1–50.1% of porosity were prepared (Table 1). Furthermore, specific surface areas of porous plates decreased from 7 to 11 m²/g at 900 °C to 0.3–0.4 m²/g at 1100 °C with firing temperature.

In this study, porous properties of plates prepared with wood charcoal powder were mainly influenced by firing temperature, but did not depend on the particle size of wood charcoal powder. The main reason for no dependence of porous properties on the particle size of wood charcoal powder was probably due to the break-down of fragile wood charcoal particles to smaller particles during a mixing and kneading with clay.

3.2 The cooling test of porous plate by evaporation of impregnated water

Figure 6 shows the test method of water absorption of porous plates fired at 1100 °C. Pictures were taken after 12 min of water immersion. Moving rate of water from the bottom to top of porous plates fired at 1100 °C with wood charcoal powder was 2–3× faster than that of plates fired at 1100 °C without wood charcoal powder (Fig. 6).

Figure 7 shows the change of surface wet temperature (T_w) of porous ceramic plates by the evaporation of absorbed water. Three plates were fired at 900 °C and the cooling effect was investigated at 22.5 °C of room temperature (T_r) and at 52–54% of relative humidity. The average pore sizes of the porous plate without wood charcoal powder fired at 900 and 1100 °C were 0.067 and 0.637 μm, respectively, and the cooling rate of porous plate with larger pores was faster than that of porous plate with smaller pores (Fig. 7a, b). With the increased formation of larger pores in the plate, the cooling rate was promoted. But the effect of particle size of wood charcoal powder on the cooling rate was not deciphered because similar porous structures (porosity and average pore diameter) were formed in porous plates fired at 900 and 1100 °C with Type A and B wood charcoal powders.

Table 1 Porous properties of clay samples fired at 900 and 1100 °C for 1 h

Samples	Firing temperature (°C)	Total pore volume (cm ³ /g)	Specific surface area (m ² /g)	Average pore size (μm)	Porosity (%)	Bulk density (g/cm ³)
Clay	900	0.175	9.43	0.067	32.1	1.83
Clay + Type A	900	0.392	10.89	0.166	49.1	1.25
Clay + Type B	900	0.385	7.41	0.154	50.1	1.31
Clay	1100	0.103	0.33	0.637	18.6	1.81
Clay + Type A	1100	0.329	0.44	2.59	42.5	1.29
Clay + Type B	1100	0.312	0.38	2.47	43.9	1.41

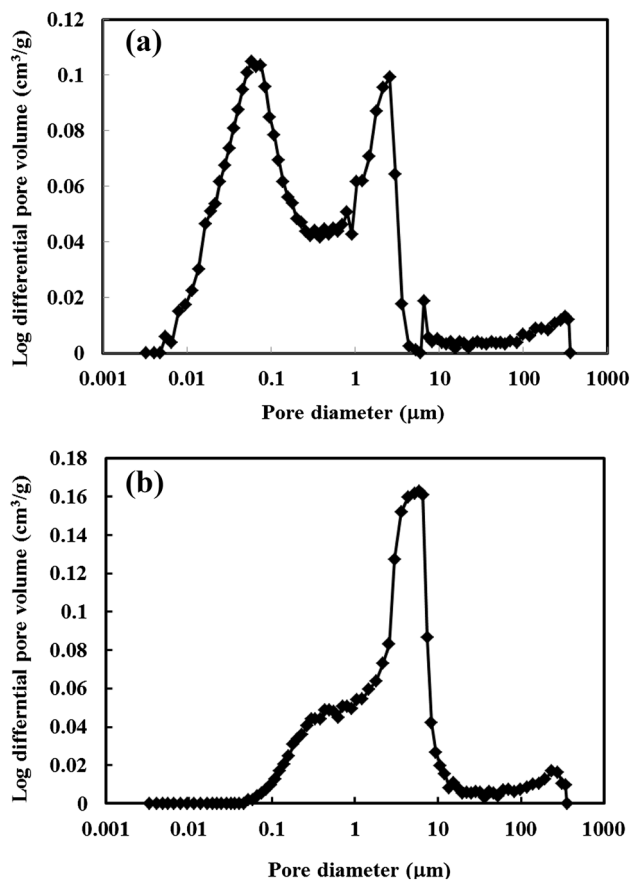


Fig. 3 Pore-size distribution of clay body without wood charcoal powder fired at **a** 900 and **b** 1100 °C for 1 h

Porous plates prepared by the addition of wood charcoal powder at 900 and 1100 °C showed the higher cooling effect than plate prepared without wood charcoal powder. Times to reach constant temperature (20.2 °C) by the cooling effect were 75 and 45 min on the porous plates fired with Type A and B wood charcoal at 900 and 1100 °C, and the cooling rate of plate fired at 1100 °C was 1.7 times faster than that of plate fired at 900 °C. The cooling temperature difference ($\Delta T = T_r - T_w$) of porous plates by the evaporation of absorbed water at 22.5 °C and 52–54% of relative humidity was around 2.3 °C.

The porous plates fired at 900 °C with wood charcoal powder have poor mechanical properties, i.e., a biscuit-like fragile structure. For actual building applications such as a low cost cooling material in summer season, the cooling ability and mechanical properties of porous plates fired at 1100 °C with wood charcoal powder are more suitable and therefore, they were further investigated.

Figure 8 shows the change of surface temperature of porous ceramic plates fired with and without wood charcoal powder at 1100 °C by the evaporation of absorbed water. The cooling test was carried out at 29 °C and 77–80% of

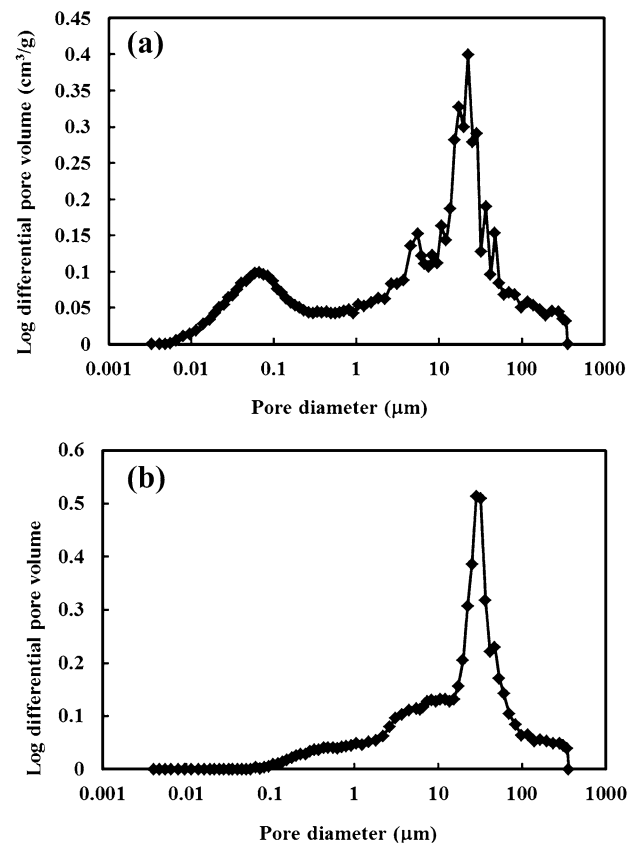


Fig. 4 Pore-size distribution of clay bodies fired with Type A wood charcoal powder fired at **a** 900 and **b** 1100 °C for 1 h

relative humidity. Surface temperature of porous plates prepared with Type A and B wood charcoal powder reached 25.7–25.8 °C after 80 min. It took a longer time to reach a constant temperature (25.7–25.8 °C) in this case due to higher relative humidity compared with that of lower relative humidity (Fig. 7). Difference of cooling rate between the two porous plates with wood charcoal powders A and B was not significant, but ΔT was around 3.2 °C.

The results of this study showed that the absorption of water in porous plates and the cooling effect were dependent on pore diameter, and the decrease of the surface temperature on the porous plates by the evaporation of water was $\Delta T = 2.3$ –3.2 °C. The decrease of the surface temperature is related to the formation of larger pores and the surface roughness of the porous plate. The effect of pore diameter, porosity and relative humidity on the cooling temperature difference of the wet porous ceramic surfaces is currently in progress.

In this paper, the effect of porous properties of the fired clay plate on the self-cooling by the evaporation of absorbed water was mainly presented and discussed. However, further studies are needed to investigate the effect of surface roughness, thermal conductivity of porous plate,

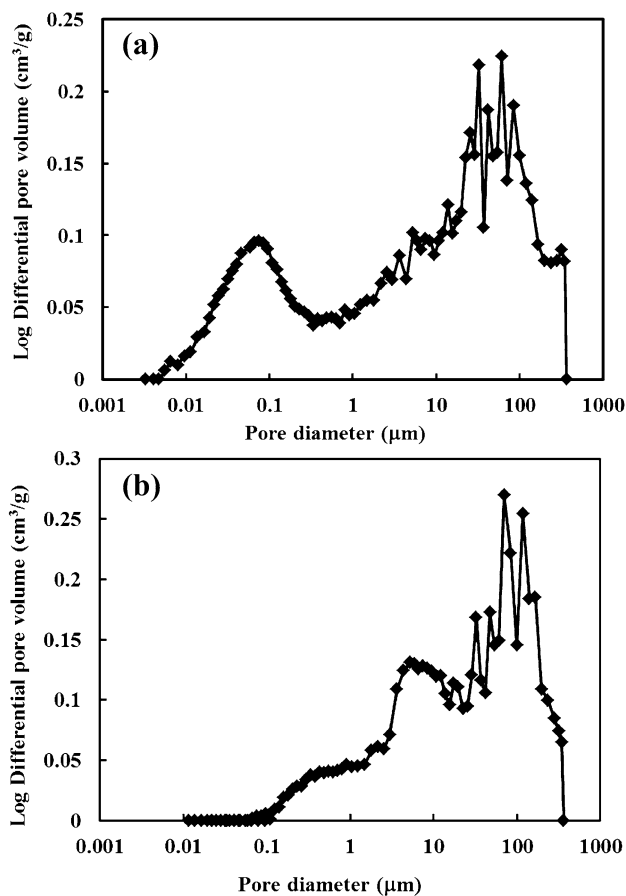


Fig. 5 Pore-size distribution of clay plates fired with Type B wood charcoal powder fired at **a** 900 and **b** 1100 °C for 1 h

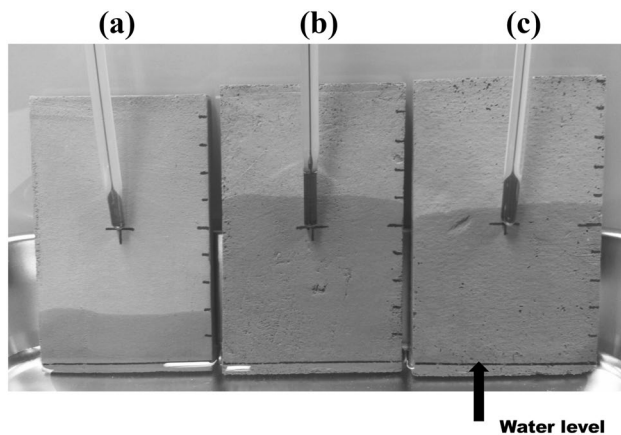


Fig. 6 Test of water absorption and measurement of surface temperature of porous plate: **a** fired at 1100 °C without wood charcoal powder, **b** fired at 1100 °C with Type A and **c** fired at 1100 °C with Type B wood charcoal powder

pump-up rate of water by capillary force and evaporation rate of water from the surface of porous plate on the self-cooling of the fired clay plates.

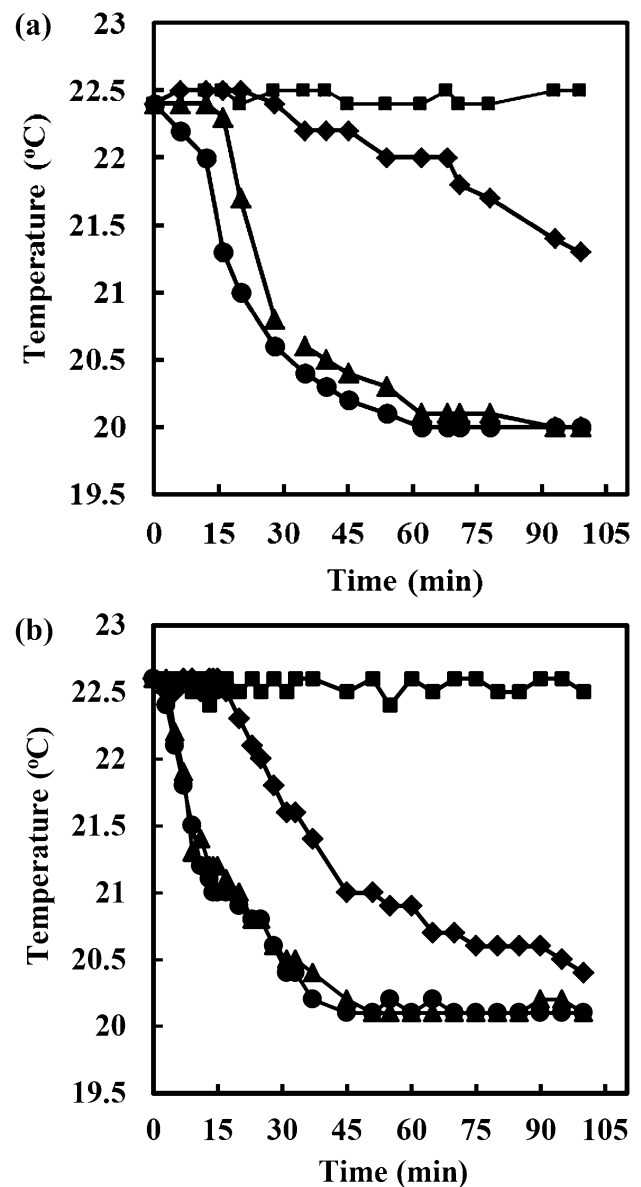


Fig. 7 The change of surface temperature of porous ceramic plates by water evaporation from the surface: **a** and **b** samples were fired at 900 and 1100 °C, respectively. Room temperature and relative humidity were 22.5 and 52%. Filled square room temperature, filled diamond clay without wood charcoal powder, filled triangle clay with Type A and filled circle clay with Type B wood charcoal powder

4 Summary

In this study, some porous ceramic plates by using clay and wood charcoal powder were prepared at 900 and 1100 °C and some porous properties, the water absorption and the cooling effect by the evaporation of absorbed water were investigated to produce eco-friendly porous ceramics for cooling. The main results are as follows:

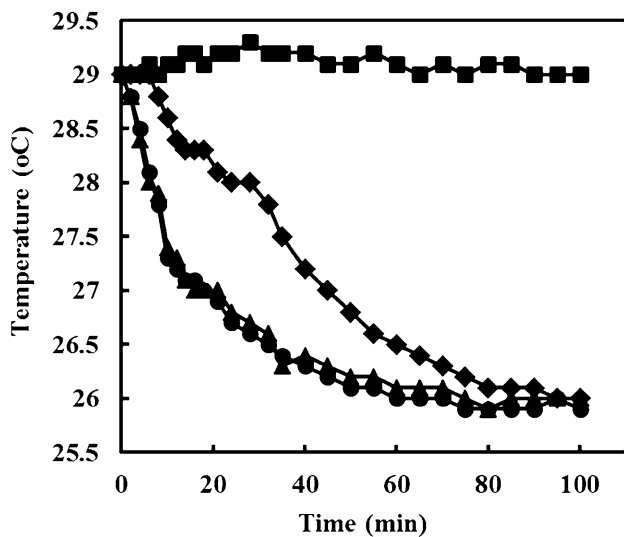


Fig. 8 The change of surface temperature of porous ceramic plates fired at 1100 °C by the water evaporation from the surface. Conditions: Room temperature and relative humidity were 29 °C and 77–80%, respectively. *Filled square* room temperature, *filled diamond* clay without wood charcoal powder, *filled triangle* clay with Type A wood charcoal powder, *filled circle* clay with Type B wood charcoal powder

- (1) Porous ceramic plates with different porous properties were prepared at 900 and 1100 °C from clay and two types of wood charcoal powder of different sizes. The content of wood charcoal powder mixed with clay was 12 mass%.
- (2) The effect of the size and morphology of wood charcoal powder on the porous properties of porous plates prepared at 900 and 1100 °C was not significant. Porous properties were dependent on the firing temperature. Total pore volume, average pore size and porosity were 0.38–0.39 cm³/g, 0.15–0.17 μm and 49–50%, respectively at 900 °C, and 0.31–0.33 cm³/g, 2.47–2.59 μm and 43–44%, respectively at 1100 °C.

- (3) By the addition of wood charcoal powder, the cooling rate of porous plates fired at 1100 °C was 1.7 times faster than that of plates fired at 900 °C and the difference in temperature (ΔT) by cooling was found to be around 2.3 °C at 22.5 °C and 52–54% of relative humidity and around 3.2 °C at 29 °C and 77–80% of relative humidity.

Acknowledgements The authors would like to thank Korea Institute of Ceramics & Engineering Technology for supporting this work. This research was supported by Ceramicware Center of Korea Institute of Ceramic Engineering & Technology under Grant No. 17-BUS010025000 (Establishment of New Value Ceramicware Industry Base).

References

1. T. Sugiyama, K. Kusumoto, M. Ohashi, A. Kamiya, *Key Eng. Mater.* **690**, 150–1558 (2016)
2. T. Kato, K. Ohsashi, M. Fuji, M. Takahashi, *J. Ceramic Soc. Japan*, **116**(2), 212–215 (2008)
3. A. Hoyano, J. He, S. Ogawa, J. Ando, S. Yamamura, H. Akagawa, K. Nakajima, K. Okada, T. Kurata, *J. Environ. Eng. AIJ*, **74**, 641, 775–782(2009).
4. H.T.M. Thu, H. Sato, *Int. J. Refrig.* **36**, 1589–1595 (2013)
5. H.T.M. Thu, H. Sato, *Int. J. Refrig.* **36**, 1596–1601 (2013)
6. V.O. Aimiwa, *Energy Conversat. Manag.* **33**(1), 69–74 (1992)
7. J. He, A. Hoyano, *Build. Environ.* **45**, 461–472 (2010)
8. E. Anyanwu, *Energy Conversat. Manag.* **45**, 2187–2195 (2004)
9. S. Riffat, J. Zhu, *Appl. Therm. Eng.* **24**, 457–470 (2003)
10. S. Riffat, J. Zhu, *J. Eng. Res.*, **1**, 46–52 (2004)
11. W. Chen, S. Liu, J. Lin, *Energy Build.* **86**, 541–549 (2015)
12. E. Velasco Gomez, F. Rey Martinez, F. Varela Diez, M. Molina Leyva, R. Herrero Martin, *Int. J. Refrig.* **28**(5), 654–662 (2005)
13. A. Mittal, T. Kataria, G.K. Das, S. Chatterjee, *Int. J. Green Energy*, **3**(4), 347–368 (2006)
14. H.T.M. Thu, A study on an eco-friendly and high-performance cooling system using evapo-transpiration. Thesis for the Degree of Ph.D. in Engineering, p. 18 (2014)
15. H. Katsuki, J. Kim, S.J. Kim, J.Y. Kim, J.H. Pee, W.S. Cho, *J. Ceram. Soc. Japan* **124**(8), 833–837 (2016)