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The thermal conductivity mechanism of sewage sludge ash lightweight materials

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Abstract

The foaming reactions and the hydration and Pozzolanic effects of processed sewage sludge ash (SSA) allow it to be used as the main ingredient to make lightweight materials. The thermal conductivity of the SSA lightweight materials (SSALM), the SSA properties and how the mixing ratio of the materials influences the heat insulation properties are investigated. The results show that the thermal conductivity of SSA is low. When at room temperature, the pores in the specimens are filled with air, hence, the thermal conduction modes of these materials will be solid or air conduction. Radiant thermal conduction and natural convection can be ignored. The characteristics of the porosity, irregular particles and lightweight after the foaming reaction lead the thermal conductivity of the SSALM low to be 0.0763–0.2474 W/m K. When the water-to-solid ratio (W/S) and the amount of aluminum powder are increased, open and connected pores are formed, which negatively affects the compressive strength and the thermal conductivity. In addition, the total pore volume and thermal conductivity of SSALM are inversely proportional.

Keywords: Sewage sludge ash (SSA); Foaming reactions; Pozzolanic effects; Thermal conductivity; Microstructure

1. Introduction

Thermal conductivity is the process of the conduction of high-temperature thermal energy within an object or between two objects in contact, which lowers the temperature. When an object is heated, the vibration of the molecules or atoms and the floating of free electrons release thermal energy to the lower temperatures through kinetic energy conduction.

According to molecular dynamics, an object's temperature is in a direct proportion to the mean kinetic energy of its composition [1]. Thermal conductivity is the capability of substances to transmit thermions, i.e., the ratio of the thermal flux to the temperature ladder. Thermal conductivity (W/m K) is the result of thermal diffusibility (cm^2/s), specific heat (J/g K) and density [2].

The thermal conductivity of a material is influenced by its own mineral characteristics, pore structure, chemical composition, moisture and temperature. The thermal conductivities of ordinary heat insulating materials range from 0.034 to 0.173 W/m K [1] Kim et al. [3] have indicated that the thermal conductivities of cement paste and cement mortar would be significantly affected by the water-to-cement ratio and by admixtures. However, the conductivity of concrete was influenced by the volume and the water content of the aggregates. When saturated and the temperature increased, the conductivity of the specimen also improved. In addition, both Kim et al. [3] and Blanco et al. [4] stated that age had no effect on the conductivity of a specimen. Scanlon and McDonald [5] indicated that the conductivity of ordinary concrete depended on its composition, and when the concrete was saturated, the conductivity generally ranged between 1.4 and 3.6 $J/m^2 s\,°C/m$. Davey [6] found that the density did not appreciably affect the conductivity of ordinary concrete, but due to the low conductivity of air, the thermal conductivity of lightweight concrete would vary with its density. The degree of saturation of concrete was the major factor because the conductivity of air (about 0.026 W/m K) was much lower than that of water (about 0.610 W/m K) [7]. Neville [8] also indicated that in concrete, increasing the moisture content by 10% increments would enhance conductivity by about one half.

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Table 1
Characteristics of cement and SSA

Materials	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O (%)	P_2O_5 (%)	Moisture (%)	Ashes (%)	Combustible content (%)	Specific gravity	Specific surface area (m^2/kg)
Cement	55.52	6.50	3.20	62.50	1.90	0.40	0.78	–	–	–	–	3.15	300
SSA	64.95	15.21	6.95	1.93	1.45	0.79	2.52	1.51	55.52	32.75	11.73	2.29	6817

On the other hand, the conductivity of water in hydrated cement paste would be weakened by more than 50%. Thus, the less water the paste contained, the higher the conductivity would be after the concrete has hardened. Tay and Yip [9] indicated that due to the porosity and low conductivity properties of sewage sludge ash (SSA), the thermal conductivity of SSA lightweight aggregates would be lower than that of normal aggregates.

The engineering properties and applications of SSA lightweight materials (SSALM) are similar with those of autoclave lightweight concrete (ALC) and autoclave aerated concrete. This study intends to investigate the thermal conduction models and heat insulation performance of foamy lightweight materials. In this paper, investigations on pore structure and thermal conductivity mechanism can be the reference to modify the mix proportion and foaming behavior of SSALM.

2. Materials and methodology

The SSA was produced from the primary setting dehydrated macromolecule sludge cakes in the Ba–Li Waste Water Treatment Plant, Taipei. Six-kilogram batches of raw sludge were air dried, burnt in an incinerator at 900 °C for 3 h, then ground in a shredding machine for 2 h until well mixed.

The gross amount of heavy metals and the toxicity characteristic leaching procedure (TCLP) of SSA met the standard requirements for hazardous industrial wastes of the Environmental Protection Administration (EPA), Taiwan. The chemical composition of the SSA is listed in Table 1. Portland cement Type I, with fineness of 300 m^2/kg (Blaine), provided the cementitious strength and alkalinity. The properties were in accordance with the ‘‘Portland cement’’ specification of CNS 61 (Chinese National Standard). Its chemical composition is shown in Table 1. The foaming agent, metallic aluminum powder, contained 91.4% of elemental aluminum, and its specific surface area (BET) was 6817 m^2/kg.

The water-to-solid ratios (W/S) were 0.4, 0.5 and 0.6. The cement over SSA weights were 20:80, 30:70 and 40:60. The aluminum powder over the solid weights (including cement and SSA) were 0.1%, 0.2% and 0.3%. Cubes, 5×5×5 cm, and planar specimens, 20×20×2 cm, were cast following the ASTM 305 and ASTM C109 processes, then used for engineering property and thermal conductivity testing. The specimens were demolded after being placed at room temperature for 24 h, then cured for 28 days at 25±2 °C in saturated lime water.

Composition analyses included X-ray fluorescence analysis (XRF), the specific surface area (BET), the gross amount of heavy metals and the TCLP. The composition SSALM analyses included the foaming ratio, water absorbability, bulk specific gravity, apparent porosity, compressive strength (CNS 1232), thermal conductivity (CNS 7332), Fourier Transform Infrared (FTIR) Spectrometer, mercury intrusion porosimeter (MIP) and SEM micrographs.

3. Results and discussions

3.1. Properties of sewage sludge and SSA

The physical and chemical properties of SSA are listed in Table 1. It is known that raw sewage sludge possesses excellent volume and weight reduction efficiency when burnt at 900 °C, the remaining ash is only 32.75%. By analyzing the gross amount of heavy metals, e.g., Pb, Cd, Cr, Cu and Zn, in the raw sewage sludge and the TCLP of the SSA, it can be seen that there was no significant variation in the gross amount of heavy metals, and the leaching concentration was much lower than the regulatory threshold. The TCLP results and concentrations of heavy metals in raw sewage sludge and SSA are listed in Table 2.

The SSA only has an ignition loss of 0.21%. Its specific gravity is 2.29, and the specific surface area is 4657 m^2/kg, much higher than the 300 m^2/kg of cement. From the SEM Fig. 1, it can be observed that sewage sludge has a porous

Table 2
TCLP results and concentrations of heavy metals in sewage sludge and SSA

Materials	Heavy metals	Pb	Cd	Cr	Cu	Zn
Sludge	Total weight [mg/kg]	0.28±0.09	1.6±0.13	9.51±0.11	33.32±1.28	176.57±2.97
SSA	Total weight [mg/kg]	1.20±0.013	4.81±0.03	21.96±1.84	89.64±3.77	567.3±4.85
	TCLP [mg/l]	0.017±0.006	ND	0.1±0.05	3.81±0.13	–
Regulation	TCLP [mg/l]	<5	<1	<5	<15	–

ND: not detected.

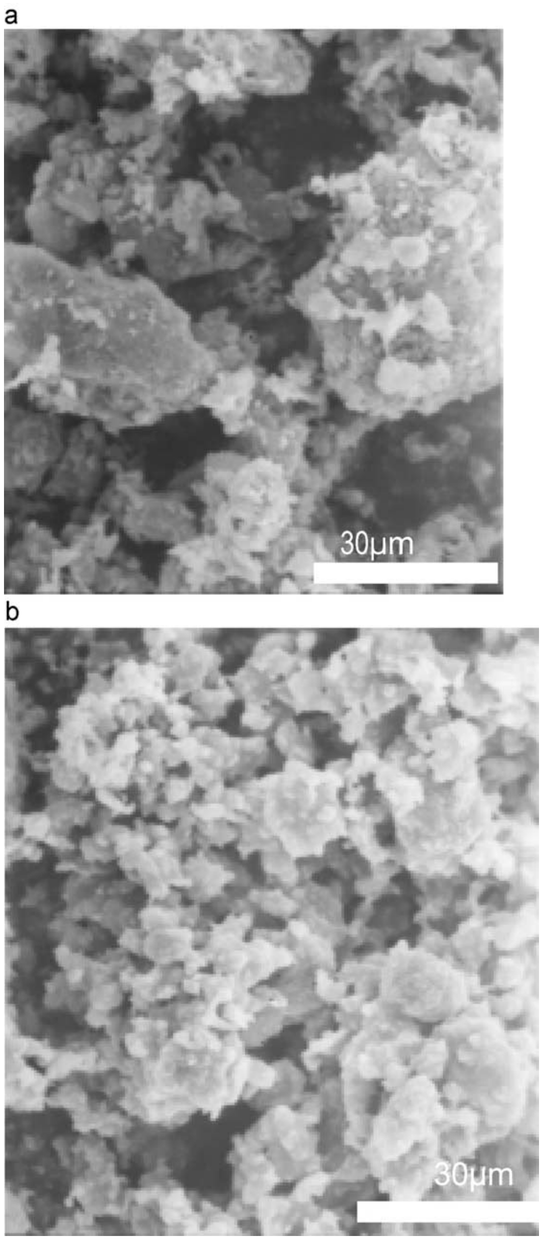


Fig. 1. Particle morphologies of SSA: (a) primary SSA; (b) secondary SSA (× 1000).

structure and irregular particles, which makes it have a high specific surface area and gives it the lightweight properties. SSA from the primary factory has a harder texture, and its properties are similar with those of sandstone, but with larger diameter particles. It also contains more SiO_2. In this study, macromolecule sludge ash is used, which only contains 1.93% CaO, and the Pozzolanic activity index of the sludge ash (85.47%) is lower than that of Class F coal ash (94.03%). The pH value of our SSA is 6.41. The required minimum alkalinity experiment for foaming demonstrates that the alkalinity of the SSA itself does not produce a foaming reaction when combined with aluminum powder, nor does the power plant coal ash, the pH value of which could reach 11.61. Therefore, it is necessary to rely on the alkaline environment provided by cement or other alkalis.

3.2. Thermal conductivity mechanism

Ordinarily, thermions can be conducted in four different ways—in a solid, in air, by radiation and by convection. However, thermions in a porous medium are conducted through the interaction of these four mechanisms.

Thermal conduction through radiation is a way to transmit energy via electromagnetic waves. Due to the effects of reflection, absorption and scattering during the transmission, the radiant energy will weaken. In this study, foamy lightweight materials are mainly made from SSA and cement, which are classified as substances with a large optical thickness and therefore can be analyzed through the diffusion approximation method. Their amount of radiation thermal conduction can be calculated by Eq.(1) [10]:

$$q_r(x) = -\frac{4}{3\sigma_{e,\mathrm{R}}} \cdot \frac{\partial e_b}{\partial x} = -\frac{4}{3\sigma_{e,\mathrm{R}}} \cdot \frac{\partial(\sigma T^4)}{\partial x} = -\frac{16}{3\sigma_{e,\mathrm{R}}} \sigma T^3 \cdot \frac{\partial T}{\partial x} \quad (1)$$

Where σ is the Stefan–Boltzman constant, σ=5.67×10^{-8} W/m^2. $\sigma_{e,\mathrm{R}}$ is the Rosseland Mean Extinction Coefficient, defined as:

$$\frac{1}{\sigma_{e,\mathrm{R}}} = \frac{\int_0^\infty \frac{1}{\sigma_{e\lambda}} \frac{\partial e_{b\lambda}}{\partial T} d\lambda}{\int_0^\infty \frac{\partial e_{b\lambda}}{\partial T} d\lambda} = \int_0^\infty \frac{1}{\sigma_{e\lambda}} \frac{\partial e_{b\lambda}}{\partial e_b} d\lambda \quad (2)$$

The extinction coefficients at different wavelengths are needed when calculating the Rosseland Mean Extinction Coefficient. An FTIR spectrometer can be used to measure the transmittances of the specimen at different wavelengths, and the extinction coefficients at the different wavelengths can be calculated using Beer's Law.

$$\tau_\lambda = e^{-\sigma_{e\lambda} L} \quad (3)$$

where τ_λ is the transmittance at different wavelengths and L is the thickness of the specimen.

Eq.(1) and the FTIR model are compared, and the formula can be rewritten as $q_r = -k_\mathrm{r} \cdot \frac{\partial T}{\partial x}$. Thus, the thermal radiation conduction coefficient k_r can be defined as follows:

$$k_\mathrm{r} = \frac{16\sigma T^3}{3\sigma_{e,\mathrm{R}}} \quad (4)$$

Fig. 2 shows the measured transmittance when the specimen thickness is 0.65 mm. The extinction coefficients at different wavelengths, shown in Fig. 3, are calculated from Eq. (3). It is found from Eq. (2) that the Rosseland Mean Extinction Coefficient is 15853.5 m^{-1} at room temperature. The thermal radiation conduction coefficient k_r=5.05×10^{-4} can then be calculated from Eq. (4). When

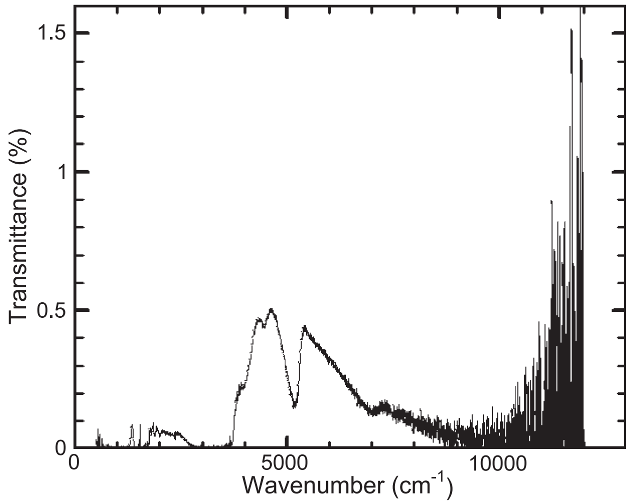


Fig. 2. Transmittance of SSALM (thickness 0.65mm).

compared with the experimental value of the equivalent thermal conductivity specimen, the radiation thermal conductivity is much less. Thus, we can see that the radiation thermal conduction effect can be ignored.

Thermal convention can only be processed in a natural way because the fluid is in a static state. The modified Rayleigh Number can be used to judge whether natural convention will occur, as shown by Eq. (5).

$$R_a = \frac{g\beta\Delta T\rho C_p KH}{v k_s} \quad (5)$$

where R_a equals the buoyancy over the adhesive resistance, K is the transmittance of the porous medium, k_s is the solid thermal conduction coefficient, v is the adhesive coefficient, g is the gravity acceleration, β is the gas thermal expansion coefficient, ΔT is the temperature difference on and at the bottom of the specimen and H is the height of the specimen. Lapwood [11] indicated that only when the Modified Rayleigh Number of the fluid was greater than the Critical Rayleigh Number, $4\pi^2$, did natural convention happen. The

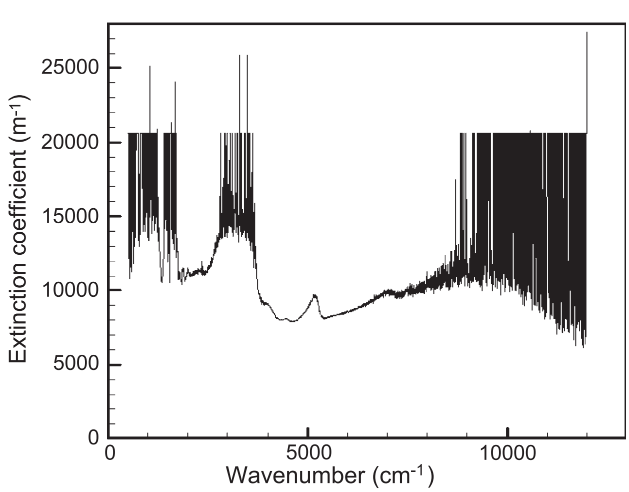


Fig. 3. Extinction coefficient of SSALM (thickness 0.65 mm).

pore size of our SSALM is not larger than 400 μm. If this material should be used for architectural purposes under room temperature and the fluid inside the pores is air, the parameters k_s, β and ΔT can be picked from the experimental data and the references for air. The Modified Rayleigh Number obtained is less than the value of the threshold limit. Thus, there is no natural convention in the specimen in this study, the fluid thermal convention effect of fluid could be ignored.

As mentioned, we can ignore the radiation thermal conduction effect for SSALM. The thermions are conducted via solid and gas transmission. In addition, the gas inside the pores is supposed to be static.

3.3. Heat insulation performance

SSALM is lightened through the foaming reactions of cement mixed with aluminum powder. As it ages, the C-S-H gels and the hydrates, such as CH, increase because of hydration reactions and the Pozzolanic effect of sludge ash and cement, which makes the specimens become denser. Table 3 and Fig. 4 show the compressive strength variation

Table 3
Properties of SSALM

Sample	A/S (%)	Bulk specific gravity	Compressive strength (MPa)	Thermal conductivity (W/m K)	Porosity (%)	Capillary pore volume (%)
PSSA	0.1	0.95	5.86	0.1591	54.42	94.20
W/S = 0.5	0.2	0.90	5.18	0.1223	61.83	88.86
C:SSA = 20:80	0.3	0.81	3.16	0.0971	66.78	95.87
PSSA	0.1	0.85	4.62	0.1179	57.59	90.75
W/S = 0.6	0.2	0.79	3.52	0.1133	64.51	95.82
C:SSA = 20:80	0.3	0.67	2.70	0.0880	71.17	92.25
PSSA	0.1	0.96	6.33	0.1786	52.21	96.89
W/S = 0.5	0.2	0.92	6.04	0.1450	58.61	94.24
C:SSA = 30:70	0.3	0.82	4.18	0.1120	63.28	95.72
PSSA	0.1	0.93	9.06	0.2474	51.28	93.52
W/S = 0.5	0.2	0.88	6.82	0.2143	56.19	90.69
C:SSA = 40:60	0.3	0.82	5.64	0.1285	59.21	95.17
SSSA	0.1	1.04	5.58	0.1066	58.36	94.99
W/S = 0.5	0.2	1.02	4.03	0.0871	63.66	95.21
C:SSA = 20:80	0.3	0.86	2.43	0.0780	68.80	97.35
SSSA	0.1	0.87	4.41	0.0947	58.88	98.82
W/S = 0.6	0.2	0.82	3.00	0.0799	66.63	98.52
C:SSA = 20:80	0.3	0.74	2.22	0.0763	66.69	98.67
SSSA	0.1	1.07	5.70	0.1283	57.79	88.98
W/S = 0.5	0.2	1.04	4.86	0.0870	60.74	96.55
C:SSA = 30:70	0.3	0.78	2.71	0.0836	64.47	95.67
SSSA	0.1	1.04	6.78	0.1510	53.62	90.93
W/S = 0.5	0.2	1.02	6.02	0.1226	55.57	97.07
C:SSA = 40:60	0.3	1.01	5.05	0.0907	62.30	94.06

PSSA: primary SSA; SSSA: secondary SSA.

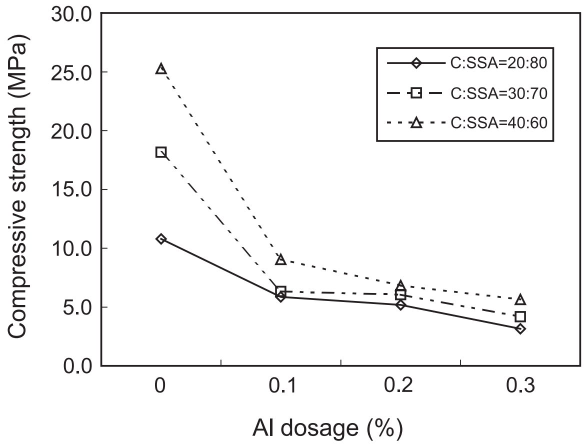


Fig. 4. Compressive strength of SSALM (W/S = 0.5; 28 days).

of SSALM with different amounts of aluminum powder and SSA usages. The thermal conductivity of SSALM ranges from 0.0763 to 0.2474 W/m K. To meet thermal conductivity, the requirements of an insulation material (0.034–0.173 W/m K), the mixing ratio should have a W/S ratio of higher than 0.5, an aluminum powder amount of more than 0.1% and an SSA usage of over 60%. The experiments show that increasing the W/S ratio and the aluminum powder amount will damage the compressive strength of SSALM more than weakening its thermal conductivity will do.

Fig. 5 shows the relationship between the thermal conductivity of the SSALM and the SSA usage. When the SSA usage increased, that is, the amounts of cement used decreased, the thermal conductivity declines accordingly. This is because of the porous properties of the SSA. The thermal conductivity of the pure solid SSA, formed under a pressure of 4000 psi, is 0.2945 W/m K, which is much less than the 0.5667 W/m K of the pure cement paste (W/C=0.38). This can be explained by the porous structure and irregular particles, which lead to the low thermal conductivity. Increasing the W/S ratio and the aluminum powder will decrease the thermal conductivity of the specimen. This is because the surplus moisture will form pores inside the paste, and the extra aluminum powder will result in significant foaming reactions. Multiple regression analysis can be adopted to analyze how the mixing parameters affect the thermal conductivity of SSALM. It is found that the aluminum powder usage has the greatest affect, the water-to-cement ratio the second, and the ratio of the cement weight to SSA weight the least. This indicates that the pore volume has a significant effect on the thermal conductivity. Fig. 6 demonstrates the inverse relationship between the total pore volume of SSALM and its thermal conductivity.

In 1990, Taiwan Power produced ALC with 65% of coal ash, 17.5% of waste carbide and 17.5% of cement. The thermal conductivity of ALC was 0.259 W/m K and that of European autoclave aerated concrete ranged between 0.087 and 0.194 W/m K [12]. However, the thermal conductivity of SSALM in this study was between 0.0763 and 0.2474 W/m K.

3.4. Microcosmic structure

MIP is used to analyze the pore structure of SSALM. The results show that pores smaller than 0.1 μm are the main products during the hydration of pure cement paste. This matches the research of Young [13]. However, most of the pores formed during the foaming reaction of aluminum powder and cement were larger than 10 μm; but the addition of SSA will increase this size consequently. The addition of aluminum powder to SSALM will generate pores of about 10 μm. Air fills the pores, leading to the low thermal conductivity of 0.026 W/m K. Thus, the SSALM specimens have the property of low thermal conductivity. When the W/S ratio was 0.5, the pore size mainly ranges from 100 Å to 0.05 mm, but when the W/S

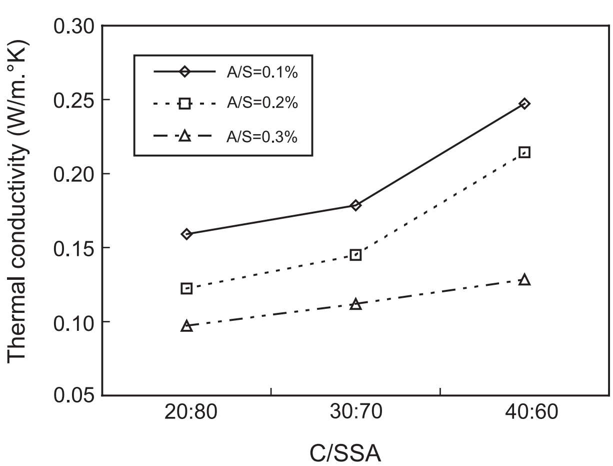


Fig. 5. Relation between SSA usage and thermal conductivity of SSALM (W/S = 0.5; 28 days).

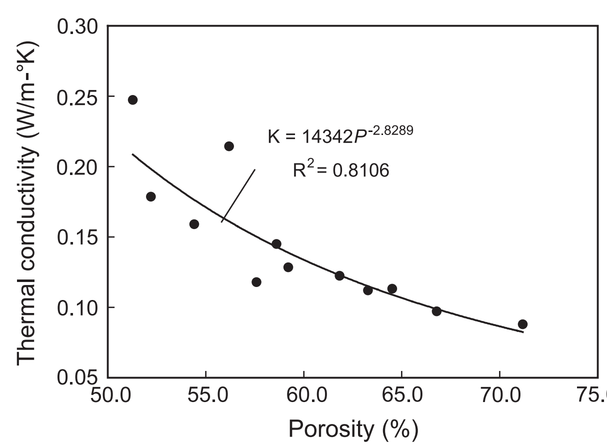
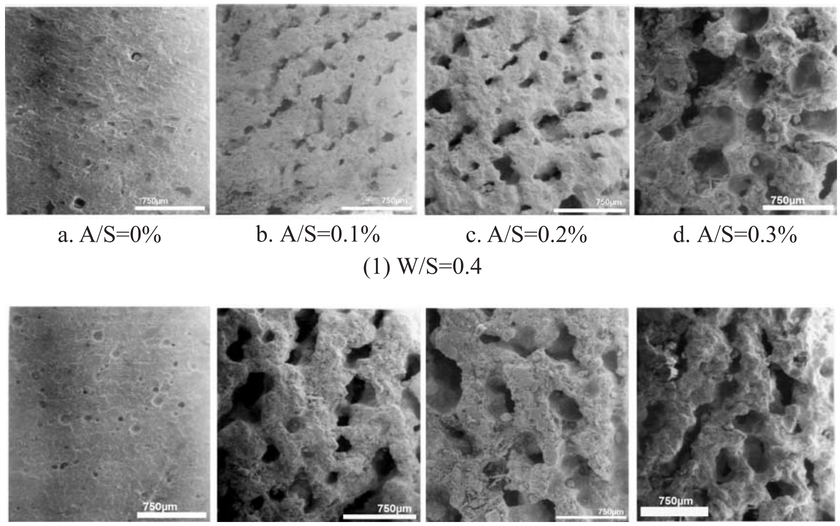


Fig. 6. Relation between total pore volume and thermal conductivity of SSALM.



a. A/S=0% b. A/S=0.1% c. A/S=0.2% d. A/S=0.3%

(1) W/S=0.4

e. A/S=0% f. A/S=0.1% g. A/S=0.2% h. A/S=0.3%

(2) W/S=0.5

Fig. 7. Pore structure of SSALM ($\times$ 40).

ratio is raised to 0.6 and 0.7, the amount of pores larger than 0.05 mm increases significantly. This shows that surplus moisture in the cement paste will form water droplets, which, in turn, larger pores after evaporation. With high water-to-cement mixing ratios and high amounts of aluminum powder usage, the specimen can easily form open and connected pores, as shown by the SEM in Fig. 7.

4. Conclusion

1. The porous structure and irregular particles of the SSA make it have the characteristics of low thermal conductivity. Moreover, because of the low thermal conductivity of SSALM, its porous structure due to the foaming reactions and the tiny pores produced during hydration, the resultant specimens will have better heat insulation property.
2. At room temperature in air, the thermal conduction of the SSALM will be via solid and gas conduction. Both radiative thermal conduction and natural convection can be ignored.
3. SSALM meets the specifications for a heat insulation material. It is necessary to have a W/S ratio higher than 0.4, an aluminum powder usage of more than 0.1% and an SSA usage of higher than 60%.
4. The mixing ratio parameters that affect the thermal conductivity of SSALM are the aluminum powder usage, the W/S ratio and the weight ratio of cement to SSA. The pore volume has an inverse relationship with the thermal conductivity of the specimen.
5. A high water-to-cement ratio and high aluminum powder usage tend to lead to the formation of open and connecting pores inside SSALM, which adversely affects the compressive strength and heat insulation properties.

5. Remarks

1. EPA: the Environmental Protection Administration, Taiwan, Republic of China.
2. CNS is the abbreviation of Chinese National Standard. CNS 61 lists the specification for Portland cement; CNS 1232 for the compressive strength test, and CNS 7332 for thermal conductivity test.

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