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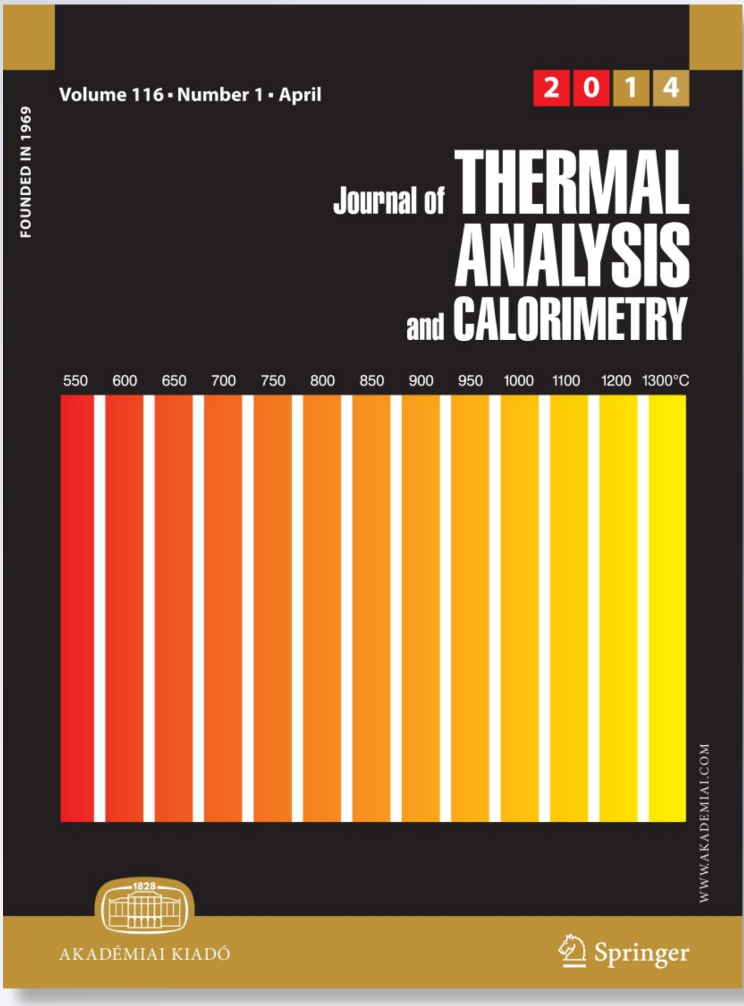

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Improvement of window thermal performance using aerogel insulation film for building energy saving

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Abstract In buildings, windows have a major influence on space heating demand and indoor environment both with respect to climate and daylight. To reduce the window coefficient of the overall heat transmission, we use aerogel. Aerogels have a high surface area, low density, open pore structure, and excellent insulation properties. We mixed pressure sensitive adhesive and aerogel (10, 15, and 20 mass%) using a homogenizer. A mixture of the adhesives and silica aerogels attached film can reduce thermal conductivity. Silica aerogels are characterized by a surface area analyzer (BET), a Fourier transform infrared spectrometer, a thermogravimetry (TG) analyzer, and probe tack method. Thermal conductivity was measured by a TCi thermal conductivity analyzer.

Keywords Building energy saving · Silica aerogel · Thermal conductivity · Insulating glazing · TCi thermal conductivity analyzer

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Introduction

The world's buildings emitted 8.3 Gt of carbon dioxide each year, accounting for more than 30 % of the greenhouse gas emissions in many developed countries. One of the most efficient methods for reducing greenhouse gas emissions in building is the reduction of heat loss and acquisition via surface coatings. Since the heat loss and acquisition via surface coatings comprises over 40 % of the building cooling and heating overload, its reduction could be effective in terms of energy reduction [1, 2]. In buildings, windows have a major influence on space heating demand and indoor environment both with respect to climate and daylight. While windows remain the thermally weakest part of the thermal envelope, they also allow the entry of solar heat and daylight [3].

Aerogels offer some of the lowest reported thermal conductivity values for any solid. The scientific basis for aerogel commercialization as advanced insulation has been established over the last decade. The increasing energy cost/consumption and increased environmental concerns have mandated the utilization of advanced thermal insulation. Despite the obvious technical advantages of aerogel, its production is not yet commercially practiced. It has often been reported that large-scale commercialization of aerogels has not been attempted [4]. Aerogels, which are nano-porous lightweight materials, were discovered more than 60 years ago. Aerogels consist of a cross-linked internal structure of SiO_2 chains with a large number of air filled pores. These pores of aerogel are very small: pure aerogel has an average pore diameter between 10 and 100 nm [5]. However, aerogels in general will have pore sizes between 5 and 100 nm, depending on the purity and the fabrication method [6]. These pores comprise from 85.0 to 99.8 % of the total aerogel volume. Due to their high porosity and their large inner surface area (up to 1,000 m^2 g^{-1}), they serve as especially active catalysts or as catalytic substrates, filters, reinforcement agents, pigments, and gellifying agents [7–9]. Aerogel is an open-cell nano-porous super insulation material made by a sol–gel process and supercritical drying technology, and has excellent insulation performance for its nano-porous structure and very small solid grain size (2–5 nm). It has a skeleton density of 2,200 kg m^{-3}, but the high porosity results in a bulk density as low as 3 kg m^{-3}, e.g., compare with the density of air of $\sim$1.2 kg m^{-3} [10]. Its perfect adiabatic capability means that aerogel has very high application potential in the heat thermal protection fields of space shuttles, nuclear reactors, and even ordinary steam pipes as high insulation materials. Zhao et al. [11, 12] demonstrated that the effective thermal conductivity of the fiber-loaded aerogel can be reduced by the various physical properties of aerogel applications such as the length-to-diameter ratio, its type, and inclination angle. Aerogel mortars as an insulation building material was researched to increase the thermal insulating performance using a chemical retreating for gel-typed aerogel procedure [13]. One disadvantage of aerogel for use as insulation material is that aerogel is brittle and easily broken up. Some researchers are therefore attempting to form a composite of aerogel with other materials with high toughness. During recent years many potential applications have been described [14–16].

In this study, the properties of the silica aerogel that had been used in the test were measured and pressure sensitive adhesive (PSA) composite is made by mixing the silica aerogel, having good insulation performance, with PSA based on the mass ratio. The composite made for the application on building windows is coated on the PET film and the bonding performance of PSA film (which is a mixture of existing PSA film and silica aerogel), and the difference in heat conductivity are confirmed. In order to determine the properties of the silica aerogel, a BET test and a thermogravimetry (TG) test were performed. In addition, the chemical reaction of the PSA-mixed silica aerogel is confirmed by way of Fourier Transform Infrared Spectrometer (FT-IR). Then, the bonding force and thermal performance of the PSA film mixed silica aerogel are confirmed by referring to the probe tack and thermal conductivity.

Materials and experimental methods

Experimental methods

Characteristic of silica aerogel (BET, TG)

Specific surface area determinations were performed using the Brunauer–Emmett–Teller (BET) method with an adsorptionmeter. Porosity was determined with a mercury porosimeter (Autopore IV). The sample with a mass of 0.0809 g was degassed at 300 °C for 2 h and nitrogen was used as an adsorbent gas. TG was conducted with a TA Instruments Q-5000 IR. This unit has the ability to decrease the ramp rate when an increased mass loss is detected in order to obtain better temperature solution of a decomposition event. The general ramp rate was 4 °C min^{-1} with a mass loss detection sensitivity. Approximately 5–15 mg of cut samples was used to determine the decomposition temperatures [17].

Characteristic of PSA-mixed silica aerogel (FT-IR)

FT-IR spectroscopy (300E Jasco) was also utilized to monitor the change of chemical groups upon curing. Clear potassium bromide (KBr) discs were molded from the powder and a pure KBr disc was used as the background. The samples were analyzed over the range of 525–4,000 cm^{-1} with a spectrum resolution of 4 cm^{-1}. All spectra were averaged over 32 scans. This analysis of the composites was performed at point-to-point contact with a pressure device [18].

Characteristic of PSA-mixed silica aerogel film (probe tack, thermal conductivity)

The probe tack was measured using a 5-mm diameter stainless steel sphere probe on the Texture Analyzer (TA-XT2i, Micro Stable Systems, UK) at 22 $\pm$ 2 °C and 60 $\pm$ 5 RH %. The standard probe tack test was divided into three stages: approaching the surface of the PSAs, contact, and detachment from the surface of the PSAs. The approaching speed of the probe was 0.5 mm s^{-1} and the probe contacted the surface of the PSAs for 1 s with a constant pressure of 100 g cm^{-2}. The debonding speed was 0.5 mm s^{-1} and the probe tack was measured as the maximum debonding force (ASTM D3330).

The TCi developed by C-Therm is a device for conveniently measuring the thermal conductivity of a small sample by using the modified transient plane source method. Contrary to other devices, TCi can measure the thermal conductivity of materials in the states of solid, liquid, powder, and paste. In addition, it can measure thermal conductivity using only one side. The TCi consists of a sensor, power control device, and computer software. A spiral-type heating source is located at the center of the sensor, and heat is generated at the center. The heat that has been generated enters the material through the sensor during which a voltage decrease occurs rapidly at the heating source, and the thermal conductivity is calculated through the voltage decrease data. The experiment method is as follows [19, 20]. TCi is appropriate in the measurement of heat conductivity for the materials that have various states such as solid, liquid, powder, and paste. However, it shows relatively large deviations in the heat conductivity measurement of thin materials such as a film. Therefore, in this test, a PSA-mixed silica aerogel film (mixed with aerogel at mass ratio) was pasted to on the surface of the glass plate, and the varying heat conductivity values were measured by comparing to the reference PSA, the aerogel free PSA film, on the same glass plate at 20 °C of a laboratory condition.

Silica aerogel and preparation

In this paper, the powder silica aerogel manufactured by EM-POWER CO., LTD in KOREA had been used. The particle size of this powder-type silica aerogel is 1–10 μm and the powder color is white. The thermal conductivity is very low with a value of 0.02 W m^{-1} K^{-1}. Such low thermal conductivity is caused by the high porosity (90 %) and large surface area (700–800 m^2 g^{-1}). Therefore, studies are being conducted to source a possible new insulation raw material which can be used in various industries. The BET result values measured in this test are summarized in Fig. 1. In addition, the surface area, pore volume and pore sized are 719.8 m^2 g^{-1}, 1.97 cm^3 g^{-1}, and 109.50 nm, respectively. Also, the TG test was performed to measure the thermal stability of the silica aerogel. The temperature was increased from 0 to 1,100 °C with intervals of 10 °C min^{-1}. As seen in Fig. 2, there was no change in mass, until the temperature reached 1,100 °C. Therefore, it was possible to confirm that the aerogel is very thermally stable and it does not decompose even in high temperatures.

T-acrylic monomers (2-EHA, AA) were synthesized as 95.5 mass% by solution polymerization. The amount of AIBN in the binders was 0.3 phr. The solid content was 40 %. The mixture was placed into a 500-mL four-neck flask equipped with a stirrer, condenser and thermometer, and heated to 85 °C with constant stirring. At the end of the exothermic reaction, the temperature was maintained for 30 min, and a blend of ethyl acetate and AIBN was added. The reaction was allowed to proceed for 0.5 and 2.5 h. Finally, polymerization was terminated by cooling the mixture to room temperature. The prepared pre-polymers were used as PSAs [21].

Results and discussion

FT-IR

The aerogel and PSA should not have a chemical reaction with each other if they have the insulation performance in mixed status. Therefore, a FT-IR test was performed to confirm that there is no chemical reaction. Figure 3 shows the FT-IR test result values of the silica aerogel powder, PSA and PSA which is mixed with 20 mass% silica aerogel. When the peak of PSA not containing aerogel and the peak of PSA containing 20 mass% aerogel were compared, it was possible to find a small shoulder in the 1,162 cm^{-1} peak for the PSA-containing 20 mass% aerogel. This peak can also be found at silica aerogel 1,162 cm^{-1}. Therefore, it is possible to know that there was no chemical reaction between two materials since the silica aerogel powder peak appeared in the PSA which is mixed of 20 mass% silica aerogel without changes in other peaks. Therefore, the pores in the silica aerogel do not disappear when the PSA and the silica aerogel power are mixed. Accordingly, it is possible to expect that the silica aerogel will demonstrate sufficient insulation performance in the PSA.

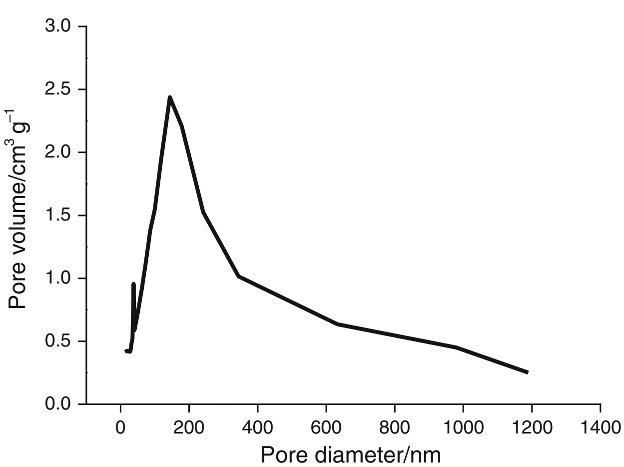

Fig. 1 Pore diameter of silica aerogel

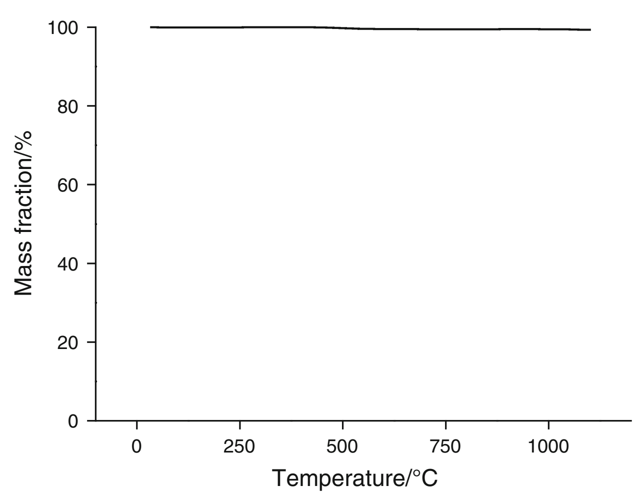

Fig. 2 TG result of silica aerogel (10 °C min^{-1})

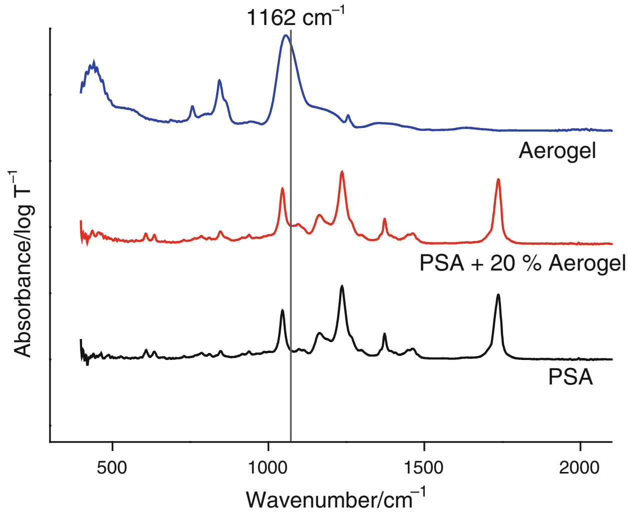

Fig. 3 FT-IR spectra of PSA, PSA-mixed silica aerogel, and silica aerogel powder

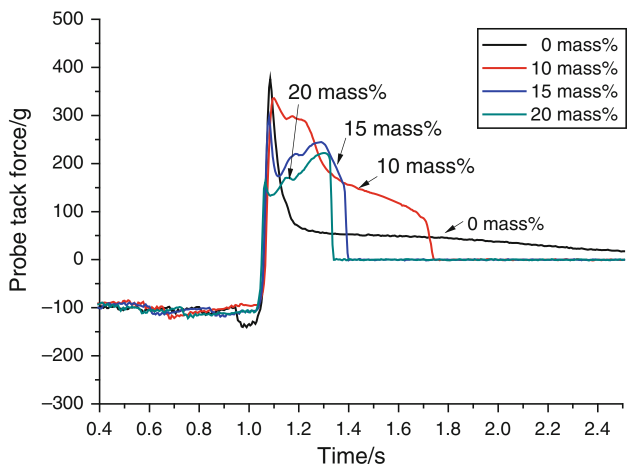

Fig. 4 Probe tack of PSA film mixed silica aerogel versus silica aerogel mass%

Probe tack

Probe tack tests are intended to be simulations of thumb or finger tack tests. The tip of a probe is brought into contact with a supported adhesive under low contact pressures for a short time and then pulled away at a fixed rate, during which the peak force of separation is measured [22].

Figure 4 shows the probe tack graph in accordance with the increase of silica aerogel mass%. It is possible to establish that, as the mass% increases from 10 to 15 and 20 mass%, the probe tack debonding force decreases. Table 1 shows the changes in the probe tack debonding force as the silica aerogel mass% increases. It is possible to determine that the overall debonding force decreases by 40 % when the aerogel

Table 1 PSA-mixed silica aerogel film probe tack debonding force versus silica aerogel mass%

Silica aerogel/mass%	Probe tack force/g
0	375.4
10	335.9
15	269.2
20	222.0

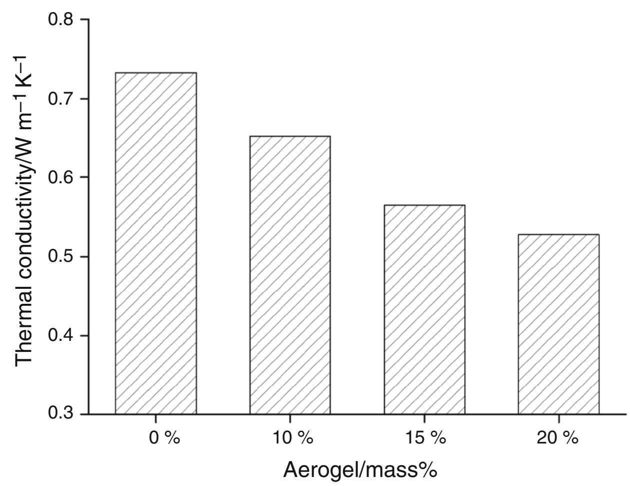

Fig. 5 Thermal conductivity of PSA film-mixed silica aerogel film versus silica aerogel mass%

content is 20 mass%. It is possible to confirm with the above results that the silica aerogel decreases the bonding force of PSA. The reason for the bonding force decrease is that the silica aerogel with small density interferes with the bonding of the film, while it floats to the bonding plane, while the solvent of the PSA-mixed silica aerogel is removed.

Thermal conductivity

The thermal conductivities of four different mass% silica aerogel films were measured by a Mathis TCi thermal conductivity analyzer (C-Therm Technologies Ltd.), and the results are shown in Fig. 5. The thermal conductivity was measured ten times and the average value was used. It was possible to confirm the relative values of thermal conductivity dependent on the silica aerogel mass% because the measurement had been performed after the PSA-mixed silica aerogel film had been pasted to a glass plate (Fig. 6). The thermal conductivity of the film not containing the silica aerogel (0 mass%) was measured as 0.773 W m^{-1} K^{-1} at room temperature. It was also possible to confirm that the thermal conductivity decreases as the aerogel mass% increases. The thermal conductivity of 10 mass% silica aerogel was 0.652 W m^{-1} K^{-1}, which was an 11 % decrease from the thermal conductivity of 0 mass%. The thermal conductivity of 15 mass% silica aerogel was

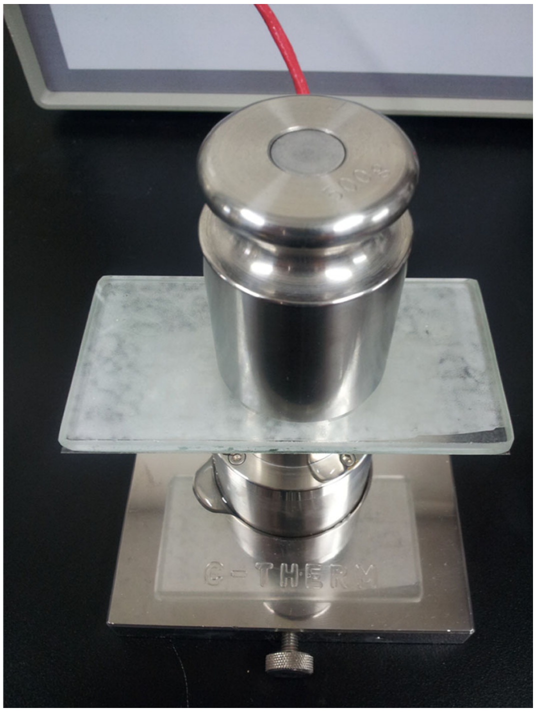

Fig. 6 Thermal conductivity measurement of PSA film-mixed silica aerogel film

0.565 W m^{-1} K^{-1}, which was a 23 % decrease from the thermal conductivity of 0 mass%. When the aerogel mass% increased to 20 mass%, the thermal conductivity decreased to 0.528 W m^{-1} K^{-1}. This means that about 32 % thermal conductivity decreases when there is 20 mass% silica aerogel. This occurs because the aerogel with many pores (these pores comprise 85.0–99.8 % of the total aerogel volume) interferes with heat conduction as the mass% increases.

Conclusions

In this study, the properties of silica aerogel that had been used in the test were measured and a PSA composite was made by mixing the silica aerogel, having good insulation performance, with PSA based on mass ratio. In order to check the existence of the chemical reaction between the PSA and silica aerogel, a FT-IR test was performed. A probe tack test was also performed to measure the debonding force of a film coated with PSA, which is a mixture of silica aerogel, dependent on the mass ratio of silica aerogel. Then, the thermal conductivity was measured using the TCi thermal conductivity analyzer to observe the changes in the heat conductivity of a film coated with PSA-mixed silica aerogel dependent on the mass ratio of silica aerogel.

According to the BET test results, it is possible for a larger surface area comparing to other fillers to expect that silica aerogel will have insulation performance. As a result of TG test, changes in mass did not occur in the silica aerogel at the high temperature of 1,100 °C. Accordingly, it is possible to expect that an insulation performance would be demonstrated in the PSA because the properties of silica aerogel do not change by temperature when the PSA-mixed silica aerogel had been made. A FT-IR test of the silica aerogel powder, PSA, and the PSA-mixed silica aerogel demonstrated that the silica aerogel and PSA do not have any chemical reaction during the synthesis process of the PSA-mixed silica aerogel, which means that they were in a physically mixed state.

Finally, the change in thermal conductivity was observed by a TCi thermal conductivity analyzer after the PSA-mixed silica aerogel had been pasted to a glass plate. It was possible to establish that the thermal conductivity of the film containing 20 mass% silica aerogel has 32 % less thermal conductivity than the thermal conductivity of the film not containing any silica aerogel. A translucent PSA-mixed silica aerogel film will be developed in the future by further studying the reaction nature of the Si-series silica aerogel properties with PSA. The developed film could be used on building windows. It will enhance the insulation performance of windows, which are the weakest parts of the building in terms of energy loss. A silica aerogel film will be developed which will be effective in reducing heating load by bypassing the daylight in winter by way of the translucent property of the silica aerogel film.

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