Silica Aerogel Thermal Insulation Coating as Commodity Usage

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Abstract. Silica aerogel-based thermal insulation coating (SA-coating) was prepared from a commercial acrylic binder. The purpose of this investigation is to determine the effectiveness of SA-coating with the application in energy-efficient home design for temperature insulation purposes. The weather acceleration test and thermal insulation property of SA-coating were investigated and compared to the original commercial binder. The weather acceleration test of SA-coating showed equivalent weathering stability and robustness compared to the original binder. The thermal insulation property was performed from an in-lab setup, called temperature difference (TD) measurement. In a closed chamber, without air circulation, the surface temperature with SA-coating was reduced by as much as 26 degrees from 90°C to ~64°C. More so, if TD measurement was performed in a ventilated area, the temperature can be reduced from 50°C to 36°C (room temperature was 31°C). The thermal conductivity of the coating at different temperatures was also measured. The water contact angle measurements and the scanning electron micrographs showed that SA-coating can be made hydrophilic to hydrophobic by simple abrasion.

1. Introduction
Thermal insulation materials for energy-efficient construction design have been widely discussed and commercialized for applications to lower energy consumption [1-3]. Materials such as, glass fiber, glass wool, or mineral wool, insulation blankets installed under the roof of buildings for cooling purposes [4]. Heat reflective thermal paints and cool-roof shields are a few examples of commercialized products available in the market. The key to these thermal insulation systems is to fill them with porous core material or material with low thermal conductivity (20-80 mW/(m K)) [5-8].

Silica aerogel (SA) is a promising material for insulation applications because of its very low thermal conductivity [9]. The thermal conductivity of silica aerogels is lower than that of still air. Besides its low thermal conductivity, the silica aerogel is extremely lightweight, hydrophobic, and has good fire and acoustic resistances [9-11]. These characteristics make silica aerogel a premier additive material for energy efficiency and protection in building materials and industrial coating.
In this paper, varying volume ratios of binder to SA were prepared. Temperature difference, thermal conductivity, weathering test, surface microstructure, and hydrophobicity of the coating were investigated to determine the optimum volume of SA needed in an acrylic binder. The objective of this research was to optimize the addition of SA in improving the thermal insulation performance of commercial acrylic binders for application as energy-saving roof-coatings for buildings.

2. Materials and Experiments

2.1. Materials and sample preparation
Commercial acrylic binder was purchased from HomeMart, Thailand. It is a liquid acrylic, waterproof product for roofs and facades with very highly flexible film. Silica aerogel (SA) was obtained from Thillium, Thailand. Tween-20 was purchased from Sigma-Aldrich, USA.

Tween-20 was first dispersed in 100 mL of water in a blender, and then 9.0 g of SA was added to the mixture. The purpose of dispersing SA in the Tween is to make SA more dispersible in acrylic binder. Tween-20 was varied from 0.0 – 0.4 grams. Tween and SA mixture were then blended with the acrylic binder. A series of binder to SA in the volume ratios of 1:1, 1:2, 1:3, 1:4, and 1:5 were prepared. Tween, SA, and binder mixtures were then cast on an aluminum sheet and left for drying at 50°C for further characterization. The casted coatings were of 1-mm and 2-mm thick.

2.2. Temperature difference (TD) measurements
The thermal insulation property was performed from an in-lab setup, called temperature difference (TD) measurement. As shown in figure 1, the temperature of the hotplate serves as the constant heat source, T_source, to be compared to the surface with SA-coating, T_coat. T_source was set to 50, 60, 70, 80, and 90°C.

![Figure 1. Setup for temperature difference (TD) measurement.](image)

Data logger attached with two thermocouples records T_source, the surface of the hotplate; and T_coat, the surface of the coating, simultaneously.

2.3. Measurement of thermal conductivity
The thermal conductivity of the coating was measured by using the C-Therm TCi, C-Therm Technologies Ltd. The instrument employs the modified transient plane source for thermal conductivity measurement. The test was conducted at room temperature (31°C), 50, 60, 70, 80, and 90°C. An accuracy check was performed on the instrument before running any tests as standard reference material and confirmed the instrument was performing well within the stated accuracy specification of 5%.
2.4. Weather acceleration test
The weather acceleration test was performed following ASTM D154. The condition runs for 4 cycles. Each cycle runs for 7 days. One cycle estimates 1.5 years equivalent. A cycle consisted of an alternating exposure of condensation at 50°C for 4 hours and exposure of UVB 313 nm at 60°C for 4 hours.

2.5. Water contact angle measurements
The water contact angle measurements were performed using a KRÜSS model G23 apparatus (KRÜSS GmbH, Germany) with a CCD camera (20x objective lens). The contact angle photographs were taken by the ManyCam software. The water drop volume used was 10 μL. The results were measured from the photographs with the ImageJ angle analysis tool. The water contact angles were measured before and after abrasion of the coated surface.

2.6. Scanning electron microscopy (SEM)
A Hitachi SU3500 scanning electron microscope operating at 5 kV was used to capture surface image of the coatings. No sputtering was required because the instrument was operated under low vacuum.

3. Results and Discussion
For the recent years, there has been extreme temperature occurrence all around the world, extreme heat (40°C or higher) has now, seems to be a common phenomenon in some parts of the world. While in other areas, extreme coldness has also been somewhat a familiar occurrence. We cope with these extreme heat with air-conditionings and extreme coldness with heaters. Both of which consume much energy in houses and buildings. For this research work, a simple thermal insulation coating was made by mixing commercial SA with commercial acrylic binder. Table 1 summarized the T_coat measured for 1-mm and 2-mm thickness coating. Volume ratios of binder to SA were varied, 1:1, 1:2, 1:3, 1:4, and 1:5. TD were measured with the heat source (T_source) at 60°C, 70°C, 80°C, and 90°C. As expected the thicker the coating, more TD could be achieved.

Table 1. Temperature difference measurements of (a) 1- and (b) 2-mm thickness coating with 0.4 g TWEEN.

(a) Coating thickness 1 mm

| Ratio of Binder to Silica aerogel | T_coat (°C) | Set T_source 60°C | Set T_source 70°C | Set T_source 80°C | Set T_source 90°C |
|----------------------------------|-------------|-------------------|-------------------|-------------------|-------------------|
| 1:0                              |             | 59.7 ± 0.5        | 71.7 ± 1.0        | 81.7 ± 1.0        | 91.3 ± 0.8        |
| 1:1                              |             | 57.0 ± 1.0        | 65.3 ± 0.6        | 71.7 ± 0.6        | 74.3 ± 0.6        |
| 1:2                              |             | 56.3 ± 0.6        | 61.7 ± 1.2        | 69.7 ± 0.6        | 72.3 ± 0.6        |
| 1:3                              |             | 53.3 ± 1.2        | 57.3 ± 0.6        | 67.7 ± 0.6        | 70.3 ± 0.6        |
| 1:4                              |             | 51.7 ± 0.6        | 55.3 ± 0.6        | 66.3 ± 0.6        | 68.7 ± 0.6        |
| 1:5                              |             | 50.0 ± 1.0        | 53.7 ± 0.6        | 64.7 ± 0.6        | 67.0 ± 1.0        |

(b) Coating thickness 2 mm

| Ratio of Binder to Silica aerogel | T_coat (°C) | Set T_source 50°C (ventilated area) | Set T_source 60°C | Set T_source 70°C | Set T_source 80°C | Set T_source 90°C |
|----------------------------------|-------------|------------------------------------|-------------------|-------------------|-------------------|-------------------|
| 1:0                              |             | 51.3 ± 0.5                         | 59.3 ± 0.6        | 70.7 ± 1.0        | 79.7±0.5          | 89.3±0.6          |
| 1:1                              |             | 46.7 ± 0.8                         | 54.0 ± 1.0        | 58.0 ± 1.0        | 68.3±0.6          | 70.7±0.6          |
| 1:2                              |             | 42.5 ± 0.9                         | 52.3 ± 0.6        | 55.7 ± 0.6        | 65.3±0.6          | 68.7±0.6          |
| 1:3                              |             | 38.8 ± 1.1                         | 50.0 ± 1.0        | 52.7 ± 0.6        | 62.0±1.0          | 66.7±0.6          |
| 1:4                              |             | 38.2 ± 0.9                         | 49.0 ± 1.0        | 52.3 ± 0.6        | 60.3±1.2          | 64.3±0.6          |
| 1:5                              |             | 36.1 ± 0.9                         | 48.0 ± 1.0        | 51.3 ± 0.6        | 58.7±0.6          | 63.7±1.2          |
Moreover, when TD was measured with T_source at 50°C in a ventilated area, T_coat on the surface of SA-coating was only ~35°C, slightly warmer than room temperature by 4°C. This is significant because it best simulates the real usage of the coating, i.e., in a ventilated environment. T_coat could be much lower if the environment had a cooling system, like air-conditioning. We believe that this SA-coating can be used in homes to reduce temperature fluctuation and help minimize energy consumption in homes, office buildings, and industrial constructions.

Thermal conductivity of SA-coating increased with increasing temperature, table 2. It is unclear why for the same coating at higher temperature, though, having higher thermal conductivity; it was able to obtain a larger temperature difference.

Table 2. Thermal conductivity of SA-coating measured at different temperatures.

| Ratio of Binder to Silica aerogel | Thermal conductivity (mW m⁻¹ K⁻¹) |
|----------------------------------|----------------------------------|
|                                  | @ 31°C | 50°C | 60°C | 70°C | 80°C | 90°C |
| 1:0 (pure binder)                | 201 ± 34 n/a n/a n/a n/a n/a |
| 1:1                              | 129 ± 6 6 9 14 4 8 |
| 1:4                              | 66 ± 2 68 ± 4 72 ± 3 81 ± 4 84 ± 3 88 ± 8 |

*n/a, the thermal conductivity exceeds the limit of the instrument*

The effect of increasing SA in the composite largely decreased thermal conductivity. Comparing the ratios 1:1 and 1:4 with T_source of 70°C, 2-mm thick; though, the thermal conductivity was 180 ± 14 mW m⁻¹ K⁻¹ to 81 ± 4 mW m⁻¹ K⁻¹, respectively. But T_coat of 1:1 was 58.0 ± 1.0 °C compared to 52.3 ± 0.6 °C that is only ~6°C difference. While when the thickness of the coating was increased from 1 mm to 2 mm, the temperature difference measurement at 70°C of 1:1 ratio could also be reduced by ~6°C (65.3 ± 0.6 °C as to 58.0 ± 1.0 °C, respectively). We concluded here that the huge difference in the value of the thermal conductivity does not necessarily be reflected in the temperature difference measurement. The thickness of the coating, however, has more contributions to the ability of a coating to reduce temperature in this case.

Weathering test (following ASTM D154) is a common standard used to test weathering stability and robustness of coatings. The test was designed to expose the coating to a simulated accelerated outdoor conditions with alternating UV exposures and humidity exposures. Chalky failure is one criteria in the standard used to determine whether the coating passes or fails. A standard cloth of testing is used to rub on the coating after each cycle; if chalk like material or debris is detected on the cloth, then the coating failed to pass the test. Chalky failure was not observed for all ratios of SA-coating of at least 4 cycles (or an equivalent of 6 years). SA-coating showed equivalent weathering stability and robustness compare to that of the original binder.

Water contact angle measurements characterized the hydrophilicity or hydrophobicity of a surface. Table 3 tabulated the contact angle of all ratios. Pure binder (1:0) had contact angle of 60 degrees and after abraded it increased to 63 degrees. This was not a significant increase. During the drying process, the more hydrophilic part of the binder was air-dried on the surface, but after abrasion the inner less hydrophilic surface of the binder was exposed.
Table 3. Water contact angle on SA coating of different ratios of Binder to Silica Aerogel before and after abrasion.

| Binder : Silica Aerogel | Contact angle before abrasion | Contact angle after abrasion |
|-------------------------|------------------------------|-----------------------------|
| 1:0 (pure binder)       | 60                           | 63                          |
| 1:1                     | 83                           | 101                         |
| 1:2                     | 92                           | 124                         |
| 1:3                     | 97                           | 141                         |
| 1:4                     | 101                          | 141                         |
| 1:5                     | 103                          | 144                         |

In 1:1 ratio, the contact angle was increased to 83 degrees before abrasion and 101 degrees after abrasion. This was because the original binder is slightly hydrophilic in nature, but SA is hydrophobic. With the exposure of SA to the surface after abrasion, the surface became hydrophobic. For volume ratios of binder:SA, with SA greater than 2 parts, the coating became hydrophobic because more SA could be found on the surface of the coating. Scanning electron micrographs of SA coating, figure 2, had irregular openings with SA protruding from the coating.

Figure 2. Scanning electron micrographs of SA coating of at (a) 50x and (b) 1,000x magnification.
4. Conclusions
In this work, a simple thermal insulation coating was made by mixing commercial silica aerogel with commercial acrylic binder. Weathering test of silica aerogel coating showed equivalent weathering stability and robustness compare to that of the original binder. Following ASTM D154, all ratios of silica aerogel coating passed at least 4 cycles (or approximately 6 years equivalent). The water contact angle measurements showed that silica aerogel coating could be made hydrophilic or hydrophobic depending of the amount of silica aerogel added. The volume ratio of binder to silica aerogel, with silica aerogel greater than 2 parts will give a hydrophobic surface. Scanning electron micrographs show silica aerogel protruding from coating.

In a closed chamber, the temperature difference measurement of silica aerogel coating can reduce the surface temperature by an average of 25%. But thermal insulation can be greatly appreciated in a ventilated environment, temperature can be reduced from a heat source of 50°C to 35°C (slightly warmer than room temperature by 4°C). Tween of 0.4 g gives best processing in blending silica aerogel into the binder.

We believe that this silica aerogel coating can be used to reduce temperature fluctuations in homes and help minimize energy consumption in homes, office buildings, and industrial constructions.

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References
[1] Cuce E, Cuce P M, Wood C J, Riffat S B 2014 Toward aerogel based thermal superinsulation in buildings: a comprehensive review, Renew. Sustain. Energy Rev. 34 273-99.
[2] Jelle B P 2011 Traditional, state-of-the-art and future thermal building insulation materials and solutions—Properties, requirements and possibilities, Energy Build. 43 2549-63.
[3] Al-Homoud M S 2005 Performance characteristics and practical applications of common building thermal insulation materials, Build. Environ. 40 353-66.
[4] Lyons A 2010 Materials for Architects and Builders, fourth ed., Elsevier Ltd., United Kingdom.
[5] Jelle B P, Gao T, Sandberg L I C, Ng S, Tilset B G, Grandcolas M, Gustavsen A 2015 Development of nano insulation materials for building constructions, Proc. of 5th Int. Symp. Nanotechnology in Construction (NICOM5) 429-34.
[6] Gao T, Jelle B P, Sandberg L I C, Gustavsen A 2013 Monodisperse hollow silica nanospheres for nano insulation materials: synthesis, characterization, and life cycle assessment, ACS Appl. Mater. Interfaces 5 761-7.
[7] Sandberg L I C, Gao T, Jelle B P, Gustavsen A 2013 Synthesis of hollow silica nanospheres by sacrificial polystyrene templates for thermal insulation applications, Adv. Mater. Sci. Eng. 2013 1-6.
[8] Jelle B P, Gustavsen A, Baetens R 2010 The path to the high performance thermal building insulation materials and solutions of tomorrow, J. Build. Phys. 34 99-123.
[9] Hüsing N, Schubert U 1998 Aerogels—Airy Materials: Chemistry, Structure, and Properties, Angew. Chem. Int. Ed. 37 22-45.
[10] Gao T, Jelle B P, Gustavsen A, Jacobsen S 2014 Aerogel-incorporated concrete: an experimental study, Constr. Build. Mater. 52 130-6.
[11] Baetens R, Jelle B P, Gustavsen A 2011 Aerogel insulation for building applications: a state-of-the-art review, Energy Build. 43 761-9.
[12] Kiil S 2015 Quantitative analysis of silica aerogel-based thermal insulation coatings, Prog. Org. Coat. 89 26-34.