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Thermal and acoustic properties of aerogels: preliminary investigation of the influence of granule size

Elisa Moretti[a,*], Francesca Merli[b], Erdem Cuce[c], Cinzia Buratti[a]

[a]*University of Perugia – Department of Engineering, Via G. Duranti 93, 06125 Perugia, Italy*
[b]*University of Perugia – CIRIAF Interuniversity Research Center on Pollution and Environment "Mauro Felli", Via G. Duranti 63, 06125 Perugia, Italy*
[c]*Department of Mechanical Engineering, University of Bayburt, 69000 Bayburt, Turkey*

Abstract

The influence of granules size in silica aerogels is experimentally investigated in terms of thermal and acoustic performance characteristics. The transmission loss (TL) is measured at normal incidence in a traditional impedance tube, whereas the thermal conductivity (λ) is evaluated using a Hot Plate apparatus, setting up an appropriate methodology, due to the nature of the sample. The results reveal that the small granules (granules size in the 0.01-1.2 mm range), which have the highest density, have the best performance both in terms of thermal and acoustic properties. Depending on the granules size, λ varies in 19-22 mW/mK range at 10°C, whereas a TL equal to 13 dB at about 6400 Hz for 20 mm thickness is obtained for small granules.

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Keywords: Silica aerogel; Thermal properties; Acoustic insulation; Building refurbishment;Transmission loss (TL); Thermal conductivity.

1. Introduction

Thermal insulation of building envelope plays a key-role in energy saving: a growing interest is focused on new materials and advanced solutions are in the centre of interest in the construction industry, also including nanomaterials, such silica aerogels [1,2]. Aerogel is one of the most promising nano-materials for use in highly energy efficient buildings and windows. It consists of a nanostructured silicon dioxide network (SiO_2, amorphous quartz) made through a sol-gel chemical processing and drying technology: it is constituted by approximately 96% of air and 4% open-pored structure of silica, which could be hydrophobic for some applications [2,3]. The material is

* Corresponding author. Tel.: +39-075-5853694; fax: +39-075 -585367.
E-mail address: elisa.moretti@unipg.it

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characterized by excellent and unique physical properties: it is highly porous (density is in the 50-200 kg/m^3 range), and it has excellent insulation performance (thermal conductivity approximately in the 0.012- 0.021 W/(mK) range at room temperature, lower than the one of air). It is characterized by a high solar energy and daylight transmittance in transparent monolithic or translucent granular forms [3,4]. Due to the very low thermal conductivity and good light transmittance, highly energy-efficient windows with granular silica aerogel in interspace [5,6,7,8] or translucent aerogel support pillars for commercial vacuum glazings are investigated [9]. Furthermore, aerogel-incorporated concrete and aerogel based renders are developed day after day and internal aerogel retrofitting on the thermal bridges are investigated for energy saving in buildings [10,11,12,13,14].

Thermal and optical performance of silica aerogels for building insulation is widely discussed in the literature [5,6,15,16,17,18], whereas the attempts for accurate determination of acoustic properties are still limited [5,6,7,10,11,19]. In this paper thermal and acoustic properties of silica granular aerogels are investigated taking into account the influence of granules size and density of the granule bed on the material performance: small granules (granules size in the 0.01-1.2 mm range), medium granules (granules size in the 0.7-2.0 mm range), and large granules (granules size in the 0.7-4 mm range) are analysed in the experimental research. The performance is evaluated using conventional methodologies (impedance tube methodology for transmission loss (TL) at normal incidence and the hot-plate method for thermal conductivity), but preliminary tests are carried out in order to set up the methodology and to properly prepare the sample, due to its granular nature.

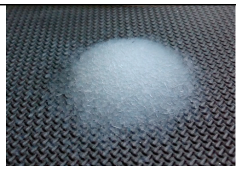
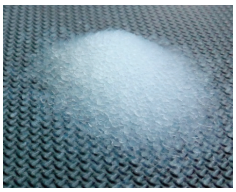
2. Material and methods

2.1. The investigated samples

The translucent granular silica aerogel investigated in the paper is supplied by Cabot Corporation, USA [20] in three different sizes: small (sample A), medium (sample B), large (sample C) granules, respectively in the 0.01-1.2 mm, 0.7-2.0 mm, 1-4 mm range are supplied and analyzed.

Table 1 shows the main characteristics of the examined samples.

Table 1. Features of the examined aerogels.

Sample	Diameter granules estimated (mm)	Bulk density estimated (kg/m^3)	Sample features	Picture
A Small	0.01-1.2	80-85	Regular shape. Small particles that form a dust.	
B Medium	0.7-2.0	70-75	Regular shape. Uniform particles.	
C Large	0.7-4.0	65-70	Irregular shape. Flat particles.	

Otherwise the particle size, they differ also in the suggested applications: the smaller granules are used in the production of plasters or materials at high thermal performance as insulation blankets, while samples B and C are specific in the field of daylighting. The samples are weighed with a precision balance in order to estimate the density; the diameter of the particles is measured by a centesimal caliber. Large granules sample shows a bulk density in the 65-75 kg/m^3 range, in agreement with the range proposed by the data sheets of the same manufacturer. Sample A has a higher specific weight for equal volume, due to a smaller amount of voids.

2.2. Thermal measurements

The thermal conductivity is measured in steady-state conditions with Heat Flow Meter method (Fox 314 HFM apparatus [21,22]), according to ASTM Standard C 518 [23] and EN ISO 12667 [24]. The sample is placed between two flat plates controlled to a set constant temperature (Fig. 1. (a)). Thermocouples fixed to the plates measure the temperature drop across the specimen and wireless thermal flux meters (HFMs) embedded in each plate measure the heat flow through the sample. The thermal conductivity can be calculated by measuring the heat flux (q in W/m^2), the temperature difference across the specimen (ΔT in K), and the thickness of the sample (s in m), at steady state, as:

$$\lambda = (s \cdot q)/\Delta T \tag{1}$$

In order to measure the granular aerogel thermal conductivity, a wood frame is constructed (with external dimensions of 0.3 x 0.3 m, and thicknesses of the wood borders equal to 5 mm), and two very thin steel plates (with external dimensions of 0.3 x 0.3 m and a total thickness of 0.4 mm) are used in order to cover the top and the bottom of the frame (Fig. 1. (b)). The plates have a negligible thermal resistance and they perfectly adhere to the Heat Flow Meter plates (hot and cold plates) so that the influence on the total thermal conductivity value of the samples could be considered negligible. The box container follows the suggestions reported in the international technical references, and in particular ASTM C687-12 [25], which includes granular types such as vermiculite, perlite and pelletized products, comparable to granular aerogels. According to the reference standard [24], when testing loose-fill materials, the thickness of the specimen shall be at least 10 times the mean dimension of grains: a thickness of 40 mm is then considered and the box is filled up manually with aerogel granules. The specimen thickness is measured by a digital system integrated in the apparatus: a mean value is supplied by the system (the thickness of the steel plates was subtracted in order to calculate the thermal conductivity). The thermal conductivity is measured at mean reference temperatures of 10°C and 23°C and the tests last at least 10 hours for each sample.

a

b

Fig. 1. (a) The Heat Flow Meter apparatus; (b) aerogel in the wood box

2.3. Acoustic measurements

The acoustic characterization of granular aerogels is carried out in terms of sound insulation properties

(Transmission Loss, TL), investigated in a traditional impedance tube (Fig. 2. (a), Kund's Tube, Brüel & Kjær) using a four microphone transfer function method [26]. TL is a key factor for the quantification of the acoustic insulation properties of materials. It is related to the sound transmission coefficient (t) as follows (2):

$$TL = 10 \cdot \log(1/\tau) \tag{2}$$

TL is measured by means of the 'two load' transfer function method, by acquiring the sound pressure in four fixed microphone positions: two consecutive acquisitions are carried out for each sample by modifying the characteristics of the tube extremity (a reflective and an absorbing material should be installed). Channels phase displacement errors are avoided by a calibration procedure. The large tube (diameter of 100 mm) is utilised for measurements in the 50-1700 Hz frequency range, the small tube in the 100-6400 Hz range. The environmental parameters of the laboratory (atmospheric pressure, air temperature and relative humidity) are measured before starting each test; the values were used in the measurement elaboration by the Brüel & Kjær PULSE LabShop [27,28].

For each size of the granules 5 different thicknesses are evaluated (15, 20, 25, 30, and 40 mm), according to the typical thickness used in glazing solutions. Three measurements for each sample are conducted by filling the tube each time and an averaged value of the TL was considered.

Due to the granular nature of the sample, a specific measurement methodology is set up: the impedance tube is fixed vertically and the granules are inserted in a sample holder purposely realized. It consists of a cylindrical steel cable supports closed at the bottom by a thin porous (Fig. 2. (b)). Preliminary measurements indicate a negligible influence on the experimental results.

a b

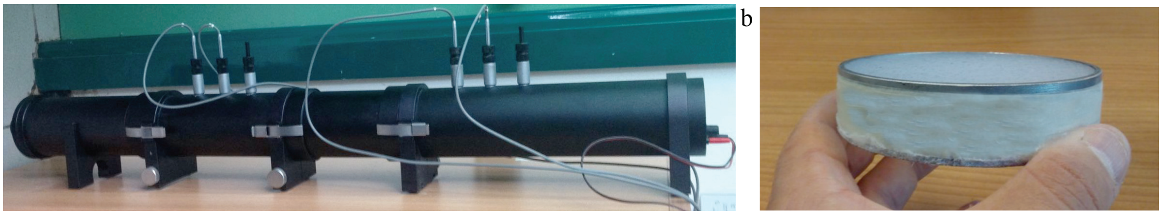


Fig. 2. (a) Impedence tube configuration for the transmission loss mesurement; (b) aerogel in the sample port.

3. Results and discussion

3.1. Thermal performance

The measured thermal conductivity for the different samples is reported in fig. 3, considering the influence of the mean reference temperatures (10°C and 23°). As expected, all the samples demonstrate excellent thermal insulation properties, better than the ones of conventional insulating materials (for instance, λ= 40 mW/mK for glass or rock wool or λ= 24 mW/mK for rigid polyurethane [21]): depending on the particle size, values of λ in the 18.6-21.4 mW/mK range at 10°C were found. The values are strictly connected to the structure of silica aerogels: the conduction in the solid silica is very limited, because the solid fraction is low (<10%) and the convection in the pores of the structure is reduced, due to their dimensions (5-20 nm). In general, for granules bed, the thermal conductivity is higher than the one of monolithic aerogel, due to the air in the inter-granular voids, which are relatively large. For smaller granules, the voids are lower and have smaller size (the density is higher) and the heat transfer by convection and radiation is reduced: a reduction of thermal conductivity of about 15% (sample A) with respect to the larger ones (sample C) was found, while the medium size aerogels (sample B) show an intermediate behavior.

Results also highlight the influence of the temperature on the thermal conductivity: as known, for all the samples the λ-value decreases of about 5-7% when the mean temperature varies from 10°C to 23°C.

The experimental results are in agreement with literature data [16,17]. Gao et al. [16] investigated the impact of aerogel particle size on thermal and lighting performance of glazing systems with silica aerogel in interspace (14 mm gap size): with respect to a conventional double glazing, the reduction in heat losses (U-value) was about 58% for large aerogel granules (particle size 3–5 mm), whereas it increases up to 63% for small sized aerogel granules (particle size <0.5 mm); however, at the same time, when compared to conventional solutions, the reduction in light transmittance was significantly increased for small granules (-81%) with respect to large ones (-38%) .

Finally, as shown in Neugebauer et al. [17], compacting a bed of silica aerogel small granules, the thermal conductivity can be diminished from 24 mW/mK (bulk density of about 68 kg/m^3 for uncompressed bed) down to 13 mW/mK (corresponding to a bulk density of about 150-165 kg/m^3, compressive strain of about 55%-59%), approaching the performance of monolithic aerogels. For these reasons, further experimental campaign should be performed in order to investigate the thermal conductivity variation depending on the filling of the wood frame: for each sample, the procedure should be repeated filling the frame each time (the volume of the voids could change), also considering different sample thicknesses.

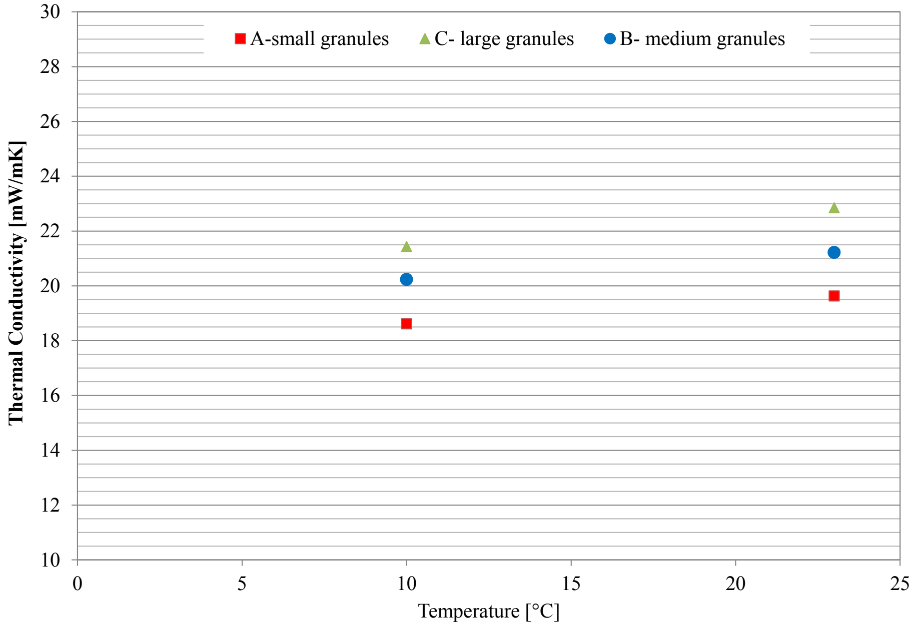


Fig. 3. Thermal conductivity of the tested aerogels: influence of the temperature and of the granules size

3.2. Acoustic performance

In this paper the results of large tube configuration are discussed only, since the internal dimensions of the tube (about 100 mm) allow easier preparation and positioning of the sample. The influence of the thickness of samples and of different particle sizes is assessed.

Figure 4 shows the transmission loss levels measured for the sample C (large granules) depending on the thicknesses: similar behaviors were found for the samples A and B. A general increasing value of transmission loss, at a fixed frequency is observed when the thickness of the samples and surface mass grow. The TL increases also as the frequency raises. The results are in agreement with the low of mass that links sound insulation, frequency and surface mass. For each sample, when the thickness increases, the first peak raises (2-3 dB) and moves towards lower frequencies, according to Literature data [29].

The influence of granules size can be evaluated with the same thickness: figure 5 shows the TL of the three samples for a thickness of 20 mm. As observed for thermal properties, the best sound insulation properties were obtained for small granules (TL=13 dB at about 1700 Hz), whereas for medium and large granules the maximum values are 8 dB and about 5 dB respectively. The trend is in agreement with Literature: the smaller granules allow to increase the attenuation and to reduce the velocity of sound in the material, because of the reduction of the air volume fraction [19].

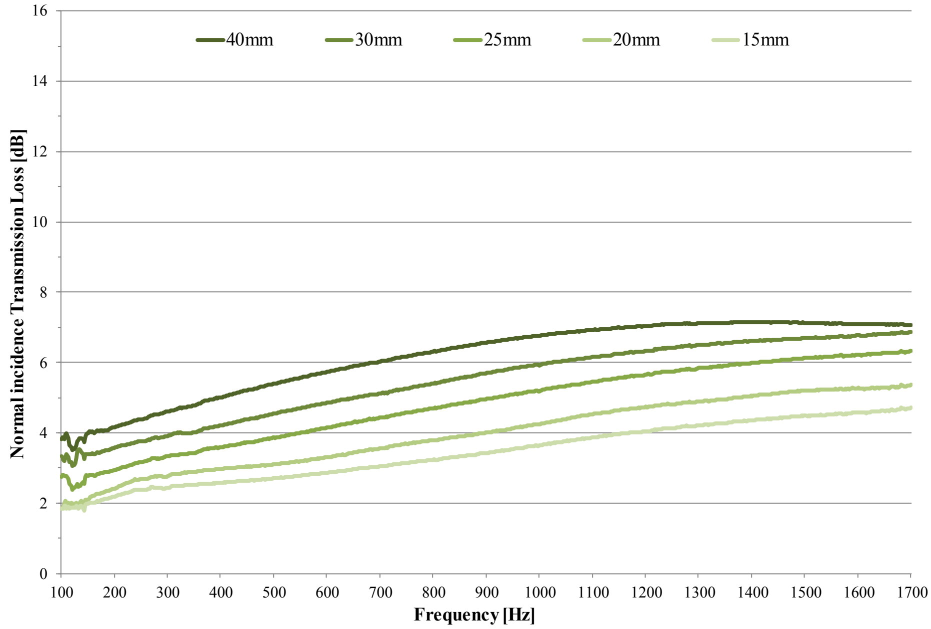


Fig. 4. Transmission loss of the sample C (large granules) for different thickness.

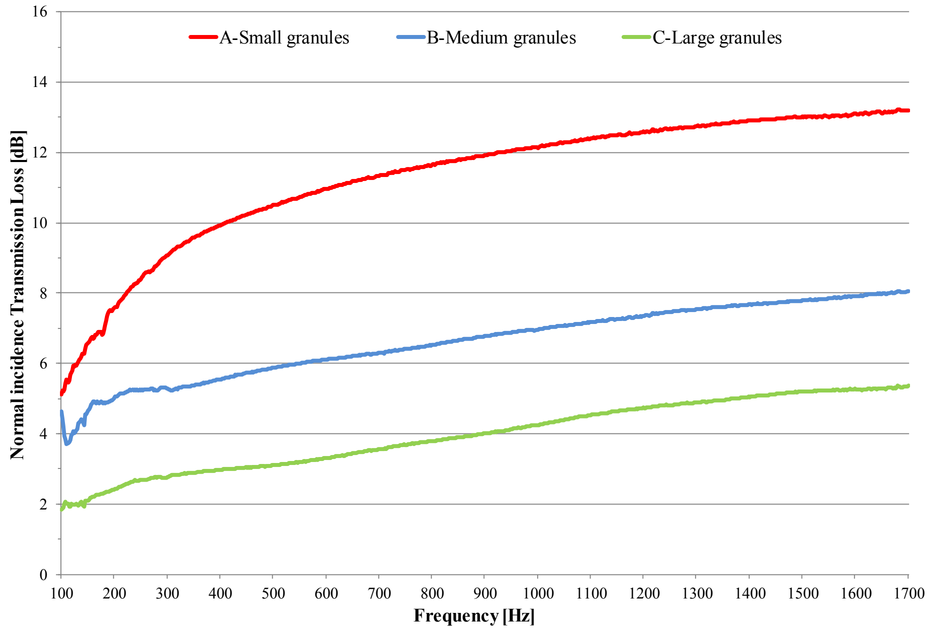


Fig. 5. Transmission loss of the three different samples for the thickness of 20 mm.

The acoustic performance of the investigated insulating materials is compared with data of a traditional inorganic fibrous material such as rock wool [21]. In the comparison (Fig. 6), a panel 3 cm thick and 95 kg/m^3 density is considered. For the larger granules (sample C), transmission loss is slightly less than the opaque material (about 2 dB). The finer grain sizes (sample B) show similar values to those of rock wool, while fro the finest granules (sample A) TL exceeds some dB (5-6 dB) the values obtained for the rock wool. Moreover, it is important to notice that the rock wool has a density greater than aerogels (95 kg/m^3 compared to 85 kg/m^3 of small granules, aerogel with higher density). The aerogel excellent acoustic properties are particularly evident because they have the advantage of being translucent, and then can be used in the applications for glazing systems, such as polycarbonate or other glazing solutions [3].

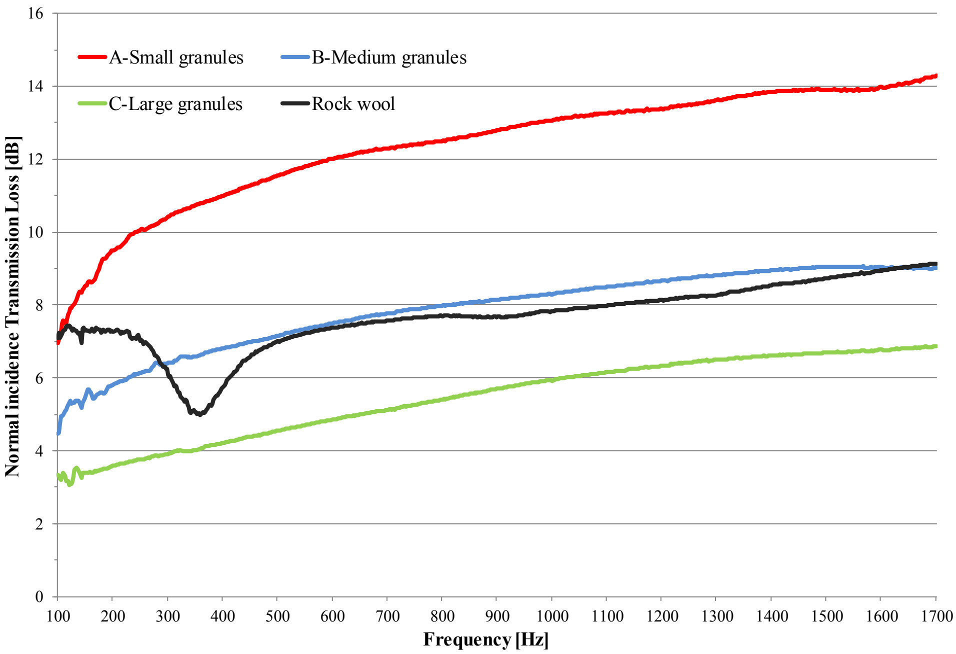


Fig. 6. Comparison between aerogels (30 mm thickness) and rock wool panel (30 mm thickness): normal incidence Transmission Loss.

4. Conclusion

Thermal (λ= thermal conductivity) and acoustic (TL= Transmission Loss at normal incidence) properties of granular silica aerogels for building insulation are investigated, taking into account the impact of granules size (small, medium, and large granules) on the performance of the bed. Due to the nature of the samples, the methodologies typically used for solid materials were properly adjusted, using wood frames (for thermal campaign with Hot Flow Meter method) or cylindrical steel cable supports (for acoustic characterization in the impedance tube or Kund's Tube) in order to contain the granules.

The experimental results reveal that the small granules (granules size in the 0.01-1.2 mm range), which have the highest density (80-85 kg/m^3), have the best performance both in terms of thermal and acoustic properties. Depending on the granules size, λ varies in the 19-22 mW/mK range at 10°C, whereas TL value equal to13 dB at about 6400 Hz for 20 mm thickness was obtained for small granules. Very good acoustic performance is in general achieved: the best sound insulation properties are observed for small granules (TL=19 dB at about 6400 Hz for 40 mm thickness), whereas for medium and large granules maximum values are in the 10-14 dB range.

Finally, the small size aerogel sample at 30 mm thickness shows a better acoustic behavior than a same thickness of rock wool, with an increasing in the TL of about 5-6 dB. In addition, aerogels have a lower density than rock wool (85 kg/m^3versus 95 kg/m^3) and are translucent, allowing to be used in grazing systems. Based on the presented results and on its decreasing cost, a great interest in aerogel is expected in the near future, especially for the building refurbishment sector, also considering superinsulation opaque aerogel- based panels.

Future works will focus on acoustic properties evaluation in terms of absorption coefficient and sound velocity estimation, also including other samples with different granule size distribution.

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