

# SOLAR OPTICAL AND THERMAL PROPERTIES OF MICRO- AND MESO-POROUS MATERIALS FOR COOLING APPLICATIONS COMPARED TO TYPICAL BUILDING MATERIALS

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## ABSTRACT

The solar optical properties of micro- and meso-porous materials that can be building integrated or roof added for evaporating cooling purposes were studied and compared with conventional building materials. The results are interpreted in correlation with their water absorption capacity. For further studying their solar optical properties, absorbance measurements were solar-weighted in accordance with the ASTM G173 standard. Mesoporous materials presented high irradiation absorbance in the IR spectrum with significant variation depending on the water loading at different relative humidity. Strong near infrared absorbance bands of water centered at around 970 nm, 1190 nm and 1450 nm are applied to a quantitative analysis of water content. The experimental results indicate the suitability of the meso-porous primarily, and secondly the micro-porous materials under study, for building integrated solar cooling applications.

## KEYWORDS

Solar cooling, water vapor cooling, micro-porous and meso-porous materials, smart materials

## 1 INTRODUCTION

One of the main environmental problems that big cities, and not only, have to face with the last decades is the so called urban heat island (UHI) phenomenon. Because of that, there is an increase in the demand for electric energy for cooling purposes, while also it is noted deterioration of the living environment due to higher pollutant emission and increase of the chemical weathering of building materials. Therefore the need for the development and the application of passive and efficient ways to cool down urban surfaces keeps on increasing.

Commonly used materials in the construction of buildings facades located in warm climates, often entrap a great amount of heat from the incoming solar radiation, leading to a respective thermal increase in the interior. Therefore significant effort towards energy conservation for buildings and urban structures is the research for cool materials and coatings as a passive cooling technique. However most of them target to minimize the surface temperature in roofs, masonries and pavements through the increase of solar reflectance and infrared emittance. Building integrated evaporating cooling (BIEC) is an alternative and sustainable way to cool the surfaces of a building or to cool the pavement of outdoor areas.

In the last few years the idea of using porous materials for the evaporating cooling of buildings has been started to be studied systematically. The principle of evaporative cooling is that stored water or night sorbed moisture are evaporated during the hot days and the porous surface temperature is reduced due to the release of the latent heat. The principle has been validated with the addition of liquid water [1],[2],[3] and only recently it was proved that the

principle can be applied by moisture sorption [4]. However while the IR spectroscopy of water vapor has been extensively studied [5], there are very few works in the NIR region where the solar-water interaction and absorbance behavior is important for the vapor cooling applications [6].

The aim of the present work is to examine the solar responsive performance of micro- and meso-porous materials in their perspective as passive solar cooling materials by means of moisture sorption. The solar optical and thermal properties of mesoporous materials are compared with those of typical building materials. The optical and thermal characterization of the samples are realized using a UV/VIS/NIR spectrophotometer over the solar spectrum (250– 2500 nm). Water sorption isotherms are conducted and assisted to further understand the optical behavior of the samples.

Moreover, the effect of water loading in the NIR absorbance spectrum of the porous materials is further investigated. Strong near infrared absorption bands of water applied to a quantitative analysis of water content in the porous materials after capillary condensation. By spectrum deconvolution analysis and fitting of combined Gaussian components the variation of components' heights in correlation with relative humidity is studied.

Finally the absorbance measurements are solar weighted using the standard solar spectrum ASTM G173 at air mass (AM) 1.5. In an attempt to further understand the samples' interaction with the solar spectrum and how relative humidity can have an impact on them, the variation of the normalized solar absorbance is presented for each spectrum UV/VIS/NIR in correlation with relative humidity. Also thermal measurements were conducted by means of the transient line heat source method.

## **2 EXPERIMENTAL PART**

Additionally with the conventional building materials, typical well ordered silicate and aluminosilicate micro- and meso-porous nanomaterials were purchased or prepared. The optical characterization of samples with pre-determined absorbed water vapor was conducted by a UV/VIS/NIR spectrophotometer (Lambda 950 of PerkinElmer fitted with a 150 mm diameter InGaAs integrating sphere that collects both specular and diffuse radiation) over the solar spectrum (200-2500 nm). The equipment was calibrated utilizing Labsphere ISO 9001:2000 certified reflectance standards. The data were solar-weighted using the reference solar spectral irradiance standard ASTM G-173 at AM 1.5.

Moisture sorption isotherms were determined by placing the samples in sealed desiccators with saturated salt solutions for controlling relative humidity while temperature was air-conditionally controlled at 25°C. Prior to measurements, samples were dried to constant mass in an air-circulated oven at 105°C. Thermal measurements were conducted by KD2 Pro from Decagon Devices. The sensor is a 30 mm dual-needle SH-1, with a size of 1.3 mm diameter x 30 mm long, 6 mm spacing, accuracy of  $\pm 10\%$  from 0.2 - 2 W/(m• K). The needle, in order to equilibrate to the surrounding temperature before beginning a measurement, was immersed and left into the sample's container for 10 minutes.

## **3 RESULTS AND DISCUSSION**

First, the optical properties of the selected materials were investigated. Figure 1 shows the absorption spectrum of the samples after their saturation in desiccators with different relative humidity. For the MESO samples (a), (b) and the MICRO sample (c), the impact of relative humidity in the absorbance spectrum behavior is obvious. Especially in the NIR region of the spectrum for the MESO samples saturated at 50% as well 77% of relative humidity, four main maxima located at c. 970 nm, c. 1190 nm, c. 1450 nm and c. 1930 nm are clearly observed, indicating the water vapor condensation within the mesopores. These

maxima correspond to the second overtone of the OH stretching band ( $3\nu_{1,3}$ ), the combination of the first overtone of the O-H stretching and the OH-bending band ( $2\nu_{1,3} + \nu_2$ ), first overtone of the OH-stretching band ( $2\nu_{1,3}$ ) and combination of the OH-stretching band and the O-H bending band ( $2\nu_{1,3} + \nu_2$ ) respectively. For the rest of the samples, which are conventional building materials, the water vapor absorption has only limited influence in their absorbance spectrum. However carbonated calcium, white cement and reflective paint, present very small absorbance for most of the spectrum. The effect is more pronounced in carbonated calcium.

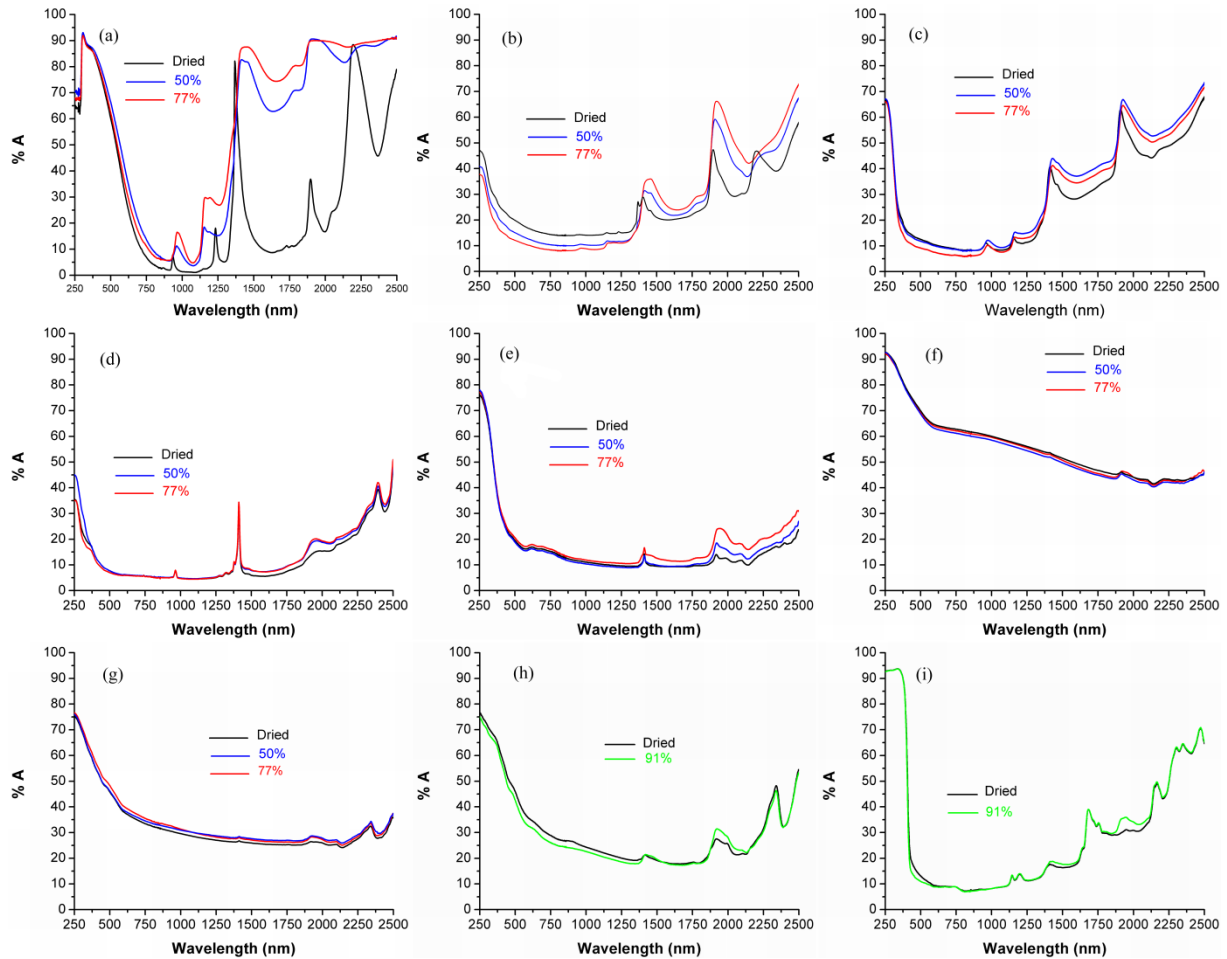


Figure 1: Absorbance spectra of a) MESO-1, b) MESO-2, c) MICRO, d)  $\text{CaCO}_3$ , e) Cement White, f) Cement Black, g) Plaster, h) Marble and i) Reflective Paint, for different relative humidity.

The different behavior of the porous samples' absorbance spectra presented in Figure 1, is due to the water vapor adsorption, and can be further interpreted through the moisture sorption kinetics of the samples. Figure 2 presents the water vapor sorption isotherm of the materials at 25 °C. As shown, water vapor sorption is particularly high for the porous samples, and especially for the MESO samples, while it is negligible for the conventional building materials.

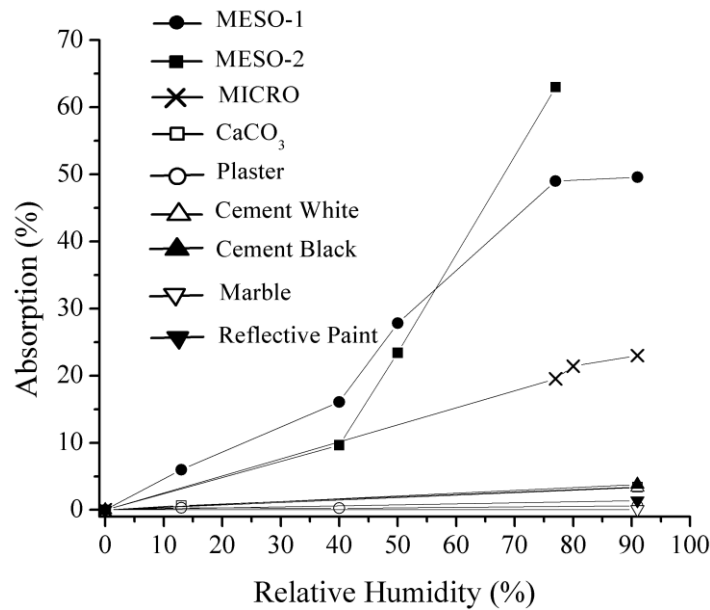


Figure 2: Water vapor sorption isotherm of the tested materials at 25 °C

The isotherms of MESO samples showed similar type behavior. The water adsorption isotherm on the MESO samples were of type V in the IUPAC classification indicating a relatively hydrophobic character in the low-pressure region of the adsorption isotherm but with a capillary condensation in regions with higher pressure leading to a total filling of the pore volume and thus to a type-V isotherm (with maximum uptake more than 60 % adsorption).

As we have already noticed from Figure 1, MESO sample's spectrum exhibits the highest variation for different relative humidity. Therefore and in order to improve our insight regarding the correlation of water absorbance and solar spectrum, the curves of three sub-bands of the spectrum with important variation in the absorbance intensity for different relative humidity were deconvoluted into their Gaussian components. These three narrow sub-bands are centered at around 970 nm, 1190 nm and 1450 nm. For the first and the second sub-band, three Gaussian components were used in the fit, while five for the third one since it was broader than the other two. The full width at half maximum for each Gaussian component was kept constant. Figure 3 presents the behavior of the components heights in correlation with relative humidity.

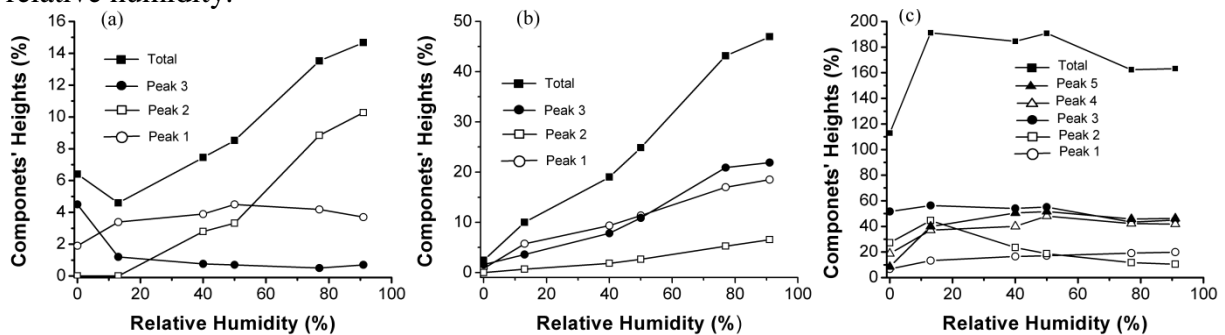


Figure 3: Variation of the Gaussian components' heights in correlation with relative humidity for three narrow sub-bands centered at around a) 970 nm, b) 1190 nm and c) 1450 nm.

Figure 3(a) corresponds to the sub-bund centered at around 970 nm. While the heights of the first and the third peak remains almost constant, the second's one keeps on increasing as relative humidity increases. Therefore, the total's peak height which results from the convolution of the three components increases almost linear as relative humidity increases. For the sub-bund centered at around 1190 nm, the increase of relative humidity results in a

linear increase of all three peaks' heights, and therefore the total's one. For the sub-band centered at around 1400 nm, the total's peak height performs an important increase between dried mode and the 13% relative humidity, and after that exhibits only small variations. The reason for this behavior is that at about 1367 nm the SiOH stretch overtone band (2v) is diminished upon addition of water molecules while the neighboring broad H-bonded OH band at 1399 nm increases, balancing the behavior of the total [7].

In order to study the optical performance of the samples under the influence of solar irradiation, the absorbance measurements were solar weighted using the standard solar spectrum ASTM G173. Figure 4 presents the solar-weighted absorption spectrum of the samples after the absorption of water vapor at different humidity. As it was expected only the absorbance spectrum of the porous samples is notably influenced by their property to absorb vapor water. Especially for the MESO-1 sample, the absorbance intensity in the NIR spectrum, which is predominately responsible for the heating effect of the sun, is strongly influenced by the relative humidity. Consequently the water vapor loading since, as it is already presented in Figure 2, MESO samples and especially MESO-1 is highly absorbent.

Furthermore it can be seen from Figure 4 that while MESO-2 and MICRO samples have small absorption spectrum for the whole range, MESO-1 sample's absorption intensity becomes very high in the UV/VIS spectrum. In addition, carbonated calcium exhibits very small absorbance spectrum, even smaller than the reflective paint's.

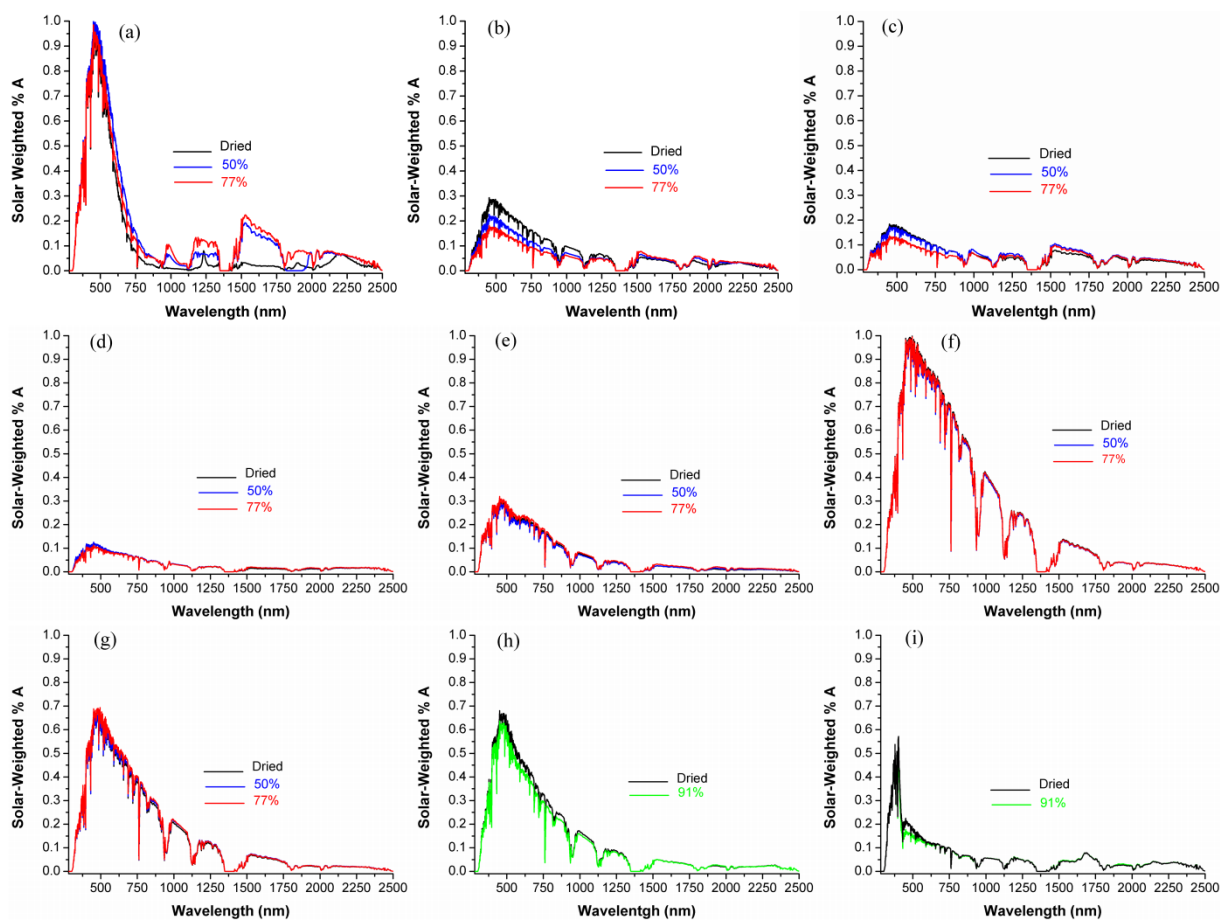


Figure 4: Solar-weighted absorbance spectra of a) MESO-1, b) MESO-2, c) MICRO, d)  $\text{CaCO}_3$ , e) Cement White, f) Cement Black, g) Plaster, h) Marble and i) Reflective Paint, for different relative humidity.

In order to further investigate the samples' behavior under the effect of solar irradiation, Figure 5 presents solar absorbance for each UV/VIS/NIR spectrum in correlation with the variation of relative humidity. The data are normalized to the total solar absorbance.

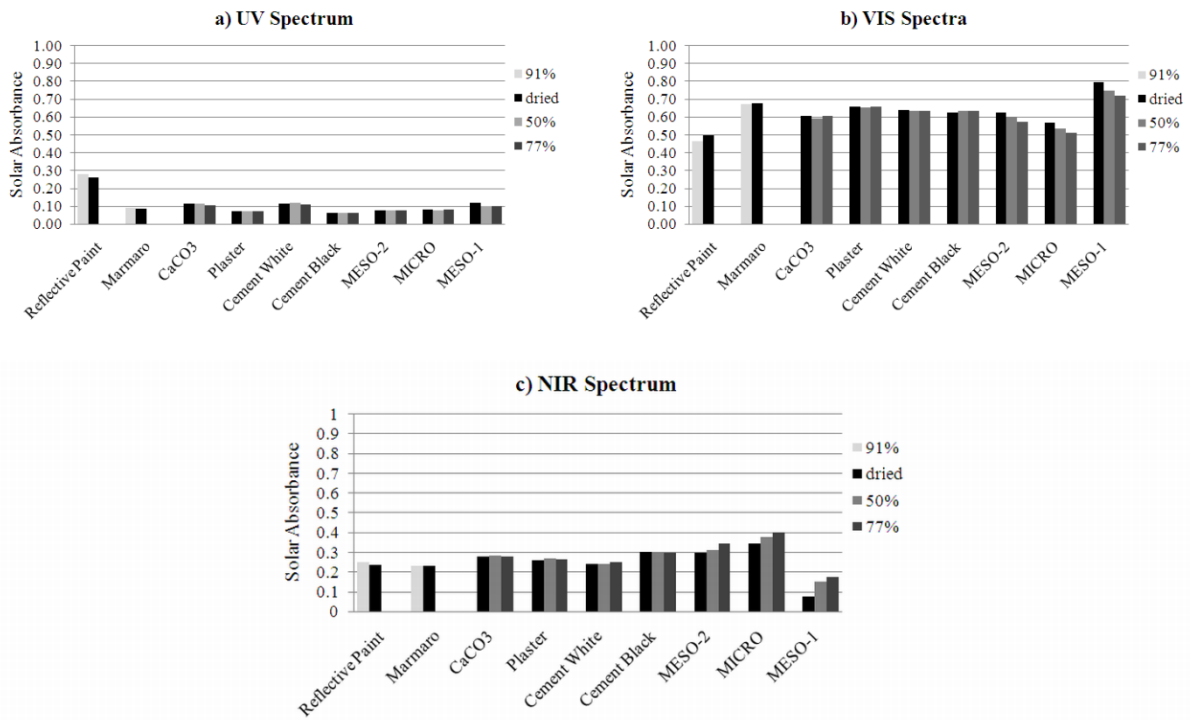


Figure 5: Variation of normalized solar absorbance in correlation with relative humidity, separately for each solar sub-bund (UV/VIS/NIR).

While for the UV spectrum normalized solar absorbance is small, with the exception of reflective paint, it becomes high for the VIS spectrum. For the NIR spectrum, normalized solar absorbance values lies between those for the UV and VIS spectra. Moreover, while for the conventional building materials the impact of relative humidity to the solar absorbance values is negligible, it is important for the MESO samples. However, in the VIS region, the increase of relative humidity results in reduced solar absorption. In the NIR region the behavior is vice versa. As it has already been presented in Figure 2 for the MESO and MICRO samples, higher relative humidity results in higher amount of absorbed water. Therefore higher amount of vapor water leads to higher solar absorbance in the NIR region.

The effect of water vapor sorption on the solar properties of the studied materials was further investigated by thermal conductivity measurements. As shown in Table 1, all samples exhibit small thermal conductivity. Moreover all of the samples show lower thermal conductivity in the dried state than the state in ambient conditions (25 °C). This is due to the water content of the MESO samples at room conditions in contrast to the empty space after drying.

**Table 1.** Thermal conductivity of the MESO samples

Sample (all in powder form)	Thermal conductivity (W/m·K)	
	Stored in Room conditions	Dried samples (200 °C for 2 h)
MESO-1	0.160	0.099
MESO-2	0.133	0.063
Cement White	0.093	0.085
Cement Black	0.124	0.108
Plaster	0.165	0.122
CaCO <sub>3</sub>	0.119	0.095

## 4 CONCLUSIONS

The optical and thermal properties of highly absorbent synthetic porous materials for building evaporating cooling applications have been investigated. In contrast with conventional building materials, MESO and MICRO samples presented significant variation in the intensity of their absorption spectrum as a function of the relative humidity in which samples remained for specific period of time, before the absorbance measurements. Especially the MESO-1 sample presented high irradiation absorbance in the NIR spectrum for higher than 50% of relative humidity.

This behavior was explained through the investigation of the water vapor sorption isotherms. In contrast to the conventional building materials, MESO and MICRO samples exhibit high water vapor sorption which for the MESO samples is of type-V. Similar absorbance behavior was also noted, by solar-weighting the experimental optical measurements with the ASTM G173 standard spectrum. The high variation of the MESO-1 sample's absorbance for different relative humidity in the NIR spectrum, and also its high absorbance for the higher relative humidity values were revealed.

Furthermore, the absorbance intensity variation and how it is influenced by water vapor sorption was investigated by fitting Gaussian components in three sub-bands of high variation. In many cases a linear relation between absorbance and relative humidity was determined. In addition, thermal conductivity measurements showed that all samples have similarly small thermal conductivity.

The findings of the present work show that porous samples, and particularly MESO-1 sample are good candidates for solar vapor cooling application. Therefore further investigation must be conducted in this direction.

## 5 ACKNOWLEDGEMENTS

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