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Experimental Analysis of Thermal Conductivity for Building Materials Depending on Moisture Content

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Abstract The presence of moisture in building envelopes can have many causes and may lead to deterioration of useful thermophysical characteristics of the materials, to weakening of the building structure, and to facilitating growth of mold. The International Standard ISO 13788 establishes a calculation procedure for the determination of hygrometric characteristics of building components and materials, assuming that the influence of moisture content on the thermal field across walls, ceilings, and roofs may be neglected. However, condensed water increases the effective thermal conductivity of building materials, thus modifying the temperature profiles across the building envelope. This effect is analogous to the one due to the material aging. In this paper, the authors show the results of effective thermal-conductivity measurements in some commonly adopted building materials as a function of moisture content, in order to assess the potential significance of interstitial condensation on thermal losses and to verify if the maximum allowed moisture content reported is useful to prevent the decay of the thermal properties of building materials.

Keywords Building materials · Conductivity variation · Deterioration · Moisture

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List of Symbols

Variables

A	Area (m^2)
I_S	Significance index
k	Coverage factor
L	Thickness (m)
m	Mass (kg)
T	Temperature (°C)
u	Standard uncertainty

Greeks

λ	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
ρ	Density of the material ($kg \cdot m^{-3}$)

Subscripts

i	Lower comparative structure
limit	Limit value
s	Upper comparative structure
w	Liquid water
ref	Reference value
RM	Reference material
sample	Sample

1 Introduction

The presence of liquid water in building structures can be caused by

- poor thermal and hygrometric design allowing condensation of water vapor between or within layers of the building envelope. This is known as "water-vapor interstitial condensation";
- condensation on inner wall surfaces whose temperature falls below the dew point (frequently near thermal bridges due to colder outdoor temperatures);
- capillary rising damp from unsealed sub-floor and foundations;
- capillary horizontal damp from adjoining embankments attached to the wall;
- accidental events; and
- rain-inadequate water-proofing.

The condensation on surfaces affects indoor air quality, by facilitating mold growth and proliferation [1] and by causing adverse health effects such as asthma, allergies, and respiratory pathologies [2]. Furthermore, the interstitial condensation implies building material deterioration. In spite of that, the current international standard concerning calculation of interstitial water-vapor condensation allows the presence of small moisture content in building envelopes [3].

In the following sections, the authors show an experimental procedure for the evaluation of changes in thermal and hygrometric building material properties due to moisture content. Some experimental results are presented and discussed.

2 Thermal and Hygrometric Performance of Building Materials

The most important thermal and hygrometric characteristics of building materials are the thermal conductivity [4], water-vapor permeability, and water absorption [5].

The Italian National Standards UNI 10351 [6] and 10355 [7] give mean thermal-conductivity and water-vapor permeability values for homogeneous materials and the thermal resistance of walls and ceilings. In general, the design conditions are very different from the reference ones [8], due to differences between laboratory and field conditions. The declared and design values may differ also because of the manufacturing process (especially in the case of polymeric materials), the quality of the raw materials [9], the age (in foam materials, the gases may diffuse away to be replaced by air), and the interaction with water, resulting in dimensional instability and/or in changing of thermal properties (as in the case of mineral wools). It is extremely important, therefore, that thermal properties are measured under environmental conditions representative of those in use. The International Standard ISO 10456 [10] specifies methods for the determination of the temperature and moisture design values from the declared ones.

In this paper, the authors present some results of an investigation carried out to show how the material structure and nature influence thermal behavior once interstitial moisture occurs. The investigated materials belong to both building materials (plaster and hollow tile) and bio-materials often used as thermal insulation (pinewood and coconut fibers) and represent different insulating classes and different structures (from fibers to compact porous materials). In particular, the present investigation is addressed to verify the claim that the maximum allowed moisture content reported in [3] is useful to prevent the decay of the thermal properties of building materials. In the authors' opinion, this topic is very important, but it has not been much investigated in the past.

3 Thermal-Conductivity Measurement

Thermal-conductivity measurements of materials generally require application of a temperature gradient across the sample. For moist materials, this gradient often causes mass transport due to evaporation and condensation of water.

In general, to take into account both the mass transport and the radiative and convective heat flow for many building materials and for different moisture contents, the *effective thermal conductivity* [11–13] is measured by stationary (steady-state) measurement techniques. Alternatively, the thermal conductivity may be measured using transient heat pulse methods [14,15] for which the low heat flow minimizes thermal gradients and mass transport but these methods are restricted to samples of low moisture content and the thermal contact resistance at the probe–sample interface and the pulse form cannot be easily controlled.

Several studies based on laboratory and field measurements have demonstrated the influence of temperature, moisture content, and surrounding atmosphere on the thermal conductivity [16,17]. Insulating materials traditionally used in buildings such as mineral wool, foam glass, polystyrene, and granular materials were shown to have a thermal conductivity rising exponentially with moisture content [16] and linearly with temperature (for temperatures less than 30 °C). Other studies have demonstrated the effects of variations on coatings [12] and composition [18] on thermophysical properties.

4 Experimental Apparatus

The experimental apparatus used to measure the effective thermal conductivity is shown in Fig. 1. A temperature gradient is established across the sample using two thermostatic baths. The sample is bounded above and below by two reference structures, each comprising a glass plate between two isothermal copper parallel plates. Under the hypothesis of one-dimensional (vertical) heat flux and insignificant horizontal variation, the *effective thermal conductivity* λ can be evaluated as the arithmetic mean of the thermal-conductivity values obtained by equating the heat fluxes measured at the top, middle, and bottom of the sample. That is, the heat flow through the sample can be determined by measuring the temperature gradient across reference glass plates for which the thermal conductivity is known. A Pyrex® glass, 30 mm thick, was used as the reference material (RM) and its thermal conductivity λ_{RM} at temperature T (in °C) is

$$\lambda_{\mathrm{RM}} = 1.43 \times 10^{-3} T + 1.06$$

with an expanded relative uncertainty of 5 % with a coverage factor $k = 2$ for a 95 % *level of confidence* [19,20].

From the calculated heat flow through the sample and the temperature gradient across it, the sample thermal conductivity can be calculated.

$$\lambda = \frac{1}{2} (\lambda_{\mathrm{s}} + \lambda_{\mathrm{i}}) \tag{1}$$

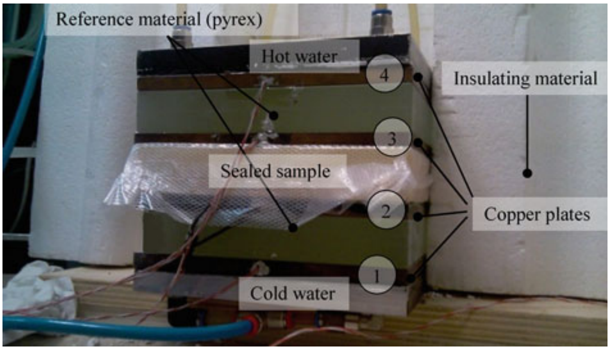

Fig. 1 Experimental apparatus

where

$$\lambda_s = \lambda_{RM,s} \frac{T_4 - T_3}{T_3 - T_2} \frac{L_m}{L_s} \tag{2}$$

$$\lambda_i = \lambda_{RM,i} \frac{T_2 - T_1}{T_3 - T_2} \frac{L_m}{L_i} \tag{3}$$

where λ_{RM} is the thermal conductivity, in $W \cdot m^{-1} \cdot K^{-1}$, of the upper (s) and lower (i) reference material plates evaluated at the mean temperature T; L_m, L_s, and L_i are the thicknesses, in m, of the sample, the upper glass structure, and the lower glass structure, respectively, and T_i's are the temperatures, in °C, of the copper-plate surfaces (see Fig. 1).

The surface copper-plate temperatures were measured using miniature calibrated Pt100 resistance thermometers inserted into 2 mm holes at the center of each plate. The steady-state condition is considered reached when the temperature differences $(T_2 - T_1)$, $(T_4 - T_3)$, and $(T_3 - T_2)$ vary <10 $mK \cdot h^{-1}$.

The sample reference conditions were obtained by means of a climatic chamber (WEISS), situated in the Laboratory of Industrial Measurements of the University of Cassino (accredited for calibration by Accredia, the Italian Institute for Accreditation). The chamber uniformity and stability are characterized by uncertainties <0.1 °C for dry-bulb temperatures between 20 °C and 50 °C and for dew-point temperatures between 30 °C and 50 °C.

5 Measurements

Porous materials will gain or lose mass (i.e., water) until thermal and hygrometric equilibrium with the surroundings is attained [21,22]. In order to determine the influence of the moisture content of building materials on their effective thermal conductivity, seven samples were kept under several hygrothermal conditions until equilibrium in the climatic chamber is reached. The samples were characterized in terms of their density and thickness, as shown in Table 1, where the uncertainty was evaluated in accordance to ISO Guidelines [23].

In order to take into account the variability of material properties due to manufacturing, two samples of each material were tested with the exception of plaster. To prevent water loss during measurements, samples were sealed using a PVC envelope 0.1 mm thick, i.e., thin enough to have negligible effect on the measured thermal conductivity.

Note that the PVC envelope introduces boundary conditions for heat and mass transfer that are different from the ones in actual use (unsealed material placed in a building envelope). Temperature gradients >8 °C were imposed across the samples under average temperatures of 10 °C and 30 °C in order to simulate extreme exposure conditions for winter and summer seasons, respectively.

Samples were wetted using a uniform spray of double-distilled water. The percentage of added moisture content was calculated as the mass of water added to the sample, m_w, divided by the mass of the sample at a steady state under commonly

Table 1 Properties of the examined samples (values of the standard uncertainty are in parentheses)

Material	Thickness, L (mm)	Density ρ ($\mathrm{kg \cdot m^{-3}}$)	Mass of the sample for reference conditions (20 °C and 50 % RH) m_{sample} (g)	Percentage maximum allowed liquid water mass $\left(\frac{m_{\text{w,limit}}}{m_{\text{sample}}}\right) \times 10^2$
Plaster	15.6 (0.05)	1130.2 (4.4)	270.19 (0.02)	0.72
Pinewood, sample (1)	31.0 (0.14)	415.9 (2.5)	490.2 (0.02)	3.0
Pinewood, sample (2)	31.5 (0.15)	413.5 (2.5)	495.3 (0.02)	3.0
Hollow tile, sample (1)	116.4 (0.18)	633.9 (2.5)	1134.2 (0.02)	0.68
Hollow tile, sample (2)	116.6 (0.19)	633.4 (2.5)	1136.1 (0.02)	0.68
Coconut fibers, sample (1)	19.0 (0.29)	322.6 (2.0)	94.2 (0.02)	ND
Coconut fibers, sample (2)	19.1 (0.28)	365.5 (2.3)	107.3 (0.02)	ND

used [1] reference conditions (in this case, dry-bulb temperature is equal to 20 °C and RH equal to 50 %), m_{sample}.

The mass of the added water and of the sample in the reference conditions has been measured by means of an electronic balance (Gibertini) at an environmental temperature of (20 ± 1) °C, with a combined expanded uncertainty less than 0.2 g (with a coverage factor $k = 2$ *for a 95 % level of confidence*).

The maximum allowed liquid water content in the material, $m_{\text{w,limit}}$, was calculated in accordance to ISO 13788 [3]. However, the coconut fibers generally used in roof insulation, were not traceable to any category included in the mentioned standard, so in this case we have determined only the *effective thermal conductivity* variations with moisture content, and these could not be used to verify the validity of the limits reported in [3].

6 Results

Results of the measurements are shown in Table 1 and in Fig. 2, where the bands represent [16,17] the combined standard uncertainty of thermal conductivity and where the content of liquid water equal to zero is referred to a sample in equilibrium at reference conditions (dry-bulb temperature of 20 °C and relative humidity of 50 %). Negative moisture content values just mean that the water content is lower than that at the reference condition.

The results show that the coconut fibers, which had been treated with a hydrophobic coating, have a thermal conductivity independent of moisture content. During measurements, water was deposited on the bottom of the sample; for this reason, the water content was not increased more than 5 %.

From the analysis of Fig. 2, it can be pointed out that the thermal conducivity variations for the examined materials are not negligible for both temperature and moisture content variations. In particular, the effective thermal conductivity is proportional to

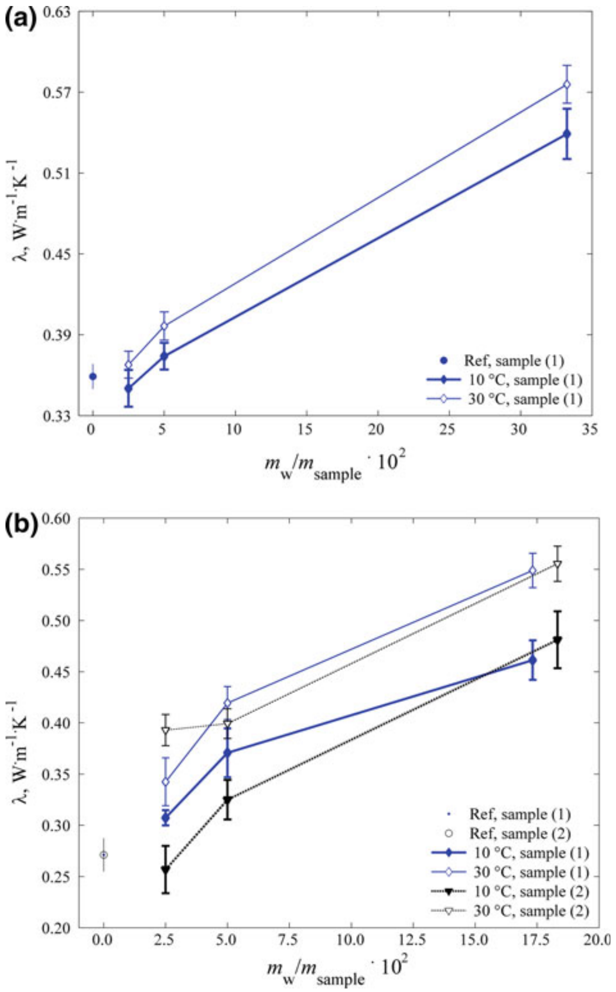

Fig. 2 Measured thermal conductivities for (a) plaster, (b) hollow tile, (c) pinewood, and (d) coconut fibers, as a function of moisture content and mean temperature

the ratio $m_{\mathrm{w}}/m_{\mathrm{sample}}$ for higher water contents and for all the examined materials. The sensitivity of the thermal conductivity to the sample water content, $\partial\lambda/\partial m_{\mathrm{w}}$, is reported in Table 2. As expected, the moisture influence is greater for insulating materials than for the others [24]. These results were compared to the ones reported in [25] for materials similar to plaster and generic wood.

As shown in Table 2, fairly good agreement is obtained for both plaster and wood. The differences, however, can be due to the different material density and thermal conductivity of the sample tested in this paper with respect to those reported in [25].

With regard to the temperature influence, the mean sensitivity coefficient $\partial\lambda/\partial T$ for plaster was found to be about $1.3 \times 10^{-3}\ \mathrm{W \cdot m^{-1} \cdot K^{-2}}$ that is in reasonably good

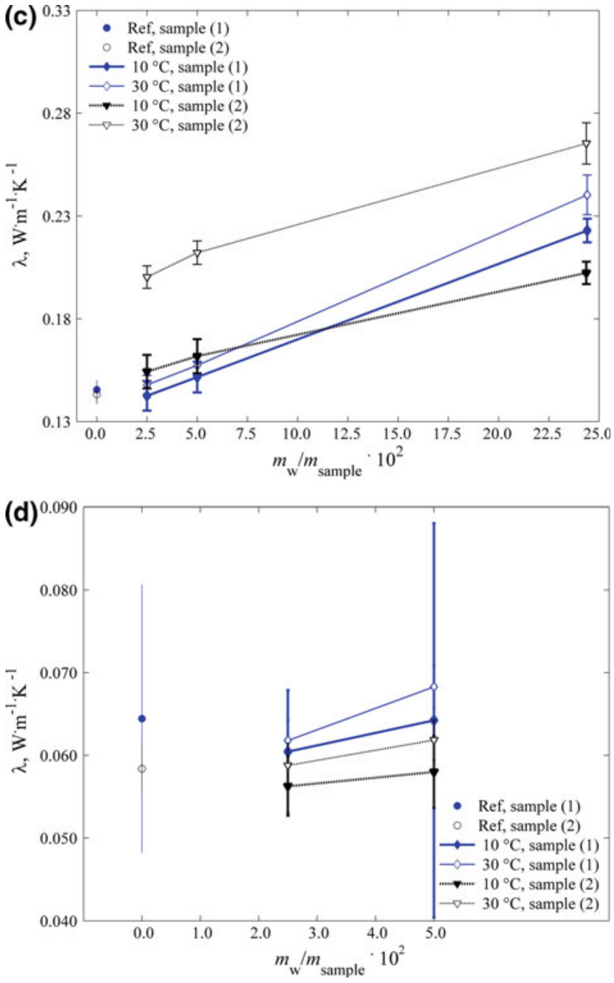

Fig. 2 continued

Table 2 Mean trend of thermal-conductivity variation against water content

Material	$\frac{\partial\lambda}{\partial m_\mathrm{w}}(\mathrm{m}\cdot\mathrm{s}^{-3}\cdot\mathrm{K}^{-1})$		
	10 °C	30 °C	[25], order of magnitude
Plaster	2.2	2.4	1.2
Pinewood, sample (1)	0.86	0.75	0.20
Pinewood, sample (2)	0.44	0.59	0.25
Hollow tile, sample (1)	0.83	1.1	NA
Hollow tile, sample (2)	0.95	1.2	NA
Coconut fibers, sample (1)	1.6	2.8	NA
Coconut fibers, sample (2)	0.64	1.1	NA

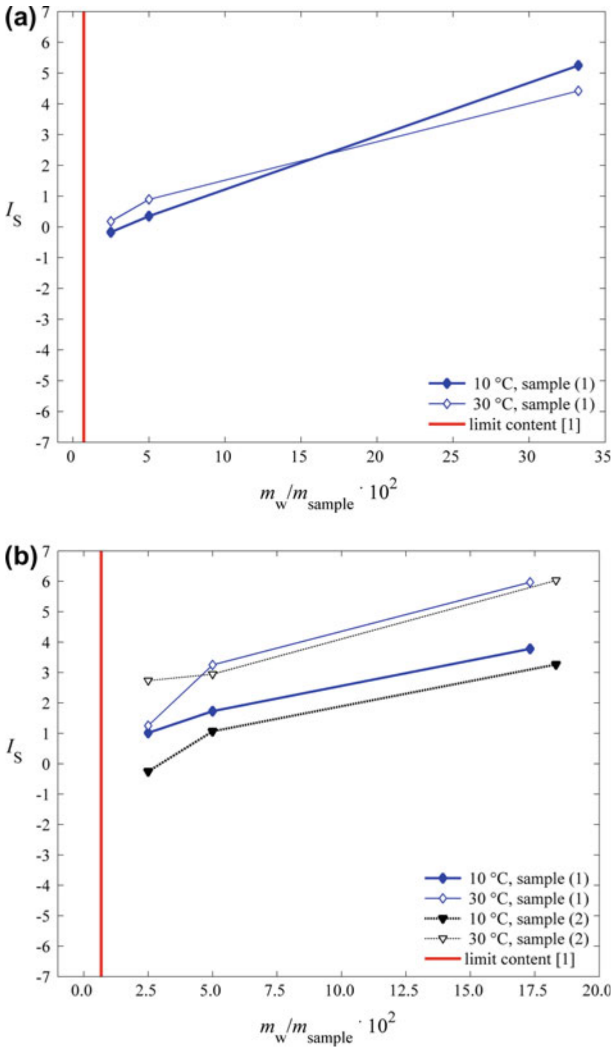

Fig. 3 Significance index for a 95 % confidence level for (a) plaster, (b) hollow tile, (c) pinewood, and (d) coconut fibers

agreement in terms of magnitude with [26], where for gypsum plaster, $\partial\lambda/\partial T$ is about equal to $6.4 \times 10^{-4}\,\mathrm{W \cdot m^{-1} \cdot K^{-2}}$.

The mean percentage variation of the thermal conductivity, with respect to the value at 10 °C is about 5 % for sample (1) and 0 % for sample (2). The first sample results are in good agreement with [27] where a percentage variation of 1 % to 2 % is considered for a temperature variation equal to 5.6 K. Unfortunately, the authors could not find results of similar investigations for the other tested materials.

Although the thermal-conductivity variation with moisture content is much greater than that observed for temperature variations (it almost doubles in the examined water

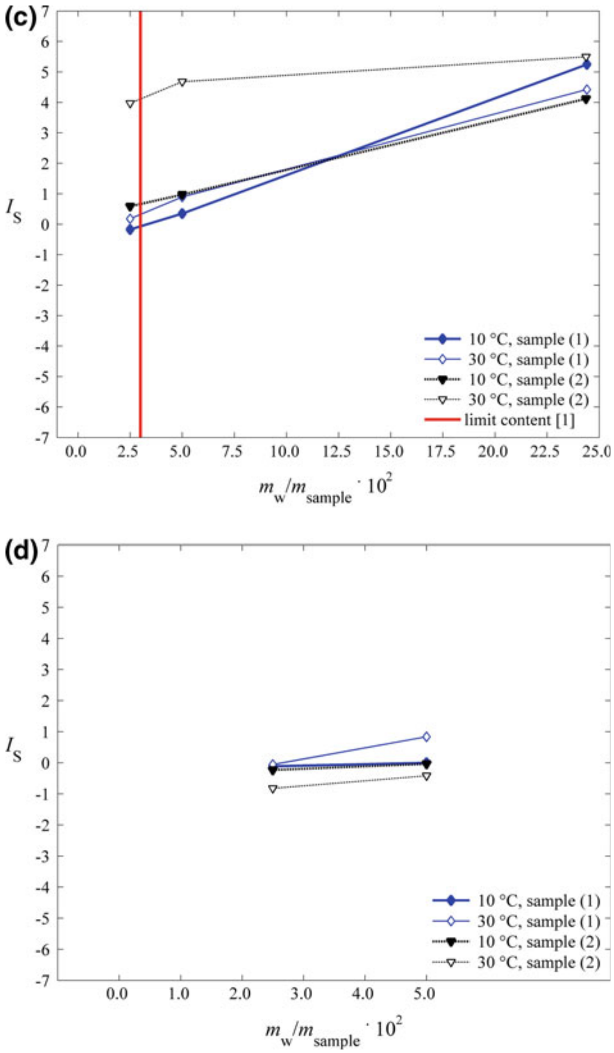

Fig. 3 continued

content range for pinewood), note that the water content limit imposed by [3] (see Table 1) is always precautionary.

The significance of the measured effective thermal conductivity is determined using the significance index [28], which is defined as

$$I_S = \frac{\lambda - \lambda_{ref}}{2\sqrt{u^2(\lambda) + u^2(\lambda_{ref})}} \tag{4}$$

where λ_{ref} is the thermal conductivity measured at 20 °C and 50 % relative humidity and $u(\lambda)$ is the standard uncertainty. If I_S satisfies the condition ($-1 \leq I_S \leq 1$), the difference ($\lambda - \lambda_{\text{ref}}$) is not considered significant for a confidence interval of about 95 %.

Figure 3 shows the dependence of the thermal conductivity on moisture content and on temperature for all samples; however, for values of $m_\text{w}/m_{\text{sample}}$ required by ISO 13788 [3], the variation of the thermal conductivity is inside the band of uncertainty of measurements, since the significance index value is included in the interval $[-1, 1]$. The only exception is the second pinewood sample with a mean temperature of 30 °C, for which the temperature effect is prevailing as shown by the curve trends.

These results confirm that the limits about moisture content reported in [3] are precautionary and assure that, for a lower moisture content, the effective thermal conductivity of building materials does not vary appreciably.

In any case, the behavior of coconut fibers seems to demonstrate that the hydrophobic coating leads to a stability of the thermal conductivity.

7 Conclusions

This paper demonstrated, that, as expected, the effective thermal conductivity of some common building materials increases with moisture content and temperature, although the significance index shows that the variation is contained within the uncertainty band limits for maximum allowed moisture content required by ISO 13788.

Future research will be oriented toward measurement of a wider range of materials, improvement of the wetting techniques and the measurement methodology used, and understanding of the influence of the PVC layer on water mass transportation inside materials and, consequently, on their effective thermal conductivity. Another goal will be the measurement of the thermal conductivity of fibrous materials subjected to several wetting–drying cycles, in order to deeply investigate the thermal-conductivity stability.

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