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Thermal conductivity assessment of cotton fibers from apparel recycling for building insulation

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A B S T R A C T

The impressive growth of the clothing market in the last decades comes along with an increase in the textile waste, nowadays mostly incinerated or landfilled. To improve the circularity of the sector, the possibility to recycle the textile waste into thermal insulation products for the building envelope has started to emerge. While the scientific literature agrees that the thermal conductivity of products based on textile waste is comparable to conventional thermal insulators, very few studies provide a comprehensive characterization of their heat transfer behavior in terms of the relevant parameters. This study focuses on post-consume cotton in the form of loose fibers with density 30, 50 and 70 kg/m^3. By exploiting complementary experimental techniques, it is found that the effective thermal conductivity ranges between 0.0381 W/(m•K) (ρ = 30 kg/m^3, T = 10 °C, RH = 17 %) and 0.0546 W/(m•K) (ρ = 50 kg/m^3, T = 30 °C, RH = 80 %). The conductivity of the loose cotton fibers is predominantly sensitive to temperature and relative humidity, while the influence of density and the vertical/horizontal orientation appear less significant. These results highlight the complexity of the characterization of the thermal performance of such fibrous materials and the need to perform tests under fully controlled environmental conditions. Moreover, they are key for an accurate prediction of the performance of such insulating materials in real building operation, possibly achieved through dynamic energy simulations including heat and vapor transfer and modelling the conductivity variation with temperature and moisture.

1. Introduction

Over the last few decades, the textile clothing sector has experienced a remarkable growth, resulting in a 40 % overall increase and in 34 % per person increase in the volume of purchased clothes in Europe from 1996 to 2012 [1], mainly driven by the rise of the so-called fast fashion, characterized by low prices, large volumes of sales and a short service life of the final products. 60 % of the textile fibers production globally is destined to the clothing sector, the rest being used for interiors, industrial textiles, geotextiles, agrotextiles and hygienic textiles, among other uses. Considering the kind of fibers, polyester dominates this textile production, accounting for 51 % in 2018, followed by cotton at 25 % [2].

The growth of the clothing market implies an increase in the amount of textile waste, consisting of both pre-consume and post-consume waste. Pre-consume waste is either produced during the manufacturing process (industrial waste ranges between 10 and 30 % of the input fibers, depending on the studies [2]), or is related to the so-called deadstock, namely garments that remain unsold. Post-consume waste consists of discarded garments.

According to one of the first global study [3], very few amount of the textile materials input in the clothing sector is reused or recycled at the end of their life (12 % in downcycling outside the textile sector, and only 1 % in a closed loop, as garment reuse or fiber recycling), while most (73 %) is being incinerated or landfilled, since recycling technologies are only starting to emerge. While it is clear that clothing production and consumption should slow, in the last years a strong interest about possible uses of textile wastes arised, trying to identify alternatives which may help increasing the circularity of the sector. Among them, and in the framework of the research for non-conventional and more sustainable insulation materials [4], such as vegetable materials or animal origin based like poultry feathers [5], some researchers started to investigate the possible applications of recycled textiles as thermal

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insulation for the building envelope.

In order to be recycled as an insulation product, the waste fabric needs to be processed. To this purpose, previous methods and technologies for the manufacture of non-woven fabrics can be used. The first step is either shredding the fabric and carding, resulting in loose fibers, or simply granulating it. The loose fibers can, in principle, serve as loose fill insulation. Then, if the aim is to produce a mat or a panel, the loose fibers or the granulates need to be bonded together, either mechanically or thermally. Mechanical entanglement can be obtained through needle-punching machines, producing flexible non-woven mats [6]. However, such technique requires a minimum length of the input fibers and typically results in low thickness mats. In turn, thermal bonding is more versatile: textile fibers or granulates are mixed with “bicomponent” fibers, whose external layer melts at lower temperature than the inner core, randomly binding fibers are adjusted to achieve target densities and mechanical resistances. Usually, this phase is preceded by a so-called air-lay process, where aerodynamic shaping is used to obtain a uniform distribution of the material on a given area [7]. Another possibility is represented by compression molding: in this case the fibers are soaked in a liquid binder, then pressed in a mold and finally dried in an oven [8].

Needle-punching is used by several Authors to produce flexible insulation mats from either acrylic or wool recycled fibers [6,9–11], from recycled wool fibers and polyester fibers recycled from plastic bottles [12], recycled cotton or wool, even mixed with poultry feathers [13]. Thermal bonding coupled with air-lay is adopted by [14] to obtain 80 % polyester 20 % bicomponent panels and by [15] to obtain different kinds of panels, made up of cotton, flax and polyester with bicomponent between 15 % and 25 % in mass. Eventually, some researchers investigated the use of recycled fibers as loose fill insulation, inserted in a polypropylene casing [16], in a copper holder for experimental testing only [17] or even directly into the wall air gap [18].

An effective thermal insulation product can be produced, from recycled textiles, because loose fibers, non-woven fabrics or textile panels behave as highly porous media that incorporate a high fraction of air into their pores. In a porous medium, heat transfer consists of conduction through the solid and the gas, convection through the gas, and radiation among the pore surfaces. An equivalent thermal conductivity is then usually adopted to effectively summarize the various heat transfer mechanisms. While the importance of conduction is obvious, the contribution of convection and radiation is not. In porous media with mostly closed cells, convection is generally assumed to be negligible if the Grashof number based on the cell size is lower than 1000, typically resulting in a minimum cell size of about 10 mm [19]. Radiation is expected to increase with the cell size and decrease with density (the lighter, the higher the transparency), while conduction is expected to increase with density, as, usually, the solid has a higher conductivity than the air or other gases. The competition between the two mechanisms, namely radiation and conduction, typically results in a minimum for the equivalent thermal conductivity trend as a function of the density [19].

Fibrous insulation materials are a specific type of porous materials where the solid matrix is composed by fibers. The onset of natural convection can be expressed by the reaching of a critical Rayleigh number, where Ra depends on the air permeability of the fibrous insulation and on the material thickness. According to [20], who performed an order of magnitude analysis, natural convection can be neglected in fibrous insulation as long as the thickness is less than 1 m, which practically covers every application in the construction sector. As far as radiation is concerned, Tilioua et al. [21] estimated from FTIR spectra the radiative thermal conductivity of insulation panels composed of a mix of recycled textile fibers, with thicknesses in the range 5.3–6.5 mm. They found an average radiative conductivity of 0.01 W/(m.K) in contrast to an overall equivalent thermal conductivity of 0.039 W/(m.K), and they conclude that radiation contribution to overall heat transfer is equal to 26 % and thus non negligible.

1.1. State of the art

The main studies related to the thermal properties of insulation materials obtained from recycled textiles, either alone or mixed with other recycled materials, are reported in Table 1, where they are reviewed according to the kind and the origin of the materials, the kind of processing operated on the waste fabrics, the typology of insulation product and, finally, the experimental methodology adopted to measure thermal conductivity. Moreover, parameters or aspects possibly impacting on the thermal conductivity that are investigated in each study are reported, such as: temperature, moisture content, density, orientation, composition, treatment, quantity and quality of the binder. In the following state of the art, approaches and results of the mentioned papers are illustrated in detail, by grouping them according to the process: firstly needle-punching, then thermoformature/compression molding and finally no binding.

Some Authors focus on non-woven fabrics obtained through needle-punching [9,10,12], typically resulting in low-thickness mats. By recycling post-production acrylic waste from a textile manufacturer, Gounni et al. [10] obtain a 12 mm non-woven mat with a density equal to 10.6 kg/m^3 resulting in a thermal conductivity equal to 0.038 W/(m•K). In [9] four kinds of mats, two of them based on wool and two on acrylic, are obtained with thickness in the range 12–14 mm and density in the range 8.2 – 14.6 kg/m^3. Thermal conductivity is measured at different temperatures, namely 10, 25 and 40 °C, finding that it increases linearly with average temperature. For a given temperature, the lowest conductivity corresponds to the wool mat with the lowest density, e.g. 0.0348 W/(m•K) at 10 °C, but it has to be remarked that a rigorous comparison among different materials cannot be done, as the density of the mats is not exactly the same.

Again, through needle-punching Patnaik et al. [12] produced five samples with different composition (coring wool, dorper wool, recycled polyester, coring wool + recycled polyester, dorper wool + recycled polyester). The thickness of the mats is analogous to previously cited works, yet density is significantly higher than in [9,10], being between 58.8 and 66.7 kg/m^3. Even in this study the effect of different temperatures (−5°C, 15 °C and 35 °C) is investigated and an increasing trend of the thermal conductivity with temperature is found. As far as the composition is concerned, no significant impact on thermal conductivity emerged. Besides, the effect of the materials’ moisture content on thermal conductivity was assessed, by measuring it after conditioning the sample in a climatic chamber at (90 ± 5) % and (23 ± 2) °C for 72 h. A null and an almost negligible increase in thermal conductivity was observed for polyester and wool mats respectively, also because the latter were sprayed in advance with silicon, to create a barrier to moisture penetration.

Mrajji et al. [13] studied the thermal properties of six needle-punched nonwoven fabrics based alternatively on waste cotton, waste wool and chicken feathers mixed with the previous fibers, with density resulting in the interval 10.0–16.7 kg/m^3. Also in this case, an increasing linear correlation is found between thermal conductivity and temperature. Although the density of the different mats is not constant, it can be noticed that wool-based mats generally show a lower thermal conductivity than cotton-based ones, and mixing with feathers helps improving the insulation performance.

Other studies investigated the performance of insulation panels obtained by adding a binder to the recycled fibers and either thermoforming or molding the mix [22,15,78,23,24]. The influence of the density on the thermal conductivity is specifically addressed by [22] for high density panels (between 203 and 491 kg/m^3) made up of polyester and polyurethane fibers from woman’s underwear manufacturing. A plot of the results as a function of the density revealed the presence of a minimum thermal conductivity equal to 0.041 W/(m•K) reached at 396 kg/m^3.

Zach et al. [15] provided one of the more comprehensive investigations of parameters affecting thermal conductivity. Five

Table 1
Literature review of experimental studies on insulation materials from recycled textile fibers.

Paper	Materials	Waste typology/ sector	Processing	Insulation typology	*Thermal conductivity measurement method*	Parameters/issues investigated							
						Temperature	Moisture	Density	Orientation	Composition	Waste treatment	Binder	Other
Briga-Sà et al. 2013 [18]	acrylic	pre-consume textile	n.a.	loose fill (fibers or fabric pieces)	in situ *heat flow meter method* [25]						x		
Valverde et al. 2013 [22]	polyester, polyurethane	pre-consume clothing textile	thermoformature	panel	*guarded-comparative-longitudinal heat flow*			x					
Jordeva et al. 2014 [16]	polyester, cotton, lycra	pre-consume textile	shredding	loose fill (fibers or fabric pieces)	*heat flow meter*					x	x		
Patnaik et al. 2015 [12]	wool, polyester	pre-consume textile (wool), packaging (pet)	needle punching	non woven fabric	*heat flow meter*	x	x			x			
Hadded et al. 2016 [17]	n.a.	pre-consume textile	shredding, air-lay thermoformature	loose fill fibers, panels	*hot* box						x		
Zach et al. 2016 [15]	flax, cotton, polyester	textile	air-lay thermoformature	panel	*heat flow meter*	x	x		x	x			
Gounni et al. 2018 [10]	acrylic	pre-consume textile	needle punching	non woven fabric	*guarded hot plate*								
Tilioua et al. 2018 [21]	cotton, wool, acrylic, polyester	textile and other	n.a.	panel	*heat flow meter, FTIR spectrophotometry*								radiative heat transfer
El Wazna et al. 2019 [9]	acrylic, wool	pre-consume textile	needle punching	non woven fabric	*guarded hot plate*	x				x			
Rubino et al. 2019a [8]	wool	textile	compression moulding	panel	*transient plane source*			x					
Rubino et al. 2019b [23]	wool	textile	compression moulding	panel	*transient plane source*			x				x	
Bourguiba et al. 2020 [25]	polyester, duck feathers	post-consume non clothing textile	n.a.	loose fill fibers	*heat flow meter (small scale), hot* box *(full scale)*					x			
Dieckmann et al. 2021 [7]	chicken feathers, denim, wool, polyester, hemp	food industry, other not specified	air-lay thermoformature	panel	*heat flow meter*	x	x	x		x			
Mrajji et al. 2021 [13]	chicken feathers, cotton, wool	food industry, other not specified	needle punching	non woven fabric	*guarded hot plate*	x				x			
Rubino et al. 2021 [24]	wool	pre-consume clothing textile	compression moulding	panel	*transient plane source*			x				x	

typologies of panels (three mono-fiber in flax or polyester and two with a mix of polyester and cotton fibers, with densities between 23.2 and 94.7 kg/m^3) were produced with a fraction of bicomponent binder between 15 and 25 %. The Authors paid particular attention to detecting moisture content and assessing its impact. Each sample is firstly exposed to 70 °C to dry and subsequently conditioned to 23 °C and 80 % relative humidity, allowing to measure a moisture content between 0.6 and 8.3 % depending on the panel. Thermal conductivity is measured for each sample at 10 °C mean temperature in dry state and after conditioning in the high humidity environment. Since the flax panel was found to be the most sensitive to moisture, it also experienced the most significant thermal conductivity increase (+ 12 %), passing from 0.0433 W/(m.K) in the dry state to 0.0495 W/(m.K). Finally, by varying the inclination of the samples between 0° and 90°, Zach et al. [15] found that the orientation has a modest influence (up to 3 %) on thermal conductivity.

Dieckmann et al. [7] studied the feasibility of an insulation panel from waste chicken feathers mixed with bicomponent fibers; such panel was then characterized and compared against several commercial panels, among which, and relevant to the scope of the present paper, a recycled denim panel. By applying increasing loads to the panels, the density was varied and the corresponding thermal conductivity measured: while feathers panel trend exhibited a minimum at about 59 kg/m^3, denim panel showed a decreasing trend between 30 and about 50 kg/m^3. Moreover, a dynamic vapour sorption test was carried out on all samples, showing that natural fibers panels are hydrophilic and their adsorption curve has a steep rise after 70–80 %, likely corresponding to the passage from the hydroscopic to the capillary regime.

In their studies [8,23,24] Rubino et al. concentrated on medium-to-high density panels produced through compression molding, by mixing post-production waste wool fibers with natural binders, with the aim to obtain more easily recyclable products with low environmental impact. Thermal conductivity measurements were performed with the Transient Plane Source technique at laboratory conditions. In [8] thermal conductivity is found to increase linearly with density, between 0.049 and 0.060 W/(m.K) when density varies between 80 and 197 kg/m^3. A simple model is then proposed for the prediction of the equivalent thermal conductivity, based on conduction in parallel in the solid and gas phases. In [23,24] the role of the binder is addressed, by comparing panels produced with natural binders (chitosan or Arabic gum) with those obtained with bicomponent PET/PET binder, revealing comparable thermal conductivity values and trends with density, likely because they are all characterized by a high porosity over 90 %.

Finally, some Authors studied the potential use of waste fabric as loose fill insulation [25,16,18,17]. Among them, Bourguiba et al. [25] analysed the thermal performance of polyester and duck feathers fibers, both obtained from recycling of upholstered bedding. They concluded that all the materials presented “good thermal performances“, with thermal conductivity values between 0.051 and 0.063 W/(m•K).

In [16] several types of pre-consume shredded polyester fabrics were investigated as loose fill insulation. Interestingly, to accommodate the materials in the heat flow meter apparatus, a sort of quilt casing in polypropylene was built for each sample. The main goal is determining the differences in thermal insulation between fabric pieces of various sizes on the one side and partially fibrous waste on the other. The measured thermal conductivity, comparable with those of traditional insulating materials, ranged between 0.052 to 0.060 W/(m·K). The Authors observed that the sample made with the smallest fabric species has a lower thermal conductivity than the one made of non-shredded waste, but the comparison is somehow complicated by the different density of the samples.

Briga-Sà et al. [18] studied the properties of two loose fill insulation from pre-consume acrylic waste, one composed of pieces of woven fabric for a density equal to 440 kg/m^3 and another made of fibers with a density of 122 kg/m^3. The loose-fill insulation is placed in the air cavity of a double wall, built in a test room at controlled indoor conditions but exposed to outdoor climate. The materials presented thermal conductivities equal to 0.103 W/(m·K) (fabric pieces) and to 0.044 W/(m·K) (fibers); the Authors concluded that an effort is needed to develop commercial products from these textile wastes, similar to quilts, that could be fixed to the surfaces facing the air gap of the wall.

A box method, based on a test facility composed of two boxes at uniform temperature separated by the tested sample, is adopted by [17] to investigate the properties of two textile wastes characterized by the same raw material with different mechanical treatment (loose fibers or panels produced with an air-lay thermoformature technique). From their results, the conclusion is derived that the mechanical treatment of the waste partially affects the thermal conductivity, resulting in 0.033 W/(m·K) for panels and 0.039 W/(m·K) for fibers, and the Authors suggest that the better performance of the panels may be due to a structure with a higher closed porosity.

From this literature review, it is clear that textile wastes have a potential use as building insulation materials, thanks to their low thermal conductivity, comparable to other conventional thermal insulators. While all the Authors find that thermal conductivity is directly proportional to the sample mean temperature [7,9,12,13,15], the dependence on density is not obvious. By comparing studies addressing this particular aspect [7,8,23,24] it can be remarked that the range of densities where thermal conductivity either decreases or increases, as well as the optimal density corresponding to the minimum conductivity, depend on the waste textile composition and also, likely, on the process adopted to transform the textile waste into an insulation product, that influences the size and the structure of the pores. The impact of moisture content is often disregarded, although it was clearly observed that, apart plastic fibers, all natural fibers absorb moisture [7] and a larger moisture corresponds to a higher conductivity [15]. As insulation materials, in the building envelope, are generally influenced by the state of the indoor and outdoor air, it is important to evaluate their thermal conductivity also as a function of the moisture content.

1.2. *Objective of the work*

It is clear from Table 1, where an overview of the recycled textile materials tested in the literature, single sourced or in a mixture, is presented, that cotton has been rarely addressed by scientific studies. Yet, it is the second most used fiber in the textile industry worldwide after polyester, and the textile fiber having by far the highest environmental impact in terms of water consumption during production [2]. Given the potential and the environmental interest to recycle cotton fibers into a bio-based insulation product, commercial products based on recycled cotton are starting to appear on the market. Their thermal characterizations are however typically limited to standard conditions, while the scientific literature demonstrates the need to investigate the potential impact of some physical parameters.

Therefore, this paper aims to contribute to the research on building insulation materials based on recycled textiles by focusing on recycled cotton fibers and by providing a wide characterization of their thermal behaviour. In order to investigate the material in itself i.e. in the simplest form, avoiding thus the possible influence of the kind of binder and the kind of process, the cotton will here be analysed as loose fibers, which to the best of the Authors' knowledge has not been done before. In order to give a comprehensive experimental characterization of this textile material, the influence on thermal conductivity of temperature, humidity, density and orientation (horizontal/vertical) will be assessed. This overall set of parameters has not been considered all at once before (Table 1). Moreover, as a further step towards application in buildings, the use of recycled cotton fibers as loose fill insulation of cavity walls is tested. Given the different aspects of the analysis, measurements are carried out with many techniques, namely *Transient Plane Source*, *Guarded Hot Plate* and finally *Heat Flow Meter* combined with *Hot and Cold Boxes*, by exploiting the specificity and the complementarity of each methodology.

2. Materials and methods

The material under investigation is post-consume cotton textile taken back to loose fibers. Firstly, the vapour adsorption characteristics of the fibers were assessed in terms of isothermal adsorption curve. Then, with reference to low and medium density insulation products for building applications, the following densities were chosen for investigation: 30, 50 and 70 kg/m^3, although the latter was sometimes difficult to achieve. As mentioned above, the thermal conductivity tests were performed with different techniques, as each of them allows to better investigate specific issues impacting on the heat transfer properties of the material. The parameters investigated with each apparatus are summarized in Table 2: the *TPS apparatus*, being it possible to insert the sample and the probe in a climatic chamber and thus control thermo-hygrometric conditions during the measurement, was specifically used to assess the influence of temperature and relative humidity; the *Guarded Hot Box apparatus*, allowing to place the sample either horizontally or vertically, was specifically used to assess the impact of the orientation; finally, the *Heat Flow Meter* methodology, combined with *Hot and Cold Boxes*, allowed to test the application of the loose fill insulation at the wall scale, as well as the influence of the temperature difference across the wall. Some conditions were tested with more than one technique, allowing to compare the results and assure coherence and robustness. Different samples were prepared by inserting the fibers into suitable casings fitting the various experimental setups.

2.1. Adsorption behavior assessment

The experimental set up for the measurement of the adsorption curve of the material consists of a high-precision balance inserted in a climatic chamber equipped with a system for the regulation of the relative humidity and of the temperature (Aquadyne DVS). A small amount of material (around 50 mg) is placed on the balance and the reference state is obtained in nitrogen atmosphere at 80 °C. Then, the relative humidity of the air in the chamber is varied at constant temperature in subsequent steps sufficiently long to allow that the sample goes into equilibrium with the humid air environment, while the mass of the sample is continuously measured. In each step, stability is assumed when mass variation is lower than 0.0001 %/min. For each step, the mass increase of the sample, representing the moisture content, is then calculated. In the present study, the adsorption curves of the cotton fibers were evaluated in two different tests at 20 °C and 30 °C. In each test relative humidity was varied between 0 % and 90 %. Experimental uncertainty of temperature, relative humidity and mass is respectively: ± 0.2 °C; from ± 0.8 % at 20 °C to ± 1.8 % at 70 °C; 1.0 μg plus 0.001 % of suspended mass.

2.2. Thermal conductivity assessment

2.2.1. Transient Plane Source measurements

A first series of thermal conductivity measurements was carried out with the Transient Plane Source (TPS) dynamic technique [27] using the Hot Disk Thermal Constant Analyser from Thermetrol Inc. The instrument consists of Kapton probes of different radii (the 10 mm one is shown in Fig. 1), a measuring bridge, a power supply and a digital multimeter. The disc, embedded between two specimens of the material, produces a heat pulse in the form of a stepwise function and at the same time detects the temperature of the specimens' surface as a function of the time. The TPS technique has the advantage of being more rapid than steady state techniques: in this case each acquisition lasted a few minutes. During this measurement time 200 points are recorded to analyze the sensor temperature increase, therefore the time step used is around one second.

The loose fibers were inserted in a custom-built wooden cubic box with 10 cm side (Fig. 1). The mass of fibers necessary to fill the internal volume with the design density was previously determined. In order to guarantee the same density below and over the probe, the mass was halved. Firstly, half the mass was inserted, then the hot disc was placed on top, and then the second half of the mass was added to cover the probe and complete the box filling. This way samples at 30 and 50 kg/m^3 were realized, while increasing the density to 70 kg/m^3 was considered potentially dangerous for the probe, that is not rigid.

In order to assess the influence of temperature and relative humidity on thermal conductivity, the samples were conditioned in a climatic chamber, where the measurements were subsequently performed. The used climatic chamber (Angelantoni Test Technologies Discovery DY1200) has a useful capacity of 1200 L, a temperature range control from −40 °C to + 180 °C, a humidity range control from 10 % to 98 % (available with temperatures between 4 °C and 94 °C) and a maximum temperature change rate of 4 °C/min. Different temperatures were set (10, 20 and 30 °C) as well as different relative humidities (10 %, 50 % and 80 %). Each condition was repeated at least 3 times, and repeated measurements were used to derive the mean values and the standard deviations, adopted as uncertainties.

Table 2
Experimental methods and corresponding investigations.

Apparatus	Parameters investigated
Transient Plane Source (TPS)	ρ, T, RH
Guarded Hot box	ρ, orientation
Heat Flow Meter	ρ, T, ΔT, application at wall scale

2.2.2. Guarded Hot Plate measurements

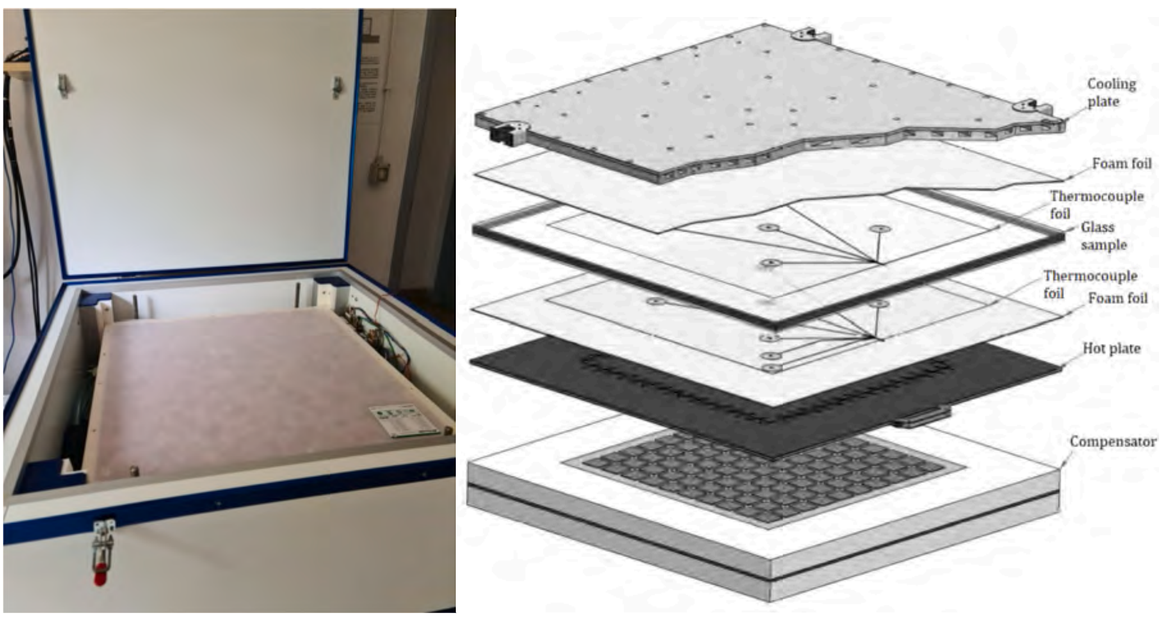
A second series of thermal conductivity measurements was carried out exploiting the steady-state Hot Plate methodology [28]. The Guarded Hot Plate apparatus, at ENEA Casaccia Research Center laboratories in Rome, consists of a central heating plate, a measurement area of 50 cm x 50 cm surrounded by a guard section 150 mm thick, and two external cooling plates. This system can host samples of maximum 80 cm x 80 cm width and length, 12 cm thick. The mean average temperature can be set between −10 °C and 40 °C and the range for thermal conductivity assessment is 0.01–2.00 W/(m•K). A PID controller is used to bring the system to the required set point temperature guaranteeing steady-state conditions; a data acquisition system collects the measured data during each test (hot plate power, chiller temperature, surface temperature of both cold and hot surfaces). Twenty-two special grade type T thermocouples are installed for the measurement of the surface temperatures of both sides of the sample. The single specimen configuration was chosen, replacing the second specimen with a thermal compensator, able to guarantee a zero-heat flow towards the lower part of the machine.

For this apparatus, the cotton fibers were inserted inside a simple wooden frame measuring 74.6 cm x 74.6 cm x 4.8 cm covered with two polypropylene sheets to limit the moisture transfer. Two different densities were analyzed, namely 30 and 50 kg/m^3. A temperature difference of 10 °C was imposed across the sample, setting the temperature of the hot plate at 20 °C and of the cold plate at 0 °C, resulting in a mean temperature of the samples equal to 10 °C. Thanks to the ability of the machine to rotate, tests can be carried out both in horizontal and vertical positions: therefore, the effects of the orientation of the panel on the measured thermal conductivity was assessed. The tests can be considered concluded when values sufficiently stable over time are recorded, i.e. when deviations of less than 1 % are noted compared to the previous measurements, taken every 25 min. In this case the average test duration was about 5 h.

Fig. 2(a) presents a view of the measuring facility with the sample mounted in and Fig. 2(b) the schematic view of the different layers of the apparatus during test, on the right. The latter reports a scheme when a glazing unit is mounted, but it applies to any sample. The thermal compensator is used when the facility is in the single sample mode, while it is removed in the double sample mode [29].

(a) (b) (c)

Fig. 1. TPS measurements: the hot disc probe (a), the wooden box partially filled with cotton fibers (b) and the box with the hot disc probe (c).



(a) *(b)*

Fig. 2. Guarded Hot Plate apparatus: the wooden frame filled with the sample (a), and a schematic view of the different layers in the apparatus during test (b).

2.2.3. Heat flow Meter measurements

The thermal conductivity of the cotton when used in a vertical wall cavity was assessed using the Heat Flow Meter method, specifically the Average Method [26]. This approach, also used in situ, measures the thermal resistance of a wall by sampling heat flux density and temperature data, and operates on the principle that thermal resistance can be approximated by the ratio between the average temperature difference and the average heat flux density, both calculated over a sufficiently long time period to minimize fluctuations:

$$R = \frac{\sum_{i=1}^{N} \left(T_{si,i} - T_{se,i}\right)}{\sum_{i=1}^{N} \varphi_i} \quad (1)$$

where R [m^{2}K/W] is the thermal resistance of the wall, T_{si} and T_{se} [°C] are the temperatures of the indoor and outdoor surfaces respectively, φ[W/m^2] is the heat flux density sampled at any of those surfaces (generally the indoor one), N is the total number of temporal data and the index i, represents the i-th timestamp. Since in this study the wall consists of a single layer of homogenous material, the thermal conductivity λ can be obtained from the definition of the thermal resistance for a solid layer with thickness s:

$$R = \frac{s}{\lambda} \quad (2)$$

Measurements are performed in a controlled laboratory setting with steady-state thermal conditions, eliminating the need for the duration constraints mentioned in [26]. Furthermore, sensors placement is easier than in *in situ* conditions, enabling the measurement of surface temperatures and heat flux densities in multiple locations on the sample and allowing the use of the standardized testing approach described in [30]. This procedure assesses the thermal resistance of complex components, such as windows and doors [31], by measuring heat flux density and surface temperatures at various locations on the sample surfaces, deemed representative of a region with uniform properties, as detailed in [32].

Experiments were performed using the Dual Air Vented Thermal box

(DAVTB) apparatus in the Building Physics Laboratory of the Energy Department of Politecnico di Milano (Fig. 3), designed to test building envelope components under user-defined thermal conditions [33–35]. It consists of two insulated chambers (box 1 and box 2, 1.5 m × 1.5 m × 1.29 m each), replicating indoor and outdoor conditions, separated by the sample and externally connected by an air recirculation system (Fig. 4), used test *Breathing Wall components* [34,35] and not involved in this work. The operative temperature in each chamber is independently controlled through of a dedicated hydronic system providing heating and cooling via radiant panels, with a theoretical range of 15 °C to 50 °C, depending on the sample properties. The control system can achieve the set operative temperatures, either in steady state [34] or in steady periodic conditions [35], with a mean squared error below 0.1 °C. The sample is accommodated in a 1.5 m × 1.5 m insulated metal frame located between the chambers.

In this work, the loose cotton fibers were packed in a plywood box (Fig. 5(a)) installed vertically in the frame. Its frontal dimensions are 1 m × 1 m, with a 5 cm design thickness. The box was further insulated on the sides, to ensure a one-dimensional heat transfer in the central section of the sample.

The main box surfaces were also used to support temperature and heat flux density sensors in the desired locations: as an example, Fig. 5 (a) and Fig. 5(b) show the sensors on the side facing box 1, all placed and glued in dedicated recesses (the side facing box 2 only features temperature probes). To ensure sample homogeneity, the filling proceeded gradually in 20 cm horizontal stripes, as indicated by the blue lines in Fig. 5(b), with an interposed mesh net to mitigate self-compaction due to gravity. Three samples with densities of 30 kg/m^3, 50 kg/m^3 and 70 kg/m^3, assumed to be representative of this kind of application in real buildings, were investigated by inserting 1.5 kg, 2.5 kg and 3.5 kg of loose material, respectively, into the 0.05 m^3 plywood box. Even though a high density like 70 kg/m^3 is difficult to achieve due to packaging issues, it was made possible by this peculiar preparation, while it could not be obtained for the *Transient Plane Source* and the *Guarded Hot Plate* apparatus. Therefore, the greater density range considered in this group of tests allowed a better comprehension of thermal conductivity trends.

For each sample, three tests were conducted at different set point values (35 °C, 40 °C and 45 °C) for the operative temperature in box 1 ($T_{op,1}$), while box 2 was consistently maintained at 20 °C ($T_{op,2}$). These settings subjected each sample to three temperature differences between the chambers (ΔT_{op} equal to 15 °C, 20 °C and 25 °C), resulting in average material temperatures of 27.5 °C, 30 °C and 32 °C, allowing to investigate the dependency of the cotton thermal conductivity on the thermal conditions. Test conditions are summarized in Table 3.

Each test was divided in two phases: a 10 + hours period to reach and stabilze the desired conditions within the sample, followed by a 24-hours data sampling phase for the actual thermal conductivity measurement, during which steady-state conditions were assured. Measurements were done every 5 s.

Concerning the sensors, surface temperatures were measured using 30 calibrated T-type Thermocouple (15 per side), with an average measurement error of 0.03 °C, while heat flux density was sampled using 11 heat flux meters (HFMby GreenTeg (18.0 mm × 18.0 mm sensing dimensions), with a ± 3 % calibration accuracy from the factory. To minimize edge effect, only the 9 central sections with equal area were considered for further calculations (red squares in Fig. 5(b)).

At the end of each test, the collected data were processed by calculating the spatial averages of the surface temperatures and the heat flux density at each timestamp i of the acquisition process:

$$\langle T_{s1} \rangle_i = \frac{\sum_{j=1}^{9} T_{s1,j,i}}{9} \tag{3}$$

$$\langle T_{s2} \rangle_i = \frac{\sum_{j=1}^{9} T_{s2,j,i}}{9} \tag{4}$$

$$\langle \varphi \rangle_i = \frac{\sum_{j=1}^{9} \varphi_{j,i}}{9} \tag{5}$$

where the index j indicates one of the previously mentioned 9 central sections of each surface. Since their area is equal, the area weighted average has been substituted with the arithmetic average. Results from Eq. (3), (4) and (5) are then used to calculate the thermal resistance of the sample, and Eq. (1) becomes:

$$R_{HFM} = \frac{\sum_{i=1}^{N} (\langle T_{s1} \rangle_i - \langle T_{s2} \rangle_i)}{\sum_{i=1}^{N} \langle \varphi \rangle_i} \tag{6}$$

Once the thermal resistance of the sample is known, Eq. (2) can be manipulated to obtain the thermal conductivity λ, assumed as:

$$\lambda = \frac{s}{R_{HFM}} \tag{7}$$

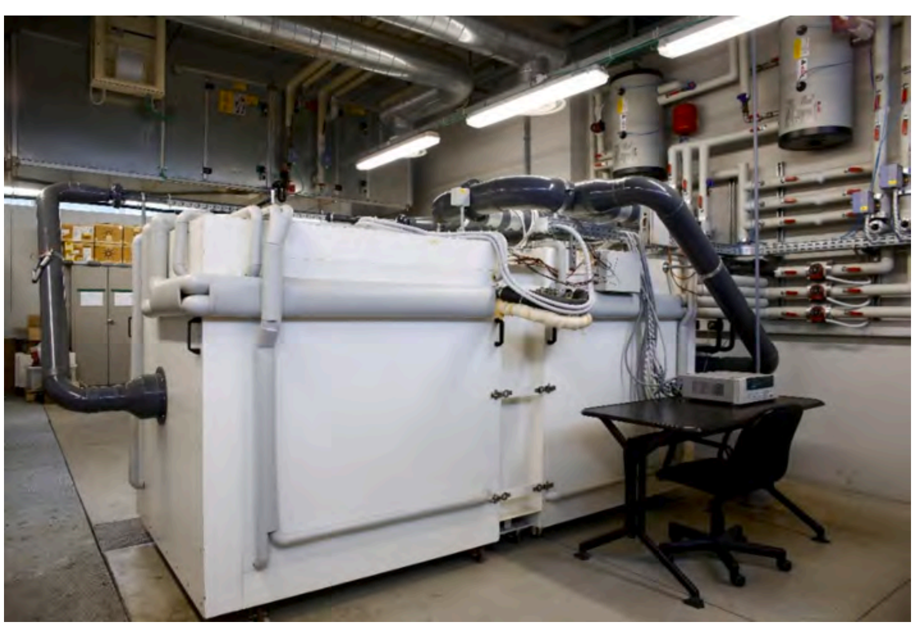


Fig. 3. TheDual Air Vented Thermal box (DAVTB) apparatus.

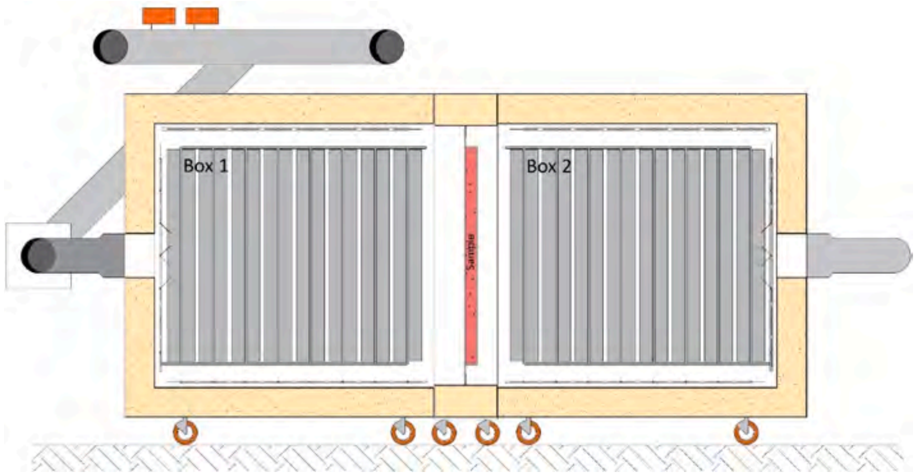


Fig. 4. vertical section of the DAVTB apparatus. box 1 and 2 are on the left and on the right of the sample, respectively.

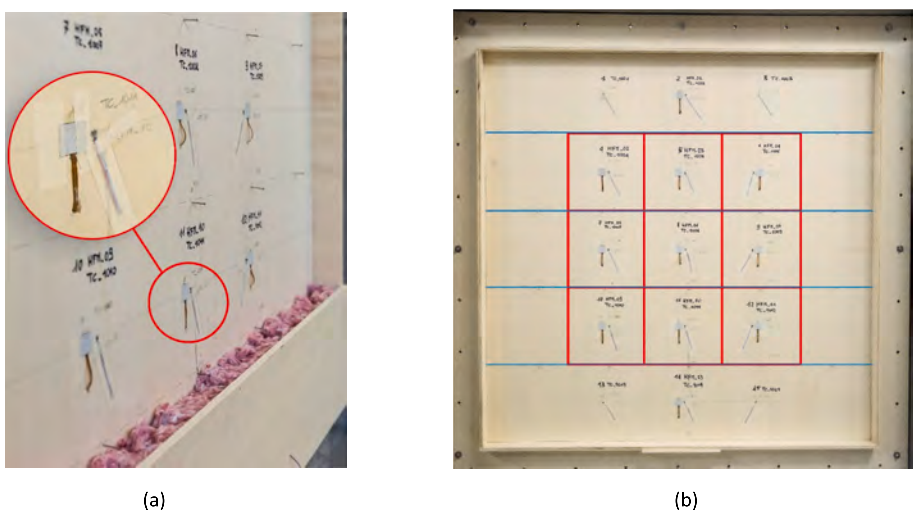


Fig. 5. Heat Flow Meter measurements. (a) detail of the sample box, with the bottom layer of cotton and all the TC and HFM exposed. (b) frontal view of the empty sample box. The 5 horizontal stripes created during the building process are highlighted by the blue lines, while the 9 red squares represent the regions corresponding to each sampling location. All the sensors on the side facing box 1 of the DAVTB are visible. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Heat flow meter measurements: temperature settings adopted in every DAVTB test.

quantity	test ΔT15	ΔT20	ΔT25
box 1 operative temperature – $T_{op,1}$ [°C]	35	40	45
box 2 operative temperature – $T_{op,2}$ [°C]		20	
temperature difference – ΔT [°C]	15	20	25
average sample temperature – T_{ave} [°C]	27.5	30	32.5

Table 4
Heat flow meter measurements: effective thickness and corresponding effective densities for the three samples considered.

ρ_{des}	$\langle s \rangle$	ρ_{eff}
[kg/m^3]	[m]	[kg/m^3]
30	0.0537	27.95
50	0.0559	44.74
70	0.0595	58.86

The samples' effective thickness, designed to be 5 cm, varied due to the flexible plywood being pressed outward by the packed cotton, especially at higher densities. To account for this, the thickness was measured at multiple points along the blue lines in Fig. 5(b) using a caliper (0.05 mm accuracy) and the average was used to solve Eq. (7) and recalculate the effective density (Table 4).

Finally, the relative measurement error for the thermal conductivity was calculated by compounding the relative uncertainties related to each of the quantities involved (surface temperatures, heat flux density and thickness) through the following equation:

$$\frac{\sigma_\lambda}{\langle\lambda\rangle} = \sqrt{\left(\frac{\sigma_{\Delta T}}{\Delta\langle T_s\rangle}\right)^2 + \left(\frac{\sigma_\varphi}{\langle\varphi\rangle}\right)^2 + \left(\frac{\sigma_s}{\langle s\rangle}\right)^2} \quad (8)$$

where σ_k is the uncertainty of the generic quantity k. Moreover, each uncertainty σ_k results from combining the instrumental accuracy (subscript *instr*) and the spatial variation (subscript *distr*) of the quantity across the 9, and is calculated as:

$$\sigma_k = \sqrt{\sigma_{k,instr}^2 + \sigma_{k,distr}^2} \quad (9)$$

3. Results

3.1. Moisture adsorption results

An example of the adsorption test results is reported in Fig. 6(a), which shows the variation of the relative humidity of the chamber in subsequent steps and the consequent increase of the sample mass due to progressive adsorption of moisture. It can be noticed that the kinetic is very quick, as about 20 min are sufficient to reach an almost stable mass, after the relative humidity is varied in a step.

Instead, in Fig. 6 (b) steady state conditions of samples at different relative humidity and temperature are shown. The cotton fibers absorb up to 11 % moisture at 90 % relative humidity in the surrounding environment: adsorption isotherms are nearly identical, suggesting the phenomena is less sensitive to temperature in the investigated conditions. As relative humidity changes from 20 % to 70 % the absorption curves are almost linear, roughly indicating a 1 % increase in moisture content as relative humidity increases by 10 %. Moreover, adsorption curves shown in Fig. 6 are in good agreement with the analogous curves reported in [7] (difference of mass variation within 1 %) and confirm that cotton fibers, as most natural fibers, are sensitive to moisture. Further, as the present characterization refers to loose fibers while the one in [7] refers to panels based on recycled denim, the similarity of the outcomes suggests that the vapor sorption behavior of the loose cotton fibers remains fundamentally the same when they are bonded to form a solid matrix: in other terms, adopted binding technologies are not able to significantly reduce the (high) total amount of fiber surface.

3.2. Thermal conductivity – TPS results

The results of the measurements performed with the TPS technique in the climatic chamber are summarized in Table 5. The lowest relative humidity condition i.e. 10 % was hardly maintained by the climatic chamber, especially at low temperatures. Therefore, it was chosen to report in Table 5 the effective average humidity registered during each test. In order to discuss the influence of the different investigated parameters on the thermal conductivity, in the following some graphs are introduced.

Thermal conductivity is very sensitive to the relative humidity of the environment, for both samples (Fig. 7). As relative humidity passes from 10 % to 80 % the thermal conductivity of the 30 kg/m^3 sample increases by 32 % and 25 %, at 20 °C and 30 °C respectively, and by 18 % at 10 °C starting with relative humidity around 20 %. For the 50 kg/m^3 sample, as relative humidity passes from 29-31 % to 80 % the thermal conductivity increase is 12 % when the temperature is 10 °C and 13 % at 20 °C. Considering always the 50 kg/m^3 sample at 30 °C passing from 12 % to 80 % RH produces an increase in thermal conductivity around 14 %. In order to compare the rates of increase, linear regression equations are also reported in Fig. 7, suggesting that low-density sample is more sensitive to relative humidity, for what concerns thermal conductivity.

Table 5
TPS results.

ρ [kg/m^3]	T [°C]	RH [%]	⟨λ⟩ [W/(m.K)]	σ_λ
30	10	17	0.0381	0.0022
		48	0.0436	0.0022
		80	0.0450	0.0012
	20	10	0.0381	0.0013
		50	0.0472	0.0005
		80	0.0503	0.0018
	30	13	0.0433	0.0019
		50	0.0497	0.0034
		80	0.0539	0.0005
50	10	31	0.0414	0.0009
		50	0.0430	0.0023
		80	0.0464	0.0020
	20	29	0.0447	0.0010
		50	0.0485	0.0017
		79	0.0506	0.0069
	30	12	0.0477	0.0028
		50	0.0530	0.0030
		80	0.0546	0.0046

The dependence of thermal conductivity on temperature is illustrated in Fig. 8. As already mentioned, the low humidity condition could not be strictly maintained, therefore, in this case, the trend with temperature is somehow disturbed by the contemporary variation of relative humidity. However, considering the trends corresponding to the 50 % relative humidity condition, which is stable, we can observe that passing from 10 °C to 30 °C thermal conductivity increases by 13 % and 23 % for the 30 kg/m^3 and 50 kg/m^3 samples respectively.

Given the significant influence of relative humidity and temperature on thermal conductivity illustrated by the previous graphs (Figs. 7 and 8), the role of the sample density can be rigorously observed by keeping both parameters constant. This consideration leads to leave out data referring to the lowest humidity at both 10 °C and 20 °C (Table 5), and to report the other data in Fig. 9. By comparing data referring to the same environmental conditions (same colors bars) it can be noticed that passing from 30 kg/m^3 to 50 kg/m^3 produces minor changes in thermal conductivity, generally consistent with measurement uncertainty. The sole significant change can be observed at 30 °C with 10 % R.H., where the thermal conductivity increases by 10 % with the increase of density from 30 kg/m^3 to 50 kg/m^3. As it was mentioned in the Introduction section, from a theoretical point of view it is expected that in a porous

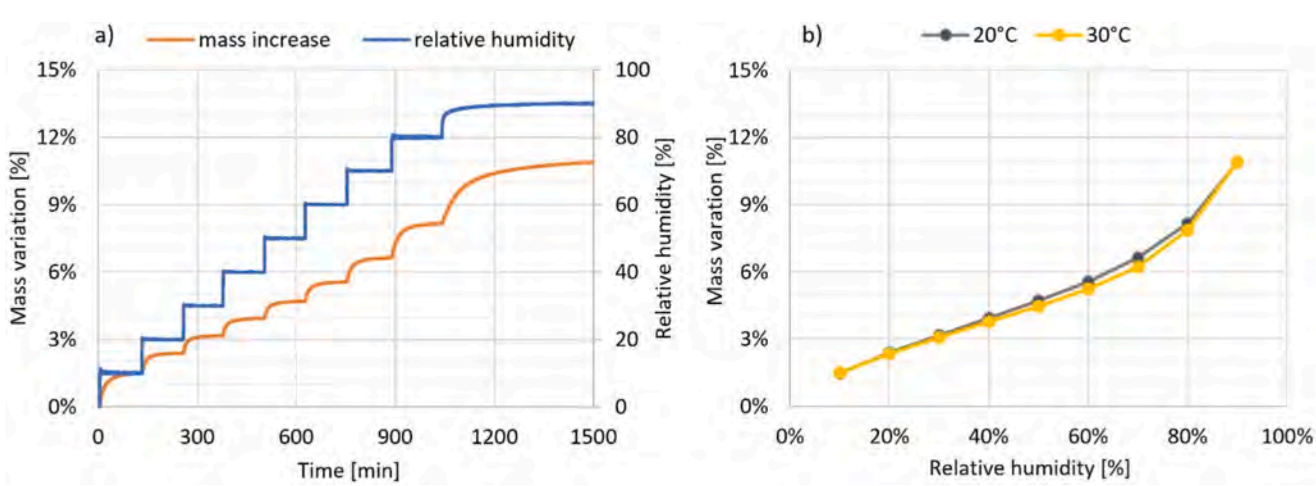


Fig. 6. Kinetics of the moisture adsorption by the cotton sample at 20 °C (a) and moisture adsorption curves at 20 °C and 30 °C (b).

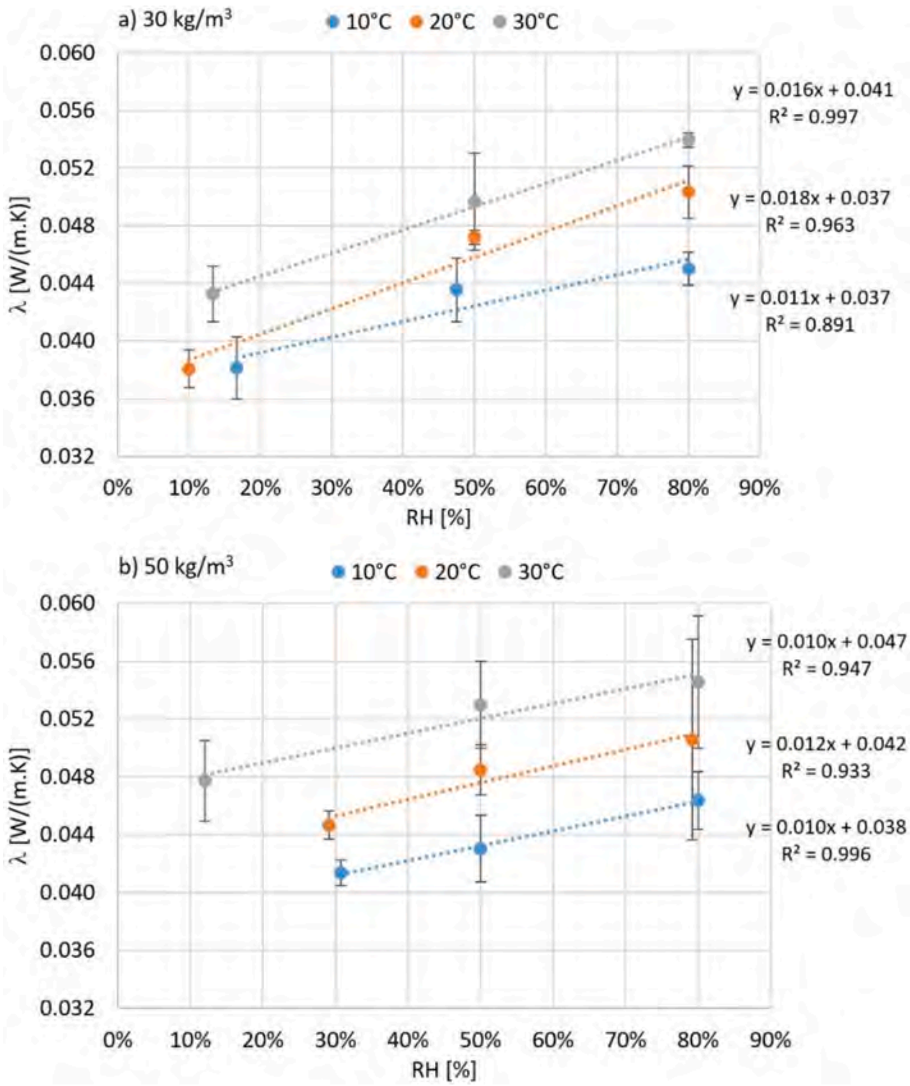


Fig. 7. TPS measurements: thermal conductivity versus relative humidity for different temperatures and sample densities (a) 30 kg/m^3 and (b) 50 kg/m^3.

material thermal conductivity at first decreases with density, reaches a minimum and then starts to increase again. However, the ranges of densities corresponding to the decreasing and increasing trends depend on the porous materials. As it was remarked in the State of the art section, depending on the material and range of density investigated, some Authors observe an increasing trend (e.g. [8]), while others observe a decreasing one and eventually capture the minimum (e.g. [7]). The modest dependence of the thermal conductivity of the cotton fibers samples on density observed in this study is thus not surprising, given also the limited density range explored.

3.3. Thermal conductivity – Guarded Hot Plate method results

First of all, the *Guarded Hot Plate* test results obtained for the sample with horizontal orientation are compared with the TPS results at the same temperature, namely 10 °C. As Fig. 10(a) shows, the *Guarded Hot Plate* method outcomes are in the range of variation of the TPS results due to relative humidity. Indeed, although the samples were conditioned at 23 °C and 50 % relative humidity for 24 h before being inserted into the Guarded Hot Plate apparatus, the relative humidity during the tests could not be controlled. Since the cotton fibers are quite sensitive to environmental humidity conditions, as the moisture adsorption tests demonstrated (Fig. 6), the effective moisture content of the sample during the Hot Plate measurements is unknown. It can be concluded that the Guarded Hot Plate results are consistent with the TPS results.

As far as the orientation of the sample is concerned, no significant difference was found in the thermal conductivity of the cotton fibers between vertical and horizontal orientation of the samples (Table 6). This outcome is coherent with the results obtained for recycled textile panels with similar densities by [15], who also found that the influence of the specimen incline on thermal conductivity is negligible. This outcome suggests that natural convection provides a marginal contribution to the heat transfer across this insulation.

3.4. Thermal conductivity – Heat flow Meter method results

The tests performed using the DAVTB apparatus and applying the HFM method allowed the evaluation of the thermal conductivity of loose cotton packed in 5 cm vertical cavity and showed a dependency of this quantity on both average temperature and density. The main results of the Heat Flow Meter test on the vertical insulation layer made of loose cotton fibers are summarized in Table 7, where the average quantities and the corresponding compounded uncertainties (calculated according to Eq.(8)) are reported. Moreover, Table 8 reports all the instrumental accuracies and the spatial distributions used to calculate the compound uncertainties.

In every test, a non-uniform distribution of temperatures and heat flux densities on the wall surfaces has been observed. More precisely,

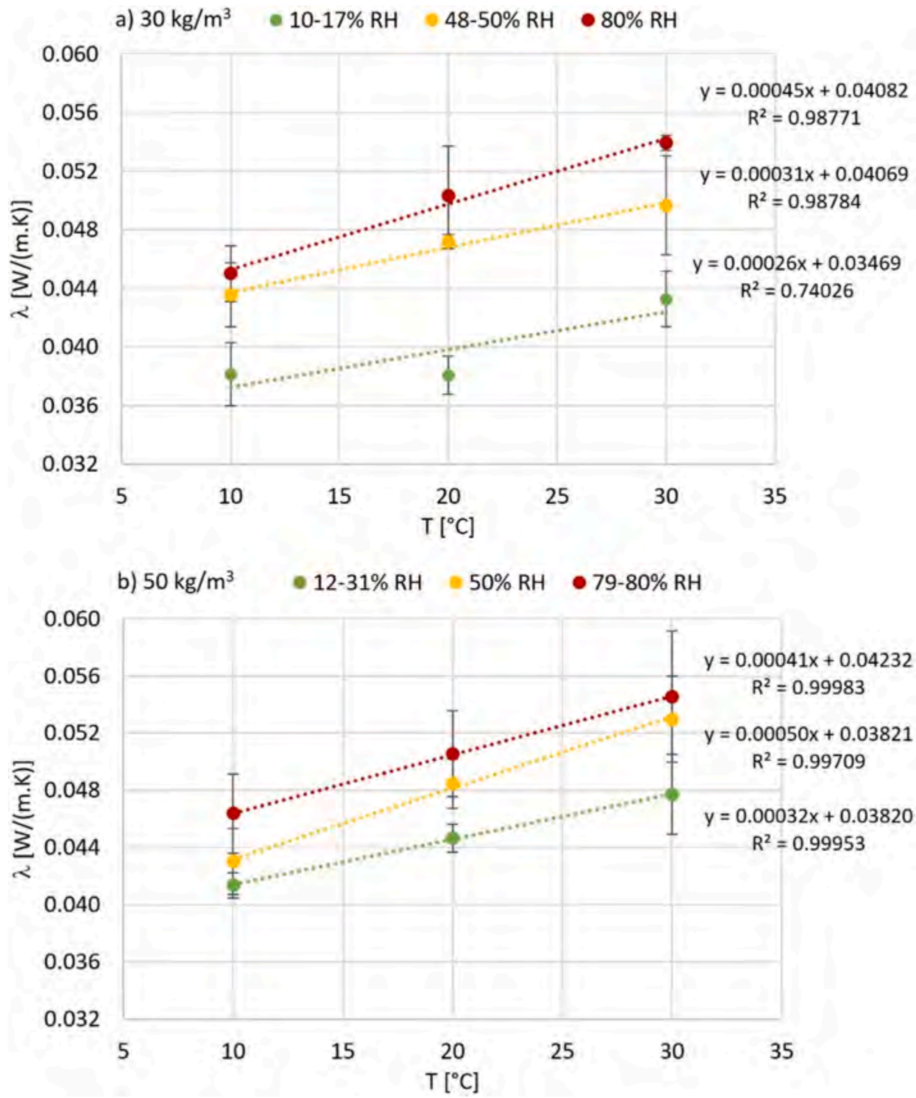


Fig. 8. TPS measurements – thermal conductivity versus temperature temperatures for sample density (a) 30 kg/m^3 and (b) 50 kg/m$^{3.}$

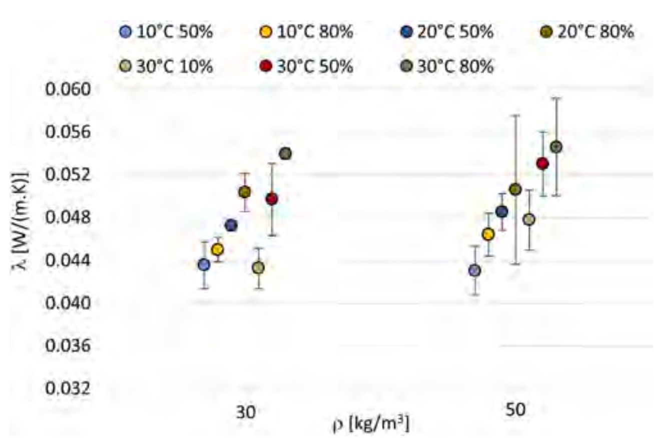


Fig. 9. TPS measurements – thermal conductivity versus density for selected temperature and humidity conditions.

temperatures grow going from bottom to top, due to the thermal stratification of air inside both boxes of the DAVTB apparatus.

An example of the distribution of the wall surface temperatures and heat flow density is reported in Table 9, referring to the sample at design density 30 kg/m^3. As this is the lowest density case, it is the most challenging from the possibility to achieve a uniform distribution of the fibers in the wall air gap. The surface temperature generally tends to increase with height (along columns in Table 9), especially for the warm surface facing the hot box at 45 °C, while horizontal variations (along lines) are less significant. In any case, the difference between local temperature and average temperature ranges between −0.52 °C and 0.44 °C. Concerning the distribution of the heat flow density, the difference with respect to the average lies between −2.8 % and + 7.8 %. Therefore, the heat transfer can be considered quite uniform over the wall surface and local measurements can be used to derive spatial averages and infer the insulation layer thermal resistance and thermal conductivity.

The thermal conductivity obtained from the spatial average of the surface temperatures and heat flow density distributions are then compared with the thermal conductivity measured through TPS method, by keeping the temperature equal, as it was done for the Guarded Hot Plate results. A consistency check is reported in 10 (b), where the TPS results referring to the tests at 30 °C are displayed as bars, ranging from the value at the lowest relative humidity equal to 10 % to the value at the highest equal to 80 %, and the Heat Flow Meter method results at 30 °C are reported with their measurement uncertainty. Although the effective density of the Heat Flow Meter samples is somehow smaller

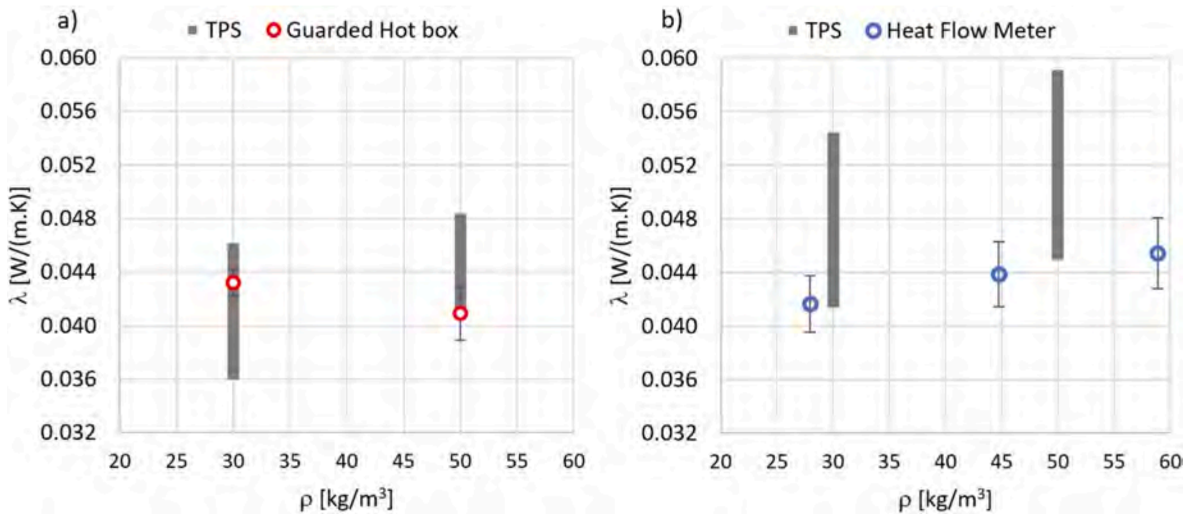


Fig. 10. Comparison between: TPS and Guarded Hot box results at 10 °C (a); TPS and Heat Flow Meter results at 30 °C (b). For TPS the whole range of results corresponding to the relative humidity span is reported.

Table 6
Guarded Hot Plate method results at 10 °C depending on the sample orientation.

	Vertical		Horizontal	
ρ	λ	σ_λ	λ	σ_λ
[kg/m^3]	*[W/(m.K)]*		*[W/(m.K)]*	
30	0.043	0.001	0.043	0.001
50	0.041	0.001	0.041	0.002

than the TPS samples, it can be noticed that Heat Flow Meter results are compatible with the TPS results, if a low moisture content is supposed for the samples in the DAVTB apparatus. As already mentioned, it is not presently possible to measure and control relative humidity in the chambers of the DAVTB apparatus. However, the relative humidity and temperature in the surrounding laboratory are relatively stable around 20 °C and 50 % relative humidity, therefore it is reasonable to infer that inside the chambers of the apparatus, that are maintained at higher temperatures (see Table 3), the relative humidity is low.

The spatially averaged thermal conductivity is shown in Fig. 11 for each test on the samples at 30, 50 and 70 kg/m^3. By increasing the hot box temperature while keeping the cold box one constant, both the operative temperature difference across the wall and the average wall temperature increase. The thermal conductivity slightly increases, although differences between the values obtained with $\Delta T = 15$ °C and $T_m = 27.5$ °C and the values obtained with $\Delta T = 25$ °C and $T_m = 32.5$ °C are within the measurement uncertainty, as shown by the error bars in Fig. 11. The question may then arise whether this variation is mainly driven by the increase in the mean temperature or in the temperature

Table 7
Summary of averages and compounded uncertainties for measurements.

design conditions			*thickness*		*temperature difference*		*heat flux density*		*results*		
ρ_{des}	ΔT	T_{ave}	⟨s⟩	σ_s	$\Delta\langle T_s\rangle$	$\sigma\Delta_{Ts}$	⟨φ⟩	σ_φ	R	⟨λ⟩	σ_λ
[kg/m^3]	[°C]	[°C]	[m]		[°C]		[W/m^2]		[m^{2}K/W]	[W/(m.K)]	
30	15	27.5	0.0537	$9.57\ 10^{-4}$	10.66	0.39	8.16	0.29	1.307	0.0411	0.0022
	20	30			14.17	0.43	11.00	0.41	1.289	0.0417	0.0021
	25	32.5			17.60	0.52	13.94	0.53	1.263	0.0425	0.0022
50	15	27.5	0.0559	$1.41\ 10^{-4}$	10.76	0.33	8.35	0.36	1.289	0.0434	0.0025
	20	30			14.36	0.39	11.27	0.47	1.274	0.0439	0.0024
	25	32.5			17.79	0.45	14.23	0.58	1.250	0.0447	0.0024
70	15	27.5	0.0595	$1.79\ 10^{-4}$	10.99	0.30	8.30	0.36	1.323	0.0449	0.0027
	20	30			14.62	0.36	11.17	0.48	1.309	0.0454	0.0026
	25	32.5			18.17	0.42	14.07	0.60	1.291	0.0461	0.0026

Table 8
Instrumental accuracies and spatial variations used to calculate compound uncertainties.

design conditions			*thickness*		*surface temperatures*				*heat flux density*	
ρ_{des}	ΔT	T_{ave}	$\sigma_{s,instr}$	$\sigma_{s,distr}$	$\sigma_{Ts1,\ instr}$	$\sigma_{Ts1,distr}$	$\sigma_{Ts2,\ instr}$	$\sigma_{Ts2,distr}$	$\sigma_{\varphi,\ instr}$	$\sigma_{\varphi,distr}$
[kg/m^3]	[°C]	[°C]	[m]		[°C]		[°C]		[W/m^2]	
30	15	27.5	$5.00\ 10^{-5}$	0.0010	0.0272	0.24	0.0272	0.11	0.08	0.28
	20	30				0.28		0.15	0.11	0.39
	25	32.5				0.11		0.19	0.14	0.51
50	15	27.5	$5.00\ 10^{-5}$	0.0014	0.0272	0.25	0.0272	0.08	0.08	0.35
	20	30				0.28		0.10	0.11	0.45
	25	32.5				0.33		0.12	0.14	0.56
70	15	27.5	$5.00\ 10^{-5}$	0.0018	0.0272	0.24	0.0272	0.06	0.08	0.35
	20	30				0.28		0.07	0.11	0.47
	25	32.5				0.33		0.09	0.14	0.59

Table 9
Heat Flow Meter method test with T $box_1 = 45$ °C, T $box_2 = 20$ °C, design $\rho = 30$ kg/m^3. Distribution of the surface temperatures and heat flow density (top) and distribution of their difference with respect to their spatial average (bottom). Data in a column and in a row refer to different vertical and horizontal positions of the probes, respectively.

$T_{s1,k}$ [°C]			$T_{s2,k}$ [°C]			φ_k [W/m^2]		
41.62	41.85	41.62	23.73	23.90	24.17	13.87	13.56	13.65
41.52	41.57	41.50	23.63	23.83	23.99	13.59	14.47	13.51
41.06	41.02	40.88	23.61	23.73	23.64	15.03	14.03	13.76
$T_{s1,k}$ - $T_{s1,m}$ [°C]			**$T_{s2,k}$ - $T_{s2,m}$ [°C]**			**φ_k - φ_m [%]**		
0.22	0.44	0.21	-0.08	0.10	0.37	-0.5%	-2.8%	-2.1%
0.12	0.16	0.09	-0.17	0.02	0.19	-2.5%	3.8%	-3.1%
-0.34	-0.38	-0.52	-0.19	-0.08	-0.17	7.8%	0.6%	-1.3%

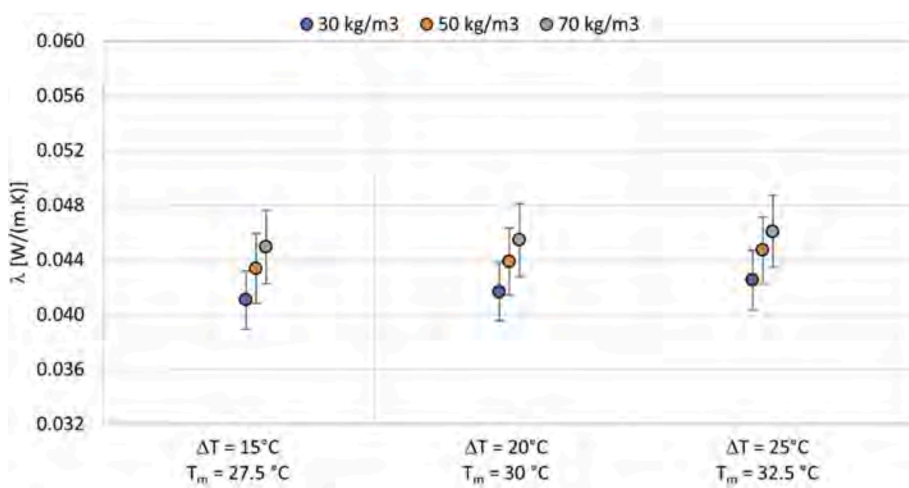


Fig. 11. Heat Flow Meter method measurements – thermal conductivity at different temperature differences across the sample wall and at different average temperature in the wall, for densities 30, 50 and 70 kg/m^3.

difference across the sample. To answer this question, the interpolation curves referring to the dependence of thermal conductivity from temperature resulting from TPS measurements can be used (Fig. 8). For the 30 kg/m^3 and 50 kg/m^3 samples at low relative humidity the slope of the regression line is equal to 0.0026 W/(m•K^2) and 0.0032 W/(m•K^2) respectively. On this basis for a temperature variation of 5 °C, between 27.5 °C and 32.5 °C, a thermal conductivity increase equal to 0.0013 W/(m•K) and 0.0016 W/(m•K) could be expected, respectively. This prediction is in good agreement with the measured increases, that are equal to 0.0014 W/(m•K) for 30 kg/m^3 and 0.0013 W/(m•K) for 50 kg/m^3 (Table 7). Therefore, it can be concluded that the temperature difference across the sample is less relevant than the mean sample temperature for the thermal conductivity. This outcome suggests again that natural convection is marginal and moreover also that an insulation layer with such thickness is substantially opaque to far infrared radiation.

4. Conclusions

In this paper for the first time the equivalent thermal conductivity of a new insulation material in the form of loose fibers obtained by recycling cotton textiles was measured. A combination of experimental techniques was adopted, encompassing steady state and transient methodologies as well as different scales, from the material to the wall. The different approaches allowed to perform a comprehensive analysis, taking into account the various parameters potentially influencing the heat transfer across the material, namely density, temperature, temperature difference, relative humidity and moisture content, orientation.

Firstly, it was verified that the results obtained from the three techniques are generally consistent with each other, considering the peculiarities of each apparatus and methodology. By grouping the outcomes from different techniques, environmental conditions and sample densities, it was found that the thermal conductivity of the recycled cotton ranges between 0.0381 W/(m•K) ($\rho = 30$ kg/m^3, T = 10 °C, RH = 17 %) and 0.0546 W/(m•K) ($\rho = 50$ kg/m^3, T = 30 °C, RH = 80 %). Since such thermal conductivity figures are in line with conventional insulation it can be confirmed that cotton fibers recycled from the apparel sector can be used as an insulation material for the building envelope.

Coming to the second research question, namely which are the physical parameters that mostly affect the thermal conductivity of the loose cotton fibers, they are identified in relative humidity, which impacts on the moisture content, and temperature. On the contrary, the dependance on density does not appear to be significant, so that an optimal density, at least in the range between 30 and 50 kg/m^3, cannot be identified. The vertical or horizontal orientation of the sample is also found to impact negligibly on the thermal conductivity.

These results remark the complexity of the characterization of the thermal performances of such fibrous materials and the need to perform tests under fully controlled environmental conditions, implementing actual methods and instruments and developing suitable standard procedures. A further consequence refers to the evaluation of the performances of such insulating materials in building applications, where they are exposed to variable environmental conditions: these results highlight the need to perform thermal dynamic simulations including heat and vapor transfer, and implementing proper models for the variation of the conductivity with temperature and relative humidity.

Finally, the heat transfer tests at the wall scale in the DAVTB apparatus showed that it is possible to use the cotton fibers to realize a rather homogeneous loose fill insulation in the air gap of a vertical stratigraphy, provided that the air gap is filled progressively per horizontal layers from the bottom to the top. Another possibility, that could be exploited in future studies, consists in developing flexible quilt casings to be filled with the loose fibers. In order to limit moisture adsorption by the cotton fibers, and thus preserve a lower thermal conductivity, the casing material could be designed to have a low vapour permeability, compatibly with the necessity to have a sufficiently breathing envelope.

CRediT authorship contribution statement

Adriana Angelotti: Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Andrea Alongi:** Writing – original draft, Investigation, Formal analysis. **Andrea Augello:** Writing – original draft, Investigation, Formal analysis. **Alessandro Dama:** Writing – review & editing, Visualization, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Stefano De Antonellis:** Resources, Investigation. **Antonino Ravidà:** Resources, Investigation. **Michele Zinzi:** Writing – review & editing, Supervision, Resources. **Enrico De Angelis:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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