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Experimental study of thermal conductivity of leather and carpentry wastes

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HIGHLIGHTS

- Thermal insulation capacity of leather and carpentry wastes was evaluated.
- Wastes were used as filling and separation materials.
- Effect of weight/volume ratio and moisture content was investigated.
- Waste materials reduce considerably the heat transfer especially in dry state.
- Leather and carpentry wastes can compete with other classical insulating materials.

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ABSTRACT

This research work is focused on analyzing the potential application of two leather wastes (wet-blue chrome shavings (CS) and leather buffing dust (BD)) and two carpentry wastes (wood shavings (WS) and sawdust (SD)) as alternative building thermal insulation materials. These industrial solid wastes are used as filling materials for hollow specimens and as separation material for cement/sand panels and plasterboards. It was experimentally investigated *the effect* of weight/volume ratio and moisture on thermal conductivity of composite specimens and material wastes. It was shown that conductivity increases with the increase of moisture content. Thermal conductivity of dry material wastes deposited between plasterboards and cement boards was then evaluated. The thermal conductivity measurements show clearly that these industrial solid wastes can compete with other insulating materials.

1. Introduction

Buildings are large consumers of energy in all countries. An effective way of saving energy is to improve the thermal insulation of buildings. This is particularly important in hot and cold climates where the energy demand is very high. The thermal insulation is needed in order to reduce the final energy consumption in buildings and to contribute to the use of unconventional regenerative sources of energy for a sustainable development [1]. The use of thermal insulation in buildings helps in extending the periods of thermal comfort without reliance on mechanical air-conditioning especially during interseasons periods [2,3]. One technique for reducing the demand of air conditioning is to apply thermal insulation in walls and roofs [4].

The continuous search for better sustainable and economic processed solutions has been the center of the attention of a broad research community worldwide [5]. Development of new thermal insulation materials requires knowledge of the thermo-physical properties of the material. Many scientific groups have oriented their research to study the thermophysical properties of lightweight construction materials and of various products such as recycled cellulose from waste packaging and paper [6,7], wood [8,9], cork [10], natural pozzolan [11], silica aerogels [12], rubber waste particles [13], mud [14], corn peel [15], sewage sludge ash [16], textile subwaste [5], straw [17], polyethylene (PET) bottle and automobile tire pieces [18], waste polystyrene [19], woven fabric waste and woven fabric subwaste [20], and recycled plastic waste [21]. The thermal conductivities of ordinary heat insulating materials range from 0.034 to 0.173 W/m K [22].

High amount of solid wastes is produced by industries. Increased restrictions on land disposal, recent increases in the costs of land disposal and decreases in the number of disposal sites

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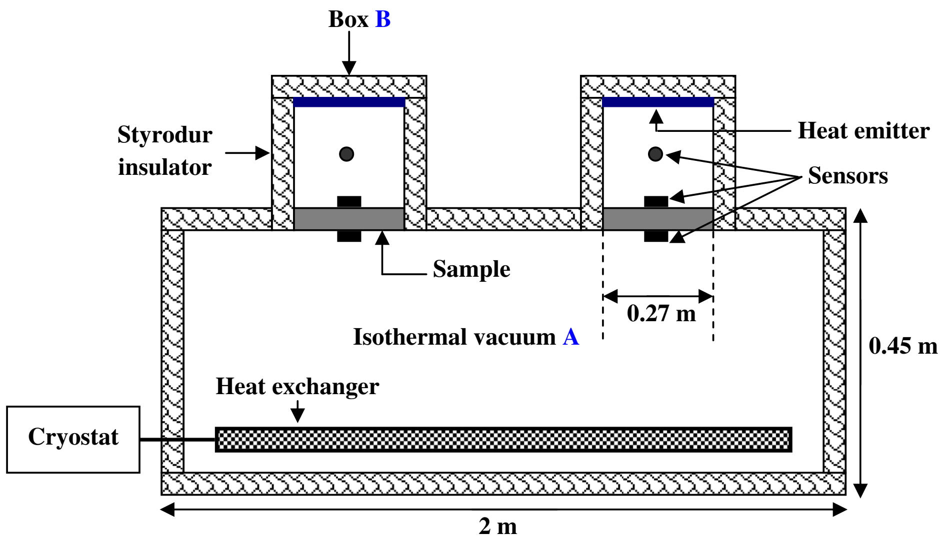

Fig. 1. Schematic presentation of the device for thermal conductivity measurement.

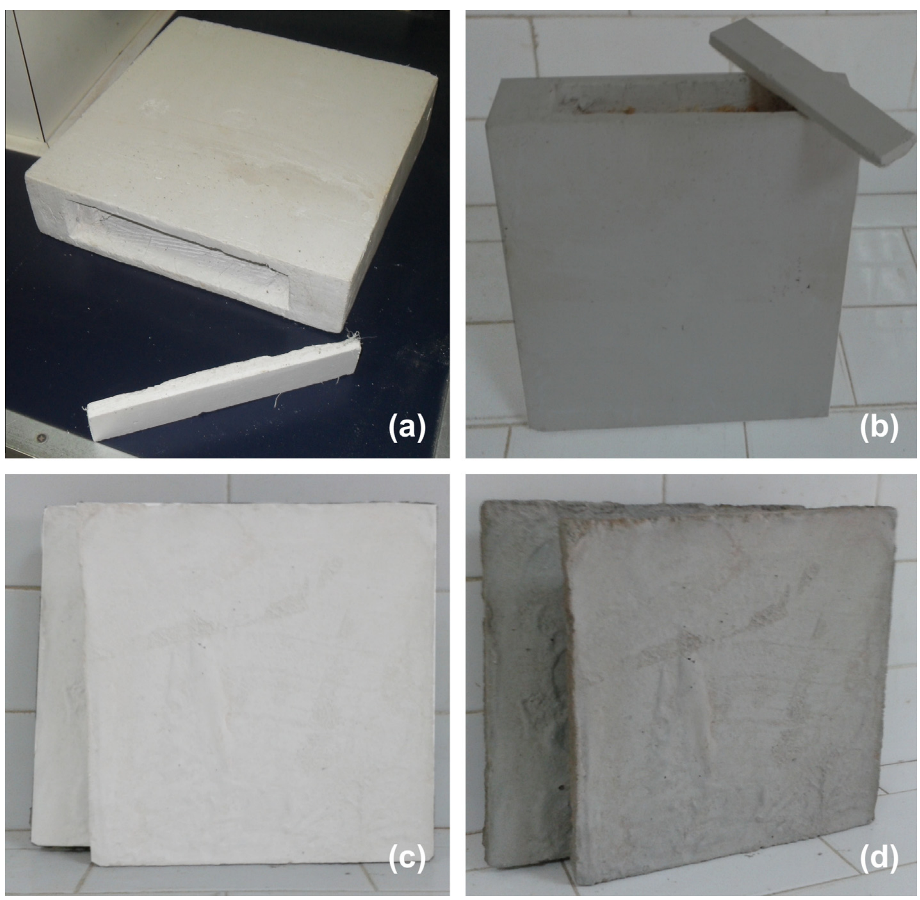

Fig. 2. Photos of hollow specimens and separated panels: (a) HSP: Hollow Specimen of Plaster, (b) HSC: Hollow Specimen of Cement/Sand (25/75), (c) plasterboards, and (d) cement/sand boards.

have combined to spur research into alternative treatments. The reuse of different types of waste can contribute significantly to sustainability. The main objective of this research work is to analyze the potential of using leather wastes (wet-blue chrome shavings and leather buffing dust) and carpentry wastes (wood shavings and sawdust) as an alternative building thermal insulation materials.

2. Materials and methods

2.1. Materials

2.1.1. Tannery solid wastes

Chrome shavings (CS) and buffing dusts (BD) generated by the leather processing industries were used in this study as raw materials. Chrome shavings are small pieces of leather shaved off when the thickness of wet blues is rendered uniform by

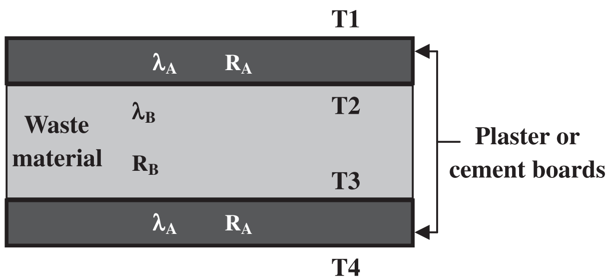

Fig. 3. Schematic presentation of multilayer composite material.

a bladed cylinder. The wet blue is the wet chrome tanned leather, without dressing. Buffing dusts are generated after treating the surface of leather by abrasion [23]. Wastes of chromium tanned leather primarily consist of chromium and proteins. These wastes are durable, stable and not subject to putrefaction. The biological stability of material is the result of complexation between chromium (III) salts and the carboxyl groups of the collagen.

The samples were collected from a commercial tanning unit in Mohammedia (Morocco). Tanned leather wastes were dried in open air and stored in sacks of plastic at room temperature before using. The moisture content of chrome shavings and buffing dusts, calculated from the sample weight before and after drying at 105 °C, is about 20%. According to the previous works of Tahiri et al. [24], leather wastes have an important percentage of proteins (78–79%) and chromium (3.0–3.3%). The density of CS and BD is 0.31 g/cm^3 and 0.27 g/cm^3, respectively.

2.1.2. Carpentry wastes

Wood shavings (WS) and sawdust (SD) are waste products resulting from wood processing. Wood shavings are produced using an automatic molding machine. Sawdust or wood dust is a by-product of cutting, grinding, drilling, sanding, or otherwise pulverizing wood with a saw or other tool; it is composed of fine particles of wood. The samples were collected from a carpentry workshop in Mohammedia (Morocco). The moisture content of WS and SD is about 11.6% and 11.1%, respectively. The density of WS and SD materials is about 0.096 g/cm^3 and 0.236 g/cm^3, respectively.

2.2. Analysis

Chrome shavings, buffing dust of leather and wood shavings were analyzed by ATR-FTIR with a Bruker Tensor 27 (Billerica, USA) from 4000 to 550 cm^{-1} with a resolution of 4 cm^{-1} using 25 scans for both sample and background.

Thermal analysis of solid wastes tested in this work was conducted using a simultaneous DSC-TGA analyzer (SDT Q600, TA Instruments) which provides simultaneous measurement of weight change (TGA) and true differential heat flow (DSC) on the same sample. The heating rate was at 5 °C/min under air atmosphere.

Observations of structure and morphology of material wastes were made using FEI Quanta 200 environmental scanning electron microscope (ESEM).

Percent moisture content is measured as the weight lost during drying the sample for 24 h in a 105 °C oven. The moisture content was determined using the following equation:

$$\text{Moisture } (\%) = \frac{W_w - W_d}{W_w} \times 100 \tag{1}$$

where W_W is the wet weight of the sample and W_d is the weight of the sample after drying.

2.3. Thermal conductivity measurement

Thermal conductivity measurements were conducted using the box method (DELTALAB, Sweden). This method is based on steady-state heat transfer. The apparatus used is an isothermal enclose with an exchanger R at its base, which contains water with glycol maintained at low temperature (about 5 °C) by a cryostat. The isothermal vacuum A is strongly isolated by means of the Styrodur insulator. Each box B has a heater and there are two environments above and below the sample. The sample of the material to be tested is put between the box B and the volume A in such a way that side flows are negligible. The dimensions of a sample were 27 × 27 cm^2. The simplified scheme of the apparatus used is shown in Fig. 1. When the permanent regime is established, the expression of thermal conductivity is deduced as follows:

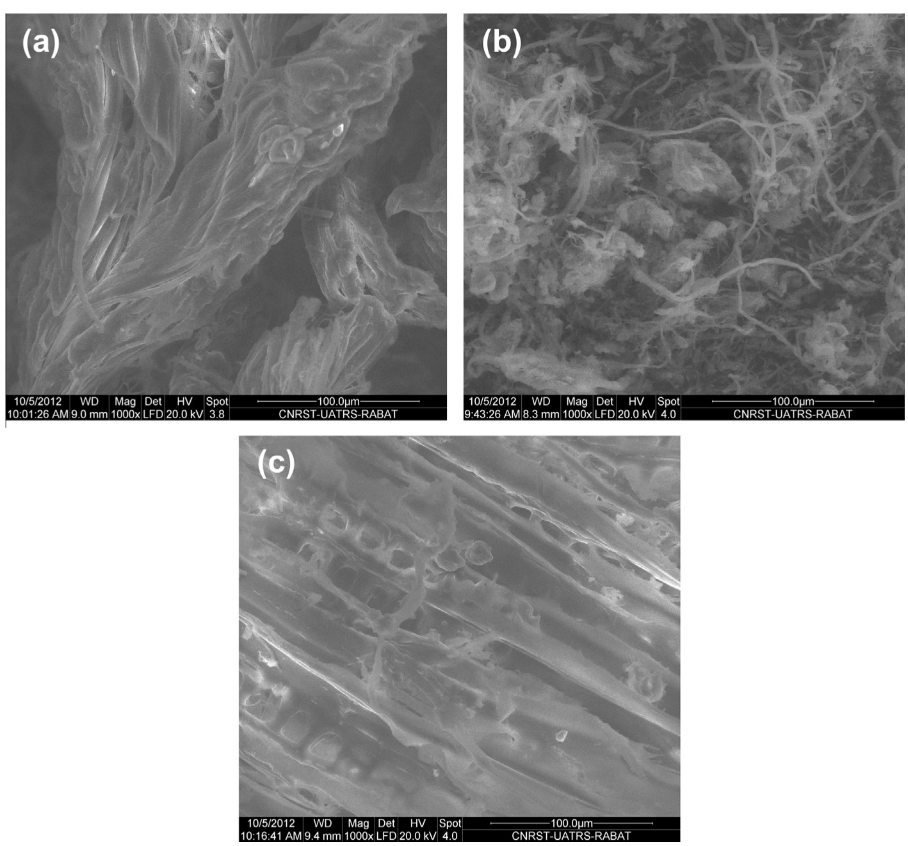

Fig. 4. Scanning electron micrograph of: (a) chrome shavings, (b) buffing dusts, and (c) carpentry wastes.

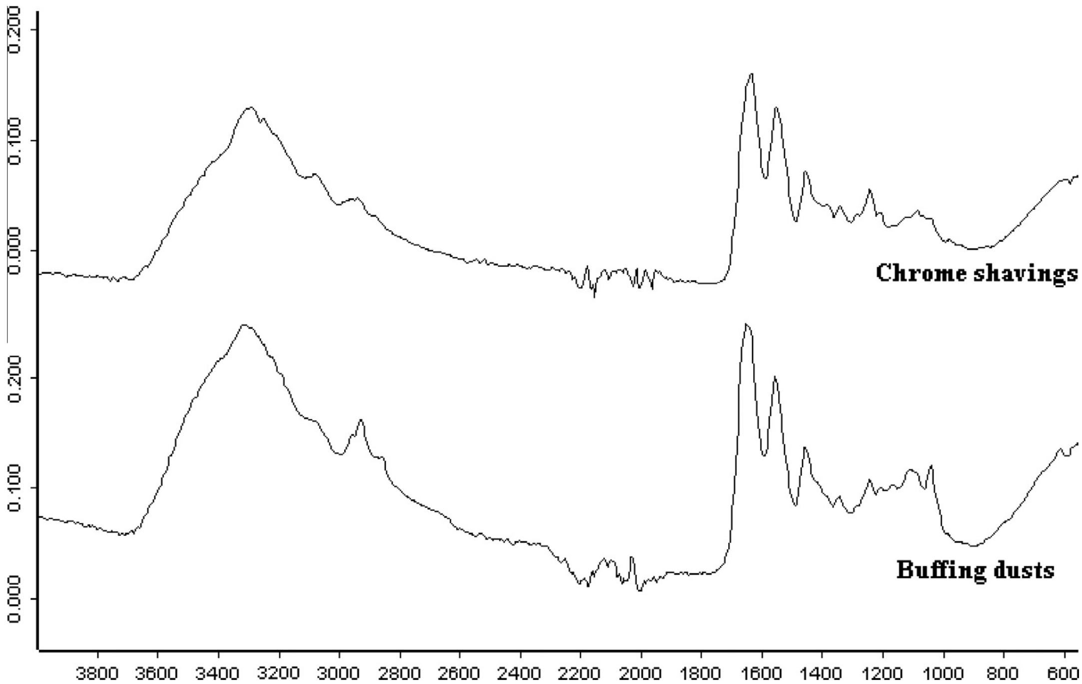

Fig. 5. Infrared spectra of chrome shavings and buffing dusts.

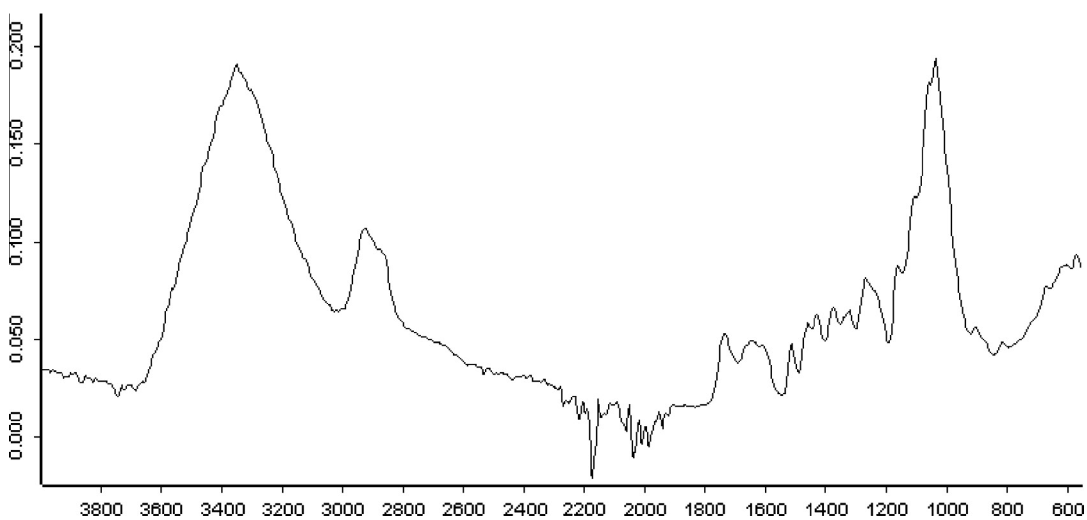

Fig. 6. Infrared spectra of carpentry wastes.

Table 1
Thermal analysis TGA-DSC of tested materials.

Material	Before 200 °C Evaporation of moisture Endothermic phenomenon Losses of mass (%)	After 200 °C Thermo-oxidation/decomposition process Exothermic phenomenon Losses of mass (%)
Chrome shavings	20.0	72.0
Buffing dusts	17.5	72.4
Carpentry waste	12.0	86.0

$$\lambda = \frac{e}{S * (T_h - T_c)}[q - C(T_b - T_a)] \quad (2)$$

q is the heat flux emitted by joule effect, λ the thermal conductivity (W/m°C), e is the thickness of sample, S the sample area (27×27 cm^2), C the coefficient of thermal loss from the box (0.16 W/°C) [25], T_h the temperature of hot surface sample (°C), T_c the temperature of cold surface of sample (°C), T_b the inside temperature of box (°C) and T_a is the room temperature experiments (°C).

Chrome shavings, buffing dusts of leather, wood shavings and sawdust were tested in this work in two ways:

(i) Firstly, as filling materials for hollow specimens (Surface 27×27 cm^2, internal vacuum volume 1250 cm^3). The three lateral sides of hollow materials are immobile and form the junction between two boards (Fig. 2a and b). After manually filling of hollow specimens with CS, BD, WS or SD, the fourth lateral side can be placed and fixed to the other

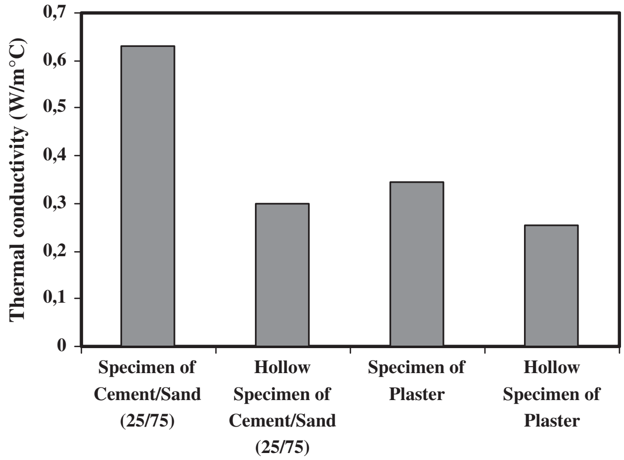

Fig. 7. Thermal conductivity of plaster and cement specimens and of their hollow form.

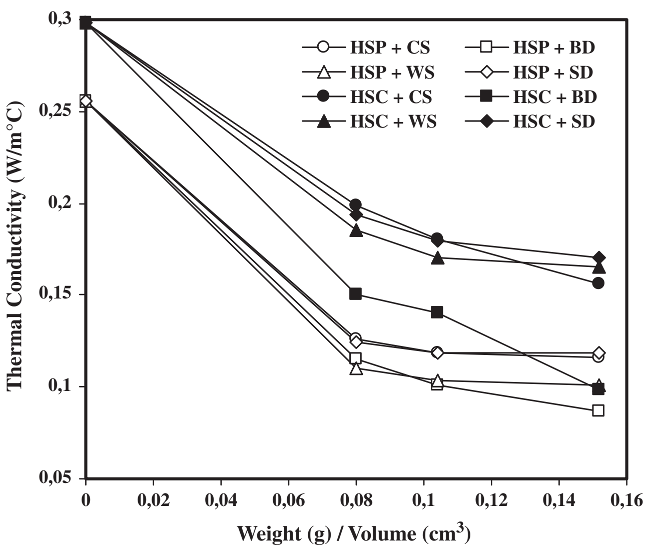

Fig. 8. Thermal conductivity of the hollow specimens filled with different mass of tested wastes. HSP: Hollow Specimen of Plaster; HSC: Hollow Specimen of Cement/Sand (25/75).

elements the manner to ensure a good seal between the inside and the outside of the specimens. Two types of hollow specimens are used: the first is made from cement and sand (25/75), and the second from plaster. Chemical characteristics of cement, sand and plaster are presented in our previous work [26].

(ii) Secondly, as separation material for cement/sand (25/75) and plaster panels (Surface 27×27 cm^2, Thickness 1 cm, Distance between boards 2 cm) (Fig. 2c and d). Composed specimens (cement board/waste material/cement board) and (plasterboard/waste material/plasterboard) are used to measure thermal conductivity of CS, BD, WS and SD (see Fig. 3).

In the case of multilayer walls, each layer is defined either by its thermal resistance R (m^2°C/W) either by its thermal conductivity λ (W/m°C) and its thickness e (m). The heat flux density for a composite wall is given by Eq. (3); it is constant throughout the wall in permanent regime.

$$\phi = \frac{T_{int} - T_{ext}}{\frac{1}{h_1 S} + \sum \frac{e_i}{\lambda_i S} + \frac{1}{h_2 S}} \tag{3}$$

h is the individual convection heat transfer coefficient of fluid (W/m^2°C), S the sample area (27×27 cm^2), T_{int} and T_{ext} are temperatures of air in contact with internal and external surface of multilayer composite material, respectively.

Each analysis of thermal conductivity was repeated three times and the results given were the average values. The deviation was less than 5%.

3. Results and discussion

3.1. Scanning electron micrographs

The scanning electron microscopic method is a good technique for showing the structure and morphology of solids. Fig. 4 presents the results of the images obtained from scanning electron micrographs (SEMs). The resulting micrographs (Fig. 4a and b) revealed that leather wastes have a highly organized structure in the form of fibers which are parallel especially in the case of wet-blue chrome shavings. On the other hand, SEM micrographs of carpentry wastes (Fig. 4c) show a highly ordered structure, they are in the form of a multilayer composite.

3.2. Fourier Transform Infrared Spectroscopy

A Fourier transform infrared spectrophotometer (FTIR) was used to investigate the characteristics of leather and carpentry wastes (see Fig. 5). From evaluation of FTIR spectra, the major feature is the band at 3300 cm^{-1} which is mainly associated with the stretching vibrations of N—H groups. The amide I band located at 1660 cm^{-1} arises from the stretching vibration of C=O groups in the proteins. The band located at 1560 cm^{-1} is due to N—H

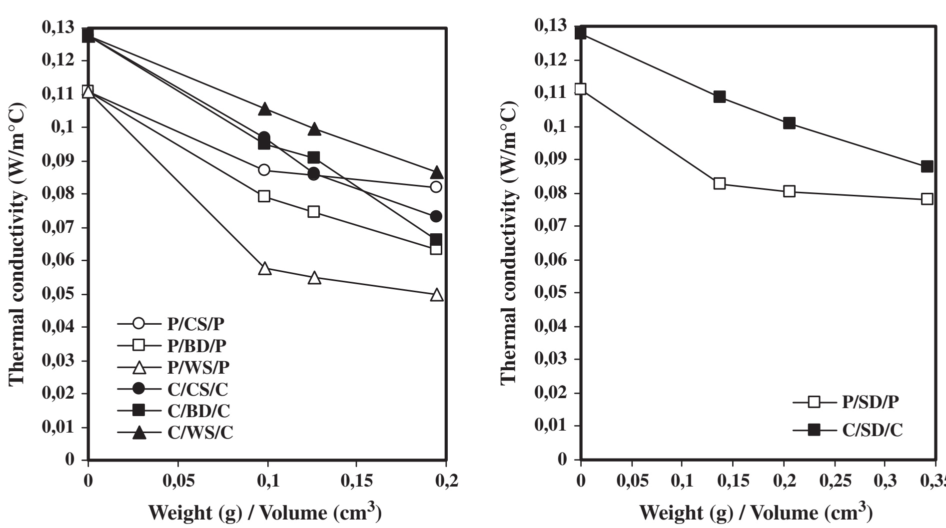

Fig. 9. Thermal conductivity of multilayer composite material as a function of weight of waste/volume ratio. P/CS/P, P/BD/P, P/WS/P, P/SD/P, C/CS/C, C/BD/C, C/WS/C and C/SD/C are composite materials ‘‘panel/waste materials/panel’’; P: Plaster panel; C: Cement/Sand panel (25/75).

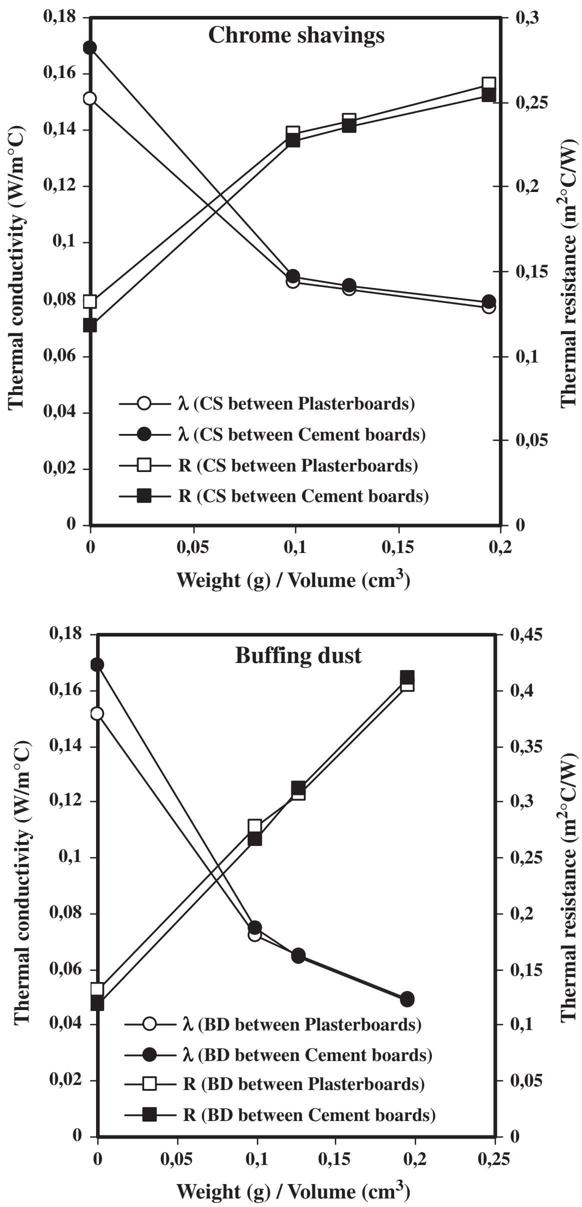

Fig. 10. Thermal conductivity and thermal resistance of raw leather wastes placed between panels.

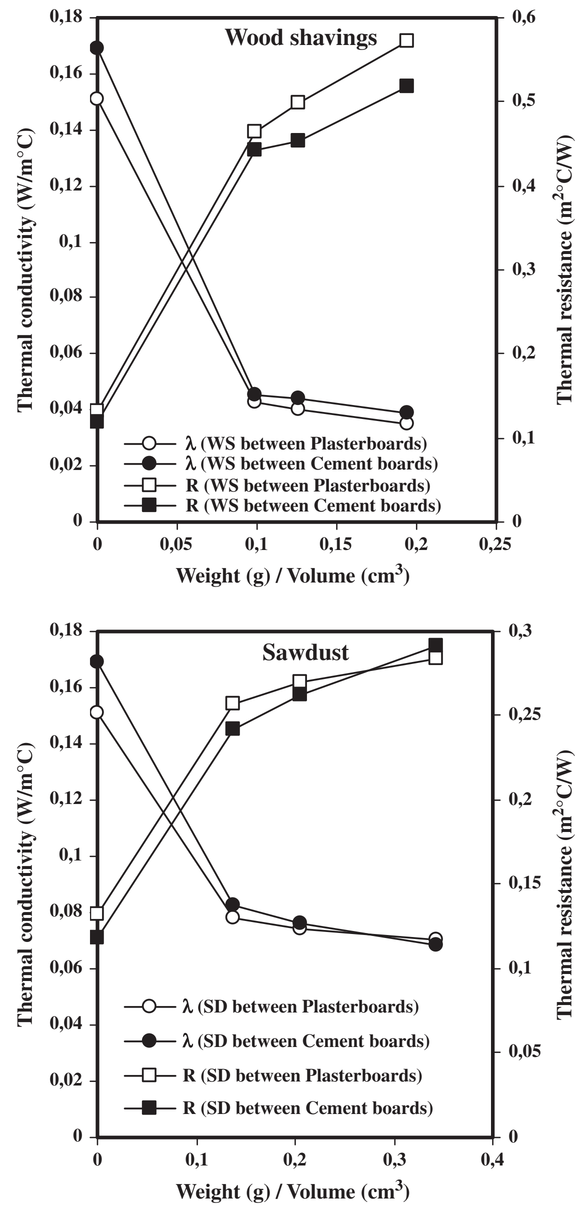

Fig. 11. Thermal conductivity and thermal resistance of raw carpentry wastes placed between panels.

stretching vibration strongly coupled to the C—N stretching vibration of collagen amide groups. The amide III centered at 1240 cm^{-1} is assigned to the C—N stretching and N—H bending vibrations from amide linkages, as well as wagging vibrations of CH_2 groups in the glycine backbone and proline side chains [27,28].

Fig. 6 illustrates the FTIR spectra of carpentry waste. The band at 3400 cm^{-1} is attributed to stretching vibrations of OH. The band at 2800–3000 cm^{-1} is attributed to stretching vibrations of C—H. Obtained spectra show also several distinct peaks in the fingerprint region between 500 and 1750 cm^{-1}. Most of the observed bands of carpentry waste represent major cell wall components and have contributions from both carbohydrates (cellulose and hemicellulose) and lignin [29].

3.3. Thermal analysis of wastes materials

Simultaneous thermal analysis TGA-DSC was used to determine simultaneous changes of mass Thermogravimetry (TG) and caloric reactions Differential Scanning Calorimeter (DSC) of tested samples. The losses of mass observed between temperatures are presented in Table 1. A first period of decreasing mass was registered before 200 °C, and corresponds to the evaporation of moisture. The loss of mass of chrome shavings, buffing dusts and carpentry waste is 20%, 17.5% and 12%, respectively. This first process consists in the loss of physical absorbed water. The corresponding phenomenon is endothermic. A second stage of mass decrease was observed after 200 °C and corresponds to the thermo-oxidation or decomposition process. The corresponding phenomenon is exothermic. The masses of chrome shavings, buffing dusts and carpentry waste were decreased by 72%, 72.4% and 86%, respectively.

3.4. Thermal conductivity study

Fig. 7 shows the experimental thermal conductivity of plaster and cement specimens and of their hollow form. Thermal conductivity of cement specimen, plaster specimen, hollow cement specimen and hollow plaster specimen are respectively 0.63, 0.35, 0.30 and 0.25 W/m°C. As it can be seen, thermal conductivity of hollow specimen is inferior to that of normal specimen because air containing in hollow specimens decreases the heat transfer. Normally, the immobile air has a very low thermal conductivity (0.026 W/m°C) [30] but it is not a good thermal insulator when it is used alone and subjected to convection. For this reason, insulator materials are used to stabilise air and improve consequently the effect of insulation.

The effect of chrome shavings, buffing dust, wood shavings and sawdust as insulator materials is well revealed from the results of measuring of thermal conductivity presented in Fig. 8. As can be seen, these material wastes decrease the thermal conductivity of hollow cement specimen by 61.3%, 71.0%, 66.4% and 61.0%, respectively when 0.152 g of CS, BD, WS and SD are used. On the other hand, the decrease of thermal conductivity of hollow plaster specimen is about 48.0%, 67.2%, 45.0% and 43.3%, respectively by using the same mass of CS, BD, WS and SD.

Leather and carpentry wastes are then tested as separation material for two type of construction panels (27 cm × 27 cm × 1 cm) made from cement/sand (25/75) and plaster. The volume between two panels (1458 cm^3) was occupied by various amounts of material wastes ranging from 0 to 0.2 g/cm^3 in the case of CS, BD and WS, and from 0 to 0.34 g/cm^3 in the case of SD. Difference between these weight/volume ratios is mainly due to the difference between densities of tested materials. Results obtained using the panels separated by leather or carpentry wastes are reported in Fig. 9. The first thing we can see is that, in presence and absence of material wastes, thethermal conductivity of hollow specimen in each case is relatively higher than that of separated panels because heat can be transferred thought the parallelepipedic surface of the elaborated specimens. On the contrary, heat cannot be transferred easily in the case of the separated boards because there is no connection between its parallel surfaces. The panels are well isolated by the styrodur insulator of the apparatus of thermal conductivity measurement. Obtained results show clearly that heat transfer decreases considerably when material wastes are used to separate construction panels. As can be seen, about 0.2 g of CS, BD and WS per cm^3 decreases the thermal conductivity by 43%, 48% and 32.1% respectively in the case of separated cement boards and by 26.2%, 43.1% and 55% respectively in the case of plasterboards. On the other hand, results revealed that about 0.34 g of SD per cm^3 reduces the thermal conductivityof cement boards and plasterboards by 31.1% and 30%, respectively.

In order to determine the thermal resistance (m^2°C/W) and the thermal conductivity (W/m°C) of each material waste, the systems "panel/material waste/panel" were considered as multilayer composite materials. Thermal conductivity of each type of panel was first measured and then thermal properties of leather and carpentry wastes were calculated. Obtained results show that the thermal

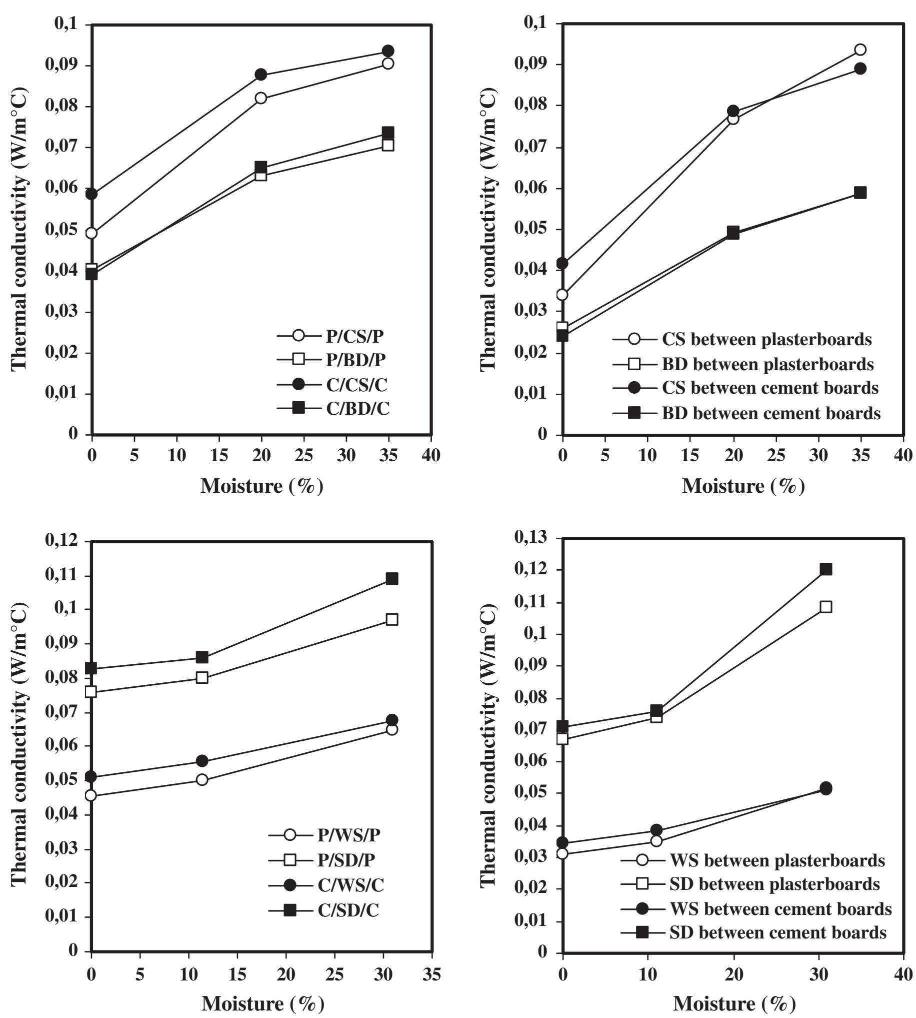

Fig. 12. Effect of moisture on thermal conductivity of multilayer composite materials and wastes deposited between panels. P/CS/P, P/BD/P, P/WS/P, P/SD/P, C/CS/C, C/BD/C, C/WS/C and C/SD/C are composite materials "panel/waste materials/panel"; P: Plaster panel; C: Cement/Sand panel (25/75).

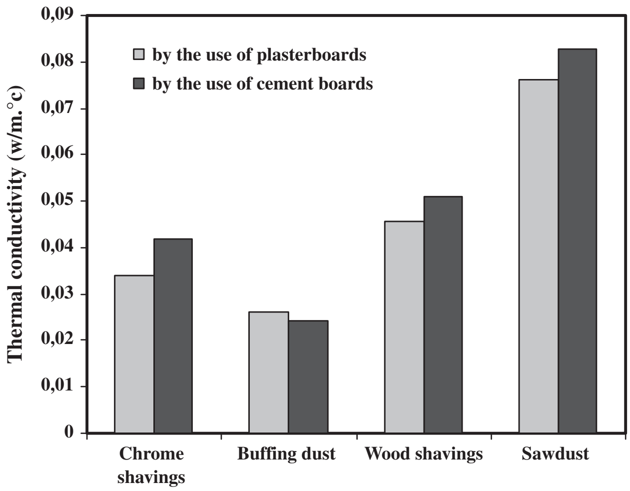

Fig. 13. Thermal conductivity of dry material wastes deposited between plasterboards and cement boards.

Table 2
Thermal conductivity of the materials tested in this work and of a number of common porous insulation materials.

Material	Thermal conductivity (W/m°C)	Reference
Chrome shavings[a]	0.034–0.042	This study
Buffing dusts[a]	0.024–0.026	This study
Wood shavings[a]	0.046–0.051	This study
Sawdust[a]	0.076–0.083	This study
Expanded polystyrene	0.036	[31]
Extruded polystyrene	0.034	[31,32]
Graphite polystyrene	0.031	[31,32]
Polyurethane	0.024	[31,32]
Polyisocyanurate	0.022	[31,32]
Loose-fill cellulose fiber	0.039–0.042	[31,32]
Mineral wool	0.033–0.040	[31,32]

[a] Weight/volume ratio: 0.2 g of dry material/cm^3.

parameters determined using plasterboard are conform to those obtained by the use of the cement board (see Figs. 10 and 11). Thermal conductivity of about 0.2 g of chrome shavings, buffing dust and wood shavings per cm^3 is 0.077–0.079 W/m°C, 0.049 W/m°C and 0.035–0.039 W/m°C, respectively. *The thermal resistance* is *inversely* proportional to the conductivity of each material waste. It is 0.25–0.26 m^2°C/W, 0.40–0.41 m^2°C/W and 0.52–0.57 m^2°C/W. The thermal conductivity and the thermal resistance of sawdust with a weight/volume ratio of about 0.34 g/cm^3 are 0.068–0.070 W/m°C and 0.28–0.29 m^2°C/W, respectively.

All these results show clearly the effectiveness of leather and carpentry wastes as thermal insulators. However, in order to have more representative results the effect of moisture must be taken into consideration. Experimental measurements of thermal conductivity as a function of moisture content from a dry state to 35% in the case of leather wastes and to 30% in the case of carpentry wastes are performed with a weight/volume ratio of about 0.2 g/cm^3. Experimental results show a significant dependence of thermal conductivity on moisture contents (see Fig. 12). When water content of waste materials increases, the thermal conductivity of all composite materials "panel/waste materials/panel" increases also. As it can be seen, thermal conductivity of composite specimens C/CS/C, P/CS/P, C/BD/C, P/BD/P, C/WS/C, P/WS/P, C/SD/C and P/SD/P increases by a factor of 1.6, 1.8, 1.9, 1.8, 1.3, 1.4, 1.3 and 1.3, respectively. On the other hand, thermal conductivity of CS, BD, WS and SD increases by a factor of 2.1–2.8, 2.3–2.4, 1.5–1.7 and 1.6–1.7. In fact, the thermal conductivity of water is 0.60 W/m°C [30], which is more than 20 times higher than of the air. Therefore, if water is present the thermal conductivity increases. Thermal conductivity of 0.2 g of dry waste materials (CS, BD, WS and SD) per cm^3 is 0.034–0.042 W/m°C, 0.024–0.026 W/m°C, 0.046–0.051 W/m°C and 0.076–0.083 W/m°C, respectively. As it can be seen, results obtained by the use of cement panels are in agreement with those obtained by the use of plasterboards (see Fig. 13).

The comparison of thermal conductivity of leather and carpentry wastes with other materials reported in the literature [31,32] is given in Table 2. As it can be seen, the insulation capacity of material wastes, tested in this study, is comparable to that of thermal insulation materials and components which are used in building industry. The thermal conductivity measurements show clearly that leather and carpentry wastes can compete with conventional insulating materials.

4. Conclusion

This experimental study was conducted on the thermal properties of leather and carpentry wastes. The material wastes, tested as filling and separation materials, decrease considerably the thermal conductivity of hollow specimen and separated boards. Overall results indicate that chrome shavings, buffing dust, wood shavings and sawdust have a low thermal conductivity especially when they are used in the dry state. Thermal conductivity of material wastes increased with increasing moisture content. By comparing their thermal insulation efficiency with that of conventional insulating materials, all waste materials tested in this work in their dry form have a good thermal conductivity and can compete with other common porous insulation materials. Due to their availability and properties, leather and carpentry wastes can both be considered as alternative and low-cost insulating materials.

It was conclude that leather and carpentry solid wastes can provide multiple applications in particular to prevent heat transfer and to save energy. In fact, their thermal insulating prosperity is most attractive and indicates a high and promising potential for development.

The purpose of our future work is the simulation of the effect of thermal insulation, by the use of leather and carpentry wastes, in order to predict the thermal behavior of the building with and without insulation.

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