Simplified Method for the Characterization of Rectangular Straw Bales (RSB) Thermal Conductivity

Leonardo Conti¹, Giacomo Goli¹, Massimo Monti¹, Paolo Pellegrini¹, Giuseppe Rossi¹, Matteo Barbari¹

¹Department of Agricultural, Food and Forestry Systems – GESAAF - University of Florence - Via San Bonaventura, 13 – 50145 Florence, Italy
leonardo.conti@unifi.it

Abstract. This research aims to design and implement tools and methods focused at the assessment of the thermal properties of full size Rectangular Straw Bales (RSB) of various nature and origin, because their thermal behaviour is one of the key topics in market development of sustainable building materials. As a first approach a method based on a Hot-Box in agreement with the ASTM C1363 – 11 standard was adopted. This method was found to be difficult for the accurate measurement of energy flows. Instead, a method based on a constant energy input was developed. With this approach the thermal conductivity of a Rectangular Straw-Bale (RSB $\lambda$) can be determined by knowing the thermal conductivity of the materials used to build the chamber and the internal and external temperature of the samples and of the chamber. A measurement metering chamber was built and placed inside a climate chamber, maintained at constant temperature. A known quantity of energy was introduced inside the metering chamber. A series of thermopiles detects the temperature of the internal and external surfaces of the metering chamber and of the specimens allowing to calculate the thermal conductivity of RSB in its natural shape. Different cereal samples were tested. The values were found consistent with those published in scientific literature.

1. Introduction

The straw packaged in rectangular straw-bales (RSB), as it comes directly after the harvesting in the field, is increasingly being used in buildings as a filling element of non-bearing walls in frame structures made of wood and steel. RSB is also used as a constituent element of bearing walls. The latter use has taken a large diffusion worldwide after the publication of the Standard ICC IRC 2015 [1].

The actual possibility to use full size RSB for construction is affected by the lack of knowledge of their physical characteristics. In particular are still unknown their mechanical, thermal, acoustic, fire resistance performances. Currently many studies have been focused on the use of natural materials in buildings, since these materials present high sustainability. Some of these researches, such as [2, 3, 4] were taken as a useful reference in the present research. As regards the use of straw as building material, a large inspiration was drawn by the following studies [5, 6, 7, 8, 9].

From the economic point of view it must be considered that only a minor part of the harvested straw finds profitable uses. One major use is the bedding for livestock farms. Sometimes straw is just abandoned in the field. One of the major problems of straw is the heterogeneity of the material itself because being a biologic material, it's growth depends among others factors by the specie of cereal, by the climatic conditions of the year and by the soil type, The baling process could also affect very much the properties of straw bales. Due to the above mentioned problems and due to the difficulty to resize a
RSB without altering its properties, the purpose of this research was to develop cheap and simple equipment and procedures suitable for the assessment of the thermal performance of full size RSB of various nature and origin in the context of Tuscany Region. To reach this goal, the guidelines of ASTM and ISO standards have been followed to the extent they can be applied.

2. Materials and Methods
For the design of the measurement apparatus for the thermal characterization of RSB the following Standards were adopted and modified in order to be applicable to our samples: ASTM C1363 – 11 [10]; ASTM D 4442 – 92 (Reapproved 2003) [11]; ASTM D 4933 – 99 [12]; UNI EN ISO 8990:1999 [13]. For the measurement of moisture content, the standard EN 13183-1 [14] was used.

2.1. Equipment and measurements
The measuring system is composed by a Metering Chamber (MC) placed inside a Climatic Chamber (CC) working at a fixed temperature. The MC is equipped with heaters and a ventilation system in order to produce a delta temperature. The measurement is done via thermocouples acquired via an acquisition board and the data saved on a PC; MC has an internal dimension of 178 by 112 by 40 mm (figure 1).

Figure 1. – The measurement apparatus of the Metering Chamber in horizontal section (1a) and in vertical section (1b)

The MC is composed by a central body, a removable rear wall and a specimen wrapper on the front. The connections between the walls are glued and assembled with a labyrinth shape, in order to avoid heat leakage. The Specimen Wrapper (WR), designed to contain the specimen, leans out from the front wall. The heating system is placed inside the MC and is contained inside a box working as infrared radiation trap. It avoids the infrared radiation to hit directly on the specimen and also on the MC walls. The internal box presents an inlet and one outlet for proper air ventilation in order to transfer the heat outside the box and inside the metering chamber. The walls of the MC and the WR are made by panels of polystyrene (BASF Styrodur) having nominal thickness of 50 mm. The panels are coupled by means of vinyl adhesive disposed on the entire contact surface to form a 100 mm nominal thickness wall. The typical emissivity of the inner surfaces is \( \varepsilon = 0.93 \), higher than the minimum required by [9] (\( \varepsilon > 0.80 \)).

Polystyrene BASF Styrodur 50 mm thick panel have a 28 kg/m\(^3\) density. The Thermal Conductivity (\( \lambda \)) declared by the manufacturer is \( \lambda = 0.034 \text{ Wm}^{-1}\text{k}^{-1} \) (at the mean temperature of 10 °C, for panels with 20-70 mm of thickness). As a check the value \( \lambda \) of the BASF Styrodur 50 mm thick panel has been measured by means of an instrument Netzsch HFM 436/3/1/E Lambda resulting 0.0338 Wm\(^{-1}\)k\(^{-1}\), very closed to the declared value.
The MC internal ventilation, necessary to ensure uniformity of the temperature inside the MC, is supplied by a ventilation system composed by 5 computer fans having the rated power of 2.28 W. The MC is contained inside a climatic chamber (CC) able to provide a constant temperature and relative humidity in order to produce a constant temperature variation between the MC and the exterior.

In order to calculate λ, the temperatures were measured by 20 thermopiles arranged on the surfaces of the internal and external walls of the MC, of the WR and of the specimen, and by 1 thermopile, arranged around the MC, for the measurement of the temperature of the interior of the CC. Each thermopile consists of several type K thermocouples. The thermopiles are connected to Pico TC08 Datalogger (figure 2).

![Figure 2. RSB specimen prepared for thermal conductivity measurement](image)

2.2. Physical characteristics of RSB specimens

The RSB is a geometrically irregular item: its size and density depends on the species and varieties of cereals used but also on the methods of cultivation and baling process.

A system for the measurement of the RSB geometry was designed and implemented, to determine the volume and the density of the straw bale. For the measurement of the sides lengths 4 “pinwheel” placeable walls have been used, while the height was measured by placing an iron bar on the RSB diagonal, by compressing it with a 25 kg mass and by measuring the height at the extremities. The dimensions defining geometrically a RSB are reported in figure 3. This method allows to preserve the main characteristics of the samples (orientation of fibres, density, etc) obtained from baling process.

![Figure 3 Geometrical description of a Rectangular Straw Bale](image)

Different species of RSB were tested in order to assess the variability of different common species in Italy. The moisture content was determined with the gravimetric method by withdrawing about 100
g of straw from the bales after conditioning at lab internal conditions (an average of 20°C and 55% of RH can be considered) for months. The mass at current state (Mcs) was determined than the sample was completely dried at 103±3°C in order to determine the dry mass. The drying temperature is the same specified for wood by the EN 13183-1 that is considered as the better compromise between rapid drying and thermal degradation of extractives and cell wall. The dry state is consider reached when a mass variation lower than 0.1% of Mcs was attained in two hours. The moisture content was determined according to equation:

\[ MC = \frac{M_{cs} - M_o}{M_o} \times 100 \]  

(1)

Since the RSB have an irregular geometric shape and size, when the bale is placed inside the WR does not completely fill the internal volume. The empty space has been filled with loose straw coming from a bale of the same batch of the one to be tested. An appropriate quantity of straw has been inserted in the empty spaces such that the entire mass of straw inside the WR have the same density of the tested bale. This filling procedure implies a negligible quantity of straw compared to the mass of a bale.

The RSB specimens shall be sealed relating to exchanges of air with the MC and the CC. For this purpose, the two surfaces in contact with MC and with the CC were closed by means of a film of Linear Low-Density Polyethylene (LLDPE) having a thickness of 23 µm and a thermal conductivity =0.33 Wm⁻¹ K⁻¹.

2.3. Calculation of thermal conductivity

The calculations needed to determine the thermal conductivity are reported in this section. All values refer to the Steady State conditions. The abbreviations are reported in table 1:

| Parameters                                      | Abbreviations | Unit of measure  |
|------------------------------------------------|---------------|-----------------|
| MC internal surface area                        | \( A_{mc, in} \) | m²              |
| MC wall thickness                                | \( L_{mc} \)  | m               |
| Sum of all (total of 8) MC interior edge lengths where two walls meet | \( \Sigma e_i \) | m               |
| MC effective area perpendicular to heat flow     | \( A_{mc, eff} \) | m²              |
| MC inside wall surface temperature              | \( t_{mc, in} \) | °C              |
| MC outside wall surface temperature             | \( t_{mc, out} \) | °C              |
| MC wall thermal conductivity                     | \( \lambda_{mc} \) | Wm⁻¹ K⁻¹ |
| MC heat flow                                    | \( Q_{mc} \)  | W               |
| WR inside surface area                           | \( A_{wr, in} \) | m²              |
| WR wall thickness                                | \( L_{wr} \)  | m               |
| Sum of all (total of 4) WR interior edge lengths where two walls meet | \( \Sigma e_{wr, i} \) | m               |
| WR effective area perpendicular to the heat flow | \( A_{wr, eff} \) | m²              |
| WR inside wall surface temperature              | \( t_{wr, in} \) | °C              |
| WR outside wall surface temperature             | \( t_{wr, out} \) | °C              |
WR wall thermal conductivity $\lambda_{wr}$ W·m⁻¹·K⁻¹

WR heat flow $Q_{wr}$ W

Specimen surface area (MC opening area) $A_{sp}$ m²

Specimen Length of the heat flow path $L_{sp}$ m

Specimen inside surface temperature $t_{sp,in}$ °C

Specimen outside surface temperature $t_{sp,out}$ °C

Specimen thermal conductivity $\lambda_{sp}$ W·m⁻¹·K⁻¹

Specimen heat flow $Q_{sp}$ W

Overall heat flow $Q$ W

The energy flow inlet to the MC is the sum of the consumption of the heat source and of the ventilation system. All this energy is converted into heat and, at steady state, passing through the walls of the MC of the WR and through the specimen. All this energy is totally absorbed from the conditioning System of the CC. The energy in input is maintained constant thanks to an appropriate stabilized supply source. By the other side the temperature of the CC is the same for the whole testing period, being $\sim 8^\circ$C ± 0.7 (the average measured temperatures will be used for the thermal conductivity calculations). In these conditions, it can be assumed the amount of heat introduced in the system is constant as well as the heat flow ($Q$), whatever is the specimen material.

Being the value of $Q$ given by the relation:

$$Q = Q_{mc} + Q_{wr} + Q_{sp}$$  \hspace{1cm} (2)$$

where:

$$Q_{mc} = \frac{\lambda_{mc} A_{mc,eff} (t_{mc, in} - t_{mc, out})}{L_{mc}}$$  \hspace{1cm} (3)$$

$$Q_{wr} = \frac{\lambda_{wr} A_{wr,eff} (t_{wr, in} - t_{wr, out})}{L_{wr}}$$  \hspace{1cm} (4)$$

$$Q_{sp} = \frac{\lambda_{sp} A_{sp} (t_{sp, in} - t_{sp, out})}{L_{sp}}$$  \hspace{1cm} (5)$$

The values $A_{mc,eff}$ and $A_{wr,eff}$ have been obtained by applying the relation (A3.2) of the ASTM [10]. The equations (3) and (4) give us the values $Q_{mc}$ and $Q_{wr}$. The overall heat flow $Q$ is known, so the equation (2) give us the value $Q_{sp}$. Now, in the equation (5) we know all values, except $\lambda_{sp}$, that is:

$$\lambda_{sp} = \frac{Q_{sp} L_{sp}}{A_{sp} (t_{sp, in} - t_{sp, out})}$$

In order to determine the RSB thermal conductivity for each specimen, tests were repeated in the same conditions of temperature.

3. Results and discussion

In order to test the correct operation of the measuring system, the thermal conductivity of lambda known reference materials was determined. The results obtained from reference materials shows how the thermal conductivity measured are very close to those reported in the specifications (table 2). These
results allow us to say that the measurement apparatus, even if simplified, is suitable for thermal conductivity determination of materials.

**Table 2. Thermal conductivity of reference materials**

| Material                  | Thermal conductivity declared (W·m⁻¹·K⁻¹) | Thermal Conductivity measured (W·m⁻¹·K⁻¹) | Thickness (mm) |
|---------------------------|--------------------------------------------|-------------------------------------------|----------------|
| polystyrene              | 0.034                                      | 0.035                                     | 103.00         |
| BASF Styrodur polystyrene| 0.034                                      | 0.036                                     | 50.00          |
| polystyrene              | 0.032                                      | 0.033                                     | 30.00          |
| Tecnofoam Wafer          | 0.028                                      | 0.029                                     | 42.00          |
| polyurethane foam        | 0.028                                      | 0.029                                     | 42.00          |
| Craft paper              | 0.028                                      | 0.029                                     | 42.00          |
| poliiso-eco              | 0.028                                      | 0.029                                     | 42.00          |
| MDF                      | 0.12-0.15                                  | 0.0929                                    | 19.00          |

The test results for each RSB are summarized in table 3:

**Table 3 Thermal conductivity of RSB**

| Code   | Cereal kind scientific name | Cereal kind local name | Cereal origin (place) | Density (kg/m³) | Thermal conductivity (W·m⁻¹·K⁻¹) | Moisture content (%) |
|--------|----------------------------|------------------------|-----------------------|-----------------|----------------------------------|---------------------|
| SB_FA01| *Triticum spelta*          | Spelt                  | Calenzano (FI)        | 79.40           | 0.0555                           | 6.2                 |
| SB_GT01| *Triticum vulgare*         | Common Wheat           | Poggio a Caiano (PO)  | 65.60           | 0.0661                           | 5.2                 |
| SB_OR01| *Hordeum*                  | Barley                 | Volterra (PI)         | 90.75           | 0.0603                           | 5.1                 |
| SB_FR01| *Triticum vulgare*         | Frassinetto            | Gambassi Terme (PI)   | 82.06           | 0.0615                           | 6.6                 |
| SB_GD01| *Triticum durum*           | Durum Wheat            | Pisa (PI)             | 85.71           | 0.0653                           | 7.1                 |

The values of the thermal conductivity of the specimens experimentally determined are consistent with values that can be found in the scientific literature, such as those found by Conti [15]. It must be observed that there is considerable variation (about 20% or 0.0106 W·m⁻¹·K⁻¹) between the minimum (*Triticum spelta*) and the maximum value (*Triticum vulgare*) of thermal conductivity. Lower variability values, between 7 and 10%, have been found for the other cereals types. No correlations between thermal conductivity and density of the samples were found and low density values do not match with the high performance conductivity values as reported by [8]. The thermal conductivity of *Triticum vulgare* (Common Wheat) and *Triticum durum* (Durum Wheat) are not compliant to expectations, when compared with the respective density values.

Same considerations can be made regard to moisture; in fact, unlike what is found in the literature, where the conductivity increases with the moisture content for the porous structure of the material, for the specimens tested correlations between two parameters have not been found.
The heterogeneous nature of the material could be the main reason for the high variability in the results as well as the difficulty to measure the sample internal and external surface temperature. For this reason, it seems difficult to find precise thermal conductivity reference values but it could be better to talk about a range of values within RSB could locate their performances.

4. Conclusions
The aim of the research was to develop simple and economic equipment in order to provide sufficiently reliable thermal conductivity values for RSB of various cereal types from Tuscany region. The adopted method, aiming to determine the thermal conductivity of a RSB in its original shape has shown to present some limits in terms of accuracy but was reliable enough to give a range of performances between RSB of different cereal types. The results obtained in this work were found to be comparable with those of other studies carried out on Rectangular Straw Bales.

It should also be specified that these tests were conducted in the laboratory, while future developments should provide an extensive testing program to evaluate the actual performance of a straw wall in the operating conditions.

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