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# Thermal and Mechanical Behavior of Straw-Based Construction: A Review

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## Abstract

Bio-based materials such as straw are becoming a promising alternative to improve the building energy performance and to reduce its carbon footprint. When compared to common building construction materials, bio-based materials control the temperature and the relative humidity variation to ameliorate the indoor comfort with a low embodied energy and CO<sub>2</sub> emission. This paper presents a comprehensive review of the thermal and mechanical properties of straw-based materials and buildings. The objective is to synthesis the work that has been carried out by the research community and to compare the results. The paper first introduces straw bale as a construction material from a historical viewpoint and in the context of the current building sector. The second part focuses on the available chemical and microstructural data of the straw fiber. The third part refers to the thermophysical and mechanical properties of the bales. The fourth part reviews the numerical and experimental studies done at the wall scale. The fifth part describes straw bale construction methods considering the regulation, structure requirements, and life cycle assessment data. Last, a critical analysis of the currently available data on straw as a building material is carried out and pending research issues are discussed. It was found that, despite abundant literature on structural and thermal properties of straw bale constructions, there is still a lack of some information. At a fiber scale, more research should be done to compare straw fibers to other natural and synthetic fibers. At a bale scale, further pH-related research is needed because it affects the material's interior conditions and durability. In addition, a thermal conductivity model for straw should be developed. On a bigger scale, the hygrothermal characteristics of various types of walls must be measured and computed experimentally and theoretically under various exterior and internal situations. More research is needed to improve the sound resistance of the straw wall by adding new layers capable of absorbing acoustic waves. Studies on the energy behavior, cost analysis, and how interior air moisture is self-regulated in straw buildings are needed at the building size. Therefore, a lack of consistent data among the different studies was noted depending on the straw characteristics.

**Keywords:** Straw bale construction, bio-based material, thermal behavior, mechanical properties, life cycle assessment

## Highlights:

- Microscopic structure characterization of straw fibers
- Thermal and mechanical properties of straw bales
- Fire and sound resistance of straw bale walls
- Life cycle assessment of a straw construction
- Energy and economic performance of straw bale buildings

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## Nomenclature

A	Area (m <sup>2</sup> )
AR	Aspect Ratio (-)
ASTM	American Society for Testing and Materials
C	Heat capacity (J/m <sup>3</sup> .K)
CO <sub>2</sub>	Carbon dioxide
C <sub>p</sub>	Thermal capacity (J/kg.K)
ρ	Density (kg/m <sup>3</sup> )
Diff	Thermal diffusivity (m <sup>2</sup> /s)
DVS	Dynamic Vapor Sorption
e	Thickness (mm)
E	Modulus of elasticity (kPa)
EAD	Equivalent Area Diameter (m)
Eff	Thermal effusivity (J/K.m <sup>2</sup> .s <sup>1/2</sup> )
EN	European Norm/standard
EU	European Union
F	Load (kN)
GWP	Global Warming Potential (kg CO <sub>2</sub> equivalent)
g <sub>v</sub>	Flux density (kg/m <sup>2</sup> .s)
ICP-MS	Inductively Coupled Plasma Mass Spectroscopy
IEEP	Institute of European Environmental Policy
L	Sample height (mm)
LCA	Life Cycle Assessment
m <sub>i</sub>	Weight (g)
MBV	Moisture Buffering Value (g/(m <sup>2</sup> .%RH))
MS	Dry matter (%)
MC	Moisture content (%)
p	Pressure (Pa)
PEI	Primary Energy Intensity (J)
RFCP	French association "Réseau français de la Construction Paille"
RH	Relative Humidity (%)
R <sub>w</sub>	The Weighted Sound Reduction Index (dB)
S	Weight of moisture-free cellulose sample (g)
s	Material layer thickness (m)
sd	Vapor diffusion thickness (m)
SEM	Scanning Electron Microscope

t	Time (min)
T	Temperature (°C)
TAPPI	Technical Association of the Pulp and Paper Industry
U	Heat transfer coefficient (W/m <sup>2</sup> .K)
VOC	volatile Organic Compounds
Wash	Weight of ash (g)
W <sub>cellulose</sub>	Weight of cellulose (g)
W <sub>i</sub>	Sound power (W)
W <sub>lignin</sub>	Weight of lignin (g)
W <sub>SE</sub>	Weight of solvent extractive (g)
W <sub>α-cellulose</sub>	Weight of α-cellulose (g)
λ	Thermal conductivity (W/m.K)
μ	Water vapor diffusion resistance factor (-)
δ	Water vapor diffusion coefficient in air (kg/ms.Pa)
ε	Strain (%)
ΔL	Elongation (mm)
σ	Stress (kPa)

## 1. Introduction

Each year, the building sector emits more than 120 million tons of CO<sub>2</sub>, making it one of the key areas in the fight against global warming and a major player in the energy transition [1]. To make the building sector more energy-efficient, strict energy consumption standards should be applied for new buildings. These criteria should require the use of low embodied energy and bio-based products [2]. Wheat, rice, oat and barley straw are examples of bio-based materials that are able to offset CO<sub>2</sub> emissions. The agriculture waste product is a renewable material from local agricultural activities that is considered carbon-neutral [3].

Despite its numerous uses, cereal straw is produced and available in large amounts that is sufficient to produce compressed straw bales. The world produces about 2000 million tons of different straw types per year. In the EU, studies have evaluated the ability of straw to save energy [4]. A study done by the Institute of European Environmental Policy shows that 110 million tons per year of dry straw were produced in 27-member states [5]. For example, France is an agricultural country with about 32 million hectares of useful agricultural area out of the 55 million hectares of the country [6]. This surface decreases each year because of the increase in the population and urbanization. Regarding the cereal production, about 9 million hectares are devoted to it, which allows France to produce 50 to 70 million tons of grain per year where the majority of these grains being wheat. It is estimated that 10% of the straw produced each year would be enough to insulate all the housing built during a year [7–9]. Today, the agriculture field in France is processing approximately 20 million tons of wheat straw, which can supply around 5000 straw bale buildings. There are about 500 new buildings each year, that is constantly increasing [10]. Therefore, if 1% of new buildings were made of straw, it would require 1% of straw production, which is well below the differences in production that may be due to climate or other conditions [11].

Primitive straw houses were built on the African plains since the Paleolithic Era, 3.3 million years ago and the revival of these constructions began more than 100 years ago. The first construction was located in Nebraska (USA) in 1886, because of the lack of wood and other building materials at that time [10]. In France, this mode of construction first appeared in 1920. The interest in this type of construction decreased by the end of the 20th century because of industrialization and the growing interest in new materials. Note that straw, as a structural or as an insulating material, concerns the construction of buildings of all sizes: from single-family homes to multi-store buildings, industrial sheds to public buildings. For example, Walker et al. [12], Mesa and Arengi [13], Ashour et al. [14], and Douzane et al. [15] studied the mechanical and hygrothermal properties of different types of straw constructions. In addition, straw can be added to conventional materials to enhance their mechanical and thermal properties. Amin et al. [16], Agwa et al. [17], Saad et al. [18], Heniegal et al. [19] and Amin et al. [20] studied the effects of the nano cotton stalk, palm leaf ashes, straw, banana, and palm leaf on the concrete.

Since the development of these structures, numerous studies have been conducted which reflect the importance of straw construction. Based on Google Scholar statistics, the number of articles containing straw as a construction material in their titles and abstracts is increasing. **Figure 1** shows the trend of publications about straw bale construction from 1990 until 2020. It can be noted that the majority of papers are experimental concerning the thermal, mechanical, and hygrothermal properties. From all the noted articles, about 70% have been carried out by university laboratories, and the rest have been done in collaboration between companies and universities. **Figure 2** presents the distribution of articles over the world. This statistic shows that about 50% of the total published articles worldwide on straw bale construction come from France, the UK, Italy, and the USA. Since authors of some articles come from different countries, the total number of studies in **Figure 1** and **Figure 2** is greater than the total number of articles collected and cited in this paper.

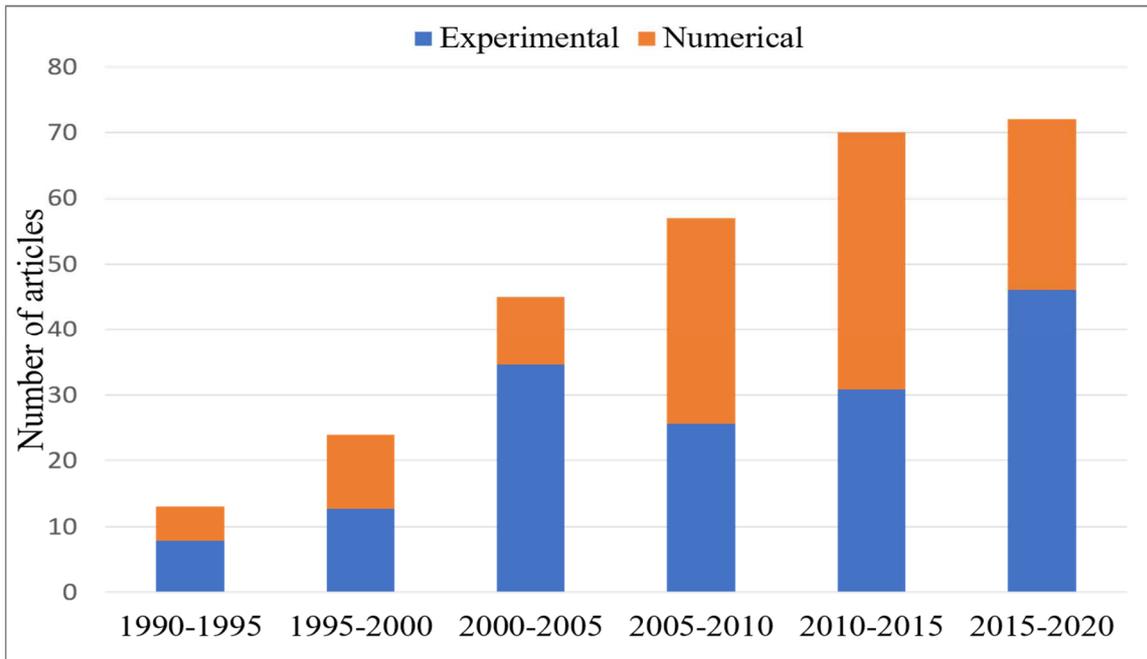


Figure 1: Experimental and numerical articles between the years 1990 and 2020

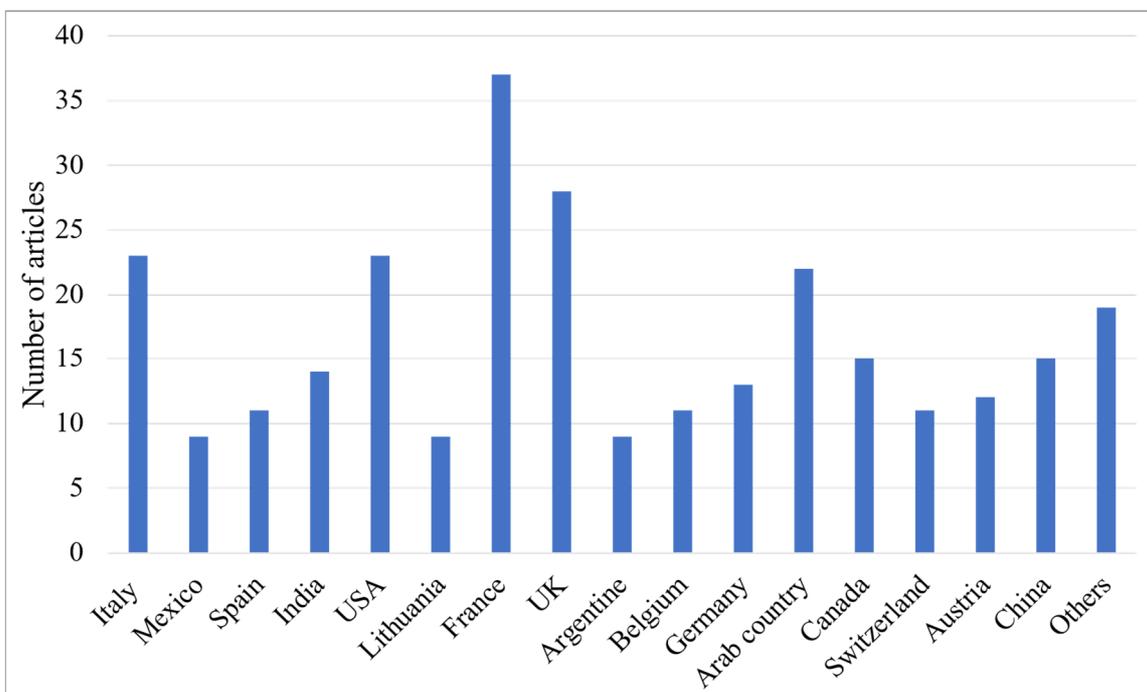


Figure 2: Number of articles done worldwide between the years 1990-2020

The present paper aims to provide a review of the existing academic literature and industry practice on straw-based construction. First, it reports investigations on the microscopic structure and chemical composition of the straw material. Then, researches on the straw bales are detailed with a focus on bale's density, porosity, thermal conductivity, capacity, effusivity, diffusivity, water vapor diffusion, load-deformation mechanical properties and PH measurements. At wall scale, works regarding the hygrothermal behavior, fire resistance, acoustic performance and environmental impact of straw-based envelopes are presented. The existing literature on a full-scale straw building is discussed next, from the viewpoints of construction systems, regulations, and energy behavior. In the synthesis section, the main findings of the existing literature are critically assessed and, more importantly, the needed future research directions are outlined to fill in the gaps in the existing knowledge.

## 2. Fiber scale

### 2.1. Microscopic structure

Many types of researches are recently carried out on straw fibers in its various forms of wheat, barley, oats, or other plant aggregates [21]. It can be explained by the common worldwide cultivation of the straw [22]. **Figure 3** shows an example of chopped straw fibers prepared to be investigated by Laborel-Preneron et al. [23].



Figure 3: Sample of straw fibers [23]

To determine the size distribution and morphology (width and length) of fibers, Laborel-Preneron et al. [23] used and analyzed ImageJ software. Only limited numbers of non-spherical fibers are appropriate for this method, [24-26]. The fibers were coated with an evaporated gold layer on a metal substrate to observe them under vacuum with a 15-kV accelerating voltage. The data, in the form of a contrasting scanned picture of the particles on a black background, enabled for the estimation of the straw fibers' length and width. These two dimensions allow the calculation of the aspect ratio ( $AR$ ), and the Equivalent Area Diameter ( $EAD$ ). The  $AR$  is calculated by dividing the length by the width. Its value determines whether the fiber is short (near 1) or long (greater than 1). The  $EAD$  of a circular cross-section fiber can be calculated by equation (1). **Table 1** shows the average values of the barley fiber diameters,  $EAD$ , and  $AR$ , as well as their deviations. It can be noticed that the fibers are long because  $AR$  is 4.1 mm (greater than 1).

$$EAD = \sqrt{\frac{4 * A}{\pi}} \quad (1)$$

where  $A$  is the area of the particle section in  $m^2$ .

Table 1: Dimension of Barley fibers [23]

Dimension	Barley straw
Major (mm)	$7.6 \pm 4.4$
Minor (mm)	$2.3 \pm 1.5$
$EAD$ (mm)	$4.0 \pm 2.1$
$AR$	$4.1 \pm 3.7$

The straw length and distribution inside a bale are very important to figure out its properties. Short fiber exhibits some advantages in comparison with the long continuous fiber, like quasi-isotropic mechanical properties. According to Ashour and Wu [27], the barley straw fibers provide better mechanical properties than wheat since the majority of fibers are short. The proportion of straw fibers

less than 2 mm long is around 95% for barley and 76% for wheat with the remainder ranging from 2 mm to 50 mm for both types.

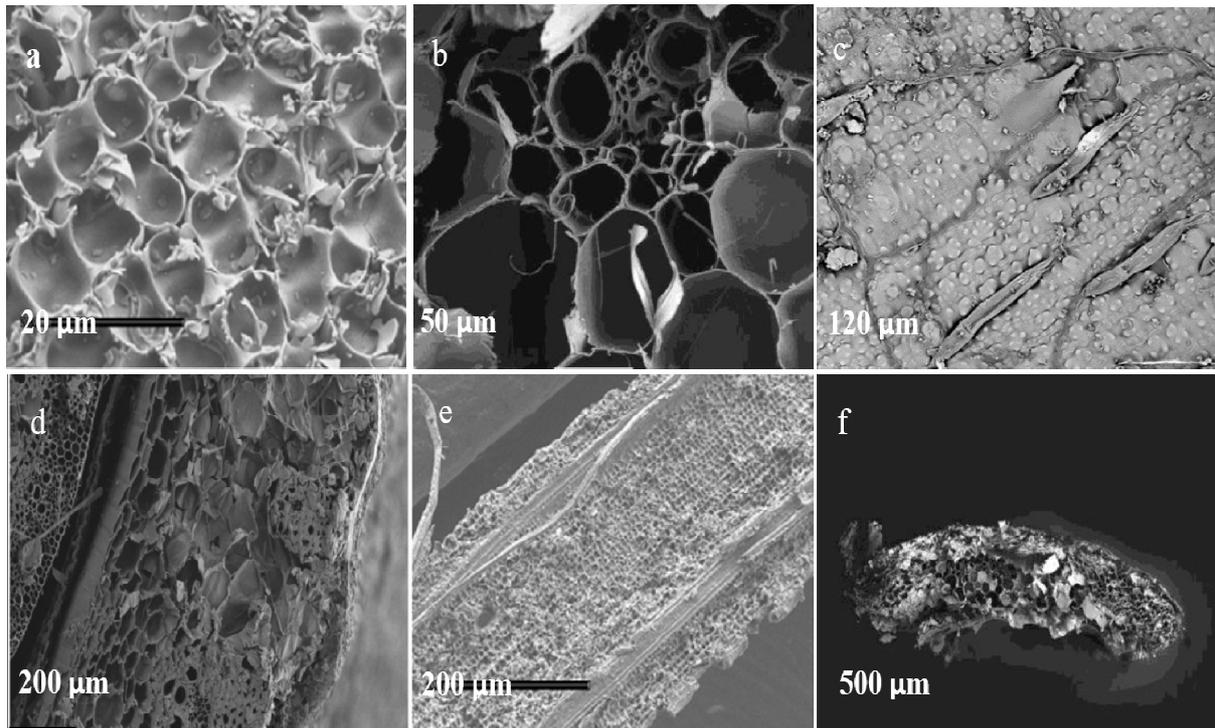


Figure 4: SEM analysis images of the surface of wheat straw (a), (d), and (e), barley straw (b) and (f), and rice straw (c) at low and high magnification factor (based on [23-26])

Laborel-Preneron et al. [23] and Bouasker et al. [25] studied the porous structure and morphology of straw fibers visually using a high resolution of 3 nm Scanning Electron Microscope (SEM). **Figure 4 (b), (c), (d) and (f)** show the microstructures of rice, barley, and wheat straw. The barley and wheat have porous multi-scaled morphologies that vary from 2  $\mu\text{m}$  to 100  $\mu\text{m}$  and 7  $\mu\text{m}$  to 20  $\mu\text{m}$ , respectively, while the rice has an orderly and compact surface. In the context of research studies on medium density fiberboards, Halvarsson et al. [26] performed the morphological analysis of wheat straw by using the SEM images. **Figure 4 (a) and (e)** display the surface of a 0.6 mm long wheat straw fiber with an ash content of 8% and silicon content of 18%. The dimensions of the pores are the same as previously. These complex shapes, according to Halvarsson et al. [26], can contain hydrophobic and inorganic substances like silicon, which delay water absorption.

Such features can have an impact on the heat transfer mechanism in the bale since a porous structure leads to lower thermal conductivity and lower water diffusion factor. This is due to the amount of water a material can hold, which is related to the porosity. In addition, those microstructural analyses give more information about the permeability of the material, which is related to the connection between the pore spaces and the sorption property.

## 2.2. Chemical composition

The chemical composition of straw depends on the location and the type of straw. In France, the French comity [28], *Comité National des co-produits*, investigated the chemical composition of straw, and defined the product as small grain cereals (wheat, barley, oats...), consisting of the rigid lignified stem of the plant harvested at maturity. The results presented in **Table 2** were obtained from a hundred analyses of straw samples. These findings showed that straw contains low water content because the dry matter quantity is 88%. In addition, it can be noticed a high quantity of crude cellulose.

Table 2: Chemical composition of the cereal straw [28]

	Average value	Extreme value
Dry matter (%)	88	85-90

Mineral matter (% MS)	7	5-10
Total nitrogen (% MS)	3.5	2-5
Soluble nitrogen (% N total)	25	20-30
Crude cellulose (% MS)	42	40-50
Calcium (g/kg de MS)	3	2-5
Phosphorus (g/kg de MS)	0.8	0.3-1.5
Magnesium (g/kg de MS)	1	0.5-1.5

The chemical composition gives information about the durability, stability, thermal, and mechanical properties of the material. The moisture content is responsible for the durability. The cellulose component enhances the stability and the thermal insulation [28,29]. The lignin component enhances the mechanical strength property [30] of the material. Moreover, the presence of lignin in high quantities means a high mechanical resistance [30]. Plazonić et al. [31] studied three different types of straw obtained from the continental Croatian field. They determined the organic and inorganic compounds of wheat, barley, and triticale straw samples by applying the isolation methods described in **Figure 5**. To calculate the ash content, the weight of the moisture-free sample  $m_1$  should be measured before any ignition procedure then the sample should be burnt at 525 °C for 3 hours (according to TAPPI T211 om-12) and the obtained mass  $m_2$  should be registered. In addition, the weight of the oven-dry sample  $m_u$  should be measured. After all, the ash content ( $W_{ash}$ ) could be calculated by equation (2).

$$W_{ash} = \left( \frac{m_1 - m_2}{m_u} \right) \cdot 100 \quad (2)$$

Similarly, the solvent extractives content  $W_{SE}$ , the klason lignin content  $W_{Lignin}$ , the cellulose content  $W_{cellulose}$  and the  $\alpha$ -cellulose content  $W_{\alpha-cellulose}$  can be determined by applying the different procedures cited in **Figure 5**. Findings of different types of straw chemical composition are presented in **Table 3**. It can be noticed that wheat straw had a better composition because it had a K-H cellulose content about 48%, a lignin content about 25%, and moisture content about 7%.

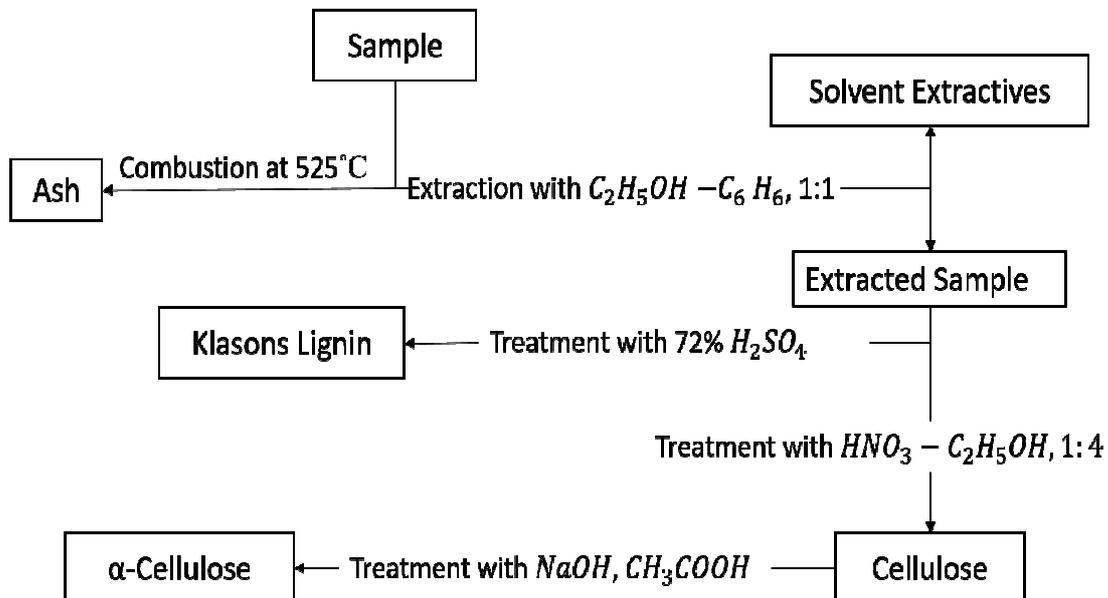


Figure 5: Diagram showing the different steps of the isolation method [31]

Table 3: Organic substance components of wheat, barley, and triticale straw using standard isolation [31]

W, %	Wheat	Barley	Triticale
Moisture	6.94	6.62	7.73

Ash 525 °C	9.27	7.14	5.27
Klason lignin	24.66	21.71	12.59
K-H cellulose	48.28	45.9	52.88
$\alpha$ -cellulose	31.47	37.97	44.22

Table 4: Macro element and ash composition of Wheat, Barley and Triticale straw [31]

Nutrient	Wheat (g/kg)	Barley (g/kg)	Triticale (g/kg)
K	10.34	5.01	13.97
Ca	3.3	3.63	2.77
Mg	1.05	0.66	0.897
P	0.59	1.30	0.48
Zn	0.054	0.18	0.023
Fe	0.047	0.102	0.036
Mn	0.031	0.0015	0.073
Cu	0.004	0.091	0.008
B	0.0035	0.102	0
Al	0.19	0.16	0.032
Bi	0.117	0.15	0.202
Si	0.071	0.147	0.007
Ba	0.042	0.0028	0.053
Cr	0.004	0.013	0.0026
Pb	0.002	0.026	0.003
Ni	0.0016	0.005	0.0024
V	0	0.66	0

Plazonic et al. [31] used the ICP-MS (Inductively Coupled Plasma Mass Spectroscopy) approach to detect the macro elements mentioned in **Table 4**. The process consisted of dissolving the ash obtained from burning the fibers. The burning step to obtain ash helps to remove the organic compounds. Besides, Nicholson et al. [32] reported in a technical report of HGCA (Cereals and oilseeds division of the Agriculture and Horticulture Development Board in the UK) typical quantities of nutrients of straw fibers, as shown in **Table 5**, to study their effect on soil physical properties.

Table 5: phosphate, potash, magnesium, and Sulphur in a different kind of straw [32]

Straw type	Phosphate (Kg P <sub>2</sub> O <sub>5</sub> /t)	Potash (Kg K <sub>2</sub> O/t)	Magnesium (Kg MgO/t)	Sulfur (Kg SO <sub>3</sub> /t)
Wheat (winter)	1.20	9.50	1.30	1.30
Barley (spring)	1.50	12.50	1.20	No data
Oat	1.60	16.70	2.20	No data
Rye	2.10	10.00	1.00	No data
Pea	3.90	20.00	1.70	No data
Bean	2.50	16.00	1.80	No data

It can be concluded that the straw chemical components are affected by the type of soil and climate conditions during the plant growth process. The chemical composition of wheat, barley and rice straw seems to forecast good hygrothermal properties and mechanical strength at the fiber scale with availability in most countries. Further investigations are required to study the hygrothermal and mechanical behavior on a larger scale in the building sector.

## 2.3. Discussion

The investigation on the chemical composition and the microstructure of the straw fibers revealed the size of the pores, the size of the fibers, their distribution, and the percentage of the major molecules and nutrients that produce them that affect the heat transfer mechanism inside the material. From SEM and image analyses, the fibers inside a bale are mainly short (1-2 mm) and extremely porous. Small fibers provide an improvement in bales' mechanical properties when compared to long and continuous fibers. For the chemical structure of various types of straw, it is clear that straw has the same composition as other varieties of wood, including lignin and cellulose. However, more research should be carried out to compare straw fibers to other natural fibers and synthetic fibers. In addition, the microstructural properties of the fibers should be combined with their mechanical and thermal properties. There is still no model of heat transfer in straw porous medium reported in the literature. There is also some absent information concerning the ultimate tensile strength of straw fibers and the fracture toughness that have seldom been measured.

## 3. Bale scale

### 3.1. Density/dimension

The straw bale dimensions, forms [33] and fiber orientation [34] are all conditioned by the hay baler. According to Nicholson et al. [32], the baler channel evolved between the years 1940 and 1980. For large rectangular shapes, the work rate reached 25 tons per hour (45 to 50 bales per hour). Bales can be circular or square, small or large, with two or three strings [35]. **Table 6** shows the various sizes, shapes, and densities of straw bales. It can be noticed from the table that square bales have higher densities than round bales. The density of square-shaped varies from 140 to 160 kg/m<sup>3</sup>, which satisfy the building requirements of many countries, as detailed in section 5.2. Small bales have a length of 40 cm to 110 cm, a width of 46 cm, and a height of 36 cm, according to Wimmer et al. [36]. Whereas large bales have a length of 300 cm, a width of 120 cm, and a height of 70 cm. Bales of significant dimensions (such as rectangular three-string bales) should be used in construction because they create a more stable structure in terms of density and weight.

Table 6: Typical bale size versus density and weight [32]

Bale		Bale size (cm)			Density (kg/m <sup>3</sup> )	Weight (kg)
		width	Height	Length		
Rectangular		40	50	90	117	20
Round	Small	120	150	-	118	250
	Large	150	180	-	103	400
Square	Small	80	90	250	160	280
	medium	120	90	250	160	420
	Large	120	130	275	140	550

Ashour et al. [27] noticed that several factors impact the bale's density such as the water content, the dimensions of the bale, the straw type, and the compressive force applied by the baler. Costes et al. [37] found that standard straw bales can have a relatively large range of density. They measured densities from 74 kg/m<sup>3</sup> to 103 kg/m<sup>3</sup> having thicknesses varying between 30 cm to 49.5 cm. Smaller densities were found by Watts et al. [34] for barley straw bales with values ranging between 54.6 kg/m<sup>3</sup> and 78.3 kg/m<sup>3</sup> and similar densities for both oat and wheat straw bales with values ranging between 81 kg/m<sup>3</sup> and 106.3 kg/m<sup>3</sup>. The baler is also likely to vary the arrangement of fibers inside the bale. The density is an important factor that should be determined before the construction process. It affects the porosity of the material, the thermal properties of the envelope, and the stability of the structures. For example, high density provides low porosity, higher thermal conductivity, and better mechanical stability. Therefore, a compromise between the mechanical and thermal properties should be done to determine an appropriate density.

### 3.2. Porosity

Porosity is referred to the void spaces that permit water and other foreign molecules to pass through. Generally, the natural fibers are considered as porous materials. Straw bales are highly heterogeneous

and porous. The porosity is determined indirectly from the apparent and actual density measurements of the samples. From **Table 7**, it can be noticed that the porosity is related to the density of the material. The total porosities of the manufactured coating (composed of sand, straw fibers, and clay), the industrial coating (composed of aggregates and a mixture of sand and clays supplied in bags) and concrete block are 34.2%, 24.8% and 24% respectively. The wood board has a total porosity of 50% and that of the straw is 93% for densities of 570 kg/m<sup>3</sup> and 100 kg/m<sup>3</sup>, respectively. This last porosity value is slightly higher than 90% that was reported by Wihan [38]. The difference results from an inevitable dispersion of the properties of bio-based materials (different varieties, different culture medium...) and measurement uncertainties (exact measurement of the volume, representativeness of the sample taken, etc.). In addition, the porosity affects the total absorption of the material. The total absorption increases by increasing the porosity. The number and the size of the pores of the material can explain it.

*Table 7: Average hygrothermal parameters of the straw compared to the construction materials (based on [39] and [40])*

Parameters	Straw bale	Concrete	Wood fiber board	Industrial coating	Manufactured coating
Density [ kg/m <sup>3</sup> ]	100	1450	570	2051	1600
Porosity [%]	93	24	50	24.8	30
Capillary absorption [ kg/(m <sup>2</sup> .S <sup>1/2</sup> )]	0.0155	0.003	0	0.068	0.047
Total absorption [%]	203.9	13	17.5	8.8	15.6
Specific heat [J/(kg.K)]	2426	850	2100	750	850
MBV [g/(m <sup>2</sup> .%RH)]	1.853	0.9-1.1	1.929	--	--

Therefore, the porosity of the straw bale affects its long-term durability and stability due to the water and vapor adsorption. Yin et al. [41] tested specimens of rice and wheat straw using the DVS (Dynamic Vapor Sorption) method and the desiccator method following BS EN ISO 12571:2013. Despite the distinct microstructures of wheat and rice, **Figure 6** shows no major deviation between the sorption and desorption isotherm of both straw types. This finding explains the fact that the straw microstructure is not directly related to its water sorption property. Straw behaves as a hygroscopic material in general, that passes through five stages during water absorption. It begins by single layers adsorption and ends by a super saturation state. The difference between the sorption and desorption curves is caused by the quantity of water vapor trapped by the pores during the desorption phase.

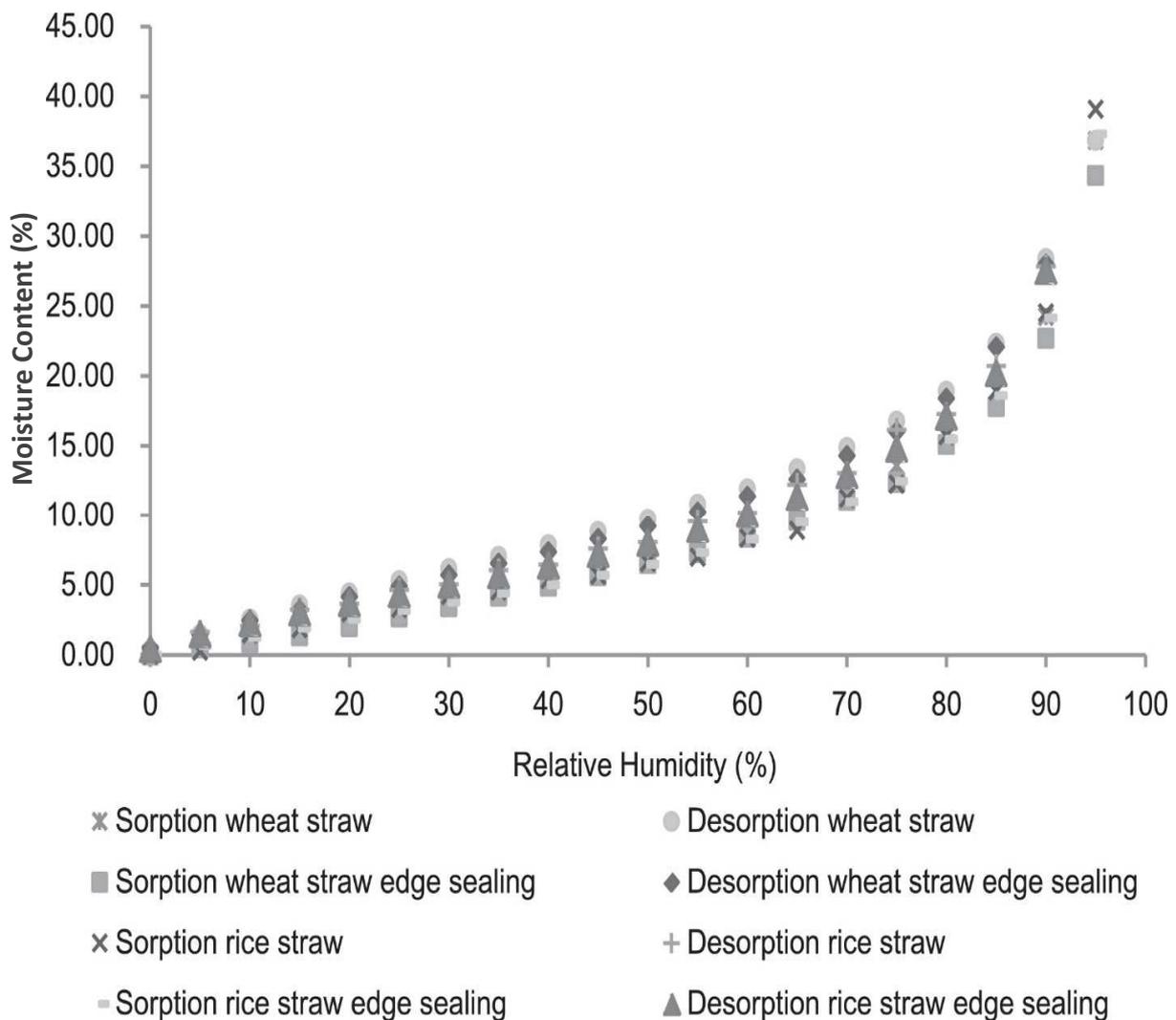


Figure 6: The variation of the RH and moisture content showing the sorption and desorption isotherm of wheat and rice straw [41]

### 3.3. Thermal conductivity

Thermal insulation represented by the U-value refers to the use of materials to reduce the rate of heat transfer. Barley, wheat, rice, and oats straw bales have excellent thermal insulation properties that can improve the building energy consumption. Generally, the straw constructions are done by piling straw bales alone in the walls and by using wooden beams for a load-bearing purpose [27]. The available literature showed that the thermal conductivity of straw bales varies with its density, moisture content, and fiber orientation. McCabe [35] investigated the thermal conductivity of two wheat straw bales; one with vertical fibers and the other with horizontal fibers. He used the hot guarded plate device for samples having densities of  $133 \text{ kg/m}^3$ . The measured values of thermal conductivity were  $0.046 \text{ W/m.K}$  for the first case and  $0.061 \text{ W/m.K}$  for the second case. Ashour and Wu [42] [27] used the same method to detect the variation of the thermal conductivity by varying the temperature and the density respectively on two different straw types: the wheat, and the barley. The considered sample was 60 cm long, 38 cm wide, and 36 cm high in both cases. **Figure 7** presents the thermal conductivity variation of wheat and barley straw bales at different temperature levels for different densities. The thermal conductivity increases when the temperature increases and the density decreases. In both cases, as the density increases, the thermal conductivity drops until reaching a certain value where it stabilizes after which it starts increases. Costes et al. [37] also evaluated the thermal conductivity of 13 samples processed at  $23^\circ\text{C}$  and 50% RH until the measurements with the guarded hot plate method.

**Figure 7** shows the augmentation of the thermal conductivity with the density measured by Costes et al. [37]. It can be noticed that results of Costes et al. [37] are contrary to those of Ashour and Wu [42] [27] that can be due to the non-mentioned orientation by Costes et al. [37]. Researchers completed their study by giving a correlation that can estimate the thermal conductivity as a function of temperature and density for the wheat and barley as shown in **Table 8**. It can be noticed that the straw type didn't affect the thermal conductivity values.

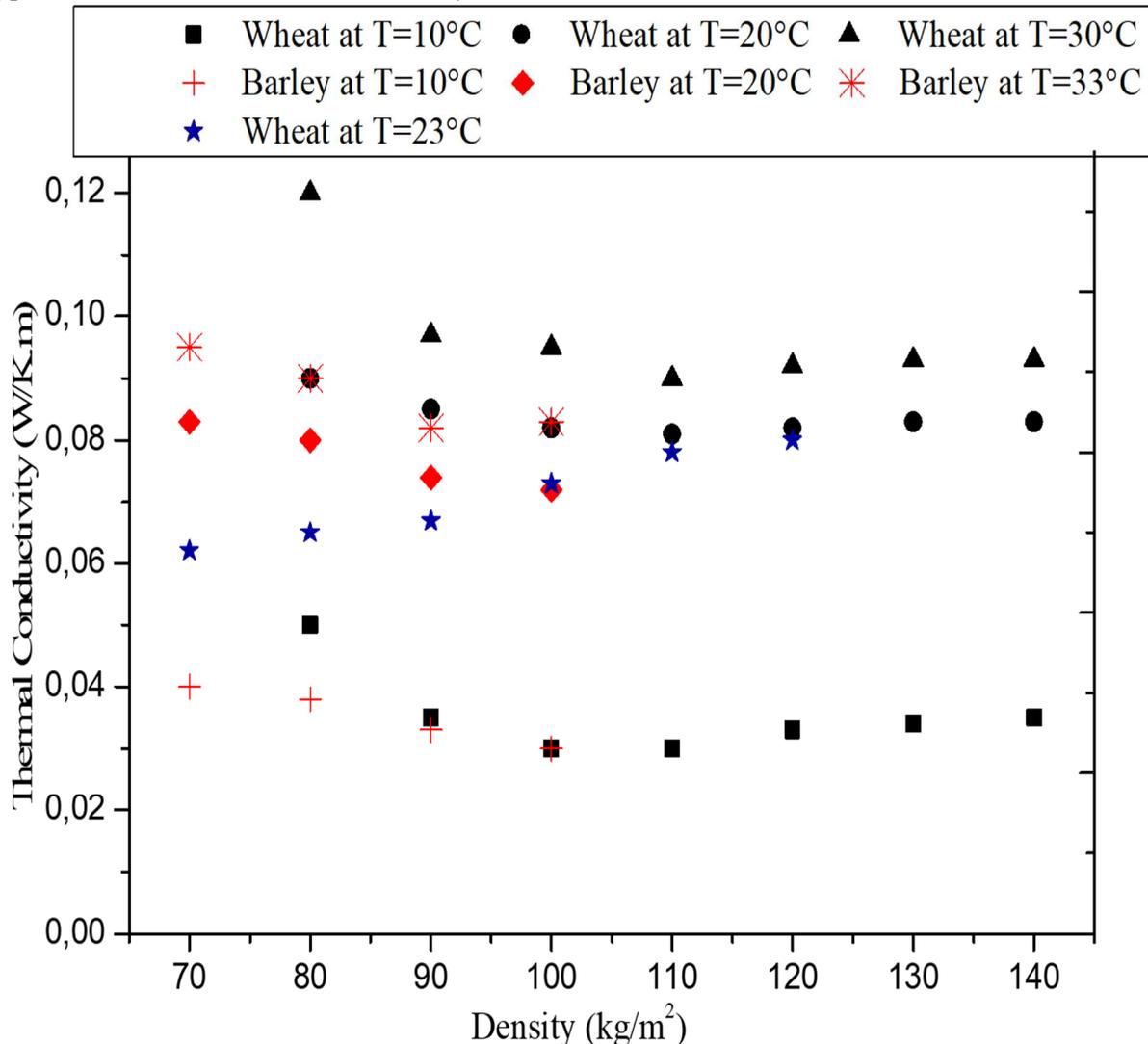


Figure 7: The thermal conductivity data for wheat and barley straw as a function of temperature and density (based on [27], [37] and [42])

Moreover, Shea [43] used a flow meter to assess the thermal conductivity of 25 cm thick samples of straw having varied densities. The measured thermal conductivities increased from 0.059 W/m.K to 0.064 W/m.K as the density increased from 63 kg/m<sup>3</sup> to 123 kg/m<sup>3</sup>. Palumbo et al. [44] analyzed a mix of barley straw (81%) and corn starch (19%) at different RH levels. Results showed that the thermal conductivity of this material was highly affected by RH. It was also noticed that the thermal conductivity rises with the moisture content since the straw is considered a porous material that can absorb water which leads to higher densities. Similar results were obtained for rice straw as reported by the experiment of Sabapathy et al. [45]. The conductivity increased from 0.06 W/m.K to 0.07 W/m.K when the RH increased from 40% to 60% as shown in **Figure 8**.

To assess the effect of the fiber length on the thermal properties, Vejeliene [46] took separately into consideration the orientation and the length of the fibers (chopped straw and defibered straw). The thermal conductivity was better in defibered and chopped straw. In addition, the thermal conductivity increased when the fibers were oriented horizontally and decreased when oriented vertically as shown in **Figure 9**. This may occur due to the variations in air volume and heat flow path. In the horizontal

case, the heat flux passes parallel through the bale via the pores, and the air affects the resistance. In the vertical case, the heat traverses perpendicularly both the air and the wall straw at a large proportion. Therefore, the resistance is provided by the air and the straw walls. Sabapathy et al. [45] and Vejeliene [46] developed correlations for effective thermal conductivity for each type of orientation having specific density, temperature, and RH. The resulting models and their regression equations are shown in **Table 8** in addition to other researches.

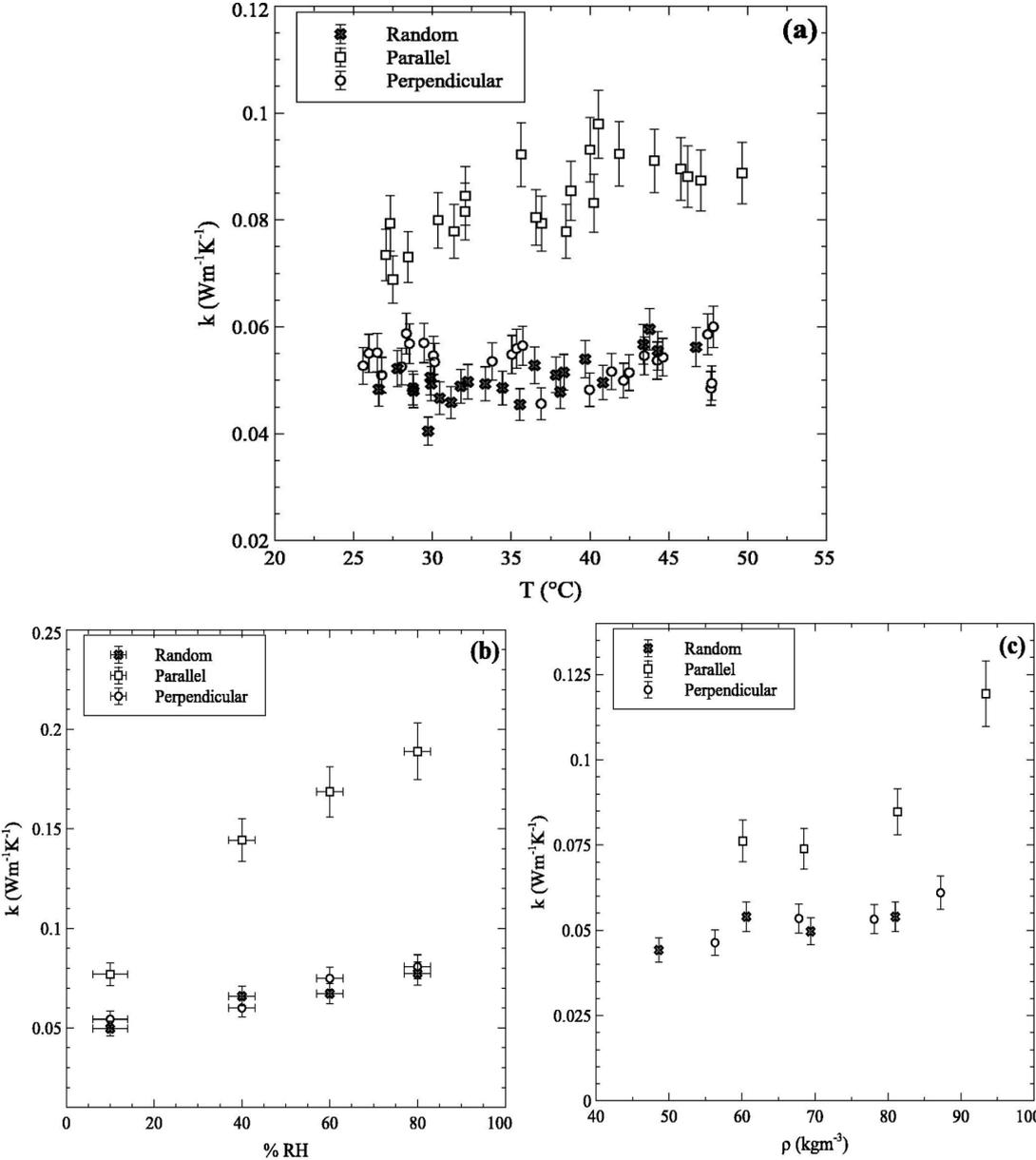


Figure 8: Thermal conductivity for different orientations with respect to (a) temperature, (b) RH, and (c) density [45]

Table 8: Different propositions of thermal conductivity correlations (with  $\rho$  the density,  $t$  the thickness,  $T$  the temperature, and  $RH$  the relative humidity)

Proposed correlation for $\lambda$ (W/K.m)	Considered Conditions	Fiber orientation	Straw type	Ref.
$0.048 + 0.00029\rho - 0.0113t$	The density range was 68-123 kg/m <sup>3</sup> . The temperature was 23°C and 50 % RH.	---	---	[37]
$0.0444 + 0.000272\rho$				
$0.046(1 + 0.009T)$	The density was estimated at 80 kg/m <sup>3</sup> . The experiment was done with a varying temperature between 10 and 40 °C.	Perpendicular	---	[47]
$0.067(1 + 0.0078T)$		parallel		
$0.037 + 0.019(RH)$	The density was 107.5 kg/m <sup>3</sup> . The temperature is 10°C with RH between 10 and 90 %.	---	Barley + corn starch	[44]
$0.09637 - 0.00146\rho + 0.0000107\rho^2$	The density range was 60-120 kg/m <sup>3</sup> . The experiment was done at 10°C and 50 % RH.	Perpendicular	Barley	[46]
$0.10312 - 0.00036\rho + 0.0000175\rho^2$		parallel		
$0.00399 - 0.00023\rho + 0.00269T$	The density range was 82-138 kg/m <sup>3</sup> .	---	Wheat	[42]
$0.0625 - 0.0005\rho + 0.002237T$	The density range was 68-98 kg/m <sup>3</sup> .		Barley	
$-0.0002 \rho^2 + 0.317\rho + 0.315(RH) - 0.042T + 30.794$ [mW/m.K]	The density range was 60-120 kg/m <sup>3</sup> . The temperature varied between 10 and 50°C and the RH 10-90 %.	Perpendicular	Rice	[45]
$-0.0103 \rho^2 + 2.196 \rho + 1.573(RH) + 0.478T - 46.072$ [mW/m.K]	The density range was 45-200 kg/m <sup>3</sup> . The temperature varied between 10 and 50°C and the RH 10-90 %.	Parallel		

Table 9: The thermal conductivity according to the densities and fiber orientations

Year	Authors	Straw type	Moisture content/ Relative humidity MC/RH (%)	Mean Temperature (°C)	Density (kg/m <sup>3</sup> )	Fiber orientation	thickness (+plaster) (mm)	Thermal conductivity (W/m.k)
1993	McCabe [35]	Wheat	MC 8.4%	20	133	perpendicular	419	0.047
						parallel	584	0.06
		Rice			123	Random	450	0.08
1997	CEC/ATI [48]	Rice	MC 11%	23	107	perpendicular	406	0,0811
						parallel	584	0,1471
2003	Ashour [42]	Wheat	----	----	82-138	----	----	0,033
		Barley		----	69-98			0,034
2004	Beck et al. [49]	Barley	----	40	80	perpendicular	22	0.041
	CEBTP [50]	----	RH 50%	23	77	----	----	0.066
2009	FASBA [51]	Wheat	0	----	81-111	perpendicular	----	0,044
					105	parallel		0,067
2011	Vejeliene [46]	Barley	RH 50 %	10	60-120	parallel perpendicular	----	0,0845-
					50-120			
		Barley chopped			35-80	random		0.039-0.045
		Barley defibered			35-80	random		0.037-0.044
2012	Shea et al. [43]	Wheat	RH 50 %	----	63-123	random	300	0,059-0,064
			----	----	115		490	0,087
2015	Wei et al. [52]	Rice	MC 10-18%	30	200-350	----	40	0.051-0.053
2016	Conti et al. [53]	Wheat	MC 12,5%	19	65,7	parallel	530	0,062
			MC 11,5%		84,1			0,07
2017	Gallegos-Ortega et al. [54]	----	RH 10%	25	115	-----	----	0.094
2017	D'Alessandro et al. [55]	----	RH 45%	22	80	----	450	0.052
2019	Cascone et al. [56]	Wheat	MC 8%	35	78	random	20	0.069
2019	Sabapathy et al. [45]	Rice	RH 40 %	30	68	random	---	0,06
						perpendicular		0,057
						parallel		0,15
						random		0,07
			RH 60 %	perpendicular	---	0,08		
		parallel		0,17				
		random		0,07				
		perpendicular		---	0,075			
	RH 80 %	parallel	---	0,19				

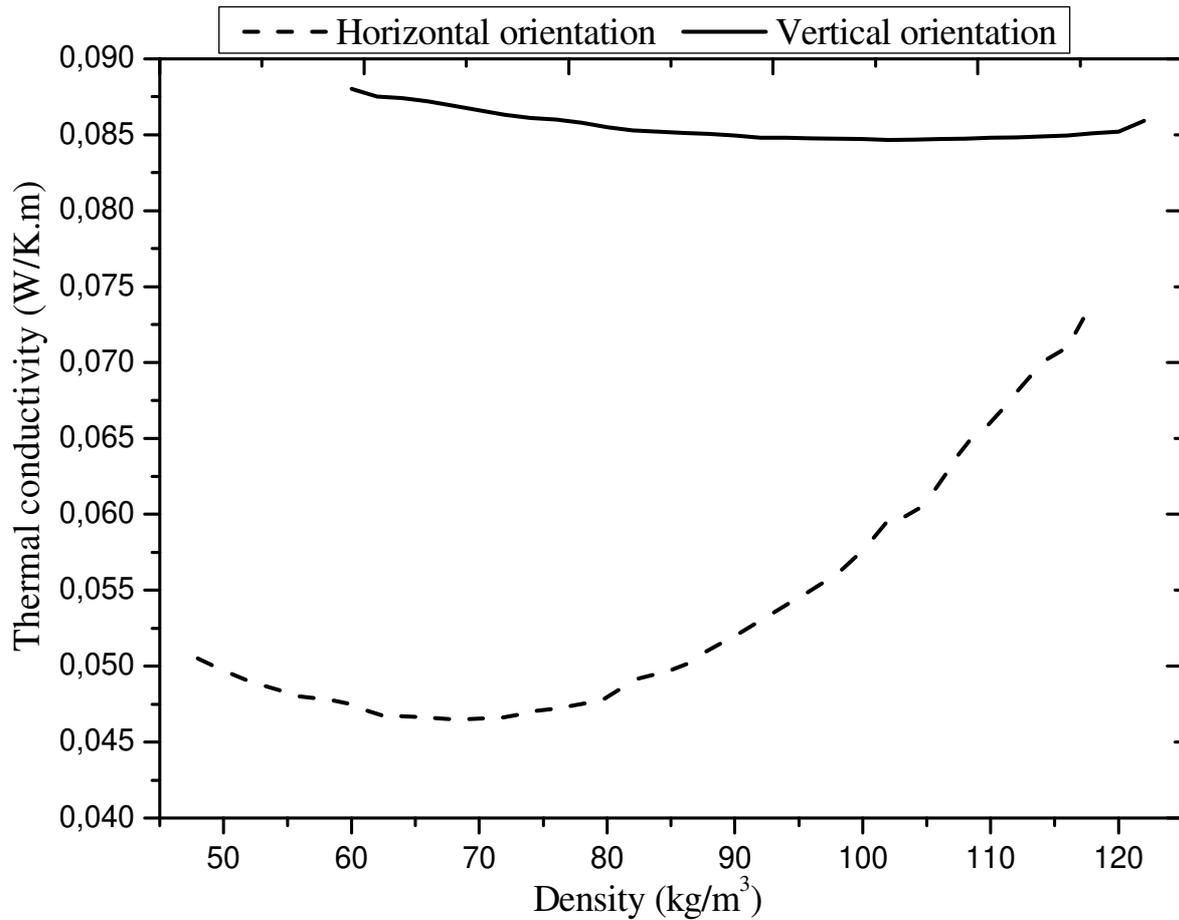


Figure 9: The variation of the thermal conductivity with respect to the density of vertical and horizontal oriented fibers (based on data from [46])

Between the years 1993 and 2019, several experiments measured the thermal conductivity for a narrow range of parameters. **Table 9** summarizes the experimental results of the thermal conductivity tested by different authors. Cases without specific direction can be considered as a mix of horizontal and vertical fiber orientation. These experiments showed that the thermal conductivity increases when the density and the moisture content increase. In addition, it shows that bales with vertical fibers have better thermal resistance than bales with horizontal fibers. A unique value for the thermal conductivity of the straw cannot be set, as it can be seen in equation (3), since many factors (straw bale density, humidity, and orientation of fibers, the temperature, and others) can affect its thermal properties.

$$0,033 [\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}] \leq \lambda \leq 0,19 [\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}] \quad (3)$$

### 3.4. Thermal heat capacity

The thermal capacity can be generally measured by a calorimeter. This parameter can be calculated according to ISO 7345 by using equation (4).

$$C = \rho \cdot C_p \quad (4)$$

where  $C$  is the heat capacity,  $\rho$  is the density and  $C_p$  is the thermal capacity. Marques et al. [57] measured the thermal capacity of rice straw by neglecting the effect of the pores between fibers. The study was carried out on bales with densities between 80 kg/m<sup>3</sup> and 100 kg/m<sup>3</sup> while the temperatures were varying between 0 °C and 40 °C. The thermal capacity was found to be between 1075 J/kg.K and 2025 J/kg.K. The volumetric heat capacity factor of wheat straw increased from 164 kJ/m<sup>3</sup>.K to 276 kJ/m<sup>3</sup>.K when the density increased from 82 kg/m<sup>3</sup> to 138 kg/m<sup>3</sup>, and the thermal heat capacity was

reported as 2000 J/kg.K [42]. Goodhew and Griffiths [58] compared the volumetric heat capacity and the specific heat capacity of straw bales to the clay-straw mixture. It was remarked that straw bale at a density of 60 kg/m<sup>3</sup> had a specific heat capacity of 600 J/kg.K and a volumetric heat capacity of 36.8 kJ/m<sup>3</sup>.K. These two values were much higher for the clay-straw mixture. The density, the specific heat capacity, and the volumetric heat capacity were 440 kg/m<sup>3</sup>, 900 J/kg.K, and 400 kJ/m<sup>3</sup>.K, respectively. Similar to the thermal conductivity, a unique value cannot be set for the thermal capacity for the same reasons. According to [59] and [60], the straw heat capacity varies within the range given by equation (5).

$$1338 [J.kg^{-1}.K^{-1}] \leq C_p \leq 2000 [J.kg^{-1}.K^{-1}] \quad (5)$$

### 3.5. Water vapor diffusion factor $\mu$ and thickness $sd$

In porous materials, diffusion takes place in the pores. According to [61], diffusion resistance factor  $\mu$  can be defined by equations (6) and (7).

$$g_v = -\delta^* dp/dx \quad (6)$$

$$\mu = -\left(\frac{\delta_{air}}{g_v}\right) * dp/dx = \frac{\delta_{air}}{\delta} \quad (7)$$

where  $g_v$  is the flux density,  $\delta$  is the diffusion coefficient at a specific temperature,  $\delta_{air}$  is the diffusion coefficient of the air and  $p$  is the pressure. The  $\mu$ -value indicates the permeability of a material to allow the water vapor passage as a function of the air properties [62]. Straw walls have a very high-water vapor permeability, which depends on the pores of the material. According to RFCP [10],  $\mu = 1.15$  for dry straw bales having a density about 100 kg/m<sup>3</sup>. According to Labat et al. [63] a straw-clay sample having a density of 350 kg/m<sup>3</sup>, had two different factors  $\mu = 2.92$  (by using the wet cup method) and  $\mu = 4.77$  (by using dry cup method). The wet and dry cups measure the vapor drive moving in both opposite directions. The water vapor diffusion factor studied by Marques et al. [57] using the dry cup method for rice straw bales having densities between 80 kg/m<sup>3</sup> and 100 kg/m<sup>3</sup>, ranged between 3 and 5.

The thickness  $sd$  is calculated by taking into consideration several assumptions such as constant temperature and  $\mu$ -value. Therefore, the flux density for the considered material and the air ( $\mu = 1$ ) can be calculated by using equations (8) and (9) (where  $s = \Delta x$ ).

$$g_{v_{mat}} = -\delta/\mu * \Delta p/s \quad (8)$$

$$g_{v_{air}} = -\delta / sd * \Delta p \quad (9)$$

Considering that, its vapor diffusion resistance of the air is the same as that of the material layer of thickness  $s$ , then both flux densities are equal and the thickness  $sd$  of the material is given by equation (10). For example, the  $sd$ -value of straw is 0.41 m for a thickness of 36 cm and  $\mu$  is 1.15.

$$sd = \mu * s \quad (10)$$

### 3.6. Thermal effusivity and diffusivity of straw

Thermal effusivity and diffusivity are parameters related to heat transfer. Thermal effusivity or thermal permeability describes the way a material exchanges heat when it comes in contact with another substance [64] and thermal diffusivity, the measure of the thermal inertia, determines the ability of a material to transfer temperature between its different surfaces and extremities. According to [64], equations (11) and (12) predict respectively the effusivity and the diffusivity. Chaussinand et al. [59] deduced these two factors from the range variation of the thermal conductivity and capacity. The effusivity and diffusivity values of the straw bales are respectively given by equations (13) and (14).

$$\text{Eff}=\sqrt{\lambda \cdot \rho \cdot C_p} \quad (11)$$

$$\text{Diff}=\frac{\lambda}{C_p \cdot \rho} \quad (12)$$

$$417 [\text{J} \cdot \text{K}^{-1} \cdot \text{m}^{-2} \cdot \text{s}^{-1/2}] \leq \text{Eff} \leq 775 [\text{J} \cdot \text{K}^{-1} \cdot \text{m}^{-2} \cdot \text{s}^{-1/2}] \quad (13)$$

$$0,1 \times 10^{-6} [\text{m}^2 \cdot \text{s}^{-1}] \leq \text{Diff} \leq 3,6 \times 10^{-6} [\text{m}^2 \cdot \text{s}^{-1}] \quad (14)$$

It can be noted that the straw walls help to gain heat to increase the indoor temperature through their low thermal effusivity. However, straw bales have low diffusivity, which can affect the heat accumulation of the wall. Therefore, an overheating problem can occur when the solar heat is intense, particularly in summer [59]. Ashour [42] reported the thermal diffusivity and effusivity variations of the wheat straw with respect to the density. It was noticed that the thermal diffusivity decreased from  $3 \times 10^{-7} \text{ m}^2/\text{s}$  to  $1.5 \times 10^{-7} \text{ m}^2/\text{s}$  when the density varied from  $82 \text{ kg/m}^3$  to  $138 \text{ kg/m}^3$ . The inverse trend was seen for the thermal effusivity which increased from  $1.49 \text{ J/K} \cdot \text{m}^2 \cdot \text{h}^{0.5}$  to  $1.79 \text{ J/K} \cdot \text{m}^2 \cdot \text{h}^{0.5}$  for the same density variation. Goodhew and Griffiths [58] showed that the thermal diffusivity of the straw bale of density  $60 \text{ kg/m}^3$  was  $18.2 \times 10^{-7} \text{ m}^2/\text{s}$ . This value decreased after mixing the straw with clay to attain  $4.6 \times 10^{-7} \text{ m}^2/\text{s}$  for a density of  $440 \text{ kg/m}^3$ . Sabapathy and Gedupudi [45] measured the thermal diffusivity of straw bale having a density of  $68 \text{ kg/m}^3$ . The obtained values ranged between  $2.4 \times 10^{-7} \text{ m}^2/\text{s}$  and  $15.3 \times 10^{-7} \text{ m}^2/\text{s}$ . In addition, they proposed correlations for the diffusivity concerning the different fiber orientations. The equations for the vertical, horizontal, and random orientation are given in equations (15), (16), and (17) respectively.

$$\text{diff} = (9.75 \times 10^{-4})\rho^2 - 0.152\rho + 0.0109(\%RH) + (8.76 \times 10^{-3})T + 6.2 \quad (15)$$

$$\text{diff} = (-3.28 \times 10^{-4})\rho^2 - 0.0429\rho + (8.2 \times 10^{-4})(\%RH) + (8.96 \times 10^{-4})T - 0.96 \quad (16)$$

$$\text{diff} = (1.29 \times 10^{-6})\rho^2 + (-9.44 \times 10^{-3})\rho + (-8.32 \times 10^{-4})(\%RH) + (4.3 \times 10^{-4})T + 1.01 \quad (17)$$

### 3.7. PH measurements

The durability of straw buildings depends on their physicochemical properties and the surrounding environment. When inside the bale is optimal for microorganisms, the latter will multiply and enhance. The pH of the straw affects the microorganisms' growth, which has a direct impact on the durability of the straw [14]. The minimum growth rate of microorganisms is in neutral environment straw. Ashour et al. [14] performed several experiments to measure the pH. Straw dried at a high temperature ( $105 \text{ }^\circ\text{C}$ ) was mixed with distilled water by a ratio of 1/9. After several measurements on 16 samples, an average value of 7.29 was found. This value refers to a neutral-alkaline environment. Bouasker et al. [25] also measured the pH of the barley straw using a pH meter. During the study, straw fibers were mixed respectively for 24 hours in NaCl solution and NaOH to eliminate moisture inside the bale. The experiment showed that the pH value was 8.3, which causes a very pronounced presence of mold. Halvarsson et al. [26] measured the pH and pH-buffering capacity for wheat straw based on the method of Johns and Niazi [65]. They found that the pH value and pH-buffering capacity value was 7.5. Therefore, to be safe, the interior environment of the bale should not be acid or alkaline.

### 3.8. Mechanical properties

The mechanical behavior of a bale depends on two main parameters; the strain  $\varepsilon$  and modulus of elasticity  $E$ . These parameters are calculated by equations (18) and (19).

$$\varepsilon = \frac{\Delta L}{L} \quad (18)$$

$$E = \frac{\sigma}{\varepsilon} \quad (19)$$

where  $\Delta L$  is the variation of the sample height, and the stress ( $\sigma$ ) depends on the load and the initial cross-sectional area).

Konecny et al. [66] evaluated the mechanical behavior of distinct wheat straw bale types, depending on the orientation of fibers. The experiments consisted of compression tests by applying forces up to 40 kN. To distribute the load, a plywood board was used with three wood beams. The samples had perpendicular (to plywood board) and parallel fibers orientation with different densities as can be seen in **Table 10**. The bales were approximately 70 cm long, 40 cm wide, and 30 cm high. For the same purpose, Ashour et al. [14] investigated 10 bales oriented horizontally and vertically, that is perpendicular to the load direction and parallel to the load direction respectively, to show their mechanical properties by applying the compression test. The bales density in all cases was 102.6 kg/m<sup>3</sup> with a moisture content of 11%. The bales dimensions were 61 cm long, 36 cm wide or high and 43 cm high or wide according to the considered case. The vertical load applied to the bale was increased in increments by one from 2 kN to 10 kN. After each increment, a dimension measurement took place. **Figure 10** and **Table 10** show the results of these experiments (with A the first loading path and B the second loading path). It can be seen that straw bales were highly deformable. The vertical strain of bales having a vertical orientation was almost proportional to the applied load. **Figure 10** revealed at 10 kN an inflection while the straws were compressed and a crushing sound was heard. An initial linear deformation up to 8 kN was followed into a major softening and hardening in the other case where the fibers are perpendicular. The full recovery wasn't observed in the tested cases of **Table 10**, whereas Ashour et al. [14] observed that straw bales returned to their original dimension after unloading.

*Table 10: Straw bale load-deformation characteristics (based on [66])*

No.	Fiber orientation	Density (kg/m <sup>3</sup> )	Load rate (mm/s)	Load (kN)	Deformation (mm)	Stress (kPa)	Strain (%)	Modulus of elasticity (kPa)
I-1	parallel	No data	0.05	9.4	22.5	26	7.5	347.7
II-1	parallel	83.6	0.2	9.7	46.9	28.2	15	187.7
II-2	parallel	83.4	0.2	8.8	48.6	28.1	15.3	183.5
III-2	perpendicular	92.9	0.4	8.4	38.4	21.3	12.7	167.8
III-3	perpendicular	97.5	0.4	7.6	56.4	20.2	18.5	109.2
III-4	perpendicular	80.6	0.4	13.8	54.7	32.4	17.2	188.2

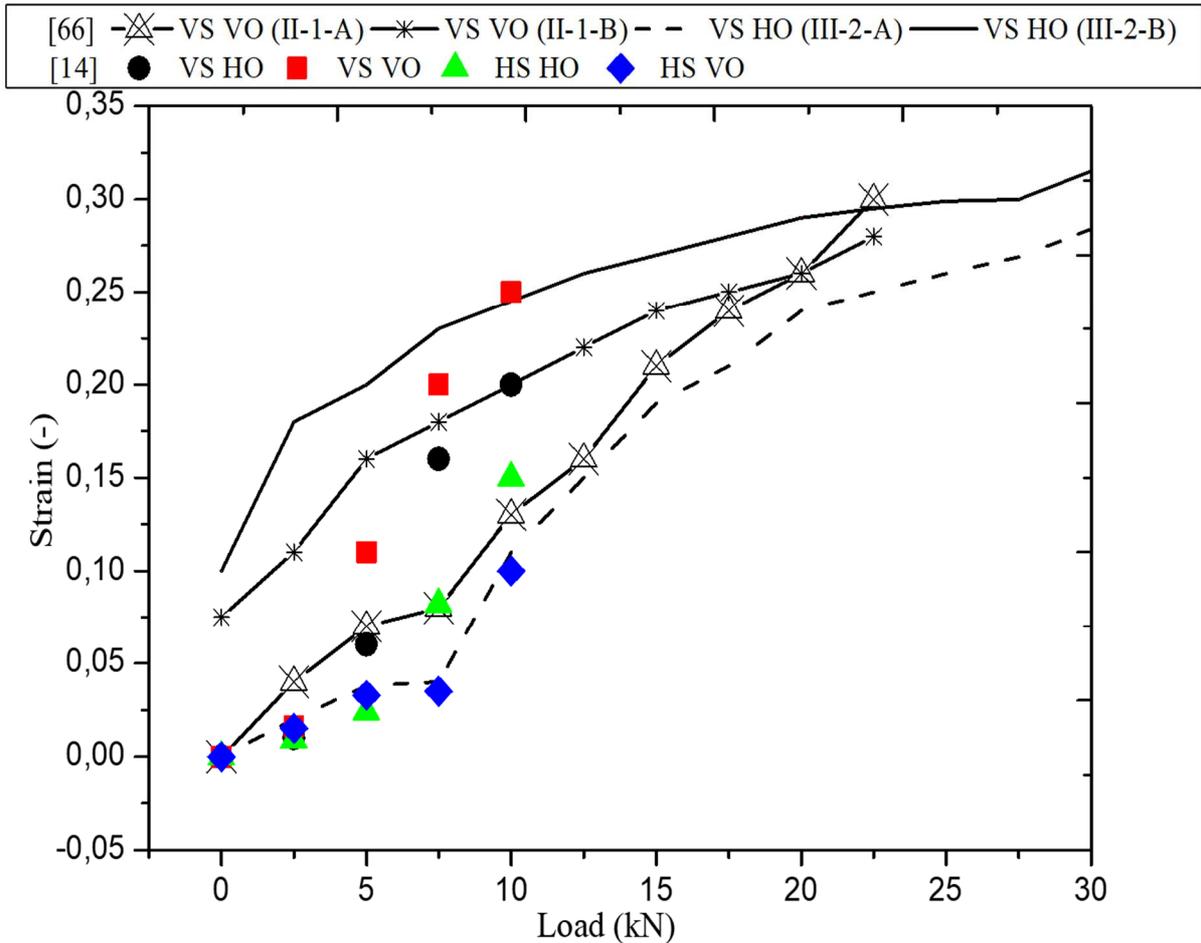


Figure 10: The vertical and horizontal strain variation (VS and HS) according to the applied load for bales oriented horizontally and vertically (HO and VO) (A the first loading path and B the second loading path) (based on [14] and [66])

In **Figure 10**, it was also noticed that horizontal bales strains were lower than for the vertical bales. The maximum strain of the horizontal bale was 0.2 while it was 0.25 for the vertical ones. In addition, the graph showed that the variation of the strain was almost proportional to the load and that the resistance of bales to deformation increases over time. Quasi-similar anisotropic behavior for horizontal and vertical bales was revealed through these experiments. However, the maximum reached value was 0.15, which is lower than the above finding. It can be noticed that the horizontally orientated bales have higher resistance to the deformation, which means higher stability in the building structure. The deformation modulus known as the elasticity modulus was investigated during the tests to determine the elasticity of the straw bales. **Figure 11** exhibits the modulus of elasticity variations with respect to the load variations. This parameter decreased when the applied load increased. In order to complete the study, Ashour et al. [14] presented the stress-strain curve, as shown in **Figure 12**, from which the modulus of elasticity can be calculated. The strain variation was nonlinear at low loads. These outputs ensure the ductile behavior of the bale since it can absorb the applied energy very well. After finishing the compression test and resetting the load, the vertical and horizontal straw bales returned to their initial dimensions after around 13 min.

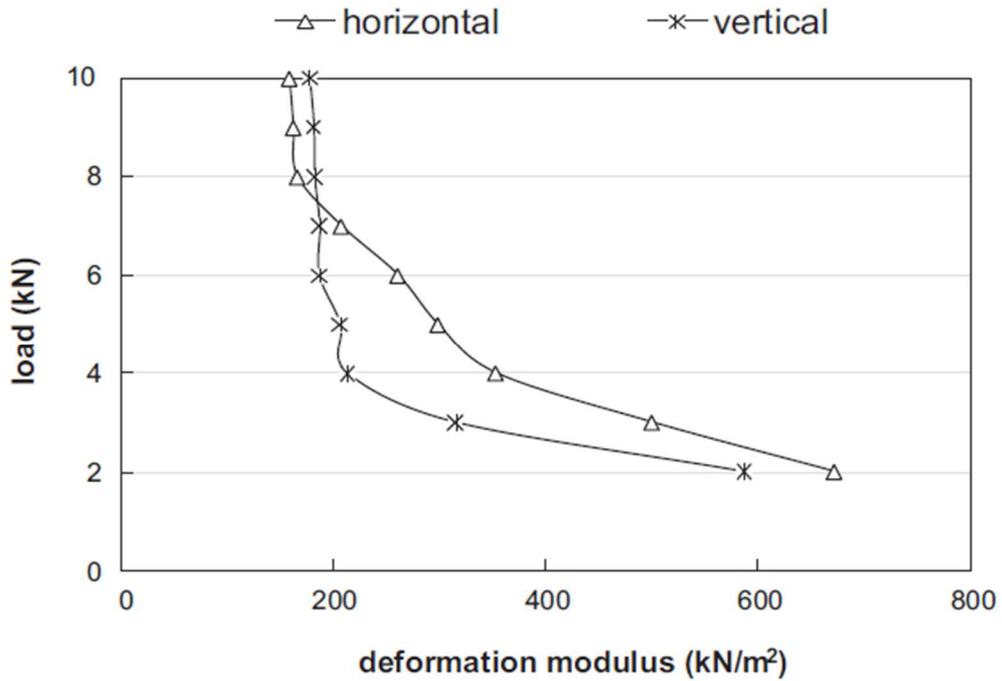


Figure 11: Variation of the deformation modulus of bales oriented horizontally and vertically [14]

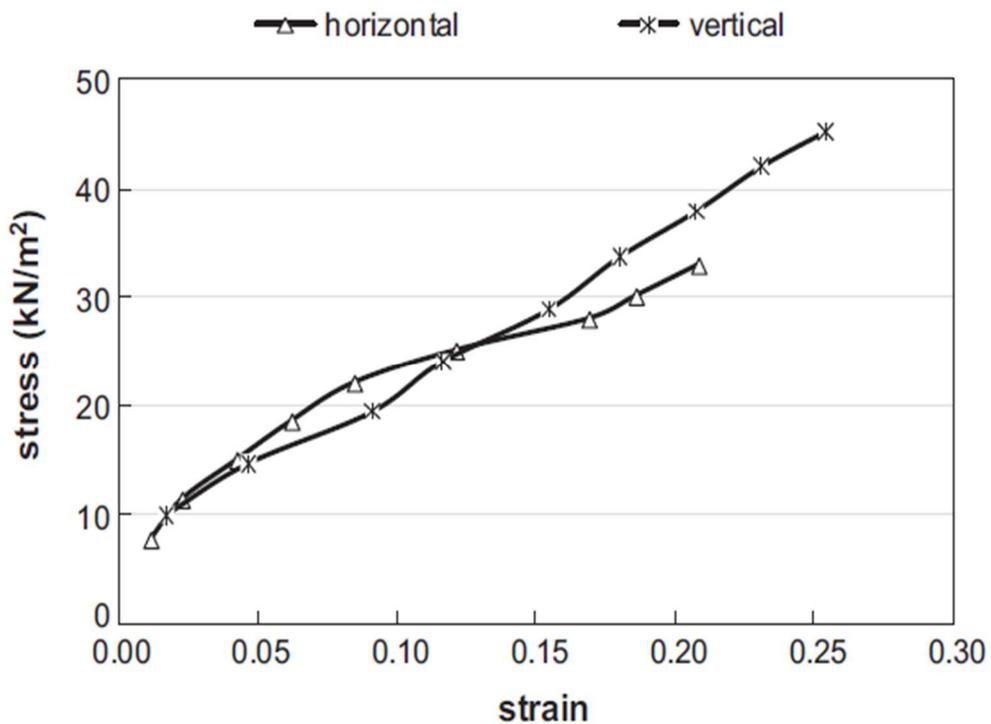


Figure 12: Stress-strain behavior for bales oriented horizontally and vertically [14]

Similar results can be found in **Figure 12** and **Table 10** for the modulus of elasticity: for densities between  $80 \text{ kg/m}^3$  and  $100 \text{ kg/m}^3$ , the modulus of elasticity varies from approximately 160 kPa to 189 kPa. For densities between  $115 \text{ kg/m}^3$  and  $140 \text{ kg/m}^3$ , Desille [67] showed that straw had a modulus of elasticity ranging from 200 kPa to 800 kPa. Other research studied the mechanical behavior of plastered straw bales. Ashour et al. [68] also conducted mechanical tests on plastered straw bale wall parts to find a modulus of elasticity of 9.45 MPa. By applying the same method, the ultimate load reached 19.2 kN/m for the unplastered wall while it reached 66 kN/m for the lime-plastered wall as reported by Goodhew et al [69]. In addition, a deflection is observed around 170 mm for the first case and 55 mm for the second case. The lime layer in the second case has reinforced the resistance of the

wall. Vardy and MacDougall [70] studied plastered wheat bales having a density of  $85 \text{ kg/m}^3$  and dimensions  $30 \text{ cm} \times 40 \text{ cm} \times 60 \text{ cm}$ . These samples had varying results, for on-edge bales the modulus of elasticity was  $18 \text{ MPa}$  and the ultimate load was about  $30 \text{ kN/m}$ , and while for flat bales the modulus of elasticity was  $12 \text{ MPa}$  and the ultimate load was  $60 \text{ kN/m}$ . According to Konecny et al. [66], the measured modulus of elasticity is highly dependent on the density including humidity of the tested sample, fibers orientation, straw type, growing location, and bale preparation.

### **3.9. Discussion**

The bale, regarded as a non-structural partition of the wall, should be thermally and mechanically inspected before being used. The characterization of this part defines the behavior of the walls and the whole building. The available literature shows that most studies focused on the variation of thermal conductivity of the bale with respect to density, temperature, humidity, and orientation of the fibers. Most tests were experimental and the results obtained for thermal conductivity ranged between  $0.03 \text{ W/m.K}$  and  $0.19 \text{ W/m.K}$ , which indicates that the material has insulating properties and that density, temperature, RH or fibers orientation are parameters to methodically control to optimize the bale thermal insulating properties. In addition, the compression tests applied to bales of varying densities showed a resilient and robust nature as the deformation can be retrieved in a short time. However, the bales thermal capacity, effusivity, diffusivity, and diffusion factor of water were generally not experimentally established, as was the thermal conductivity. In addition, further pH-related studies should be carried out as they have a strong effect on the inner bale conditions and durability. In the same way, extreme other mechanical measurements can be performed to identify the influence of factors like load intensity, load direction, load rate, bale density, straw nature, fibers orientation on compressive strength, and Young's modulus of the straw bale.

## **4. Wall scale**

### **4.1. Hygric and thermal properties**

The wall internal temperature and RH are affected by several factors. These two parameters depend on the surrounding environment and the wall characteristics. First, the received solar heat radiation depends on the orientation of the wall. Second, the location of the wall and the period (month) affect the quantity of received day light, temperature fluctuations, and humidity of surrounding air. Walker et al. [12] associated the exposure time of straw to damp with its degradation. In addition, authors added that the material can be subjected to aerobic and anaerobic degradation due to the extreme exterior conditions.

Mesa and Arengi [13] studied the hygrothermal properties of straw walls experimentally and numerically. The experiment consisted of using a climatic chamber to control the temperature and humidity. The wall was composed of  $38 \text{ cm}$  of straw covered by lime plaster on the outside and clay plaster on the inside surface. The experimental findings were used in WUFI to reproduce the numerical model of the walls. The numerical and experimental models yielded the same results. The data showed that after three days, the temperature was able to reach an equilibrium state whereas the humidity equilibrium was reached after ten days. This behavior can be explained by the high thermal and moisture storage capacity of the material. Ashour et al. [14] performed an experimental study on a ground stage wall located in Germany to study the variation of temperature and RH at different locations in a straw wall. The straw was covered by mud stucco and its total thickness was  $50 \text{ cm}$ . The sensors (RH and T) were installed in the surfaces and inside the wall at a height of  $140 \text{ cm}$  from the floor. The temperature sensors inside the straw bales showed an approximately stable temperature regardless of the sharp variation in temperature between day and night. Consequently, the presence of straw bales decreased the influence of the outside temperature fluctuation on the inside temperature, which was detected by the smoothed inside temperature variation. The low thermal conductivity of the straw bales provides thermal insulation, which was detected by the temperature difference between the temperature of the outer plaster and the temperature at a distance of  $20 \text{ cm}$  inside the bale. In terms of thermal comfort, the before mentioned behavior of straw bales provided suitable comfort conditions. Using straw bales having a density of  $102.6 \text{ kg/m}^3$  and starting with an ambient temperature of  $23.1$

°C, an initial temperature increases by 0.5 °C was detected as shown in **Figure 13**. After 450 hours, the temperature decreases gradually to 23.21°C.

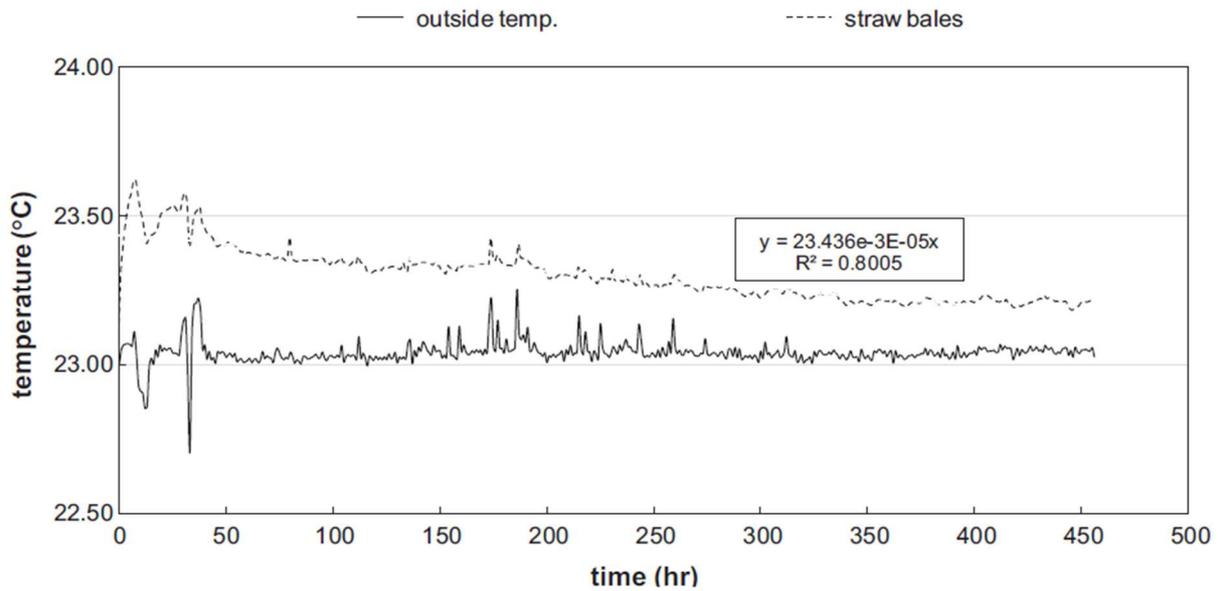


Figure 13: Variation of straw temperature (dotted line) and outside temperature (black line) as a function of time [14]

The variation of the humidity in the straw wall was also followed by Ashour et al. [14] as presented in **Figure 14**. The difference of RH between the outside and the inside of the bale decreased from around 10 % to 7 % during 24 hours. This difference continues by decreasing after 261 hours to reach about 2.63 %. It was noticed from the RH curves that the absorption of humidity was slow since it can take more than 300 hours to attain the exterior RH value. Therefore, two hypotheses can be considered regarding the above measurements. Firstly, the RH migration through the straw wall is low. Secondly, the straw walls provide acceptable indoor thermal comfort.

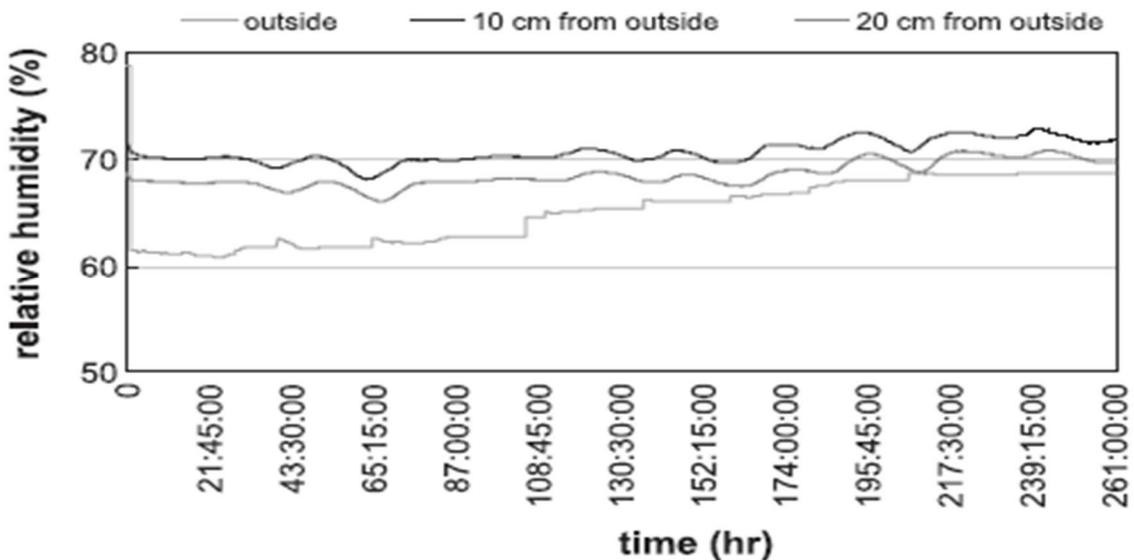


Figure 14: Relative humidity in different locations in the straw bale wall [14]

Thomson and Walker [71] monitored the moisture-induced degradation of a straw bale construction by following the temperature and humidity variations of the wall for three years, in a wind-driven rainy climate. The tested wall was composed of a 360 mm straw layer and a 35 mm exterior lime layer. It was concluded that the exterior layer caused an initial rise in RH. **Figure 16** represents the variation of the humidity in the wall between 2009 and 2012 with respect to the Fraunhofer Institute isopleth limits (FIB-Mold expected growth). It was noticed that at specific temperatures, some RH values overpassed

the limit. Thus, this type of straw wall is subjected to mold growth followed by its degradation. Researchers removed a core of the outer layer from the wall lower half to conduct a gravimetric assessment of the straw moisture content, which was found 28.5%. Moisture contents higher than 20% accelerate material degradation. In addition, a degradation test was performed to monitor the microorganism growth. To this end, the temperature and humidity were set at 21.5°C and 87% respectively and the CO<sub>2</sub> level was measured as an indicator of the mold growth. It was found that the moist straw could not develop microorganisms since the CO<sub>2</sub> remained constant for about 20 days.

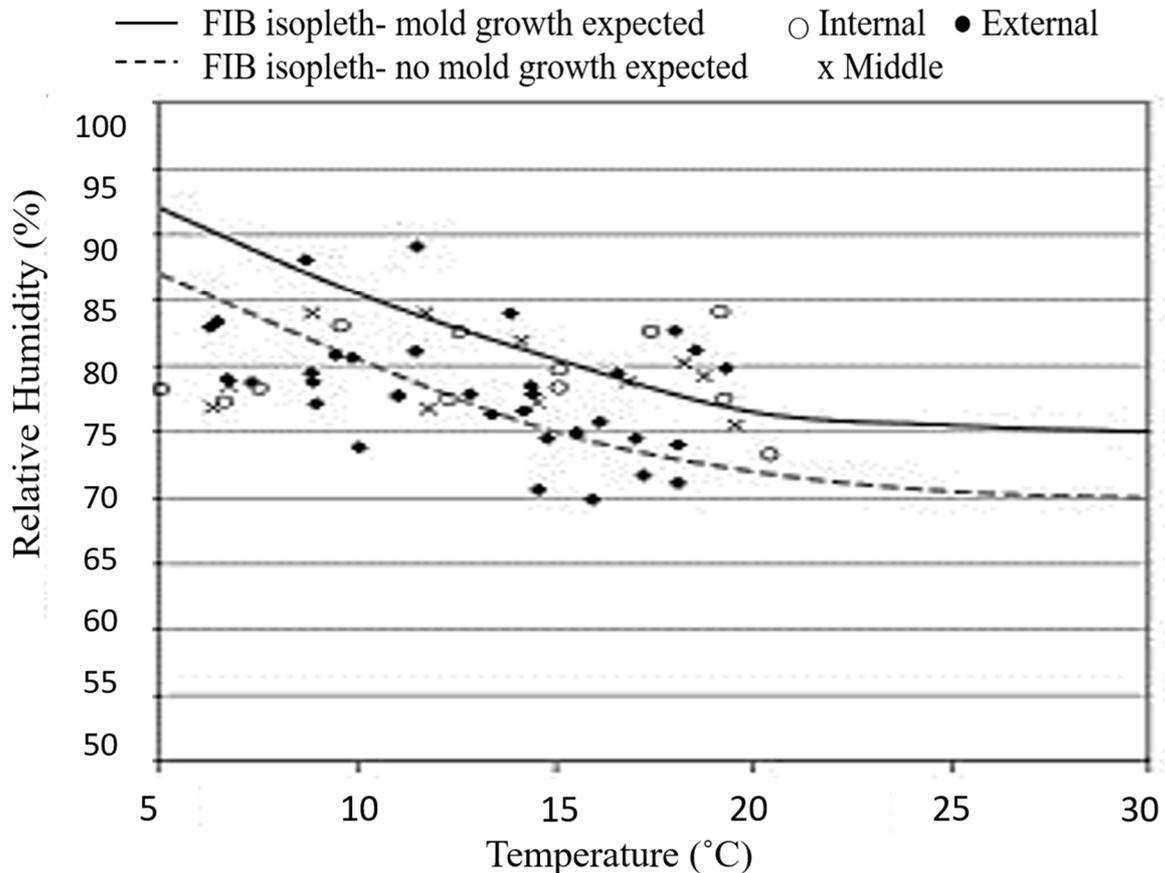


Figure 15: The variation of the relative humidity while varying the temperature at a different location in the wall [71]

Moreover, Robinson et al. [72] investigated the moisture level in a one-room straw building of 8.5 m<sup>2</sup> floor area. The exterior and interior wall surfaces were covered with a lime mortar layer of thickness 20 mm and 10 mm, respectively. The exterior lime layer was applied two times, 12 days apart. In this way, the wall could absorb the CO<sub>2</sub> and the water content increased. The purpose of this experiment was to see the impact of the wet layers on the straw materials by measuring the moisture content in the wall. Results showed that the application of a wet layer on the dried one had no effect. A 5% increase of moisture was observed after the application of the first layer on the exterior and interior side between days 0 and 12 and between days 21 and 37, respectively. In addition, through this experiment, it was noticed that the moisture content of the straw bales varied between 20% and 25%. Sabapathy and Gedupudi [73] tested rice straw walls experimentally to show their hygrothermal property. The walls were part of a 4 m<sup>2</sup> cell and had a thickness of 10 cm. A network of thermocouples was installed on the wall surfaces and inside the walls. In addition, temperature and humidity sensors measured indoor and outdoor air conditions. The indoor and outdoor RH varied between 40% - 80% and 50% - 95%, respectively. The average indoor and outdoor temperatures were 28 °C and 40 °C respectively.

The straw did not store a high quantity of moisture even though the walls were exposed to high humidity levels for a long time. The wall time lag was found to be 3 hours.

Generally straw walls are covered by vapor-permeable materials as lime renders and clay plasters. These layers help to mitigate the risk of degradation associated with the moisture presence [12]. Walker et al. [12] recommended to test the hygrothermal performance of the straw wall numerically before starting construction. The steady state and dynamic models can indicate if there is a risk of moisture within the structure based on the local conditions.

The variation of the temperature inside the wall can help to determine two important parameters in the building sector. The time required for the heat waves to propagate from the outer surface to the inner surface is known by the time lag. The ratio of the temperature variation of the inner to outer surface temperature is known as the decrement factor. The time lag and the decrement factors equations are respectively given by equations (20) and (21).

$$\phi = t_{max} - t_{out,max} \quad (20)$$

$$f = \frac{T_{max} - T_{min}}{T_{out,max} - T_{out,min}} \quad (21)$$

where  $t_{max}$  and  $t_{out,max}$  are the time in an hour to have the maximum interior and the exterior temperature, respectively.  $T_{max}$ ,  $T_{min}$ ,  $T_{out,max}$  and  $T_{out,min}$  are the maximum and minimum temperatures of the internal and external surfaces.

Walls with good dynamic thermal performance have a high phase shift ( $\phi > 10$  hours), whereas  $\phi < 6$  hours refers to poor performance. A lower decrement factor indicates a higher ability of the wall to attenuate the amplitude of the periodic heat wave transferred in dynamic conditions. The time lag and the decrement factor caused by the insulation property of straw can be calculated from **Figure 13** as 10 hours and 0.1 respectively. Douzane et al. [15] results showed 6 hours' time lag and a 0.08 decrement factor. Gallegos-Ortega et al. [54] experiments on a straw building in Mexico revealed 9.12 hours' time lag and a 93.5% temperature reduction knowing that the RH inside the straw was about 10%. These values are acceptable regarding the outdoor conditions.

## 4.2. Heat transfer coefficient of a straw wall

The U-value, in general, depends on the wall layers, their thermal conductivity, and their thickness. In [50], a straw wall of dimension 2.05m x 3.30m x 0.36m, was realized with framework and coatings to measure the U-value of the wall. It consisted of two coats each of 2 cm, one in lime plaster, and the other in plaster hemp-lime as in the actual walls of Montholier [50]. A U-value equal to 0.25 W/m<sup>2</sup>. K was obtained. This low U-value indicates a good steady thermal performance. The result corresponds to an equivalent conductivity of the straw of 0.095 W/m.K. This value is greater than the conductivity of the straw material because this includes the presence of the wood frame ( $\lambda = 0.12$  to 0.15 W/m.K) and hemp mortar. The U-value of a straw wall studied by Rye and Scott [74] was 0.16 W/m<sup>2</sup>. K for a thickness of 43.5cm with lime plaster having a  $\lambda = 0.8$  W/m.K. Cascone et al. [56] obtained a U-value about 0.281 W/K.m<sup>2</sup> for a wall composed of plaster board (thickness=1.3cm), air gap (thickness=2.7cm), straw (thickness=20cm), air gap (thickness=2cm) and faux stone panel (thickness=2.5cm).

Researchers in [75] found that a 450 mm straw wall has a U- value equal to 0.11 W/m<sup>2</sup>.K, while the U-value of a wall is composed of 105 mm brickwork, 75 mm mineral fiber, 100mm light concrete block, and 13 mm lightweight plaster is 0.33 W/m<sup>2</sup>.K. In the same context, the U-value of a wall composed of 100 mm concrete block, 75 mm mineral fiber, 100 mm concrete block, and 13 mm plaster is 0.4 W/m<sup>2</sup>.K, and of another composed of 100 mm concrete block, 75 mm mineral fiber, 100 mm concrete block and 13 mm plaster is 0.29 W/m<sup>2</sup>.K. Sabapathy and Gedupudi [73] calculated the U-value of a rice straw wall that has a thickness of 10 cm. They found that the thermal transmittance was about 0.6 W/m<sup>2</sup>.K. Therefore, the straw bale wall presents good thermal insulation properties.

### 4.3. Acoustic performance

The study of the acoustic properties of a wall has been very important in the construction sector as it can enhance the indoor comfort of a zone in a building. For this reason, construction materials should have the ability to absorb the sound waves and resist their transmissions [55]. In this review, two parameters were used to investigate the sound resistance of a straw wall. According to ISO 10140-2, these parameters are the sound absorption coefficient and the sound reduction index, which can be calculated by equation (19) and equation (20) respectively.

$$R=10 \log \frac{W_1}{W_2} \quad (19)$$

$$R_w=10 \log \frac{W_1}{W_2+W_3} \quad (20)$$

where  $W_1$  is the incident sound power,  $W_2$  is the radiated sound power and  $W_3$  is the sound power radiated by the surrounding elements around the tested wall (as in real cases).

D'Alessandro et al. [55] investigated the acoustic properties of straw with a density of 55 kg/m<sup>3</sup> at frequencies ranging from 50 to 1600 Hz. The sound absorption coefficient at 7 cm was larger than at 5 cm, and the coefficient reached 0.78 at 7 cm before dropping to 0.6 at 1.6 kHz, as shown by the curves in **Figure 16**. The porous nature of the straw was confirmed by the increasing and subsequently decreasing behavior at both locations.

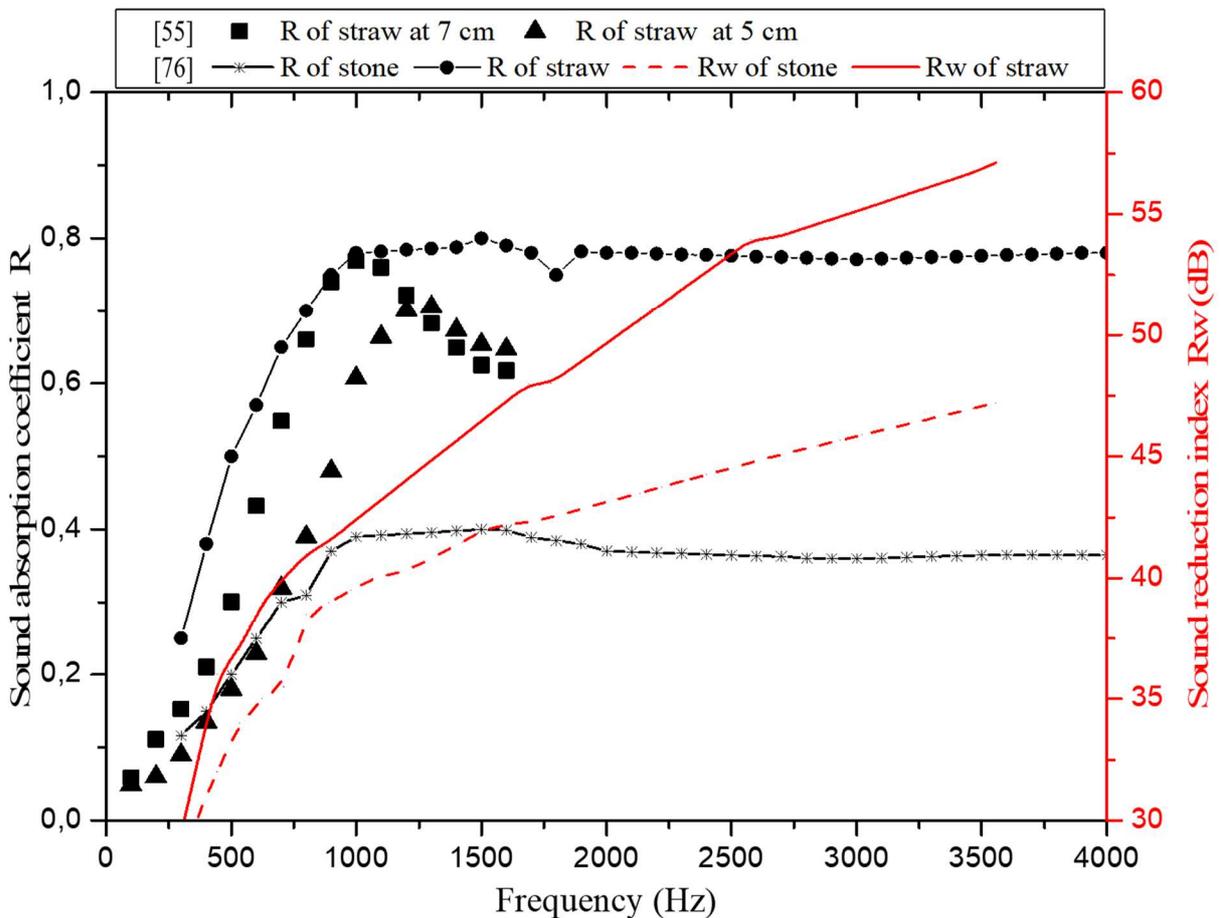


Figure 16: Sound absorption coefficient and sound reduction index of straw and stone (based on [55] and [76])

Trabelsi and Kammoun [76] also tested a 45 cm thick straw bale wall with a bale density of 120 kg/m<sup>3</sup>. The superficial density of the unplastered straw wall was around 52 kg/m<sup>3</sup> while for the plastered wall it was around 67 kg/m<sup>3</sup>. Their results showed an identical shape curve to that obtained

with D'Alessandro et al. [55]. These results highlight acceptable acoustic absorption coefficients at medium and high frequencies with a sound reduction index around 58 dB. During the experiments, the straw walls were compared to stone walls in **Figure 16** and showed higher reduction index values but with a difference of only 1 to 10 dB depending on the frequency.

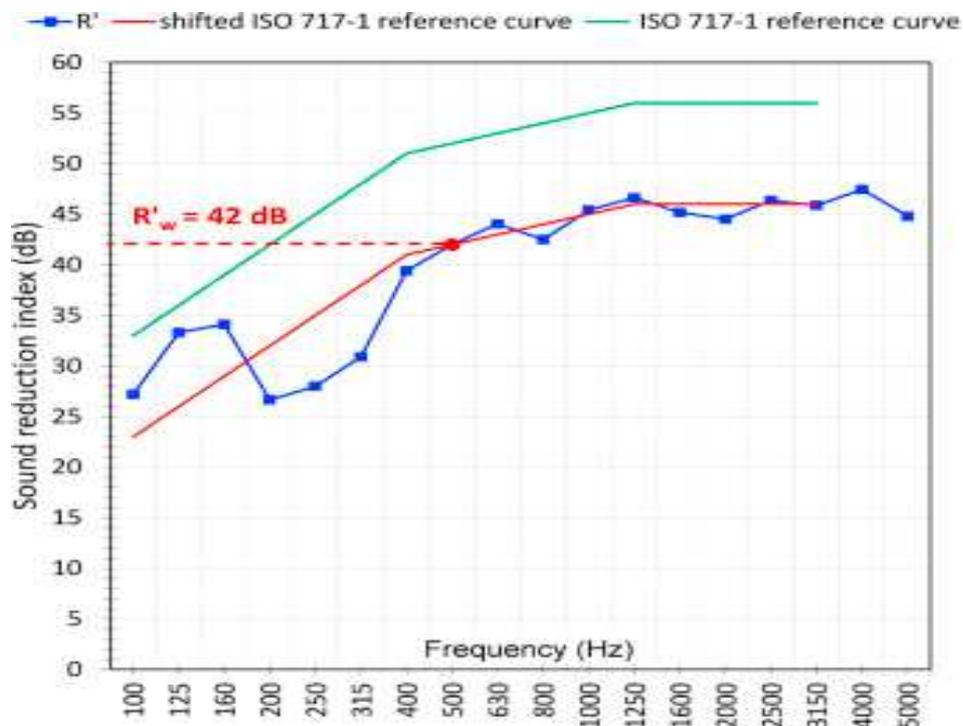


Figure 17: The calculated sound reduction index of a 50 cm thick straw wall according to the ISO 717-1 [55]

In addition, they did the same test on a straw bale wall having a thickness of 50 cm. The obtained results are given in **Figure 17**. The found curves show a quite poor performance with a weighted apparent sound reduction index of 42 dB at 500 Hz. Nevertheless, this value is lower than that obtained for conventional wall materials where it can exceed 60 dB [77]. Dalmeijer [78] also tested a section of a straw bale wall having a thickness of 46 cm. 2.5 cm and 3.5 cm thick clay layers, respectively covered each side of the wall. At the end of the experiment, he noted a sound reduction index of 53 dB. However, this value could not be exact since the tested area was around 1.88 m<sup>2</sup> while the required area is around 10 m<sup>2</sup>. Another straw wall type was tested by Wall et al. [79]. The experiment consisted on calculating the reduction sound index of a 35 cm straw wall covered by 3.5 cm of lime render layer. After emitting 100 dB white noise to the exterior side and measuring the background noise, the calculated  $R_w$  value was 44 dB.

From these experiments, it can be noticed that the acoustic performance of a straw wall depends on its thickness and its outside/inside layer. However, the sound reduction index of these types of walls is ranged between 42 and 53 dB.

#### 4.4. Fire resistance tests

The fire resistance characteristic of construction materials is a principal parameter that can determine the security of the building in critical cases. The test that led to the discovery of this property was defined through the years by the international standard of ISO 834-1. This test can be done by using furnaces in a lab to model the fire through the wall. The ISO temperature-time relation expressed in equation (22) was accepted by the Eurocode and classified as the nominal relation up to 1992 [80]. Then this relation was improved with equation (23) by the ASTM to give more accurate results.

$$T = 345 \log_{10}(8.t+1) + 20 \quad (22)$$

$$T = 750 [1 - e^{-3,79553\sqrt{t}}] + 170,41 \sqrt{t} + T_0 \quad (23)$$

where  $T$  is the gas temperature in the furnace,  $t$  is test time and  $T_0$  is the initial temperature.

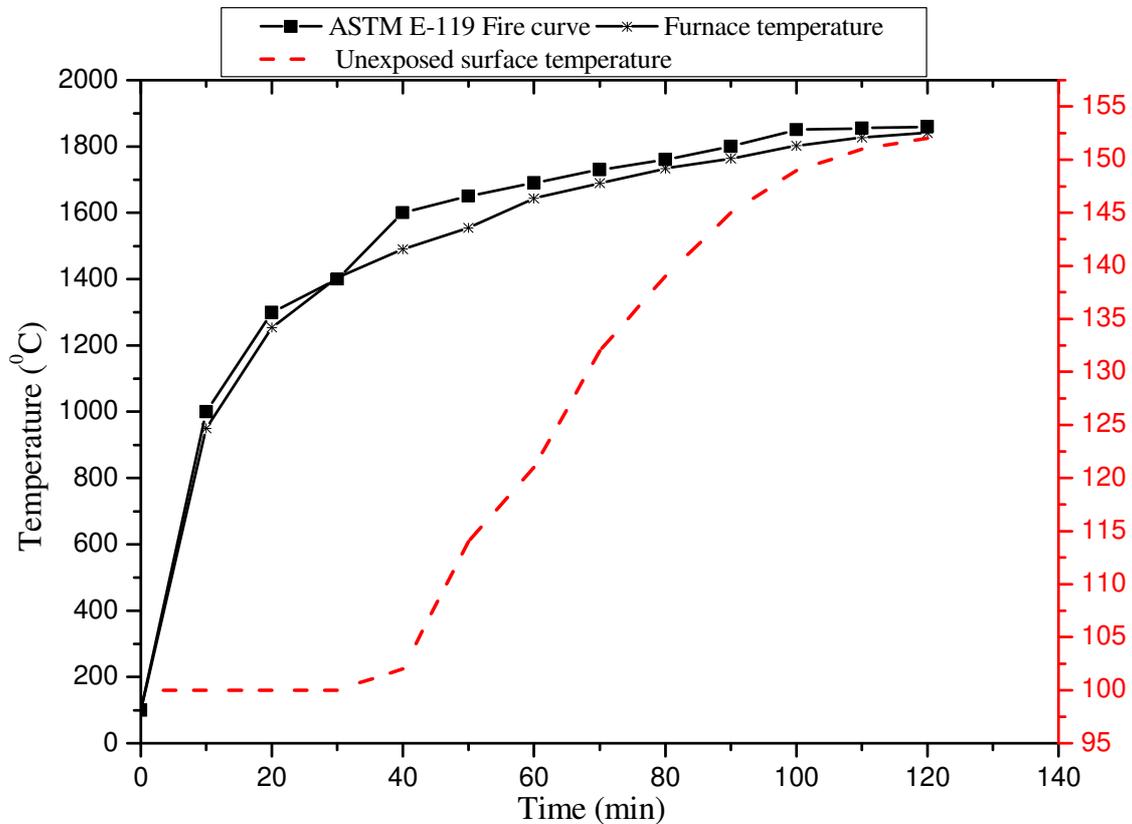


Figure 18: Temperature-time curve of the ASTM E-119, the furnace and the unexposed surface of the straw bale wall (based on [80])

Several tests were made to classify the straw regarding its fire resistance. According to [81] and [82], straw bales were proved to have good resistance to fire since oxygen quantity inside the material is low, which does not support the combustion. Therefore, the material was classified as B - S1 - d0 material [83], where B is used to describe the straw as a fuel product with very low flashover, S1 describes a low smoke production and d0 indicates the absence of flaming droplets and debris generated by the straw. For the same purpose, fire tests were carried out on plastered (cement layer) straw walls by the National Research Council of Canada in 1980. The wall withstood temperatures higher than 1000 °C for 2 hours before the cracks start appearing at the surface. The test was also done for plastered bales, which were able to resist a 43°C temperature during 4 hours [80]. The next year, similar tests were carried out by Theis [84]. The study was based on a comparison between plastered and unplastered straw walls. In both cases, temperature variations have met the standard requirements. During the fire tests, it was noticed that the joints between the bales were weak regions since the burns started to appear there. In addition, the added layer on the surface of the wall has improved its resistance for up to 3 hours. In 2001, two studies investigated the resistance of the straw against high temperatures. Firstly, the Technical Institute of Vienna tested the plastered straw wall for 90 minutes [82,83] similar to the ASTM E-119 test. Secondly, in Danish research, one side of the plastered straw wall was exposed directly to the flame. This side resists the 1000 °C temperature for around 30 minutes [84] without the temperature increase of the opposite side. In 2006, the U.S. Ecological Building Network characterized a non-loadbearing straw bale wall by achieving fire tests [87], [80]. The tested area was 15.5 m<sup>2</sup> composed of 19.2 kg rectangular bales. To reinforce the resistance, a 13 mm cement layer from both sides covered the wall. **Figure 18** presents the temperature variation of the

furnace, which conformed to the standard and the unexposed surface temperature. It was noticed that the average maximum temperature of the unexposed surface reached only 150 °C while the wall encountered 2 hours the fire. Moreover, loadbearing plastered straw walls were performed according to Czech regulations to show the compression effect on the fire resistance [80]. The applied load rate was 200 N/s in the first case and 333 N/s in the second case. In this test, the first case walls were able to resist the fire for 2 hours and 26 minutes while in the second case, they resist for 1 hour and 6 minutes. In 2009, in the UK, Wall et al. [79] tested the fire resistance of a straw wall covered by a lime render layer. The total thickness of the wall was 49 cm, its height, and width 3 m. After fixing the wall to the oven, the temperature was raised to 700 °C for 30 min and then raised to 900°C for 44 min before attaining 1000°C. The total air pressure measured in the oven was 101345 Pa. It was noticed that after 90 min the lime render started falling from the wall. The test was stopped after 135 min at a temperature of 1065 °C. During the experiment, the temperature of the other side of the wall increased from 13 °C to 50 °C. It was reported that this type of wall exceeds the requirements of the UK building regulations by more than four times.

The fire resistance of different types of straw walls revealed encouraging results. These results may vary based on the coating layer type and the density of the bales. Therefore, the straw walls well covered can be easily compared to the other bio-based building conventional materials.

#### 4.5. Economic and environmental performance

The choice of the material at the wall scale should be made by considering other criteria that are the climate conditions, the material availability, price, carbon footprint, and energy consumption. The conventional known materials have been replaced by bio-based materials even in the building sector to decrease the pollution level. In this context, the environmental performances of the straw walls were taken into consideration in different research to fulfill the above purpose.

Table 12: Different wall material comparison [88]

Number of required per m <sup>2</sup> of wall	Thermal conductivity (W/(m. K))	Thermal transmittance U-value (W/(m <sup>2</sup> .K))	Energy per m <sup>2</sup> wall (MJ/m <sup>2</sup> )	Emission of CO <sub>2</sub> (kg CO <sub>2</sub> /m <sup>2</sup> )
85 fired bricks	0.9	3.9	488	30
11 concrete blocks	0.64	3.2	169	9.6
7 straw-clay blocks	0.18	0.86	40	3.4
3 straw bales	0.07	0.16	28	2.5
3 half straw bales	0.07	0.32	14	1.3

Gonzales [88] investigated a half-straw-bale wall, a whole-straw-bale wall, and a straw-clay wall. These cases were compared to brick walls and concrete block walls as can be seen in **Table 12**. In his study, he covered a 140 m<sup>2</sup> envelope with the considered materials and noted their performances. The lower thermal conductivity and higher thermal resistance were reached by the whole straw wall. The use of straw material in the case of Gonzales showed the lowest energy consumption and CO<sub>2</sub> emission for low transportation distance reasons. For example, 500 non-local straw bales transported from 700 km away have 27 MJ embodied energy per bale. It should be noted here that the transportation energy of bales should be lower than for the bricks or the concrete due to higher densities. **Table 12** showed clearly the advantageous thermal and environmental performances of the straw walls. Szasz et al. [89] compared the brick walls and straw bale walls. The U-value of straw walls was 0.094 W/m<sup>2</sup>.K and for brick walls was 0.2 W/m<sup>2</sup>.K. The results show that brick has a GWP of 85 kg CO<sub>2</sub>/m<sup>2</sup> and PEI of 1400 MJ/ m<sup>2</sup> while straw bale has a GWP of -70 kg CO<sub>2</sub>/m<sup>2</sup> and a PEI of 400 MJ/ m<sup>2</sup>.

Table 13: Calculation of straw bale and brick wall costs per m<sup>2</sup> [90]

Walls	Materials	Thickness (m)	Price (€/m <sup>2</sup> )
Strawbale wall	Loam plaster	0.035	12.07
	Straw bale	0.04	22.5
	Loam plaster	0.02	6.89
	Lime plaster	0.015	6.25
	Total	0.47	47.71
Brick wall	Lime cement plaster	0.02	3.88
	Honeycomb brick	0.25	15.51
	EPS	0.28	31.92
	Lime cement plaster	0.015	2.91
	Total	0.565	54.22

Table 14: Price and environmental impact of different types of the wall [91]

comparison of conventional walls with straw walls	U-value (W/m <sup>2</sup> .K)	Price (€HT/m <sup>2</sup> )	price of the thermal resistance unit per m <sup>2</sup> (€HT/m <sup>2</sup> )	greenhouse gas emission (kg CO <sub>2</sub> / m <sup>2</sup> )	gray energy (kWh/m <sup>2</sup> )
Conventional wall isolated from the inside	0.33	166	55	+35	129
Conventional wall isolated from the outside	0.22	185	42	+41	212
Wall with distributed insulation (cellular concrete)	0.26	209	55	+75	208
Coated straw wall on both surfaces	0.14	266	37	-14	76
Straw wall with cladding and plasterboard	0.13	231	30	-52	101

Borjan et al. [90] also compared the straw wall to the brick wall economically and environmentally. Both studied cases had a U-value of 0.12 W/m<sup>2</sup>.K. The primary energy (PEI) of the brick wall (985.65 MJ/m<sup>2</sup>) was found 9 times higher than the straw wall (104.83 MJ/m<sup>2</sup>). In addition, the global warming potential (GWP) was 61.5 kg of CO<sub>2</sub> equivalent for the brick and -50 kg of CO<sub>2</sub> equivalent. From an economic point of view, the cost of both materials was estimated without adding the price of the structural frame material and the logistics tools. The prices are shown in **Table 13** referring to the Austrian market. In a conclusion, the brick wall's total price is found to be higher than the straw wall by 14% per one-meter square. The cost-saving was high in a straw case since this material is a local product. Mutani et al. [92] estimated, in Italy, the straw wall price by around 1200 €/m<sup>2</sup> and the standard wall price by around 1500 €/m<sup>2</sup>. Probably, this small difference was due to the low price of the straw and the high cost of the labor for specialized construction.

To sum up, the ecological side is not the only advantage of the straw material as it can be used as a cheap building material with high thermal resistance. **Table 14** exhibits the thermal resistance, the environmental impact, and the prices of the conventional and straw walls. Despite the higher price per meter square of the straw, its lower thermal resistance and greenhouse gas emissions make it a competitive material.

## 4.6. Discussion

In general, the straw walls should be sealed to prevent the deterioration of the fibers. Plasters offer various properties to the wall that may lead to positive or negative consequences. It can improve the insulating properties of the straw wall and its mechanical strength and, at the same time, may not provide a sufficient vapor barrier. The composition of a straw wall (plasters type, air gap, layers thickness) is thus of fundamental importance and has a strong influence on the hygrothermal performances but is also highly dependent on the climatic conditions. Thus, the hygrothermal properties of various types of walls must be experimentally measured and/or calculated under different external and internal conditions. More detail on the fire tolerance test of various types of walls is required. As far as acoustic efficiency is concerned, there is a lack of studies on improving the sound resistance of the straw wall by introducing new layers that have the potential to absorb acoustic waves. In addition, new tests are required to identify straw wall mechanical properties under extreme stresses, such as tests defining the wall's ability to withstand hurricane wind power. The goal is to observe the deflection of the wall every time the force is increased. Such tests should compare straw walls of various layer structures and propose solutions to reinforce them. These future researches should allow offering simple wall building regulations under different climatic and extreme conditions.

## 5. Building scale

### 5.1. Construction system

There are three main forms of straw bale construction; load bearing method, infill method, and prefabricated panel method. Walker et al. [12] described these construction methods as in situ methods of building. In the three cited methods, straw bales should be prepared and stocked in a dry environment. As mentioned in the above sections, straw bales used for construction purposes should have a rectangular shape and a density higher than  $80 \text{ kg/m}^3$ . The mechanical stability of the wall depends on the orientation of the bale and the fibers inside it. The best performance was noticed for horizontal fibers and bales laid on its largest face.

#### 5.1.1. Structural bale house or Nebraska style or load-bearing method:

This method of building was started by the Nebraskans in the USA [93], [27]. It consists of preparing a foundation and placing the bales on top of each other successively. Usually, the foundation of the structure is decided before putting the bales in their places. It can be modified in some cases to minimize the amount of concrete or any conventional material. Generally, the two types of foundation are known as slab on grade or raised floor. Then the straw blocks will be fixed to the foundation and pinned one to the other. This step will be repeated until the required height is reached. At that moment, the roof plate will come to close the built zone. In this method, the bales will support the weight of the roof since there is no structural framework. It is important at the end to properly fix the envelopes to stabilize the whole building and to distribute the weight. **Figure 19** represents the process of assembling the bales according to the load-bearing system. Small gaps may appear at the end between the compressed bales, which can let the water, and the moisture migrate from the exterior to the interior. The problem can be solved by filling the gaps with straw fibers. The openings issue, the windows, and the area of the doors in the wall have to be done while achieving the walls by specifying their borders with wood box pinned into the bales. The different parts of the building should be covered by plasters to retard the moisture and to reinforce the acoustic and fire resistance. According to Walker et al. [12], lime- and earth-based coatings are mostly used in Europe, while in North America cement (often combined with nonhydraulic lime) coatings are more common.

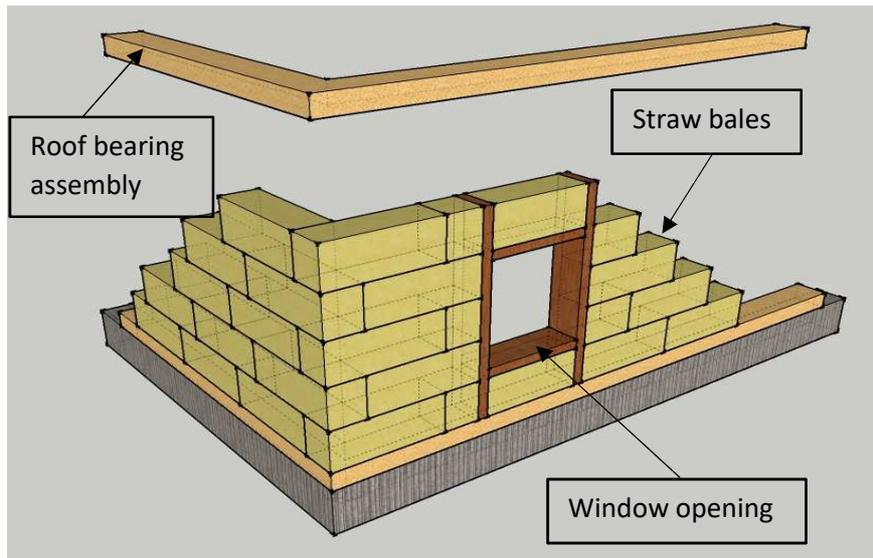


Figure 19: Load-bearing wall and roof plate construction [94]

The current method has guidelines that should be followed for safety and stability reasons [27]. For example, being an important structural part of the building, the wall thickness should be above 36 cm. Generally, this thickness can be easily passed by using large bales and plasters. The height of a 58.4 cm thick wall is limited to 3.3 m, but professional engineers can exceed this value. Moreover, the most important parameter that in addition affects the thermal properties, the fire resistance, and the sound resistance is found to be the applied load or the compression load. The live and the dead load on the top of the straw walls are limited to 1757 kg/m<sup>2</sup> and have to be applied at the wall center.

#### 5.1.2. Nonstructural bale or infill method:

The first step of this method, after finishing the foundation, is to place the beams and post. These supports can be from concrete, steel, or even wood. As a next step, the bales are added to fill the frames and to build the walls by providing the insulation property for the building. **Figure 20** shows the process of building according to the infill method. The bales are tested in compression before filling the frames. The weight of the roof in this case is supported by the beams and not by the bales. It was noticed through the years that the architects prefer this system of construction since the method of building is already established. As mentioned above the envelope should be plastered once the process is done.

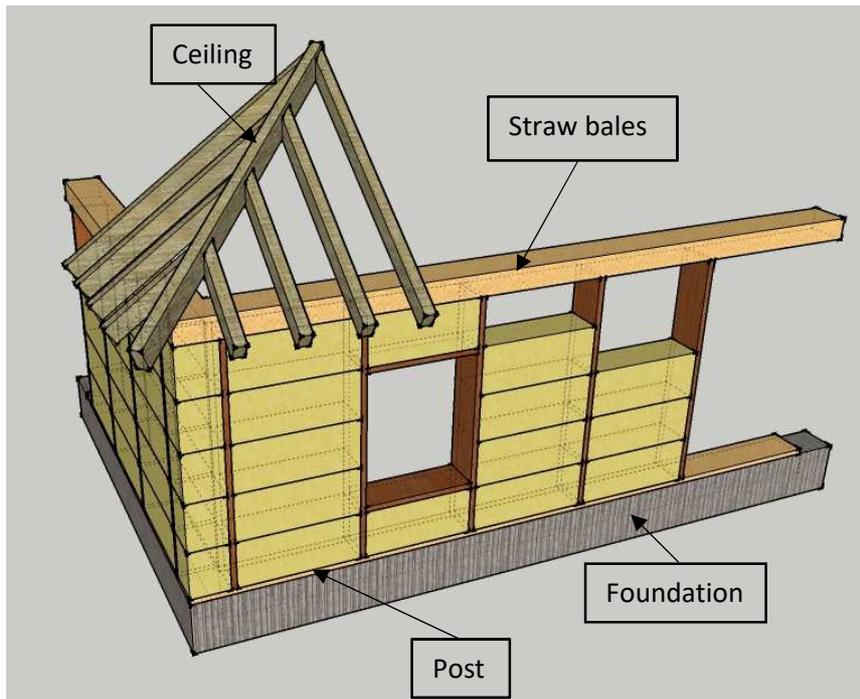


Figure 20: Infill wall and structure section [94]

It should be known that the foundation and the first row of straw bales should be at least 15 cm separated by wood or any other material [27]. Concerning the unsupported wall length of 58.4 cm thickness, it can exceed 3.3 m and reach around 7.6 m. In this method, the openings are treated as structural elements that can participate to support the wall and roof loads by using heavy frames. For the electrical and plumbing parts, installations can be placed in the interior surface of the walls and roofs or specified empty spaces. The minimum depth of the wire or the tubes should be 3.2 cm from the interior finishing of the wall.

### 5.1.3. Lightweight frame or timber framework method (GREB):

The construction technique GREB (named as its creators) is currently the most common technique for straw construction. This technique appeared in Quebec in 1990 and has since been used in many countries of the world. The objective was to seek solutions to environmental problems. It has been promoted particularly in France since 2002 (20-30% of constructions and major self-construction). It has developed in the Nordic country because it is appreciated for its thermal and technical characteristics. The thermal insulation is ensured by the straw bales, which are inserted in a double frame forming a tunnel structure. All these elements are connected by strips and metal connections (screws and nails) [3], [95]. One of the most important design features of a straw bale house is to distribute the loads as evenly as possible around the whole building. It uses a timber framework that is so lightweight that it cannot stand up alone. The straw is an essential part of the structural integrity of the building and it works with the timber to carry a load of floors and roof as shown in **Figure 21**.



Figure 21: GREB technique [3]

In this method, timber posts should be located at corners and the extremities of the windows and doors openings. In addition, they are designed in such a way to allow the timber wall plate at different floor levels to be slotted down into them once the straw bales are in place. This process can provide the essential load to compress the bales since it makes the structure more stable. Generally, the building is constructed by keeping the wall plate and roof 100 mm above the finished straw wall height before removing the bracing and props that allow the compressive settlement of the straw wall [75].

## 5.2. Regulations

Through the years, every country defined its regulations in the building sector. The purpose of deciding such regulations is to ensure the safety and comfort of humans. Regulations precise every single detail of a building to meet such as the walls layers, the indoor thermal comfort, the wall sound resistance, and many other essential parameters.

**Table 14** presents regulations and codes concerning straw constructions in different countries. These codes appeared in 2011 and added distinct information for this type of buildings. In particular, they insisted on the thermal insulation of the walls, their acoustic resistance, their stability, and their fire resistance. In addition, the durability of the straw building was inspected since it depends highly on the moisture content inside the structure. In 2015, an appendix for the bale construction appeared and started to be applied by the International Residential Code (IRC) for one and two-floor level buildings [96]. The appendix contains terms definitions and technical information about the straw bales and the straw walls. Any type of straw can be used to compose a bale such as wheat, rice, barley, and oat. The bales used for construction were set to be rectangular with a minimum height and thickness of 30 cm. Strings used to tie the bales can be synthetic or natural fibers and even metal. Ties should not be less than 0.8 cm. This element is important since it can maintain the bale dry density at around  $104 \text{ kg/m}^3$ . The dry density is calculated by dividing the dry weight (by subtracting the moisture weight) of the straw fibers by the volume of the bale. The moisture content should be less than 20% of the bale weight. Bales are pinned internally and externally to have a stable wall. Pins can be from steel, wood, or bamboo with respectively 13 mm, 19 mm, and 13 mm diameter. The distance between two successive pins can maximum be 61 cm. A straw building can last 100 years if it was properly protected and accurately covered. Plasters can protect the walls from deterioration due to the moisture presence and the micro-organism presence. In addition, these layers are also used to mechanically reinforce the walls and to restrict the passage of air and vapor through the bales. The minimum plaster thickness is defined to be 1 cm and it could be made from cement, clay, and wood.

Table 14: Different countries having regulations concerning straw bale constructions (based on [97])

Country	About the regulation	year
Denmark.	The Danish Building and Urban Research Institute published a guide for all testing and design issues concerning straw construction.	1994
USA	Strawbale building code acted as a pioneering document for the industry and the other strawbale building codes.	1996
Belarus	The code includes requirements for the quality, moisture content, and density of the straw bales, which can only be used for insulation infill and not to support the weight.	1999
Germany	Straw can be used only to thermally insulate the building.	2006
Canada	The building code of Canada defined the process of construction, the maintenance procedure, and the fire system of straw buildings.	2011
France and the Czech Republic	The code was carried by the government. Therefore, straw buildings should have a technical detailed report to obtain a building permit.	_____
Australia	Building Code of Australia classified straw constructions as an alternative solution in the building sector.	_____

### 5.3. The building and its energy impact (LCA)

Straw buildings can save energy by employing their low embodied energy and insulation property. In addition, the carbon footprint is low compared to the other conventional materials. In this section, the impact of straw buildings will be investigated.

Atkinson [60] considered a small strawbale cabin in the UK with one bedroom and living room. Its external dimensions are approximately 4 m x 10 m. It was built using the load-bearing method. The bales were approximately 1m long, 0.475 m wide and 0.4 m high. **Table 15** lists the materials used to build the small cabin. As it can be seen, the used materials have different energy rates. The total embodied energy of the straw wall has been calculated as approximately 2360 kWh, with an average of 73 kWh/m<sup>3</sup> for the wall and approximately 6000 kWh/m<sup>3</sup> for the roof.

Chaussinand et al. [98] also assessed an office building having an area of 300 m<sup>2</sup> in Swiss constructed by using wheat straw and wood frames. The study was performed against two sets of temperatures (winter and summer in Lausanne, Swiss) using the ASHRAE 14-2002 method [99]. The final energy consumption was found to be around 3800 kWh. The primary annual energy (PEI) of the building was finally assessed around 8.9 kWh/m<sup>2</sup>, based on a primary and final energy ratio of the wood about 0.7. Results also showed that 19 m<sup>2</sup> of solar panels were enough to generate the annual consumed electricity by the building. The electricity was used for mechanical ventilation, domestic hot water, and lights. Each year the electricity consumption was about 2080 kWh. This value was 10 % less than the energy consumed in the standard office buildings. This study revealed that the energy impact of straw in buildings (for heating) is excellent compared to the other materials.

Table 15: Materials used in the Straw Bale Cabin and its embodied energy classification [60]

	Volume (m <sup>3</sup> )	Embodied energy (energy rating)
Foundation:		
Steel chassis	0.07	Extremely high 0 %
Supporting timber	0.45	Low 6%
Walls:		
Wheat straw	28.2	Very low 85%
Lime plaster	1.35	Medium 7%
Clay plaster	0.93	Very low 85%
Plastic straps	---	Extremely high 0 %
Windows and doors:		
Softwood windows	0.17	Medium 7%
Double glazed units	0.04	Very high 0 %
Redwood doors	0.19	Medium 7%
Roof:		
Cedar shingles	1.3	Very low 85%
Stainless steel nails	---	Extremely high 0 %
Roof timber	0.8	Low 6%
Wood fiberboard	0.45	Medium 7%
Clay plaster	0.32	Very low
Floor:		
Plywood	0.12	High 2%
Timber joists	0.57	Low 6%
Thermafleece	5.43	Very low 85%
Floorboard	0.24	Medium 7%

A Life-Cycle Analysis of 18 houses (an area of 200 m<sup>2</sup>) was performed by Alcorn and Donn [100] to find the embodied energy and embodied CO<sub>2</sub>-eq in their materials. As result, they noticed that straw bales constructions with a timber frame emit about 1900 kg of CO<sub>2</sub> equivalent per year and have an annual consumption of energy of 37.9 GJ while a standard house with conventional insulation, wood timber, and concrete floor consume about 41.7 GJ energy per year and emits about 2197 kg of CO<sub>2</sub> equivalent per year. These results show the advantage of straw material as bio-based in reducing heating energy and CO<sub>2</sub>-eq emissions.

#### 5.4. Discussion

Since the advent of straw as a construction material, various construction methods have arisen, from load-bearing and frame infill to prefabricated panels. Each method has its advantages and drawbacks as shown in **Table 16**. However, the literature shows that such methods have not been sufficiently characterized in terms of their inherent benefits and drawbacks from thermal, mechanical, and engineering viewpoints. For example, it is still unclear which construction method provides the best thermal comfort and energy savings or which method is the worst in terms of seismic resistance. Experimental and numerical studies should be carried out to this end. At the same time, a series of measurements and simulations on straw buildings are required to assess their life cycle from the harvesting stage to the end life of the materials.

Table 16: Advantages and disadvantages of the load bearing, infill, and GREB methods (based on [75])

	Advantages	Disadvantages
Load-Bearing method	It is a simple and fast method allowing flexible designs and shapes.	Straw bales should be stored in a dry environment even during the building process.
	The method requires basic principles.	Only 50 % or less area of the wall can be windows and doors.

	Small or large buildings with multi-store can be done.	The maximum unbraced wall length is 6m.
Infill method	Every part of the building can be prepared before placing the straw bales.	More complicated to build than the Nebraskan style.
	The frame can be steel, concrete, or wood and made off-site.	Specific skills are needed to construct the frames.
	The openings frame is more stable than the Nebraskan style	It uses a large amount of timber or wood.
GREB method	The roof can be placed before the straw bales.	Technical skills are needed to ensure the stability of the structure.
	Framework and posts can be pre-constructed.	More complicated than the above methods
	Openings are more stable than in both above methods	

## 6. Straw embedded in composite construction materials

Straw can be used also as an enhancement material by mixing it with conventional material such as concrete, hollow bricks...etc. Belhadj et al. [101] compared the thermal properties of sand concrete to barley straw sand concrete mixture. These two types of materials were used to build an external wall in the Arid Region. In the first composite, the sand and cement densities were  $1316 \text{ kg/m}^3$  and  $350 \text{ kg/m}^3$  respectively, while the total density after mixing was  $2042 \text{ kg/m}^3$ . In the second composite, the sand, the cement and the barley densities were  $1245 \text{ kg/m}^3$ ,  $350 \text{ kg/m}^3$ , and  $15 \text{ kg/m}^3$  respectively, while the total density was  $1895 \text{ kg/m}^3$ . Results showed that the density of sand concrete was improved by 8%. In addition, the thermal conductivity of both composites was measured and the time lag and the decrement factor of both walls were calculated. Straw enhanced the thermal insulation of the sand concrete since the thermal conductivity was  $1.4 \text{ W/K.m}$  for the first material and  $1.32 \text{ W/K.m}$  for the second material. For the time lag and decrement factor, it was noticed that the straw was able to ameliorate both factors by 1 h and 20%, respectively. Zhang et al. [102] studied the thermal properties of the straw and cement blocks that composed the exterior side of the north wall of a solar greenhouse. The wall thermal conductivity was  $0.075 \text{ W/m.K}$ . Its volumetric specific thermal capacity was  $0.187 \times 10^6 \text{ J/m}^3 \cdot \text{K}$ . The indoor temperature was higher than the outside by  $3.4^\circ\text{C}$  during winter and  $11.5^\circ\text{C}$  during summer. These values can prove the ability of the material to store heat and provide good thermal insulation. Hou et al. [103] investigated the influence of the coupled heat and moisture transfer on building envelop composed from hollow concrete blocks filled with straw fibers. The thermal conductivity of the composite was  $0.04 \text{ W/k.m}$ , the density was  $257 \text{ kg/m}^3$  while the thermal conductivity of the concrete was  $1.515 \text{ W/k.m}$ , and the density was  $2050 \text{ kg/m}^3$ . In addition, the hygrothermal property of the envelope was studied by following the variation of the temperature and humidity of the materials while controlling the air conditions on one side of the wall. Results showed that the presence of straw stopped the temperature and the moisture transfer in the structure since it has a low water vapor permeability coefficient. Agwa et al. [17] mixed rice straw ash with cement to characterize the material mechanically. Three mixtures of rice straw ash were used (5%, 10%, and 20%) with the same quantity of cement each time. In general, the use of straw ash had a positive effect on mechanical properties. For example, the compressive strength increases by 10% for the second mixture. This increase was explained by the pozzolanic activity and the micro filling abilities of the straw ash. The second mixture also showed the highest tensile strength and it was 32% higher than that of plain concrete. This increase was explained by the lower ratio of potassium oxide  $\text{K}_2\text{O}$  in the straw ash. For the flexural strength, an increase of 22% was noticed for the second mixture. This increase was explained by the increase of the compressive strength that affects directly this factor. Sabapathy

and Gedupudi [104] studied the influence of straw, used to insulate a concrete structure, on cooling and heating loads for different exterior conditions. The straw was able to minimize the fluctuation of the heat flux at the interior side of the wall. 10 cm of the straw layer was enough to decrease the maximum cooling and heating loads to 45 W/m<sup>2</sup> and 40 W/m<sup>2</sup> respectively. Therefore, the energy savings varied between 67% and 96%. Ahmadi et al.[105] evaluated the properties of 55 kg/m<sup>3</sup> density wheat straw as an insulating layer to fired clay hollow bricks. Results showed a positive effect for the presence of straw. For example, the thermal transmittance varied between 0.87 W/m<sup>2</sup>.K and 1.0 W/m<sup>2</sup>.K for a wall filled with a straw while for an empty wall, it varied between 1.78 W/m<sup>2</sup>.K and 2.07 W/m<sup>2</sup>.K. The use of compressed straw to insulate the fired clay hollow bricks can save fuel and energy consumption. It was noticed by the values of effectiveness ratio of energy saving (42.97%), and the fuel savings (1835 W).

## 7. Synthesis

Straw bale construction dates back to the invention of the baling machine and appeared in the USA around 1886. It was imported to Europe in the early eighties during the energy crisis. Now it is gaining attention to decrease the CO<sub>2</sub> emissions and the energy consumption caused by conventional construction materials and buildings. This review shows the performance of straw as an agricultural byproduct construction material, starting from the microscopic scale to the building scale, passing through the bale and wall scale.

Straw fibers size distribution and morphology analysis showed that, regardless of the straw type, the majority (76-90%) of fibers are 2 mm long, which gives bales more important mechanical properties than long and continuous straw fibers. In addition, it showed that fibers have a porous structure, which leads to lower thermal conductivity and water diffusion factor. Straw's mechanical and thermal properties are also affected by the chemical composition of this material. The composition of cereal plants, including wheat, barley, and triticale is similar to wood. It contains about 45% of KH-cellulose, 30% of  $\alpha$ -cellulose, and 7% of moisture, which provide a stable and durable material. Moreover, it contains about 25% of Klason lignin that is responsible for increasing its mechanical strength properties. Bales, in their different dimensions and shapes, can have a variety of densities for construction utility that range between 80 kg/m<sup>3</sup> and 130 kg/m<sup>3</sup>. This variation affects the thermal conductivity of straw bales. Several researchers showed that the thermal conductivity depends not only on the density's bale but also on the straw type, the fibers orientation, and the RH or moisture content. For a heat flow perpendicular to the fibers' main orientation, the thermal conductivity decreases with the increasing density, while when the heat flow is parallel, the thermal conductivity increases with increasing bale density. This can be explained by the resistance of the air and the straw walls against the heat flow when it is perpendicular, and by only the air resistance when it is parallel. In general, straw bales can feature thermal conductivity as low as 0.033 W/K.m and up to 0.19 W/K.m.

Experimental characterization of mechanical resistance shows that straw bales feature non-linear stress-strain behavior at lower loading levels and higher anisotropic behavior with the vertical strain when the fibers are vertically orientated than when they are horizontal. After removing the loads, bales generally exhibit a complete recovery of deformation, which represents their elastic behavior. The modulus of elasticity ranged between 200-300 kPa for low densities (80-90 kg/m<sup>3</sup>) bales. The stress-strain curves show the flexibility of the material since the modulus of elasticity varies little under elastic loads and stays within the linear regime. The bales' density, thickness, and moisture content, as well as the other wall layers such as plaster finishing, affect straw walls U-value, the most important property in presenting the thermal insulation capacity of a wall. Experiments on different thicknesses and densities showed that a straw wall transmittance could be optimum with a value of 0.25 W/K.m<sup>2</sup>. In all cases, for such types of walls, the time lag for the propagation of heat from the outer surface to the inner surface is about 6 to 10 h for a decrement factor lower than 0.1, which are good thermal inertia properties. Moving to the sound insulation aspect, straw bale walls cannot be considered as good sound insulating structures, since their lightweight limit their efficiency at low frequencies. Studies showed that the sound reduction index  $R_w$  range between 45-58 dB which is lower than 60 dB for conventional wall materials. Regarding the lack of oxygen inside the compressed bales, the

material offers a high tolerance to flame and temperature rise. Various fire tests revealed that straw walls meet national building code requirements. Plastered straw walls, for example, according to ASTM E119-05a have a fire endurance of 2 hours. In 1994, regulations appeared all over the world to specify the shape, density, and size of bales, to give a specification for the pins, ties, and moisture content. To ensure the protection of the material, walls should be finished and protected from the weather (RH) and fire. Many full-scale studies describe the construction technics of straw houses, Nebraska, Infill, and GREB, giving each one pros and cons. In all cases, straw buildings have less embodied energy and consume less final energy during operation than conventional buildings, thus fulfilling the purpose of the use of bio-based material. **Table 17** resumes the properties of several construction materials when compared to straw. A topology diagram, seen in **Figure 22**, replicates the properties of straw material in buildings.

*Table 17: Properties of different material*

Material	Thermal conductivity (W/m.K)	Density (kg/m <sup>3</sup> )	Specific heat (J/kg.K)	water vapor diffusion $\mu$
Concrete	1.13 [106]	1440-2400 [106]	1000 [106]	50-150 [107]
Straw	0.05-0.12 [59]	70-200 [32]	1500 [59]	1.5 [107]
Brick	0.3-1.1 [108],[109]	1600-1800 [106],[109]	1000 [106]	15 [107]
Steel	45 [108]	7800 [108]	480 [108]	10 <sup>6</sup> [107]
Wood/timber	0.14-0.22 [110]	600-1500 [108],[110]	1200 [110]	40 [107]
Fiberglass	0.045 [111]	1500 [112]	700 [113]	1 [107]
Gypsum	0.5 [106]	1300 [106]	1000 [106]	7-10 [107]

Despite all these researches, some information to characterize and standardize the material is still missing in the literature. Regarding the thermal characterization, more experiments concerning the variation of the thermal conductivity versus the moisture content for different types of straw are needed. Researchers studied extensively the conductivity and its variations while the variation of the specific heat, the diffusion factor, and pH has been insufficiently searched. These factors should be studied in detail while varying the density, the RH, the fiber's orientation, and the type of straw. On the wall scale, studies on the mold formation on straw wall surfaces are lacking. In this respect, no condensation isopleths as a function of the wall structure for varying hygrothermal boundary conditions can currently be found in the literature. At the building scale, there are still very few numerical studies on the energy behavior of straw-based buildings depending on the wall structures, the building location, and its scenarios of occupation and operation. The role of straw as a regulator of indoor air moisture is also insufficiently documented. Such future studies should consider the variability of the results, due to the changing nature of the thermophysical properties of this bio-based material over time. Based on the energy results, the economic feasibility of such buildings should be more intensively searched, especially in terms of payback period and life cycle cost. Regarding the mechanical characterization, while the strain under compressive stress and the modulus of elasticity have been searched, the literature lacks studies on straw bale response to torsional and shear stresses. More important, information on the effect of the bending stress on the bale thermal conductivity is missing while bale bending may happen when employed as floor or roof material.

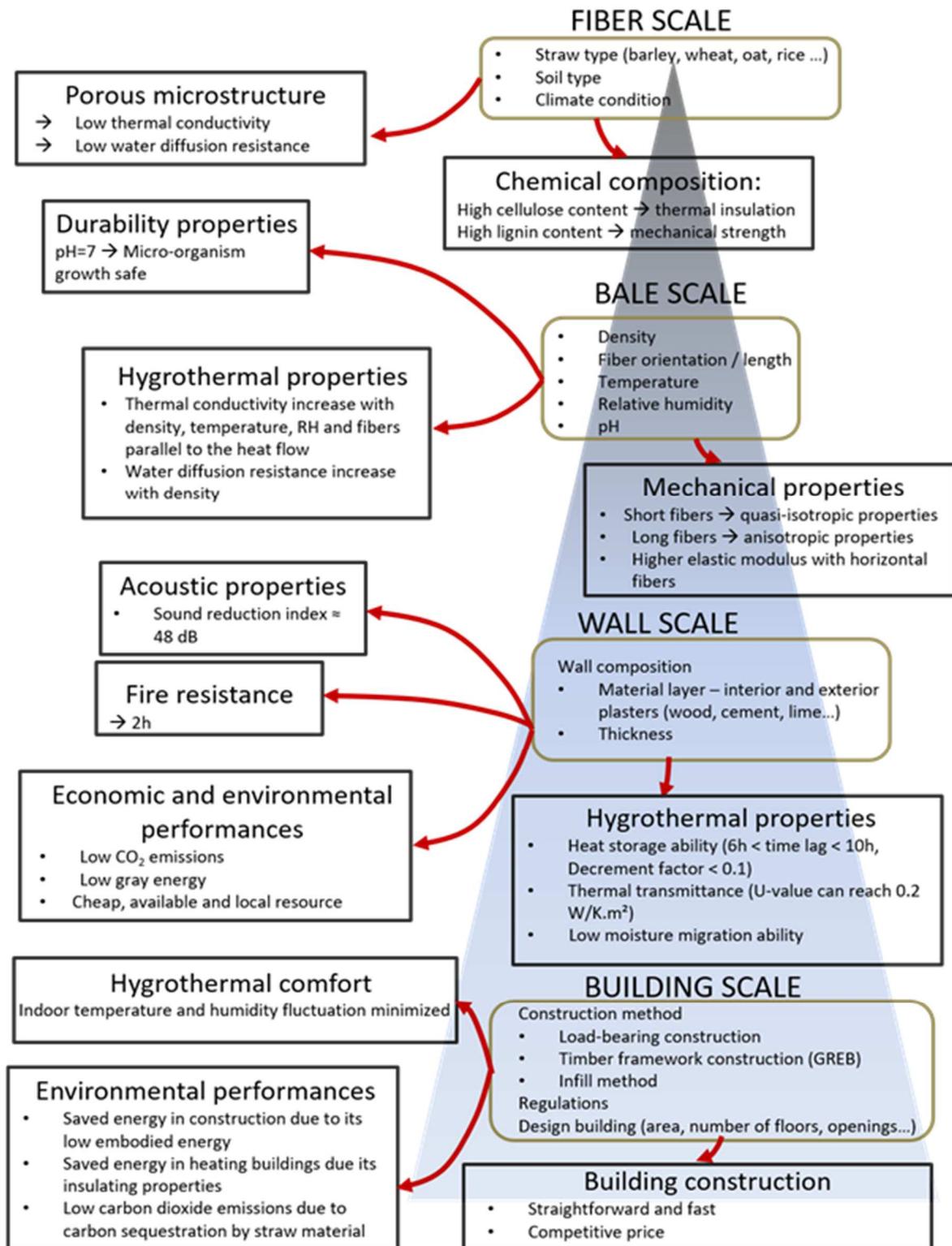


Figure 22: Diagram showing the characteristics of straw at different scales

## 8. Conclusion

This review aims to highlight the results achieved so far by studies on straw as a construction material, as well as to identify aspects that need to be further investigated. The general idea of having a bio-based building is to minimize the energy consumption and the CO<sub>2</sub> emissions having an environmental impact. Over the years, straw bale construction has evolved and spread all over the world. Strawbale has good fire and sound resistance, can create an insulating layer, and resist the flow of heat. This

product can last many years but it has to be protected from moisture, vapor, and water by using a different kind of coating as mentioned in several international regulations. Generally, to set up a straw building, the type of the straw should be chosen based on its availability around the work area. This step is important because it can reduce the CO<sub>2</sub> emissions and the embodied energy caused by the transportation of the material. Secondly, the bales should be tested to check their density and RH according to the regulations of the country. Last, the construction method should be chosen according to the site conditions. The analyzed studies represent an important step forward in the dissemination of straw bale building practices as a recognized construction technique, especially in situ testing, which gives a quantitative assessment of the physical and mechanical properties. Although, a lack of consistent data among these studies was noticed due to the wide variety of characteristics that this material presents. On the fiber scale, straw fibers should be compared with the natural and synthetic fibers regarding their microstructural properties to highlight their mechanical and thermal properties. On the bale scale, all the thermal properties should be studied regarding density, fiber orientation, relative humidity, and temperature. On the wall scale, studies should be focused on the hygrothermal properties of various types of walls under different conditions. For the acoustic aspects, the sound insulation of straw walls should be improved by adding new layers. On the building scale, the mechanical behavior of different straw buildings should be carried out under extreme conditions. At the same time, life cycle and economic analysis should be done to show the importance of straw buildings.

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