Construction and Building Materials 259 (2020) 120385

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Review

A review of material properties and performance of straw bale as building material

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HIGHLIGHTS

- The thermal conductivity increases linearly with bulk density ρ ($60 \leq \rho \leq 120$ kg/m^3).
- The isotherm sorption curves of straw bale are similar to wood.
- Young's modulus and Poisson's ratio depends on bulk density and bales orientation.
- A wall structure of 500 mm thickness has U-value between 0.1 and 0.2 W.m^{-2}.K^{-1}.
- Straw bale has less environmental impact compared to typical insulation materials.

ARTICLE INFO

Article history:
Received 31 January 2020
Received in revised form 29 June 2020
Accepted 26 July 2020
Available online 31 August 2020

Keywords:
Straw bale
Material properties
Heat, air and moisture transport
Energy
Life cycle assessment
Soundproofing
Fire resistance
Mechanical performance

ABSTRACT

Straw bale constructions are considered as a promising solution towards the goal of decarbonisation of building sector. In particular, its use as an alternative thermal insulation and load-bearing material has been promoted. This study provide a thorough review of material properties of straw bale including mechanical, thermophysical and hygric. Furthermore, mechanical, hygrothermal, energy and acoustical performance as well as life cycle assessment of straw bale constructions are reviewed and discussed. The critical evaluation of the recent research confirms that straw bales can provide satisfactory results as thermal insulation material compared to conventional materials, while in parallel reflects a high potential for constructions with low embodied emissions. The potential of straw bale is tackled by the lack of consistent representation of material properties, which is controversial to the significant amount of the relevant scientific results that have been reported during the last years. This review provides a systematic framework that can function as basis for future research on straw bales as building material.

Contents

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https://doi.org/10.1016/j.conbuildmat.2020.120385

1. Introduction

The building and construction sector accounted for 36% of final energy consumption and 39% of energy and process related greenhouse gas (GHG) emissions in 2018, with 11% of which resulted from manufacturing of building materials [1]. Decarbonizing this particular sector is essential to tackle the global warming and mitigate the climate change. Three measures have been proposed to reduce the GHG emissions from building: i) reducing energy consumption during service life as well as embodied energy in buildings, ii) switching to low carbon fuels, or iii) controlling the emissions of non-CO_2 GHG gases [2]. United Nations Environment Programme (UNEP) has recommended the purchasing of building material based on low embodied carbon and energy, as one way to reduce the environmental impact in building sector [1]. In its 2018/19 annual report, the World Green Building Council (WorldGBC) has also called for all new buildings should have at least 40% less embodied carbon by 2030, and to be net zero embodied carbon by 2050 [3]. The embodied energy and carbon in construction materials are especially important in places with high construction activities and availability of affordable low carbon and low energy materials that can be used to achieve low life cycle energy buildings [4].

Straw is the left-over stalk of cereal plants, e.g. wheat, maize, rice, barley, oats, rye and sorghum, after grain has been harvested. Chemically straw is composed mostly of cellulose and lignin, the same major components of wood. It contains no nutrition and is traditionally used as bedding for livestock, burned, ploughing back to soil, or treated as supplement for animal feed [5]. Straw is also used as a renewable energy source for biomass energy generation [6]. However, it might be more beneficial if the straw can be used as building material, acting as a mean to store carbon, at the same time reducing the dependency of using other high embodied energy materials. If a straw in a building need to be replaced or disposed, it could be composted afterwards. The straw bale as building materials can provide particularly benefits in regions where straw has become an unwanted by-product.

The straw bale buildings were first constructed in late 1800s in Nebraska, USA with the development of steam powered baler. Even in earlier days, walls made from either tied bundles of straw coated with clay or compacted loose straw mixed with clay have been constructed for centuries throughout Asia and Europe [7]. There are two basic styles of straw bale construction, refer to Fig. 1, with other varieties and hybrid methods in used [8]. Post and beam (framing) style uses a structural framework to support roof loads, and the straw bales are either wrapped outside the framework or in filled between the framing members. Load bearing (Nebraska) style bale buildings use the straw bale themselves to support the roof and first floor if any, where a structural roof plate is placed on top of the walls, and the compressed straw bale system draws

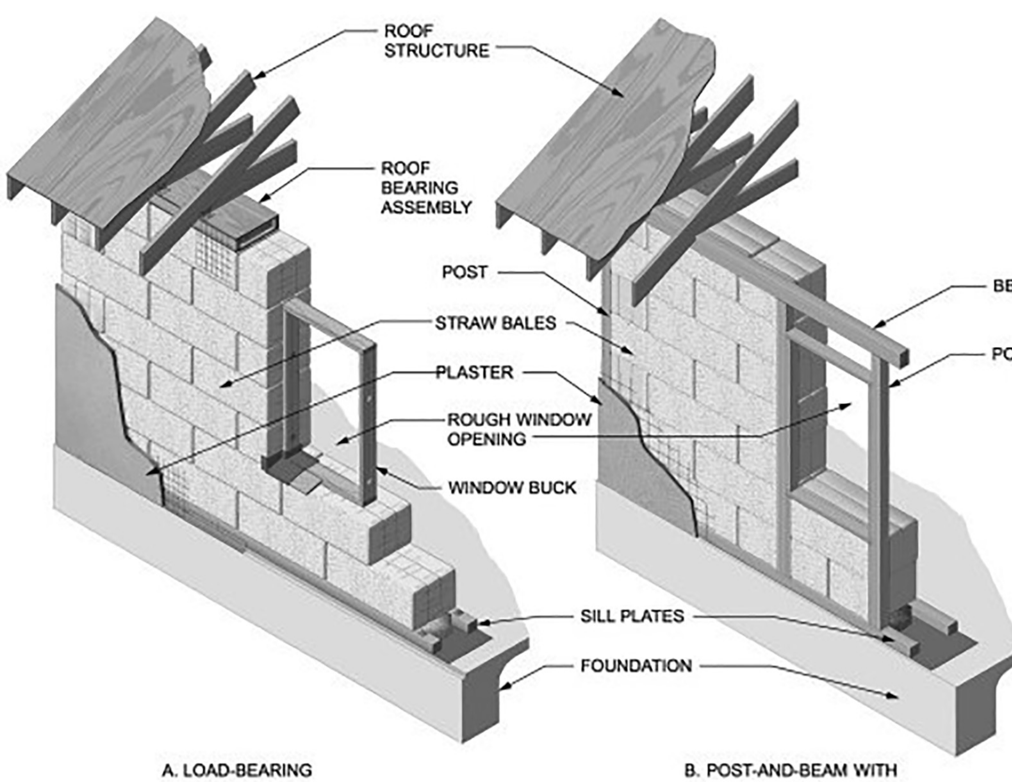

Fig. 1. Straw bale wall systems. Credit: Figure AS101.2 Excerpted from the 2018 International Residential Code; Copyright 2017; Washington, D.C.; International Code Council. Reproduced with permission. All rights reserved. www.ICCSAFE.org.

this roof plate down toward the foundation. Recommended prescriptive requirements for the straw bale construction are also covered under Appendix S in the 2018 International Residential Code (IRC).

Straw bales are primarily functioning as thermal insulation material in straw bale buildings. However, based on a market research done in 2014, the use of organic plant derived materials such as straw bale as thermal insulation material is not widely practiced yet in Europe. It is noted that most frequently used thermal insulation materials are the inorganic mineral fibrous materials, e.g. glass-wool and stone-wool, follow by the organic fossil fuel derived foams, e.g. expanded and extruded polystyrene and polyurethane, whilst all other materials cover the remaining 1% of the market [9].

In a survey to different stakeholders of construction industry by White et al. [10], from the perspective of non-practitioners of straw bale building, there is a lack of available standardized materials and methods regarding straw bale construction. However, practitioners of straw build believe that the main barrier on further diffusion of straw bale construction around the world is the lack of general knowledge and inaccurate perceptions of straw build as well as the limited accessibility to skilled labour. Another survey to architecture students by Erbil et al. [11] revealed that while the beneficial environmental characteristics of buildings in straw bale are recognized, the technical characteristics of straw bales are not well understood compared to other conventional building materials. Similar to other natural building materials, two UK studies [12,13] concluded that further and more organised research is required to develop straw bale with sufficient technical data, so that the engineers and architects have solid background to use it in mainstream constructions, and get accepted by the homeowners, insurers and local authorities.

2. Review on basic properties of straw bale

In this section, hygrothermal, sound and mechanical properties of straw bales are reviewed based on previous tests and studies. The focus is on the relation between various basic properties of straw bale with bulk density, as available in the market. Basic straw bale without finishing or additive is primarily discussed, however studies on straw bale with common surface finishing such as plaster is also briefly presented when the basic properties of straw bale structures can be influenced by its finishing.

2.1. Thermal conductivity λ

The thermal conductivity of straw bale has been measured and reviewed in more than 40 peer review technical papers. Fig. 2 summarizes the steady-state thermal conductivity measurements of straw bale against density from different studies. The majority of these measurements [14–24] were determined in accordance with guarded hot plate method, based on ISO 8302:1991. The other two steady-state methods which have been used in the straw bale studies are measurement using heat flow meter apparatus [25] based on ISO 8301, and measurements using small hot box apparatus [26–28] based on EN-ISO 8990:1994 or ASTM C1363-19 [29]. Thermal conductivity can also be measured comparatively quicker using transient method, such as transient plane source method [30], transient line-source method [31] and other method using thermal probe for measurement [32], though a more complex analytical process needs to be applied compared to steady-state method.

In general, thermal conductivity of straw increases with bulk density ρ, however different correlations have been reported in various studies (Fig. 2). Linear correlation in the range of 60–130 $kg{\cdot}m^{-3}$ was observed by Costes et al. [16] using guarded hot plate method, and Shea et al. [25] using heat flow meter method. However, studies from Marques et al. [14], Reif et al. [15] and Cascone et al. [18] indicate a rather weak correlation between bulk density and thermal conductivity of straw bale. A non-linear relation was also suggested by Vėjelienė [34] where optimum thermal conductivity was observed in the density range of 50–80 $kg{\cdot}m^{-3}$, and the thermal conductivity increase when their densities are fall below or exceed above that range.

Fig. 2 indicates no significant deviation of thermal conductivity from different sources of straw, e.g. barley [20,21], wheat [15,16,18,26,28] or rice [14]. Overall, straw with fiber oriented perpendicular or random to heat flow showed lower thermal

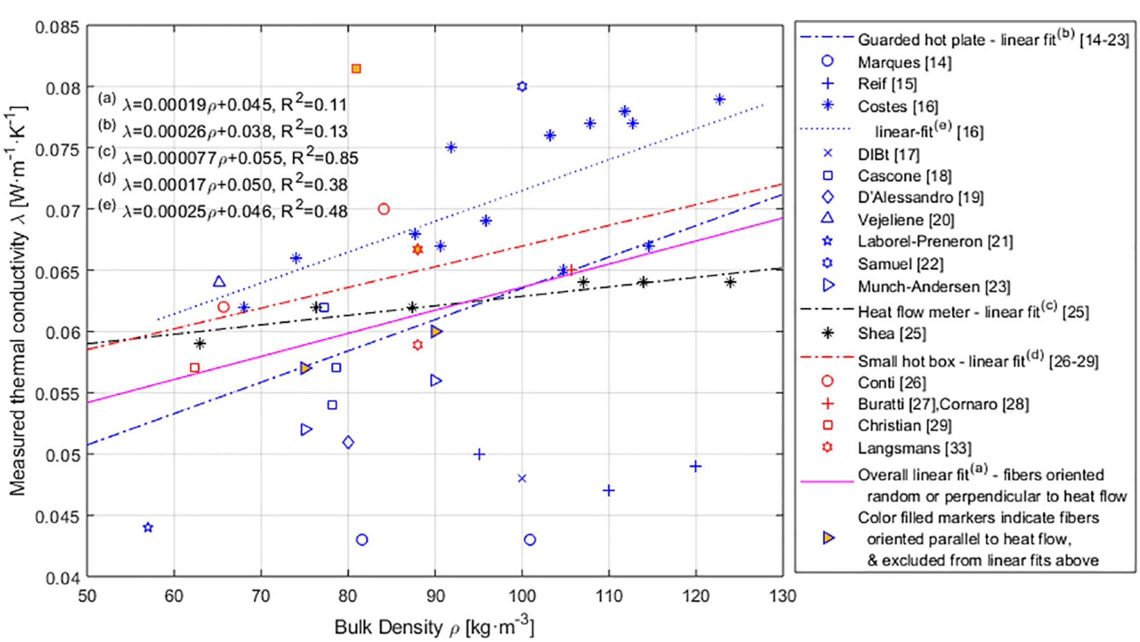

Fig. 2. Measured Thermal Conductivity vs Density based on studies from Marques [14], Reif [15], Costes [16], DIBt [17], Cascone [18], D'Alessandro [19], Vejeliene [20], Laborel-Préneron [21], Samuel [22], Munch-Andersen [23], Shea [25], Conti [26], Buratti [27], Cornaro [28], Christian [29], Langmans [33].

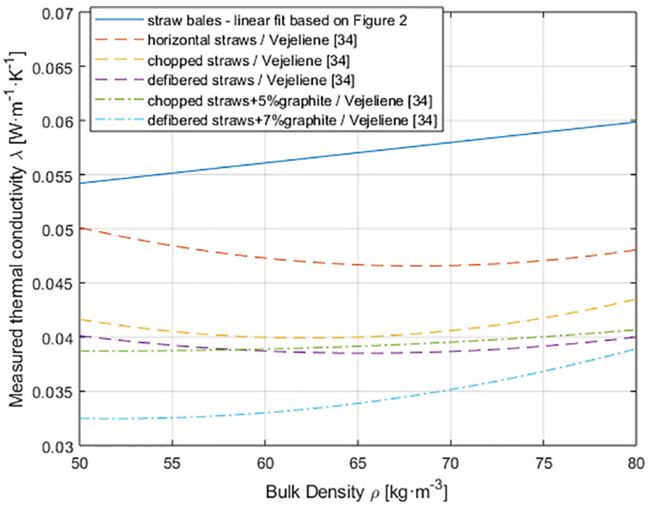

Fig. 3. Thermal conductivity of straw bales based on linear regression model from Fig. 2 in comparison with processed straws based on study from Vėjelienė [34].

conductivity compared to those arranged parallel, as observed by Munch-Andersen and Andersen [23], Christian et al. [29], Langsmans et al. [33], Vėjelienė [34] and Douzane et al. [35]. The physical structure of straws inside a straw bale will also influence its thermal conductivity; based on experiments from Vėjelienė [34], defibered straw showed lower thermal conductivity compared to chopped straw, which in turn was lower than unprocessed straw (Fig. 3). Like other insulation materials, the thermal conductivity of straw increase with increasing temperature and moisture content.

Compared to the most used insulation material such as mineral wool, EPS, XPS, etc. which can achieve thermal conductivity around 0.035–0.040 $W{\cdot}m^{-1}{\cdot}K^{-1}$ [36], the thermal conductivity of straw is comparable higher in the typical range of 0.053–0.065 $W{\cdot}m^{-1}{\cdot}K^{-1}$, which is in the same range with other wood fiber insulation material. An increase of 30–90% thickness of straw insulation layer would need to be added to achieve the same thermal insulating performance compared to other insulation material.

2.2. Specific heat capacity c_p

The specific heat capacity c_p of crushed fine straw increased with increasing temperature using differential scanning calorimeter (DSC) method based on ASTM E1269-11 / EN 821-3 / ISO 11357-4, from 1075 ± 204 $J{\cdot}kg^{-1}{\cdot}K^{-1}$ at 0 °C to 2025 ± 417 $J{\cdot}kg^{-1}{\cdot}K^{-1}$ at 40 °C, reported by Marques et al. [14]. In a separate study by Samuel et al. [22] using differential thermal analysis (DTA) method, dry specific heat capacity 2426 $J{\cdot}kg^{-1}{\cdot}K^{-1}$ was obtained. However, if to consider the void between straw fibers due to their inhomogeneous nature, an indirect method using analytical solutions has been proposed where the specific heat capacities up to 3847 ± 605 $J{\cdot}kg^{-1}{\cdot}K^{-1}$ was obtained at temperature of 23 °C and 50% humidity, which are higher compared to using either DSC or DTA methods [14]. For reference, the specific heat capacity of other similar fiber insulation material such as loose-fill cellulose fiber is at 1600 $J{\cdot}kg^{-1}{\cdot}K^{-1}$ and wood based project is in the range of 1700 to 2000 $J{\cdot}kg^{-1}{\cdot}K^{-1}$ based on the given tabulated design values from ISO 10456:2007 [36].

Thermal diffusivity is inverse proportional to specific heat capacity. In a study using transient plane source method by Sabapathy and Gedupudi [30], the correlation of thermal diffusivity with respect to air temperature θ, relative humidity φ and bulk density ρ were measured and results range from 0.24×10^{-6} to 1.53×10^{-6} $m^2{\cdot}s$. In this study, straws with parallel orientation against heat flow showed higher measured thermal diffusivity compared to those with perpendicular and random orientation. In another study, Goodhew and Griffiths [32,37] used iterative method based on thermal-probe measurements, and higher thermal diffusivity of $1.82 \pm 0.05 \times 10^{-6}$ $m^2{\cdot}s$ was obtained.

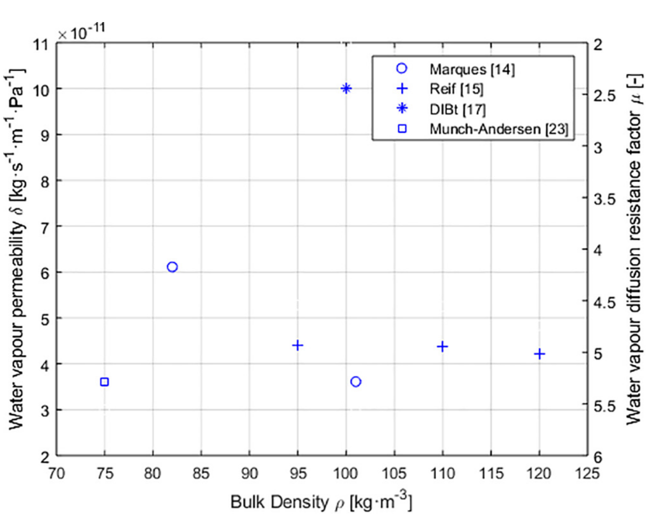

Fig. 4. Measured water vapour permeability based on studies from Marques [14], Reif [15], DIBt [17], Munch-Andersen [23].

2.3. Water vapour permeability δ

The water vapour transmission properties can be determined using test method as per EN 12086. Fig. 4 summarizes the water vapour permeability δ and water vapour diffusion resistance factor μ measurements of straw bale against density ρ from different studies [14,15,17,23]. No significant correlation between density and water vapour permeability was found based on these studies, however Lebed and Augaitis [24] observed a slight increment of vapour diffusion resistance factor with increasing density. Based on Fig. 4, the water vapour resistance factor of straw bale is close to the unit, i.e. similarly to the insulation materials such as mineral wool and other organic plant-based materials, and significantly lower than organic fossil fuel-based materials such as EPS and XPS [36].

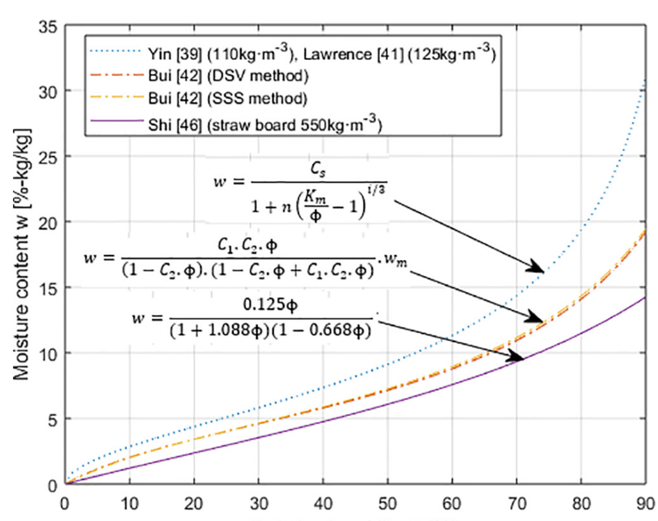

Fig. 5. Proposed equation to predict moisture content w of straw against relative humidity φ based on studies from Yin [39], Lawrence [41], Bui [42], Shi [46]. C_s, n, K_m, i, C_1, C_2 and W_m are the constants.

2.4. Hygroscopic sorption properties, moisture content and water absorption

The moisture content of straw bales have been found being in the range of 10% ≤ u ≤ 12% at 23 °C and 80% humidity [14,17,26,38] which is closed to other wood fiber based products [36] and it can be determined using either ISO 12570:2000 or ASTM D4933:16.

The hygroscopic sorption properties of straw bale can be determined as per guideline ISO 12571:2013, either using desiccator method or climatic chamber method. Majority of the papers used climatic chambers or dynamic vapour sorption (DVS) devices for the hygroscopic sorption measurement on straws [14,21,39–42], and some supplemented with desiccator method using saturated salt solutions (SSS) for comparisons [39,42,43]. Fig. 5 shows some of the proposed moisture storage isotherms, reported in different studies [14,21,33,39,41–45].

The different type of straw, i.e. wheat and rice in Yin et al. [39], wheat and oat in Carfrae et al. [43], has been proposed of having negligible impact on their equilibrium moisture content. However, Bouasker et al. [44] that showed the desorption kinetics of barley straw was slower than the wheat straw near saturation. In study by Ashour [45], the sorption rate of barley straw was higher than wheat straw, and this may be due to higher pores observed in the wheat straw which slow down the absorption rate. In addition, the isotherm sorption curves of straw was observed to be similar to the sorption curves of wood (Ramin, Pine and Oak) [43].

The hygroscopic sorption characteristics were mainly impacted by their physical conditions, i.e. open ended straw, such as trimmed straw, will equilibrate faster than closed ended straw, such as folded straw, as described by Yin et al. [39]. Studies of the straw fibers in straw bale have shown two distinct layers of cell structures in straw samples [20,44,47,48]: an outer layer with denser and smaller capillaries and an inner layer with porous and larger capillaries with thinner cell walls. In studies by Vejeliene et al. [20] and Bakatovich et al. [47], after applying loads on the straw samples, the outer layers of the cells were fragmented, while the inner layer was deformed. When higher load applied, the inner layer of the straw cell was collapsed. It was also observed that the outer and inner layers were not bonded well in the samples [20]. This means the microstructures of the straw will be easily deformed into various conditions during the baling and sampling process, and this may explain the deviations of thermal and hygroscopic performance of straw samples in many experiments. In general, the sorption and desorption curves of the same straw sample showed a hysteresis pattern.

In term of water absorption capacity, the short-term water absorption of straws can be determined as per EN ISO 29767:2019 (replace EN 1609) using partial immersion method, which simulate the water absorption caused by 24 h raining period. An increase of mass close to 100% was observed on test samples from Marques et al. [14] and Lebed and Augaitis [24], and higher water absorption values were observed on higher density samples. Full immersion method were used to check the absorption capacity of straws if used as aggregate material, and water absorption coefficient in the range of 290–414% were observed by Laborel Préneron et al. [21] and Bouasker et al. [44]. An increase of water absorption with increasing temperature was observed by Bouasker et al. [44].

2.5. Mechanical properties

The compressive resistance of straw bales is particularly important if they are used as load-bearing structure in a building. Studies on the compressive stress–strain curve of straw bales showed a non-linear behavior in a deformed S-shape [38,49–51], with a narrow curves in the beginning corresponding to the setting of the testing device to fit the sample, followed with a near linear elastic behaviour, and continued to the last stage with a perceived effect similar to hardening behavior, due to the nature of material (Fig. 6). Hysteresis loops were also reported by Lecompte and Duigou [49] and Ashour et al. [38] in the stress–strain curve of the straw bales, where the straw bales recovered from their deformation after removal of loads, but in a longer time frame which varied between 10 and 13 min for a complete recovery [38]. This viscoelasticity behaviour enables straw bale to store deformation loads, e.g. to absorb the seismic loads in an earthquake. Cyclic tests on straw bales by Maraldi et al. [52] observed the capability of straw bales to dissipate energy during the cyclic loading, but decreased and reached an asymptotic value as cyclic loading progresses. In the same paper by Maraldi et al. [52], both creep test (strain on imposed load) and relaxation tests (stress on imposed displacement) were carried out, and confirmed the viscous behaviour of straw bales, and similarly both stress (on creep test) and

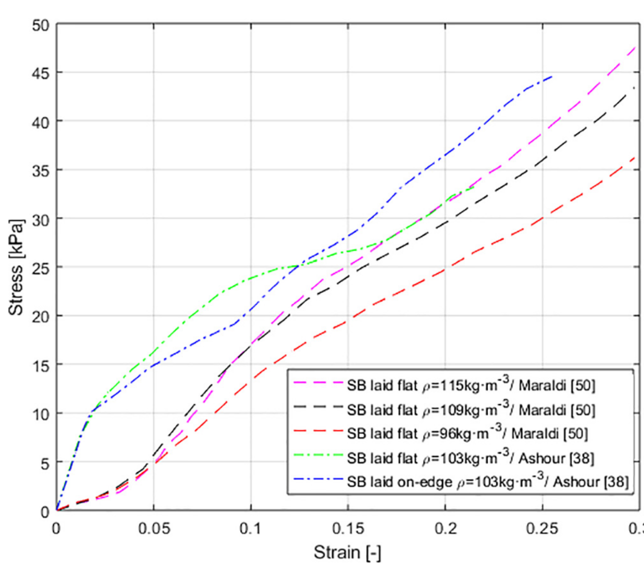

Fig. 6. Stress–strain curve at low strain based on studies from Ashour [38] and Maraldi [50].

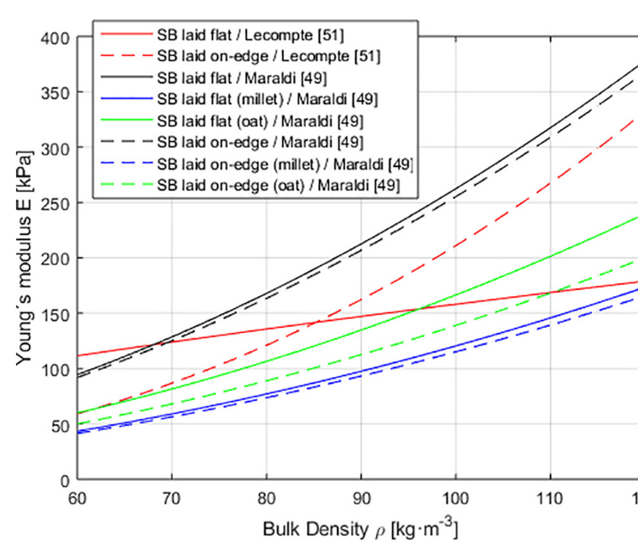

Fig. 7. Young's modulus of straw bales based on study from Lecompte [51] and Maraldi [49].

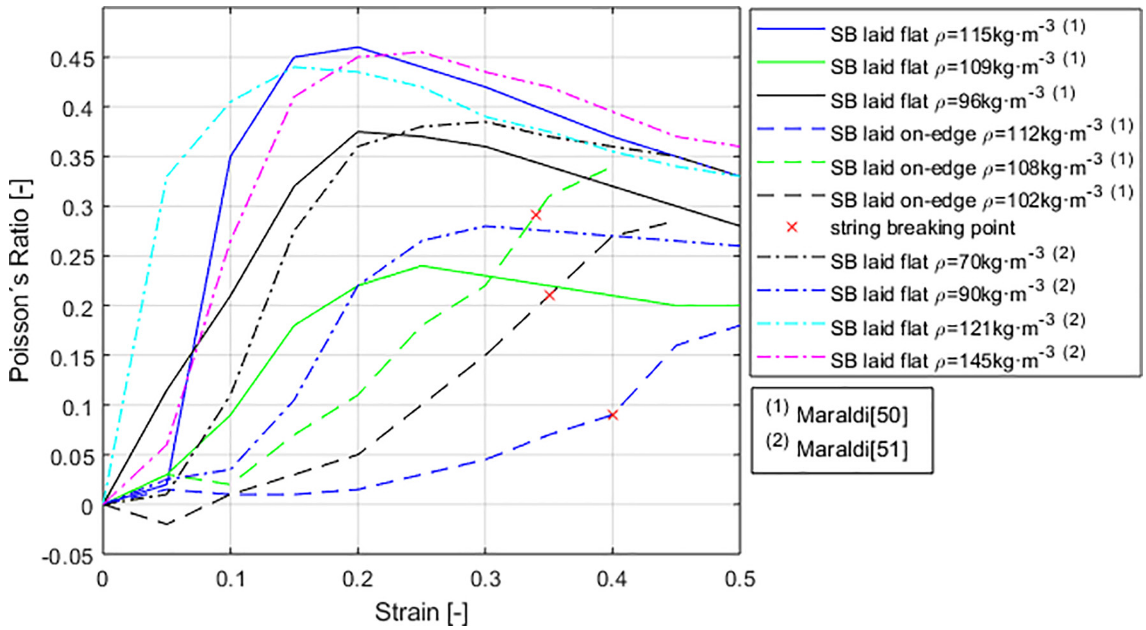

Fig. 8. Poisson's ratio against strain of tested straw bales based on study from Maraldi [50,51].

strain (on relaxation test) will settle down to an asymptotic value eventually.

Measurement of Young's modulus and Poisson's ratio are used in the study of deformation of straw bales under stress. Correlations between Young's modulus E and density ρ has been suggested, with E = a.ρ^2 proposed by Maraldi et al. [51] and a power law function E = a.ρ^b proposed by Lecompte and Duigou [49], where constant *a* and *b* depend on the orientation and type of straw bales (Fig. 7). Young's modulus for on-edge (vertical, typically parallel to heat flux direction) bales was observed to be lower than flat (horizontal, typically perpendicular to heat flux direction) bales in these studies, which may be due to geometrical reasons linked to loading area and slenderness. Using Lecompte and Duigou [49] as reference, the Young's modulus values between 100 and 200 kPa were observed from wheat straw bale samples with density of 80 to 100 kg•m^{-3}. Vardy [53] reported modulus values are ranging from 150 to 430 kPa for flat bale, and 210 kPa for on-edge bale at density 85 kg•m^{-3}. A non-linear rheological model of straw bales behavior under compressive loads has also been proposed by Molari et al. [54], with the geometry and density aspects of a straw bale taken into account in their model.

Similar to Young's modulus, the Poisson's ratio of the straw bale depends on the orientation of the bales, where flat bales have a higher Poisson's ratio compared to on-edge bales [45,50,51]. Maraldi et al. [50,51] reported that the sampled bales did not show a constant Poisson's ratio during the loading, where for flat bales the Poisson's ratio increased with increasing strain until reaching the maximum value and then decreasing, and for on-edge bales the Poisson's ratio continuously increased up to their breaking point (Fig. 8) [50,51]. Ashour [45] suggested that the Poisson's ratio was affected by the bale density, however no strong correlation was found between density and Poisson's ratio in a more recent study by Maraldi et al. [51]. Using Maraldi et al. [51] as reference, Poisson's ratio of 0.2 to 0.5 with mean value of 0.4 were observed

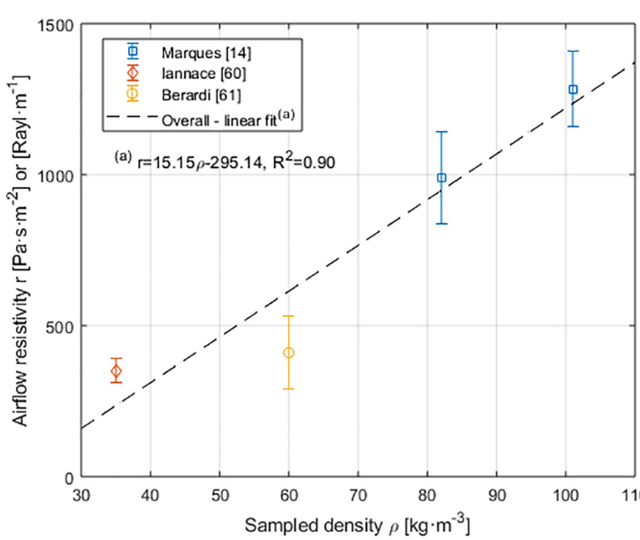

Fig. 9. Airflow resistivity r of straw bales based on studies from Marques [14], Iannace [60], Berardi [61].

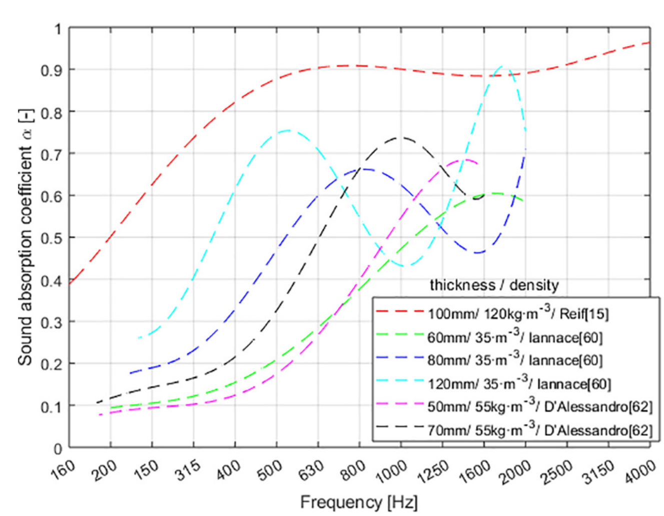

Fig. 10. Sound absorption coefficient of different thickness and density of straw bales based on studies from Reif [15], Iannace [60], D'Alessandro [62].

for flat bales, while ratio of 0.1 to 0.3 and mean value of 0.2 were observed for on-edge bales.

Traditionally, straw bales used in building construction are applied with plasters/stucco such as lime, clay or cement, and the plaster will act as weather resistance barrier and provide additional reinforcement. The strength of the plastered straw bale mainly depends on the compressive resistance and thickness of the plaster, and the structure failures could be caused by either buckling or crushing of the plaster [53,55,56]. A refined compressive field theory for plastered straw bale walls had been investigated Palermo et al. [57] to predict the stress–strain response to in place shear and axial loads. Prefabricated modular straw bale wall panel is also used in the building construction nowadays. These modular panels are typically formed using a timber framing and infilled with dry and compressed straw bales inside the timber frame. The modular panels can then be either secured with plaster [58] or a sheathing plate [59] which will influence their overall structural performance.

2.6. Airflow resistivity r

Airflow resistance of straw can be determined using ISO 9053-1. The airflow resistivity increases with straw density ρ (Fig. 9), as higher density of straw will reduce the air permeability and further resist the sound waves to transmit through the straw [14,60,61]. The significant standard deviation values observed in these measurements are related to inhomogeneous nature of straw.

2.7. Sound absorption coefficient α

Sound absorption coefficient α of straw bale had been measured in several studies. Most of the measurements were determined based on ISO 10534-2 using transfer function method [19,60–62]. The other studies were done either based on ISO 10534-1 using standing wave ratio method [15] or refer to ASTM E1050-19 [63].

The sound properties improved with the increasing density ρ of straw bale, with optimum value obtained around bulk density ρ of 110 kg·m^{-3} by Reif et al. [15]. It was also measured that the sound absorption coefficient increased with a thicker layer of straw bale, and at the same time the higher absorption value moved towards the lower frequencies' region [19,60,62,64] (Fig. 10). This was illustrated in D'Alessandro et al. [19], where the highest measured absorption coefficient moved from 0.70 at 1300 Hz (at 0.05 m thickness) to 0.78 at 1000 Hz (at 0.07 m). In D'Alessandro et al. [62], it was observed that no significant influence of moisture content on the sound absorption properties of straw bale. Additionally, an improvement of acoustics properties was measured if mixing cellulose fibers in the straw bale [15]. Trabelsi and Kammoun [64] noted that treated straw bale with cement has a similar sound absorption coefficient compared to untreated straw bale and concluded that effect of straw treatment has minimal effect on the sound properties. There is also research from Huang et al. [65] on creating acoustic bio-metamaterials based on straw characteristics, and in the same study provided a comprehensive explanation of the acoustic properties of straw based on the design of straw-inspired metafluid (MCS).

Straw bale is considered as porous material, thus it displays a high sound absorption property, but in general poor at low frequencies, which can be improved by using higher density straws.

3. Review on performance of straw in a building environment

In this section, thermal, energy and moisture performance, fire resistance, sound insulation performance and life cycle assessment of various straw bale structures and buildings will be reviewed.

3.1. Hygrothermal performance

Thermal conductivity λ of plant fiber-based insulation material such as straw bale is highly depending on hygrothermal performance in a building. If subjected directly to excessive moisture level, there is high possibility of mould growth and straw degradation, and its thermal insulation performance will be reduced. Fig. 11 shows the maximum moisture content observed on the tested straw bale walls in different locations. Fig. 12 summarizes results of mould growth and consequent degradation reported in

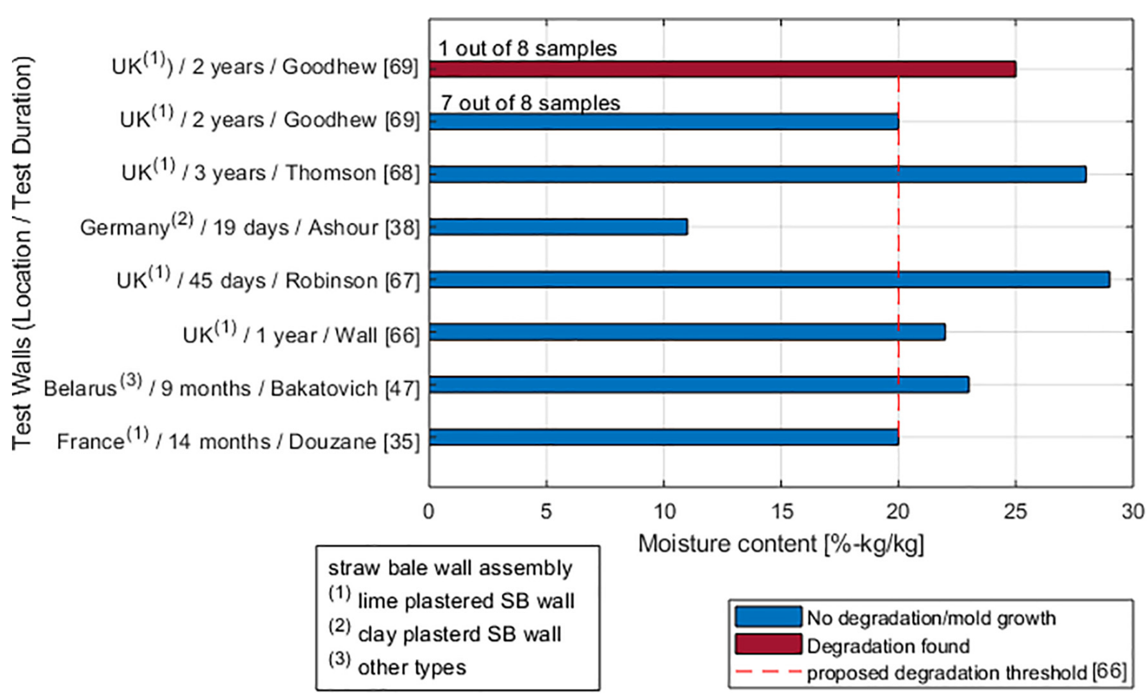

Fig. 11. Moisture content of tested straw bale walls based on studies from Douzane [35], Bakatovich [47], Wall [66], Robinson [67], Ashour [38], Thomson [68], Goodhew [69].

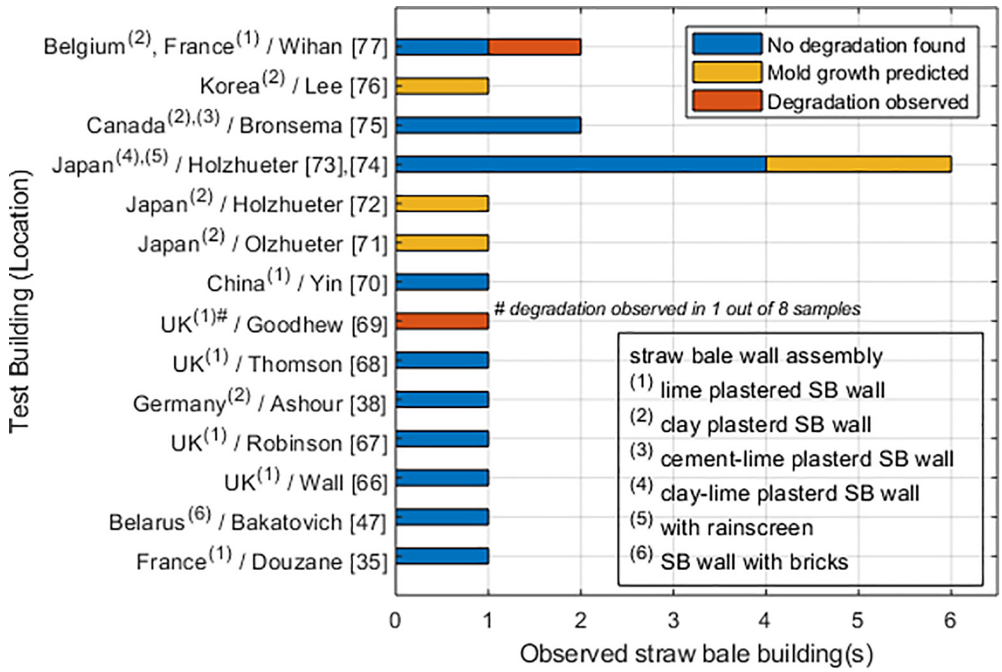

Fig. 12. Mould growth prediction and degradation observation in straw bale walls based on studies from Douzane [35], Bakatovich [47], Wall [66], Robinson [67], Ashour [38], Thomson [68], Goodhew [69], Yin [70], Olzhueter [71] Holzhueter [72], Holzhueter [73 74], Bronsema [75], Lee [76], Wihan [77].

more than 20 different straw bale buildings. Some studies have reported findings based on numerical simulations instead. Overall, the findings indicate a significant risk of mould growth and degradation on straw bale in a building if straw bale is not properly constructed and protected.

As a preventive measurement, increment of carbon dioxide concentration in the straw bale can be used as an early detection of mould growth, as CO2 is a product of aerobic respiration of microbial activity. An experiment by Thomson and Walker [68] on mould growth of fresh straw (sample taken from fresh dry bale) compared to old straw (sample taken from a 3-year old rendered wall) was done at a controlled environment at high relative humidity 87%. While the sampled old straw did not show any new mould growth, the fresh straw appeared to suffer from mould growth on the surface. On a second test in the same study, straw samples were exposed to high relative humidity, following with drying and re-exposure. While mould growth was observed on the first exposure, there was no mould growth observed on the re-exposure stage. These results implied that there is a risk of mould growth on fresh straw within a new wall if exposed to high humidity environment.

Mould growth potential can also be done based on biological resistance assessment as per EN ISO 846. A biological test was done on rice straw sample by Marques et al. [14] and was graded at level

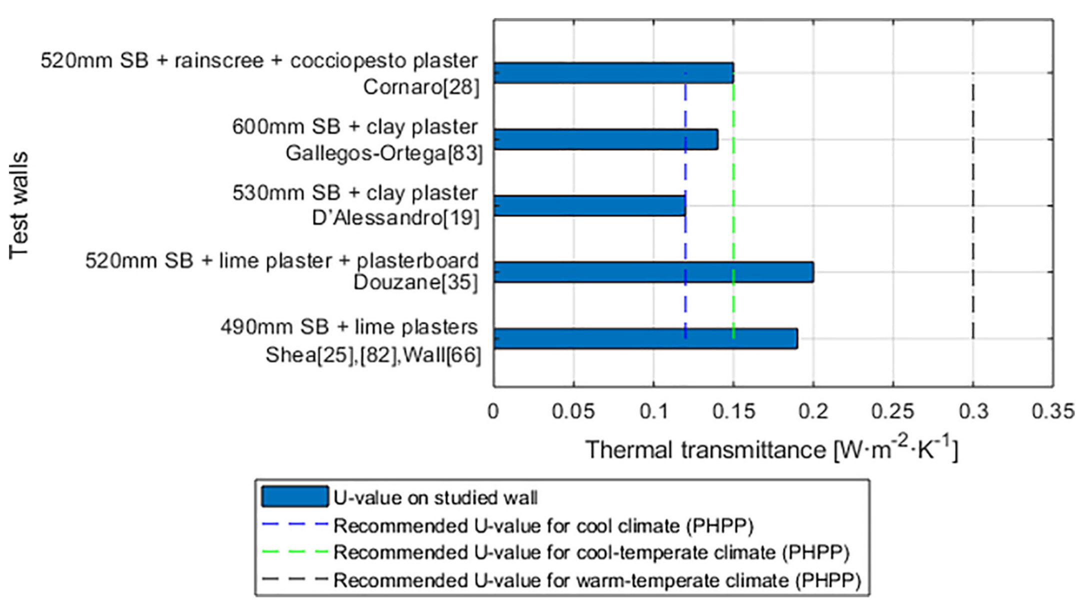

Fig. 13. Thermal transmittance (U-value) of straw bale walls based on studies from Shea [25,82], Wall [66], Douzane [35], D'Alessandro [19], Gallegos-Ortega [83], Cornaro [28].

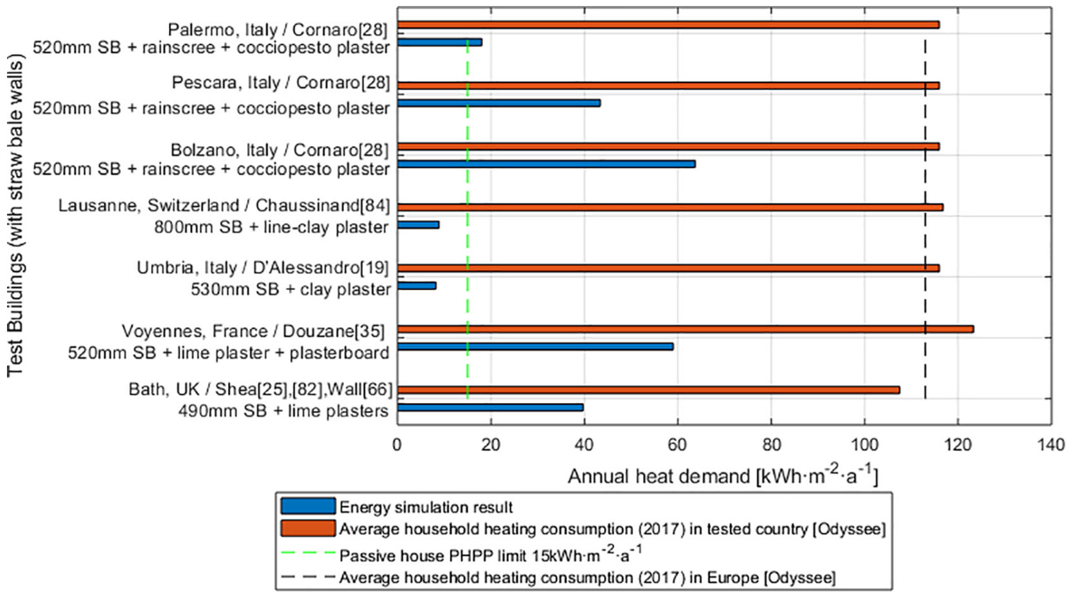

Fig. 14. Energy simulation of straw bale buildings based on studies from Shea [25,82], Wall [66], Douzane [35], D'Alessandro [19], Chaussinand [84], Cornaro [28]. Reference is made to Odyssee database [81].

3 as per EN ISO 846, where mould growth was visible to naked eye based on the testing conditions. Alternative methods to determine mould growth potential for building materials have been proposed by Johansson et al. [78] and Stefanowski et al. [79].

It is also worth to note that in a study by Bouasker et al. [44], mould growth was observed in inner surface area of the barley sample, while nothing was observed on the outer surface. This may be due to storage and handling of the straw sample before testing. Other study such as using harmless biocidal to prohibit mould growth had been explored. Experiment by Küünal et al. [80] using low concentration of Ag MNPs (silver metal nanoparticles) as biocidal in straw had demonstrated the effectiveness of using them against mould growth.

3.2. Thermal analysis and building energy performance

In-situ measurement of thermal transmittance of the building element can be measured either using heat flow meter method as per ISO 9869-1 or infrared method for frame structure as per ISO 9869-2. Fig. 13 shows the thermal transmittance of straws bale walls that can be achieved in different studies. For a wall structure consists of around 500 mm thickness of straw bale, it can achieve thermal transmittance U-value in the range of 0.1 to 0.2 $W.m^{-2}.K^{-1}$, which is at the borderline of recommended PHPP U-value for cool and cool-temperate climate zones, however well within the recommended PHPP U-value for warm-temperate climate zone.

Fig. 14 shows the energy performance of straw bale building in term of heating demand in different field studies. These heat demands are then compared to the average household heating consumption in year 2017 in the tested country [81], together with passive house PHPP standard. In general, the heating demand of straw bale building (wall with around 500 mm thickness of straw bale) is lower than the average household heating demand in respective country. However, most of the tested buildings cannot achieve the stringent passive house PHPP requirement.

The straw bale thickness in a wall is the main factor that will influence the thermal and energy performance of a straw bale building. Other contributing factors such as wall finishing, airtightness and thermal bridge have been investigated. Airtightness tests were carried out on a straw bale prototype house by Shea et al. [82] and Wall et al. [66], where 1.36 $m^3{\cdot}h^{-1}{\cdot}m^{-2}$ at 50 Pa was achieved in initial test. Further improvements, e.g. additional sealing around the windows and wall structures were applied, and the second test showed 0.86 $m^3{\cdot}h^{-1}{\cdot}m^{-2}$ at 50 Pa (equivalent to 0.84 h^{-1}), which exceed the stringent passive house criteria at n_{50} = 0.6 h^{-1} but is considered acceptable. Another study by Chaussinand et al. [84] on an 800 mm thick of straw bale wall with lime-clay plaster concluded that plaster on straw wall reduced the heating demand but provide less protection against overheating. This means different finishing design of straw bale wall assembly shall be considered based on different climate zones.

3.3. Fire resistance

Straw bales are typically used as main load-bearing structure in a wall or as in-filled insulation material in a load bearing wall. Their fire resistance requirement will be depending on the fire class and hazard class as per their local regulation. As references, general fire resistance tests requirements can be found in ISO 834-1 / EN 1363-1 / ASTM E119-19, while specific fire test requirements for load-bearing wall can be referred to ISO 834-4 / EN 1365-1, and ISO 834-8 / EN 1364-1 can be used for non-load-bearing wall.

Most of the fire resistance tests were done on plastered straw bale wall. A fire resistance test as per EN 1364-1 was done by Wall et al. [66] on a lime plastered straw bale wall, which took around 90 min for the lime plaster to fall from the straw bale, and the test continued for another 45 min until the exposed surface of straw bale had charred black. This qualified the plastered straw bale wall sample with a fire rating of 135 min, exceeding the 30 min requirement as per their local (UK) regulation. In another fire test by Munch-Andersen and Andersen [23], a clay plastered straw bale wall had qualified at least 30 min rating, which also exceeding their local (Danish) regulation. Other fire tests done in Austria, Czech Republic and USA have been mentioned in review papers by Theis [85] and Džidić [86], where fire rating from 30 to 146 min were achieved for different straw bale wall configuration.

Standalone assessment of straw bale was carried out by Deutsches Institut für Bautechnik (DIBt) on an un-plastered straw

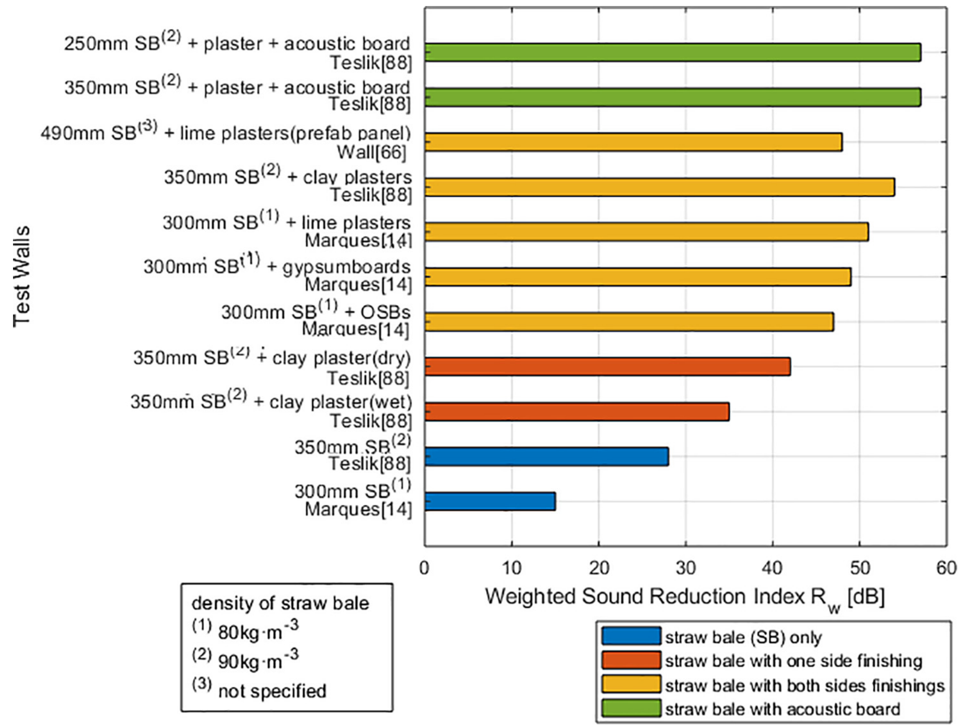

Fig. 15. Airborne Sound Insulation Performance as per ISO 10140-2 in different laboratory studies from Teslik [88], Marques [14], Wall [66].

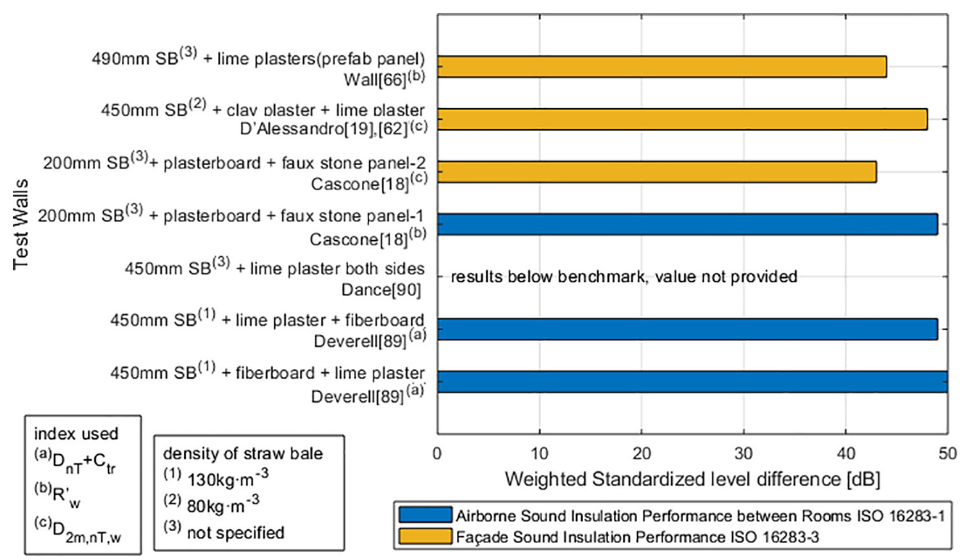

Fig. 16. Sound insulation field studies from Deverell [89], Dance [90], Cascone [18], D'Alessandro [19,62], Wall [66].

bale commercial product, and the product has been classified as Class E following EN 13501-1:2007 + A1:2009 [17], meaning it is considered a combustible material that have a contribution to fire and only able to resist ignition for a short period. A mathematical model of the smouldering combustion and heat transfer of plastered straw bale was also explored by Apte et al. [87]. In this study, both lime-plastered and clay-plastered straw bale were subjected to different radiant heat treatment and their smouldering reactions were monitored and compared to their model. The model did not manage to fully simulate the actual fire behavior of straw bale, however provided a good theoretical understanding on this subject.

3.4. Sound insulation performance

Since straw bale is mainly used only in a wall system compared to others building components (e.g. roof, floor), most of the studies were focusing on their airborne sound insulation performance. Fig. 15 shows the laboratory testing on airborne sound insulation of straw bale wall prototype according to ISO 10140-2 [14,66,88]. Fig. 16 show the field testing on the airborne sound insulation performance of straw bale wall between rooms according to ISO 16283-1 [18,89] and façade sound insulation performance of the straw bale wall according to ISO 16283-3 [18,19,62,66]. The

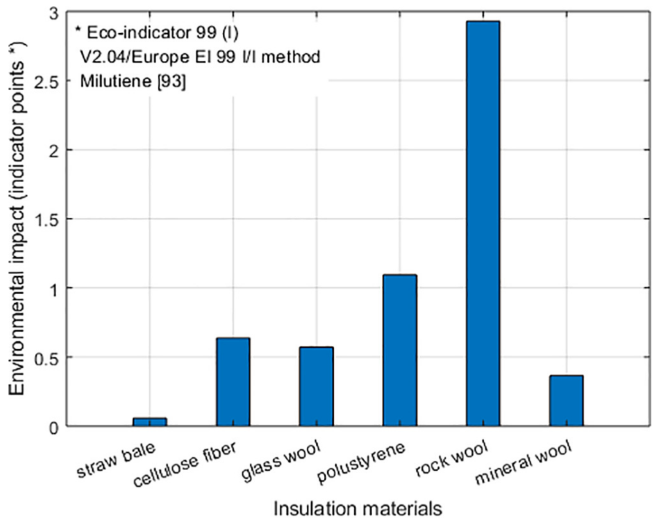

Fig. 17. Total environmental impact of different insulation materials under similar thermal insulation performance based on study from Milutiene [93].

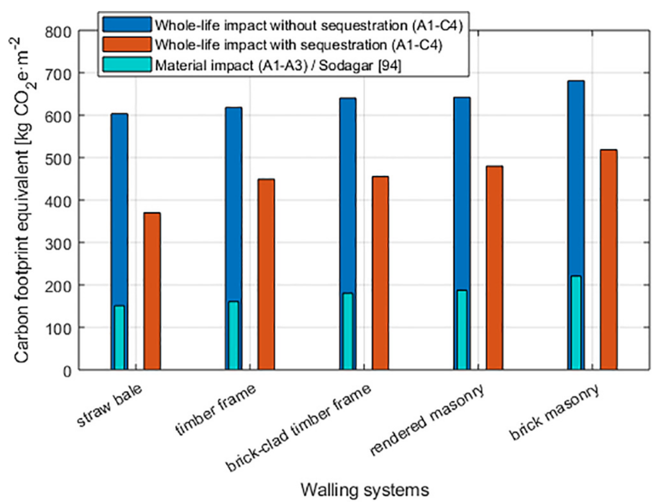

Fig. 18. Whole building life cycle assessment over 60 years based on study from Sodagar [94].

weighted sound reduction index can be calculated as per ISO 717-1.

In general, the airborne sound insulation performance of a straw bale wall depends on the finishing such as plaster, acoustic board, etc. as reported in Teslik et al. [88] and Marques et al. [14], and less influenced by the straw bale itself which are typically protected within the finishing. The field tests on the straw bale buildings showed a mixed results, but in general poor performance was observed by Dance and Herwin [90], Cascone et al. [18], and D'Alessandro et al. [19], even if studies from Deverell et al. [89] and Wall et al. [66] showed a satisfactory result. However, the poor airborne sound performance on the tested walls may not be due to the straw bale itself, but by the workmanship, flanking factor or finishing methods.

3.5. Life cycle assessment

In an on-farm environment impact study on the straw end-practices, Palmieri et al. [91] used life cycle assessment (LCA) for 3 different scenarios: incorporation in the soil, straw burning and baling. While there is no doubt that open field burning is environmentally unfriendly, the study also shows the burden of straw incorporation in the soil as fertilizer is higher than straw baling for local energy. In a separate LCA study by Mattila et al. [92] comparing using straw bale as construction material and using them as biochar application to soil, the environmental impact of straw bale construction is significantly lower than biochar application.

Several studies [93–95] have been done to compare the environment impact of straw bale building with different insulation materials and construction technique. Milutienė et al. [93] compared normalized environmental impact of different load-bearing and thermal insulation materials (Fig. 17) shows straw bales has the least environmental impact compared to other insulation materials (mineral wool, cellulose fiber, polystyrene, etc.), and only seconded to light clay brick as load bearing structure compared to sawn timber, concrete or sand-lime brick. González [95] reported a low embodied energy result on using straw bale as wall construction material in Andean Patagonia region at 2.5 kgCO2 eq·m^{-2}, comparing to other common local building material such as fired bricks at 38 kgCO2 eq·m^{-2} and concrete blocks at 11 kgCO2 eq·m^{-2}.

In another LCA study, Sodagar et al. [94] compared a lime plastered straw bale wall with different configuration of wall (timber framed and masonry) and insulation materials (wood fiber, mineral wool), the result shows a lower global warming potential (GWP) of straw bale house (604 kgCO2 eq·m-2 over 60 years) compared to other configurations (e.g. 618 kgCO2 eq·m-2 for engineering timber frame), and a better performance if also consider the carbon sequestration factor (Fig. 18). Using the energy performance data of straw bale buildings in different field studies (Fig. 14) and Sodagar et al. [94], Fig. 19 shows their annual operational CO2 emissions, calculated based on the average household energy demand and respective national grid electricity performance. In overall the annual in-use energy and associated CO2 emission of straw bale buildings are lower than the impacts from average household in Europe.

Taking a straw bale house in Umbria Italy as example [19], the main contributor of embodied energy for a straw bale infilled timber framed wall is timber (0.93 MJ·m^{-2}·a^{-1}) followed by straw bales (0.36 MJ·m^{-2}. a^{-1}) and steel (0.28 MJ·m^{-2}·a^{-1}). However, it should be noted that the GWP contribution of external walls compared to other building elements are comparable low. A building in Waddington UK with loadbearing straw bale walls [94] shows its external walls contribute only 3% of the total emissions of the building, while the floors, ceilings and roof have a much higher GWP contribution.

It should be noted that the low environmental impact of using straw bales in a building, instead of functionality and building cost, is the main factor driving the growth of straw bale construction in recent years. A 2014 market survey was carried out by Larisa and Peggi [96] with straw bale house owners regarding their straw bale buildings, the straw bale homeowners considered ecological factor of straw bale building is more valuable compared to economic, functional or aesthetic value.

4. Conclusion

This review systematically summarizes the material properties of straw bale as well as the performance of straw bale structures, in order to contribute to a more organized landscape around this innovative and sustainable building material.

Straw bale can provide a satisfactory thermal insulation, however in real applications a thicker layer would be necessary if compared to other conventional insulation materials such as mineral wool, EPS or XPS, because of slightly higher thermal conductivity. To achieve energy performance goals in a cool or cool-temperate

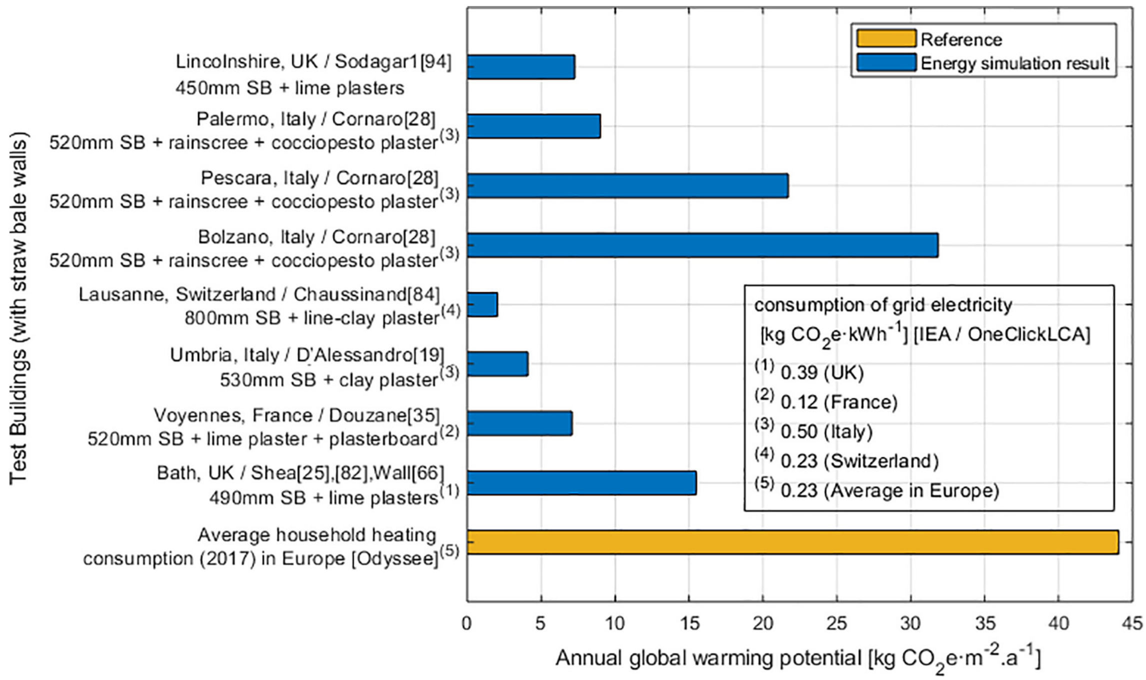

Fig. 19. Annual global warming potential (operation) from different tested straw bale buildings.

climate, it would require generally elements thicker than 0.5 m, while applications in a warm-temperate climate give more flexibility regarding eventual design of building envelope, from this point of view. As a natural product, straw bale is vulnerable to mould growth and further degradation, when exposed to environments with excess moisture. Research shows that moisture content under 20% will ensure no moisture-related degradation. The existing studies report controversial results whether the type of straw affects the moisture storage function and adsorption/desorption, nevertheless the isothermal sorption curve of straw appear to be similar to timber products. Finishing, e.g. plaster, plays an important role on the mechanical strength, sound insulation performance and fire resistance of a straw bale building.

The environmental impact of straw bale is significantly less compared to other thermal insulating materials, when normalised by thermal conductivity. Straw bale as load-bearing material shows lower carbon footprint compared to other structural systems, such as timber, brick and masonry. If the focus is on the operational emissions, global warming potential for straw bale is lower than the European average that corresponds to the average household heating consumption. Further performance improvement of straw bale as building material can be achieved by getting combined with different additives in the straw bale structure, such as harmless biocidal to reduce the mould growth risk, or additional fibrous material that may improve the thermal performance. Further research in this direction is recommended so that straw bale will become competitive to other thermal insulating materials in the market.

There is also a perceived lack of standardized technical data and recommended best practices on utilizing straw bale in building construction. An adequate technical dataset of straw bale and standardized procedures of construction are essential for further spread to wider audiences. In this direction, the listing of straw bale as a typical building material in building codes and standards, with tabulated design values, will contribute to increase use by engineers and practitioners and bridge the gap between its environmental potential and the actual adoption by building construction industry.

5. Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

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

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