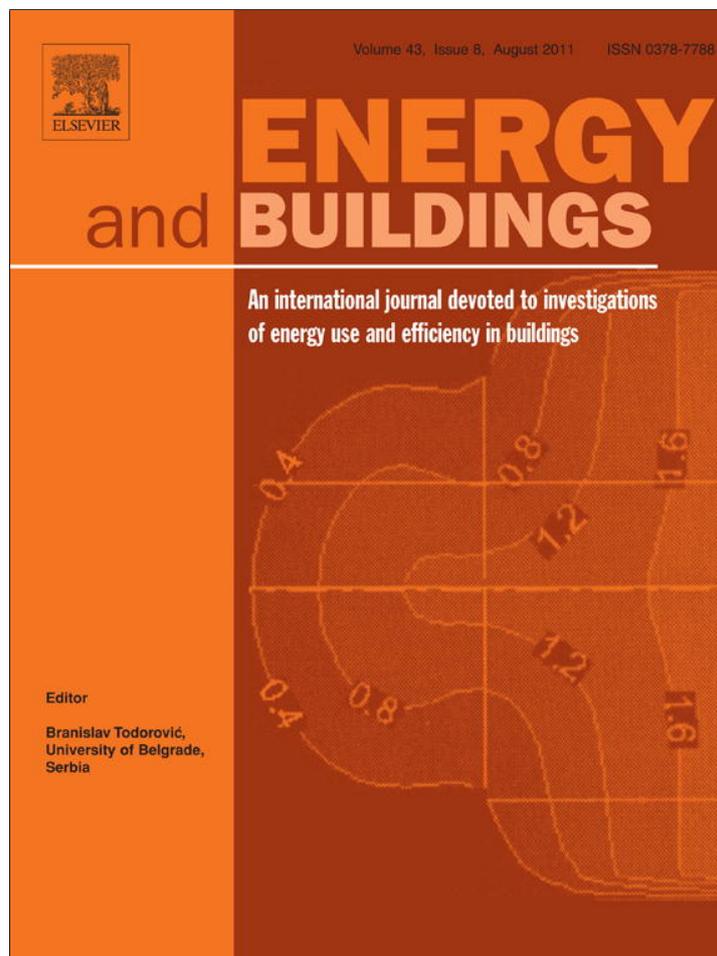


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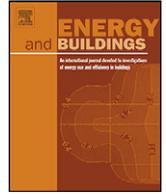
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Performance of straw bale wall: A case of study

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ABSTRACT

This research aimed to evaluate a straw bale house located in Bavaria, Germany. An extensive test program was carried out. The experimental work includes compression tests, moisture content, thermal stability of bales and pH. The in situ work includes temperature and relative humidity inside the straw bale wall. The stress–strain behavior of straw bales was investigated including nonlinearity and anisotropy. Thermal stability of bales under constant temperature and relative humidity was studied considering time dependence. The moisture content of straw bale was about 11%, while pH value inside the bale was about 7.29. Moreover, the temperature and the relative humidity between the interior (inside straw bale wall) and the exterior were investigated.

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1. Introduction

Straw is a natural product, grown by photosynthesis during a half or one-year period, fueled by the sun. Straw is currently produced in surplus to requirements, so it is cheap and easily accessible in most countries. It is the end product of growing crops; so using it for building purposes present a sustainable and ecological way of recycling. The use of straw bales as construction material has many advantages [1]. Buildings with straw bales are energy-efficient, durable, attractive and even fire-resistant. According to Desborough and Samant [2], the public would generally accept straw dwellings, especially when supported by wide dissemination of information about the material properties of straw and the construction possibilities. Additionally, built environment professionals find straw to be an excellent construction material and recognize that some of its limitations can easily be overcome. Earlier studies [3] showed that a compacted straw bale with a render layer of about 4 cm on all sides survived an externally imposed heat flux of 29 kW m⁻² for 10 min without severe cracking of the render or ignition of the straw within the bale. A straw bale without render readily ignited when subjected to the same heat flux. Clearly, the render contributes to the fire safety of straw bale construction by providing an insulating barrier between the heat source and the straw and also providing a barrier to oxygen transfer from

the atmosphere into the straw. Straw bales have also been used to provide retrofit insulation for existing homes. The bales are much cheaper than adobe and have become common in high-end estate constructions.

On the other hand, faced with the worldwide shortage of forest resources, the construction industry is showing interest in the production of particleboard from agricultural residues [4]. Agoudjil et al., [5] reported that date palm wood is a good candidate for the development of efficient and safe insulating materials when compared to the other natural materials. While Becchio et al. [6] studied the effects of the addition of wood aggregates on both mechanical and thermal properties of concrete. Goodhew and Griffiths [7] found that, the thermal conductivity of straw bale is 0.067 W/mK. Wheat straw contains a large amount of fiber with the potential to replace wood for particleboard fabrication. Particleboard with a density ranged from 0.59 to 0.8 g/cm³ is designated as medium-density particleboard [8]. It has broad applications for both structural and non-structural uses. Also barley straw is a significant raw material in cellulose production as an energy resource [9–14]. The reuse of co-product straw in this manner is considered an environmentally friendly material, which helps to reduce heat in the house during summer and keeps warmth during winter. The high silica content in the straw makes it resistant to decay, and its long fiber characteristic is good for building houses [15]. Modern buildings have tremendous impact on the environment in their life cycle. It results in different problems and has significant influence on climate change because of the energy use for production, building, maintenance and demolition [16,17]. Some

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studies on straw bales have been carried out in the past. Ashour [18] reported that strength of bale in the vertical orientation was higher than those in the horizontal orientation and the deformation modulus decreased gradually with increasing load. The deformation modulus of vertically oriented bales was found to be higher than those of the horizontal oriented bales. Some studies on earth plaster in straw bale buildings have been carried out in the past. The influence of natural reinforcement fibres on the erosion properties of earth plaster materials was studied by Ashour and Wu [19]. The fiber content and fiber type are found to have remarkable effect on the erosion resistance of the plasters. The straw fiber has also effect on the strength and ductility of earth plaster for straw bale buildings [20]. The interaction between earth plaster for straw bale buildings and environment conditions were studied. The effect of relative humidity on equilibrium moisture content is more pronounced than temperature [21]. The shrinkage crack formation of earth plaster decreases with increasing fiber content and increased with increasing soil content [22]. While, Ashour et al. [23] found that the thermal conductivity for earth plaster reinforced with straw fibres decreased with increasing straw fiber content, and increased with increasing sand content. The excellent property of straw bales for acoustic insulation was shown in [24]. However, most experimental work in the literature was carried out on straw bales in laboratory.

There are numerous publications on straw bale construction in literature. However, most publications deal with either laboratory testing or construction practice. A combination of housing project with extensive testing program is rarely found. We present an attempt to combine a housing project with straw bales with an extensive testing program. The measurements include the following points: (1) the in situ measurements include the behavior of temperature and relative humidity inside the straw bale wall under natural conditions. (2) The laboratory measurements include bale dimensions, bale weight, compression test, compaction test, moisture content and pH.

2. Description of building

Straw bales can be used either as load bearing structure or as infill wall. For the infill wall system, there are different techniques such as post and beam structures and frame (truss) structures with straw infill. The latter is widely used in construction practice. The loads are carried by the frame structures and the insulation is provided by the straw bales. The building under study is constructed with wooden frames and straw infill.

In addition to the mechanical behavior of straw bales, it is very important to evaluate temperature and relative humidity inside the wall under natural conditions. A straw bale house in Germany was chosen for our investigations. The orientation of the straw bales inside the wall was horizontal. The house consisted of two floors as shown in Fig. 1. The wall thickness is about 50 cm. The wall consists of calcium stucco as outside plaster (1 cm), outside plaster (2 cm), straw bale wall (45 cm) and inside plaster (2 cm). The house includes different rooms such as bathroom, bedroom, living room, kitchen and others.

3. Experimental programs

3.1. In situ testing

In situ measurements are important to evaluate the performance of straw walls under natural conditions. The in situ testing included the temperature and relative humidity inside the straw bale walls. The sensors for measuring the thermal and humidity behavior were installed at different locations throughout the



Fig. 1. House for case study.

wall. The commercial temperature and relative humidity sensors of the type of Negative Temperature Coefficient (NTC) were used for this investigation. The capacitive humidity sensors contain a glass substrate with a humidity-sensitive polymer layer between two metal electrodes. The measuring signal is proportional to the relative humidity and is independent of the atmospheric pressure. The probe pipe is made of aluminum with a diameter of 12 mm. The device covers a wide measurement range, from 5% to 98% for relative humidity and from -20 to $+80$ °C for temperature.

Plastering is very important for the durability of straw bale constructions. The wall consisted of three layers such as outside plaster, straw wall and inside plaster. So the sensors should cover all positions. The temperature sensors were installed on the plaster surface and inside the wall. The sensors were placed in the different locations such as outside temperature, outside plaster surface, between outside plaster and straw wall, 10 cm from outside, 20 cm from outside, between straw wall and inside plaster and inside plaster surface as shown in Fig. 2. The temperature and relative humidity properties were measured in the ground floor. The sensors position for the ground floor was at south east wall and 1.4 m above the floor.

3.2. Laboratory measurements

The in situ tests were supplemented by extensive laboratory tests including bale dimensions and densities, moisture content, pH and thermal stability and mechanical properties under compressive load.

3.2.1. Bale dimensions and densities

Linear dimensions of the bales, i.e. length, width, and height were measured. The bales were weighed to obtain the bale density.

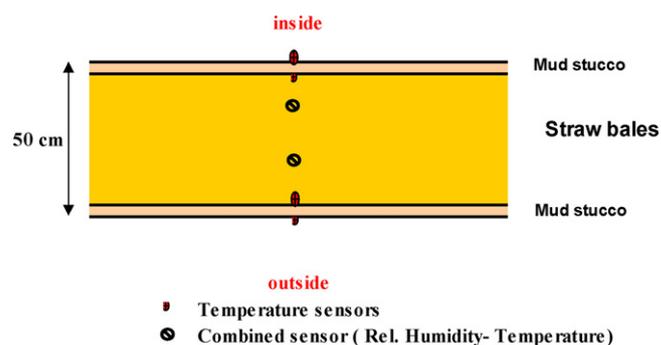


Fig. 2. Sensors positions inside the wall.



Fig. 3. Bales inside the climate chamber under compensation test condition.

3.2.2. Moisture content

The moisture content of straw bales was measured according to [25]. The bales were put in an oven at 105 °C until reaching a constant weight. The samples were weighed before and after drying. Then, the moisture content was calculated according to $MC = ((W_m - W_d)/W_d) \times 100$, where MC is the moisture content of the bale as a dry basis, W_m is the moist weight (kg) and W_d is the dry weight (kg).

3.2.3. Measurement of pH values

Straw is an organic building material. The environmental, physical and chemical properties of straw inside the bales are of importance for the durability of straw buildings. The environmental conditions include temperature, relative humidity, Oxygen and pH. When the condition inside the bale is optimal for micro-organisms, the growth of these micro organisms will be enhanced. The growth of micro-organisms leads to straw deterioration and has negative effect on the durability of straw building. On the other hand, the pH value, i.e. an acidity or alkalinity environment, is important for the growth of micro-organisms. A total of 16 samples were used to measure the pH values with 4 straw replicates for straw from the house under studying. To make an extraction for measuring the pH, the straw was dried at 105 °C for 24 h and 5 g from dried straw were mixed with 45 gram of distilled water at a ratio of 1:9 between straw and water. The straw was mixed with water for 30 min. Then, the pH measuring was started, and its value was measured every 60 min over a period of 5 h.

3.2.4. Thermal stability of bales

The tests were carried out to measure the temperature and relative humidity in straw bales. The measurements were made when equilibrium was reached between the straw bale and the ambient. The test was carried out according to [26]. A total of 10 bales were used for this test. A dual sensor was placed at the centre of each bale. The tests were carried out in a climate chamber with 23 °C and 78% relative humidity (Fig. 3). The test was performed under high relative humidity to study the temperature and humidity transfer from surrounding environment to straw bales.

The test was terminated when the temperature and relative humidity inside the bales became equal to those in the climate chamber.

3.2.5. Mechanical properties

The mechanical properties were investigated by compression tests according to [27]. The tests were carried out on a total of 10 straw bales from the building. The straw bales were tested in horizontal and vertical orientations. For the case of horizontal



Fig. 4. Straw bale in compression test.

orientation, the dimensions of the bales were about 61 cm length 43 cm width and 36 cm height. For the case of vertical orientation, the dimensions were about 61 cm length 36 cm width and 43 cm height.

A vertical load of about 2 kN was applied to the bale at the beginning of the test. Afterwards, the vertical load was increased in increments by 1 kN to reach the maximum load of about 10 kN. The loading piston was then stopped after each increment and the bale dimensions were measured as shown in Fig. 4. At the end of each test the bales were dried to measure the moisture content. The stress, horizontal strain, vertical strain and the deformation modulus were evaluated (see also [28]). The strain is defined as the displacement of the bale divided by the original height of the bale. The deformation modulus is calculated as the ratio between stress increment and strain increment.

4. Results and discussion

4.1. Bales dimensions, density, moisture content and pH value

The average of bales density was 102.6 kg/m³. The moisture content of bales is responsible of its deterioration as a result of the microbial activity. The average moisture content was about 11%. The moisture content of about 15% is thought to be safe for the straw bale according to [29].

The average of pH value of straw inside the bales was about 7.29. This means that the condition inside the bales is alkaline. This pH value is typical for straw material. Beside the moisture content and pH values inside the bales are important for the microbial activity. Fungi and microorganisms may activate inside the bales and cause deterioration of the bales and decrease the building life. Further research in this area is needed in the future.

4.2. Mechanical properties

4.2.1. Stress and load

Fig. 5 shows the relationship between the applied load and the stress for horizontally and vertically oriented straw bales. The cross-sectional area was about 0.204 m² in the vertical direction and 0.276 m² in the horizontal direction. The applied load started with 2 kN and increased in increments to reach 10 kN at the end

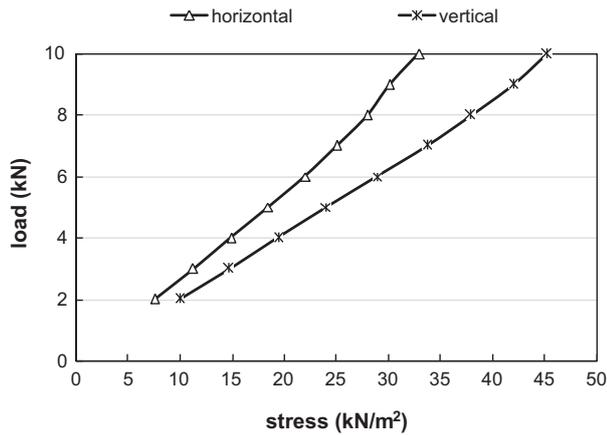


Fig. 5. Stress in straw bales.

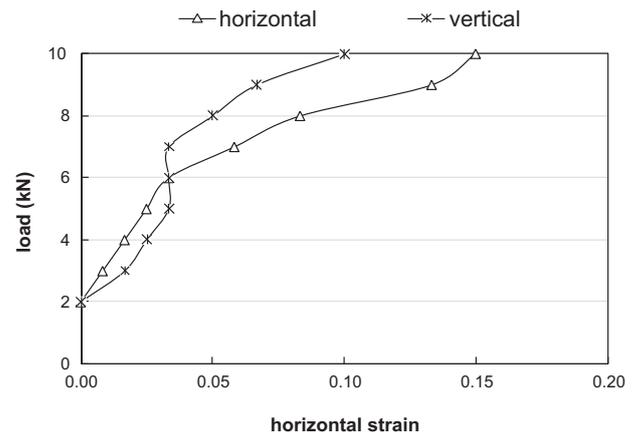


Fig. 7. Horizontal strain for straw bales under compression test.

of test. The figure shows that the stress increases with increasing load for both vertically and horizontally oriented bales. At the beginning (2 kN load), the average stress was about 9.95 kN/m² for the vertical orientation. This was higher than that of the horizontally oriented bales of 7.6 kN/m². While at 10 kN load, the same trend can be observed, the average stress was about 45.2 kN/m² at vertical orientation while it was 32.9 kN/m² for the horizontally oriented. The difference in stresses for the vertical and horizontal orientations was due to the different cross-sectional areas.

The overall average stress (28.4 ± 12.3 kN/m²) for vertical orientation was higher than that of horizontal orientations (21.1 ± 8.7 kN/m²). This may be due to the fact that the bales of horizontal orientation have larger cross-section area compared to that of bales of vertical orientation. Also, the direction of the straw stems in the vertical orientation is different from that in the horizontal orientation.

4.2.2. Vertical strain

The vertical and horizontal deflections were measured for vertical and horizontal orientations. Fig. 6 shows the relation between load and vertical strain for vertically and horizontally oriented straw bales. For small load up to about 2 kN there is only very small strain in the bales.

For vertically orientated bales, the maximum strain was about 0.25 and the minimum strain was about 0.017. It is clear that the resistance to deflection increases with applied load. For horizontally oriented bales, the vertical strain ranged from 0.011 to 0.208. The results showed that, the vertical strain ranged from 0.017 to

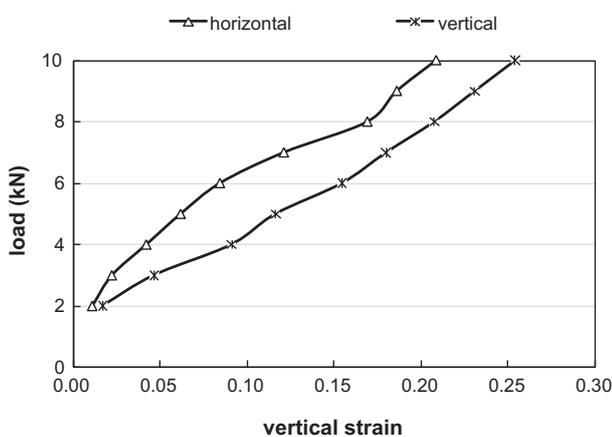


Fig. 6. Vertical strain of straw bales under compression test.

0.254 at loads from 2 to 10 kN for the vertically oriented bales while it ranged from 0.011 to 0.208 for the horizontally oriented straw bales.

The vertical strain values increased with increasing load for both vertical and horizontal orientations. It is also clear that the vertical strain values for vertical orientation were higher than those for horizontal orientation.

4.2.3. Horizontal strain

Fig. 7 shows the relationship between the horizontal strain and load of vertically and horizontally oriented straw bales. By increasing the load, horizontal strain was observed where it reached to a minimum of 0.10 at 10 kN for vertical oriented bales and 0.15 for horizontal oriented bales.

The average horizontal strain for the horizontal oriented bales is greater than that of vertical oriented bales. The average horizontal strain ranged from 0.04 ± 0.03 for the vertical oriented bales which it ranged from 0.06 ± 0.05 for the horizontally oriented bales.

It is worthily to be noticed from Figs. 6 and 7 that, the vertical strain is higher than the horizontal strain for both vertically and horizontally oriented bales.

4.2.4. Deformation modulus

Fig. 8 shows the relationship between the deformation modulus and the applied load for the straw bales at different orientations. The deformation modulus is calculated as the ratio between stress increment and strain increment. It can be seen that the deformation

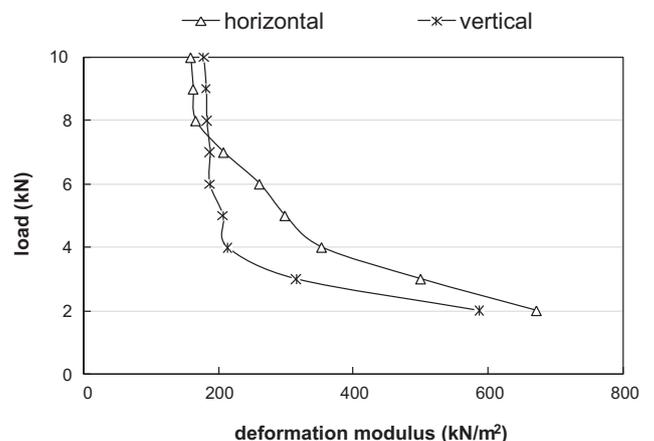


Fig. 8. Deformation modulus during compression test.

Table 1
The average temperature at different locations.

Time (h)	Outside temp. (°C)	Outside plaster surface	Between outside plaster and straw	10 cm	20 cm	Between straw and inside plaster	Inside plaster surface
0	12.70	12.10	12.50	13.73	13.43	13.50	13.70
24	11.78	11.82	11.97	13.89	13.72	12.40	12.04
24–96	9.69	10.87	11.24	12.51	12.57	10.78	11.62
96–261	11.84	12.53	12.62	14.31	14.17	12.96	13.26

modulus decreases with increasing load for both bale orientations. The stress–strain behavior of straw bales is nonlinear.

It can be seen that the deformation modulus decreased gradually with increasing load. At the load of about 4 kN the deformation modulus reached 213 kPa and remained unchanged for the vertically oriented bales. While for the horizontally oriented bales, the deformation modulus reached a constant of 165 kPa at the load of about 8 kN. The reduction in deformation modulus was attributed to the initial compression of the voids among the straw fibres. The constant modulus at higher load represented the resistance of well compressed straw bales. The reduction of the deformation modulus does not mean that the resistance against deflection decreases. The resistance still increases nonlinearly. These experimental results in agreement with those reported in [18,30,31].

4.2.5. Stress–strain relationship

Fig. 9 shows the stress–strain curves for vertically and horizontally orientated straw bales. The nonlinear behavior can be clearly observed. It is worth to mention that all bales showed highly resilient behavior, i.e. the deformation was recovered after the load was removed. However, the recovery of deformation after load removal took several minutes. The time required for a complete recovery of deformation varied between 10 and 13 min for both vertically and horizontally oriented bales.

4.3. Thermal stability of bales

Readings of the temperature and relative humidity were taken every 5 min. In general some of 450 h were needed.

4.3.1. Temperature measurements

Fig. 10 shows the temperature of straw bales from the house under study with time together with the ambient temperature of about 23 °C. The tests were performed on straw bales with an average density of about 102.6 kg/m³. Starting from an initial temperature of about 23.1 °C, the temperature in bale showed an initial sharp increase to about 23.6 °C followed by a gradual decrease to about 23.21 °C at 450 h. The difference between the surrounding temperature and bale temperature decreased with time. This is

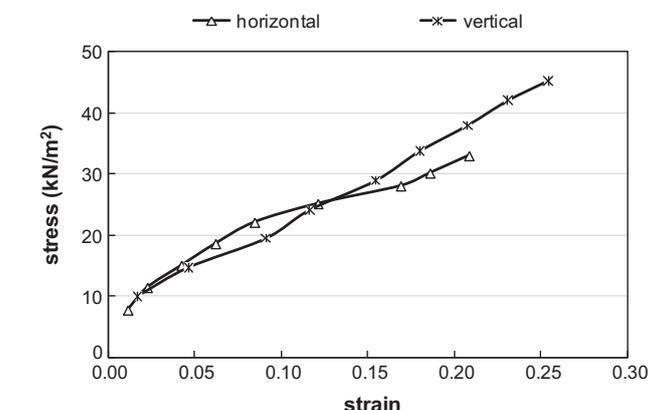


Fig. 9. Stress–Strain relationship for straw bales during compression test.

ascribed to the insulation function of the straw material. A closer examination of the data showed that temperature decreased with time according to an exponential equation with the correlation of about 80.05%.

4.3.2. Relative humidity

Fig. 11 shows the relative humidity of straw bales from the house of case study with time together with the surrounding relative humidity of about 78%. The test was started with an initial relative humidity of about 68.65% in bale. After an initial steep increase the relative humidity increased gradually with time to reach 76.4% after 450 h. The difference between the surrounding relative humidity and the relative humidity in bale decreased with time. At 400 h this difference was about 3.44%. At the end of test (after 450 h), this difference was only about 2.55%.

It is interesting to observe that the temperature and relative humidity in bales differed from the outside condition even after 450 h. The results showed that relative humidity increased with time according to an exponential equation ($r=94.04$). Also, the results demonstrated the excellent insulation function of straw materials against the outside relative humidity. This could be owed to the low moisture content of straw. Therefore, it took very long time to reach equilibrium with the outside conditions.

4.4. Temperature and relative humidity behavior inside the walls

4.4.1. Temperature measurement

Fig. 12 shows the temperature evolution inside the wall at different locations of the straw bale wall of the ground floor. It is shown that the temperature gradient increased from outside (low temperature) towards the inner side of wall. Moreover, the extreme outside temperature peaks were smoothed out by the straw wall.

Table 2 shows the average temperature at different locations and times inside the straw bale wall. At the beginning, the average temperatures were 12.7, 12.1, 12.5, 13.73, 13.43, 13.5 and 13.7 °C for outside temperature, outside plaster surface, between outside plaster and straw bale, 10 cm in straw, 20 cm in straw, between straw and inside plaster and inside plaster surface, respectively.

After 24 h, the temperature increased towards the wall interior, where the temperature difference between the outside temperature and the different locations are 0.04, 0.19, 2.11, 2.04, 0.62 and 0.26 °C for outside temperature, outside plaster surface, between outside plaster and straw bale, 10 cm in straw, 20 cm in straw, between straw and inside plaster and inside plaster surface, respectively.

After 96 h, the temperature percentages between the ambient temperature and the wall interior were 12.18, 16, 29.1, 29.7, 11.25 and 19.9% for outside plaster surface, between outside plaster and straw bale, 10 cm in straw, 20 cm in straw, between straw and inside plaster and inside plaster surface, respectively. It is interesting to observe that the percentage inside straw is higher than the outside plaster. While it were 29.1% and 29.7% for 10 and 20 cm inside straw. This may be due to the fact that the outside plaster is influenced by outside conditions and its lower thermal insulation in comparison with straw.

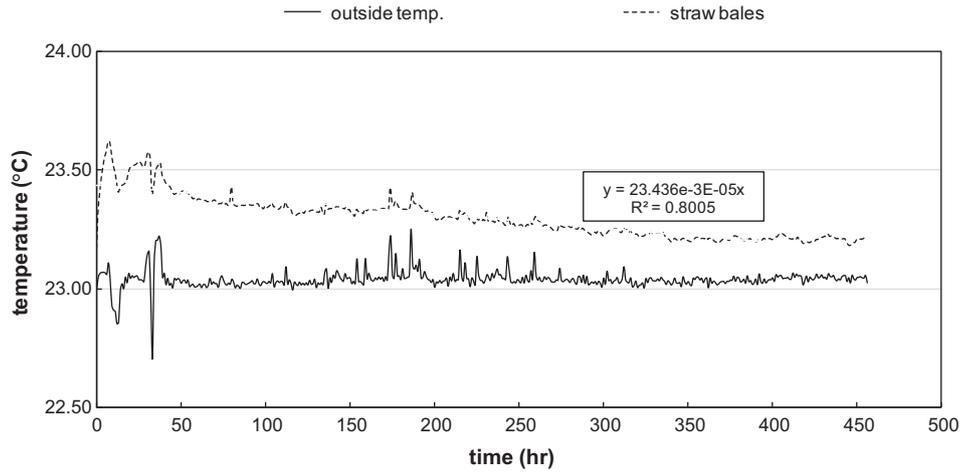


Fig. 10. Temperature evolution of straw bale.

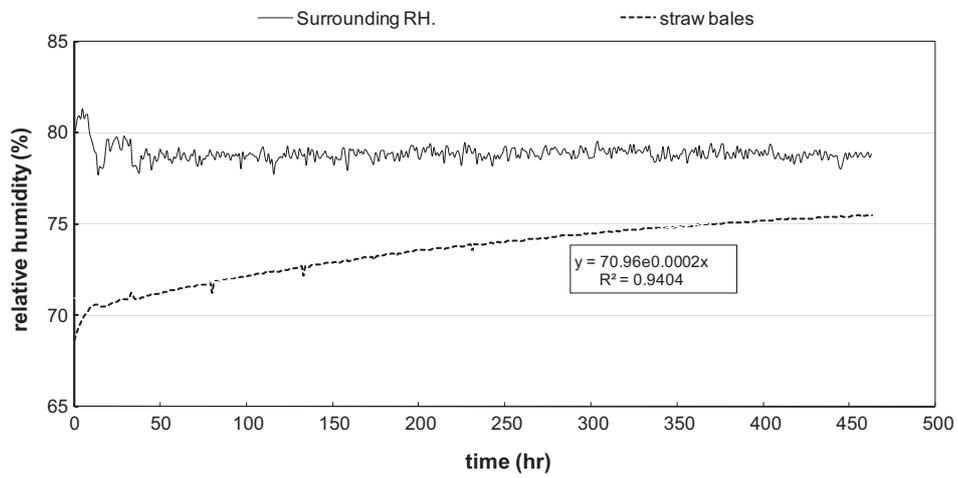


Fig. 11. Evolution of relative humidity inside the bale.

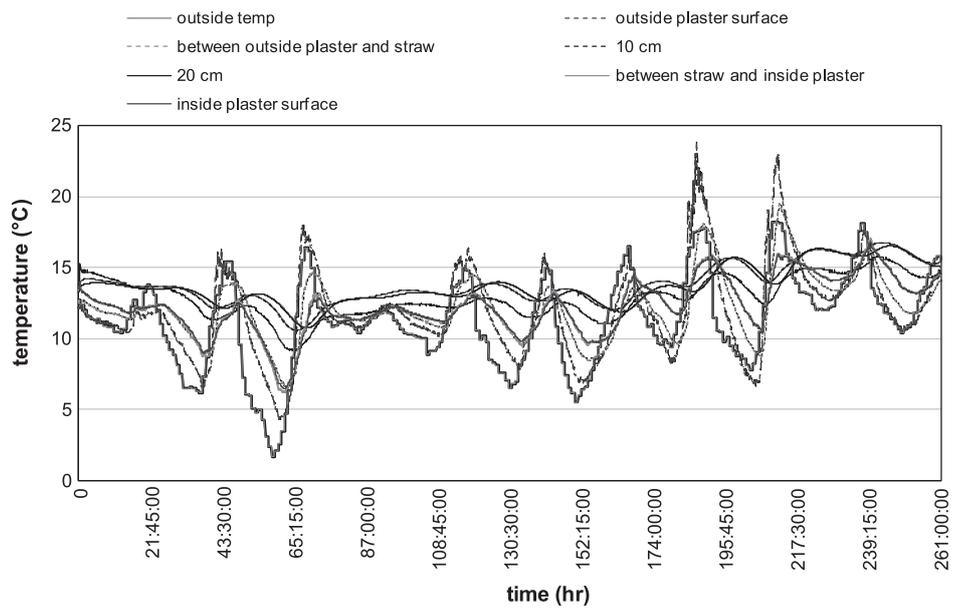


Fig. 12. Temperature evolution across straw wall of the ground floor.

Table 2
The average relative humidity at different locations.

Time (h)	Outside relative humidity (%)	10 cm from outside	20 cm from outside
0	78.77	71.76	68.82
24	61.58	70.25	67.94
24–96	62.33	69.72	67.50
96–261	67.39	71.26	69.16

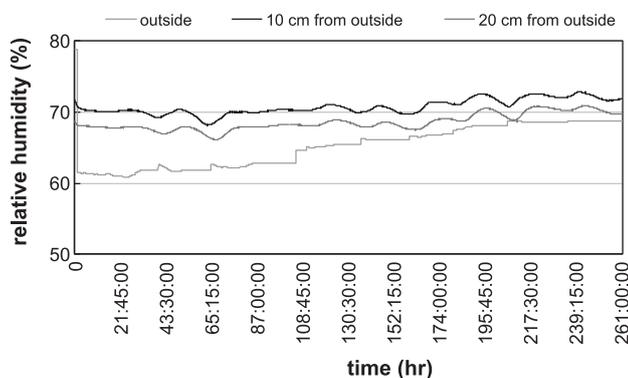


Fig. 13. Relative humidity distribution inside the wall for the ground floor.

At the end of the test (261 h), the temperature percentages between the outside temperature and the other side of the wall bales were 5.83, 6.59, 20.86, 19.68, 9.46 and 111.99% for outside plaster surface, between outside plaster and straw bale, 10 cm in straw, 20 cm, in straw, between straw and inside plaster and inside plaster surface, respectively.

Table 1 and Fig. 12 show also that the temperature inside the straw wall was stable despite the large difference of outside temperature between day and night. The results revealed that straw wall smoothed out the extreme temperature peaks outside and provide better living conditions.

4.4.2. Relative humidity

Relative humidity values were recorded at different locations, i.e. outside house and inside the wall (at 10 cm and 20 cm from external surface). Fig. 13 shows the relative humidity evolution inside the wall at different locations. The average values are given in Table 2. At the beginning, the average relative humidity values were 78.77, 71.76 and 68.82% for outside relative humidity 10 cm in straw, and 20 cm, in straw, respectively.

After 24 h, the relative humidity difference between the outside relative humidity and the different location are 8.67 and 6.36% for 10 and 20 cm, respectively. After 96 h, the relative humidity percentages between the surrounding relative humidity and the other side of the wall bales were 11.86 and 8.29% for 10 and 20 cm, respectively. After 261 h, the relative humidity percentages between the outside relative humidity and the other side of the wall bales were 5.74 and 2.63% for 10 and 20 cm, respectively.

Table 2 and Fig. 13 show also that the relative humidity behavior inside the straw wall is stable although there are large variations outside between day and night. At the beginning of the test, the relative humidity inside the straw bale wall was higher than those outside. This means that the moisture migration through the straw bale wall was very slowly.

5. Conclusions and recommendations

There is only a small database in literature for straw buildings in the northern hemisphere. The research work provides systematic measurements of several important variables in a house

with straw bale walls in Germany. An extensive testing program was carried out. The straw bales showed nonlinear stress–strain behavior with pronounced nonlinearity at lower loading level. The bales showed apparent anisotropic behavior with the vertical strain for vertical orientation higher than those for horizontal orientation. Upon load removal the bales showed time dependent behavior with the time required for a complete recovery of deformation at about 10 to 13 min. The measurements of temperature and relative humidity showed that the straw walls had excellent properties to provide excellent living conditions. The extreme outside temperatures were smoothed out by the straw walls. Admittedly, the time of some measurements was too short particularly the relative humidity in bales, which plays an important role in the long term behavior of straw walls. The moisture content of the straw bales was about 11%, which was less than 15% (safe condition for straw bale buildings). The pH value inside the bale was about 7.29, which implied an alkaline environment. More in situ measurements are needed to provide more confidence in the durability of straw bales in the northern hemisphere.

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