Light Clay and Straw Bale-Based Building Technologies

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Abstract. The article deals with issues related to light clay and straw bale in modern housing. It presents the characteristics of clay and straw, as building materials. Attention is paid to the possibility of using these raw materials for building walls in single-family houses. In addition, the paper presents a thermal analysis for this type of walls and the resulting conclusions, which allow for the treatment of straw bale and light clay as a viable alternative to commonly used technologies for erecting buildings. According to the PN-EN ISO 6946: 2008 standard, thermal resistance and heat transfer coefficient were calculated for selected vertical partitions. Other natural building technologies have been omitted.

1. Introduction.
The basic need of all people is to have an own shelter - home, in which they would feel safe and well. For thousands of years men have been using for construction purposes raw materials available in their close vicinity. Until today, we admire ancient structures, which have endured and delight us with their beauty. This study concerns building structures made of local and only slightly processed materials, including straw and clay. Technologies providing for the use of these construction materials are poorly known and not much popularised. In the 21-st century, there are efforts made to employ advanced building technologies while potential of simple technologies is not seen. Building based on natural materials is available for everyone, and it meets the criteria of sustainable development - the development, in which environment and people are in the first place. This sort of building makes it possible to engage in the construction process occupants, friends and other people, who do not have to possess specialist qualifications. It allows aware response to the demand of sustainable development including social integration. Simple building construction technique of straw bales or light clay allows employing excluded persons, who may build homes for their own needs by themselves.

Research in the field of natural building technologies are not numerous. In the study conducted by Miccoli et al. [1], a comparison of the mechanical performance of structural elements built in three basic techniques, earth block (adobe) masonry, rammed earth and cob, is presented. Up to present, few studies are available concerning the mechanical behaviour of straw bales in buildings [2]. Aims at investigating the behaviour of straw bales and leads to recommendations for required bales densities. Robinson et al. [3] investigated the viability of straw bale construction, in particular, its resistance to

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moisture. Similarly, González [4] investigated two options for the use of straw to fill envelop walls in the Andean Patagonian region: the direct use of straw bales, whether in whole or in halves, and the manufacturing of straw-clay blocks. All straw options analysed result in significantly better thermal performance than current choices of fired bricks or concrete blocks, which are commonly used in the region. In turn, Ashour et al. [5] evaluated a straw bale house located in Bavaria, Germany. The experimental work included compression tests, moisture content, thermal stability of bales and pH. Goodhew et al. [6] examined the use and accuracy of a moisture probe used in the walls of a straw-bale building. The measurements from a number of moisture probes placed in the walls of a case study straw-bale building over a 2-year period are presented. Similarly, Lawrence et al. [7] concluded results from a study on moisture monitoring in straw bale construction, and includes the development of an empirical equation which relates straw moisture content to surrounding microclimate relative humidity and temperature. Ashour et al. [8] presented results from a study on the thermal conductivity of some natural plaster materials that could be used for straw bale buildings. This paper presents specification of the above materials, used in construction. Attention has been paid to the potential of using light clay and compressed straw bales to build walls in single-family houses.

In addition, the paper presents a thermal analysis for this type of walls and the resulting conclusions, which allow for the treatment of straw bale and light clay as a viable alternative to commonly used technologies for erecting buildings. According to the PN-EN ISO 6946: 2008 standard, thermal resistance and heat transfer coefficient were calculated for selected vertical partitions. Other natural building technologies have been omitted.

2. Low-tech versus natural building

Today, modern material and technological solutions: concrete, steel, glass, as well as intelligent systems are the synonyms of modernity and luxury. The low-tech is at the opposite end of contemporary housing. The low-tech solutions are based mainly on tradition and local, inexpensive materials, which do not require any special treatment and are easily available, as e.g. soil, clay, straw, or sand [9]. Human hands are required for building in the first place, and thus the use of complex technology and expensive expert knowledge is reduced. Family, friends, or neighbours may participate in the construction process, which considerably reduces building costs. The low-tech skips complex technological solutions and supports natural, generally available, unprocessed materials. The building market dominated by gigantic concerns does not support development of those solutions, which do not allow them making money. As a result, it is difficult to popularise this building method. In spite of this, the low-tech features are met more and more often, and they perfectly match the ideas of sustainable development.

Less construction materials and energy is needed to erect a building in this technology, compared to conventional building. The materials being used may be taken from recycling and allow reuse after the end of building service life. The natural building is based on materials taken from environment. Straw, clay, or wood is obtained from local, often family-owned businesses. This is the way to support local development and cultural independence of a region. The low-tech technology-based natural building is ecological. Material production does not require high-energy and high-temperature processes and no CO2 is generated. As a result of this, there is considerably less energy required to erect a building than in case of conventional procedures. Materials are transported locally only, and the structure is fully biodegradable, after the end of service life leaving no harmful waste hard to degrade in the environment. Natural building allows carrying out many works individually, or with the help of people, who not necessarily have high qualifications. Construction material is inexpensive. This sort of building is available for everyone, creates jobs locally and integrates people. All these qualities are characteristic precisely for sustainable development.
3. Wall building technology

There are more than ten different methods of clay and straw based building. Wall construction and its erection method also changes depending on an employed technology. The most popular procedures include:

- erection of walls made of straw bales or light clay and plastered with clay,
- erection of monolithic walls consisting of clay and straw mix in boarding,
- compaction of dry sandy clay with gravel in a formwork using a pneumatic hammer, or forming soil and clay blocks in mechanical presses.

This study presents a method used to erect walls of straw bales and light clay in wooden framework.

3.1. Light clay walls

The whole building structure: walls, floors and roof can be made of pine poles. This method is simple and guarantees considerable savings due to low cost of poles. However, it requires greater amount of labour than in case of using a skeleton construction of wooden beams or scantlings. Very often the roof and floor structures are made using conventional methods, or of prefabricated elements. Poles with diameter 10-15 cm are cut along in half, and the so-called mine timber elements with diameter up to 25 cm are cut into quarter rounds. These are joined using connectors to form ladders, latticework and trusses. They work as carrying posts, floor beams and rafters (Figure 1). Several posts joined with transoms and crosses form a single modular component. Wall modules should have the height of a single storey. Floor latticework is made of half-poles, 12 cm in diameter. Their span may reach up to 7.5 m. Poles are made of local and ecological material. Due to preserving properties of clay, with which they will be plastered, they do not need to be put to planing on four sides, or pressure impregnation [10].

Houses built in light wooden framework technology allow fast and efficient erection of a structure. Most often, timber used to make the framework is pinewood with moisture content not exceeding 18%, kiln-dried, which ensures effective protection against pests and bacteria, impregnated and planed on four sides, with chamfered edges. The timber cannot show any signs of blue stain and/or decay. It is required to remove any remaining bark from its surface. It should not have many knots, cracks and twists. The greatest advantage of this framework is the option of structure prefabrication. Assembly of this structure takes from 1 to 7 days, depending on its size and complexity. The spacing of posts in the framework shall be adapted to the type of wall filling, at the same time minimising the use of timber [11].

The skeleton walls may be filled with light clay blocks/bales. The light clay technology involves forming clay and straw bales in previously prepared moulds and presses. The technology is called light
clay, because the blocks do not make the load-bearing structure, but only thermal insulation. Large metal trough may be used for mixing straw with clay suspension. There are many techniques that allow mixing these materials together. Conventional method involves treading or mixing with rake and hoe. This takes plenty of time, therefore it is good to use an excavator with a bucket. The desired shape of blocks is obtained in a mould. Then, the blocks need to be compressed mechanically and placed on wooden platforms prepared earlier, where they should be drying for minimum 2-3 days. Then, they should be turned upside down and left to dry for several weeks. It is important to protect them against rain in case of bad weather conditions. Owing to the drying process, the use of blocks in construction works is independent of season; moreover, it is possible to plaster the blocks earlier, which reduces duration of construction works. Blocks prepared and dried earlier are laid in the framework on clay, clay-cement, or clay-lime mortar with chopped straw and chaff added (Figure 2). The advantages of this procedure include low contraction and minor subsidence of filling. It is good to adapt block dimensions to the framework module and wall thickness (ca. 50 cm). Light clay blocks also prove to work well as material for division walls [12].

3.2. Straw bale walls
Generally, construction methods using the straw-bale technology may be divided into two groups, depending on the function of compressed straw bale in the wall. The first style used is the Nebraska style, encountered in the oldest buildings made of compressed straw, precisely in the State of Nebraska. Straw bales have the carrying - structural function in the wall (Figure 3), and thus the name ‘load bearing’. This method involves placing straw bales in layers so as to avoid overlapping of vertical joints in successive layers. Vertical rods are driven in so as to stiffen the structure - each of them should run through three rows of bales at the same time. Wooden or bamboo rods are allowed, as well as steel reinforcement bars. One of the advantages of the load bearing solution is less consumed timber. This allows reduction of costs and making the building process more environment-friendly. Wood is used only to make lintels, window and door openings, tie beams, floors and rafter framing; whereas, straw compression under load constitutes a considerable problem. Considering this, adequate knowledge and experience is needed to make this structure. Tie beams with weight of floors and rafter framing are the elements, which stabilise and compress straw through pressure exerted on the wall. The use of straw bales as a load-bearing structure limits building size to 2 storeys. Higher buildings require using strongly compressed bales, which are practically unavailable in Poland. The load bearing technology is poorly spread due to the biases of investors, contractors and designers, as well as unfavourable building regulations.

Figure 2. Light clay bales and their laying method [12]
The system with wooden construction (Figure 4) is a more popular and more frequently used straw-bale variant. In this option there is no problem with structure calculations carried out by designers, and there is no compression or subsidence of straw. Safe load-bearing structure of light wooden framework allows building features of any size, and bale quality and compression degree is less important. A considerable advantage of this technology is the possibility to make a roof before commencement of works with straw bales, which allows builders work independently of weather. Straw works here as an insulator and filler. Compared to the load bearing system, this solution requires greater amount of timber and labour, which increases costs, but a building can be larger.

Wooden structure framework is filled with straw bales. In order to ensure wall rigidity, the bales are staggered, and vertical rods are driven in from top more or less every three layers, same as in case of the load bearing solution. The bales should overlap at least 20-30cm. The first layer of bales is laid onto reinforcement bars coming out of the foundation, or fixed to the structure permanently. While erecting the wall, bale moisture content shall not be higher than 15%. It is possible to use horizontal compression with hydraulic lifts in order to obtain proper compression ratio for bales in a wall.

A support for the lift is fixed temporarily between load-bearing structure elements, while the lift is turned downwards. A board is laid on a ready bale layer, and then the layer is compressed using the lift. The handle of straw stuffing tool, which looks like a wooden hammer, is used for local replacement of straw losses. The last bale is laid under the wall plate using steel slide or plywood. In this way, the bale is placed correctly and eliminates any possible heat leakage bridges.

As giant bricks, straw bales have to be cut to wall size. The less cuts, the better. Fibres in bales running in parallel to the wall surface constitute better thermal barrier due to greater amount of obstacles-stalks on the way. However, in Poland it is hard to obtain such an ideal arrangement and compression; therefore it is acceptable to have straw laying perpendicular to the wall. This orientation of stalks provides better plaster adhesion surface than in bale with fibres along partition thickness. The drawback of this solution involves uncovered capillaries in straw - as a result water absorption on this side is greatest. Walls should be designed in straw bale length module. The modules and heights should be calculated taking into account the possibility of compression of each bale by 50-75mm in height. Bale cutting requires first to have the block seamed at a required length, and only then to cut the original string. Hand-held tools can be used to cut and smooth ready wall surface before plastering, but the most common and efficient method is to use saw with minimum 400mm-long blade.
Figure 4. Wooden framework filled with straw bales [14, 15].

Windows, doors and other openings in a wall have to be surrounded with wooden frames, which will sustain the loads of straw bale compression or own weight of bricks made of light clay. The frames may be fixed to load-bearing structure of the house, or may be set as floating in wall. Windows should be situated as close to external walls as possible to ensure wall protection from water. Windowsills cannot be too wide. They have to protrude beyond wall outline, and be provided with protective, vertical elements covering the wall to allow water flow away from it.

4. Thermal and moisture properties of building partitions

The PN-EN ISO 6946 [16] standard provides a method for calculating the thermal resistance and heat transfer coefficient of building components that separate the internal and external environment, with the exception of doors, windows, glazed components and those that transfer heat to the ground, as well as components, through which air supply is expected. Heat transfer coefficient is an important parameter that allows for determining the thermal properties of a partition. It is defined for homogeneous-layer building partitions, building partitions with at least one composite layer and for components with layers of varying thickness.

The heat transfer coefficient is expressed by the equation:

\[
U = \frac{1}{R_T} \left[ \frac{W}{m^2 \cdot K} \right]
\]  

Where:
- \( R_T \) - total thermal resistance of a building partition,
- \( R_T \) for homogeneous partitions is described by the formula:

\[
R_T = R_{si} + R_1 + R_2 + \ldots + R_n + R_{se} \left[ \frac{m^2 \cdot K}{W} \right]
\]  

Where:
- \( R_{si} \) - heat transfer resistance on the inner surface,
- \( R_1 + R_2 + \ldots + R_n \) - design thermal resistance of each layer,
- \( R_{se} \) - heat transfer resistance on the outer surface,
- Thermal resistance of a homogeneous layer with thickness \( d \) is obtained from the equation:

\[
R = \frac{d}{\lambda} \left[ \frac{m^2 \cdot K}{W} \right]
\]  

Where:
- \( d \) - thickness of the material,
- \( \lambda \) - design thermal conductivity of the material.

The PN-EN ISO 13788 [17] standard presents a simplified method of calculating the temperature of the inner surface of the building component, under which, at a known temperature and humidity of indoor air, mould or condensation on surfaces can develop. It also provides methods for assessing the risk of indoor condensation due to water vapour diffusion. The risk of mould growth occurs at relative
humidity above 80% for several days. To prevent the formation of mould, it is important to fulfil the condition:

\[ f_{Rsi} > f_{Rsi,\text{min}} \]

where:

- \( f_{Rsi} \) - temperature on the inner surface,
- \( f_{Rsi,\text{min}} \) - minimum permissible temperature on the inner surface, determined on the basis of the internal and external climate.

The calculation is carried out for each month of the year [18]. The internal humidity and acceptable volumetric moisture at saturation are determined. It is also possible to calculate the partial pressure of saturated steam at the surface and assume a critical relative humidity at the surface. Then, the minimum temperature of the analysed area is determined.

To calculate the temperature and humidity parameters, a partition composed of homogeneous layers without a layer of air is used. In order to simplify the calculations it was assumed that the supporting structure made of the timber, if it is constructed on the entire thickness of the wall as a continuous structure, has no substantial effect on the conduction of heat through the wall. This is associate with a large wall insulation thickness in relation to the cross-section of the superstructure columns. Flow of heat takes place in the horizontal direction, which is defined by \( R_{\text{si}}=0.13 \) and \( R_{\text{se}}=0.04 \). Internal moisture conditions are adopted for constant internal temperature of 20\(^\circ\)C and a constant relative humidity of 50%. When checking the criterion for preventing surface condensation of partitions, regardless of the type of partition, the heat transfer resistance value on the inner surface of the partition of \( R_{\text{si}}=0.25 \frac{m^2\cdot K}{W} \) is adopted.

The first step compares the heat transfer coefficients for different wall thickness, made in straw-bale and light clay technology (Figure 5). The analysis was performed for the same wall thicknesses, calculated together with the clay plaster. In the case of light clay, double-sided plaster with a thickness of 3 cm on each side was used. For straw bales, 7cm of external plaster and 4cm of internal plaster was assumed.

**Figure 5.** Comparison of the heat transfer coefficients for different thicknesses of walls made of light clay ● or pressed straw ● (Source: own).

"Regulation on technical conditions to be met by buildings and their location" gives the limit value of heat transfer coefficient \( U=0.23 \) [W/m\(^2\)K] for the outer wall. In addition to meeting the requirements of heat transfer, it is worth considering the optimal thickness of the walls. Due to the low cost of insulating the walls, it is best to choose the thickness of about 50cm. This will create a well-insulated partition, satisfying, e.g. in the case of straw bales, almost twice the thermal requirements. It will also have an appropriate heat storage mass and greater rigidity. At the same time, the wall thickness of about 50cm will provide the required sound insulation. The use of thicker insulating material is associated with a greater reduction in living space and possible higher costs of the wooden frame. The following section presents a thermal and moisture analysis of a building with wall thickness of 56cm (Table 1, Table 2). Construction of a partition:
Table 1. Properties of the light clay wall materials used.

| No | The layer      | d [m] | \( \lambda \) [W/mK] | \( \mu \) | R [m²K/W] | s₀ [m] |
|----|---------------|------|---------------------|--------|----------|--------|
| 1  | clay plaster  | 0.03 | 0.58                | 10     | 0.052    | 0.3    |
| 2  | light clay    | 0.5  | 0.1                 | 10     | 5        | 5      |
| 3  | clay plaster  | 0.03 | 0.58                | 10     | 0.052    | 0.3    |

Inside

Table 2. Properties of the straw bale wall materials used.

| No | The layer      | d [m] | \( \lambda \) [W/mK] | \( \mu \) | R [m²K/W] | sd [m] |
|----|---------------|------|---------------------|--------|----------|-------|
| 1  | clay plaster  | 0.07 | 0.58                | 10     | 0.121    | 0.7   |
| 2  | straw bale    | 0.45 | 0.08                | 1.3    | 5.625    | 0.585 |
| 3  | clay plaster  | 0.04 | 0.58                | 10     | 0.069    | 0.4   |

The effective value of the temperature coefficient on the inner surface of the barrier is determined by the value of heat transfer coefficient \( U \) element and the heat transfer resistance at the inner surface \( R_{si} \).

For light clay:
The total thermal resistance of a partition:
\[ R_t = 5.273 \text{ m}^2\text{K/W}. \]

The heat transfer coefficient of the building partition (without taking into account corrections for leakage and connectors \( \Delta U \) and allowance for linear bridges \( \Delta U_k \)):
\[ U = 0.19 \text{ W/m}^2\text{K}. \]

The value of temperature coefficient for the partition:
\[ f_{R_{si}} = 0.968 \]
For straw bale:
The total thermal resistance of a partition:
\[ R_t = 5.985 \text{ m}^2\text{K/W}. \]

The heat transfer coefficient of the building partition (without taking into account corrections for leakage and connectors \( \Delta U \) and allowance for linear bridges \( \Delta U_k \)):
\[ U = 0.167 \text{ W/m}^2\text{K}. \]

The value of temperature coefficient for the partition:
\[ f_{R_{si}} = 0.972 \]

Due to the same value for the temperature coefficient of the two partitions, a minimum value of the \( f_{R_{si},min} \) coefficient in individual months is as follows (Table 3).

The highest value \( f_{R_{si},min} =0.679 \) was obtained for the critical month of January. the condition that \( f_{R_{si}}=0.968 > f_{R_{si},min}=0.679 \) is met. Therefore, the analysed building partitions are designed properly in terms of avoiding mould growth.

The calculated value of the dew point temperature is \( T_s = 9.23^\circ\text{C} \) for all months of the year. This indicates that the temperature on the inner surface of the building partition, which fluctuates around \( 19.5^\circ\text{C} \), is higher than the dew point temperature plus \( 1^\circ\text{C} \). Partitions were therefore designed in
Table 3. Value of the minimum fRsi coefficient.

| Months   | fRsi, min |
|----------|-----------|
| 1        | January   | 0.679    |
| 2        | February  | 0.659    |
| 3        | March     | 0.583    |
| 4        | April     | 0.385    |
| 5        | May       | -0.054   |
| 6        | June      | -1.235   |
| 7        | July      | -2.688   |
| 8        | August    | -1.837   |
| 9        | September | -0.117   |
| 10       | October   | 0.359    |
| 11       | November  | 0.548    |
| 12       | December  | 0.64     |

5. Summary and conclusions

Building based on light clay and straw bales is still rarely observed and used. There is no standardisation of straw as a building material. Moreover, obsolete standards regarding clay building constitute a major obstruction for quick development of natural building of this type in Poland. There is no promotion, or modern scientific and research base, which would allow introducing these materials into the building market on an industrial scale. On the other hand, rapidly disappearing natural resources, increasing energy costs and the European Union tightening thermal standards may soon help in changing the attitude of state and people to these natural building methods. These technologies are needed, since they give an opportunity to reduce CO₂ emissions and thus pollution of natural environment.

Building based on light clay and straw bales is simple, ecological and available for everyone. It fits in the ideas of sustainable development, supports local businesses and allows integration of people while designing and building a house. Investors may reduce incurred costs through their own financial contribution at different stages of building process, and later they can save on heating.

All these positive aspects, as well as good thermal results of calculations, allow stating with full responsibility that straw and light clay is a real alternative for commonly used building erection technologies.

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