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LIGHT CLAY AND STRAW BALE SOLUTIONS IN CONTEMPORARY HOUSING CONSTRUCTION

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Abstract:

The article presents issues related to solutions with light clay and straw bales in the contemporary housing construction. Building using straw bales and light clay is simple, eco-friendly and accessible to all. It fits in the ideas of sustainable development, supports local businesses and gives the opportunity to integrate people while designing and building a house.

The article presents the thermal analysis for this type of walls and subsequent conclusions that allow the treatment of straw and light clay as a viable alternative to the commonly used technologies of erecting buildings.

Keywords:

light clay, straw bales, housing construction.

1. LOW-TECH vs NATURAL BUILDING

Contemporary material and technological solutions - concrete, steel, glass as well as intelligent systems are synonymous with modernity and luxury nowadays. At the other extreme of modern building construction is low-tech. Low-tech solutions are based primarily on tradition and local low-cost raw materials not involving any special treatment, which are readily available, such as soil, clay, straw or sand. Construction requires mainly human manual labour, while limiting the use of complex techniques or the expensive expertise. Families, friends, or neighbours may participate in the construction process, which largely reduces building costs. Low-tech does not require complex technical solutions and supports natural areas, unprocessed materials. The construction market dominated by giant construction companies does not support the implementation of solutions, which do not bring lucrative profits. Hence, the widespread dissemination of this construction method is difficult. Nonetheless, low-tech objects are becoming more and more common and perfectly fit into the ideas of sustainable development.

Sustainable development means 'the socio-economic development, in which the integration process of political, economic and social activities takes place, while maintaining natural balance and permanence of basic natural processes in order to guarantee the possibility of satisfying the basic needs of individual communities or citizens of the present generation and the generations to come.[1]' An object's key features indicating sustainable development can be described using four *R*: reduce, reuse, recycle and renewable.[2] There is less material used for the construction of such an object than for a conventional building. Recycled materials should be used, which would be possible for reuse after the life of a building finishes. Natural building derives materials from the environment. Straw, clay or wood is obtained from local, often family, businesses. Thus supporting local development and the cultural independence of the region. Natural building in low-tech technology is ecological. The production of materials does not require high energy and high-temperature processes, does not produce CO_2, thereby consumes less energy needed to erect a building than conventional construction. Transport of materials takes place only locally. The structure, however, is fully biodegradable and at the end-of-life leaves no harmful hard-to-decompose waste. Natural construction enables the self-performance of multiple works, or with the help of people not necessarily highly skilled. It is accessible to all, creates local job positions and integrates people. The building material is cheap. All of these features are specific for sustainable development [1].

2. HYGROTHERMAL PERFORMANCE OF BUILDING PARTITIONS. THE CASE STUDY

The PN-EN ISO 6946 norm [2] provides the method for calculating the thermal resistance and heat-transfer coefficient for building components that separate its interior from the outdoor environment, with the exception of doors, windows, glazed components, those allowing heat-transfer to the ground, and also components which provide air conditioning. The heat-transfer coefficient is an important parametre, which allows the determination of thermal properties of the partition. It is defined for partitions of homogeneous layers, partitions with at least one non-homogeneous layer and components in layers of variable thickness.

The heat-transfer coefficient [2] is expressed by the equation:

$$U = \frac{1}{R_T}, [\frac{W}{m^2 \cdot K}] \tag{1}$$

R_T – the total thermal resistance of the partition

[1] The Act – the Environmental Protection Law Article 3 paragraph 50.

[2] *Jerzy Baryłka, „Wymagania proekologiczne w budownictwie na przykładzie przepisów prawa budowlanego i prawa o wyrobach budowlanych"*

The total thermal resistance of the partition R_T for homogeneous partitions [2] is described by the formula:

$$R_T = R_{si} + R_1 + R_2 + \ldots + R_n + R_{se}\,,\ [\frac{m^2 \cdot K}{W}] \quad (2)$$

R_{si} – the thermal resistance on the inner surface

$R_1 + R_2 + \ldots + R_n$ – the computational thermal resistances of each layer

R_{se} – the thermal resistance on the outer surface

The thermal resistance of a homogenous layer with a thickness of d [2] is obtained from the equation:

$$R = \frac{d}{\lambda}\,,\ [\frac{m^2 \cdot K}{W}] \quad (3)$$

d - the material thickness

λ - the calculation factor of thermal conductivity of the material.

The PN-EN ISO 13788 norm [3] presents simplified methods for calculating the temperature of the inner surface of a building element, below which, at known temperature and humidity of indoor air, the mould growth or the water vapour condensation may appear on surfaces. It also provides the assessment method of the risk of the inner condensation resulting from the water vapour diffusion. The risk of the mould growth occurs at relative air humidity exceeding 80% for several days. It is important to satisfy the following condition so as to prevent mould:

$f_{Rsi} > f_{Rsi,min}$

where:

f_{Rsi} - the temperature factor on the inner surface,

$f_{Rsi,min}$ - the minimum allowable temperature factor on the inner surface, determined on the basis of the internal and external climatic conditions.

Calculations are carried out for each month of the year. The indoor air humidity and limit volume humidity when reaching saturation point is determined. It is also possible to calculate the partial pressure for the saturated water vapour and take a critical relative humidity on the surface. Then the minimum temperature of the surface in question is determined.

A partition made of homogeneous layers without air layers was adopted to calculate hygrothermal parametres. In order to simplify calculations it was assumed that if the superstructure made of timber is not formed as continuous throughout the thickness of the wall, it does not significantly affect the heat transfer through the wall. It has to do with high thickness of wall insulation in relation to cross sections of columns of the superstructure. The heat stream flows in a horizontal direction, which is defined by R_{si}=0,13 and R_{se}=0,04. Internal humidity conditions were adopted for the constant internal temperature of 20°C and the constant relative humidity at the level of 50%. When verifying the criterion for preventing surface condensation of partitions, regardless of the type of partition, the following value of heat-transfer resistance on the inner surface of the partition was adopted: R_{si}=0,25 $[\frac{m^2 \cdot K}{W}]$.

At the first stage there were compared heat-transfer coefficients for different wall thicknesses (Table 1) made in the straw-bale and light-clay technology. The analysis was performed for the same wall thickness, taken in aggregate with clay plaster. In the case of light clay the 3cm-thick plaster was applied on both sides. The 7cm-thick external plaster and 4cm-thick internal plaster were adopted for straw bales.

Table 1. The comparison of the heat-transfer coefficient for different thickness of walls made of light clay or compressed straw

	Wall thickness [cm]				
	36	46	56	66	76
Light clay	0,305	0,234	0,19	0,159	0,137
Straw bale	0,287	0,211	0,167	0,138	0,118
	Heat transfer coefficient U [W/m*2K]				

Source: Own study

'Regulation on technical conditions to be met by buildings and their location' establishes the limit value (maximum) of the heat-transfer coefficient U=0,25 [W/m²K] for the outer wall. In addition to meeting the requirements of heat-transfer, the optimum thickness of the walls is worth considering. Taking into account the low cost of the wall insulating material, the best choice is the thickness oscillating around 50cm. Then, the well-insulated partition is received, which e.g. through the straw bales almost doubles satisfying the thermal conditions. It will also have a suitable heat storage mass and higher stiffness. At the same time only the wall thickness of approx. 50cm will provide the required sound insulation. The use of thicker insulating material is associated with greater reduction of the usable floor area and possible higher costs of timber framing. The following section focuses on the analysis of the hygrothermal design of 56cm-thick walls.

The construction of the partition:

Table 2. Properties of the materials used in the light clay wall

Nr	Name of layer	d [m]	λ [W/mK]	μ	R [m²K/W]	S_d [m]
Outside						
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						

Source: Own study

Table 3. Properties of the materials used in the straw bale wall

Nr	Name of layer	d [m]	λ [W/mK]	μ	R [m²K/W]	s_d [m]
Outside						
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
Inside						

Source: Own study

where:

R – the thermal resistance,

d – the layer thickness,

λ – the heat conductivity coefficient,

μ - the relative diffusion resistance coefficient,

s_d – the equivalent diffusion coefficient

The effective value of the temperature factor on the inner surface of the partition is determined on the basis of the heat-transfer coefficient of the U element and the heat-transfer resistance on the inner surface R_{si}.

For light clay:

The total thermal resistance of the partition: $R_t = 5.273$ [m^{2}K/W].

The heat transfer coefficient of the partition without taking into account corrections to leaks and fittings ΔU and additions to linear bridges ΔUk): U = 0.19[W/m^{2}K].

The value of the temperature factor of the partition: $f_{Rsi} = 0.968$.

For straw bales:

The total thermal resistance of the partition: $R_t = 5.985$ [m^{2}K/W].

The heat transfer coefficient of the partition without taking into account corrections to leaks and fittings ΔU and additions to linear bridges ΔUk): U = 0.167[W/m^{2}K].

The value of the temperature factor of the partition: $f_{Rsi} = 0.972$.

Due to the same value of the temperature factor for the two partitions, the minimum values of the temperature factor f_{Rsi} in particular months are as follows:

Table 4. The value of the minimum temperature factor: f_{Rsi}

	Month	min f_{Rsi}
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

Source: Own study

The greatest value $f_{Rsi,min}$ = 0,679 was obtained for the critical month - January. The condition f_{Rsi}=0,968 > $f_{Rsi,min}$=0,679 was satisfied. Therefore, the analysed partitions have been designed properly so as to avoid the mould growth.

The calculated value of dew point temperature is T_s=9,23°C for all months of the year. This shows that the temperature on the inner surface of the partition, which oscillates around 19,5°C, is higher than the dew point temperature of 1°C. Partitions have therefore been designed in accordance with the technical requirements (the Regulation of the Minister of Infrastructure of 12th April 2002) relating to the dew point temperature.

In order to verify the wall in terms of the occurrence of interstitial condensation the flow of condensation g_c inside the partition should be calculated for each month. The internal condensation does not take place in the wall made of light clay (Table 5).

For walls made of straw bales it was calculated that the inside water vapour condensation would occur in the months from November to March. However, the evaporation of the total condensate is predicted during the summer months.

Condensation occurs between the clay plaster layer and straw bales. It achieves the greatest value in January g_c=0,28981 (Table 6).

Table 5. Temperature, saturation pressure, pressure, the amount of the condensate in the light clay wall in January

Partition		Contact surfaces			
Nr	Layer	Tn	P n, sat	P n	g c
		[℃]	[Pa]	[Pa]	[kg/m²]
Outside: T=-3 [℃], ϕ=85[%]					
		-2,83	482,34	404,14	0
1	clay plaster				
		-2,61	491,37	445,09	0
2	light clay				
		18,71	2157,18	1127,53	0
3	clay plaster				
		18,93	2187,11	1168,48	0
Inside: T=20 [℃], ϕ=50[%]					

Source: Own study

Table 6. Temperature, saturation pressure, pressure, the amount of the condensate in the straw bale wall in January

Partition		Contact surfaces			
Nr	Layer	Tn	P n, sat	P n	g c
		[℃]	[Pa]	[Pa]	[kg/m²]
Outside: T=-3 [℃], ϕ=85[%]					
		-2,85	481,53	404,14	0
1	clay plaster				
		-2,39	500,29	721,67	0,28981
2	straw bale				
		18,8	2168,66	987,03	0
3	clay plaster				
		19,06	2204,12	1168,48	0
Inside: T=20 [℃], ϕ=50[%]					

Source: Own study

The heat transfer coefficient for walls made of straw is greater than for light clay walls. There is no risk of the mould growth in both partitions. According to calculations for the Polish climate during the winter the moisture condenses in straw bale walls, but in April it completely evaporates into the environment. It should be remembered that the method used in the standard is the simplified assessment of the hygrothermal state, which does not take any account of the impact of the material moistness on its insulation and destruction.

3. COSTS OF MATERIALS AND LABOUR

The idea underlying the natural housing construction is to make as much as possible own labour contribution during erecting an object. This is possible due to the simplicity of construction and the absence of the need to use complicated tools.

Table 7 shows the costs of building a house of light clay of the usable area of 100 m^2. The costs for a house of straw bales will be very similar to those shown for clay. In both cases, the entire structure is the same apart from the material necessary to insulate the erected walls. Despite the use of different materials the attention should be paid to the fact the clay cubes take a lot of time to prepare, but then it is fast to erect and finish walls of them. While the time required for laying straw bales in the frame is much shorter, finishing them with clay plasters takes a lot more time. Hence, the costs of using these two low-cost building materials in the perspective of the entire construction are similar.

Table 7 shows a comparison of the costs of a house made entirely by a construction company, craft workers or in the economic manner – with own means. The house in question is slab-on-grade, with a functional attic. Approximately 30 working hours are necessary to construct 1 m^2 of the usable area of a natural house.

Table 7. The cost of building a house in the light clay technology

I. House-building costs	**Usable area**	**1 m^2 of usable area**
A. Executed by a company – turn-key project	PLN 320 thousand	PLN 3,200
B. Executed by craft workers	PLN 145 thousand	PLN 1,450
C. Own work	PLN 90 thousand	PLN 900
II. Costs of the completed raw state		
A. Executed by a company – turn-key project	PLN 210 thousand	PLN 2,100
B. Executed by craft workers	PLN 90 thousand	PLN 900
C. Own work	PLN 52.5 thousand	PLN 525

Source: Own study

The expenditures are connected with own contribution, accessibility of raw materials, as well as the costs of hiring qualified employees or a company. In Poland, there are several professional companies dealing with constructing houses of light clay and straw bales. However, as the competition is small and such clay plastering is very time-consuming, labour prices are high. Up to 50% of all construction expenditure is estimated to come from labour costs. Some works may be too difficult to implement them with own means. Laying foundations, making a structure frame and a roof may be outsourced to a company, while other elements, often expensive works, may be made with own hands. The availability of cheap wood from the forest, having clay on the plot and easy access to the straw can bring significant savings. Below there are shown examples of prices and quantities of raw materials:

The price of 1 m^3 clay purchased in a mine or a gravel pit as a waste is EUR 5 -10. When the clay is bought at a brickyard or a clay pit its cost is EUR 60 / tonne. The amount of 15 - 20 m^3 of clay is needed to build a house.

The cost of 1 tonne of dry straw is approximately EUR 60. A bale of pressed straw costs EUR 1, depending on dimensions. There are approximately 1000 pieces needed to build a house, which gives about 10 tonnes of straw when using straw-bale technology.

The pole construction is the cheapest, as 1m^3 of pine poles bought at the forester's is EUR 50 - 70. Approximately 17 m^3 of poles is necessary to build a house, which gives a total cost of less than EUR 800. About 81 m^3 of wood must be taken to perform roofing. The cost of 1 m^3 of aspen or poplar is approximately EUR 40. In the case of the use of shavings the cost is of EUR 10 / m^2 [4].

The abovementioned savings on materials depend on their availability in a given area. Low costs of raw materials can translate into a greater number of man-hours to execute a construction or prepare materials for work, as well as more expenses in the case of employing skilled workers. The low cost of straw or clay does not make the house much cheaper than a traditional brick-built one. The cost of a raw wall constitutes only several per cent of the cost of the entire construction. The total price of the house is influenced by many factors such as own contribution, the use of niche solutions for point foundations, igloo-shaped roofs or straw roof insulation.

Real savings for natural houses arise only during their operation, provided proper performance without thermal bridges.

Natural houses provide different standards of comfort compared to the traditional construction. Their warm and breathable walls, made entirely from natural and raw materials give the feeling of living in harmony with nature.

4. ADVANTAGES AND DISADVANTAGES OF LIGHT CLAY AND STRAW BALE BUILDING CONSTRUCTION

Both clay and straw offer numerous properties desired by the builders. Clay regulates air humidity. It has the ability to absorb moisture and release it back quickly. It effectively regulates humidity in a room. Relative humidity in buildings made of clay is 50%. This prevents mucous membranes from drying off, as well as allows avoiding the accumulation of dust in a room. It is energy saving and reduces pollution, since very little energy is required to have it prepared. It can be found on the construction site or nearby, thus reducing transport costs. Clay stores heat efficiently and preserves wood used as the frame of the house. Wood surrounded by clay is dried or remains dry. In this way clay makes it resilient to fungus and insect attack. Unroasted clay is reusable. After being grinded and wetted it can be re-used for construction. Clay is also able to absorb harmful substances; it neutralises odours, e.g. tobacco smoke. Hence, it purifies and ionizes the air.

The disadvantage of clay is the possible contraction when drying up. It can occur under a poor choice of a mixture of clay and straw, or too little humidity. A wall plastered with clay if not impregnated is not water-resistant without impregnation.

Moreover, straw is cheap and easily available material. Production of straw bales does not require complicated processes or heat treatment. Owing to that, there is no carbon dioxide emission, just the contrary. During its growth straw absorbs carbon dioxide from the atmosphere. Hence, straw bales are building material with a negative indicator of the carbon footprint. It has a very favourable heat transfer coefficient, increasing in the case of laying straw in parallel to the surface of the partition.

A common ecological feature of the technologies in question is their full bio-degradability after the life service. Straw, as a building material, combined with clay plaster creates a natural microclimate in a room. Such a wall has a low diffusion resistance and clay has high water absorption capacity, which provides the room with natural humidity regulation and breathable walls.

Both technologies offer the opportunity to save energy and curb greenhouse gas emissions at every stage of the building construction and usage.

In the case of applying the straw bale technology a big disadvantage are laborious multi-layer clay plasters, which must tightly cover the entire surfaces of walls so as to protect them against fire and pests. However, clay plasters do not need as a long time to bond as lime plasters. They also have the higher resistance to mechanical damage.

Whereas the great light clay technology's disadvantage is laborious and time consuming when preparing bricks in moulds. However, putting partitions is a simple and easy process.

Both of them are 'light' technologies, which also permit the use of lighter foundations. Clay and straw are non-standard building materials. As a result some difficulties in designing and planning construction time may appear. There may be a problem with obtaining raw materials of the required quality of the compaction of bales, or clay greasiness and purity. Furthermore, experience and knowledge is necessary to assess these natural materials' suitability for construction purposes.

CONCLUSION

Light clay and straw bale housing construction is still unusual and not commonly applied. Straw has not been normalised as building material and the old standards for building of clay have been in force, which represents a major barrier to the rapid development of this type of natural building in Poland. The promotion and a modern scientific and research base would contribute to bringing these materials on the construction market, at industrial scale. On the other hand, rapidly vanishing natural resources, increasing energy costs and tightening European Union's heat standards may soon help to change the attitude of the state and people to these natural building methods. These technologies are needed, as they offer the opportunity to reduce CO_2 emissions and environmental pollution.

The conducted hygrothermal analysis has showed a very good performance of walls made both of straw bales and light clay. The mould growth and water vapour pose no threat to the walls.

Building using straw bales and light clay is simple, eco-friendly and accessible to all. It fits in the ideas of sustainable development, supports local businesses and gives the opportunity to integrate people while designing and building a house. It allows the costs reductions by contributing own work at various stages of construction, and later when exploited - through savings on heating.

All these positive aspects, as well as good results of hygrothermal calculations allow to treat straw and light clay with full responsibility as a viable alternative to the commonly used technologies of erecting buildings.

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