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Research Article

Construction Time of Three Wall Types Made of Locally Sourced Materials: A Comparative Study

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Similarly to any other industry, the construction sector puts emphasis on innovativeness, unconventional thinking, and alternative ideas. At present, when sustainable development, ecology, and awareness of people's impact on the environment grow in importance, low impact buildings can become an innovative alternative construction technology for the highly industrialized construction sector. The paper presents a comparative study of three walls made of available materials used locally, which can be classified as biosourced materials, in terms of construction time. The comparison of times necessary to make 1 m^2 of the wall allows us to decide which building technology is more advantageous in terms of the construction duration. A shorter construction time means lower labour costs and lower expenses for construction machines. In order to obtain answers to the questions posed, the authors made extensive searches of source data on the time-consuming building works which used locally sourced materials. Reference is made to "Temporary principles of erecting clay buildings" issued by the Institute of Housing Construction in Warsaw (Poland). Three types of walls made of locally sourced materials were studied: a wall made of clay blocks insulated with mineral wool boards, a wall made of clay compacted in formwork, and one insulated with mineral wool boards and wooden frame structure filled with straw bales and cladded with fibreboards. The layers have been chosen in such a manner that heat transfer coefficient values for the studied variants are as equal as possible (0.2 $W/m^2 K$), thus allowing a reliable comparative study.

1. Introduction

Modern material and technological solutions—concrete, steel, glass, and intelligent systems—have become the synonyms of modernity and luxury [1]. Buildings made of locally sourced materials are on the other extreme of modern construction. These solutions are based primarily on tradition and local, low-cost raw materials that do not require special treatment, which are readily available, such as soil, clay, straw, and sand. Human hands are the main building force, while the use of complicated techniques or expensive expertise is limited. Low impact buildings avoid complex technical solutions and support generally accessible raw materials. The construction market, dominated by giant construction companies, does not support the development of such solutions since they are not profitable. This makes it difficult to popularize such a building method on a large scale. Despite this, buildings made of locally sourced materials are becoming more common and perfectly fit into the idea of sustainable development.

The most important features of a building characterized by sustainable development can be described using four Rs: reduce, reuse, recycle, and recover [2]. Less material and energy are used to build such a building compared to conventional construction The materials used should be recycled and should allow for reuse after the end of the life of the building. Low impact buildings derive the materials from the surrounding environment. This supports local development and cultural independence of the region. Production of materials does not require high energy and high temperature processed and does not produce CO_2, so it consumes less energy needed to construct the building than conventional building construction. Transport of materials is only done locally [3]. And the structure itself is completely biodegradable, and after the end of its life, it does not leave harmful waste, hard to break down by the environment. Building made of locally sourced materials allows for carrying out a lot of the work on one's own. It is available to all and creates local jobs [4].

Research in the field of natural building technologies is not numerous. Among them in paper [5] 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. Such study is presented in [6] and aims at investigating the behaviour of straw bales and leads to recommendations for required bale densities. In [7], the viability of straw-bale construction has recently been investigated, in particular, its resistance to moisture. Similarly in [8], two options for the use of straw to fill envelop walls were investigated 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, in [9] was evaluated a straw-bale house located in Bavaria, Germany. The experimental work included compression tests, moisture content, thermal stability of bales, and pH. Reference [10] examines 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 [11] concludes results from a study on moisture monitoring in straw-bale construction and includes the development of an empirical equation which relates the straw moisture content to surrounding microclimate relative humidity and temperature. Reference [12] presents results from a study on the thermal conductivity of some plaster materials that could be used for straw-bale buildings. Walls constructed in the straw-bale technology can boast excellent health qualities, which are difficult to obtain in traditional technologies [13].

Up until today, few studies are available concerning the time of construction of walls made of locally sourced materials. In this paper, the construction time of 1 m^2 of three types of walls built in these technologies was studied. The layers of the walls were chosen in such a manner that the heat transfer coefficient values for the studied variants are as equal as possible (0.2 $W/m^2 K$), thus allowing a reliable comparative study:

(i) A wall made of clay blocks insulated with mineral wool boards

(ii) A wall made of clay compacted in formwork, insulated with mineral wool boards

(iii) A wooden frame structure filled with straw bales and cladded with fibreboards

Construction time allows us to tell which technology is more advantageous. In order to obtain answers to the questions posed, the authors made extensive searches of

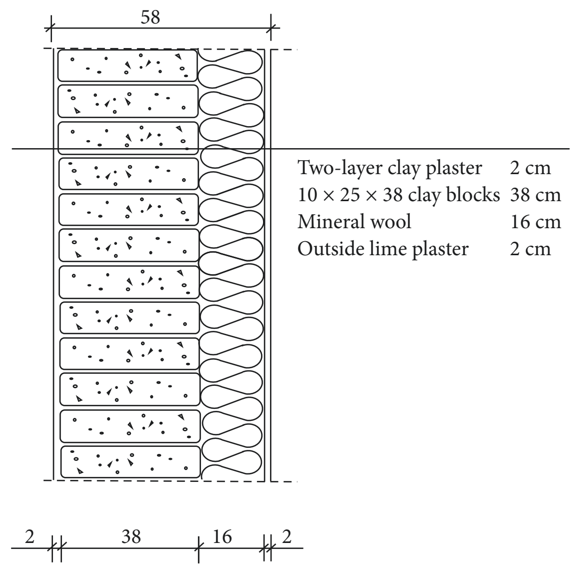

Figure 1: Cross section of the clay block wall.

source data concerning the timing of building works using locally sourced materials. Literature does not actually present any time standards. The exception is "Temporary principles of erecting clay buildings" issued by the Institute of Housing Construction in Warsaw (Poland), which were used in the comparison.

2. Characteristics and Technical Parameters of Studied Walls

2.1. Wall Made of Clay Blocks Insulated with Mineral Wool Boards. The first studied structure was a wall made of 10 × 25 × 38 cm clay blocks insulated with mineral wool boards. The structural layer of the wall is 38 cm thick (Figure 1). On the outside, the wall will be insulated with 16 cm thick mineral wool boards and covered with lime plaster. On the inside, the wall will be covered with a two-layer clay plaster. Wood fibreboards have also been considered as insulation as more environmentally friendly, but this solution is presently too expensive to be compared with affordable EPS (expanded polystyrene).

2.2. Wall Made of Clay Compacted in Formwork, Insulated with Mineral Wool Boards. The other studied solution was the wall made of clay compacted in the formwork whose structural thickness was 30 cm (Figure 2). The formwork was demountable panels. The remaining wall layers were the same as in the clay block wall.

2.3. Wooden Frame Structure Filled with Straw Bales and Cladded with Fibreboards. The third variant was the wall made of small 31 × 41 × 70 cm straw bales placed in wooden frame structure (Figure 3). The frame structure will be erected in the timber-frame house technology where posts are made as frames, so-called ladders. The wooden frame skeleton will be cladded on both sides with 12-millimetre fibreboards for

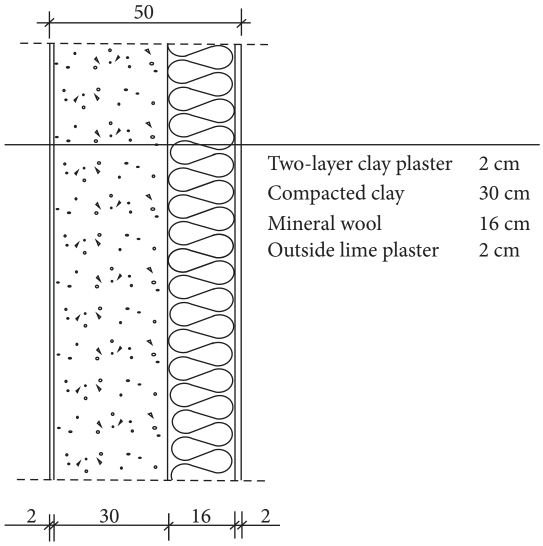

Figure 2: Cross section of the wall made of clay compacted in formwork.

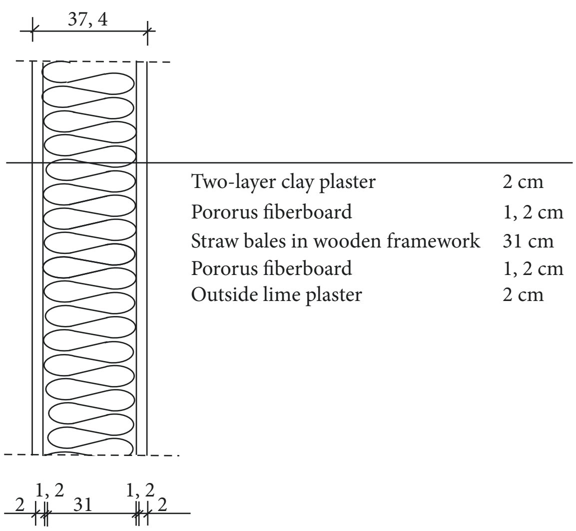

Figure 3: Cross section of the wall made in the straw-bale technology.

Table 1: Density and thermal conductivity of used materials.

	Material type	Density (kg/m^3)	Thermal conductivity λ (W/m K)
Insulation materials	Straw bales	100	0.073
	Porous fibreboard	300	0.060
	Mineral wool boards	160	0.037
Structural materials	Compacted clay and clay blocks	1800	0.900
	Pine wood	450	0.200
Materials	Lime plaster	1700	0.700
	Clay plaster	900	0.300

Source: own study, based on [14].

Table 2: Thermal properties of a clay block wall.

Layers	d (m)	λ (W/m K)	R (m^2 K/W)	U (W/m^2 K)
R_{si}			0.13	
Two-layer clay plaster	0.020	0.300	0.06666667	
Clay blocks	0.380	0.900	0.42222222	
Insulation: mineral wool	0.160	0.037	4.32432432	
Lime plaster	0.020	0.700	0.02857143	
R_{se}			0.04	
Total d	0.580	RT	5.012	0.200

Source: own study.

Table 3: Thermal properties of a compacted clay wall.

Layers	d (m)	λ (W/m K)	R (m^2 K/W)	U (W/m^2 K)
R_{si}			0.13	
Two-layer clay plaster	0.020	0.300	0.06666667	
Compacted clay	0.300	0.900	0.33333333	
Insulation: mineral wool	0.160	0.037	4.32432432	
Lime plaster	0.020	0.700	0.02857143	
R_{se}			0.04	
Total d	0.500	RT	4.923	0.203

Source: own study.

Table 4: Thermal properties of a straw-bale wall.

Layers	d (m)	λ (W/m K)	R (m^2 K/W)	U (W/m^2 K)
R_{si}			0.130	
Two-layer clay plaster	0.020	0.300	0.067	
Fibreboard	0.012	0.060	0.200	
Straw bales in frame structure	0.310	0.073	4.247	
Fibreboard	0.012	0.060	0.200	
Lime plaster	0.020	0.700	0.029	
R_{se}			0.040	
Total d	0.374	RT	4.912	0.204

Source: own study.

Table 5: Dependence of studied technologies on seasons and weather conditions.

Wall type	Works can be performed all year long	Works strongly dependent on weather conditions
Clay blocks	Yes	Yes
Compacted clay	No	Yes
Straw bale	No	Yes

Source: own study based on [14, 16, 17].

Table 6: Time necessary to make $10 \times 25 \times 38$ cm clay blocks.

Clay preparation difficulty	Compound preparation	Making of elements	Squaring of elements	Putting in trestles	Total time	Total time
			m-h/100 pcs			m-h/m^2
Medium-cohesion	2.52	5.82	0.42	0.50	9.26	
801–1400 g/5 cm^2			m-h/m^3			$8.99 \times 0.38 = 3.42$
	2.45	5.65	0.41	0.49	8.99	

Source: own study.

Table 7: Time necessary to build the clay block wall (wall thickness 38 cm).

	Masonry works	Transport		Making of mortar	Auxiliary works	Total time
		Blocks	Mortar			
				m-h/m^3		
Ground floor	3.37	1.24	0.15	0.467	0.2	5.427
1st floor	3.37	1.88	0.20	0.467	0.21	6.127

Source: own study.

Table 8: Various works (wall thickness 38 cm).

Work	Unit	Time
Extra to the full wall for making corners	m-h/mb	0.23
Extra for making window reveals	m-h/mb	0.23

Source: own study.

Table 9: Time to make clay mortar for masonry works and plastering.

Making mortar with a machine	Manual sieving		Total time	Total time (per m^3 of the wall)	Total time (plaster)
	Sand	Clay			
	m-h/m^3			m-h/m^3	m-h/m^2
1.5	0.9	1.0	3.4	0.317	0.034

Source: own study.

good adhesion and improved thermal insulation. The wall will have a lime plaster on the outside and two-layer clay plaster on the inside.

3. Thermal Conductivity λ and Heat Transfer Coefficient U

Thermal conductivity λ (W/m K) is a measure of how well a material insulates the flow of heat. Porous, low-density materials have low thermal conductivity and hence are better insulators in comparison with denser materials.

While it is quite easy to obtain information on physical properties of typical construction materials, obtaining such information on locally sourced materials may prove a challenge.

The thermal conductivity of a straw bale and any other material depends on its compaction and moisture content. The values for straw bales in Table 1 are based on the studies conducted in November 2015 by the Building Research Institute in Warsaw (Poland) [15]. The study comprised evaluation of a $600 \times 600 \times 200$ mm straw bale, with density of about 100 kg/m^3.

The thermal conductivity of compacted clay, clay blocks, and clay plaster depends on the clay composition and used admixtures. Table 1 gives values for highly compacted (compacted clay and clay blocks) and medium-compacted clay (clay plaster).

The heat transfer coefficient "U" is a measure of how well a building enclosure transfers heat. The "U value" is expressed in W/(m^{2}K) and denotes how many watts of thermal energy pass through 1 m^2 of enclosure when the temperature difference between the inside and the outside is equal to 1 K. The lower the heat transfer coefficient is, the better the insulation properties a particular enclosure has.

The heat transfer coefficient is expressed by [3]

$$U = \frac{1}{R_T} \ \left(\mathrm{W}/\mathrm{m}^2\mathrm{K}\right), \quad (1)$$

where R_T is the total thermal resistance of a building partition, and total thermal resistance R_T for homogeneous partitions is described by the formula:

$$R_T = R_{si} + R_1 + R_2 + \cdots + R_n + R_{se} \ \left(\mathrm{W}/\mathrm{m}^2\mathrm{K}\right), \quad (2)$$

where R_{si} is the heat transfer resistance on the inner surface, $R_1 + R_2 + \cdots + R_n$ is the design thermal resistance of each layer, and R_{se} is the heat transfer resistance on the outer surface.

Thermal resistance of a homogeneous layer with thickness d is obtained from the following equation:

$$R = \frac{d}{\lambda} \ \left(\mathrm{m}^2\mathrm{K}/\mathrm{W}\right), \quad (3)$$

where d is the thickness of the material and λ is the design thermal conductivity of the material.

Tables 2–4 present the calculations of a heat transfer coefficient for the studied walls. The layers have been chosen in such a manner that the "U" values for the studied variants are as equal as possible, thus allowing a reliable comparative study.

Table 10: Time necessary to make inside clay plasters (1 layer).

Mortar making	Plastering	Transport	Additional works	Scaffolding	Extras	Total time
			m-h/m^2			
0.034	0.284	0.022	0.013	0.061	0.038	0.452

Source: own study.

Table 11: Time necessary to make 1 m^2 of the clay block wall.

Operation	Standard time	
	m-h/m^2	%
Making clay blocks	3.416	40
Making inside clay plasters	0.904	11
Erecting clay block wall	2.339	28
Thermal insulation: mineral wool boards	1.154	14
Making outside lime plasters	0.640	8
Total	8.453	100

Source: own study.

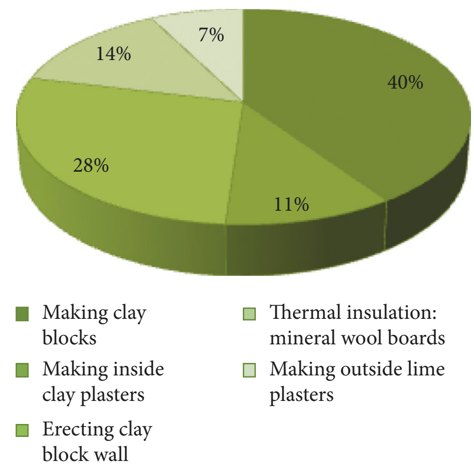

Figure 4: The percentage of the share of individual operations in making of 1 m^2 of the clay block wall.

4. Seasonality of Construction Works and Dependence on Weather Conditions

In temperate climate, the construction works and their effectiveness depend on the season and weather. Clay and straw are particularly sensitive to weather conditions and must be protected from water and subfreezing temperatures. After being put into the structure, the straw will be protected by the plaster, and clay must be protected from water at all times.

The construction works with locally sourced materials must be performed during a warm and relatively dry period, generally from late spring to early autumn. The works with conventional materials can be performed all year long if suitable precautions are taken, with exception of really low subfreezing temperatures. The exceptions among the locally sourced materials are dried clay blocks which also can be installed all year long if suitable precautions are taken.

In that area, conventional materials have a clear advantage over the alternative materials, although conventional materials must be protected from a long-term exposure to water and subfreezing temperatures. Such protection is however much simpler that in case of locally sourced materials.

Straw must not be wet when installed as it takes a long time to dry. Styrofoam, on the other hand, does not absorb water and is easy and quick to dry. Clay must be protected from precipitation at all times during the construction works by special roofing and by eaves when the building is in use. Dependence of studied technologies on seasons and weather conditions is given in Table 5.

5. Time of Making 1 m^2 of the Wall

5.1. Clay Block Wall. The study of time required to perform works in case of clay block walls refers to the "Temporary Principles of Erecting Clay Buildings" by the Institute of Housing Construction [16]. The standard times are expressed in m-h/m^3—man-hours per cubic metre of the clay block wall.

Standard times for making the clay blocks (Table 6) include maintenance of the storage yard for finished blocks, maintenance of machinery, tools, and fixtures, and squaring of the blocks and putting them in trestles. They do not, however, include storage yard levelling, construction of protective roofing, and excavation of drainage ditches.

Clay block walls are erected in the same manner as brick walls (Tables 7 and 8). The standard times include erecting walls using clay mortar, transport of blocks and mortar for a distance up to 20 m, and additional mortar mixing. The clay block walls are measured in m^3, and the openings in excess of 1 m^2 are subtracted from the wall volume.

Clay mortar should have the same composition as clay blocks (Table 9). The standard time for making clay mortar includes handling auxiliary materials at the distance of 10 m, mixing mortar with water, and operation and maintenance of machinery. The standard time does not include making a box for the mortar preparation and placement and relocation of machines used to make the mortar. The penultimate column of the Table 5 includes the time for making the mortar needed to erect 1 m^3 of the final clay block wall. The last column includes the time for preparing the mortar needed to make 1 m^2 of 1 cm thick plaster.

The clay plastering standard times include additional works: substrate wetting using a hose, surface scratching with a rake, application of plaster strips and skim coat and trowelling, and others (preparation and substrate cleaning) (Table 10). The clay plaster is made in layers, each 1 cm thick.

The time of making 1 m^2 thermal insulation using mineral wool boards has been taken from the Contractors Estimator KNR 33/2/4. The standard time for application of outside paster has been taken from the Contractors Estimator KNR 202/906/2.

Table 12: Time necessary to prepare the clay for compaction.

Clay preparation difficulty	Clay placement for mixing	Transport of admixtures	Processing with milling machine	Pouring into moulds	Total time
Medium-cohesion			m-h/m^3		
801–1400 g/5 cm^2	0.51	0.52	0.08	0.35	1.46

Source: own study.

Table 13: Time necessary to make compacted clay walls.

	Formwork	Loading, transport, and unloading for formwork	Charge levelling	Compaction	Total time	Total time
		m-h/m^3				m-h/m^2
Ground floor	3.10	2.88	0.72	0.95	7.65	2.295
1st floor	3.38	2.92	0.75	0.95	8.00	2.40

Source: own study.

Table 14: Various works.

Various works	Unit of measure	Quantity
Placement of levelling layer under ceiling beams for load-bearing outside walls plus extra for more difficult formwork and compaction	m-h/m	1.00
Placement of levelling layer under ceiling beams for load-bearing inside walls plus extra for more difficult formwork and compaction	m-h/m	2.00
Placement of window templates, removal completion of works, plus extra for more difficult formwork and compaction		
Window templates above 0.5 m^2	m-h/pc	0.55
Window templates below 0.5 m^2	m-h/pc	0.40
Door templates above 0.5 m^2	m-h/pc	0.55

Source: own study.

Table 15: Time needed to build 1 m^2 of the compacted clay wall.

Operation	Standard time	
	m-h/m^2	%
Making inside clay plasters	0.904	15
Making compacted wall in formwork	3.248	55
Thermal insulation: mineral wool boards	1.154	19
Making outside lime plasters	0.604	11
Total	5.946	100

Source: own study.

The time to make 1 m^2 of the clay block wall (Table 11 and Figure 4) has been averaged due to various units of measure for intermediate operations (e.g., prefab lintels are expressed in m-h/m).

5.2. Compacted Clay Walls. The study of time required to make compacted clay walls also refers to the "Temporary Principles of Erecting Clay Buildings" by the Institute of Housing Construction [16]. The standard times are expressed in m-h/m^3—man-hours per cubic metre of the compacted clay wall.

Time to prepare the clay (Table 12) for compaction includes its mixing with cracking prevention admixtures and pouring into moulds after mixing. It does not include cutting of fibrous materials and protecting the materials from precipitation. The amount of prepared clay compound is measured in cubic metres. 1 m^3 of the compacted wall is an equivalent of about 1.55 m^3 of loose mixture.

Standard times for making compacted clay walls (Table 13) include transport of the mixture to the hoist at the distance of maximum 20 m, transport on the scaffolding at the distance of maximum 20 m, pouring into formwork, levelling of the poured layer, compaction, placement of window and door templates, and making of lime battens or placement of ceramic inserts. The standard times, however, do not include protecting the walls from weather conditions, making the insulation, handling of window and door templates, and making of the levelling layer as a cover for lintels (Table 14).

The unit of measure for walls in excess of 24 cm in thickness is m^3, and up to 24 cm in thickness is m^2. Openings larger than 1 m^2 should be subtracted from the wall volume.

The times of making the clay (Table 15 and Figure 5) mortar for inside plasters, mineral wall insulation, and outside plasters are identical as in case of the clay block wall. The time to make 1 m^2 of the compacted clay wall has been averaged due to various units of measure for intermediate operations (e.g., prefab lintels are expressed in m-h/m).

5.3. Straw-Bale Walls. The standard times for erecting walls in the straw-bale technology (Table 16 and Figure 6) have

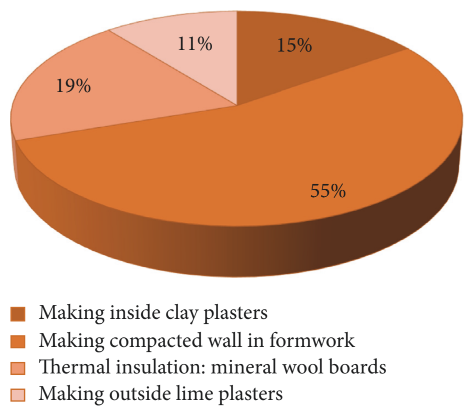

Figure 5: The percentage of the share of individual operations in making of 1 m^2 of the compacted clay wall.

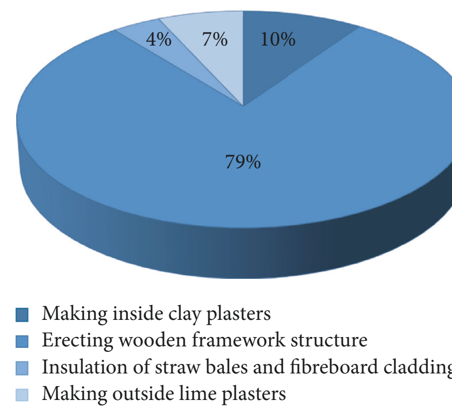

Figure 6: The percentage of the share of individual operations in making of 1 m^2 of the straw-bale wall.

Table 16: Time needed to build 1 m^2 of the straw-bale clay wall.

Operation	Standard time m-h/m^2	%
Making inside clay plasters	0.904	10
Erecting wooden framework structure	7.437	79
Insulation of straw bales and fibreboard cladding	0.366	4
Making outside lime plasters	0.640	7
Total	9.347	100

Source: own study.

been taken from the Contractors Estimator. The amount of labour needed to fill the wooden structure with straw bales has been determined analogously to the Contractors Estimator's item 202/613/6. The standard times for making inside clay plasters are identical as for the clay walls.

The time to make 1 m^2 of the compacted clay wall has been averaged due to various units of measure for intermediate operations.

6. Conclusions

The comparison of times necessary to make 1 m^2 of the wall allows us to decide which construction technology is more advantageous in terms of construction duration. The small surfaces in the wall or surfaces with numerous windows and doors, as well as the drying time between Earth wall making and rendering operation, are calculated by additional time; therefore, they were not taken into account in this paper. The shorter construction time means lower labour costs and lesser expenses for construction machines.

In the case of investors, the construction time is an important measure of project success, as the shorter payback periods mean a quicker opportunity to reinvest or reuse financial resources.

The construction time is equally important for people building a home for themselves. It is a huge advantage for them to be able to perform the works in a favourable weather and to move in and use the house earlier.

The studies and Figure 7 allow us to draw the following conclusions:

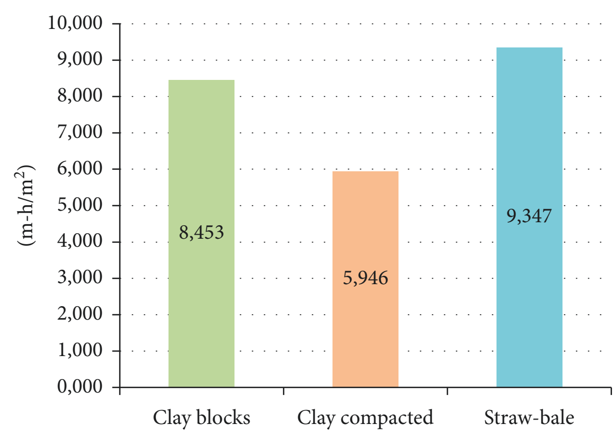

Figure 7: Time to make 1 m^2 of the wall in individual technologies.

(i) Compacted clay walls have the shortest wall erection time from among the studied natural building technologies.

(ii) Time to make 1 m^2 of the clay block wall is significantly longer as a result of a very time-consuming clay block preparation process. In the paper, it was assumed that blocks are made in-house, using mainly materials available free at the construction site.

(iii) The straw-bale technology had the worst results in the comparison. The factor which determines the long time needed to make 1 m^2 of the straw-bale wall is the necessity to erect the wooden framework structure.

(iv) Two-layer clay plaster can be an alternative to other contemporary inside wall finishing solutions.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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