IOP Conf. Series: Materials Science and Engineering **96** (2015) 012076 doi:10.1088/1757-899X/96/1/012076

Thermal Transmittance and the Embodied Energy of Timber Frame Lightweight Walls Insulated with Straw and Reed

M Miljan[1,2] **and J Miljan**[1]
[1]Estonian University of Life Sciences, Institute of Forestry and Rural Engineering, Department of Rural Building, Tartu, Kreutzwaldi 5, Estonia

E-mail: matis.miljan@emu.ee

Abstract. Sustainable energy use has become topical in the whole world. Energy gives us comfort we are used to. EU and national regulations determine energy efficiency of the buildings. This is one side of the problem – energy efficiency of houses during exploitation. But the other side is primary energy content of used materials and more rational use of resources during the whole life cycle of a building. The latter value constitutes about 8 – 20% from the whole energy content. Calculati[3]ons of energy efficiency of materials lead us to energy efficiency of insulation materials and to comparison of natural and industrial materials taking into account their thermal conductivity as well as their primary energy content.
Case study of the test house (built in 2012) insulated with straw bales gave the result that thermal transmittance of investigated straw bale walls was according to the minimum energy efficiency requirements set in Estonia U = 0.12 – 0.22 W/m^{2}K (for walls).

1. Introduction

World's demand for energy is increasing and greenhouse gas (GHG) emissions are rising. A big part of these processes is caused by building sector. In Europe 40% of the produced energy is consumed by building industry and 36% of GHG is produced by buildings [1]. In the USA homeowners spend an estimated 29% of their total energy-related expenditures on space heating alone, whereas commercial buildings spend more than 15% percent annually [2]. Berge had investigated how the embodied energy input of the building materials, usually about 85-95%, is distributed: a) direct energy consumption in extraction of raw materials and the production, b) secondary energy consumption invested in machinery, heating and lighting of the factory and the maintenance of the working environment, c) energy in transport of the necessary raw and basic materials depending on distance,

[2] To whom any correspondence should be addressed.

type of used fuel and method of transport [6]. Renewed data for calculating embodied energy of building materials is available in the database of the University of Bath [3, 5].

Using these data the calculations were done to find out the embodied energy of 1 m^2 of the five mostly used lightweight wall structures in Estonia for small residential houses. The U value of these walls was calculated as equal.

- Rendered lightweight block wall with 150 mm EPS insulation – 248 kWh/m^2;
- Timber cladding on lightweight block wall with 100 mm with mineral wool insulation – 223 kWh/m^2;
- Rendered 375 mm porous concrete block wall – 186 kWh/m^2;
- Hollow concrete block wall with stone cladding and with 100 mm mineral wool insulation – 173 kWh/m^2;
- Timber frame wall with timber cladding and with 100 mm + 50 mm mineral wool insulation – 139 kWh/m^2.

All wall structures in this case were done using industrial building materials [7]. The most energy effective was timber frame wall with timber cladding and mineral wool insulation energy content of which was 139 kWh per wall square meter.

The next step was to find out if any of the natural insulation materials is worth of use. Four different wall structure fragments were built into the window openings of the laboratory in the autumn of 2009 and measurements of temperature, RH and heat flow were done during winter. Results show that thermal transmittance of the wall fragments insulated with horizontally placed compressed reed, rendered with 50 mm of clay plaster inside and outside was U = 0.145 W/m^2K. Wall fragment built of straw bales and rendered with 50 mm of clay plaster from both sides has U = 0.182 W/m^2K and wall fragment built of reed bales and rendered with 50 mm of clay plaster from both sides has U = 0.148 W/m^2K [6, 8]. As reed turned out to be such a good insulation material, a small test house was built in 2010 to measure reed insulation properties more precisely and at the same time to determine the time and material consumption to calculate energy efficiency of the building. Walls of the test house had different structures: reed was placed loose and compressed in one wall horizontally and in one wall vertically. The third wall was built of handmade reed panels and the fourth wall was done of reed bales. Walls were 450 mm thick and rendered with 50 mm clay plaster from both sides. The measured thermal transmittance of walls was U = 0.207 – 0.383. The most heatproof wall was done of horizontally placed compressed reed and the worst was vertically compressed reed wall. [9] Later the calculations were done to determine the embodied energy of 1 m^2 of timber frame wall, insulated with reed (700 mm) and rendered with clay plaster, with U = 0.1 W/m^2K.

As the straw is the waste of agricultural activity, the next idea was to build a small house with straw bale walls to reduce the embodied energy content of insulation material. Calculated U = 0.092 W/m^2K and the respective thickness of the wall was 900 mm. The aim of this work was to determine the real thermal transmittance of the wall structure and to find the embodied energy content as well.

2. Methods

The office insulated with straw bales was built specially to carry out investigations.

2.1. Structure of the house with straw bale walls

The bearing structure of the house was done from straw bales, which were anchored together with metal bars pressed from upside down. Used bars were with 25 mm diameter, 2 m long and cc 1200 mm. The dimensions of wheat straw bales were: h = 1200 mm, w = 900 mm, l = 2200 mm, weight of a ball was 500 kg (figures 1, 2, 3). Straw bales were insulated from foundation using EPS plates (25 mm). On the top of the walls OSB plates were placed and on this layer timber beams (100 x 150 mm) were fixed for building the roof.

Figure 1. View of the straw bale office.

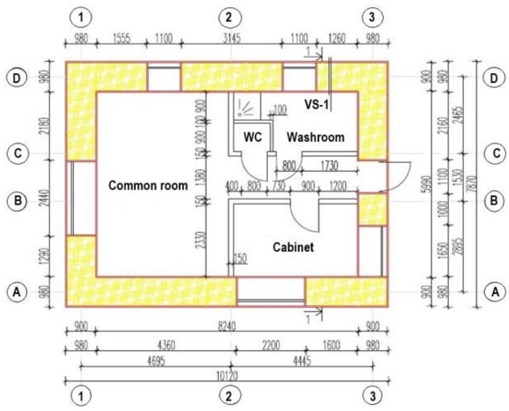

Figure 2. Plan of the office with straw bale walls.

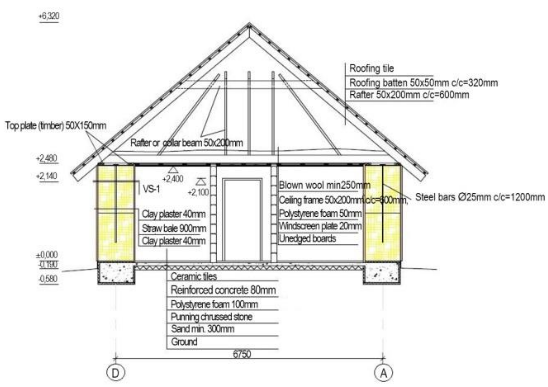

Figure 3. Cross-section of the office with straw bale walls.

To calculate the embodied energy content of one m^2 of the straw bale wall the amount of every used material was taken into account. To find the energy content of clay plaster the case study was done in the factory of Saviukumaja [4]. The following values were calculated separately: 1) mining of clay and sand, 2) transportation of sand and clay to the factory, 3) energy (electricity, fuels) consumption during preparation work: crushing, sieving, mixing renders, 4) energy consumption for sieving out non usable sand (stones 23%) (figure 5). Amount of the human work wasn't taken into account. Embodied energy of other used materials (including straw bales) was taken from the database of the University of Bath [3].

2.2. Measurements and placement of measuring devices
Measurements of thermal transmittance were done in non-steady environment beginning from February 2012 until February 2013. Data were recorded with 30 minutes intervals in Almemo and HOBO data recorders. Temperature and relative humidity were measured with several pairs of thermocouples, placed as shown in figure 4. Heat flow through wall was measured with heat flux plate.

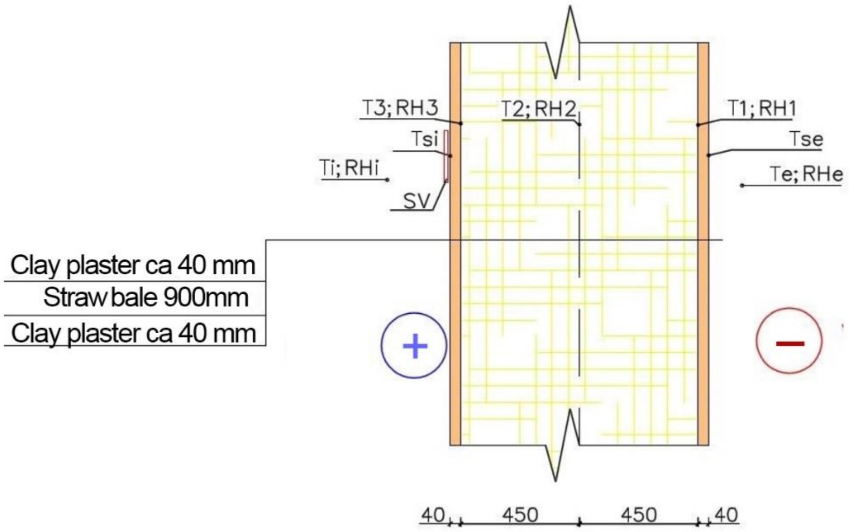

Figure 4. Placement of measuring devices (MD) on the cross-section of the wall.

2.3. Measured data and used equations
Next data were measured to achieve the set up aims.
Measured data:
T_e - outside temperature °C, MD: Hobo U12-006 with TMC6-HD
T_i - inside temperature °C, MD: Hobo U12-011
T_{si} - temperature on the wall outside °C, MD: FQA 019 C, datarec. Almemo 2890-9
T_1, T_2, T_3 - temperatures in different layers of the wall °C, MD: FHA 646 R
T_{se} - temperature on the wall inside °C, MD: Hobo U12-006 with TMC1-HD
RH_i - relative humidity in the room %, MD: Hobo U12-011
RH_e - relative humidity outside %, MD: Hobo U12-011

RH_1, RH_2, RH_3 - relative humidity in different layers of the wall %, MD: FHA 646 R
Heat flow (SV) - W/m^2K, MD: FQA 019 C, datarec. Almemo 2890-9

The minimum temperature during this year was -29 °C and maximum 34 °C. The mean room temperature was 21 °C and RH = 40.4%. The mean outside temperature was -5 °C and RH = 90.3%.

2.3. Results

During the year of investigation, the measured mean thermal transmittance of the straw bale wall was U = 0.125 W/m^2K which is in accordance with the requirements for the building walls stated in Estonia (0.12–0.22 $W/(m^2 \cdot K)$) (for walls) [11]. The measured thermal transmittance differed from the calculated value which was U = 0.092 W/m^2K. One of the reasons might be the clay plaster, because the soft clay penetrates into the straw and therefore decreases the effective thermal insulation layer and the second reason is that the density of straw bales differs quite a lot. Calculations of the embodied energy of the straw bale wall are presented in table 1.

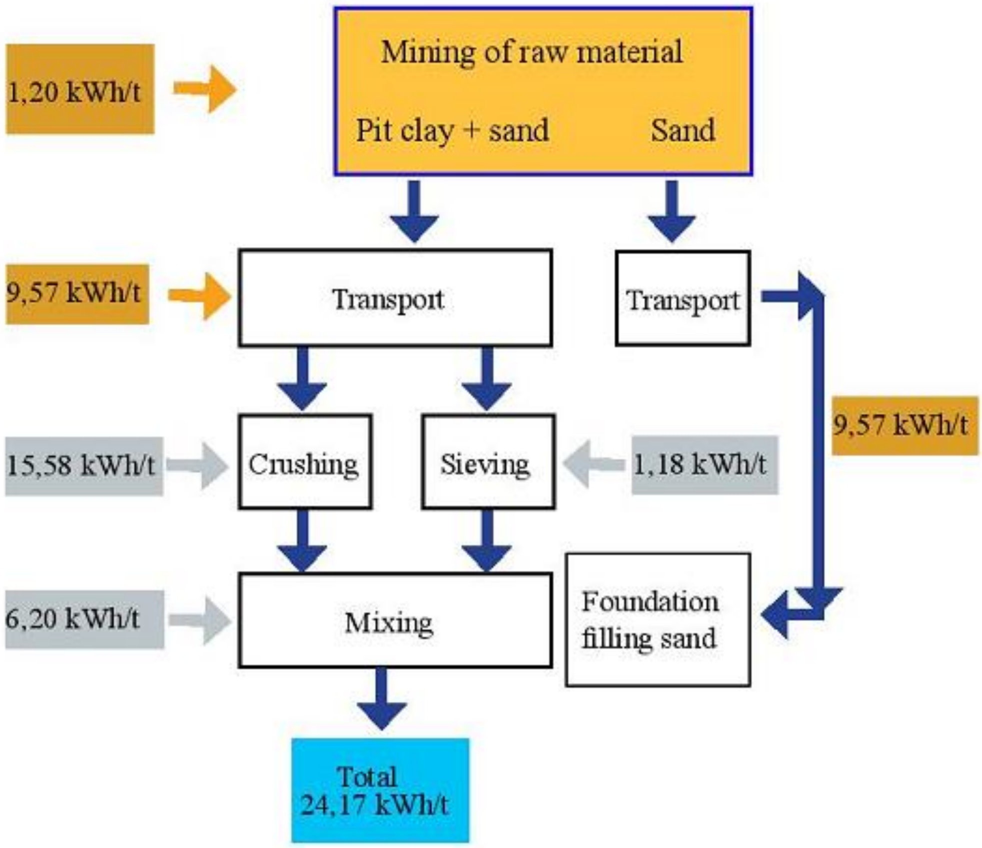

Figure 5. Embodied energy content of clay plaster (case study in the factory of Saviukumaja).

Table 1. Embodied energy content of the straw bale wall (case study at Tammistu).

Material	Energy content		Amount	Total
	MJ/kg	kWh/kg	kg	kWh
EPS	88.60[3]	24.61	16	394
Straw bales	0.24[3]	0.066	12600	840
Clay plaster (1:3)		0.09[2]	8000	193
Sand sieved off		0.04[2]	1380	16
Steel bars	8.80[3]	2.44	124	303
Particle board	9.50[3]	2.64	233	615
Timber	7.80[3]	2.17	535	1161
			Total	3522

From table 1 we can see that timber and particle boards are the main contributors to the total energy consumption. Embodied energy consumption of the straw bale wall was 55 kWh/m^2. [10]
For comparison the calculation of timber frame wall was done. The results are presented in table 2.

Table 2. Embodied energy content of the timber frame outer wall.

Material	Energy content	Amount	Total	Total
	MJ/kg	kg	MJ	kWh
Timber cladding	7.80	905	7059	1976
Mineral wool 150 mm	16.6	270	4482	1255
Mineral wool 100+100	16.6	360	5976	1673
Wind proof plate	7.40	300	2220	621
Steam proof film	83.10	20	1662	465
Gypsum plate	6.75	1000	6750	1890
Frame timber	7.80	1461	11396	3190
		Total	39545	11070

Embodied energy consumption of the timber frame wall was 173 kWh/m^2. [10] Thermal transmittance of both walls was the same.

3. Conclusions

The results of presented research show that for evaluating the energy efficiency of a building it is not enough to assess only thermal transmittance of enclosures. One should take into account the embodied energy of the used materials. Calculations and measurements show that using natural insulation materials instead of industrial ones we may save about three times, as the embodied energy content of the compared walls was 55 kWh/m^2 against 173 kWh/m^2. These results are in the same order of magnitude as obtained in one of our previous investigations [5] where the embodied energy of reed insulated timber frame wall was 37 kWh/m^2 and that of timber frame wall insulated with mineral wool was 178 kWh/m^2. Minke [16] had also calculated embodied energy of different walls and the results are similar to ours. The straw bale wall with U = 0.11 W/m^{2}K has energy content 54 kWh/m^2 and embodied energy in timber framed wall insulated with rockwool was 175 kWh/m^2. Assuming that, we

IOP Conf. Series: Materials Science and Engineering **96** (2015) 012076 doi:10.1088/1757-899X/96/1/012076

suggest that the energy consumption of used materials should also be taken into attention. On the basis of calculations done by measurements, there was no threat for condensate arising inside the wall [10].

4. References

[1] International Energy Agency 2013 FAQs: Renewable energy assessed in Jan 2015, Key World Energy Statistics accesssed in Jan 2015 [Available]: http://www.iea.org/aboutus/faqs/renweableenergy/
[2] U.S. Department of Energy 2011 *Buildings Energy Data Book* Expenditure data are from 2010
[3] Hammond G and Jones C 2011 ICE V2,0 [Available]: www.bath.ac.uk/mech-eng/sert/embodied
[4] Shvoerov A 2013 The impacts of using industrial and natural construction materials to embodied energy of building *Master Thesis of Rural Building of EULS* p 88
[5] Hammond G P and Jones C I 2012 Embodied energy and carbon in construction materials *Proc. of the Institution of Civil Engineers Energy* pp 87–98
[6] Berge B 2009 *The Ecology of Building Materials* second ed. Architectural Press p 427
[7] Miljan M and Miljan J 2013 Embodied energy in reed insulated structures *Compendium Reed and the Possibilities to use it EULS and TTU* pp 72–78
[8] Miljan M J and Miljan J 2013 Thermal transmittance of enclosures of the test house *Compendium Guidebook of Reed Business EULS* pp 38–40
[9] Miljan J and Kukka E 2009 Eestis enamkasutatud välispiirete primaarenergia sisaldus *Ehitaja J* **9** pp 72–75
[10] Miljan M J, Miljan M and Miljan J 2013 Thermal Conductivity of Walls Insulated with Natural Materials *Proc. of LUA Fac of Rural Engineering Civil Engineering'13 Part 1 vol.* 4 p 175
[11] Miljan M, Miljan M J, Miljan J, Akermann K and Karja K 2014 Thermal transmittance of reed-insulated walls in a purpose-built test house *J. in Internet Mires and Peat*
[12] Saar L 2013 A case study of hygdro-thermal properties of enclosures and indoor climate of the house built of straw bales *Master Thesis of Rural Building of EULS* p 82
[13] Minimum Requirements for Energy Performance Chapter 2 § 12 Requirements for the building envelope, State Gazette of Estonian Government 09.01.2015
[14] U.S. Department of Energy 2011 *Buildings Energy Data Book* Expenditure data are from 2010
[15] Minke G and Krick B 2009 *Handbuch Strohballenbau* p 139