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# Resilience of Raw-Earth Technology in the Climate of Middle Europe Based on Analysis of Experimental Building in Pasłęk in Poland

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**Abstract:** The article concerns the experimental building in raw-earth technologies situated in Ecological Park in Pasłęk, in the northeast part of Poland with rather severe climate characteristics for middle and east Europe. The purpose of the designing and realization of the building was to demonstrate the methods of construction in traditional raw-earth technologies with current modifications and then to create the possibility for long-term research and observations at the site visits during the buildings' exploitation. The building was designed as energy efficient with a passive solar system, green roof, and space arrangement. Construction effects of exploitation were checked. Also, physical aspects were analyzed and thermal-humidity environmental parameters were measured with specialized equipment. Examples of such measurements with appropriate conclusion are presented. Based on the analyses, the authors evaluate the resilience of the applied technology under the given climate conditions, as one of the possible sustainability technologies that can be used in Poland under given restrictions.

**Keywords:** resilience; raw-earth; construction technology; interdisciplinary research; rammed earth; architecture; sustainability; low-tech

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## 1. Introduction

Negative climatic changes have been observed in recent decades and the causes for that are connected with human activities. This is especially true of traditional ways of energy production from non-renewable energy sources and other technological processes emitting $CO_2$ and other gases into the atmosphere causing the so-called greenhouse effect. Knowledge of these problems is widening and attempts to find adequate solutions are undertaken in various fields. Nowadays, sustainable attitudes are presented in various areas such as sociological, environmental, functional, technological, and infrastructural; and active interrelations of these areas are necessary to achieve satisfactory effect [1]. Energy efficiency is becoming particularly important, in the context of a clean energy and low pollution economy [2]. Earthen technologies were used in central Europe historically for many centuries. In Poland in the first decade after WWII due to war damage and lack of materials, earthen technologies were again used, even appropriate norms were issued. Then the industrial building materials replaced traditional technologies. The energy crisis of the 1970s caused a search for alternative technologies [3]. Activity of the CRAterre institute in Grenoble or the institute in Kassel led by Gernod Minke may be good examples. Earth technologies are popular in countries with a warmer climate than that of eastern and northern Poland as Australia, Germany, France, Holland [4–7] but it is not popular in Poland. When trying to answer this question it should be verified, among other things, whether this technology is a solution resistant to climatic conditions prevailing in Poland. Influence on the low popularity of this type of building technology may be the fact that there are few Polish language publications (standards and recommendations date back to the early post-war period) on this subject and few projects adapted to our climatic conditions. This relates to low knowledge of the technology among people designing and constructing buildings and, as a consequence, low awareness and popularity of this technology among investors. This trend is slowly beginning to change, as the ecological awareness of potential investors, who are looking for pro-ecological solutions and technologies, is growing. This effect and results of conducted analyses concerning durability of building technology in our climate, may contribute to an increase in the number of objects made in earth technology, assuming that a qualified workforce will be obtained.

In the case of technological and infrastructural area, the following aspects should be taken under consideration: impact of local environment, function and space arrangement of the object, choice of building materials, transport, ways of erecting the building, expected exploitation conditions, and possible recycling. In technological development towards pro-environmental and energy efficiency solutions two trends are visible which can be named "high tech" and "low tech". The first is characterized by using advanced technical arrangements to obtain final positive results. In most cases the production of necessary equipment and materials require initial energy (still most of it is from non-renewable energy sources and leave a carbon footprint). The "passive house" concept with all characteristic construction and equipment arrangements such as heat pumps or roof collectors may be a good example of such an object. Positive pro-ecological results are accomplished in longer perspective.

In the "low tech" trend technology, natural and low-processed materials are used, possibly obtained in close locations (transport reduction). Also, appropriate spatial arrangement of the building helps to achieve a positive energy balance. The positive experiences of the past are very often copied with modern modifications. Among materials there are timber constructions, various conglomerates containing natural particles (wood, straw, hemp), raw earth, clay, local stone. The building belonging to this group is a subject of the present text. It is an experimental building situated in an Ecological Park in Pasłęk.

Erecting of the experimental building and connected further activities were initiated at the Architectural Faculty of the Warsaw University of Technology by prof. Teresa Kelm who contacted notable institutes in Europe and some in USA. She organized a working team which carried out research and designing work as well as a didactic program dedicated to technologies of raw earth, especially rammed earth. It consisted of lectures and practical exercises such as production and testing raw earth elements. An important part of this action was also visiting seminars at the production plant of straw and clay blocks and similar constructions situated close to town of Pasłęk. Town authorities were interested in pro-ecological matters organizing conference and other actions and this resulted in the choice of the site for experimental building in this town.

Design and erection of the building were possible after obtaining a grant from the Ministry of Science. The main realization was executed in years 2005–2009. Afterwards some finishing and additional works were financed by the town of Pasłęk and finally the building was completely finished, and the ownership and administration was passed from the university to the town in 2012. The building is used as the management office of the Ecological Park, an exhibition area, and ecology workshops for young people.

After some years of normal exploitation our team carried out a series of inspections and tests to check construction matters as well as physical performances of building elements and impact on internal microclimate. Inspections were executed with specialized tools, in different times of the year (high, moderate and low ambient temperature). The description and characteristics of the building, presentations of tests at site visits, and conclusions are presented below.

A sustainable attitude towards contemporary architecture occurs in various areas, also in earthen constructions. The Terra [In]cognita project funded within the framework of the European programme "Culture 2007–2013" was aimed at encouraging the preservation of this type of construction heritage and the development of contemporary earthen architecture.

Selections of significant earthen construction were awarded. The experimental building in Paslek in 2011 received the award—Outstanding Earthen Architecture in Europe [8,9].

In the articles presenting rammed earth technology solutions, the mechanical characteristic and durability of the solutions [10–13] and the selection of suitable composites as fibers [12], proportions of cement [14], and contemporary construction technologies [15,16] are among the most frequently discussed issues. Architectural and technical solutions also apply to other locations [17,18] and checked in quality control [19]. The aim of this research is to assess the possibility of using earth technologies in Poland (in the eastern and northern part), as a sustainable and pro-environmental solution that meets legal and utility requirements. The article is divided into the following parts: presentation of the design assumptions and construction of the experimental rammed earth building in Pasłęk, description of the research methods used, presentation of the results of thermo-humidity measurements carried out on 1 August 2018, analysis of the research results, summary, and conclusions regarding the truth of the research hypothesis that the rammed earth technology can be used in the design and construction of buildings in Poland, as an example of a technology resistant to the existing climatic conditions and by ensuring an appropriate microclimate inside the building and appropriate thermal insulation parameters.

## 2. Characteristics of the Experimental Building in Pasłęk in Poland

The building is situated in the Ecological Park at the south-east part of a flat green area where outdoor events are organized. It is one-story detached, covered with a single pitched roof building. It has an irregular plan with a longer axis in the east-west direction. Thus, principles of energy-optimal design are achieved: the southern wide elevation has a big, glazed surface, in this case in the form of a fully glazed veranda (green house). The northern wall is practically solid. The main entrance to the building is located on the western side and is connected through the vestibule with the one-spatial didactic and exhibition hall located in the eastern part of the building. This area is connected with an external terrace on the east side of the building and through two glazed doors with a veranda on the south side. A kitchenette and toilet are attached to the main space in the western part. The usable internal space is 75.5 $m^2$ and the cubic capacity 250.0 $m^3$ (Figure 1).

(**a**) (**b**)

**Figure 1.** View of the building (**a**) from northern side (**b**) south-east side.

The energy-efficient construction was a leading idea. Rammed earth in the formwork was chosen for the structural and external walls. In order to reduce costs of transport the soil from excavations on the plot was used. Some of the walls have an irregular curved layout to check technological possibility and difficulties of such arrangements and also to enrich the final visual effect. To achieve necessary thermal performances, the external walls were supplemented with additional layers. Traditionally the internal layer has a structural function and thermal additions are on the external side. The external walls were designed and constructed as three-layer partitions but in an experimental way we decided to situate the load-bearing layer outside. It is in the form of rammed earth monolithic walls compacted in formwork using a pneumatic compactor and our task was to check how the exposed earth surface will behave in the severe climate of northern Poland (Figure 2a). An additional task of such an arrangement was to show the natural surface of the compacted earth wall as an illustration and presentation of an unusual technology. The internal layer of the external wall was made of clay and straw compacted mass blocks. They are finished with earth plaster to regulate the humidity of the interior and partly with a natural surface impregnated with varnish in order to stop the material from chipping (Figure 2b). The space between the structural external layer and the internal blocks is filled with thermal insulation material—here mineral wool [10].

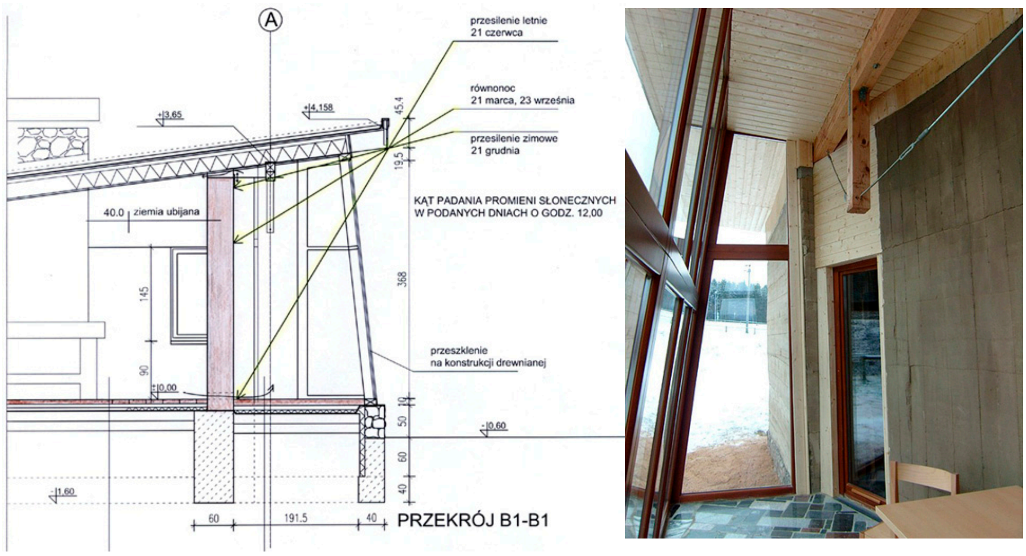
(**a**) (**b**)

**Figure 2.** Building under construction and completed: (**a**) Compacting of raw earth mixture with pneumatic compactor in wooden formwork (**b**) Internal walls: pressed earth blocks with no finish (left side). Clay and straw compacted mass blocks finished with earth plaster (right side of door) and with natural finish (right side).

The earth's mass taken from local excavation was modified to achieve structural durability. Mineral composition consisted of sand (70%), dust fraction (18%), clay fraction (11%). Due to the contact of the walls with the air moisture and freezing periods, a stabiliser—6 to 8% by weight of cement—was added to the earth's mass. The heat transfer coefficient $\lambda$ was 0.870 W/mK. An internal layer of clay and straw blocks $\lambda$ was 0.350 W/mK and thermal insulation within the middle gap, mineral wool had $\lambda$ of 0.040 W/mK. Parts of the internal walls surface was covered with earthen plaster with $\lambda$—0.870 W/mK. Such a combination gave a U value of 0.34 W/m$^2$K. Thermal resistance R (m$^2$K/W) were: rammed earth wall 0.40–0.460 m, thermal insulation 0.08–2.00 m, clay and straw blocks 0.12–0.340 m, and earthen plaster 0.015–0.020 m. Designed U value conformed with regulations and in practice the thermal barrier both in winter and summer time proved properly constructed. In the year of preparing the Building Permit Design U value recommended for such building required in the Polish Building Code was 0.45 W/m$^2$K. The internal microclimate is comfortable even in very hot days and heating with a simple stove for wood in winter is sufficient. Heat accumulation of solid walls is very effective. Additional electrical heaters practically are not used.

Earthen mass wall surfaces, both outside and inside, have the ability to react to surrounding humidity—absorbing its excess and giving back the accumulated humidity in dry surrounding. The external walls are protected from direct rainwater with wide eaves, so only air humidity can attack wall surface. The aforementioned regulating ability of the material and air movement secure the wall from degradation by frost. Observations for many seasons proved that severe climate does not affect earthen materials.

The wall between the main hall and glazed veranda is in the form of a single layer load-bearing wall of rammed earth without any thermal insulation. The task of such an arrangement was to allow the heat accumulated in the veranda space to pass to the main area through structural material (Figure 3) [20]. Partition walls are made of pressed earth blocks without any additional finishing (to present other raw earth technology).




(**a**) (**b**)

**Figure 3.** Veranda with accumulation wall: (**a**) Section through glazed veranda and accumulation wall. Arrows show angle of sun rays on March 21 and December 21 at 12:00 pm. (**b**) View of glazed veranda and accumulation wall.

The floors on the ground were damp, insulated with a bitumen membrane laid on the underlay concrete and thermally with polystyrene foam. A broken stone slab floor with concrete subfloor is a thermal accumulation mass. The foundations of the building are benches and foundation walls made of reinforced concrete and thermally insulated with foamed polystyrene inserts. The damp-proofing is made with bitumen membrane and adhesive. For the necessity of protecting the earth mass of the walls against water and ground dampness, the earthen wall is elevated about 50 cm above the ground level and supported by a concrete foundation finished with natural stone.

The external walls above the window openings are made as wooden frame walls, insulated with mineral wool with internal vapour-barrier insulation, external wind-barrier insulation and wooden boarding on both sides. The roof is a single pitched, with wooden wall plates, purlins, and rafters. A layer of weather-resistant tundra greenery was laid on the roof. In order to protect the rammed earth walls from direct rainwater, the roof eaves were extended from the wall line at a distance of around 80 cm.

## 3. Materials and Methods

The experimental building in Pasłęk was designed at spatial concept and materials solutions in order to conduct appropriate inspections, research and analysis of building wear during years of exploitation. Foreseen measurements will allow definition of thermal-humidity environmental parameters. Most important is the analysis of the effective performance of used pro-ecological solutions—passive solar heat gains allowed due to the location of a glass veranda and accumulation wall with southern exposure. Also, thermal insulation properties of external partitions—walls and roof—were tested.

Measurements were made during different seasons (summer and winter seasons and two intermediate ones) as well as at different hours during each of the chosen days. Site measurements were conducted as follows:

- Mounting of a weather station inside the building—measurements of air temperatures and humidity.
- Analysis with thermo visual camera, identification of potential thermal bridges.
- Using other specialized equipment listed below to check specific physical conditions.

Used equipment to take following measurements:

- Anemometr testo 410-2 shows interior air temperature and humidity and air movement at place of measurement. Producer: Testo SE & Co. KGaA, Titisee-Neustadt, Germany
- Trotec BM 22—shows surface dampness (humidity) and may be used for building materials as well as for wood. It is used by touching the surface with two metal needles. Producer: Trotec, Heinsberg, Germany
- TROTEC BP 25 scanner using laser rays focused on wall surface. Combined measurement results show surrounding air temperature, wall surface temperature, degree of humidity, and assumed dew point for current physical conditions. Producer: Trotec, Heinsberg, Germany

In addition, an architectural and technical site visit was carried out to assess the durability of the rammed earth elements in the given climatic conditions. The assessment was based on observations made since the building was constructed.

## 4. Results

The temperature and air movement were measured using a Testo 410-2 anemometer, the dew point values in the wall using a TROTEC BP25 dew point scanner, the humidity and temperatures in the surroundings and on the wall using a TROTEC BM 22 humidity indicator and the thermal behaviour of the walls. All measurements were taken on 1 August 2018 at 2:00 pm with an outdoor temperature of 30 degrees Celsius and 45% humidity.

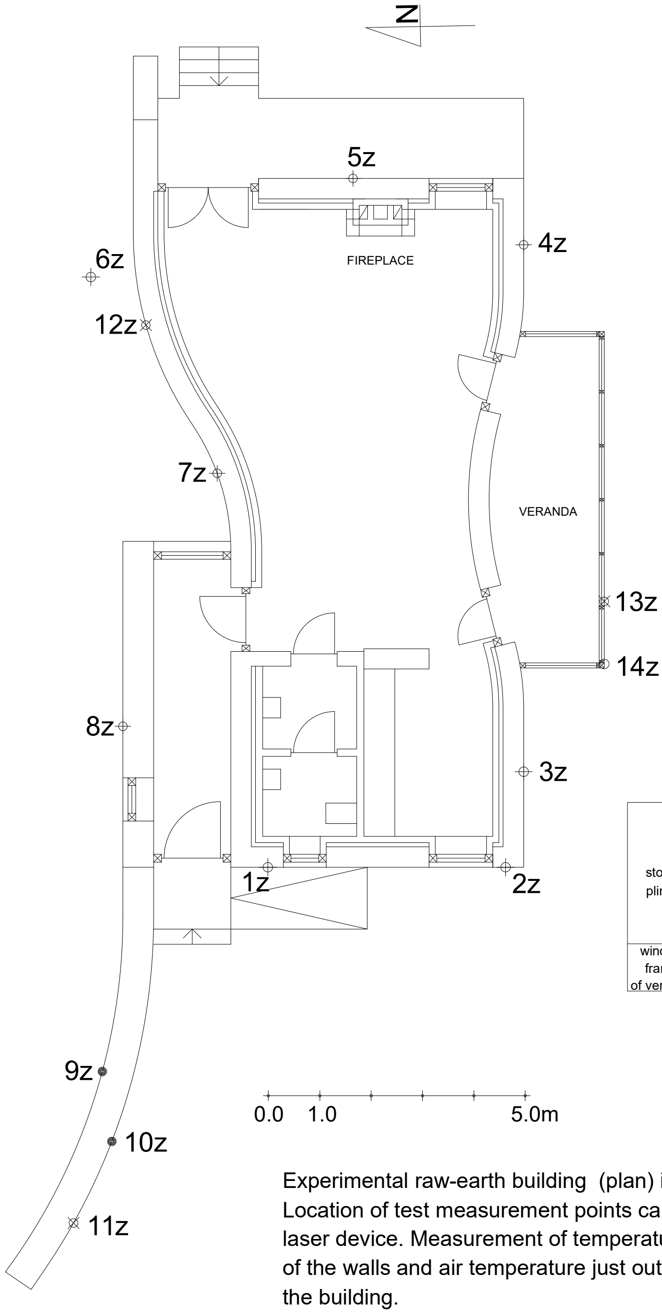
### *4.1. Tests Were Carried Out Using TROTEC BP 25*

Measurements of temperature and humidity on the surface of the external wall and air temperature of outdoor surfaces were taken for specified points on the figure below (Figure 4).

The following diagrams and charts show the results of the measurement data collected on the day of the survey. Each of the diagrams and charts relates to data collected at individual measurement points by the selected measuring devices. The results of measurements with the Trotec BP 25 of exterior of the building are shown below (Figure 5).

Measurements of temperature and humidity on the surface of the interior wall and air temperature of interior surfaces were taken for specified points on the figure below (Figure 6).

The results of measurements with the Trotec BP 25 of interior of the building are shown below (Figure 7).




| | MEASURMENT POINTS | Two<br>temperature on the wall surface at the measuring point<br>°C | Tdo<br>dew point temperature at the measuring point<br>°C | Tao<br>air temperature at the wall at the measuring point<br>°C | Ho<br>air humidity at the wall at the measuring point<br>% |
|---|---|---|---|---|---|
| | 1z | 36.9 | 23.0 | 36.6 | 59.5 |
| | 2z | 37.1 | 24.3 | 37.3 | 45.0 |
| | 3z | 37.1 | 22.8 | 37.3 | 46.0 |
| | 4z | 30.4 | 22.0 | 36.3 | 42.8 |
| | 5z | 30.3 | 21.7 | 36.4 | 41.3 |
| | 6z | 28.6 | 21.6 | 37.1 | 44.2 |
| | 7z | 26.1 | 22.0 | 36.2 | 45.0 |
| | 8z | 26.7 | 23.3 | 36.1 | 50.0 |
| EXTERNAL SCREEN WALL | 9z | 27.9 | 23.2 | 36.7 | 50.0 |
| EXTERNAL SCREEN WALL | 10z | 41.6 | 23.5 | 37.0 | 46.7 |
| EXTERNAL SCREEN WALL | 11z | 43.5 | 24.2 | 38.1 | 46.2 |
| stone plinth | 12z | 25.6 | 21.4 | 35.8 | 47.7 |
| stone plinth | 13z | 48.0 | 25.8 | 38.9 | 46.6 |
| window frame of veranda | 14z | 57.0 | 27.6 | 39.6 | 42.3 |

Experimental raw-earth building (plan) in Pasłęk, Poland.
Location of test measurement points carried outside the building with BP25 laser device. Measurement of temperature and humidity on the surface of the walls and air temperature just outside the measurement point outside the building.

- ⌖ 1z/8z - measurement points outside the building on the wall surface at a height of 1.2m
- ● 9z/10z - measurement points outside the building on the surface of the external screen wall at a height of 1.2m
- ⊠ 11z/13z - measurement points outside the building on the surface of the stone plinth at height of 0.3m
- ○ 14z - measurement point outside the building on the surface of the verandas' window frame

(measurements on 01/08/2018 with the **Trotec BP 25**)

**Figure 4.** Plan of the experimental raw-earth building in Pasłęk with the placement of measurement points carried outside the building with BP 25 laser device.

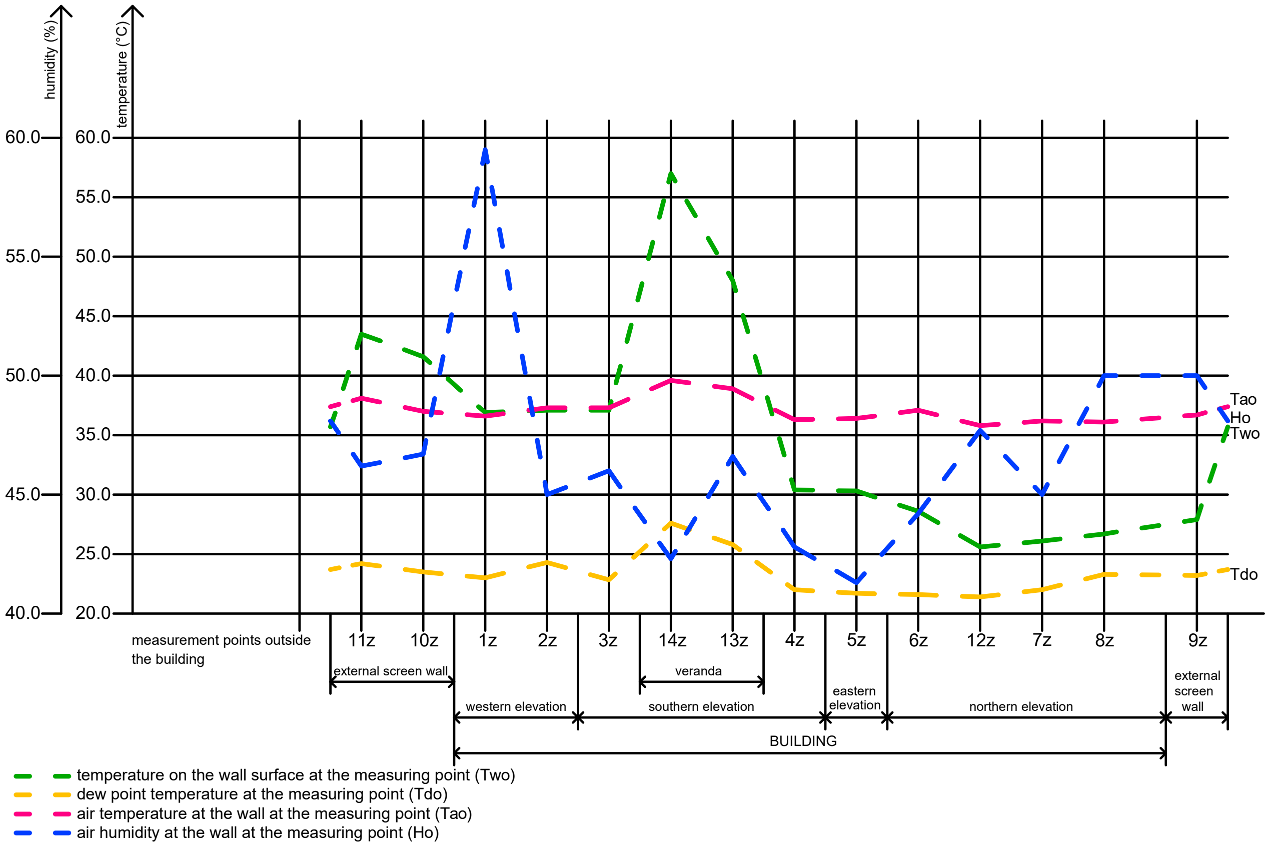
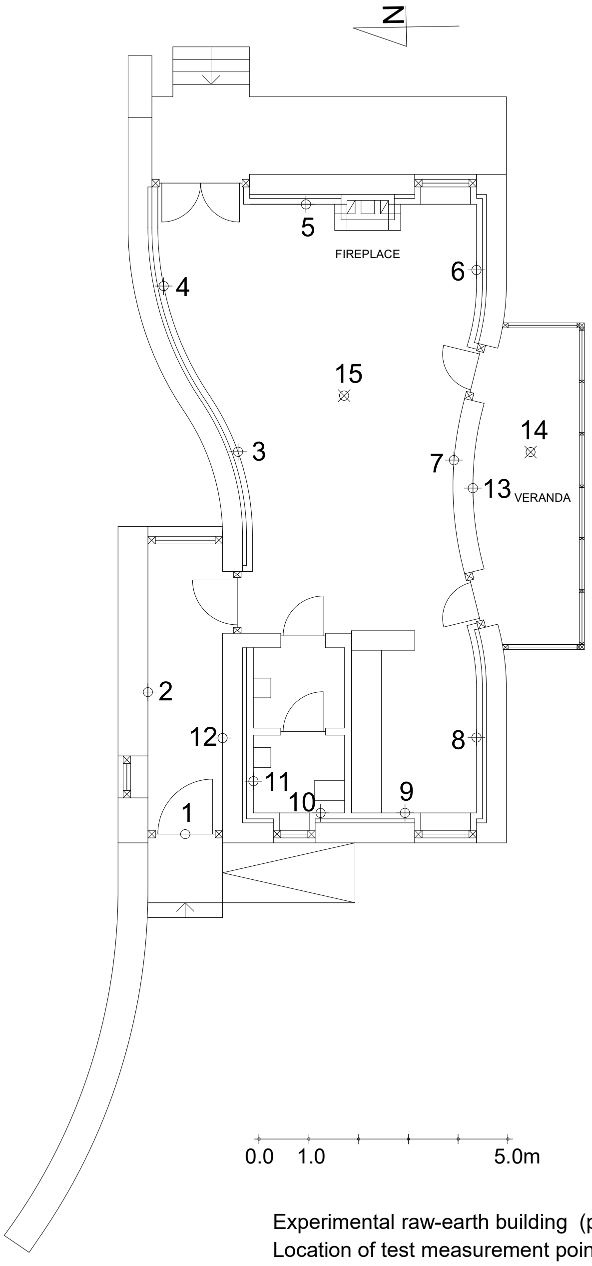



**Figure 5.** Temperature and humidity of the walls outside the building (measurements on 1 August 2018 with the Trotec BP 25.




| | | MEASURMENT POINTS | Tw<br>temperature on the wall surface at the measuring point<br>°C | Td<br>dew point temperature at the measuring point<br>°C | Ta<br>air temperature at the wall at the measuring point<br>°C | H<br>air humidity at the wall at the measuring point<br>% |
|---|---|---|---|---|---|---|
| entrence door | | 1 | 28.7 | 22.0 | 29.1 | 67.7 |
| | | 2 | 26.5 | 21.6 | 28.8 | 67.9 |
| | | 3 | 27.5 | 21.9 | 29.4 | 64.5 |
| | | 4 | 27.9 | 21.9 | 27.8 | 65.5 |
| | | 5 | 27.7 | 21.9 | 27.4 | 65.6 |
| | | 6 | 27.6 | 21.9 | 27.5 | 65.9 |
| | | 7 | 29.0 | 22.0 | 28.9 | 63.2 |
| | | 8 | 27.9 | 21.9 | 27.8 | 67.2 |
| | | 9 | 28.2 | 22.1 | 28.2 | 68.2 |
| | | 10 | 26.6 | 21.8 | 28.9 | 67.5 |
| | | 11 | 26.6 | 22.2 | 28.7 | 69.1 |
| | | 12 | 26.4 | 21.7 | 28.8 | 67.8 |
| | VERANDA | 13 | 38.3 | 24.0 | 38.4 | 74.0 |
| floor | VERANDA | 14 | 39.6 | 24.3 | 39.9 | |
| floor | | 15 | 27.2 | 22.4 | 26.8 | |

Experimental raw-earth building (plan) in Pasłęk, Poland.
Location of test measurement points carried inside the building with BP25 laser device. Measurement of temperature and humidity on the surface of the walls and air temperature just outside the measurement point inside the building.

○ 1 - measurement point inside the building on the internal surface of entrance door at a height of 1,2m

⌖ 2/13 - measurement points inside the building on the internal surface of walls at a height of 1.2m

⊠ 14/15 - measurement points inside the building on the interior floor surface

(measurements on 01/08/2018 with the **Trotec BP 25**)

**Figure 6.** Plan of the experimental raw-earth building in Pasłęk with the placement of measurement points carried inside the building with BP25 laser device.

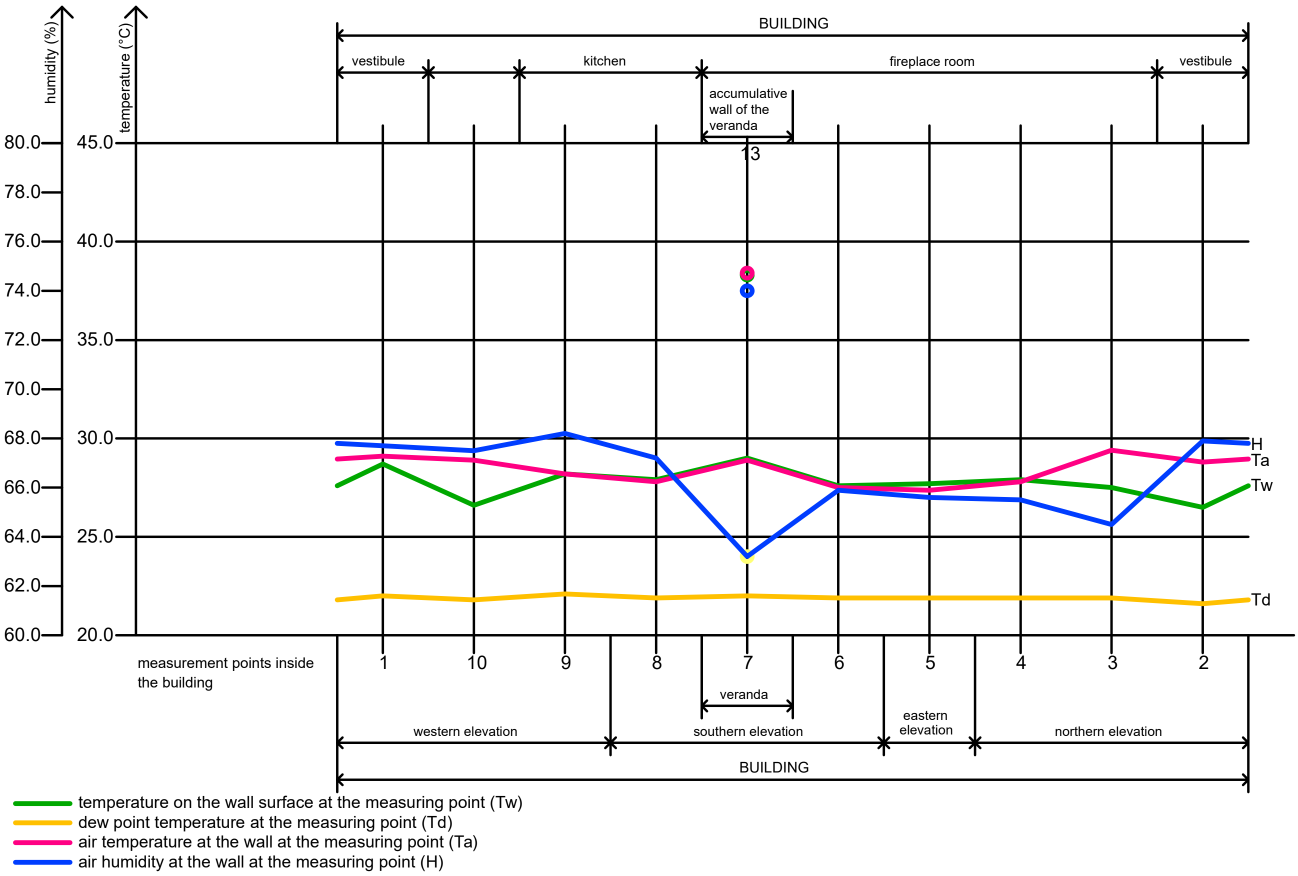
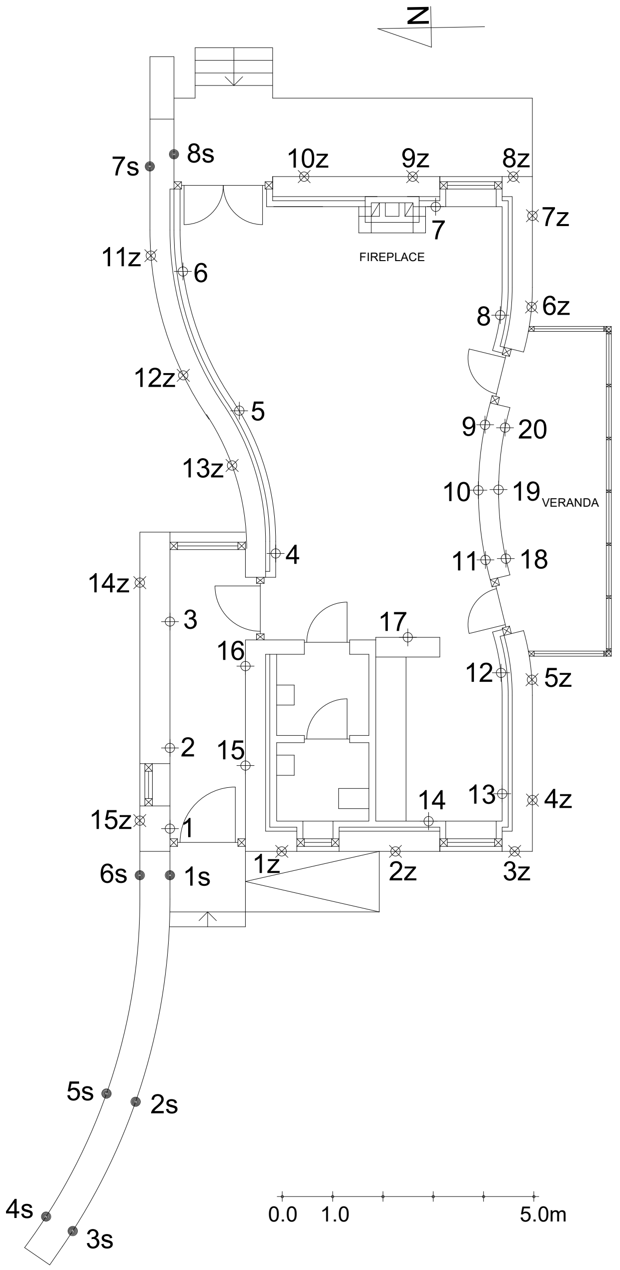



**Figure 7.** Temperature and humidity of the wall inside the building (measurements on 1 August 2018 with the Trotec BP 25).

### *4.2. Tests Were Carried Out Using TROTEC BM 22*

Measurements of the humidity of the material of the wall were taken for specified points on the figure below (Figure 8).

The following diagrams and charts show the results of the measurement data collected on the day of the survey (Figure 9).




| MEASUREMENT POINTS INSIDE BUILDING | h humidity of the wall surface % |
|---|---|
| 1 | 0.7 |
| 2 | 0.8 |
| 3 | 0.8 |
| 4 | 0.9 |
| 5 | 0.9 |
| 6 | 0.9 |
| 7 | 0.8 |
| 8 | 0.9 |
| 9 | 0.6 |
| 10 | 0.7 |
| 11 | 0.6 |
| 12 | 0.9 |
| 13 | 1.0 |
| 14 | 1.0 |
| 15 | 0.7 |
| 16 | 0.7 |
| 17 | 0.6 |
| 18 (VERANDA) | 0.5 |
| 19 (VERANDA) | 0.5 |
| 20 (VERANDA) | 0.5 |

| MEASUREMENT POINTS OUTSIDE BUILDING | H humidity of the wall surface % |
|---|---|
| 1z | 0.8 |
| 2z | 0.9 |
| 3z | 0.8 |
| 4z | 0.7 |
| 5z | 0.7 |
| 6z | 0.7 |
| 7z | 0.6 |
| 8z | 0.7 |
| 9z | 0.7 |
| 10z | 0.7 |
| 11z | 0.8 |
| 12z | 0.7 |
| 13z | 0.9 |
| 14z | 0.8 |
| 15z | 0.9 |
| 1s (EXTERNAL SCREEN WALL) | 0.9 |
| 2s (EXTERNAL SCREEN WALL) | 0.7 |
| 3s (EXTERNAL SCREEN WALL) | 0.7 |
| 4s (EXTERNAL SCREEN WALL) | 0.9 |
| 5s (EXTERNAL SCREEN WALL) | 0.8 |
| 6s (EXTERNAL SCREEN WALL) | 0.9 |
| 7s (EXTERNAL SCREEN WALL) | 0.8 |
| 8s (EXTERNAL SCREEN WALL) | 0.8 |

Experimental raw-earth building (plan) in Pasłęk, Poland.
Location of test measurement points carried out with **BM 22.** Moisture measurement of wall material inside and outside the building at a height of 1.2 m above floor or ground level.

- 1/20 - measurement points of wall humidity inside building
- 1z/15z - measurement points of moisture contents in the wall outside building
- 1s/8s - moisture measurement points of external screen wall

(measurements on 01/08/2018 with the **Trotec BM 22**)

**Figure 8.** Plan of the experimental raw-earth building in Pasłęk with the placement of measurement points carried inside the building with BM 22.

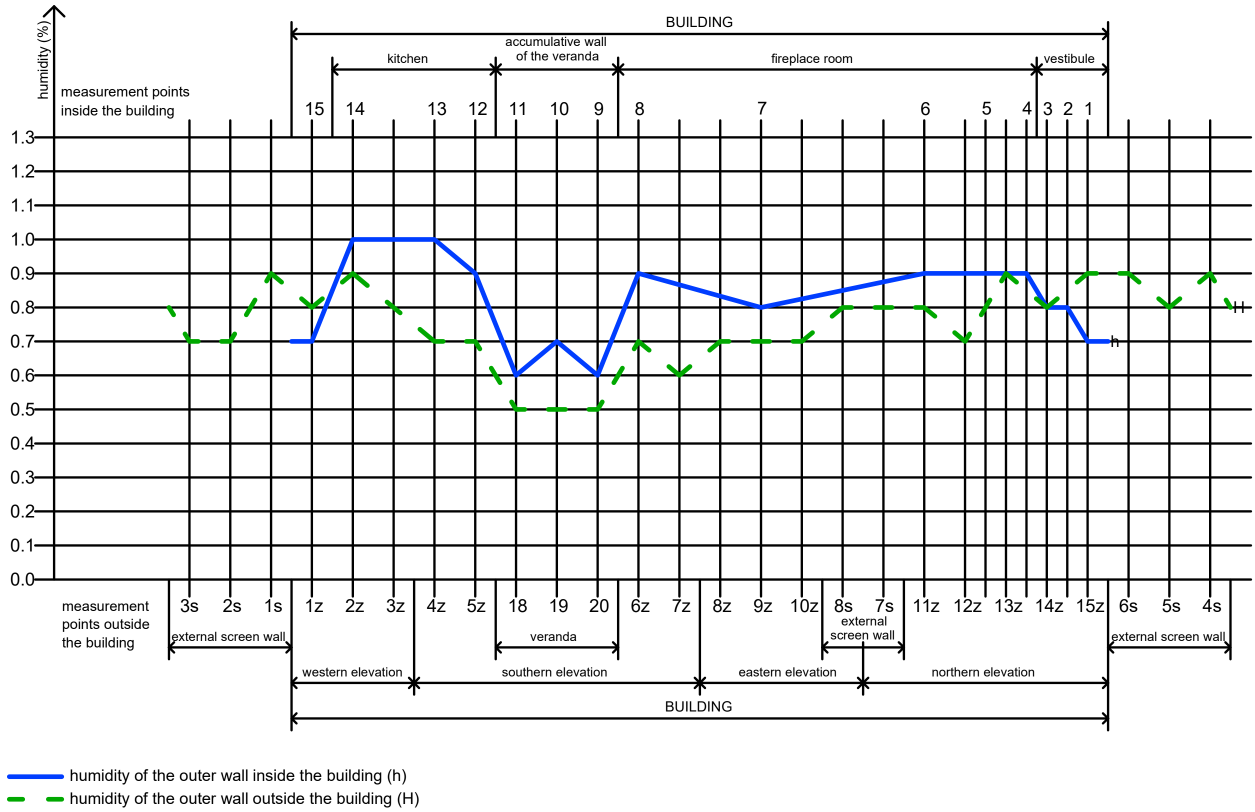
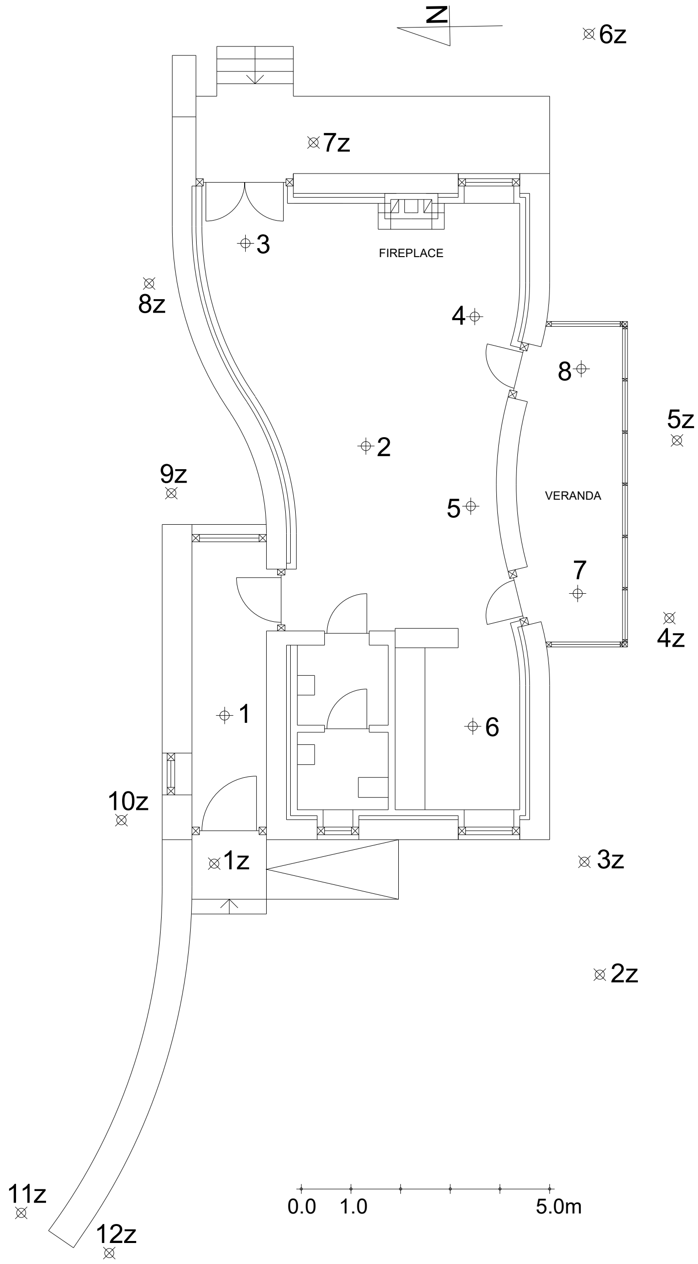



**Figure 9.** Wall humidity inside and outside the building (measurements on 1 August 2018 with the Trotec BM 22).

### *4.3. Tests Were Carried Out Using Testo 410-2*

Measurements of temperature and humidity on the surface of the walls and air temperature were taken for specified points on the figure below (Figure 10).

The following diagrams and charts show the results of the measurement data collected on the day of the survey (Figure 11).




| | MEASURMENT POINTS | h/H air humidity % | t/T air temperature °C | V wind speed m/s |
|---|---|---|---|---|
| MEASUREMENTS INSIDE THE BUILDING | 1 | 62.9 | 22.3 | |
| | 2 | 60.7 | 28.8 | |
| | 3 | 61.8 | 28.5 | |
| | 4 | 61.6 | 28.4 | |
| | 5 | 60.0 | 29.8 | |
| | 6 | 62.2 | 28.5 | |
| | 7 VERANDA | 43.1 | 40.5 | |
| | 8 VERANDA | 46.0 | 39.0 | |
| MEASURMENTS OUTSIDE THE BUILDING | 1z | 54.2 | 32.1 | 0.5 |
| | 2z | 52.7 | 32.6 | 0.6 |
| | 3z | 54.3 | 32.0 | 0.7 |
| | 4z | 44.3 | 32.7 | 1.2 |
| | 5z | 44.9 | 34.5 | 1.2 |
| | 6z | 40.3 | 36.4 | 0.4 |
| | 7z | 43.8 | 32.5 | 0.2 |
| | 8z | 47.6 | 33.2 | 1.4 |
| | 9z | 48.8 | 33.0 | 1.1 |
| | 10z | 50.9 | 32.4 | 1.2 |
| | 11z | 50.8 | 31.5 | 1.1 |
| | 12z | 53.2 | 33.2 | 0.8 |

Experimental raw-earth building (plan) in Pasłęk, Poland.
Location of test measurement points carried out with TESTO 410-2**.**
**M**easuring the air temperature and humidity inside and outside the building at a height of 1,5 m above the floor or ground level.

⌖ 1/9 - measurement points inside the building
⌧ 1z/12z - measurement points outside the building

(measurements on 01/08/2018 with the **TESTO 410-2**)

**Figure 10.** Plan of the experimental raw-earth building in Pasłęk with the placement of measurement points carried inside and outside the building with TESTO 410-2.

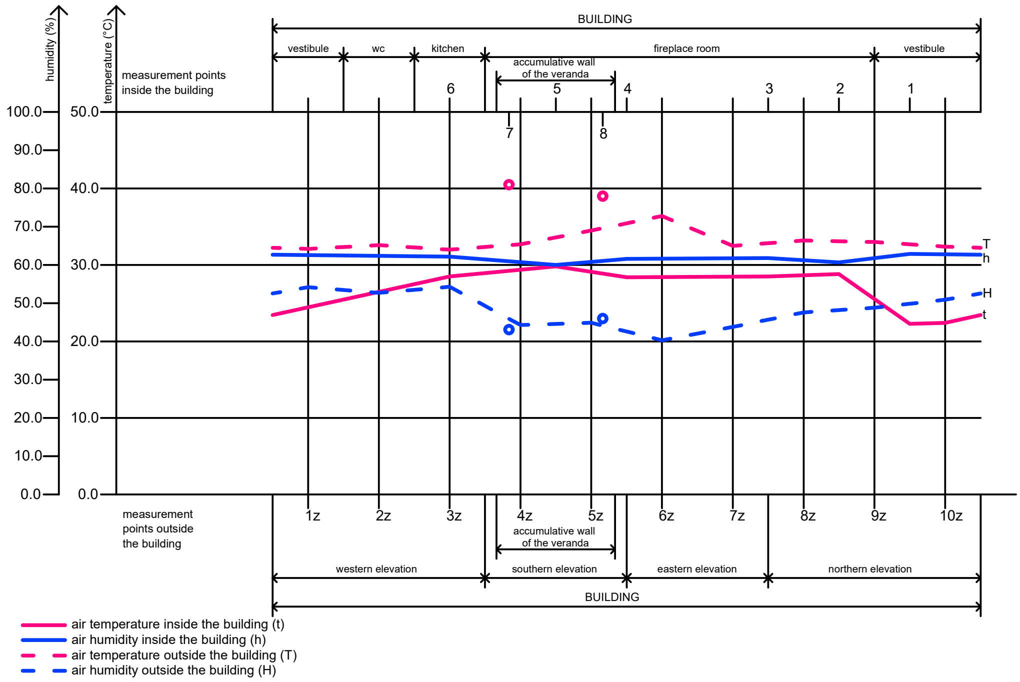



**Figure 11.** Air temperature and humidity inside and outside the building (measurements on 1 August 2018 with the TESTO 410-2).

### *4.4. Architectural and Technical Site Visit*

During the architectural and technical site visit, observations of the resilience of raw-earth technology to the climate conditions were conducted. The biggest danger for this technology is water. Observations are shown on the photos for each elevation with visible defects on the wall after tie bars were used during wall construction, after raining water in the plinth zone and defects on some corners (Figures 12–15).

**Figure 12.** View on the western elevation with visible points after tie bars were used during wall construction and defects in the corner of the wall. Photos taken during architectural and technical site visit on 1 August 2018.

**Figure 13.** View on the eastern elevation with visible points after tie were bars used during wall construction. Photos taken during architectural and technical site visit on 1 August 2018.

(**a**) (**b**)

**Figure 14.** View on the south elevation (**a**) with visible defects on the screen wall in the plinth zone near landing and flight of stairs. (**b**) On south elevation points after tie bars were used during wall construction are visible near veranda. Photos taken during architectural and technical site visit on 1 August 2018.

**Figure 15.** View on the north elevation with visible defects in the stone plinth zone and visible points after the tie bars were used during construction. Photos taken during architectural and technical site visit on 1 August 2018.

No defects of the raw-earth walls were observed in the interior (Figure 16).

(**a**) (**b**)

**Figure 16.** View of the internal wall without any defects. View on accumulation wall between interior and veranda–rammed earth surface. (**a**) View on layered external wall–straw and clay blocks surface (**b**). Photos taken during architectural and technical site visit on 1 August 2018.

The texture of the walls built using different technologies are still clearly visible (Figure 17).


(**a**) (**b**)

**Figure 17.** Texture of the external walls built with raw-earth technology (**a**) screen wall built from raw and strew blocks (**b**) external wall built as rammed earth in formwork. Photos taken during architectural and technical site visit on 1 August 2018.

## 5. Discussion

### *5.1. Results of Tests Were Carried Out Using TROTEC BP 25*

Tests carried out with the TROTEC BP 25 (dew point scanner) show some differences in both temperature, humidity, and dew point temperature occurring at a given measuring point marked on the partition.

By comparing the values of the measured humidity at individual measuring points some differences between the particular measurements can be observed. In the summer, when the outside temperature was definitely higher than the inside temperature, the humidity on the partition was definitely higher inside the building.

On the test day, when the outdoor temperature was several to a dozen degrees higher than the indoor temperature, an interesting phenomenon of a definite difference between the temperature measured on the surface of the partition and the dew point temperature measurement was observed. The differences in the interior reach from 4.5 to even 6.1 °C, and in the case of the veranda even 14.4 °C at point 13 and 15.3 °C at point 14. In the exterior measurements these differences reach between 3.4 and 7 °C on the north wall, while on the south wall the differences are between 8.4 and 14.3 °C, and as much as 29.4 °C in the glazed veranda. However, the highest differences occur on the west wall reaching a difference of 12.8 and even 13.9 °C. It is important to note that nowhere is there a point where the dew point temperature exceeds the temperature on the partition or the ambient temperature. Walls behave similarly in winter, when the dew point temperature both inside and outside the building is also lower than the ambient temperature. It proves that there is no dew point in the studied partitions. Therefore, it can be concluded that the building is temperature stable. Even with a high level of humidity in the rooms, the stability of the dew point temperature is maintained.

The use of the glazed veranda on the south side of the building as a kind of greenhouse accumulating temperature is confirmed by a definitely higher temperature inside it than in other points of the building. The use of the veranda has fulfilled its role as a temperature accumulator. Although the temperature in the veranda is considerably higher, still no dew point was detected in the wall between it and other rooms.

### *5.2. Results of Tests Were Carried Out Using TROTEC BM 22*

As a result of the data collected at several measurement points with the TROTEC BM 22 (moisture meter), wall phenomena can be observed concerning the moisture level in the wall.

The survey on 1 August 2018 showed that in the interior of the building at most measurement points the moisture level varied between 0.6 and 0.7, the highest moisture level of 1.0 was observed in the kitchen room.

An interesting observation is that the lowest measurement was on the outside of the external wall but facing the veranda. Here the measurement showed the lowest value of humidity at 0.5. This may be caused by the relation between the southern exposure and the positions of the points inside the veranda, which is heated by the sun in summer. As the differences between the individual measuring points outside and inside the building are of the order of a few tenths it can be concluded that the hay will remain stable.

### *5.3. Results of Tests Which Were Carried Out Using Testo 410-2*

As a result of the data collected at several measurement points with the Testo 410-2 (anemometer), the temperature and humidity phenomena in the rooms can be observed.

The collected measurement results are similar to the humidity measurements collected with the TROTEC BP 25 device; they show higher humidity values inside than outside the building. Using this device, the humidity on the veranda was tested, where by far the lowest percentage values of humidity were recorded. The humidity at point 7 on the veranda was 19.8% lower than at point 1, which is located in the vestibule. This shows that the veranda with its glazed wall reduces the humidity inside the building. The veranda also recorded the highest temperatures of 39 and 40.5 °C, while in the other rooms the temperature varied between 28.5 and 29.8 °C. A thermally interesting phenomenon occurs in the vestibule room. Despite the fact that the external wall in this room has no thermal insulation, the lowest internal temperature occurs there.

### *5.4. Results of Architectural and Technical Site Visit*

Durability of raw-earth technology is enough to conclude that this technology can be used in the climate of middle Europe under some conditions. Architects should design eaves to protect external walls against the raining water. Also, in all zones connected with the flat, external surfaces (landings, flights of stairs) or the ground should be made using plinth made from materials that allow the raining water to drain, e.g., stone. The esthetic view after 6 years of usability is very good. The texture of the raw-earth is very well-maintained. Drawings after formwork and differences due to other technologies are clearly visible also after the period. Architects and investors should remember that some points after tie bars were used during wall construction could be visible on some sites. Interior walls made in raw-earth technology do not have any defects.

## 6. Conclusions

As a result of the data collected in the raw earth building, it should be emphasized that the building retains its energy saving values and is fully stable. It should be noted that the smooth connection of rammed earth walls in the building in Pasłęk contributed to the reduction of the possibility of thermal bridges. Every thermal bridge contributes to heat loss and changes the conditions inside and outside the building. Thermal bridges also contribute to a deterioration in living comfort.

Very important data has been collected regarding humidity conditions that influence the walls' behavior and problems with dew point occurrence. In the building it was observed that also in the summer period when air humidity inside was much higher than outside the building kept thermal stability. The dew point examination in the building in Pasłęk during the summer period showed that there is no temperature on any of the examined walls favorable for the occurrence of a condensation phenomenon on the walls. This is important for the absence of moisture problems.

The architectural and technical site visits conducted during 6 years show that rammed earth technology is possible to use in the climate of middle Europe in Poland [21,22]. It makes a future improvement of raw-earth technology possible, which now is not so popular and does not have any regulations in Poland. So far our research proved that the rammed earth building is a technology resilient to the characteristic local climate conditions.

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