Measurement of thermal, hygric and physical properties of bricks and mortar common for the Polish market

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Abstract. Hygric, thermal and physical properties were determined for building materials typical for the Polish market. One type of mortar and two types of masonry bricks were studied. Thermal diffusivity and specific heat of dry materials were found using the flash and differential scanning calorimetry methods, respectively. Water vapour permeability was tested using the cup method for a single temperature of 23°C and for two ranges of the air relative humidity (from 0 to 50% and from 50 to 94%). The permeability tests were performed according to ISO 12572:2016. Measurements of the sorption isotherms were carried out using the environmental chamber method, according to ISO 12571:2013. The results of measurements of the apparent and true density of the considered materials were used to determine their porosity. The presented measurements concerned materials involved in physical and numerical experiments aimed at quantitative and qualitative analyses of heat and moisture transfer during drying of building materials and walls.

1. Introduction

The knowledge of building material properties is especially important to face current challenges related to economy, health care and environmental protection. Detailed models of heat and mass transfer help to design the user-friendly, environment-friendly, sustainable and energy-efficient buildings, but they need material properties of building materials as the input data. The number of measurement of these properties available in the literature is high and rapidly growing due to the extensive interest and funding. Additionally, the properties for many building materials are catalogued in the engineering databases and in computer programs such as WUFI® [1] and can be used to model heat and moisture transport in building components. Nevertheless, there is a continuous need for new measurements of the material properties which may be justified by three main reasons.

Firstly, each material sample is unique in terms of its transport properties, which depend on the details of manufacturing process. It has been shown that manufacturing technique affects microstructural parameters such as porosity, pore size distribution and dominant pore orientations [2] which have the profound impact on heat and mass transport properties of materials such as bricks. The second reason having influence on the properties is the type of base material and additives used in production, which are strongly location dependent. This is especially true for the recently promoted materials with sustainable, organic components that are different for different regions where the material is manufactured. Because of this, the literature results cannot be universally applied.
When equipped with reliable measurement techniques, laboratories should be able to obtain consistent measurement results. Nevertheless, discrepancies in the published data can be found, which are especially characteristic for measurements of the moisture transport properties, which is the third reason justifying the need to measure the properties of each building material involved in scientific research and construction of new buildings [3]. The main difficulty in measurement of hygro-thermal properties is associated with long time required to obtain the equilibrium or steady state conditions. The required stabilization times may be counted in weeks and months. Due to that, the measurement errors and sources of uncertainty are relatively slowly eliminated. Therefore, the results obtained by different laboratories for the same material may be significantly differ, especially if the water transport properties were measured by unexperienced personnel [3].

The literature regarding the measurement of the hygric, thermal and physical properties of building materials is relatively rich [4-6]. Classical methods in that field are considered reliable and many of them are standardized by ISO, DIN and ASTM [5, 6]. The majority of standardized methods for the measurement of the air and water transport properties is based on the steady state assumption. In recent years, methods utilizing the unsteady state conditions have been intensively developed [7, 8]. In general, they allow for faster measurements, but mathematical description and modeling which accompanied them is much more complex than for steady state methods. Some authors emphasize that in many applications the building materials are subjected to dynamic environmental conditions for which the properties measured in the steady state are not accurate [7, 8]. On the other hand, classical methods are based on simple principles which make the measurements easier to design and the results easier to interpret. Due to these reasons, steady state methods are still globally used, as the basic means of measurement, and as the reference for results obtained using other methods.

This paper concerns the measurement of thermal, hygric and physical properties of bricks and mortar common at the Polish market. Apart from previously listed reasons to carry out measurements of the building material properties it is also worth to note that studies demonstrating large number of properties for the single material are seldom presented. The attempt to comprehensively characterize materials of interest was motivated by the need to verify mathematical and numerical models of heat and moisture transport in the building materials which were developed within the “DryWall” project (no. POIR.04.01.02-00-0099/16). The aim of the ongoing project is optimization of the thermo-injection drying technique [9]. In this project, experimental stands devised to investigate drying of walls and single bricks were built alongside with the numerical and analytical models of drying phenomena [2, 10-15]. This paper presents measurement results for materials used in the project, i.e., the fired red brick, silicate brick and one type of a mortar.

2. Materials
Objects of further investigation were three types of the masonry materials: red brick, silicate brick and mortar which are commonly available on the market in Poland.

3. Properties
Different material properties such as hygric, physical and thermal were investigated for three types of materials of samples in selected direction only. In the case of samples cut for vapor permeability measurements the standard ISO 12572:2016 limits possible ways of preparation of samples as it required relatively large samples of particular geometry. In the case of red and silicate bricks the direction through the height of the brick was the only one which fulfill ISO 12572:2016 standard requirements. Moreover, this direction is of interest because moisture is usually transported from the ground along the height of the wall. In the case of measurement of thermal properties of the red and silicate bricks, the investigation of anisotropy of their thermal conductivities was shown in the previous work [2]. However, in this paper thermal diffusivities and thermal conductivities of bricks were presented only in the direction through the thickness of the brick. This direction was selected because of the highest temperature gradients and heat flux occur between inner and outer side of the wall.
3.1. Hygric

3.1.1. Vapor permeability. The cup method was used to measure vapour permeability of samples made of the mortar and masonry bricks: red and silicate one. For bricks the measurements were carried out for direction along the height of the brick. The measurements were performed according to the standard ISO 12572:2016. The principle of this method is water vapor transmission through the investigated sample sealed to an open dish (figure 1). The dish was made of the high-temperature-resistant glass and the openings between the dish and the sample were sealed using the building silicone and technical stearin.

![Figure 1. Assembly of the testing dish and sealed sample.](image)

A difference in the partial vapour pressure $p_v$ between the inner space of the dish and controlled atmosphere of the environmental chamber causes water vapour to penetrate the sample in through-thickness direction. Change of the mass of the whole assembly was measured. This procedure allows to determine water vapour flux $G$, water vapour flux density $g$, corrected water vapour flux density $g_{me}$, water vapor transmission $w_{me}$, as defined in the ISO 12572 standard. The correction of calculated water vapour flux density was performed according to the ISO 12572 standard, because the assembly contained occluded edges. Two different sources were separately applied to enforce water vapour transmission through the samples. Calcium chloride (desiccant) and aqueous solution of potassium nitrate assured the relative humidity of 0% and 94% inside the testing assembly, respectively. The environmental chamber was used to assure stable relative humidity of 50% and average temperature 23°C outside of the assemblies, so that the water vapour was transmitted in both directions: outside and inside of testing dishes. The results of those measurements (vapor permeability $\delta_{me}$) are showed in table 1.

![Table 1. Results of vapor permeability investigation.](image)

| Sample type   | Relative humidity inside the dish | Red brick | Silicate brick | Mortar |
|---------------|----------------------------------|-----------|----------------|--------|
|               | 0% | 94% | 0% | 94% | 0% | 94% |
| $G$ (kg s$^{-1}$) | 8.535·10$^{-9}$ | -1.270·10$^{-8}$ | -1.405·10$^{-6}$ | -6.999·10$^{-6}$ | 2.304·10$^{-9}$ | -4.070·10$^{-9}$ |
| $g$ (kg m$^{-2}$ s$^{-1}$) | 6.732·10$^{-7}$ | -9.632·10$^{-7}$ | 2.759·10$^{-7}$ | -7.076·10$^{-7}$ | 1.756·10$^{-7}$ | -3.077·10$^{-7}$ |
| $g_{me}$ (kg m$^{-2}$ s$^{-1}$) | 7.142·10$^{-7}$ | -1.022·10$^{-6}$ | 3.099·10$^{-7}$ | -7.945·10$^{-7}$ | 1.877·10$^{-7}$ | -3.285·10$^{-7}$ |
| $w_{me}$ (kg m$^{-2}$ s$^{-1}$ Pa$^{-1}$) | 5.087·10$^{-10}$ | -8.273·10$^{-10}$ | 2.207·10$^{-10}$ | -6.431·10$^{-10}$ | 1.337·10$^{-10}$ | -2.659·10$^{-10}$ |
| $\delta_{me}$ (kg m$^{-1}$ s$^{-1}$ Pa$^{-1}$) | 1.136·10$^{-11}$ | -1.941·10$^{-11}$ | 5.104·10$^{-12}$ | -1.467·10$^{-11}$ | 4.082·10$^{-12}$ | -7.991·10$^{-12}$ |

The properties presented in table 1 were calculated according to formulas mentioned in the standard ISO 12572:2016. Sets of samples consisted of four assemblies of each materials type and source used during the test. The permeabilities were investigated in pairs with a set of assemblies containing different source (i.e., $\varphi = 0%$ and $\varphi = 94%$), so that opposite directions of water vapor transmission were obtained.
Despite the differences between results obtained for each pair of sets, their orders of magnitude are similar.

3.1.2. Sorption. Investigation was performed according to the standard ISO 12571:2013 with use of environmental chamber. Ten samples of each material type were cut from the inner part of bricks and mortar block and subsequently subjected to drying with the vacuum assisted furnace. The test was performed on samples with a mass of approximately 30 g. Precisely controlled parameters by the environmental chamber were set as follows: \( T = 23^\circ \pm 0.5^\circ \text{C}; \) \( \varphi_1 = 30\% , \varphi_2 = 53\% , \varphi_3 = 76\% \) and \( \varphi_4 = 90\% \). Change in a mass of samples during conditioning were determined with the analytical balance. In order to calculate the amount of the absorbed water, dry samples were exposed to the inner condition of the environmental chamber. According to the standard an equilibrium state of the sample was assumed to be valid as soon as its mass change of three consecutive measurement did not exceed 0.1%. Then relative humidity was changed to the next value. The results of measurements were shown in figure 2.

![Figure 2](image_url)

**Figure 2.** Sorption and desorption characteristics for: A) red brick, B) silicate brick and C) mortar.

Figure 2 shows characteristics of the absorbed water vs the relative humidity as an average determined from ten samples of each investigated material. The black symbols in the figures denote the datapoints obtained during the first stage – sorption process – where relative humidity was increased to the next humidity point after samples reached the equilibrium. The circular symbols denote the datapoint obtained during the second stage – desorption process. The relative humidity of \( \varphi_4 = 90\% \) was the common point for two mentioned stages. In figure 2B and 2C the hysteresis of sorption-desorption...
process can be observed. Exception is the red brick (figure 2A), for which the datapoints of both stages overlap in the range of their standard deviation.

3.2. Physical

The pycnometer and geometric method were used to determine the apparent density and real density of the samples, respectively. Four samples of each type were investigated, and the averaged results of measurements were collected in table 2. Determination of apparent density ($\rho_{\text{apparent}}$) required the samples to be fragmented into a powder which was performed with a mechanical mixer. Such sample preparation leads to pores opening and causes the pycnometric liquid to infiltrate and immerse fragmented particles more easily. Before each measurement, the pycnometer was calibrated with the deionised water ($< 0.10$ S m$^{-1}$). Samples in the form of powder had been dried in a vacuum-assisted furnace with following parameters: $T = 110^\circ$C, $t = 72$ hours and vacuum $p_{\text{vac}} = 95$ kPa. Then, the sample was put into the pycnometer, mixed with water and degassed under the same vacuum level for 30 min in order to assure good infiltration of each particle. Additionally, all assembly was left for 5-6 hours in room temperature.

The real density ($\rho_{\text{real}}$) of the samples was determined according to geometric method based on measurement of the mass and sample dimensions. In order to minimize errors quite large (i.e., 100×100×150 mm), cuboidal shaped specimens were prepared. The slide calliper and analytical balance were utilized to determine the sample volume and mass.

Determination of both densities allowed to calculate the sample porosity $P$ according to following formulae:

$$P = \left(1 - \frac{\rho_{\text{real}}}{\rho_{\text{apparent}}}\right) \times 100\%$$

Results of both measurements are shown in table 2.

**Table 2. Physical properties of samples.**

| Sample type     | Number of samples | $\rho_{\text{real}}$ (g cm$^{-3}$) | Std dev. | $\rho_{\text{apparent}}$ (g cm$^{-3}$) | Std dev. | $P$ (%)   |
|-----------------|-------------------|------------------------------------|----------|--------------------------------------|----------|-----------|
| Red brick       | 4                 | 1.763                              | 0.015    | 2.585                                | 0.030    | 31.8      |
| Silicate brick  | 4                 | 1.740                              | 0.026    | 2.588                                | 0.029    | 32.8      |
| Mortar          | 4                 | 1.795                              | 0.031    | 2.579                                | 0.033    | 30.4      |

3.3. Thermal

3.3.1. Thermal diffusivity. Thermal diffusivity was determined with the use of the flash method (LFA 447, Netzsch) at three temperatures: $T_1 = 30^\circ$C, $T_2 = 45^\circ$C and $T_3 = 60^\circ$C. Samples of three materials were cut from the inner part of bricks and dried before the measurement. For bricks the measurements were carried out for direction along the thickness of the brick. The results are shown in figure 3A.

3.3.2. Specific heat. Specific heat was determined with use of the differential scanning calorimeter DSC 7 (Perkin Elmer). Samples of three materials were cut from the larger parts of bricks and dried before investigation. Measurements were performed in the argon atmosphere (10 ml/min) with the heating rate $v_r = 10$ K/min. In figure 3B variation of the specific heat with temperature was shown for selected temperature values.

3.3.3. Thermal conductivity. Thermal conductivity of each type of building materials was calculated according to the indirect method based on the following formula:

$$k = ac \rho_{\text{real}}$$
where: \( a \) is the thermal diffusivity, \( c_p \) is the specific heat and \( \rho_{\text{real}} \) is the real density. The average value of each particular property was used in calculation. The results are shown in figure 3C.

The highest thermal diffusivity (figure 3A) is observed for samples made of the mortar \( a = 0.969 \text{ mm}^2 \text{ s}^{-1} \) at \( T = 30^\circ \text{C} \) to \( a = 0.918 \text{ mm}^2 \text{ s}^{-1} \) at \( T = 60^\circ \text{C} \). Values lower by approximately 4% characterize samples cut from the silicate bricks. Thermal diffusivity of the red brick is lower, ranging from \( a = 0.458 \text{ mm}^2 \text{ s}^{-1} \) at \( T = 30^\circ \text{C} \) to \( a = 0.431 \text{ mm}^2 \text{ s}^{-1} \) at \( T = 60^\circ \text{C} \).

In the case of specific heat, similar values can be observed for the red brick and silicate brick. The largest difference between them does not exceed 3%, whereas the specific heat of samples made of the mortar is higher than this of the silicate brick by approximately 12% (figure 3B). The specific heat increases with temperature for each sample type.

Thermal conductivity was calculated according to eq. (2). It required the direct measurement of thermal diffusivity, specific heat as well as the sample density. It must be noted that the last property was determined in the room temperature and was assumed to be constant over the investigated temperature range. The lowest thermal conductivity was observed for samples cut from the red brick which values are in the range from 0.596 \( \text{W m}^{-1} \text{K}^{-1} \) to 0.624 \( \text{W m}^{-1} \text{K}^{-1} \). Thermal conductivity of the second sample (the silicate brick) was found higher than that of the red brick by approximately 87%. In the case of mortar, its thermal conductivity is approximately 130% of the thermal conductivity of the red brick.

![Figure 3](image.png)

**Figure 3.** Thermal properties of samples made of red brick, silica brick and mortar: A) thermal diffusivity, B) specific heat and C) thermal conductivity.

### 4. Summary

In this paper, three types of the masonry materials: red brick, silicate brick and mortar were measured to find their hygric, physical and thermal properties. Determination of these properties is essential as
many studies associated with prediction and modelling of heat and moisture transport during drying of building walls are conducted. Building materials common for the Polish market were comprehensively characterized using classical methods. The water vapour permeability was measured with the cup method according to the standard ISO 12572:2016. The next hygric parameter that was investigated in this paper was the sorption ability performed in accordance with the standard ISO 12571:2013 using the environmental chamber. Moisture absorption in the hygroscopic range is a long-term process as equilibrium state for each moisture point was obtained in approximately 10-12 days. Four samples of each material type were prepared and investigated. It was observed that the sorption-desorption process is characterized by the hysteresis in the case of samples cut from the silicate bricks and mortar. The data points obtained for the red brick in this two-stage test did not show this behavior.

Measurements of physical properties such as the apparent density and real density allowed to calculate the porosity of materials according to the eq. (1). The obtained values of the real densities were used in the subsequent calculation of thermal conductivity. Difference in the range from 30.4% to 31.8%.

The thermal conductivity of each masonry material was determined according to the indirect method that is based on measurements of the thermal diffusivity, specific heat and real density. The investigation of thermal properties was carried out at three temperatures covering the range of working temperatures in the experimental drying stand. The stand was developed and subsequently modified to study the heat and moisture transport during drying process in a building wall [14, 15]. The results of measurements on thermal properties showed that samples made of silicate bricks and mortar possess thermal conductivity higher than red bricks, respectively by 87% and 130%.

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