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THERMAL PROPERTIES OF HISTORICAL HUNGARIAN MASONRY BRICKS

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Abstract: *Hungary's building stock, primarily constructed in the 19th and 20th centuries from traditional masonry, includes bricks of varying quality and material properties. Current renovation legislation mandates compliance with thermal requirements, but aged materials' thermal properties are often unknown, complicating energy conformity verification. This research examined historical masonry bricks from 11 Hungarian brickworks from the early 20th century to create a database for better understanding and preserving historical buildings' energetic performance. Thermal properties, including diffusivity, conductivity, and volumetric heat capacity, were determined using the modified transient plane source method, and density was tested. This paper presents a comparative analysis of the measured data. The findings provide essential data for building energy calculations and computational modelling of masonry constructions' thermal performance.*

Keywords: *building physics, historical construction materials, masonry bricks, thermal conductivity, specific heat capacity, density*

1. INTRODUCTION

The built environment in Central Europe, particularly Hungary, includes many historical masonry buildings of cultural, historical, and architectural value. These structures, primarily from the 19th and 20th centuries, feature masonry as vertical load-bearing elements. Early 1800s constructions used timber slabs and arches for horizontal support, evolving to bent steel beam slabs, and by the 1910s, reinforced concrete was common [1]. Later, prefabrication, prestressed, and formwork slab systems developed during the world wars. The scarcity of quality materials led to using unspecified materials, complicating renovations. Preserving these buildings is essential, mainly due to climate change and the need for improved energy performance standards.

In the early 20th century, brick production in Hungary underwent significant developments and transformations, reflecting both industrial advancements and socio-economic changes in the region. Brickworks played a pivotal role in the construction sector, supplying materials essential for the burgeoning urbanization and industrialization of the era. Hungary experienced rapid urban growth during this period, particularly in Budapest and other major cities. The demand for housing, infrastructure, and industrial buildings fuelled the expansion of brick production. Brickworks increased across the country, utilizing locally available clay deposits, which varied in quality and composition depending on the region. Technological advancements in brickmaking processes were notable during this time. Traditional methods, such as hand-moulding and firing in clamp kilns, gradually became more efficient [2]. The introduction of mechanized brick presses and continuous kilns improved production capacity and quality control. These innovations increased output and standardized the dimensions and characteristics of bricks, facilitating mass construction projects.

Significant progress has been made in modelling and simulation tools for heat, air, and moisture (HAM) transport in buildings and systems. Based on the research of the last years, one could even say that the hygrothermal simulations of building elements and building structures [3], such as porous building materials [4], solid masonry walls [5], prefabricated panels [6], insulated masonry or concrete [7], lightweight concrete walls [8], lightweight timber walls [9] or various cladding structures [10] are becoming more and more common. However, these tools are rarely integrated into building simulation environments, often oversimplifying structures and thermal bridges due to the lack of reliable thermophysical input data for materials and intrinsic limitations in the simulation models, especially concerning the geometric features of heritage buildings [11]. The study of the hygrothermal properties of historical bricks is essential for understanding the performance and preservation of historical buildings. These properties significantly impact masonry structures' energy efficiency, durability, and overall integrity. Hygrothermal properties, including thermal conductivity, thermal diffusivity, volumetric heat capacity, and moisture transport characteristics, are critical in evaluating how historical bricks respond to environmental conditions. These properties influence the thermal comfort of interiors, the durability of the masonry, and the building's resistance to moisture-related damages. Thermal conductivity and diffusivity are fundamental in determining how bricks transfer heat. The research on the hygrothermal characterisation of historical materials, especially for old bricks, remains less advanced. Engineers and researchers usually use existing materials database, like the WUFI database for example, to evaluate the hygrothermal response of a brick wall to climatic variations. Some studies have focused on these properties in historical bricks to assess their performance under current climatic conditions. Pavlík and Pavlíková [12] found significant variability in the thermal conductivity of historical Czech bricks based on composition and age. Similarly, Oumeziane [13] highlighted how regional manufacturing techniques affect the hygrothermal properties of early 20th-century French clay bricks. Çam and Uğurlu Sağın [14] emphasized the influence of production methods and firing temperature on the porosity and mechanical strength of Byzantine bricks from Anaia Church, Kadıkalesi. This research underscores the importance of accurate thermal property data for energy performance calculations in historical buildings. Additionally, Sýkora et al. [3] compared the hygrothermal properties of Central European bricks from various historical periods, revealing distinct behaviours based on region and era, which are crucial for conservation and restoration projects.

This study measured thermal properties such as thermal diffusivity, thermal conductivity, volumetric heat capacity, and density using the modified transient plane source (MTPS) method. The comparative analysis of these measurements provides essential data for energy calculations and computational modelling of thermal performance in masonry constructions. This research aims to enhance the understanding of the hygrothermal behaviour of historic masonry buildings, addressing the lack of data on old bricks and discrepancies between experimental results and numerical simulations.

2. MATERIALS AND METHODS

2.1 *Materials*

The first step of the research was to collect, identify and prepare samples. It should be highlighted that the sample collection on site is particularly complex because of the patrimonial value of the industrial buildings. Renovation projects or demolition works remain the only opportunities to collect samples.

Hungary was home to 314 operational brickworks in the early 20th century [2], each contributing to the rich architectural tapestry of the region. This study examines 11 types of historical Hungarian masonry bricks sourced from various brickworks, as seen in Table 1, representing different manufacturing technologies and material compositions. These brickworks provide diverse samples, which is crucial for understanding the variability in thermal properties due to various manufacturing processes and material compositions.

Number	***Manufacturer***	***Pattern***
I	Gróf Esterházy Ferencz Gőztéglagyár, Tata	
II	Kőszénbánya Téglagyár Társulat, Budapest	
III	Christoph Ialics, Budapest	
IV	Antal Durvay Gőztéglagyár, Budapest	
V	Anton Holtzspach, Budapest	
VI	István-téglagyár, Pestszentlőrinc	
VII	Magyar Kerámiai Gyár Rt., Budapest	
VIII	Salgótarjáni Téglagyár, Salgótarján	
IX	Sümegi Téglagyár, Sümeg	
X	Sződrákosi Téglagyár Társulat (Floch-Reyhersberg), Sződrákos	
XI	Újlaki-téglagyár, Óbuda	

Table 1. List of brickworks and bricks examined

The standard dimensions of the small solid bricks used were 30 x 14 x 6.5 cm with a tolerance of ±1 cm, although smaller samples were required for subsequent thermal testing purposes. All samples were cut along X-Y-Z directions, creating two samples per plane for 66 samples, as seen in Figure 1, in favour of investigating the effect of irregularities and inhomogeneities on the thermal properties. A wet grinder was used to create a smooth surface along the cutting edges to help the MTPS sensor fit as accurately as possible during measurements.

a) b)

Figure 1 a) Creating of different planes of samples and b) all samples of different masonry bricks

2.2 *Methods*

2.2.1 *Physical characterization*

Prior to commencing measurements at 10 °C and 10% relative humidity, the samples were dried in accordance with MSZ EN ISO 12570 [15], a standardized procedure for determining the moisture content of building materials.

Initially, the samples were prepared and weighed to determine their initial mass. Ensuring that the samples were representative of the material and appropriately sized for testing was critical. The samples were then placed in a drying oven set to a specified elevated temperature, typically around 105 °C, which is chosen to effectively remove moisture without causing thermal degradation of the material. The samples were dried until they reached a constant mass, defined as a mass change of less than 0.1% over 24 hours.

The samples were periodically removed from the oven and weighed throughout the drying process. This drying and weighing cycle continued until the mass of the samples stabilized, indicating the complete evaporation of moisture. The drying process took approximately one week, after which the final density of the dried samples was calculated based on the geometry and weight of the samples. A calliper with an accuracy of 10^{-2} mm and a precision balance with an accuracy of 10^{-2} g were used to determine the dry bulk density.

2.2.2 *Thermal characterization*

In this study, the fast and accurate transient plane source technique was employed using the ISOMET 2114 device to measure the thermal properties of materials. The principle of this method involves increasing the temperature of the material with a small constant current, where the temperature rise is dependent on the material's thermal transport properties. The transient thermal properties measured include thermal diffusivity, equivalent thermal conductivity, and volumetric heat capacity. The measurements were conducted under controlled conditions of 10 °C and 10% relative humidity (RH) in a climatic chamber. Each sample underwent two measurements to ensure accuracy, with the average values being reported. In total, 132 measurements were completed, averaging approximately six measurements per day over two months. By monitoring temperature increase over a short period after the start of the experiment, it is possible to obtain the equivalent thermal conductivity, and the thermal diffusivity expressed in Eq.1.

$$\alpha = \frac{\lambda}{\rho c_p} \left[\frac{m^2}{s}\right] \quad (1)$$

In this relation, λ [W/mK], c_p [J/kgK] and ρc_p [J/m^{3}K] are, respectively, the equivalent thermal conductivity, the specific heat and the volumetric heat capacity. They depend on the moisture content in the material.

a) b) c)

Figure 3 Tools of thermal characterization: a) MTPS probe, b) climatic chamber and c) sensor installation

2.3 *Steady state coupled heat and moisture simulation*

In this paper, detailed finite element method (FEM)-based steady-state thermal and coupled heat and moisture transfer (HAM) simulations were performed using COMSOL Multiphysics 6.1 following MSZ EN 15026 [16]. The study assessed and compared the thermal and moisture transmittance and temperature factors of the wall-slab connection of the Horcsik slab, incorporating the effects of thermal bridges through linear thermal and moisture transmittance evaluations. In Hungary, the Horcsik slab, internationally referred to as the Kleine slab, was among the five most widely used historical slabs that became prevalent in the 1930s. This system featured a ribbed design with brick inserts integrated into a reinforced concrete slab, supported by steel beams. Material properties were determined using MSZ EN ISO 10456 [17] and the WUFI PRO 6.6 database [18]. Additionally, the masonry elements' thermal conductivity, specific heat capacity, and density were derived from laboratory measurement results.

The slab's Geometric models (seen in Figure 4) were created in AutoCAD 2023 and exported to COMSOL Multiphysics 6.1.

Local weather data for moisture transport boundary conditions were based on ÉKM 9/2023 decree. Internal air conditions and equivalent vapour diffusion thicknesses of boundary layers were set according to MSZ EN 15026 [16]. The calculation methodology followed MSZ EN ISO 10211 [19].

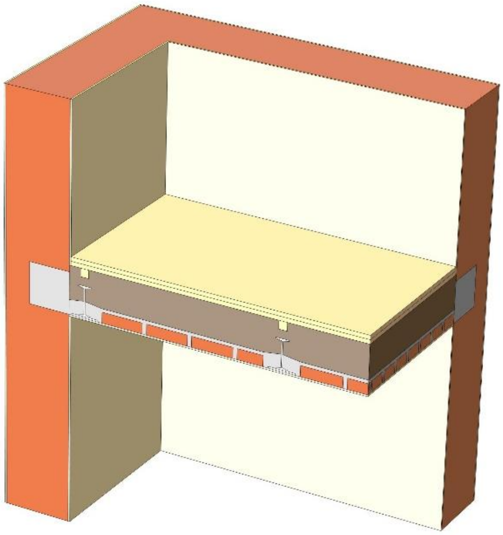


Figure 4 2-way wall-slab corner connection of Horcsik slab in COMSOL Multiphysics 6.1

The χ point thermal transmittance for the structural design was calculated using the provided equation (Eq.2), considering L_{3D} for the junction, U_i for wall surfaces, and Ψ_j for linear thermal transmittances along connections.

$$\chi = L_{3D} - \sum_{i=1}^{N_i} U_i * A_i - \sum_{j=1}^{N_i} \Psi_j * l_j \;\; [\frac{W}{K}] \tag{2}$$

The temperature factor (f_{Rsi}) was used to assess structural durability and hygrothermal performance, verifying that designs with values below 0.7 (DIN 4108-2 [20]) are inadequate and at risk of mould growth. The temperature factor is calculated according to MSZ EN ISO 10211 [19], as seen in Eq.3.

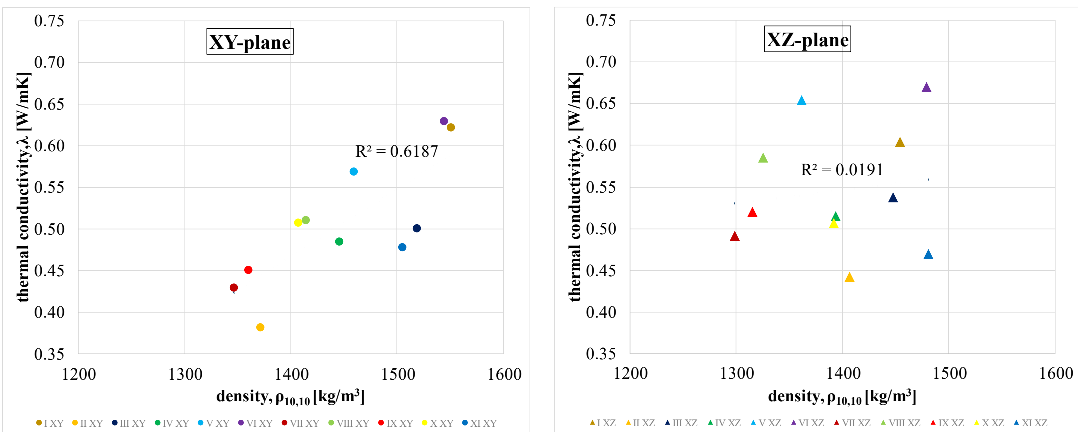
$$f_{Rsi} = \frac{T_{s,min} - T_e}{T_{i-}T_e} \;\; [-] \tag{3}$$

3. RESULTS AND DISCUSSION

3.1 *Thermal conductivity in the function of density (at 10 °C and 10% RH)*

The investigation into the relationship between density and thermal conductivity across various directions for diverse brick types yielded notable insights. Figure 5 shows thermal conductivity values ranging from 0.3518 to 0.7106 W/mK, corresponding closely with literature data, while densities varied between 1235 and 1551 kg/m³. In the XY-plane, a pronounced positive correlation was observed ($R^2 = 0.6187$), indicating that higher densities generally correspond to increased thermal conductivity. Conversely, in the XZ-and YZ- planes, the R^2 value is very low and cannot be interpreted within a scientific framework. Aggregating average values per brick type improved the correlation somewhat ($R^2 = 0.2723$), indicating a general trend of rising thermal conductivity with density across different brick types.

These findings underscore the importance of detailed compositional analysis in comprehensively understanding the factors influencing thermal conductivity. Historic masonry bricks often exhibit material heterogeneity due to variations in raw materials, manufacturing techniques, and environmental exposure over time, leading to non-uniform density distributions that affect their thermal properties along different planes (XY, XZ, YZ). These bricks also exhibit anisotropic properties, with thermal conductivities and specific heats varying depending on the measurement direction relative to the brick's orientation, influenced by grain orientation, pore alignment, and structural layers. Additionally, the construction orientation of bricks—whether laid horizontally (XY-plane) or vertically (XZ-or YZ-planes)-can impact their thermal properties due to heat flux and moisture exposure differences.



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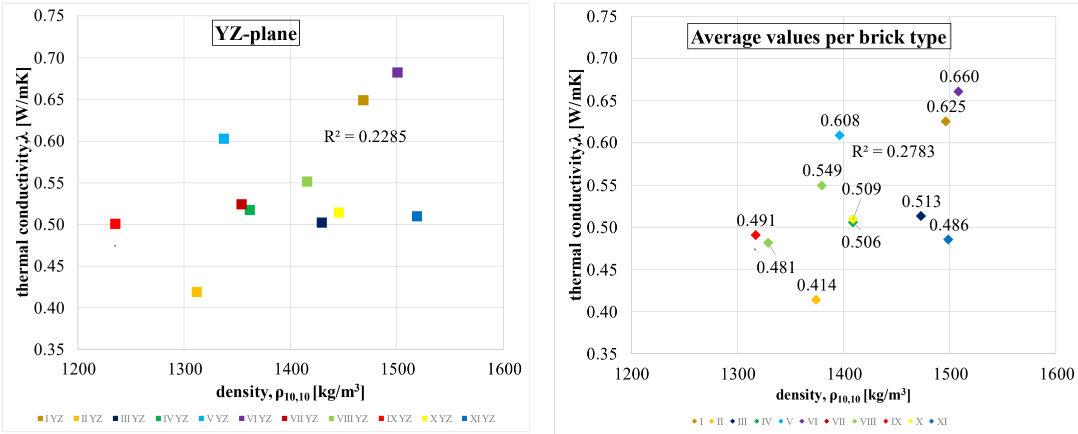
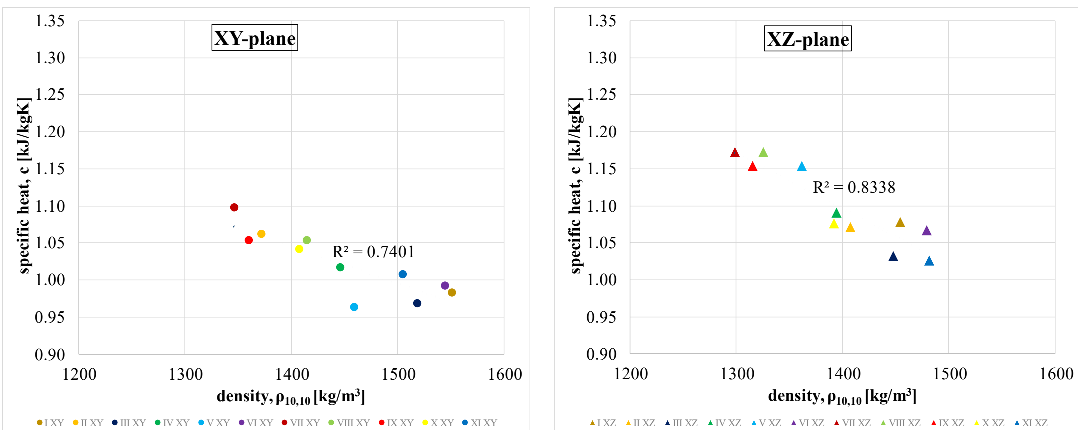


c) d)

Figure 5 Results of thermal conductivity values in function of density: a) XY-plane, b) XZ-plane, c) YZ-plane and d) average values based on all measurements

3.2 *Specific heat in the function of density (at 10 °C and 10% RH)*

The results depicted in Figure 6 highlight a strong correlation between specific heat and density across multiple directions (XY, XZ, YZ), with coefficient of determination (R^2) values consistently ranging from 0.74 to 0.83. The obtained R^2 coefficient range indicates a robust relationship between specific heat and density irrespective of orientation. Interestingly, correlations were marginally weaker in the XY direction than in the XZ and YZ directions, suggesting potential variations in specific heat capacity along the horizontal plane. Specific heat values ranged from 0.941 to 1.284 kJ/kgK, falling within anticipated ranges from existing literature. The study also emphasized the significant influence of moisture content on specific heat measurements, highlighting the importance of environmental conditions in thermal property assessments of historical bricks. Environmental conditions such as moisture content, temperature fluctuations, and exposure to weathering over time can influence the microstructure and, thus, the thermal properties of historic masonry bricks. These factors also can lead to directional variations in specific heat and thermal conductivity.



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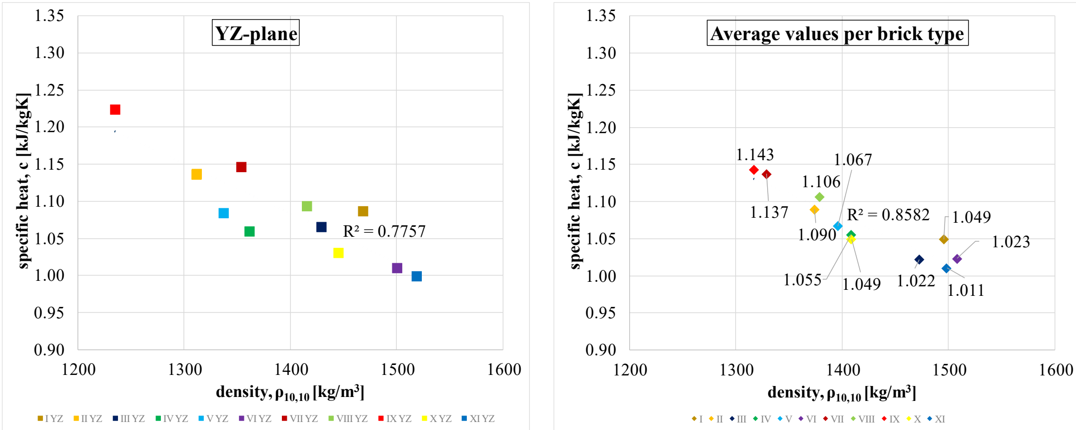
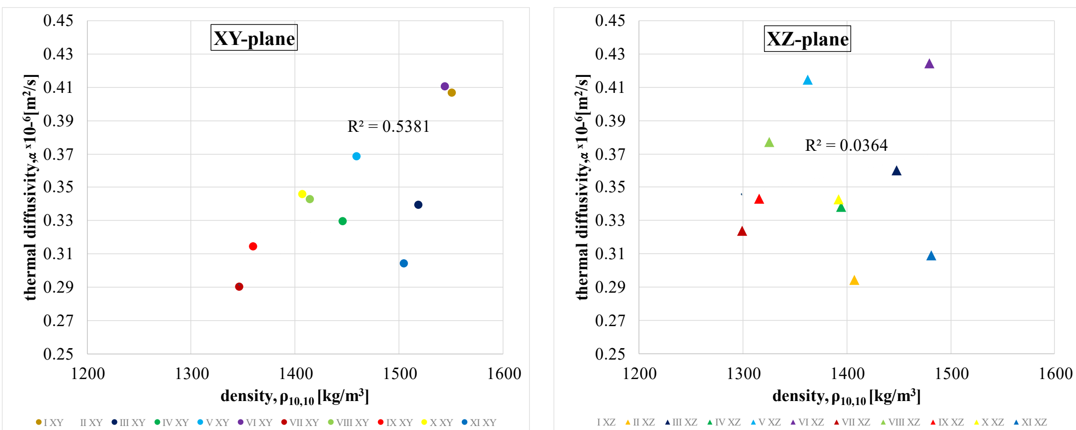


c) d)

Figure 6 Results of specific heat in the function of density: a) XY-plane, b) XZ-plane, c) YZ-plane and d) average values based on all measurements

3.3 *Thermal diffusivity in function of density (at 10 °C and 10% RH)*

Figure 7 reveals a moderate correlation between thermal diffusivity and density across different directions (XY, XZ, YZ) of historic masonry bricks, with R^2 values exceeding 0.5 in the XY direction. The obtained R^2 coefficients indicate a stronger relationship between thermal diffusivity and density when measured horizontally compared to other orientations. In the other directions, the R^2 value cannot be interpreted, thus further measurements and investigations are necessary to explore the correlations. The range of thermal diffusivity values, from 0.248 to 0.469 x 10^{-6} m²/s, remained consistent across all directions, indicating uniformity in the bricks' thermal transport properties regardless of orientation. It is important to highlight variations in measurement techniques and equipment sensitivity, which can contribute to slight discrepancies in the recorded thermal properties. Different methods to determine thermal conductivity, specific heat, and thermal diffusivity may yield results that vary slightly depending on the measurement direction.



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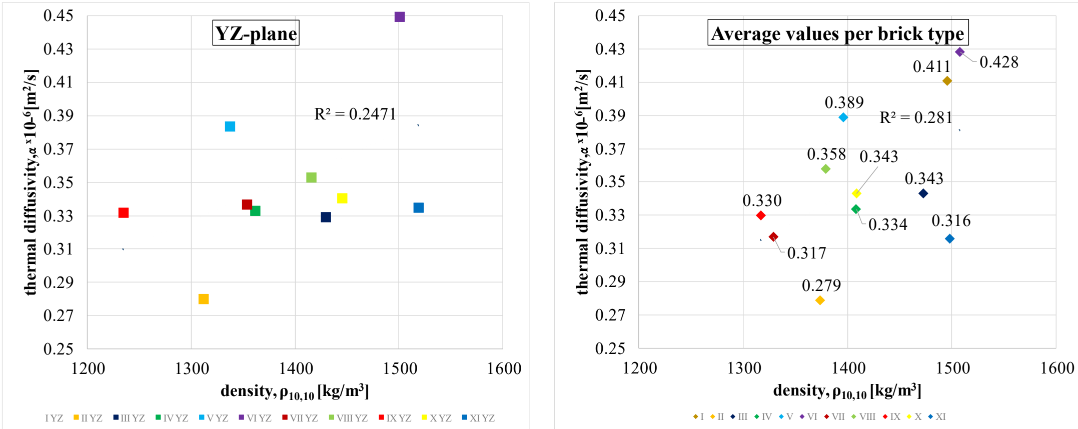

c) d)

Figure 7 Results of thermal diffusivity in the function of density: a) XY-plane, b) XZ-plane, c) YZ-plane and d) average values based on all measurements

3.4 *Implementing measured thermal properties in COMSOL Multiphysics*

The findings from evaluating thermal properties such as thermal conductivity, density, and specific heat capacity of historical masonry bricks are crucial for their accurate representation in COMSOL Multiphysics simulations. Implementing the minimum and maximum values of thermal conductivity allows for a comprehensive assessment of hygrothermal performance of these structures. The evaluation of the results of Table 2 reveals significant variations between simulations using laboratory measures and standardized thermal properties.

Thermal conductivity ranges from 0.350 W/mK to 0.710 W/mK, with percentage differences reaching up to 56%. This wide disparity indicates substantial variability in heat transfer characteristics, which is crucial for accurately modelling building performance. Similarly, U-values ranges from 0.740 W/m²K to 1.450 W/m²K, with differences up to 49%, highlighting considerable variability in heat loss calculations. Linear thermal transmittances also exhibit notable differences, particularly in perpendicular orientations (Ψ_{par}), where values range from 0.438 W/mK to 0.644 W/mK, varying by up to 55%. The point thermal transmittance values show substantial differences, respectively. The laboratory minimum value is significantly lower, by 79%, while the maximum value is even lower, by 86%, suggesting even better insulation properties. This discrepancy highlights the conservative nature of the simulated results using standardized data, which likely aim to ensure safety by overestimating potential heat loss. The temperature factor, f_{Rsi}, is crucial for assessing the risk of mould growth. Since 0.629 is lower than the threshold value for mould growth, simulation results using the standardized properties leads to nonconformity, while measured values are above 0.7. The laboratory minimum value shows a 28% increase, reaching 0.806, while the maximum value shows a 17% increase at 0.738, compared to the baseline using the standard data.

	MSZ EN ISO 10456	***lab. meas. minimum***	***abs. difference [%]***	***lab. meas. maximum***	***abs. difference [%]***
λ [W/mK]	0.800	0.350	56%	0.710	11%
U [W/m²K]	1.450	0.740	49%	1.290	11%
Ψ_{par} ***[W/mK]***	0.580	0.363	37%	0.260	55%
Ψ_{perp} ***[W/mK]***	0.593	0.644	9%	0.438	26%
χ [W/K]	0.495	0.105	79%	0.067	86%
f_{Rsi} ***[-]***	0.629	0.806	28%	0.738	17%

Table 2 Difference between simulation results based on standard and lab-measured thermal properties

Figure 8 compares temperature distribution and relative humidity in a 2-way wall-slab corner connection of Horcsik-slab with standard thermal conductivity values (left) and laboratory-measured values (right). Temperatures range from 0 °C to 20 °C. The laboratory-measured simulation shows improved thermal performance, with less pronounced gradients and warmer edges, indicating reduced heat loss and better insulation. Relative humidity ranges from 0.4 to 0.8, with higher levels (0.7-0.8) concentrated at the bottom corners and edges. The laboratory measurements yielded a more uniform humidity distribution, suggesting better moisture control and reduced mould risk, enhancing structural integrity.

Case studies utilizing these extreme values illustrate significant differences in simulation outcomes, highlighting the impact of varying material properties on thermal behaviour predictions. Notably, standard values often used for safety reasons may tend to overestimate thermal conductivity, potentially affecting simulation accuracy. Moreover, considering the temperature factor, where values under 0.7 can promote mould growth, underscores the importance of precise material characterization to mitigate potential environmental impacts. Integrating these findings into simulation models enhances their predictive capability and informs practical conservation strategies aimed at preserving historical masonry structures while optimizing their thermal performance and environmental sustainability.

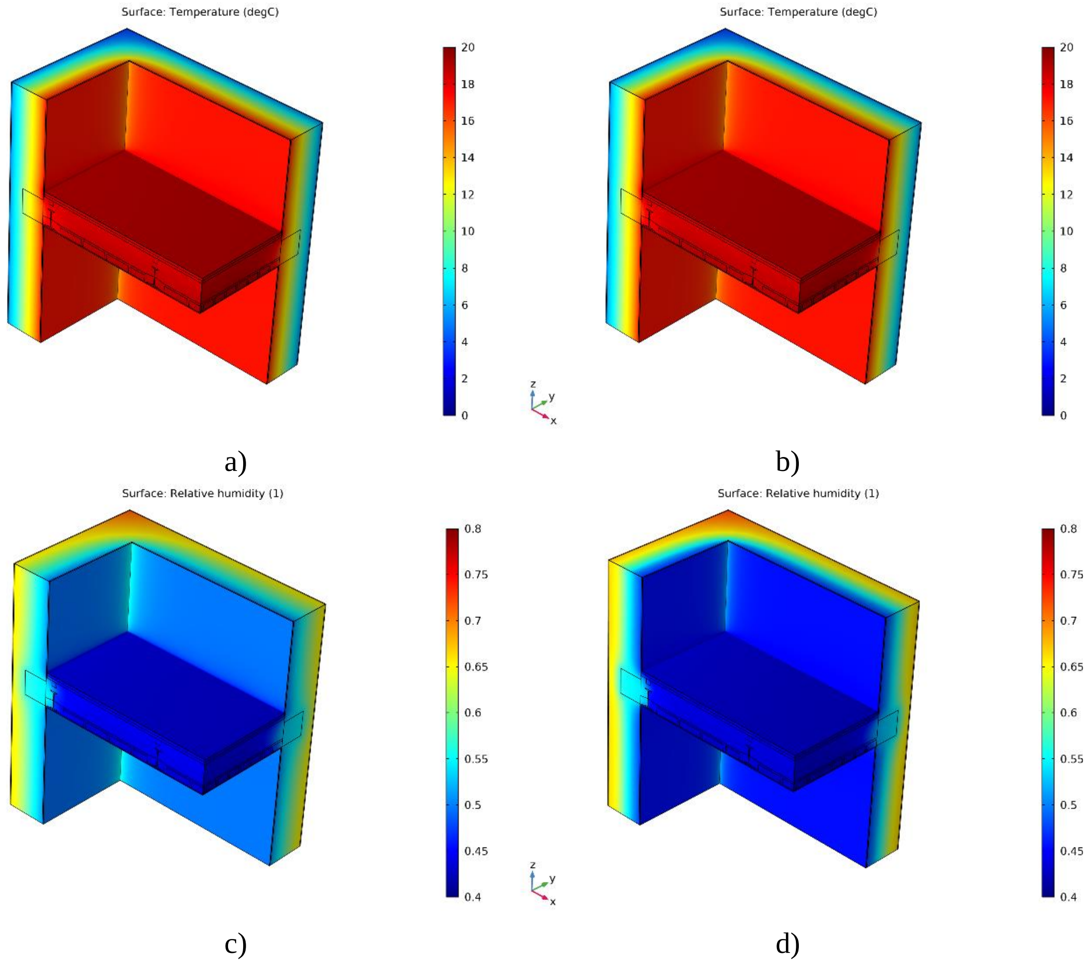

Figure 8 Temperature distribution and relative humidity 2-way wall-slab corner connection of Horcsik-slab a) temperature distribution using standard material properties, b) temperature distribution using laboratory measured material properties, c) relative humidity distribution using standard material properties, d) relative humidity distribution using laboratory measured material properties

4. CONCLUSION

This study examines the hygrothermal properties of eleven types of historical masonry bricks to address existing material gaps and enhance thermal and moisture performance modelling in buildings. The results support typology-based hygrothermal modelling of historical buildings through dynamic simulation analysis by providing a comprehensive database of these properties. The study reveals a significant deviation in results based on the material type and measurement direction, indicating the need for further research.

The results of the selected case study reveal significant discrepancies between the minimum and maximum thermal conductivity obtained from laboratory measurements and those derived from simulations using standardized material properties. Standard values tend to overestimate thermal conductivity by almost 56%, resulting in higher temperature gradients and potentially overestimating heat loss. While this "in favour of safety" approach ensures caution, it may not accurately reflect thermal performance. Using laboratory measurements provides a more accurate representation, leading to potentially more efficient and effective thermal management strategies.

Future research tasks include conducting a detailed composition analysis of the bricks, extending the investigation to additional hygrothermal properties such as vapour diffusion resistance, water absorption, liquid transport coefficient, and sorption and desorption isotherms, continuing measurements under varying conditions of temperature and relative humidity, utilizing other laboratory measurement methods to verify findings, such as density and thermal conductivity, and exploring reconstruction and energy efficiency renovation options for historical buildings. By expanding the scope of research and employing diverse methodologies, the study aims to develop a more robust understanding of the hygrothermal behaviour of historical masonry bricks, thereby aiding in the preservation and energy-efficient renovation of historic structures.

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REFERENCES

[1] **D. Badik-Szabó**, "A Proposal for Utilization of Vaults as Floor-slab Structures in Contemporary Architecture," *YBL J. Built Environ.*, vol. 9, no. 1, pp. 141–151, Jun. 2024, doi: 10.2478/JBE-2024-0014.

[2] **P. Kronavetter**, "A magyarországi téglagyárak építészeti öröksége," 2023, Accessed: Jul. 11, 2024. [Online]. Available: https://www.kozep.bme.hu/storage/uploads/99dbc3fc-359a-4db2-90d7-0bdbc4949614/1691-kronavetter_p_ertekezes.pdf.

[3] **J. Sýkora, M. Šejnoha, and J. Šejnoha**, "Homogenization of coupled heat and moisture transport in masonry structures including interfaces," *Appl. Math. Comput.*, vol. 219, no. 13, pp. 7275–7285, Mar. 2013, doi: 10.1016/J.AMC.2011.02.050.

[4] **K. Abahri, R. Belarbi, and A. Trabelsi**, "Contribution to analytical and numerical study of combined heat and moisture transfers in porous building materials," *Build. Environ.*, vol. 46, no. 7, pp. 1354–1360, Jul. 2011, doi: 10.1016/J.BUILDENV.2010.12.020.

[5] **J. Sýkora, J. Vorel, T. Krejčí, M. Šejnoha, and J. Šejnoha**, "Analysis of coupled heat and moisture transfer in masonry structures0," *Mater. Struct.*, vol. 42, no. 8, pp. 1153–1167, 2009.

[6] **P. Pihelo, M. Lelumees, and T. Kalamees**, "Influence of Moisture Dry-out on Hygrothermal Performance of Prefabricated Modular Renovation Elements," *Energy Procedia*, vol. 96, pp. 745–755, Sep. 2016, doi: 10.1016/J.EGYPRO.2016.09.137.

[7] **M. Ibrahim, E. Wurtz, P. H. Biwole, P. Achard, and H. Sallee**, "Hygrothermal performance of exterior walls covered with aerogel-based insulating rendering," *Energy Build.*, vol. 84, pp. 241–251, Dec. 2014, doi: 10.1016/J.ENBUILD.2014.07.039.

[8] **T. Colinart, D. Lelievre, and P. Glouannec**, “Experimental and numerical analysis of the transient hygrothermal behavior of multilayered hemp concrete wall,” *Energy Build.*, vol. 112, pp. 1–11, Jan. 2016, doi: 10.1016/J.ENBUILD.2015.11.027.

[9] **R. McClung, H. Ge, J. Straube, and J. Wang**, “Hygrothermal performance of cross-laminated timber wall assemblies with built-in moisture: field measurements and simulations,” *Build. Environ.*, vol. 71, pp. 95–110, Jan. 2014, doi: 10.1016/J.BUILDENV.2013.09.008.

[10] **P. Pihelo, H. Kikkas, and T. Kalamees**, “Hygrothermal Performance of Highly Insulated Timber-frame External Wall,” *Energy Procedia*, vol. 96, pp. 685–695, Sep. 2016, doi: 10.1016/J.EGYPRO.2016.09.128.

[11] **G. G. Akkurt** *et al.*, “Dynamic thermal and hygrometric simulation of historical buildings: Critical factors and possible solutions,” *Renew. Sustain. Energy Rev.*, vol. 118, p. 109509, Feb. 2020, doi: 10.1016/J.RSER.2019.109509.

[12] **Z. Pavlík, T. Kulovaná, J. Žumár, M. Pavlíková, and R. Černý**, “Experimental analysis of material properties of historical ceramic bricks and their potential current replacements,” *Struct. Stud. Repairs Maint. Herit. Archit. XIV*, vol. 1, pp. 327–335, Jul. 2015, doi: 10.2495/STR150271.

[13] **Y. Aït Oumeziane, A. Pierre, F. El Mankibi, V. Lepiller, M. Gasnier, and P. Désévaux**, “Hygrothermal properties of an early 20th century clay brick from eastern France: Experimental characterization and numerical modelling,” *Constr. Build. Mater.*, vol. 273, p. 121763, Mar. 2021, doi: 10.1016/J.CONBUILDMAT.2020.121763.

[14] **E. Çam and E. Uğurlu Sağın**, “Characteristics and Production Technologies of Byzantine Building Bricks from the Anaia Church in Western Anatolia,” *Clays Clay Miner.*, vol. 71, no. 4, pp. 397–415, Aug. 2023, doi: 10.1007/S42860-023-00247-3/TABLES/9.

[15] MSZ EN ISO 12570:2000, “Hygrothermal performance of building materials and products. Determination of moisture content by drying at elevated temperature (ISO 12570:2000),” *Hungarian Stand. Inst.*, 2000.

[16] MSZ EN 15026:2023, “Hygrothermal performance of building components and building elements. Assessment of moisture transfer by numerical simulation,” *Hungarian Stand. Inst.*, 2023.

[17] MSZ EN ISO 10456:2008, “Building materials and products. Hygrothermal properties. Tabulated design values and procedures for determining declared and design thermal values (ISO 10456:2007),” *Hungarian Stand. Inst.*, 2008.

[18] Fraunhofer IBP, “WUFI PRO 6.6 [computer program].” Accessed: Oct. 24, 2022. [Online]. Available: https://wufi.de/en/2022/06/29/release-wufi-pro-6-6-and-wufi-2d-4-4/.

[19] MSZ EN ISO 10211:2017, “Thermal bridges in building construction. Heat flows and surface temperatures. Detailed calculations (ISO 10211:2017),” *Hungarian Stand. Inst.*, 2017.

[20] DIN 4108-2:2013-02, “Thermal protection and energy economy in buildings - Part 2: Minimum requirements to thermal insulation,” *Ger. Stand. Inst.*, 2013.