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Exploring the variability of hygrothermal material properties in historic bricks in London

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Abstract: In the UK, a large number of traditional buildings are made of solid brick walls. If appropriate retrofit measures are taken, these buildings can contribute to achieving the UK Government's pledge to reduce greenhouse gas emissions. The vast majority of solid brick buildings in London are non-insulated. Adding internal wall insulation is one possible energy retrofit measure, however, the insulation layer can alter the moisture balance of the wall. Since the hygrothermal properties of the existing building materials can influence the moisture balance of the wall considerably, identifying the wall type and understanding its hygrothermal properties is extremely important in building retrofit. The objective of this study is to explore the variability of the hygrothermal properties of different bricks from one wall located in London. Several brick samples are selected from one case study wall in London. The hygrothermal properties of 21 historic bricks were measured, including the absorption coefficient, bulk density, drying coefficient, water content at capillary saturation to determine the variability. The experimental results show variability of some material properties, particularly the absorption coefficient. This can potentially have significant implications for solid wall retrofit and material property characterization.

1 Introduction

The building sector is one of the biggest contributors to global energy consumption and greenhouse gas emissions [1]. According to statistics, building energy consumption accounts for about 25% of total global energy consumption, and building carbon emissions account for around 30% of global carbon emissions [2, 3]. In the UK, the number of newly constructed buildings each year is small. For instance, in 2022, new buildings were less than 1% of the existing building stock [4]. A large number of existing buildings are made of brick and stone, many of which feature solid walls [5]. These buildings which have poor energy performance were responsible for nearly 30% of housing stock energy consumption and 36% of carbon emissions in the UK [6]. Retrofitting them, therefore, has a high potential for building stock performance improvement, and can also considerably contribute to achieving UK Government's pledge on reducing greenhouse gas emissions by 100% before 2050.

According to the Energy Saving Trust, the walls of dwellings are responsible for a third of its heat loss [7]. Nearly 91% of solid wall homes were without insulation at the end of 2021 [8] and the vast majority of solid wall buildings in London (approximately 1.5 million) are uninsulated [9]. Adding thermal insulation is one of the most effective methods for solid wall building energy retrofit [10]. However, the insulation layer will affect the movement of internal water and air to change the moisture balance of the wall. Excessive moisture content can lead to the deterioration and degradation of building materials, which can negatively affect building energy efficiency [11]. Consequently, evaluating the thermal and moisture performance of historic solid buildings is one the most significant steps in building energy retrofit.

Performing hygrothermal simulations is one of the most practical methods for understanding moisture transfer mechanisms, which can be used to assess moisture performance in historic solid wall buildings [12]. Simulations consider different parameters of building components, such as hygrothermal material properties and boundary conditions, under various heat and moisture loads, and provide moisture content and moisture flux distribution in the wall as output. Nevertheless, an important limitation of hygrothermal simulations is the lack of data on existing construction material properties including bulk density, absorption coefficient, drying coefficient, water content at capillary saturation, porosity, water vapor diffusion, etc. [13]. These properties play an important role on moisture transfer in the wall layers. For instance, a high absorption coefficient is associated with higher levels of rainwater absorption and can result in higher moisture risk on wall insulation. Although some currently available databases are associated with modern building material properties, there is a limited amount of measured data about material properties in historical solid brick buildings. Moreover, a great number of historic solid buildings used handmade bricks, unlike most modern buildings, which apply manufacturing production techniques. It is hypothesized that manual production leads to high variability of hygrothermal material properties [14]. In addition, the wall materials can change over time due to external climate exposure and internal occupancy activities, which can affect the wall hygrothermal performance over time. Even for the same wall in one building, their material parameters will be different to a certain extent, which means that it is necessary to understand the variability of hygrothermal material properties in historic solid brick buildings in order to reach a reliable risk assessment.

This study aims to explore the variability of the hygrothermal material properties of different bricks from one wall located in London. It is envisaged to be the first step towards developing a methodological framework for the assessment of hygrothermal properties in historic buildings, which can inform and facilitate historic solid wall building energy retrofit decisions.

2 Methodology

2.1 Tested Samples

In the study, the variability of material properties was evaluated for the 21 brick samples shown in Figure 1. Fourhygric material properties were measured: bulk density, absorption coefficient drying coefficient and water content at capillary saturation. These bricks are handmade and were collected from one wall located in London. Although they are from the same wall, their texture, shape and size can vary.

Figure 1 Brick samples

2.2 Bulk Density

Bulk density measurements were performed according to BS EN 772-4:1998 [15]. The brick specimens were dried in the oven until the loss in mass between two determinations was less than 0.1% of the mass to measure the dry mass of the specimens ($m_{dry,s}$) and these specimens then were submerged in water at 25 °C for 24 hours and weighed again to obtain the mass at capillary saturation ($m_{sat,s}$). Also, the apparent mass under water ($m_{w,s}$) was measured with a balance connected to the submerged bricks by means of an aluminium frame.

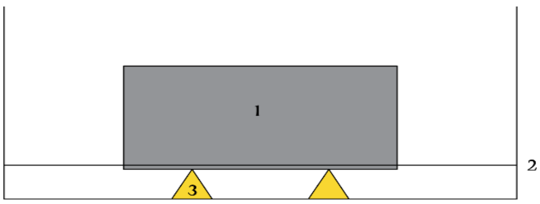
The expression (1) takes into account the bulk density (kg/m^3) of specimens:

$$\rho_{b,s} = \frac{m_{dry,s} \times \rho_w \times 1000}{m_{sat,s} - m_{w,s}} \quad (1)$$

where ρ_w is the density of water (kg/m^3)

2.3 Absorption Coefficient

The water absorption coefficient was estimated based on BS EN ISO 15148:2002 [16]. Firstly, these sealed specimens were placed under environmental conditions with 23±5°C and 50±5% RH until the mass of each specimen stabilised to within 0.1% of its total mass and measured their initial mass (m_i). Then four supports as shown in Figure 2 were introduced in a container with an even bottom and water was injected into the container until the water level which was around 3±2mm was above the supporters. The water level should remain constant throughout the experiment. Later, the sealed bricks were put into the container one by one, immersing their exposed surfaces in water. The brick specimens needed to be taken out quickly every 3, 5, 10, 20, 30 and 60 minutes to record the mass (m_t) corresponding to its time point. After measurement they were put back into the container immediately. Last, the area of exposed surface (A) of each specimen should be calculated.



Note: 1 – Brick Sample 2 – Water level 3 – Supports

Figure 2 Experiment apparatus

The equation (2) for the difference between the mass (kg) at each weighing time and the initial mass (kg) per area calculation could be expressed as follows:

$$\Delta m_t = (m_t - m_i)/A \qquad (2)$$

The absorption coefficient A_w (kg/m^2·s$^{1/2}$) calculation equation (3) is as follows:

$$A_w = \frac{\Delta m_{tf} - \Delta m_0}{\sqrt{t_f}} \qquad (3)$$

Where t (s) is the square root of the weighing time $\sqrt{t}$; Δm_{tf} (kg/m^3) is the value of Δm on the straight line at time t_f; t_f (s) is the period of the experiment; Δm_0 is the line back to zero where it cuts the vertical axis.

2.4 Drying Coefficient

The process of determining drying behaviour was carried out according to BS EN 16322:2013 [17]. The 21 brick specimens were immersed in water to be saturated until the difference between two successive weight measurements at an interval of 24h was less than 0.1% of mass of the specimens. Then these specimens were sealed except from the top. The initial mass of specimens was recorded as (m_{max}). After that, prepared specimens were taken into a climate chamber at 23±1°C and 50±3% RH and measured at time intervals defined in BS EN 16322:2013 [17]. The drying process typically included two phases in Figure 3. The first drying phase was distinguished by a linear weight loss through time because the loss of mass was defined by evaporation from a film on the surface, which was maintained by capillary transport from high moisture content inside. The second phase was characterized by slower change of water content due to vapor diffusion with lower water content inside, which was depended on the material properties of the specimens [18].

The drying index can be obtained through equation (4):

$$M_i = (m_i - m_f)/A \qquad (4)$$

Where m_i (kg) is the mass of the specimen at time t_i. m_f (kg) is final mass of the specimen at t_f.

The calculation equation for drying coefficient (h$^{1/2}$/m) could be expressed [19]:

$$\mathrm{D} = \frac{\sqrt{t_{d,2nd}}}{h} \qquad (5)$$

Where $t_{d,2nd}$ (h) is the time of the duration of the second phase. h (m) is the height of the specimen.

2.5 Water content at capillary saturation

Water capillary moisture content can be derived from absorption coefficient experiment. Then 21 samples were submerged in water for more than 24 hours until the sample mass remained unchanged and reached capillary saturation to get $m_{sat,s}$. Comparing $m_{sat,s}$ with $m_{dry,s}$ can get the mass of water stored in the sample, and finally get θ_{cap} to see the water storage capacity of each sample.

The water content at capillary saturation θ_{cap}(kg/m^3) can be calculated with equation (6)

$$\theta_{cap} = \frac{m_{sat,s} - m_{dry,s}}{V} \qquad (6)$$

Where V (m^3) is the volume of the specimen.

3 Result and Discussion

The calculation results of bulk density and absorption coefficient are presented in histograms in Figure 3-4. The values of different material properties are showing obvious distribution and absorption coefficient has a more dispersive distribution.

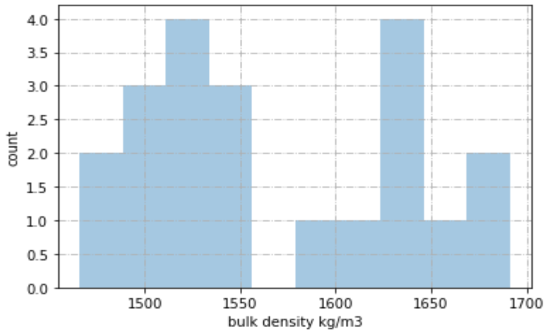


Figure 3 Bulk density results

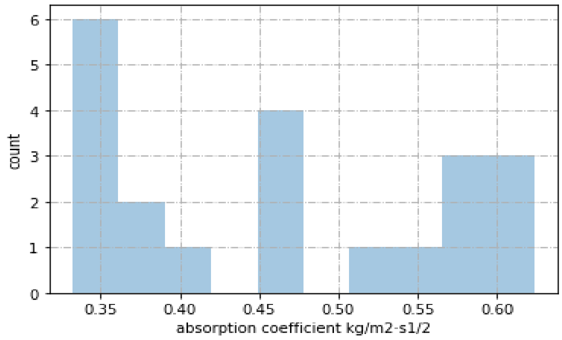


Figure 4 Absorption coefficient results

Figure 5 shows the drying process of specimens. The two phases can be identified according to the drying curve and then the time duration of the second phase can be obtained to calculate the drying coefficient, presented in Figure 6. And the Figure 7 shows water content at capillary saturation results.

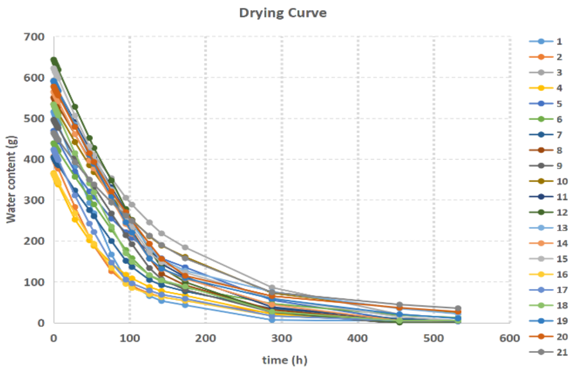


Figure 5 Drying curves

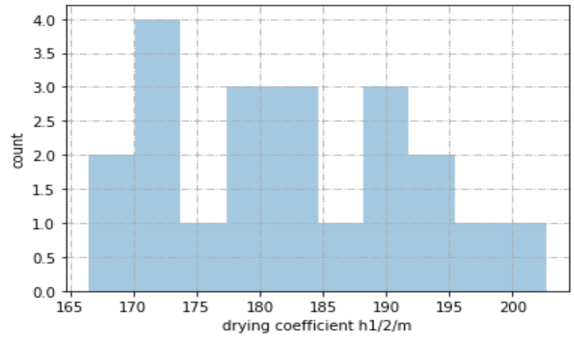


Figure 6 Drying coefficient results

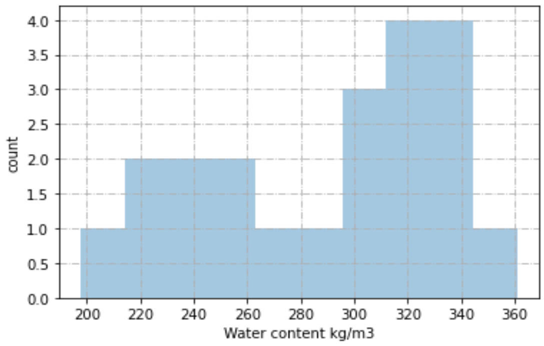


Figure 7 Water content results

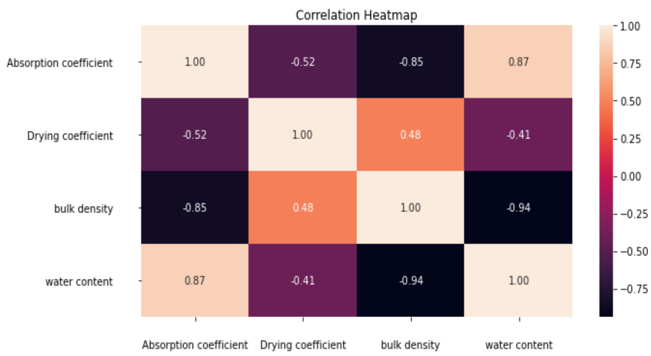


Figure 8 Material property correlation heatmap

In order to better understand the variations, Mean value, SD (Standard Deviation), CV (Coefficient of Variation), Min value to Max range that can see the whole value range are calculated in Table 1. The CV and Min to Max range of the absorption coefficient are much higher than the other -three properties, indicating that the data of the absorption coefficient is not only more scattered relative to the average

[20] but also has a larger range of values. As a result, the absorption coefficient of historic handmade brick can be more variable compared with bulk density drying coefficient and water content at capillary saturation. This could be the result of variations at different stages of the manufacturing process. The density is linked to the milling process, which removes air from the clay. This has a direct influence on the pore structure [21], although this is also strongly influenced by the firing process. For example, clamp-fired bricks are known to be more variable than kiln-fired bricks. Furthermore, compared with a pilot study on material database in Germany that collected brick samples from one specific building [22], it can be seen that the distribution of the same property tested in this study for hand-made bricks in the UK is larger (see Table 1). Particularly, regarding the absorption coefficient, the SD, CV, Min to Max value range of brick specimens from UK are all much larger than the brick specimens collected in Germany. Furthermore, in the Delphin material database, the range of bulk density for the "old building brick" category is from 1469.3 kg/m^3 to 2048.8 kg/m^3, and the range of absorption coefficient is from 0.006 kg/m^2 s$^{1/2}$ to 0.489 kg/m^2 s$^{1/2}$. In summary, results for most samples are within the range found in the Delphin database [23], although the results suggest high variability in material properties for the UK building under analysis. Future efforts should be focused on investigating the variability of water absorption for a larger number of traditional brick clusters and assessing its impact on the moisture balance of traditional walls. In addition, a correlation heatmap is used to analyse the connection between different properties in Figure 8. The absorption coefficient shows a strong negative correlation with bulk density, as does bulk density with water content at capillary saturation. Conversely, there is a strong positive correlation between water content at capillary saturation and the absorption coefficient. The drying coefficient has a moderate correlation with other three properties. Consequently, it can be acknowledged that the lower bulk density can lead to greater the absorption coefficient and higher water storage abilities of samples.

Table 1 Material properties variability: comparison of material properties with data from one building in Germany

	Bulk density	Absorption coefficient	Drying coefficient	Water content at capillary saturation	Bulk density in literature [22]	Absorption coefficient in literature [22]
	kg/m^3	kg/m^2·s$^{1/2}$	h$^{1/2}$/m	kg/m^3	kg/m^3	kg/m^2·s$^{1/2}$
Mean	1570.67	0.4644	182.30	291.25	1952.2	0.142
SD	69.10	0.1026	10.06	47.16	21	0.016
CV	4.39%	22.09%	5.50%	16.19%	1.08%	11.27%
Min	1466.18	0.3322	166.52	197.83	1871.0	0.111
Max	1691.26	0.6238	202.65	360.91	1979.8	0.160
Min-Max range	15%	87.8%	21.69%	82.43%	5.8%	44.1%

Firstly, this result shows that there is a certain variability on the material properties of handmade bricks and the variability will be different across different properties. It is impossible to measure the properties of every brick in a building that needs to be retrofitted; therefore, simulations need to consider the variability of handmade bricks. The results of this study can have significant implications for historic solid brick wall retrofit. If the variability is well characterized, techniques such as Monte-Carlo simulation could be adopted to improve the understanding moisture risks in walls built from inherently variable masonry. Secondly, information on hygrothermal properties for building materials is currently missing in the UK. This study can be a starting point for the characterization of material properties in historic buildings in the UK by providing representative material data for the London building stock. In addition, the results will contribute to filling the gap towards a better understanding of moisture risks during retrofit, and enable a moisture-safe reduction of greenhouse gas emissions in solid wall buildings.

4 Conclusion

This study collected 21 brick specimens from one wall located in London to evaluate the variability of hygrothermal properties in historic bricks through testing four material properties. The results include distributions of four material properties. It was found that the absorption coefficient had the highest variability for the analysed handmade bricks, followed by the water content at capillary saturation, suggesting that paying attention to such properties can improve the accuracy of hygrothermal simulations. These results can be a good starting point for characterising solid wall buildings in London and contributing to decision-making in building retrofit.

In future studies, simulation can be used to verify the effect of variability on wall moisture performance; more material properties such as water vapor diffusion, porosity etc. need to be tested and explore their property variability. The work will also result in much-needed hygrothermal data collection for historic UK building materials.

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