Department for Energy Security & Net Zero

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DEEP Report 4.00

Brick Material Properties

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Prepared for DESNZ by

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Executive summary

Thermal and hygrothermal simulations are undertaken to estimate energy performance, condensation risks, the potential for moisture accumulation, and timber rot. These simulations use default book values to estimate the material properties of solid brick walls. This report investigates the variability of brick properties found in solid walled homes in the UK and compares these to the default book values. It also explores how varying material property inputs in models affects thermal performance and moisture risk in solid walled homes.

Retrofitting solid external walled homes has been found to pose moisture related risks, and so there is a need to understand how to install retrofits that will not cause additional risks in these homes. This study includes the results from specialist materials laboratory testing of eight different bricks commonly found in UK homes. These tests provided details on the material properties that influence heat and moisture transfer through bricks.

The results indicate that there was a wide range in the thermal conductivity of the bricks (which is the main determinant of heat loss), although some had broadly similar conductivities to the ranges in the software. This meant that six of the eight bricks tested had U-values much higher than the 1.7 W/(m^2·K) assumed for existing solid walled homes in the RdSAP software used for generating EPCs, with the average being 2.1 W/(m^2·K). This means that some solid walled homes may have worse EPC values and higher heat losses than they are currently assumed to have. Furthermore, it means that the benefit of retrofit could be greater for these homes than models predict. However, despite this variation, all the bricks would require similar retrofit solutions to achieve the target 0.3 W/(m^2·K) in Part L of the Building Regulations for upgrading solid walls. This was identified as between 95 mm and 105 mm of mineral wool external wall insulation (EWI); demonstrating the negligible variation in thermal performance of bricks in insulated solid walls.

Additionally, according to assessments performed in TRISCO software, seven of the eight uninsulated bricks were predicted to have surface condensation risks due to the variation in their thermal conductivity. EWI would, however, eliminate the risk on all homes.

Variations in hygrothermal properties were also pronounced. Since there is no single standard by which to evaluate moisture risks, two assessments were performed in WUFI software. Firstly, it was found that only two of the eight bricks may be at risk of moisture accumulation above 1, which include a commonly used fletton brick. The second assessment showed that a different two bricks spent more than 1 % of their time at risk of timber rot. This highlights the need to use multiple assessment criteria to define risk.

The assessments also showed that two bricks using book value properties in WUFI, ‘handmade’ and ‘historic,’ had significantly greater risk than any of the sampled bricks, spending over 16 % of the simulation time exposed to conditions where timber rot is a risk. This shows the importance of using actual brick properties data when estimating moisture risk in solid walls.

Additional testing should be undertaken to further explore the relationship between physical properties and hygrothermal performance of bricks. Book value defaults for estimating thermal performance and moisture risk may need expanding to cover a wider range of UK brick types.

1 Introduction

Physical and thermal tests on eight bricks have been performed, sourced from the DEEP case study dwellings and from other sites in the UK to ensure a spread of brick types commonly found in the UK housing stock.

1.1 Project aim

Undertaking materials testing of bricks is costly and time consuming, meaning it is not reasonable for individual domestic retrofit projects to perform their own tests. Thus, default book values are used in software to inform energy models and risk-based thermal and hygrothermal simulations for domestic retrofit risk assessments. These simulations can support the delivery of a risk-based approach to delivering retrofits in UK homes.

Core samples were taken from solid walled homes in the UK on which specialist materials laboratory testing was undertaken to derive useful data on the brick's thermal and moisture transfer properties. These properties were compared to the appropriate default book values used in thermal and hygrothermal software to undertake risk assessments.

The results from the material testing were used to establish whether the default book values of material properties are appropriate when predicting moisture risks in UK homes, and to provide an indication of the range of performance in the bricks sampled. The project also uses the results from the laboratory tests to infer how the brick properties affect the likely U-value of the walls tested, as well as how their properties affect condensation risk and moisture accumulation risk.

The information from these tests may be used to determine if there is merit in undertaking a more extensive testing regime to develop a UK-based materials properties database to support risk evaluations. DEEP is concerned with the insulation of solid external walls; however, it would be possible to repeat this research for cavity external walls.

2 Sampling

Core samples from common solid external walled constructions have been collected to gauge how much variability there may be across different brick types in the UK.

The sample comprised a combination of 100 mm bore core samples taken through the entire thickness of the wall constructions, and a whole brick collected from the sites. In total eight core samples were collected from homes (including whole bricks from 5 of these homes).

The coring technique used to take core samples from the sample homes is relatively 'clean,' compared with trying to remove brickwork specimens by hand using mechanical tools. Removing large areas of walling by hand often results in samples being fractured or broken, so core samples tend to provide more complete samples. The core also has the benefit of giving a mix of brick and mortar. The importance of this varies; for example, where fine joints are used, the mortar forms a smaller proportion of the wall.

The core samples were located at various locations throughout the UK. The locations for each brick are listed below and each site was given a reference code:

- Leeds, West Yorkshire 17BG
- Maltby, South Yorkshire 56TR
- Stoke on Trent LC01
- Coalville, Leicestershire SJ01
- Bedford, Bedfordshire SJ02
- South Lambeth, London SJ03
- Loughborough, Leicestershire 55AD
- Harehills, West Yorkshire 01BA

LC01 is a 'Fletton brick'. This is one of the most popular bricks found in the UK, with good representation across the country, as it was commonly used after the Second World War in the rebuilding drive and post-war housing boom. In the 1960s, the Fletton brick was the most popular brick in the UK, with the Kings Dyke facility in Whittlesey producing 16 million bricks a day. The other bricks sampled were generally specific to an area, e.g., the brick coded 01BA was identified as a Leeds Whittaker brick, which is specific to Leeds and other parts of West Yorkshire.

Although the eight bricks that were sampled represent a good spread, more bricks would need to be sampled in different areas to understand the national variation of brick properties. Specific brick producing areas which are not represented include Merseyside, Cornwall, and the East Midlands.

The results from the eight bricks sampled are either from solid bricks, or those containing a 'frog,' i.e. a depression in the underside of the brick into which mortar is placed; this is representative of bricks used for solid external wall construction.

Missing from the sample are more modern brick types, such as three-hole perforated and multi-perforated clay bricks, as well as common non-brick solid wall constructions such as York dressed stone, Cotswold stone or concrete wall types.

3 Testing

Lucideon Ltd carried out physical testing on the full brick samples (five in total) including:

- Brick Dimensions in accordance with BS EN 772-16-2011 Determination of Dimensions
- Compression testing in accordance with BS EN 772-1-2011+A1-2015 Determination of Compressive Strength
- Net and Gross Density in accordance with BS EN 772-13-2000 Determination of Net and Gross Density
- Voids testing (water method) in accordance with BS EN 772 - 3 - Methods of test for masonry units - Part 3: Determination of net volume and percentage of voids of clay masonry units by hydrostatic weighing
- Capillary Saturation in accordance with BS EN 772-11-2011 Determination of Initial Rate of Water Absorption
- Water Absorption (5-hour boil methods) in accordance with BS EN 772 - 7 - Methods of test for masonry units - Part 7: Determination of water absorption of clay masonry damp proof course units by boiling in water
- Water Absorption (24-hour Method) in accordance with BS EN 772-21-2011 Determination of Water Absorption Cold Soak
- Porosity in accordance with BS EN 993-1:2018 - Determination of Apparent Porosity and Bulk Density

The following tests were carried out on the eight cores obtained from the different sites:

- Thermal conductivity testing
- Specific heat capacity testing
- Water vapour resistivity testing
- Hygroscopic sorption @ 80 % humidity

4 Results

4.1 Brick dimensions

Table 41 shows the variability observed in brick dimensions.

Table 4-1 Brick dimensions

Sample	Length brick (mm)	Width brick (mm)	Height brick (mm)	Length frog (mm)	Width frog (mm)	Area frog (mm^2)
01BA	226	105	77	162	64	10296
17BG	230	108	85	n/a	n/a	n/a
56TR	230	110	79	173	60	9621
LC01	215	102	65	179	73	13089
SJ01	227	108	74	n/a	n/a	n/a
SJ02	222	105	66	141	43	6109
SJ03	224	107	65	162	49	7981
55AD	230	113	76	n/a	n/a	n/a

Firstly, smaller bricks have higher ratios of mortar when assembled in a wall. Since the core samples included elements of brick *and* mortar, this may be captured in the data to some extent. However, the core samples (100 mm diameter) may not be sufficiently large to investigate the significance of the mortar-to-brick ratio, and the variation in brick sizes in this sample was low (65-85 mm in height).

Secondly, understanding differences in the frog area, such as whether the frogs were filled with mortar, or if they acted as an air pocket, was outside the scope of the tests. However, it should be noted that the frog does impact on thermal and hygrothermal performance.

4.2 Brick thermal properties

The most influential characteristics of bricks on their thermal performance are thermal conductivity and specific heat capacity.

Thermal conductivity is the most significant property for the study of heat loss and surface condensation risks. The higher the thermal conductivity, the lower the thermal resistance. Bricks with higher conductivity, therefore, will also have higher U-values, more heat loss, and cooler internal surfaces, resulting in higher risk of internal surface condensation.

The results for the sample are outlined in Table 4-2. The table also includes the book values used in common hygrothermal software package WUFI Pro[1], and BR 443 values[2] which are used in numerical thermal simulation software packages such as TRISCO[3].

Table 4-2 Brick sample thermal properties

Sample	Thermal conductivity W/(m·K))	Specific heat capacity@ 20 °C (MJ/m^{3}K)	Specific heat capacity@ 40 °C (MJ/m^{3}K)	Specific heat capacity@ 60 °C (MJ/m^{3}K)
01BA	1.109	2.081	2.299	2.247
17BG	0.742	1.805	1.851	2.003
56TR	0.811	1.683	1.826	1.897
LC01	0.767	1.859	2.049	1.868
SJ01	0.624	1.515	1.625	1.799
SJ02	1.286	2.365	2.339	2.23
SJ03	0.593	1.831	1.843	1810
55AD	0.789	1.419	1.530	1650
BR 443 Inner	0.56	N/A	N/A	N/A
BR 443 Outer	0.77	N/A	N/A	N/A
WUFI	0.6	1.4025	N/A	N/A

[1] Fraunhofer Institute for building physics (2021)

[2] BRE (2019) Conventions for U-value Calculations. BR 443.

[3] Physibel (2020) TRISCO version 14.0w

Figure 41 compares the sample thermal conductivity against modelling default book values. As can be seen, all samples except 01BA and SJ02 are in relatively close agreement with one another and within ~30 % of the default book value range. Samples 01BA and SJ02 are substantially higher, exhibiting up to twice the thermal conductivity assumed in simulations.

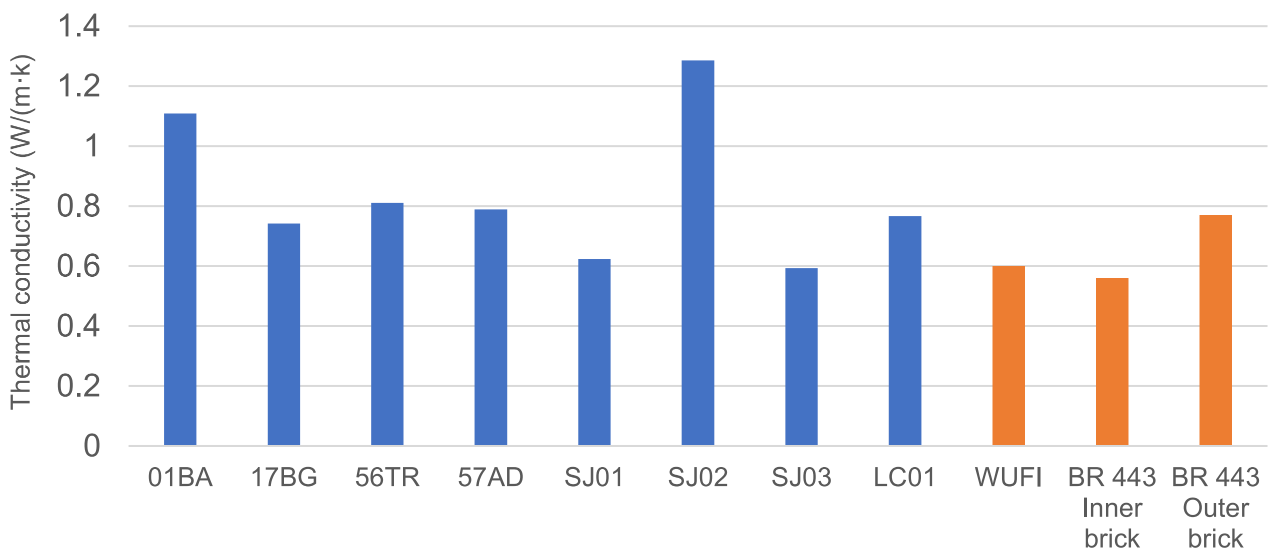

Figure 4-1 Thermal conductivity (W/(m·K)) of samples (blue) and book values (orange)

The findings show that thermal conductivity of solid walled homes varies depending on which bricks homes are constructed with. Some uninsulated solid walls will therefore have naturally lower U-values than others. This has several implications for modelled heat losses and moisture risks. The impact that the observed variations in thermal conductivity have on solid wall U-values is presented below in Figure 4-2. In-situ measurements for four homes that were part of the broader DEEP retrofit case studies described in DEEP report 2.01 are also shown for reference.

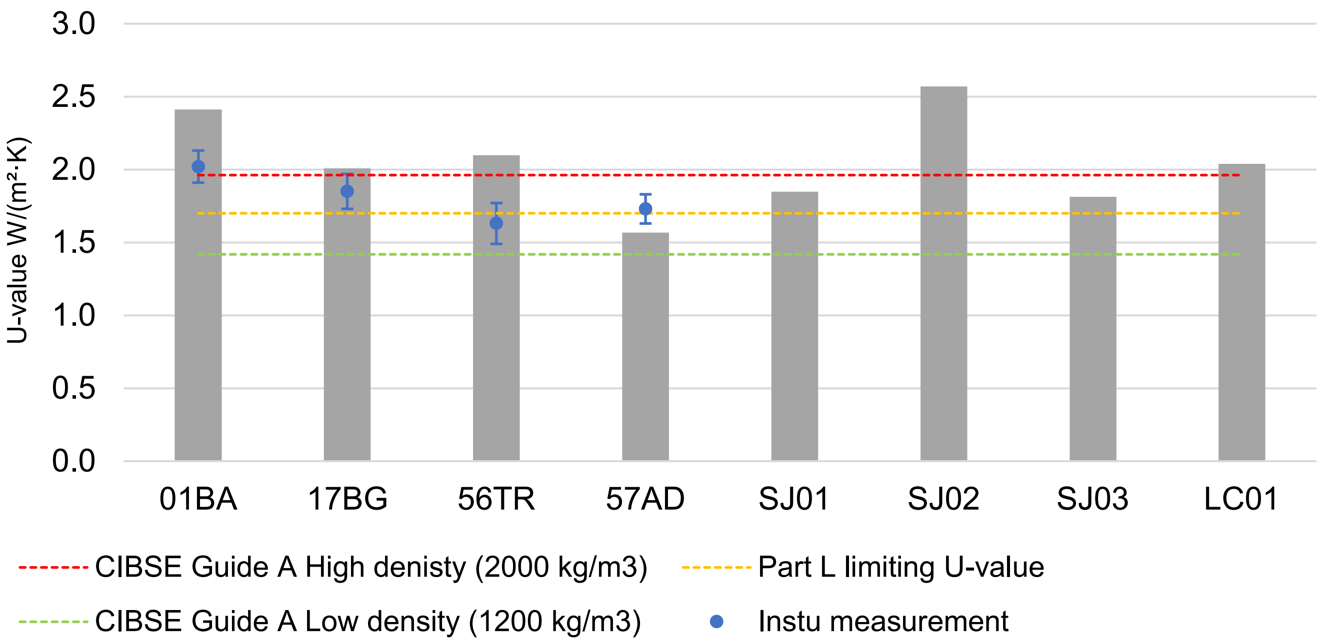

Figure 4-2 Calculated pre-retrofit U-value (W/(m²·K)) of measured samples (grey) compared to in-situ measurements (blue), book values (yellow, red, and green)

The average simulated U-value, shown in Table 4-2, was 2.1 W/(m^2·K) and ranged between 1.6 to 2.6 W/(m^2·K). The CIBSE Guide A book-values have an average of 1.7 W/(m^2·K) — the same value used in Energy Performance Certificates (EPCs). The CIBSE values range from 1.4 to 2.0 W/(m^2·K). Five homes had predicted U-values beyond this, and seven of the eight had U-values higher than the 1.7 W/(m^2·K) default used in EPCs. This suggests that solid walls have the potential to have much higher heat loss than predictions, though the sample size in this study is too small to make broad generalisations.

Further analysis into the implications that this natural variation in starting U-values has on internal surface condensation risks was undertaken by calculating the temperature factor for walls made from each of the bricks using TRISCO software. A condensation risk occurs if the temperature factor drops below 0.75. The analysis found that the six bricks which had the highest U-values showed surface condensation risk. This means that condensation risk may be present in solid walled homes, but the risk is lower if they have lower U-values. Additionally, having a temperature factor below the 0.75 threshold does not necessarily mean homes will have condensation, only that the risk is present.

Also shown in Table 4-2 are in-situ U-values measured at four homes in the DEEP case study field trial from where brick samples were sourced. These results show measured U-values were not as high as models predicted for three out of four bricks, perhaps due to uncertainties in the wall material make up assumed in the models. Given that modelled U-values could be worse than measured, in some instances, predictions of risk and high heat loss in models may be overestimated for these homes.

The target U-value stated in Approved Document Part L for upgrading solid walls during retrofits is 0.3 W/(m^2·K). For an assumed uninsulated solid wall with a U-value of 1.7 W/(m^2·K) in an EPC, applying 100 mm of mineral wool EWI can meet this target. To investigate how brick thermal conductivity affects post-retrofit wall U-values, scenario analysis was undertaken using TRISCO to model the U-value achieved by retrofit with 100 mm of EWI. The thickness of insulation that would be required to achieve a U-value of 0.3 W/(m^2·K) for a typical solid brick wall was also investigated for each brick thermal conductivity.

It was found that when fitted with 100 mm of mineral wool EWI the U-value in almost all scenarios decreased to the target value. The average uninsulated U-value across the sample was 2.1 W/(m^2·K) falling to an average insulated U-value of 0.31 W/(m^2·K). This suggests that variations in pre-retrofit solid wall U-values do not significantly affect the retrofit solution required to achieve Part L target U-values. This was confirmed by comparing the insulation thickness required to be fitted across the bricks to achieve the U-value target of 0.3 W/(m^2·K), which showed thicknesses only varied from 95 mm to 105 mm.

Variations in brick thermal conductivity may therefore be relatively important for uninsulated solid walled homes, affecting their plain element heat loss and condensation risks. However, the variation becomes less significant if insulation is installed on walls.

The specific heat capacity of a brick also influences its thermal performance: higher specific heat capacity means potentially higher heat losses. Figure 4-3 compares the specific heat capacity of the brick samples at 20 °C, 40 °C and 60 °C to their dry thermal conductivity.

It was observed that brick samples with greater specific heat capacity at each temperature also had greater thermal conductivity, i.e. they were positively correlated.

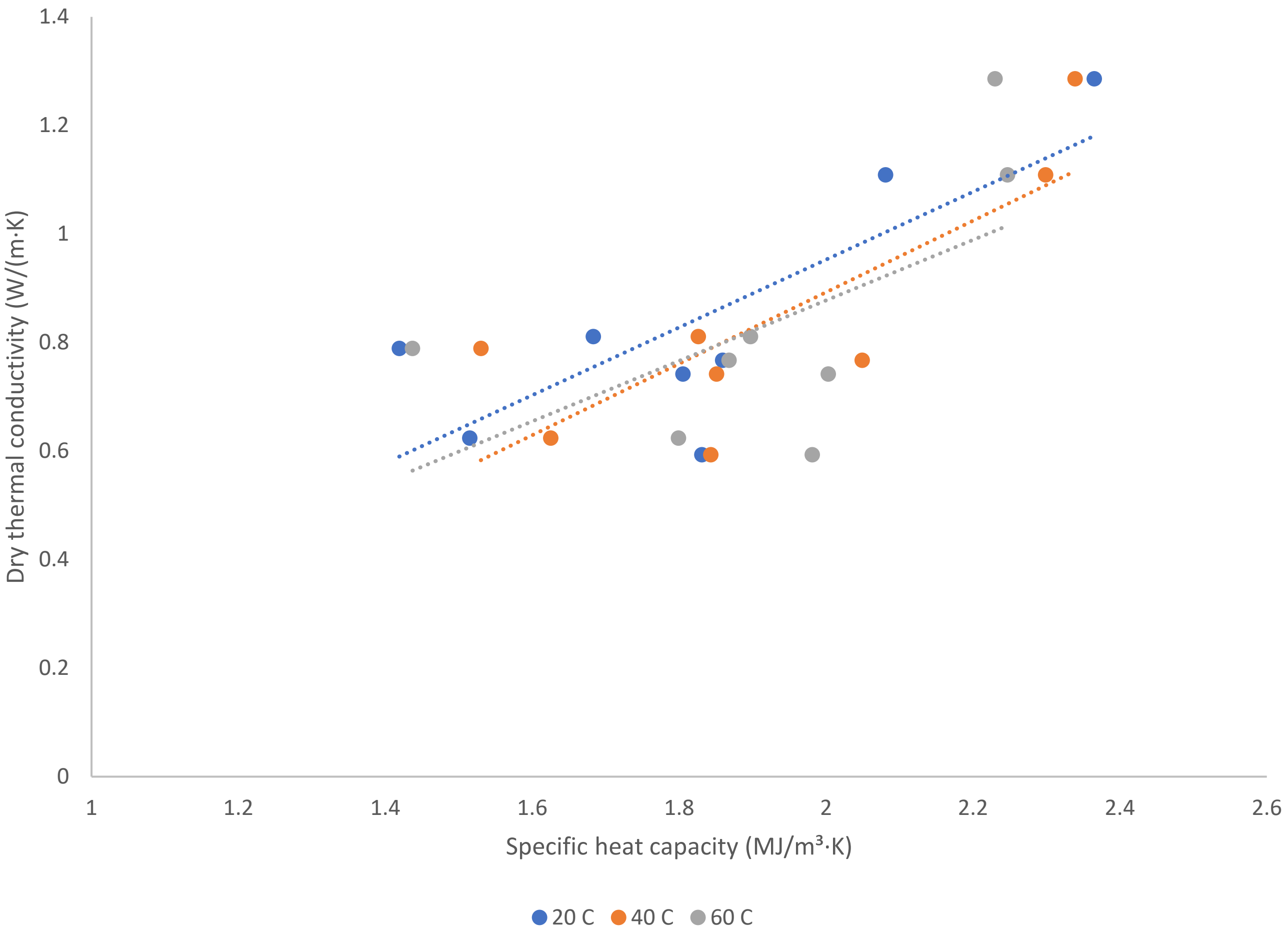

Figure 4-3 Plot of specific heat capacity against dry thermal conductivity of brick samples

The following sections compare a range of other material properties of the bricks to thermal conductivity to investigate if other material properties of bricks can be used as an indicative evaluation of its overall thermal performance. If this is the case, it is possible that a relatively simpler and cheaper test could be performed on brick samples to infer their thermal performance and avoid having to undertake more costly tests, such as those undertaken in this report, to derive the thermal conductivity directly.

4.3 Brick strength

Table 43 compares the differences in brick strength of the sample bricks. As can be seen, there is a broad range in both crushing load and compressive strength of the bricks, indicating that their material properties vary substantially.

Table 4-3 Brick strength

Sample	Crushing load (kN)	Compressive strength (N/mm$^{2)}$	Gross density (kg/m^3)
01BA	1333.1	98.5	2120
17BG	1800.5	73	1910
56TR	569.28	36.5	1820
LC01	433.4	49.3	1330
SJ01	986.7	40.3	1730
SJ02	2358	137.1	2080
SJ03	1395.8	87.8	1810
55AD	1179.2	45.2	1650

If compressive strength is plotted against thermal conductivity (see Figure 44), the data from the sample suggests a positive correlation, i.e. thermal conductivity increases as the compressive strength increases. However, due to the very small sample involved, this correlation needs to be treated with caution and some significant outliers to the trend were found, such as SJ03.

Figure 45 compares the relationship between gross density and thermal conductivity. A similarly positive correlation was again found, although outliers were clear. For instance, the Fletton bricks (LC01) were an outlier to the general trend, having the lowest gross density (1200 kg/m^3), yet having a thermal conductivity (0.76 W/m.k) similar to those samples with a gross density of 1800 kg/m^3.

Although the range in brick strength in the sample is wide, the number of sampled bricks is too low to draw any firm relationships. Additionally, minimum brick strength in common use in the UK building stock is around 15 N/mm^2, suggesting that this sample does not cover the full range of brick strengths used in the UK. For instance, relatively low strength handmade bricks include the Yellow London Stock brick, which is used extensively in the South East.

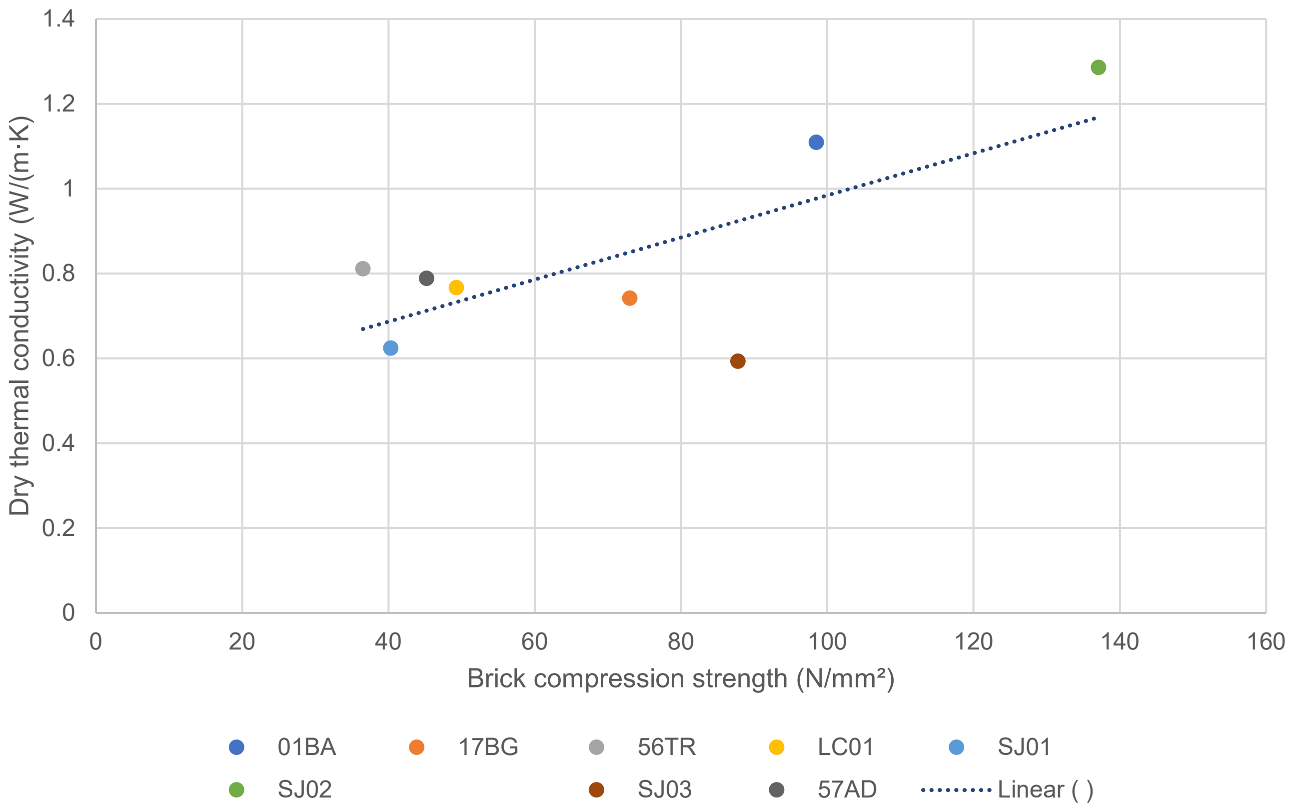

Figure 4-4 Compressive strength vs thermal conductivity

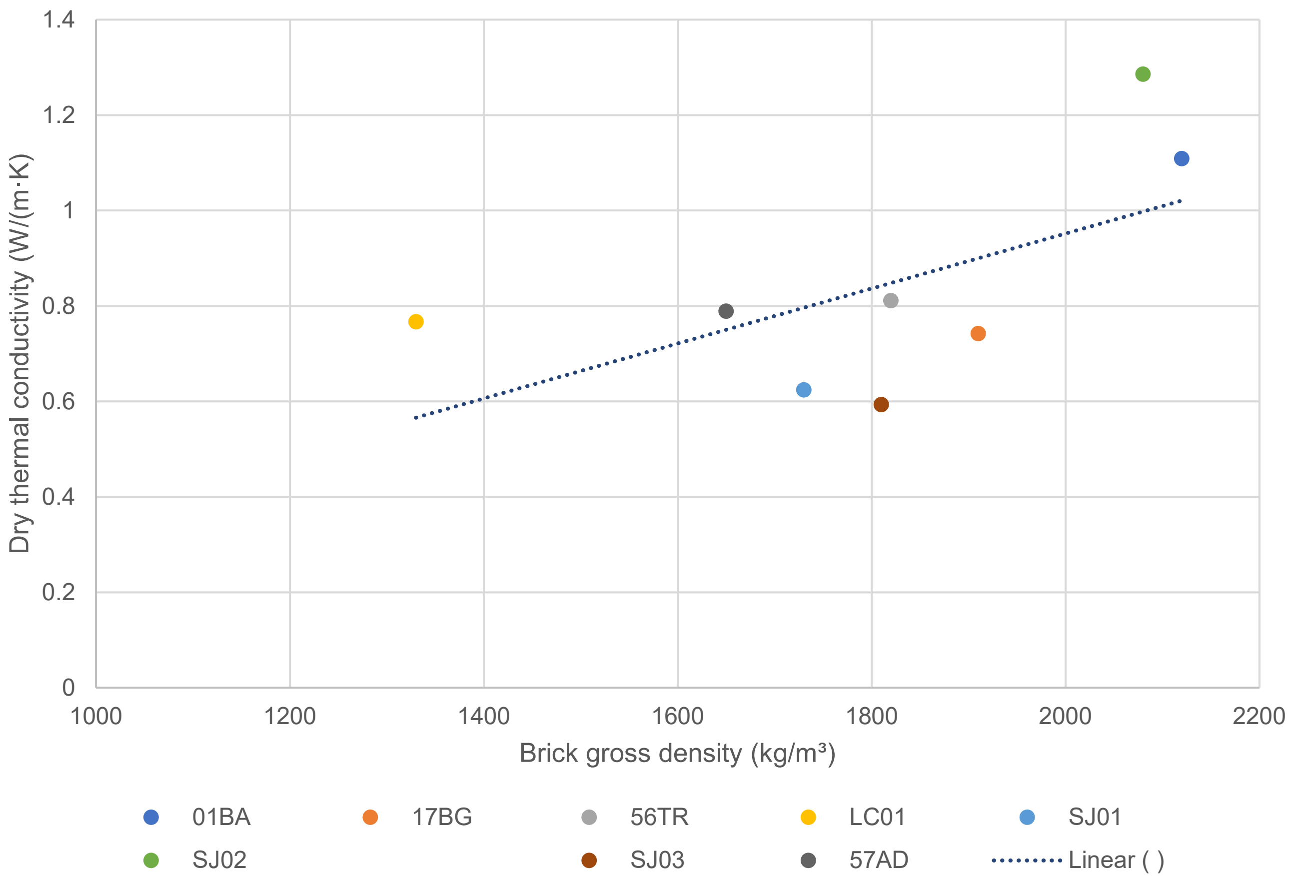

Figure 4-5 Gross density vs thermal conductivity

4.4 Brick saturation and absorption

Two properties that influence how bricks take on, store, and regulate moisture are the capillary saturation and water absorption, which are shown in Table 44 and Table 45, respectively. There is a substantial range in performance across the sample observed. The impact of some of these characteristics on thermal conductivity is illustrated in Figure 46.

Table 4-4 Capillary saturation

Sample	Capillary saturation (kg / m^2 / min)
01BA	0.04
17BG	0.45
56TR	0.34
LC01	0.32
SJ01	0.41
SJ02	0.13
SJ03	0.09
55AD	0.14

Table 4-5 Water absorption

Sample	Dry Wt (g)	Soak Wt (24 Hrs) (g)	Water absorption (24 Hr) (%)	Soak Wt (5Hr boil) (g)	Water absorption (5 Hr) (%)
01BA	3758	3929	5	3979	5.9
17BG	4053	4399	9	4496	11
56TR	3674	3987	9	3987	8.5
LC01	1885	2293	21	N/A	N/A
SJ01	3125	3541	13	3680	17.8
SJ02	3224	3246	1	3286	1.9
SJ03	2778	2882	4	3032	9.1
55AD	3265	3675	12	3805	16.6

As can be seen in Figure 46, there is a relatively clear correlation, where bricks with higher water absorption capability have a lower dry thermal conductivity. Outliers are prominent again however, e.g. LC01 and SJ03, which are skewing the overall trend.

The implication of this is that bricks that are more likely to absorb water may also be those that are better able to limit heat transfer. However, the sample size is too small to draw any definitive conclusions and more investigations would be needed to understand how the thermal conductivity of bricks impacts their ability to dry out following wet weather.

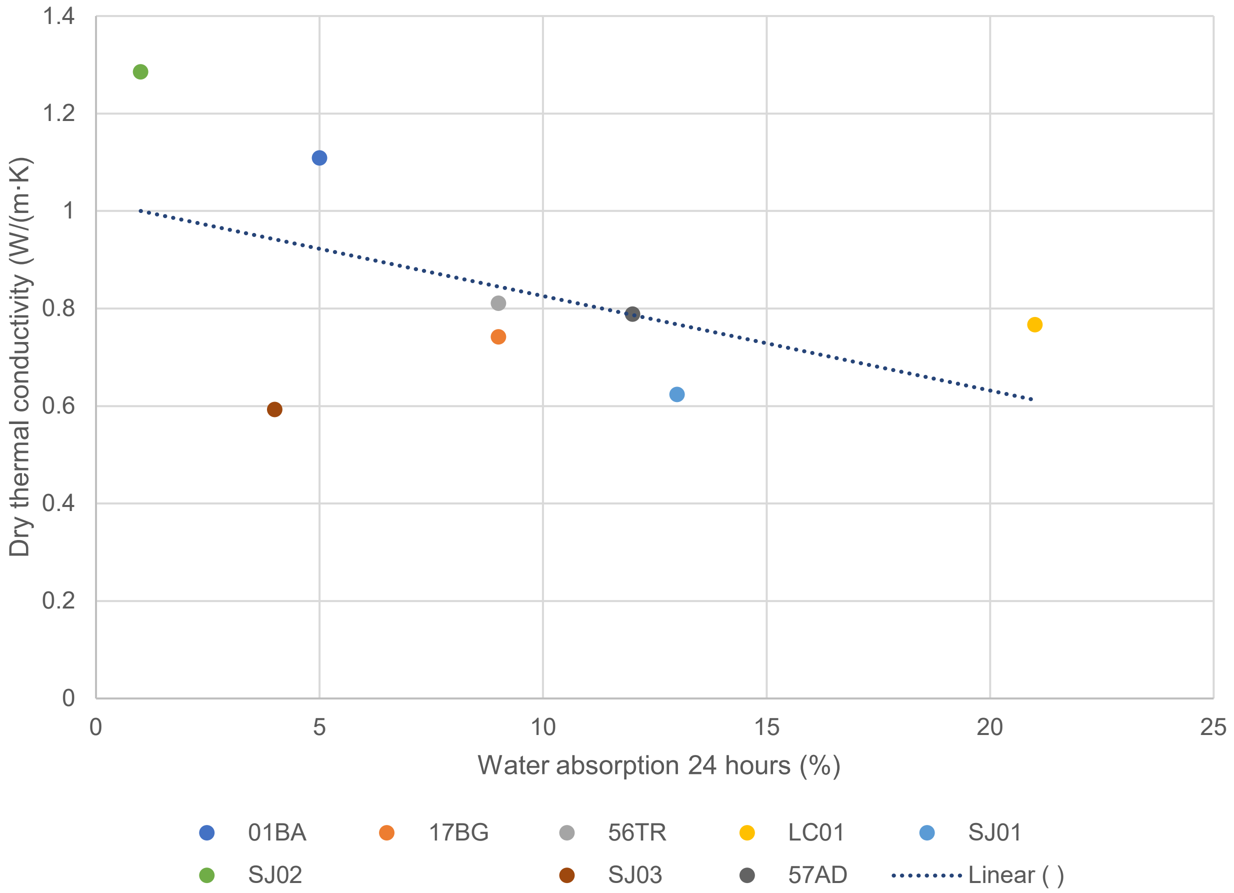

Figure 4-6 Water absorption (24 hours) vs dry thermal conductivity data when sampled.

4.5 Brick vapour, porosity, and hygroscopic sorption

The final properties that were investigated were the vapour, porosity, and hygroscopic sorption. These characteristics will influence how moisture transfers through the brick and so influence how moisture accumulates in the external walls.

The results from these tests are shown in Table 4-6. As can be seen, the properties vary substantially, with some of the bricks exhibiting values that are double those of other bricks in the sample. The data can also be used to investigate the significance of varying material properties on the risk of surface condensation and moisture accumulation predicted by WUFI software, which are further explored in Section 4.6 and 4.7.

Table 4-6 Brick vapour, porosity, and hygroscopic sorption

Sample	Porosity %	Water vapour diffusion coefficient (μ)	Vapour resistivity (MNs/g)	Hygroscopic sorption at RH = 80 %
01BA	10.32	98.5	2.58	0.083
17BG	7.30	73.0	1.74	0.076
56TR	18.23	36.5	2.49	0.007
LC01	34.92	49.3	2.82	0.409
SJ01	24.00	40.3	1.90	0.202
SJ02	1.62	137.1	7.75	0.379
SJ03	7.30	87.8	14.96	0.107
55AD	22.47	45.2	2.32	0.041

The porosity and water vapour diffusion coefficient of samples are compared against the dry thermal conductivity in Figure 4-7 and Figure 4-8. The observed trend in Figure 4-7 is for dry thermal conductivity to reduce as the porosity of the brick sample increases. This is likely due to the greater proportion of air voids in the brick samples of greater porosity, as air has greater thermal resistance than solid fired clay.

This fits in with the trend observed when comparing dry thermal conductivity to gross density, seen in Figure 4-5, where the greater the proportion of pores in the brick, the lower the density. A similar comparison can also be made with water absorption, seen in Figure 4-6, where the greater the proportion of pores in the brick, the more capacity there is to hold water within the internal structure. Figure 4-8 further builds on the relationship between hygrothermal properties and dry thermal conductivity. Greater values of water vapour diffusion coefficient (μ) are associated with greater dry thermal conductivity (higher values of μ indicate a greater resistance to water vapour). In this situation, the more porous a brick is, the less resistance it will have to the passage of water vapour due to the internal pore structure. The results are thus indicative of trends existing, but more data is needed to define specific correlations between material properties, thermal performance, and moisture risks.

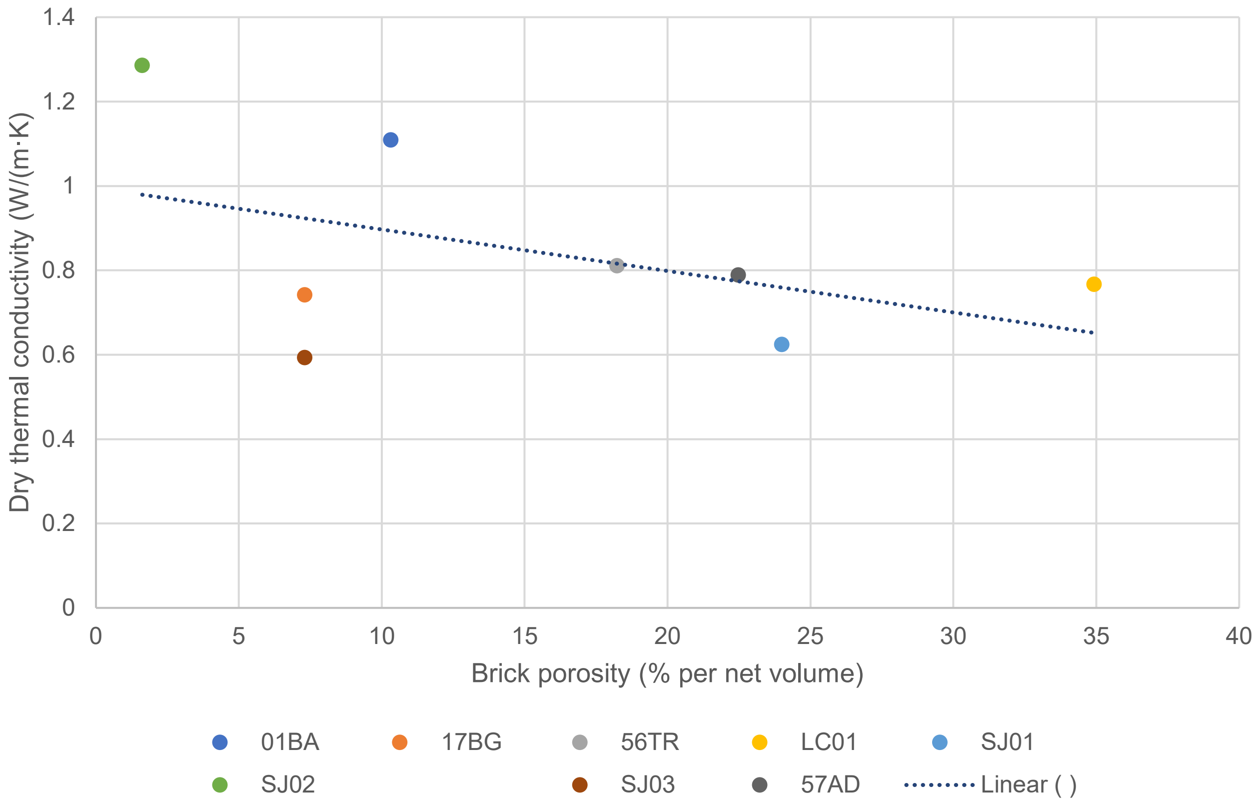

Figure 4-7 Plot of sample porosity against dry thermal conductivity

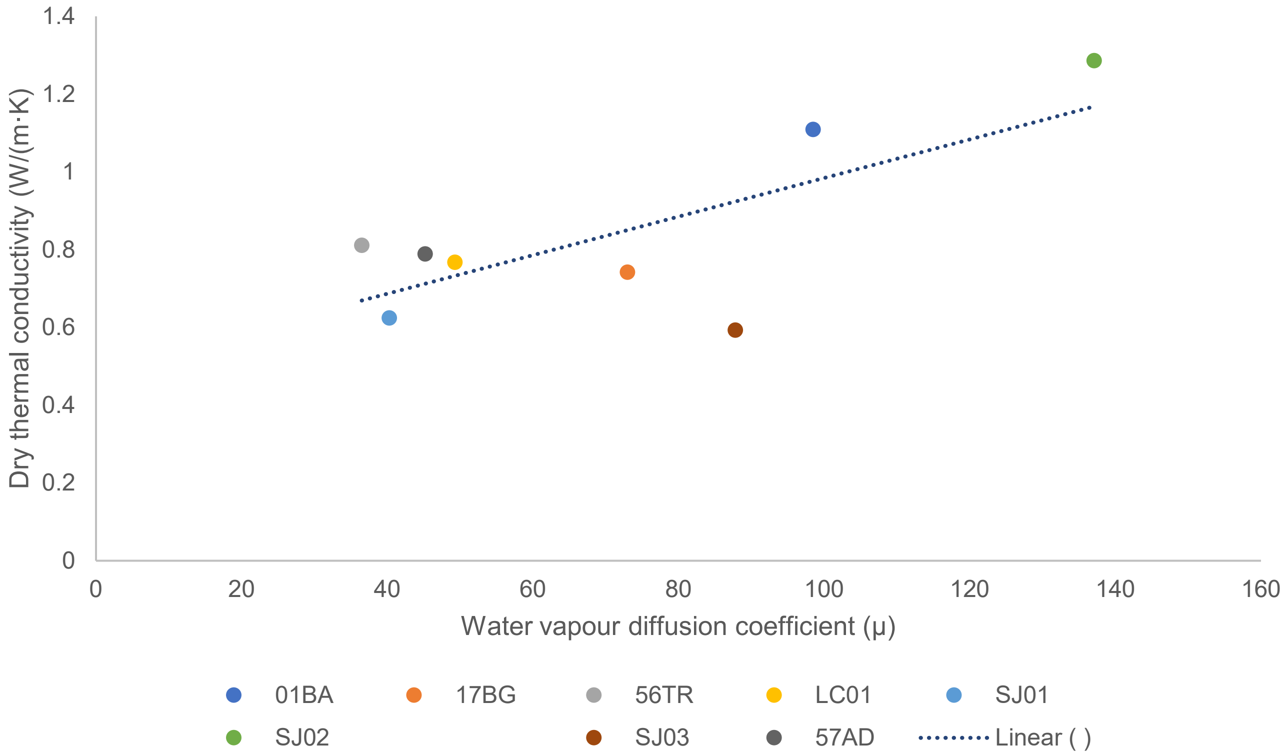

Figure 4-8 Plot of sample water vapour diffusion resistance coefficient against dry thermal conductivity

4.6 Comparison to tabulated values

Using measured material inputs in thermal and hygrothermal simulations can help improve the accuracy of modelled outputs. However, measuring the hygrothermal properties of bricks is impractical for many projects. A comparison between the properties of the measured DEEP sample bricks and software default book values is given in Table 47 below.

Table 4-7 Measured and default brick hygrothermal properties by source.

Source	Name	Density (kg/m³	Porosity (%)	Specific heat capacity (J/kg·K)	Thermal conductivity (W/(m·K))	Diffusion resistance factor (μ)
Measured DEEP sample	01BA	2120	10.32	982	1.109	98.5
	17BG	1910	7.3	945	0.742	73
	56TR	1820	18.23	925	0.811	36.5
	LC01	1330	34.92	1398	0.767	49.3
	SJ01	1730	24	876	0.624	40.3
	SJ02	2080	1.62	1137	1.286	137.1
	SJ03	1810	7.3	1137	0.593	87.8
	55AD	1650	22.47	1012	0.789	45.2
WUFI database	Brick extruded	1650	41	850	0.6	9.5
	Brick, hand formed	1725	38	850	0.6	17
	Brick, historical	1800	31	850	0.6	15
CIBSE Guide A	Brick (fired clay)	1200	-	-	0.36	-
		1300	-	-	0.4	-
		1400	-	-	0.44	-
		1500	-	-	0.47	-
		1600	-	-	0.52	-
		1700	-	-	0.56	-
		1800	-	-	0.61	-
		1900	-	-	0.66	-
		2000	-	-	0.7	-

Two sources for default tabulated brick thermal properties were used for comparison: CIBSE Guide A, and the WUFI database used in the WUFI hygrothermal simulation software.

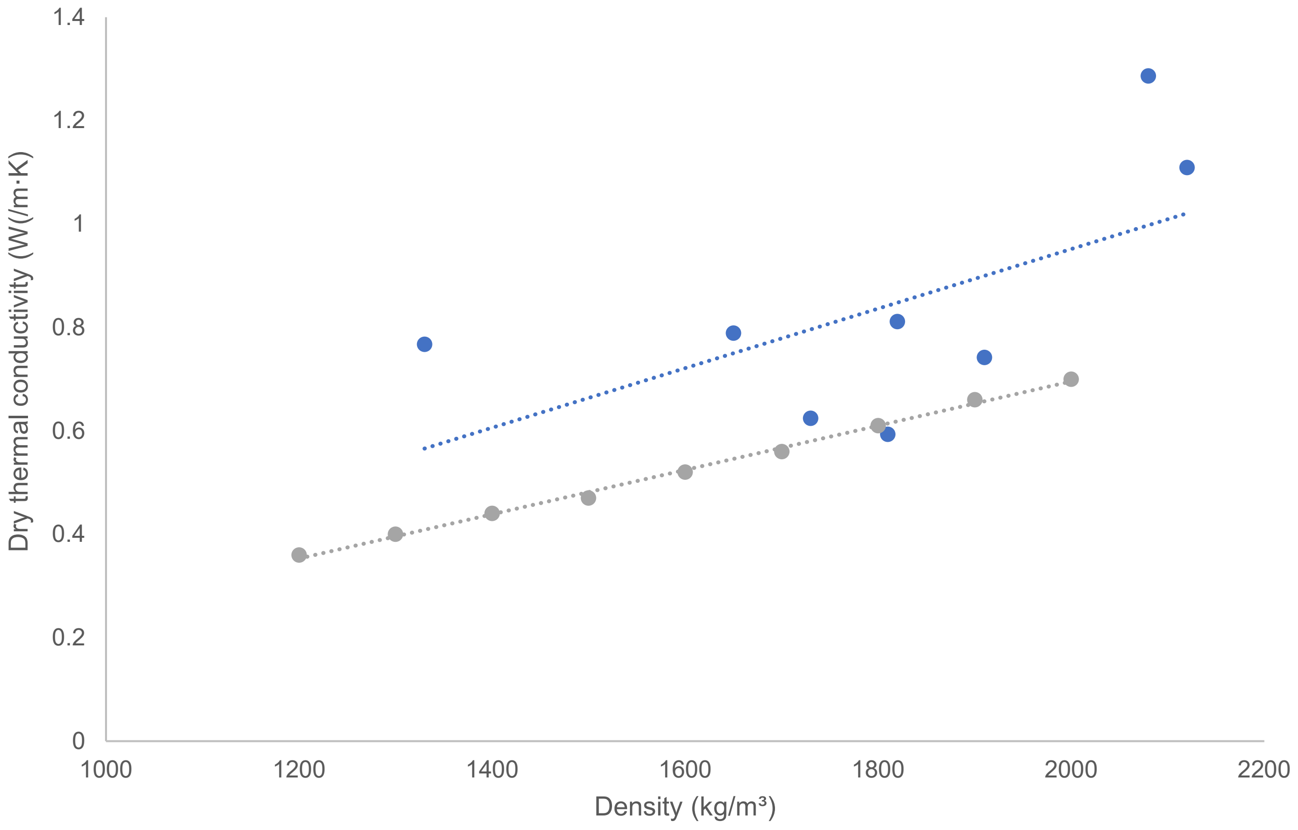

Figure 4-9 Plot of CIBSE Guide A (grey) and measured (blue) density against dry thermal conductivity

The values found in CIBSE Guide A only provides thermal conductivities of bricks based on a range of brick densities from 1200 to 2000 kg/m³. However, the density of two of the samples measured was outside of this range. Brick density and thermal conductivity from CIBSE Guide A and the measured values are compared in Figure 4-9 (WUFI database values are excluded as thermal conductivity is assumed to be the same for each of the three brick types).

Observing the trend lines in Figure 4-9, both the measured and CIBSE Guide A tend to increase thermal conductivity when density increases. However, the measured samples tend to have a greater thermal conductivity for a given density than the book values in CIBSE Guide A. In these cases, using CIBSE Guide A book values in calculations of U-values and thermal bridging assessment could lead to an underestimation of heat losses compared to the measured values for this sample.

It is also possible to compare the hygrothermal properties of the bricks in the WUFI database. The more advanced hygrothermal functions of materials in WUFI are difficult to compare with the measurements taken, since they are embedded in the software and not reported in a comparable format. Therefore, it is not known how updating some of the materials but not others will affect the reliability of the simulated outputs.

Three brick materials with defined properties are found in the WUFI database. The default book values of these can be compared to those in the measured sample. For instance, the densities of the brick materials in the WUFI database all fall within the range of bricks measured, but the porosity of the WUFI materials appears high; exceeding the measured range in some instances.

The specific heat capacity and thermal conductivity of the bricks in the WUFI database were found to be below the range of the measured bricks. The WUFI bricks also have vapour resistance factors lower than the measured bricks.

Due to these variations, it appears that using the WUFI bricks would likely lead to an under estimation of heat flows into wall build-ups, and an over estimation of moisture movement into the wall, compared to the measured bricks in this sample. Additional research is required to determine if this would be the case more broadly for other brick types.

4.7 Hygrothermal simulation findings

It is useful to consider the impact that differing brick hygrothermal properties have when used in hygrothermal simulations to determine condensation risks in solid walls. This section explores these differences by using WUFI software to assess what the impact would be of retrofitting Internal Wall Insulation (IWI) on solid walls made up of the sampled bricks.

WUFI Pro version 6.6 software (Fraunhofer Institute for Building Physics, 2014) was used to construct models and to simulate the hygrothermal behaviour. WUFI Pro is a one-dimensional hygrothermal simulation software package that allows users to create models out of layers with varying thicknesses. Within the software, users can assign material properties from a database or create/adapt materials based on manufacturer or experimental data. The resulting model is then used to simulate the movement of moisture and heat through the material over a set number of 1-hour time steps.

The initial internal temperature in the simulation was set at 20 °C and relative humidity 80 %. The external climate was based on a reference year of hourly weather data from Leeds. The internal climate selection used the EN 15026 Indoor Climate. The models were oriented toward the north as default in the simulation software. Simulations were run for a period of three virtual years (26,280, 1-hour intervals). As no year-on-year increase in water accumulation was found, this suggests the walls are in equilibrium after the three-year simulation.

The default book value bricks selected from the WUFI material databases include: ‘WUFI extruded’, a modern extruded brick fired in a tunnel kiln; ‘WUFI hand-formed', a hand-formed brick using old manufacturing process; and ‘WUFI historical’, an inhomogeneous brick from 1500 AD.

Measured hygrothermal parameters of the sampled bricks discussed in Section 4.6 were used to create custom materials within WUFI: density, porosity, specific heat capacity, thermal conductivity, and water vapour diffusion resistance factor (Figure 410).

Porosity of a material may be expressed as a percentage and is calculated by dividing the total volume of empty space by the total volume of the material. Porous materials contain many pores, while non-porous materials have few to no pores. Most building materials fall into the category of being porous; few have such low porosity that they can be classified as non-porous, for example metal and glass. Diffusion resistance factor (μ-value) is the rate of vapour diffusion in a material compared to still air. Still air has a baseline μ-value of 1 and all other materials have a μ-value greater than 1.

The moisture storage function, free water saturation is calculated using the following equation:

Free water saturation = density / (sample weight × (24 Hr soak weight – sample weight))

The reference water content is calculated by multiplying the free water saturation by Hygroscopic sorption at RH = 80 % in Table 45.

Using 01BA as an illustration, the free water saturation was 96.47kg/m^3 and the reference water content was 8.007 kg/m^3 (Figure 410). The free water saturation must be higher than the porosity in order to run a WUFI simulation.

All of the measured bricks meet this requirement, with the exception of the 17BG brick. The measured free water saturation for 17BG is 160 kg/m^3, which exceeds the 73 kg/m^3 (7.3 %) porosity. As such, the measured free water saturation was changed to 73 kg/m^3 so that WUFI could run its simulation.

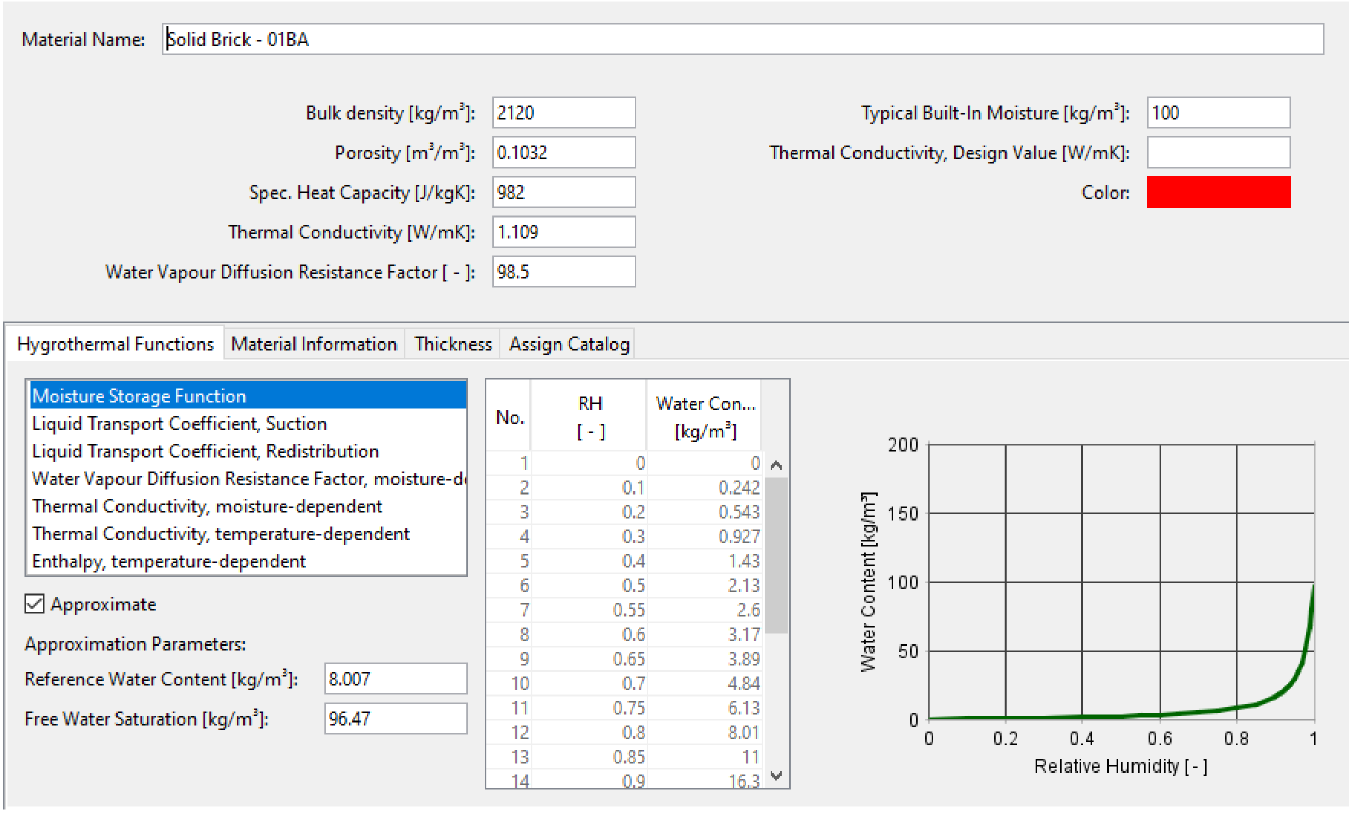

Figure 4-10 WUFI inputs using 01BA brick as an illustration.

4.7.1 Moisture content within the inner brickwork

Figure 411 highlights that some bricks have substantially more moisture accumulation than others, specifically LC01, which was a common Fletton brick. LC01 had an average of 5.80 % moisture content in the inner brickwork, and SJ01 had an average of 1.8 %.

These values were much higher than both other bricks in this study, and WUFI book values, all of which were <1 % moisture content. Investigation showed that LC01 (117 kg/m3) and SJ01 (46.5 kg/m3) had much higher reference water contents than other bricks (1 to 15 kg/m3), which may be driving the moisture accumulation.

This is particularly noteworthy since the extent of the upper moisture content shows that some homes are at significantly higher risk of moisture in walls than other homes. This could have consequences for the risk of rot and other damp issues, and they may be very susceptible to changes that could place during wall retrofits. However, the risk of water accumulation by itself may not be sufficient to determine if any problems with damp or timber rot will manifest, since there are multiple variables which influence this.

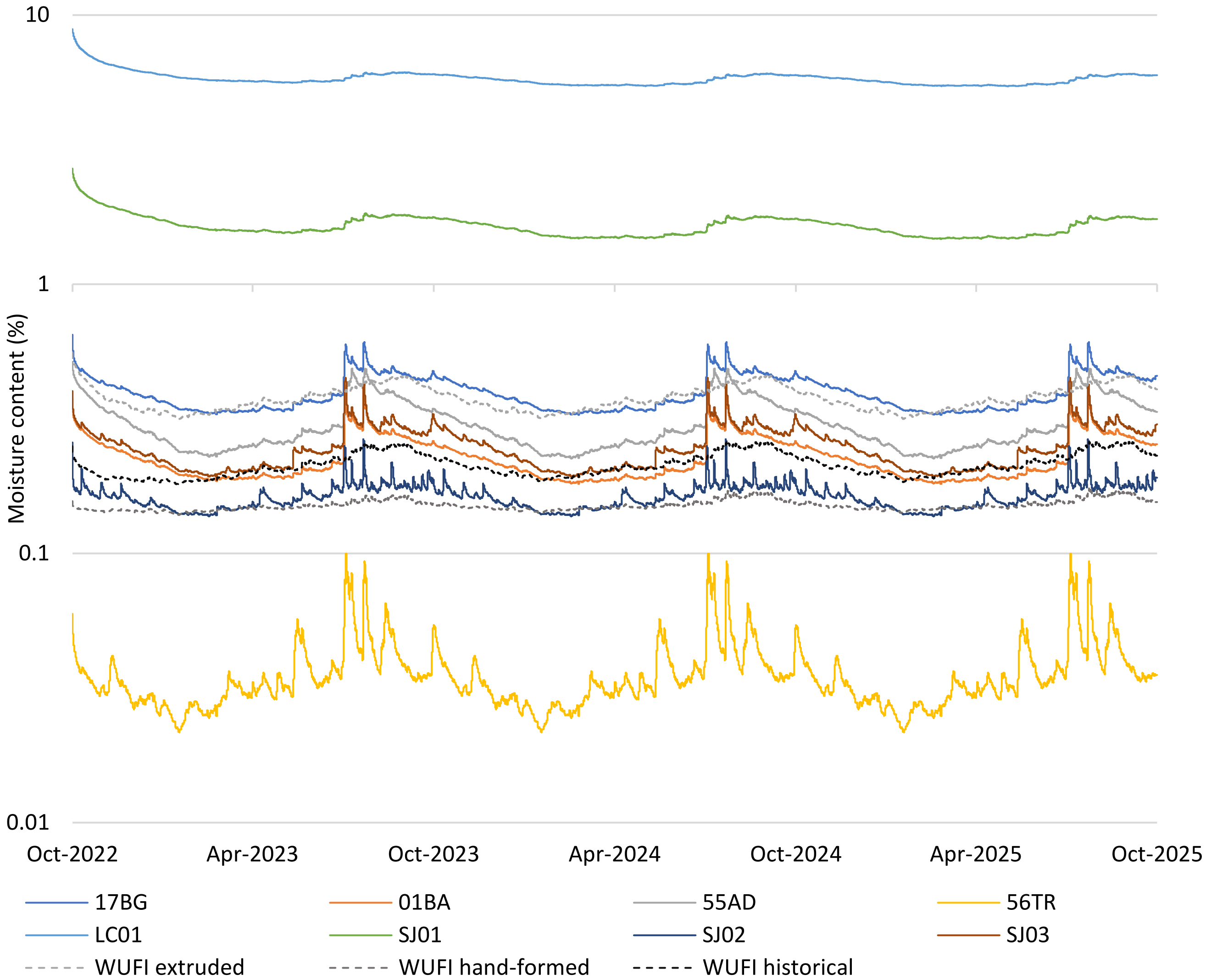

Figure 4-10 Percentage of moisture content in inner brickwork of measured samples compared to book values (in logarithmic scale)

4.7.2 Timber rot risk at the joist ends

The risk of mould growth and rot within the timber joist ends is high when moisture levels are high. Relative humidity over 80 % allows mould growth to occur, and dry rot within timber favours temperatures over 20 °C. Thus, these relative humidity and temperature thresholds can be used to evaluate timber rot risk.

Temperature and humidity were measured at the boundary between the air/mortar layer that is 10 mm thick, and the inner brickwork layer as this is the expected location for joist ends within a wall.

Table 4-8 summarises the number of 1-hour intervals during which conditions are conducive to mould or rot growth at the joist ends. Out of the measured bricks, 56TR (5.4 %) and 55AD (2.2 %) have a greater risk for timber rot than other types of bricks (less than 1 %). It is worth noting that LC01, SJ01 and WUFI extruded, have no risk, even though LCO1 and SJ01 had the highest moisture accumulation risk. This suggests that moisture risk evaluation is complex, and data on individual moisture properties are not adequate for predicting risk.

Of the WUFI bricks, it was found that two out of three had a significantly higher timber rot risk, spending around 16 % of the time at conditions that may result in rot.

These differences in the proportion of time spent at conditions where risk exists may be due to how hygrothermal parameters differ between hand-formed and historical bricks when compared to those that were sampled; since the manufacturing process affects the material properties of the bricks.

Table 4-8 Timber rot risk between the air/mortar and inner brickwork layer for sampled bricks and book values

House	Hours over 80 % RH	of which over 20 °C	% of time at risk
17BG	30	30	0.1 %
01BA	250	247	0.9 %
55AD	609	588	2.2 %
56TR	2392	1410	5.4 %
LC01	0	0	0.0 %
SJ01	0	0	0.0 %
SJ02	27	27	0.1 %
SJ03	279	243	0.9 %
WUFI extruded	0	0	0.0 %
WUFI hand-formed	10272	4377	16.7 %
WUFI historical	8797	4284	16.3 %

5 Conclusions

The material properties of eight bricks were tested using laboratory tests. The results show that there are substantial differences in the properties across the sample. It is likely, therefore, that solid walled brick homes will have different thermal and moisture characteristics depending on which bricks they are constructed from. This has implications for their heat losses as well as their surface condensation and moisture accumulation risks.

Four of the eight bricks, including the most common Fletton brick type, had similar thermal conductivity to the range of book values defaults used in the heat loss simulations. However, six of the eight bricks had higher U-values than the 1.7 W/(m^2·K) assumed for uninsulated solid walls in EPCs for existing buildings. The average U-value across the sample was 2.1 W/(m^2·K). The findings also suggested that seven out of eight bricks were likely to have surface condensation risks in uninsulated walls, with only the brick with the lowest U-value being deemed to have no risk.

Thus, energy modelling of uninsulated solid walled homes may be made more accurate by using specific material properties rather than relying on book defaults. However, further analysis showed that despite the variation in uninsulated wall U-value, all the brick walls tested would still require broadly the same retrofit solution (between 95 and 105 mm mineral wool EWI) to meet the Building Regulations target of 0.3 W/(m^2·K). This means that once solid walls are retrofitted, the thermal performance of the underlying brick becomes much less significant, since the U-value will be driven mainly by the insulation. Energy models of solid walled homes post-retrofit are therefore more likely to be reflective of actual performance even when they use default inputs.

The investigations also revealed that several physical properties, such as brick strength, density, and porosity, are correlated with thermal characteristics of the bricks. More research, including sampling a larger number of bricks and brick types, may identify if an appropriate methodology could be developed to infer thermal characteristics from physical properties, or whether simple laboratory testing could be carried out to avoid costly thermal conductivity tests.

To investigate how the material properties of bricks affected the moisture risks, two assessments were performed. Firstly, simulations run in WUFI showed six of the bricks had broadly the same or lower water accumulation as the assumed bricks in the models. However, LC01 and SJ01 had significantly greater moisture accumulation. More investigation is needed to understand how water accumulation may manifest as problems in solid walls. Furthermore, research is also needed to understand why inner brickwork moisture content levels vary by such a large degree.

Secondly, risk of timber rot was assessed and showed that two bricks tested, 55AD and 56TR, spent over 1 % of the time at conditions where timber rot may occur, while conversely, LC01 and SJ01 had no risk of timber rot. This shows the importance of considering multiple criteria when attempting to quantify moisture risks in solid brick walls.

The analysis also revealed that the handmade and historic default bricks in WUFI expressed significantly greater risk being exposed to conditions where rot may occur for over 16 % of the time. This highlights that relying on default values to assess moisture risk may result in inappropriate assessments or conclusions that have high degrees of uncertainty.

Although the sample of bricks presented in this evaluation is limited, it provides useful insights into the variability of bricks in the UK and highlights that the use of default book values may not always be appropriate.

It is recommended that tests are undertaken on a larger sample of bricks to understand the range of values encountered in the field, for the purposes of thermal performance predictions and moisture risk assessment, as well as to determine what proportion of the national housing stock is likely to have material properties that do not conform with the default book values.

There is no single standard way to evaluate moisture risks; indeed, different assessment methods can offer conflicting insights into which brick has moisture risk. Consequently, a comprehensive understanding of moisture risks requires consideration of multiple assessment methods. The creation of guidance around which criteria and conditions constitute high and low risks could support designers and inform the wider industry on how to support building maintenance and low risk retrofit.

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