EVALUATING THE PERFORMANCE OF A HIGH THERMAL MASS DWELLING: COMPARING PREDICTIONS AND IN-SITU MEASUREMENTS

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Improved building fabric performance is essential for the decarbonisation of buildings. Evaluating fabric performance is often predicted; but inaccuracies are present within commonly used prediction methodologies. Accurate measurement of building fabric is therefore advantageous when identifying the improvement made through retrofit. The QUB/e method is a practical and effective method of measuring the whole building performance in low-to-medium thermal mass properties. In this paper, a property of high thermal mass was studied for the first time with the QUB/e method. The results identify challenges in undertaking QUB/e measurements in the application of high thermal mass including the impact of stored solar heat contributions resulting in a wider dispersion of measurements. In the case presented; a significant prediction gap is identified when comparing the predicted and measured results. The implications of the prediction gap observed include a change in the regulatory EPC band of the property. Additionally, using performance measurements would avoid overestimations of the reported decarbonisation and annual cost saving benefits of future retrofit works to improve the property at 2.3 Tonnes of equivalent CO2 emissions and £570 respectively.

Keywords: building performance; building regulation; energy; measurement

INTRODUCTION

Building Performance Evaluation

Energy use from buildings accounts for 19% of the UK's greenhouse gas emissions (HM Government, 2020). The performance of building fabric will play a crucial role in decarbonising this sector through energy efficient retrofits and high performance in new constructions reducing heating demand. This will in turn contribute to tackling fuel poverty; an issue that is exacerbated by increasing energy costs.

The current regulatory method for evaluating building fabric performance uses predicted values of fabric performance based on the age and construction of the building. These values are used to compute the HTC (Heat Transfer Coefficient) of the building and its annual energy use. The HTC characterises whole house heat loss

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through both transmission and infiltration and details the power required to achieve a given internal / external temperature difference in units of W/K (BSI, 2017). This process is used to determine the EPC (Energy Performance Certificate) banding of the building's energy performance.

It has been identified that assumptions in such calculation methodologies may not always be accurate, manifesting in a “prediction gap” a difference between actual and predicted energy performance (Fitton, 2021; Marshall *et al.,* 2017).

Awareness of the prediction gap has highlighted the benefits of measuring building performance, particularly the HTC (Deb *et al.,* 2021). Building performance measurement used in legislation could potentially be introduced soon, although it is acknowledged that the lack of a thoroughly validated method could inhibit this (Fitton, 2021).

Measuring the performance of existing building stock enables the construction sector to "Build Back Wiser" in respect of conducting more meaningful building performance evaluation compared to that completed through predictions. Accurate performance evaluations are of high importance when completing energy efficient retrofit to determine what improvement (if any) has been achieved (BSI, 2022). The work presented aims to further understanding of the QUB/e measurement technique for wider application.

QUB/e Method

The QUB/e method is an in-situ measurement technique, developed by Saint-Gobain capable of measuring the as built HTC and U-values of an unoccupied property within a single night. As such it has potential to be a cheaper and quicker technique than conventional alternatives (Alzetto, Farmer, *et al.,* 2018). The procedure consists of a constant heat input and a free cooling phase of equal length, taking place at night to limit the impact of solar radiation. The thermal response of the building takes the form of a first order differential equation, and the associated algebra can be used to compute the HTC of the building and its elemental U-Values (Meulemans *et al.,* 2017).

Development of the method has identified the optimal power input for the heat input stage can be determined through the dimensionless parameter α (Alpha). α characterises the power input against starting internal/external temperature difference and HTC_{ref}, a reference HTC. Studies have identified that an α value of between 0.4 - 0.7 results in the most accurate results with tests of shorter lengths (<10 hours) being more influenced by this variable (Alzetto, Meulemans, *et al.,* 2018; Meulemans *et al.,* 2017). To date, little work has been done on exploring the most appropriate method of determining HTC_{ref} for this purpose.

The duration of the QUB/e test makes it attractive to those wanting to measure building fabric performance. The single night duration is advantageous over HTC measurement through the established coheating test (2+ weeks) (Johnston *et al.,* 2013) and standardised U-Value measurement through the heat flow meter (HFM) method (ISO 9869) which requires 3 Days (BSI, 2014).

In addition to theoretical justification (Ahmad *et al.,* 2020; Alzetto, Meulemans, *et al.,* 2018), several studies have been conducted that validate the precision and/or accuracy of the procedure through completing field testing. These include:

- 150+ comparative QUB/e, coheating and HTC measurements on a 1900's property located in a climate chamber for various retrofit configurations (Alzetto, Farmer, *et al.,* 2018; Meulemans *et al.,* 2017).
- 150+ QUB/e tests completed on a detached 1950's uninsulated masonry property for two air permeability configurations (Sougkakis *et al.,* 2021).
- Comparative QUB/e, coheating and HFM measurements on a modern low energy house (Sougkakis *et al.,* 2021, 2017)
- Further international validation studies have been completed (Alzetto, Meulemans, *et al.,* 2018; Sougkakis *et al.,* 2018) and QUB/e has formed part of government funded building performance evaluation projects TIWI (Meulemans *et al.,* 2020) and SMETER (HM Government, 2022).

These studies validate QUB/e across property characteristics of age, insulation levels and air permeability. The impact of thermal mass has not been explicitly explored.

Thermal Mass

The thermal mass of a building is its ability to absorb, store and release heat and can be a beneficial feature in building design (Wallin, 2010). Measurement of high thermal mass (e.g., stone) buildings is valuable as common methods of predicting fabric performance for these constructions are not accurate (Baker, 2011). However, measurement of such buildings can be challenging. When conducting a co-heating test several days may be required for the building to reach heat saturation required for the test to commence (Johnston *et al.,* 2013). It has also been suggested that longer data-aggregation intervals are required to smooth the effects of stored heat within the building fabric, further elongating the required duration (Stamp *et al.,* 2013). Furthermore, when undertaking U-Value measurement of high thermal mass, stone constructions, a minimum test duration of two weeks is suggested to take account of "the thermal inertia of the wall" (Baker, 2011).

Traditional building performance evaluation methods clearly experience challenges with high thermal mass dwellings. Given that QUB/e is relatively new, further understanding of how the QUB/e results are impacted by thermal mass and its relationship with solar radiation is also required.

METHOD

Research Design

This study aims to answer the following research question: "What are the benefits and disadvantages of measuring the performance of a high thermal mass dwelling through the QUB/e method, when compared to predicting performance?". A quantitative case study method will be used. Case studies are beneficial in exploring relationships that are not well defined (Gray, 2018). The QUB/e method has been the subject of many validation studies, though none on a high thermal mass building. This research presents the first QUB/e case study of a high thermal mass building.

Description of the Property

A series of QUB/e tests were completed on a farmhouse located in North Yorkshire, England originally constructed in the 1800's, pictured in Figure 1. The external walls of the house are approximately 500mm thick sandstone.

Assuming a thermal capacitance of 0.78KJkg^{-1}K^{-1} (Waples and Waples, 2004) gives the property a characteristic thermal mass parameter of 1,110KJm^{-2}K^{-1} positioning it comfortably above the indicative value used in SAP (Standard Assessment Procedure) for high thermal mass dwellings of 450KJm^{-2}K^{-1} (BRE, 2014). The testing was completed on the property in its uninsulated state prior to a fabric orientated retrofit.

Figure 1: External View of Farmhouse

Table 1 details the characteristics of the farmhouse building fabric along with predicted U-Values calculated by the BRE U-Value calculator software and /or SAP (Appendix S). Since its original construction there have been multiple additions to the property including a ground floor extension and conservatory. The property is also adjoined to a converted former barn introducing an effective solid party wall to the property, for the purposes of this study the conservatory and the former barn area are excluded from the thermal perimeter of the property. The air permeability was measured at 19.8m^{3}m^{-2}hr^{-1}@50Pa post study. The maximum allowable air permeability for new build homes is 10m^{3}m^{-2}hr^{-1}@50Pa indicating the building is leaky by modern standards.

Table 1: Farmhouse Building Fabric Characteristics

Fabric Element	Construction	U-Value BRE Calculator / SAP (Wm-2K-1)
External Walls	500 mm Sandstone	2.44 / 2.00
Ceiling (Main House)	Pitched Roof insulated at ceiling level. 12.5 mm plaster + 100 mm mineral wool insulation	0.42/ 0.40
Ceiling (Ground floor extension)	Pitched roof no insulation. 12.5 mm plaster	2.50 / 2.30
Floor	50 mm screed + 100mm rock straight on ground	0.60 / 0.64
Windows (7 No.)	Single glazed windows with wooden frames	- / 4.80
Windows (4 No.)	1980's double glazed units with wooden frames	- / 2.80
Windows (5 No.)	Modern style double glazed units	- / 2.00
Doors	Single glazed glass with wooden partitions (assumed same performance as single glazed windows)	-/ 4.80

Reference HTC and Predicted Performance

The predicated U-Values listed in Table 1 will allow for comparisons against measured values. These were used to predict the property performance and calculate HTC$_{ref}$ to determine the ideal heat input and starting temperature for the QUB/e tests.

HTC_{ref} was computed using the BRE domestic energy model that mirrors the calculation basis for SAP, used in production of EPC's. Comparing this predicted performance to measurements will identify any prediction gap that would occur if this was the sole method of evaluating pre-retrofit performance.

The U-values used to compute HTC_{ref} were those listed in Table 1 using BRE calculated values for opaque elements and SAP values for glazing. In the absence of thermal bridging details, a global Y value of 0.15 $Wm^{-2}K^{-1}$ was used as an estimate of thermal bridging losses throughout the property. The infiltration rate was based on 0.83 air changes/hour, an estimate considering the property construction and low quality of seals around openings. The measured air permeability was not used as this was unknown when the study was undertaken. This calculates $HTC_{ref} = 548$ W/K that would be used to set up the QUB/e tests.

Testing and Analysis Procedure

Testing was conducted at the property over a ten-night period in January 2022. The optimal heat input and internal temperature was calculated referring to HTC_{ref} and the forecast external temperature. A power input of 7.5 kW was sized though a combination of 2 kW and 500 W heaters giving an optimal initial temperature difference ~6 K to achieve an α value in the recommended range. A larger power input would have been preferable as it would allow for greater range of temperature difference whilst still resulting in a compliant α value. However, this needed to be balanced against the limits of the electrical supply of the property.

The following monitoring equipment was deployed. The power draw of heaters was monitored through a kWh pulse counter, a second set of thermostatically and timer-controlled heaters were used to maintain the optimal starting temperature. Temperature sensors were placed on a tripod in each room to ensure a central representative temperature. Two external temperature sensors were shielded and placed outside to monitor the external temperature along with a south facing pyranometer to measure solar radiation. Huskeflux heat flux plates (HFP) were affixed to external walls, glazed elements for U-value measurement along with the ground floor and elements facing the conservatory and barn areas that were excluded from the thermal perimeter.

20 QUB/e tests were performed at 10-, 6-, 4- and 2-hour duration. A 10-hour test duration represents a minimum, ideal, test duration. Shorter durations have been demonstrated as being accurate in several properties although more influenced by the α value (Alzetto, Meulemans, *et al.,* 2018) and problematic on U-Value measurement on elements of higher thermal mass (Sougkakis *et al.,* 2022). The inclusion of the shorter durations aims to identify whether they can be effective in QUB/e HTC measurement in this instance of extreme thermal mass. Shorter durations could be advantageous in locations with shorter nights and position QUB/e as an evening measurement activity rather than overnight if required by project time constraints.

Over the testing period measurement of U-values was also undertaken in line with ISO 9869, which could then be compared to the QUB/e measurements. The HTC and U-Values were determined using established QUB/e algebra (Alzetto, Meulemans, *et al.,* 2018; Meulemans *et al.,* 2017). The QUB/e measurement uncertainty was calculated through Taylor's series of uncertainty propagation (Ghiaus and Alzetto, 2019). By evaluating the spread of results and comparing measurements to predictions the suitability of QUB/e on high thermal mass buildings and the impact of solar can be determined.

FINDINGS

QUB/e U-Value Measurements

The accuracy and precision of the QUB/e U-Value measurements are evaluated in Table 2. Statistical measures of RMSE (Root Mean Square Error) and MBE (Mean Bias Error) are presented to describe the dispersion of the QUB/e measurements against the ISO 9869 method. The average QUB/e results are also compared against their corresponding predicted performance used to compute HTC_{ref}.

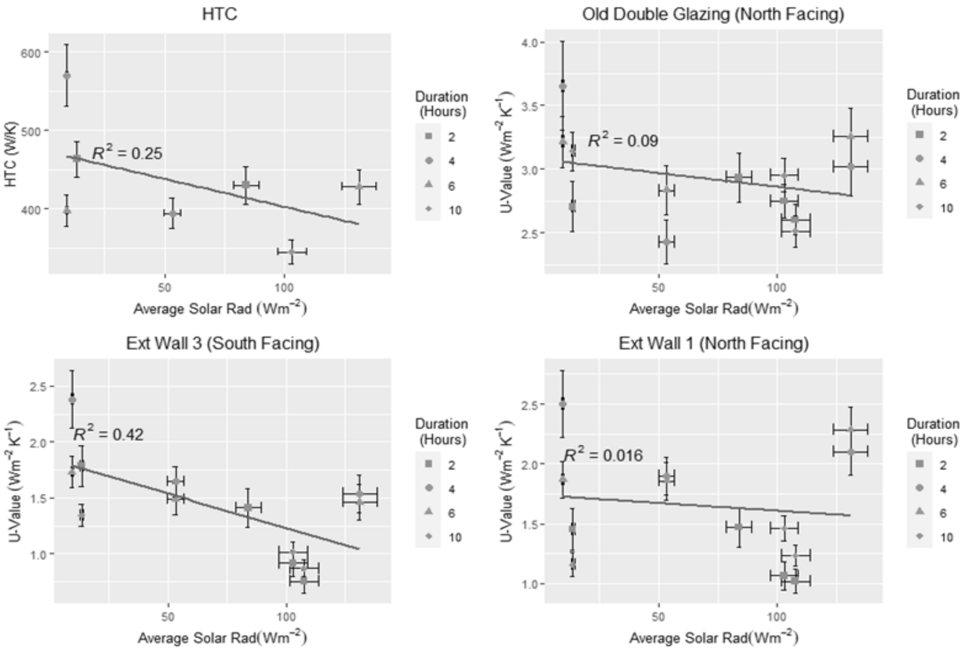
Table 2: Summary of QUB/e and HFM U-Value Measurements

U-Value (Wm-2K-1)

HFP (Orientation)	Average QUB/e Result	ISO 9869 Result	RMSE	MBE	+/-% QUB/e Against Prediction
Ext Wall 1* (North)	1.48±0.37	1.45±0.12	0.47 (32%)	0.21 (14%)	-38.38%
Ext Wall 2* (South)	0.55±0.34	0.51±0.14	0.46 (90%)	0.22 (44%)	-76.90%
Ext Wall 3 (South)	1.22±0.43	1.30±0.33	0.48 (37%)	0.13 (10%)	-49.28%
Ext Wall 4 (East)	1.20±0.23	1.19±0.07	0.27 (23%)	-0.02 (2%)	-49.96%
Ext Wall 5 (North)	1.54±0.38	1.98±0.14	0.49 (25%)	-0.12 (6%)	-35.77%
Modern Double Glazing (South)	1.31±0.15	1.37±0.03	0.18 (13%)	-0.05 (4%)	-34.63%
Old Double Glazing (North)	2.76±0.26	2.45±0.08	0.49 (20%)	0.38 (15%)	-1.49%
Single Glazing 1 (South)	4.63±0.50	4.93±0.07	0.62 (13%)	-0.15 (3%)	-3.54%
Single Glazing 2 (North)	4.56±0.61	4.53±0.18	0.93 (21%)	0.35 (8%)	-5.08%

* HFP did not reach the 5% convergence criteria of ISO 9869

Figure 2: QUB/e U-Value and HTC Measurements against Solar Radiation



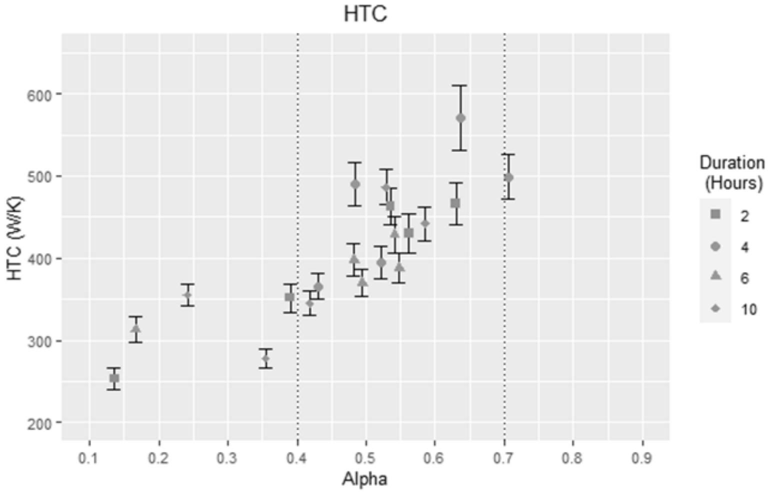
For all measurement points the average QUB/e measurements are comparable to those undertaken via ISO 9869, albeit with larger associated uncertainty. The uncertainty associated with the external wall measurements is more significant than those reported in studies for uninsulated walls of lesser thermal mass (Sougkakis *et al.,* 2022). Higher RMSE values are also observed for the external walls than glazed elements indicating that the overnight duration of QUB/e is better suited to lower thermal mass elements. This variation can be impacted through stored solar contributions that are significant in the external walls. The relationship between the measured U-values and average solar radiation recorded prior to the QUB/e test is illustrated in Figure 2. This shows a clear correlation for South facing measurements and little to no correlation for North Facing measurement evidenced by the low R squared value.

Considering this impact of solar, placing HFP on elevations that are not exposed to direct solar radiation would limit this impact and still allow the performance to be measured. This approach would not be possible for HTC measurements. Furthermore, a larger temperature difference would promote monodirectional heat transfer and lessen the proportional impact of any stored solar, this would in turn require a larger initial power input.

QUB/e HTC Measurements

The HTC measurements shown in Figure 3 are more stable between the recommended α limits of 0.4 and 0.7 although appear tightly clustered around centre of this range, indicating a heightened sensitivity to the parameter. Tests of 10-hour duration still follow this pattern indicating that, in the application of a high thermal mass dwelling, a duration of 10 hours is still impacted by the α value, and a longer duration may be necessary to limit this impact. During the testing, obstacles in achieving a compliant alpha value were identified. These include differences between the observed and forecast external temperature and the recorded power input differing from the installed rated power, possibly due to voltage fluctuations at the property. If only a single night was allocated for testing, these could result in an invalid test.

Figure 3: HTC measurements Against Alpha Value with Recommended α limits (dotted lines)



The mean result for the HTC measurements is 408.73 ± 10.46 W/K respectively with a range of 55% relative to the mean. This range of results is higher than those observed in previous works (Sougkakis *et al.,* 2021, 2022). Contributing to this dispersion of results is the impact of stored solar contributions. This creates an additional heat input to the property not accounted for in the analysis resulting in a lower HTC measurement, as shown in Figure 2. It is also likely that the high air permeability the of the property is contributing to the dispersion of results. The HTC consists of transmission and infiltration losses, the latter of which is significant due to the high air permeability. Infiltration losses are liable to vary with wind conditions and internal / external temperature difference. The effectiveness of QUB/e on buildings with such high air permeability characteristics has not been researched and cannot be isolated in the tests performed; this is an area that should be investigated further.

Comparing Measurements and Predictions

A prediction gap is evident when comparing the values of measured and predicted performance. The mean HTC measurement is -25% its predicted performance. This phenomenon is likely to be particularly pertinent to dwellings such as the farmhouse under evaluation. This is because such dwellings are often not homogenous with varying composition, cavity presence and mortar fraction (Baker, 2011). This is evidenced by varying external wall U-values in Table 2 being on average -50% that of the predicted value. 'Ext Wall 2' had a much lower U-Value than all other measurement points. This area was in an extension area of the house, possibly having a different construction than the main property despite appearing similar. This shows the advantage of performance measurements over predictions in evaluating building fabric that is heterogeneous.

The prediction gap identified impacts on the perceived energy performance of the property. Using the predicted performance equates to an EPC band F property, but substituting the mean measured HTC for HTC_{ref} would lower the banding to E. This is significant as the EPC grading is often the only interpretation of energy performance the public (including potential house buyers) will review. Moreover, had only the predicted performance been used, this would have resulted in an overestimation of the cost saving and decarbonisation benefits achieved through future retrofit. Assuming heating through a gas boiler, a fuel cost of 5p / kWh and current carbon factors, this would result in an additional £ 570 of annual heating cost and 2.3 Tonnes of CO2 equivalent emissions being assumed in the pre-retrofit baseline. The risk of such discrepancies should be considered by policy makers on retrofit, failing to conduct meaningful performance evaluation will discredit building decarbonisation plans. An analysis of EPC data shows there are at least 409,000 properties of sandstone construction in England and Wales. If the prediction gap from this case study were extrapolated to all these dwellings, 900,000 Tonnes of annual CO2 equivalent emissions retrofit savings would be overestimated in Sandstone properties alone, jeopardising national decarbonisation targets.

Whilst the benefits of performance measurement have been discussed it should be noted that completing measurements is more disruptive and potentially costly than predictions. Whilst the duration of the QUB/e test is preferable to other measurement techniques (Alzetto, Farmer, *et al.,* 2018) it would be required that residents or the construction team vacate the property to enable set up, completion and take down of the test. Comparatively, predicted HTCs could potentially be completed as a desk top exercise with minimal or no disruption.

CONCLUSIONS

The work presented shows that conducting QUB/e measurements on a high thermal mass property is possible. However, as with other measurement techniques the nature of the construction and its interaction with solar radiation introduce challenges into conducting measurements. As such a larger dispersion of results is observed compared to lower thermal mass properties.

Whilst measurement of high thermal mass properties is challenging, doing so can enable the construction sector to "Build Back Wiser" as commonly used methods of predicting performance for such dwellings are not accurate. The resulting prediction gap has impacts on the EPC banding of the property as well as the reported decarbonisation and cost saving benefits of retrofit works. To further the validation of QUB/e and answering of the research question, follow up measurements should be conducted on the property in its post-retrofit insulated state.

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