THE SPAB RESEARCH REPORT 1.

U-VALUE REPORT

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1. Introduction

The SPAB Research Report 1 U-value Report sets out the findings out of research work carried out into the subject of the heat loss (U-values) of traditionally-built walls. The report provides a brief background description of the origins of this project and sets out the scope of its enquiry, this is followed by a methodology chapter which gives an account of the methodologies involved in both the measurements and calculation of U-values. There is then a section on the results from the previous three year's worth of *in situ* U-value monitoring, where the walls under examination are broken down into various descriptive sub-headings and their thermal performance as measured *in situ* is scrutinised. This section is then followed by an examination of this *in situ* performance in relation to that predicted for the same walls by means of a standard U-value calculation procedure and compares and contrasts the two sets of U-values. The report concludes with a discussion of the consequences of the discrepancy between measured and calculated U-values with regard to the refurbishment of solid walls and the reduction of heat loss from traditional buildings.

Research Report 1. was first published in October 2010, this is the second revised edition published in November 2012.

2. Background

The 2009-2010 SPAB U-value research project originally evolved from a 'Science and Heritage' research proposal developed in collaboration with Dr Paul Baker of Glasgow Caledonian University to improve the energy efficiency of the SPAB offices in 37 Spital Square, London. In the light of limited research in this area the project was to act as a demonstration exemplar that would inform architecturally sensitive refurbishment work on historic buildings. Part of the project included the use of heat flux sensors to monitor heat transfer through the walls of 37 Spital Square in response to the lack of data concerning the thermal performance of old buildings. Unfortunately the 'Science and Heritage' project did not receive the necessary grant funding but the monitoring element of the research, albeit in a modified form, was enabled by the identification of an MSc Historic Building Conservation researcher interested in the energy profiles of historic buildings.

In consultation with Dr Paul Baker, Caroline Rye, then a student at the University of Portsmouth, working with Jonathan Garlick, Technical Officer at the SPAB, embarked on a programme of research to look at the *in situ* U-values of traditionally built walls. A traditional building is defined by English Heritage as being a building of solid wall construction built with permeable fabric[1] and this definition applies to the majority of walls examined in this research. The range of wall types included solid cob and stone walls, timber-framed structures with a variety of different infill materials and some walls with air gaps. The range of walls examined was intentionally diverse in order to contrast with similar work undertaken by Dr Paul Baker on behalf of Historic Scotland where the walls under review were predominantly stone, and likewise research proposed by English Heritage where the intention was to gather data for brick buildings. In addition to the accumulation of *in situ* U-value figures for various traditional construction types a further exercise was undertaken in collaboration with Cameron Scott, as part of the MSc element of the research, which compared the *in situ* U-values with figures calculated using a U-value calculating programme widely used within the construction industry, BuildDesk v3.4. The discrepancy between the figures produced by the two different U-value estimating methods was significant and provides evidence for claims that standard calculating methods underestimate the thermal performance of traditionally built buildings.

Following on from the success of this initial research and the interest generated by the first edition of Research Report 1. the SPAB decided to continue its work on the U-values of traditional walls. During the winter seasons of 2010 -12, 46 more U-value measurements have been made of 34 different walls, including walls that are part of a broader Building Performance Survey. (The SPAB Building Performance Survey looks at seven properties that are undergoing refurbishment work and measures various aspects of their performance both before and after these 'improvements'. This is the subject of the second SPAB report, Research Report 2.) The walls examined between 2010-12 were mostly solid wall constructions of historic origin with the exception of a modern straw bale construction and measurements taken from a Hemp/Lime house at Haverhill in Suffolk. Eighteen 'refurbished' walls, that is walls that have recently had modern insulation materials added, have also been measured. Once again the *in situ* U-value measurements recorded on site were compared with U-values calculated for these same walls using the U-value calculator BuildDesk v.3.4.

3. Methodologies

3.1 *In situ* U-value monitoring procedure

An *in situ* U-value is a non-destructive means of measuring thermal transmittance in site-specific, pre-existing building elements. It uses a heat flux monitor in combination with interior and exterior temperature measurements taken over time; in this way an *in situ* U-value is able to take into account thermal inertia (mass) and the effect of temperature change and other climatic conditions.

The monitoring procedure described below has been developed by Dr Paul Baker during work undertaken for Historic Scotland and follows the principles set out in prEN 12494 *Building components and elements - in situ measurement of thermal resistance and thermal transmittance* (a draft re-working of ISO 9869).

A Hukseflux HFP01 heat flux sensor is attached to the interior surface of the wall under investigation (Fig. 1). The sensors are 80mm in diameter and 5mm thick. The sensors were mounted by firstly applying a layer of double-sided adhesive tape to the back of the sensor. Secondly, low tack masking tape was applied to the wall. Finally, the heat flux sensor was applied firmly to the masked area. This arrangement was generally satisfactory for two or more weeks monitoring on painted or plastered surfaces. Wallpapered surfaces were not generally used in case of damage. On occasion, if a wall surface was uneven, such as a bare stone or limewashed rubble wall, it was necessary to attach the sensors using a small quantity of silicon sealant.

Figure 1. Heat Flux Sensor and surface temperature thermocouple.

Sensor locations were chosen to avoid probable thermal bridge locations near to windows, corners, etc., with the sensor ideally located about halfway between window and corner, and floor and ceiling. In addition, a thermographic camera was used to survey the internal face of the wall to ensure a general uniformity of surface temperature and thus establish a representative site for the placement of the sensor (Fig. 2). The heat flux data was logged on a Campbell Scientific CR1000 data logger. The Campbell data logger also recorded the surface temperature of the same wall using a type-T thermocouple taped onto the surface of the heat flux sensor (Fig. 1).

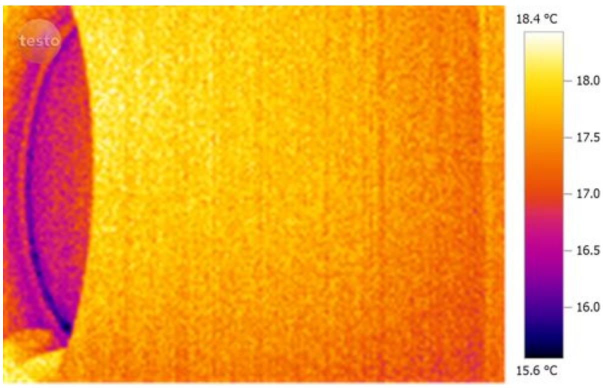

Figure 2. Thermographic image showing temperature range across a wall.

If necessary, in order to provide additional information concerning room conditions for data verification purposes, internal air temperature and relative humidity levels were monitored using dual channel Gemini TinyTag Plus 2 TGP-4520 loggers placed in proximity to the wall under investigation.

External temperatures were measured using a separate Gemini TinyTag Plus 2 TGP-4520 data logger which could be mounted outdoors. Thermistor probes were used to measure external air temperature and, generally, external wall surface temperature. Each external air temperature sensor was placed in a radiation shield which was secured, for example, onto a drainpipe (Fig. 3). Crimp-on terminals were used to fix surface temperature sensors to mortar joints, by drilling and plugging joints. Figure 3 shows the method of mounting external surface temperature sensors. In some cases external surface temperature sensors were not used either to avoid damaging the exterior surface of the building, for example, a rendered finish, or owing to difficult access.

Figure. 3. Air and surface temperature sensors.

Sensors attached to Campbell Scientific loggers were logged at 5 second intervals and averaged over 10 minutes, whilst Tinytag loggers recorded 10 minute averages of data logged at 1 minute intervals.

3.2 *In situ* U-value data analysis

Ideally, the monitoring should be carried out during the winter months when there is the greatest possibility of extremes of interior and exterior temperature difference. Given that the monitoring conditions are non-steady state, it is considered necessary to monitor for about two weeks or, preferably longer, in order to collect sufficient data to estimate *in situ* U-values. The long test duration also allows the thermal capacity of the wall to be accounted for.

The data is then used to calculate a U-value figure as a cumulative average over time (Equ. 1).

$$U_t = \frac{1}{\dfrac{\sum_{0}^{i=t} \Delta Ts_i}{\sum_{0}^{i=t} Q_i} + r_{int} + r_{ext}}$$

Equation 1. from Baker, 2008.[2]

The surface temperature difference across the wall (ΔTs) is determined in order to establish its thermal resistance. The temperature difference, as a cumulative average, across the wall (ΔTs_{i}) is divided by the cumulative average of the heat flux figure (Q_i). From this figure the sum of the standard internal and external surface resistances ($+r_{int} + r_{ext}$) are added, = 0.17m^{2}K/W) and a small correction applied for the resistance of the heat flux sensor (6.25 x 10^{-3}) is subtracted. Finally, the reciprocal of this total is taken to convert the resistance to a U-value (W/m^{2}K). In instances where it was not possible to gather external surface temperature information external air temperature was used instead and the equation does not include the external surface resistance figure (0.04m^{2}K/W). The uncertainty of the U-values estimates is about ±10%.

The U-value figure can then be plotted against time to check the quality of the data, i.e. variations should damp down and the value should approach an asymptote. Figure 4 shows the effect of increasing the length of the monitoring period on the estimate of the U-value using the averaging procedure as described above. A period of at least a week is required before the U-value estimate stabilises to within ±5% of the final value determined from about 27 days data.

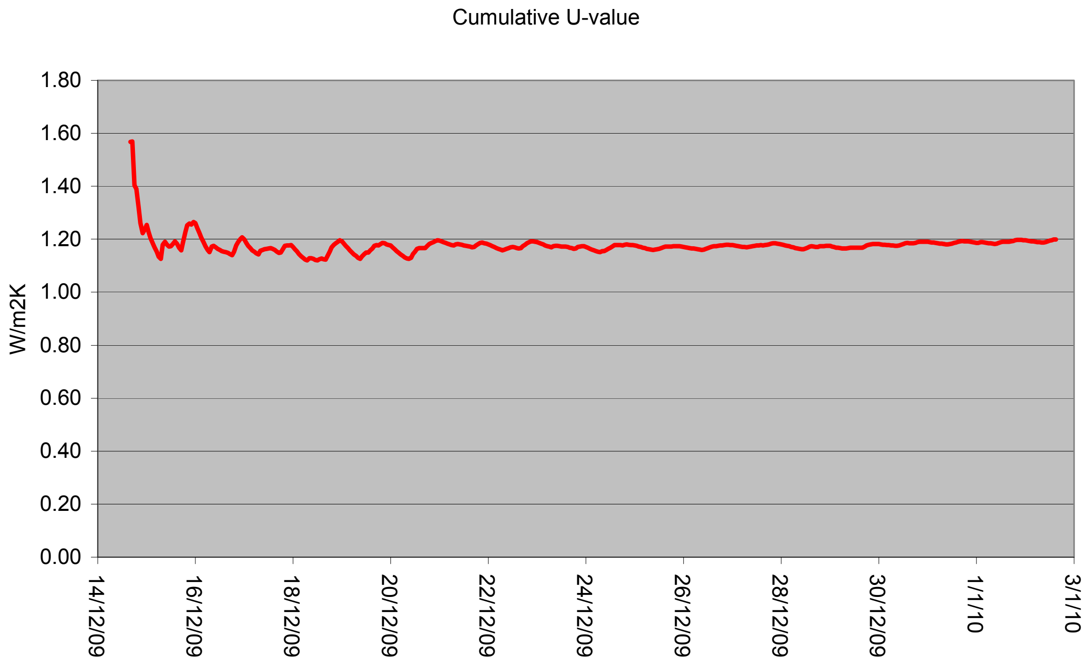

Figure 4. The stablising effect of durational monitoring. (from Baker, 2010.[3])

3.3 Calculated U-value methodology (BR 443)

U-values derived through calculation require the material characteristics of a building element to be known and defined quantitatively. Modern building elements are normally made up of a series of discreet layers of a single material, each with a known thermal conductivity and thus, through a simple summing of resistances, the U-values of these walls can be assessed at the design stage.

Historic buildings with their traditional constructions present specific difficulties in this respect as, although it maybe possible to determine the overall width of a wall, its exact build-up can be difficult to define. For example, traditional walls can be conglomerate in nature with a number of different materials combined in varying proportions to form a heterogeneous whole, e.g. straw and clay to form a cob wall. Or, in other instances, a material and/or its quantity remains unknown, for example, the proportion of mortar, voids and stone involved in the core of a stone wall. In some cases it was possible to define a build-up for the walls involved in the *in-situ* monitoring as these walls had been the subject of recent survey or building work but in the absence of specific information, in order to compare the *in-situ* U-value results with calculated figures, it was occasionally necessary to approximate data.

BuildDesk is a U-value calculating software package widely used throughout the UK building industry. BuildDesk calculations are based on the standards set out in the document BR 443 'Conventions for U-value calculations'[4] which underpin building regulation energy conservation legislation and are also the basis of various energy assessment procedures. As a market leader with a robust methodology and good usability, BuildDesk was deemed an appropriate choice of software for the U-value comparison calculations.

The element to be calculated was first defined, in this instance, an external wall with the default internal and external resistances (0.13 W/m^2K and 0.04 W/m^2K respectively). The various layers involved in the wall build-up were identified and added incrementally, the width of the particular material was entered and a resistance figure for each layer calculated from its thermal conductivity value. The information used in the calculation is sourced either from catalogues of materials that are pre-loaded within the BuildDesk software or alternatively can be entered directly by the user. Some materials used in traditional constructions are not to be found in the catalogues and here it was necessary to create new materials and enter thermal conductivity information for them from a variety of sources. However, there is in general a dearth of thermal conductivity data for traditional building materials and this contributes to additional uncertainty within calculation processes.

As has been previously stated some traditional constructions can not readily be broken down into separate layers and on some occasions, within the software, it was deemed appropriate to treat these materials as 'inhomogeneous layers' with percentage proportions given for the combined materials. For example, a lath and plaster finish was treated as two layers; a 10mm inhomogeneous layer of 83.33% wood and 16.87% lime and sand plaster and a further layer of 15mm plaster making an overall depth of 25mm. During the early part (2009-10) of this research a further anomaly was encountered when trying to calculate stone walls. The software allowed a separate mortar fraction to be entered when calculating a brick or block wall but this was not possible when specifying stone within the build-up. In effect this meant that the wall was being calculated as if it was a solid slab of stone, without taking into account the thermal effect of the mortar. Partly as a result of this research work this anomaly within the calculating software has been corrected and it is now possible to define a block size and mortar fraction for a stone wall.

The BuildDesk U-value calculations for the comparative part of the 2009 -10 research data set were carried out with the help of Cameron Scott of Timber Design Ltd. Further information about values and assumptions made in the calculating process are given in Tables 1 and 2.

4. Results and Discussion

The range of walls monitored was deliberately diverse and included historic walls walls which had been subject to recent repair and refurbishment and a few modern examples. Specific wall types consisted of mass masonry walls of granite, slate, limestone, gritstone, malmstone and flint (both as ashlar block and rubble constructions) and a section of concrete block repair work. Unfired earth-based materials were monitored either as mass wall constructions in the form of cob walls (earth and chalk) or as part of infilling material for a timber-frame as straw/clay and wattle and daub. Other timber-frame infill materials included brick and more modern infills such as hemcrete, mineral wool, sheep's wool, woodfibre board and reedboard, sometimes layered with the earlier brick material. Measurements were also taken on the timber studs of the frame itself. Almost all of the walls surveyed were solid walls of traditional (i.e. permeable) construction although a few of these walls contained cavities or air gaps formed by the addition of a lining to the interior wall face set off from the wall by battens. Five of these linings were historical consisting of either lime plaster on laths or timber paneling, others were of more recent origin when cavities had been created by fitting an additional layer to the existing wall often as part of an insulation strategy, such as the examples of stone and brick walls drylined with plasterboard, polystyrene sheets or sheep's wool. Most of the walls studied had an internal finish of lime and/or gypsum plaster and either no external finish or an external lime render. Four newly built walls, of hemp/lime, straw bale, straw/clay and a polyisocyanurate 'sandwich' were also examined, two within timber-frame structures. These timber-frame constructions also incorporated cavities in the form of a ventilated air gap behind a weatherboard external finish.

In order to structure the findings and allow some basis for comparison, the sample group has been broken down into two basic wall 'types', homogeneous and heterogeneous. Homogeneous indicates that the wall is solid and (ignoring internal and external finishes) made predominantly from a single material e.g. limestone. Heterogeneous refers to a wall where the body of the wall consists of more than one material and/or incorporates some form of air gap within its build up. These two groupings can then, to a limited extent, be further ordered in terms of their relative densities, that is subdivided between heavy weight walls made of high density materials and light weight walls of lower densities.

Tables 1 and 2 (p. 14.) detail each wall studied; its location, material build-up and the two U-value figures derived for it, one *in situ*, the other a BuildDesk calculated value. Also given in these tables are details concerning thermal conductivities and their sources, as well as other assumptions used in the U-value calculation.

There is some uncertainty about a few elements of the build up and wall thickness data within the study. Burrow Farm near Taunton is a multi-period farmhouse built principally of rendered stone and cob which has been the subject of much alteration and repair over the years. A south-west facing bedroom wall (4c) was described as being a wall consisting of a concrete block repair but there was no absolute certainty about this and the *in situ* value recorded is similar to one achieved for a cob wall of the same width at the same location. On the opposing wall of the same room, a large cavity had been formed by a primitive dry-lining using deep studs placed against the interior face of a thin exterior cob wall to support a lath and lime plaster internal finish. Here it was not possible to say for certain the exact width of the cavity and this figure has been estimated from photographs of the exposed wall head taken during repair work. Abbeyforegate in Shrewsbury is an early nineteenth century three storey house, its was difficult to determine the exact dimensions of the gable end wall of the second floor bedroom, created from a previous partition wall when part of the terrace was demolished, therefore these dimensions have been extrapolated from other wall dimensions found within the house.

4.1 Results Tables

Table 1. Homogeneous Walls.

ID	Location	Principal material	Wall Build Up detail	mm	Thickness	In-situ U-value	Calculated U value	λ value used M/WK	λ value source	Calculation Notes
	HOMOGENEOUS									
4b	BURROW FARM		Lime plaster	15				0.800	BS/EN 12524	
	Stawley, Taunton		Granite	400				2.800	BS/EN 12524	Granite (2500 kg/m3)
			Cement render	13				1.000	BS/EN 12524	
	Bedroom - east wall	Stone	Lime roughcast render	25	453	**1.75**	**2.56**	0.800	BS/EN 12524	
7a	OXENHAM FARM		Gypsum skim	3				0.570	BS/EN 12524	
	Sigford, Newton Abbott	Stone	Granite	507	510	**1.27**	**2.42**	2.800	BS/EN 12524	Granite (2500 kg/m3)
5c	HIGHER UPPACOTT		Lime plaster	10				0.800	BS/EN 12524	
	Poundgate, Newton Abbott	Stone	Granite	615	625	**0.76**	**2.49**	2.800	BS/EN 12524	In situ figure anomolous?
6a	YOULDITCH FARM									Granite (2500 kg/m3)
	Peter Tavy, Tavistock	Stone	Granite/slate rubble	650	650	**1.25**	**1.96**	2.800	BS/EN 12524	Granite fig. used (2.2 for slate)
6b	YOULDITCH FARM									Granite (2500 kg/m3)
	Peter Tavy, Tavistock	Stone	Granite/slate rubble	200	200	**2.16**	**3.87**	2.800	BS/EN 12524	Granite fig. used (2.2 for slate)
25a	MILL HOUSE		Granite	580				2.800	BS/EN 12524	
	Drewsteignton		Lime plaster	20				0.800	BS/EN 12524	
	NW Wall Grd Floor Study - high	Stone	Tanking & gypsum	3	603	**1.24**	**2.45**	0.570	BS/EN 12524	Granite @ 2500 kg/m3
25b	MILL HOUSE		Granite	580				2.800	BS/EN 12524	
	Drewsteignton		Lime plaster	20				0.800	BS/EN 12524	
	NW Wall Grd Floor Study - low	Stone	Tanking & gypsum	3	603	**1.50**	**2.45**	0.570	BS/EN 12524	Granite @ 2500 kg/m3
18a	MANOR FARM									
	Stockbridge, Hampshire		Flint/chalk rubble	500				3.500	BS/EN 12524	
	W Wall 1st Fl Master BedRm south end	Stone	Lime Plaster	25	525	**1.01**	**2.91**	0.800	BS/EN 12524	Basalt @3600kg/m3
18b	MANOR FARM									
	Stockbridge, Hampshire		Flint/chalk rubble	500				3.500	BS/EN 12524	
	W wall 1st Fl Master BedRm north end	Stone	Lime Plaster	25	525	**0.95**	**2.91**	0.800	BS/EN 12524	Basalt @3600kg/m3
8a	11 BELCOMBE PLACE									
	Bradford on Avon		Lime plaster skim	5				0.800	BS/EN 12524	
	Office - north wall	Stone	Limestone (ashlar)	170	175	**2.01**	**3.01**	1.100	BS/EN 12524	Soft Limestone
9a	FARRINGDON									
	Oxfordshire		Lime plaster	15				0.800	BS/EN 12524	
	Bedroom - south wall	Stone	Limestone (ashlar)	415	430	**1.62**	**1.77**	1.100	BS/EN 12524	Soft Limestone
9b	FARRINGDON									
	Oxfordshire		Lime plaster	15				0.800	BS/EN 12524	
	Bedroom - east wall	Stone	Limestone (rubble)	465	480	**1.05**	**1.64**	1.100	BS/EN 12524	Soft Limestone
10a	KIRKLINGTON									
	Oxfordshire		Limewash	1				0.570	BS/EN 12524	
	Living Room - south wall	Stone	Limestone	625	626	**1.47**	**1.35**	1.100	BS/EN 12524	Soft Limestone
10b	KIRKLINGTON									
	Oxfordshire		Limewash	1				0.570	BS/EN 12524	
	Living Room - south wall	Stone	Limestone	280	281	**1.83**	**2.35**	1.100	BS/EN 12524	Soft Limestone
22a	APRIL COTTAGE		Limestone (Horton) rubble	499						
	Lower Brailes, Banbury		Lime plaster	20				0.570	BS/EN 12524	
	N. Wall Grd Floor Living Rm/Office - low	Stone	Gypsum skim	3	522	**1.39**	**2.03**	0.570	BS/EN 12524	
22b	APRIL COTTAGE		Limestone (Horton) rubble	499						
	Lower Brailes, Banbury		Lime plaster	20				0.570	BS/EN 12524	
	N. Wall Grd Floor Living Rm/Office - high	Stone	Gypsum skim	3	522	**1.49**	**2.03**	0.570	BS/EN 12524	
24a	THE OLD ARMOURY		Lime render	40				0.800	BS/EN 12524	
	Ashburton, Devon		Limestone rubble	534				1.700	BS/EN 12524	
	E. Wall Grd Floor Sitting Rm - low	Stone	Lime plaster	20	594	**1.33**	**1.79**	0.800	BS/EN 12524	Hard Limestone 2200 kg/m3
24b	THE OLD ARMOURY		Lime render	40				0.800	BS/EN 12524	
	Ashburton, Devon		Limestone rubble	534				1.700	BS/EN 12524	
	E. Wall Grd Floor Sitting Rm - high	Stone	Lime plaster	20	594	**1.04**	**1.79**	0.800	BS/EN 12524	Hard Limestone 2200 kg/m3
11b	HUCKERS COTTAGE									
	Selborne, Hants		Gypsum plaster	15				0.570	BS/EN 12524	
	Landing - east wall	Stone	Malmstone (Upper Greensand)	310	325	**1.45**	**3.02**	2.300	BS/EN 12524	Natural sedimentary rock
21a	WHITE HOUSE FARM		Gritstone rubble	549				2.300	BS/EN 12524	
	Skipton		Lime plaster	3				0.570	BS/EN 12524	
	S Wall 1st Floor Bedroom - low	Stone	Cement skim	20	572	**1.63**	**2.31**	1.000	BS/EN 12524	Silica @ 2600 kg/m3
21b	WHITE HOUSE FARM		Gritstone rubble	549				2.300	BS/EN 12524	
	Skipton		Lime plaster	3				0.570	BS/EN 12524	
	S Wall 1st Floor Bedroom - high	Stone	Cement skim	20	572	**1.62**	**2.31**	1.000	BS/EN 12524	Silica @ 2600 kg/m3
4c	BURROW FARM		Lime plaster	15				0.800	BS/EN 12524	
	Stawley, Taunton		Concrete block/Cob?	460				1.188	BS/EN 12524	Density 1800 kg/m3
	Middle Bedroom south wall	Block	Lime roughcast	25	500	**0.88**	**1.65**	0.800	BS/EN 12524	In situ range 0.83 - 0.93
1c	BLEWBURY		Lime plaster	12.0				0.800	BS/EN 12524	
	Oxfordshire		Brick panel infill	102.5				0.560	BS/EN 12524	
	Landing - south east wall	Brick	Lime render	20.0	134.5	**2.48**	**2.49**	0.800	BS/EN 12524	
12a	37 SPITAL SQUARE							0.770	Build Desk	Outer Brick work
	London		Brick	460				0.560	Build Desk	Inner Brick work
	South wall 3rd floor staircase	Brick	Lime plaster	18	478	**0.76**	**1.11**	0.800	BS/EN 12524	
20a	116 ABBEYFOREGATE		Brick	362				0.805	Build Desk	Outer Brick work
	Shrewsbury		Lime plaster	16				0.800	BS/EN 12524	Inner Brick work - 0.560
	South wall Grd floor Sitting Rm	Brick	Gypsum skim	2	380	**1.48**	**1.52**	0.570	BS/EN 12524	
20c	116 ABBEYFOREGATE		Brick	230				0.805	Build Desk	Outer Brick work
	Shrewsbury		Lime plaster	16				0.800	BS/EN 12524	
	Bedroom W Gable, N side of chimney	Brick	Gypsum skim	2	248	**2.13**	**2.10**	0.570	BS/EN 12524	
20d	116 ABBEYFOREGATE		Brick	230				0.805	Build Desk	Outer Brick work
	Shrewsbury		Lime plaster	16				0.800	BS/EN 12524	
	Bedroom W Gable, S side of chimney	Brick	Gypsum skim	2	248	**2.33**	**2.10**	0.570	BS/EN 12524	
29a	RECTORY GROVE,		Lime plaster	35				0.800	BS/EN 12524	
	Clapham, London		Brick	345				0.560	BR 443	Inner layer brick
	Hallway - north wall	Brick			380	**0.88**	**1.34**	0.770	BR 443	Outer layer brick
26a	C2a Inner		Lime plaster	20				0.800	BS/EN 12524	
	New Court, Trinity College, Cambs		Brick	570				0.560	BR 443	
	Sitting rm - east wall	Brick	Roman cement	10	600	**0.68**	**0.86**	1.000	BS/EN 12524	OPC Render
26b	C2a Outer		Lime plaster	30				0.800	BS/EN 12524	
	New Court, Trinity College, Cambs		Brick	460				0.560	BR 443	
	Bedroom rm - west wall	Brick	Limestone	150	640	**0.77**	**0.90**	1.400	BS/EN 12524	2000 kg/m3
26c	E3 Outer		Lime plaster	30				0.800	BS/EN 12524	
	New Court, Trinity College, Cambs							0.560	BR 443	
	Bedroom rm - south wall	Brick	Brick	570	600	**0.78**	**0.90**	0.770	BR 443	
26d	G4a Outer		Lime plaster	30				0.800	BS/EN 12524	
	New Court, Trinity College, Cambs							0.560	BR 443	
	Bedsitting rm - south wall	Brick	Brick	570	600	**0.64**	**0.90**	0.770	BR 443	
26e	L4b Outer		Lime plaster	20				0.800	BS/EN 12524	
	New Court, Trinity College, Cambs		Brick	570				0.560	BR 443	
	Bedsitting rm - west wall	Brick	Roman cement	10	600	**0.71**	**0.86**	1.000	BS/EN 12524	
4a	BURROW FARM		Lime plaster	15				0.800	BS EN 12524	
	Stawley, Taunton		Cob	400				0.800	Timber Design	
			Cement render	13				1.000	BS EN 12524	
	Bedroom - east wall	Cob	Lime roughcast render	25	453	**0.91**	**1.24**	0.800	BS EN 12524	
7b	OXENHAM FARM									
	Sigford, Newton Abbott	Cob	Cob	510	510	**2.26**	**1.11**	0.700	Timber Design	
23a	THE FIRS		Cement render	40				1.000	BS EN 12524	
	Riddlecombe, Devon		Cob	617				0.730	BS EN 12524	Devon Earth Building Association
			Clay & Lime plaster	20				0.800	BS/EN 12524	
	S. Wall Grd Floor Office - low	Cob	Gypsum skim	3	680	**1.05**	**0.93**	0.570	BS/EN 12524	0.73 low density cob
23b	THE FIRS		Cement render	40				1.000	BS EN 12524	
	Riddlecombe, Devon		Cob	617				0.730	BS EN 12524	Devon Earth Building Association
			Lime plaster	20				0.800	BS/EN 12524	
	S Wall Grd Floor Office - high	Cob	Gypsum skim	3	680	**0.76**	**0.93**	0.570	BS/EN 12524	0.73 low density cob
19a	SHEPHERDS HOUSE		Lime render	40				0.800	BS/EN 12524	
	Stockbridge, Hampshire		Chalk cob	442				1.100	BS/EN 12524	
	West Wall Grd Floor Sitting Rm	Cob	Lime plaster	20	502	**0.90**	**1.55**	0.800	BS/EN 12524	Soft Limestone@ 1800 kg/m3
19b	SHEPHERDS HOUSE		Lime render	25				0.800	BS/EN 12524	
	Stockbridge, Hampshire		Chalk cob	435				1.100	BS/EN 12524	
	N wall grd floor Sitting Room	Cob	Lime plaster	20	482	**1.02**	**1.61**	0.800	BS/EN 12524	Soft Limestone@ 1800 kg/m3

Table 1. Homogeneous Walls cont.

HOMOGENEOUS

ID	Location	Principal material	Wall Build Up detail	mm	Thickness	In-situ U-value	Calculated U value	λ value used M/WK	λ value source	Calculation Notes
1d	BLEWBURY		Lime plaster	12				0.800	BS/EN 12524	
	Oxfordshire		Timber stud	100				0.180	BS/EN 12524	
	Landing - south east wall	Timber	Lime render	20	132	**1.66**	**1.31**	0.800	BS/EN 12524	
1f	BLEWBURY									
	Oxfordshire									
	Bedroom - north west wall	Timber	Timber stud	100	100	**1.49**	**1.38**	0.180	BS/EN 12524	
1g	BLEWBURY		Lime plaster	12				0.800	BS/EN 12524	
	Oxfordshire		Hemcrete panel infill	150				0.110	Manufacturers	Density 480 k/m3
	Bedroom - north west wall	Hemcrete	Lime render	12	174	**0.87**	**0.64**	0.800	BS/EN 12524	
27a	HEMP HOUSE		Lime plaster	15				0.800	BS/EN 12524	
	Haverhil, Suffolk		Hemp lime	180				0.110	Evard & de Herde 20	440 kg/m3
	Bedroom - west wall (south side)	Hemp/Lime	Lime render	15	210	**0.40**	**0.56**	0.800	BS/EN 12524	
27b	HEMP HOUSE		Lime plaster	15				0.800	BS/EN 12524	
	Haverhil, Suffolk		Hemp lime	180				0.110	Evard & de Herde 20	440 kg/m3
	Bedroom - west wall (north side)	Hemp/Lime	Lime render	15	210	**0.47**	**0.56**	0.800	BS/EN 12524	
11a	HUCKERS COTTAGE		Lime plaster	20				0.800	BS/EN 12524	
	Selborne, Hants.		Straw clay	300				0.100	Franz Volhard	Density 300kg/m3
			Lime clay plaster skim	5				0.910	Timber Design	
			Air gap	50				0.278	BS EN ISO 6946	Well ventilated air layer
	Landing - south wall	Straw/Clay	Western red cedar w/board	23	398	**0.28**	**0.30**	0.130	BS/EN 12524	
16a	WALLED GARDEN		Lime render	85				0.800	BS/EN 12524	
	Childrey, Oxfordshire		Straw bale	300				0.052	FASBA	Association of Straw Bale Building
	East wall grd floor master bed Rm low straw	Straw Bale	Lime plaster	50	435	**0.16**	**0.16**	0.800	BS/EN 12524	
24c	THE OLD ARMOURY		Asbestos sheet	6				0.166	Engineering Toolbox	
	Ashburton, Devon		Rockwool	85				0.037	Manufacturers	
			Plasterboard	9.5				0.190	Manufacturers	
	East Wall 1st Fl Bedroom - low	Mineral Wool	Gypsum skim	4.5	105	**0.46**	**0.43**	0.570	BS/EN 12524	
24d	THE OLD ARMOURY		Asbestos sheet	6				0.166	Engineering Toolbox	
	Ashburton, Devon		Rockwool	85				0.037	Manufacturers	
			Plasterboard	9.5				0.190	Manufacturers	
	E Wall 1st Fl Bedroom - high	Mineral Wool	Gypsum skim	4.5	105	**0.35**	**0.43**	0.570	BS/EN 12524	

Table 2. Heterogeneous Walls.

HETEROGENEOUS

ID	Location	Principal material	Wall Build Up detail	mm	Thickness	In-situ U-value	Calculated U value	λ value used M/WK	λ value source	Calculation Notes
5a	HIGHER UPPACOTT	Stone &	Gypsum skim	3				0.570	BS/EN 12524	
	Poundgate, Newton Abbott	Newtonite	Newtonite lath	10				0.080	Manufacturers	Fillcrete - Panelvent (approx.)
			Air gap	75				0.417	BR443	Unventilated airspace
	Living room - south wall		Granite	715	803	**1.07**	**1.38**	2.800	BS/EN 12524	Granite [2500 kg/m3]
25c	MILL HOUSE	Stone & PIR	Gypsum skim	3				2.800	BS/EN 12524	
	Drewsteignton		Plasterboard	12.5				0.125	BS/EN 12524	
			Air gap	25				0.139	BR 443	
			PIR Board	100				0.022	Manufacturers	
			Tanking & gypsum	3				0.570	BS/EN 12524	
			Lime plaster	20				0.800	BS/EN 12524	
	NW Wall Grd Floor Study		Granite	580	744	**0.16**	**0.19**	2.800	BS/EN 12524	Granite @ 2500 kg/m3
8b	11 BELCOMBE PLACE	Stone &	Gypsum skim	3.0				0.570	BS/EN 12524	In situ range 0.96 - 0.97
	Bradford on Avon	Plasterboard	Plasterboard	12.5				0.250	BS/EN 12524	
			Air gap	10.0				0.067	BS EN ISO 6946	Unventilated - Horiz. heat flow
	Bedroom - east wall		Limestone (ashlar)	170.0	195.5	**0.97**	**1.90**	1.100	BS/EN 12524	Limestone - soft
28a	POUND FARM	Stone &	Gypsum skim	3				0.570	BS/EN 12524	
	Woolbedding, W. Sussex	Plasterboard	Plasterboard	13				0.210	BR 443	
			Air gap/battens	25				0.132	BS 6946/BS EN 12524	Unventilated - Horiz. heat flow
			Lime plaster	20				0.800	BS/EN 12524	
	Sitting rm south wall High		Lower Greensand	590	650	**0.76**	**0.87**	0.850	BS/EN 12524	Density 1500 kg/m3
28b	POUND FARM	Stone &	Gypsum skim	3				0.570	BS/EN 12524	
	Woolbedding, W. Sussex	Plasterboard	Plasterboard	13				0.210	BR 443	
			Air gap/battens	25				0.132	BS 6946/BS EN 12524	Unventilated - Horiz. heat flow
			Lime plaster	20				0.800	BS/EN 12524	
	Sitting rm south wall - low		Lower Greensand	590	650	**0.86**	**0.87**	0.850	BS/EN 12524	Density 1500 kg/m3
29b	RECTORY GROVE,	Brick &	Gypsum skim	3				0.570	BS/EN 12524	
	Clapham, London	Plasterboard	Plasterboard	13				0.210	BR 443	
			Air gap/battens	215				0.991	BS EN ISO 6946	
			Lime plaster	25				0.800	BS/EN 12524	
								0.560	BR 443	Inner layer brick
	Living rm - west wall		Brick	340	593	**0.88**	**0.93**	0.770	BR 443	Outer layer brick
26f	E3 Inner	Brick, lath &	Lime plaster	19				0.800	BS/EN 12524	
		Lime plaster	Lath & Lime plaster	8				0.304	BS/EN 12524	
			Air gap/battens	35				0.176	BS 6946/BS EN 12524	
	New Court, Trinity College, Cambs		Brick	570				0.560	BR 443	
	Siting rm - north wall		Roman cement render	43	675	**0.59**	**0.70**	1.000	BS/EN 12524	OPC Render
26g	L3 Inner	Brick, lath &	Lime plaster	18				0.800	BS/EN 12524	
		Lime plaster	Lath & Lime plaster	7				0.304	BS/EN 12524	
			Air gap/battens	35				0.176	BS 6946/BS EN 12524	
	New Court, Trinity College, Cambs		Brick	570				0.560	BR 443	
	Bedsitting rm - west wall		Roman cement render	10	640	**0.61**	**0.72**	1.000	BS/EN 12524	OPC Render
26h	E4 Outer	Brick, lath &	Lime plaster	20				0.800	BS/EN 12524	
		Lime plaster	Lath & Lime plaster	8				0.304	BS/EN 12524	
			Air gap/battens	35				0.176	BS 6946/BS EN 12524	
	New Court, Trinity College, Cambs		Brick	477				0.560	BR 443	
	Sitting rm - west wall		Limestone	150	690	**0.70**	**0.74**	1.400	BS/EN 12524	2000 kg/m3
12b	37 SPITAL SQUARE	Brick &	Brick	460				0.770	Build Desk	Inner Brick work - 0.560
	London	Timber Panelling	Air gap	22				0.112	BS EN ISO 6946	
	South wall 3rd floor staircase		Timber panel	8	490	**0.71**	**0.88**	0.120	Build Desk	
14a	ST ANNS ROAD	Brick &	Plasterboard & skim	15				0.120	Build Desk	
	Faversham	Sheeps wool	Second Nature Thermafleece	150				0.039	Manufactures	
			Air gap	50				0.278	BS EN ISO 6946	
			Lime plaster	30				0.800	BS/EN 12524	
			Brick	215				0.770	BS/EN 12524	
	East wall 1st fl Bedroom		Render.	40	500	**0.30**	**0.24**	0.800	BS/EN 12524	
14b	ST ANNS ROAD	Brick &	Sto acrylic render	6				0.700	Manufacturers	
	Faversham	Polystyrene	Expanded polystyrene	100				0.027	Build Desk	
			Cement render	30				1.000	Build Desk	
			Brick	215				0.770	Build Desk	
	South wall 1st fl Bedroom		Plaster	30	381	**0.53**	**0.26**	0.800	BS/EN 12524	
15a	LITTLE TRITON	Brick &	Brick	220.0				0.770	Build Desk	
	Blewbury, Oxfordshire	Polystyrene	Air gap/battens	50				0.278	BS EN ISO 6946	
	North wall grd floor Sitting Rm west end brick		Thermaline	30				0.040	Manufacturers	
			Gypsum skim	4	304	**0.61**	**0.79**	0.570	BS/EN 12524	
15b	LITTLE TRITON	Brick &	Render	24				0.800	BS/EN 12524	
	Blewbury, Oxfordshire	Polystyrene	Brick	215				0.770	Build Desk	
	North wall grd floor Sitting Rm east end render		Air gap/battens	50				0.278	BS EN ISO 6946	
			Thermaline	30				0.040	Manufacturers	
			Gypsum skim	3	322	**0.56**	**0.77**	0.570	BS/EN 12524	

Table 2. Heterogeneous Walls cont.

	HETEROGENEOUS									
ID	**Location**	**Principal material**	**Wall Build Up detail**	**mm**	**Thickness**	**In-situ U-value**	**Calculated U value**	**λ value used M/WK**	**λ value source**	**Calculation Notes**
20b	116 ABBEYFOREGATE	Brick &	Insulating render	40				0.200	Manufacturers	
	Shrewsbury	Insulating render	Brick	122				0.636	Build Desk	
			Lime plaster	16				0.800	BS/EN 12524	
	W wall grd floor Sitting Room		Gypsum skim	2	180	**2.09**	**1.71**	0.570	BS/EN 12524	
20e	116 ABBEYFOREGATE	Brick &	Lime plaster	8				0.540	Manufacturers	
	Shrewsbury	Woodfibre	Woodfibre insulation	40				0.039	Manufacturers	
			Lime plaster	16				0.800	BS/EN 12524	
			Brick	228				0.636	BR 443	
	W wall grd floor Sitting Room		Insulating render	40	332	**0.63**	**0.62**	0.200	Manufacturers	
20f	116 ABBEYFOREGATE	Brick &	Lime plaster	8				0.540	Manufacturers	
	Shrewsbury	Woodfibre	Woodfibre insulation	40				0.039	Manufacturers	
			Lime plaster	12				0.800	BS/EN 12524	
	South wall Grd floor Sitting Rm		Brick	345	405	**0.48**	**0.59**	0.805	BR 443	Outer Brick work
1a	BLEWBURY	Brick &	Lime plaster	12.0				0.800	BS/EN 12524	
	Oxfordshire	Reedboard	Reedboard	20.0				0.056	Manufacturers	
			Brick panel infill	102.5				0.560	BS/EN 12524	
	Bedroom - south east wall		Lime render	20.0	154.5	**1.12**	**1.33**	0.800	BS/EN 12524	
17a	GOSWELLS	Brick &	Brick	230.0				0.770	Build Desk	Inner Brick work - 0.560
	Cholsey, Oxfordshire	Reedboard	Reed mat	10				0.056	Manufacturers	
	N. wall grd floor Kitchen high		Lime plaster	33	273	**1.06**	**1.34**	0.800	BS/EN 12524	
17b	GOSWELLS	Brick &	Brick	230				0.770	Build Desk	Inner Brick work - 0.560
	Cholsey, Oxfordshire	Reedboard	Reed mat	10				0.056	Manufacturers	
	N. wall grd floor Kitchen low		Lime plaster	33	273	**1.16**	**1.34**	0.800	BS/EN 12524	
4d	BURROW FARM	Cob &	Lime plaster	15				0.800	BS/EN 12524	
		lath & plaster	Lath & Lime plaster	10				0.242	BS/EN 12524	83% timber & 17% plaster
	Stawley, Taunton		Air gap	175				0.833	BR443	150mm Unventilated Airspace
			Cob	400				0.700	BS/EN 12524	
	Bedroom - north wall		Lime roughcast	25	625	**1.57**	**0.98**	0.800	BS/EN 12524	
23c	THE FIRS	Cob &	Limewash	1				0.570	BS/EN 12524	
	Riddlecombe, Devon	Insulating Render	Lime plaster	25				0.800	BS EN 12524	
			Cob	580				0.730	Devon Earth Building Association	Low density Cob
			Stone	37				2.300	BS/EN 12524	
	S. Wall Grd Floor Office - low		Insulating render	40	683	**0.72**	**0.61**	0.660	Manufacturers	
1e	BLEWBURY	Wattle &	Lime plaster	12				0.800	BS/EN 12524	
		Daub	Daub	40					Timber Design	1.7 tonnes per m3
	Oxfordshire		Wattle	23				0.800	BS/EN 12524	Hardwood Timber [700 kg/m3]
			Daub	40				0.180	Timber Design	1.7 tonnes per m3
	Bedroom - north west wall		Lime render	10	125	**2.03**	**2.35**	0.800	BS/EN 12524	
3a	BLEWBURY	Wattle &	Lime plaster	4				0.800	BS EN 12524	
	Oxfordshire	Daub	Daub	50				0.800	Timber Design	1.7 tonnes per m3
			Wattle	25				0.180	BS EN 12524	Hardwood Timber [700 kg/m3]
			Daub	50				0.800	Timber Design	1.7 tonnes per m3
	Living Rm - north west wall		Lime render	15	144	**1.69**	**2.19**	0.800	BS EN 12524	
1b	BLEWBURY	Timber &	Lime plaster	12				0.800	BS/EN 12524	
	Oxfordshire	Reedboard	Reedboard	20				0.056	Manufacturers	
			Timber stud	100				0.180	BS/EN 12524	
	Bedroom - south east wall		Lime render	20	152	**0.57**	**0.89**	0.800	BS/EN 12524	
1h	BLEWBURY	Timber &	Lime plaster	12				0.800	BS/EN 12524	
	Oxfordshire	Hemcrete	Hemcrete	50				0.110	Manufacturers	Density 480 kg/m3
	Bedroom - north west wall		Timber stud	100	162	**0.77**	**0.71**	0.150	BS/EN 12524	
13a	TYLAND FARM	Woodfibre &	Lime render	15				0.800	BS/EN 12524	
	Maidstone, Kent	Sheepswool	Steico Protect woodfibre	80				0.049	Manufacturers	
	South wall 1st fl office		Thermafleece PB20	100				0.039	Manufacturers	
			Lath & plaster	30	225	**0.35**	**0.27**	0.800	BS/EN 12524	
13b	TYLAND FARM	Woodfibre &	Lime render	15				0.800	BS/EN 12524	
	Maidstone, Kent	Sheepswool	Steico Protect woodfibre	80				0.049	Manufacturers	
			Thermafleece PB20	100				0.039	Manufacturers	
	West wall 1st fl office		Lath & plaster	30	225	**0.19**	**0.27**	0.800	BS/EN 12524	
2a	BLEWBURY	Polyisocyanurate	Gypsum skim	3.0				0.570	BS/EN 12524	
	Oxfordshire		Plasterboard	12.5				0.250	BS/EN 12524	
			Plywood sheathing	12.0				0.130	BS/EN 12524	
			Celotex	90.0				0.023	Manufactures	
			Battens/ventilated airgap	25.0				0.278	BS EN ISO 6946	
	Modern Extension		Cedar boarding	25.0	167.5	**0.14**	**0.26**	0.130	BS/EN 12524	
16B	WALLED GARDEN	Polyisocyanurate	Celotex	90				0.023	Manufactures	
	Childrey, Oxfordshire		Ply (kerto)	50				0.130	BS/EN 12524	
			Air gap	203				1.101	BS EN ISO 6946	
	East wall grd floor master bed Rm high celo		Ply	5	348	**0.46**	**0.24**	0.130	BS/EN 12524	

4.2 Uncertainties

There are three *in situ* U-value results which are widely divergent from those measured on similar materials in the study. The U-value of 0.76 W/m^2K for a 615mm thick granite wall recorded at Higher Uppacott (5c) seems extremely low. Conversely, the value 2.26 W/m^2K for a 510mm cob wall recorded at Oxenholm Farm (7b) seems high and at this location there is the possibility of thermal bridging affecting the final result due to poor sensor placement in close proximity to an intermediate floor (Fig. 5). Example 9b from a house in Farringdon in Oxfordshire gives a figure of 1.05 W/m^2K for a limestone rubble wall. When plotted against similar wall types this figure does not conform to an overall trend and therefore may possibly be treated as an outlier or is the result of a high proportion of mortar and voids within that particular wall construction (Fig. 6).

Figure 5. Cob sensor placement at Oxenholm Farm (7b).

4.3 *In situ* results - Homogeneous Walls

Given the wide variety of wall constructions and the range of wall thicknesses, no simple cross comparisons can be made between material types and thermal performance. However, the results do reveal some interesting observations regarding the relative performance of different materials and constructions.

4.3.1 Heavyweight Homogeneous Walls

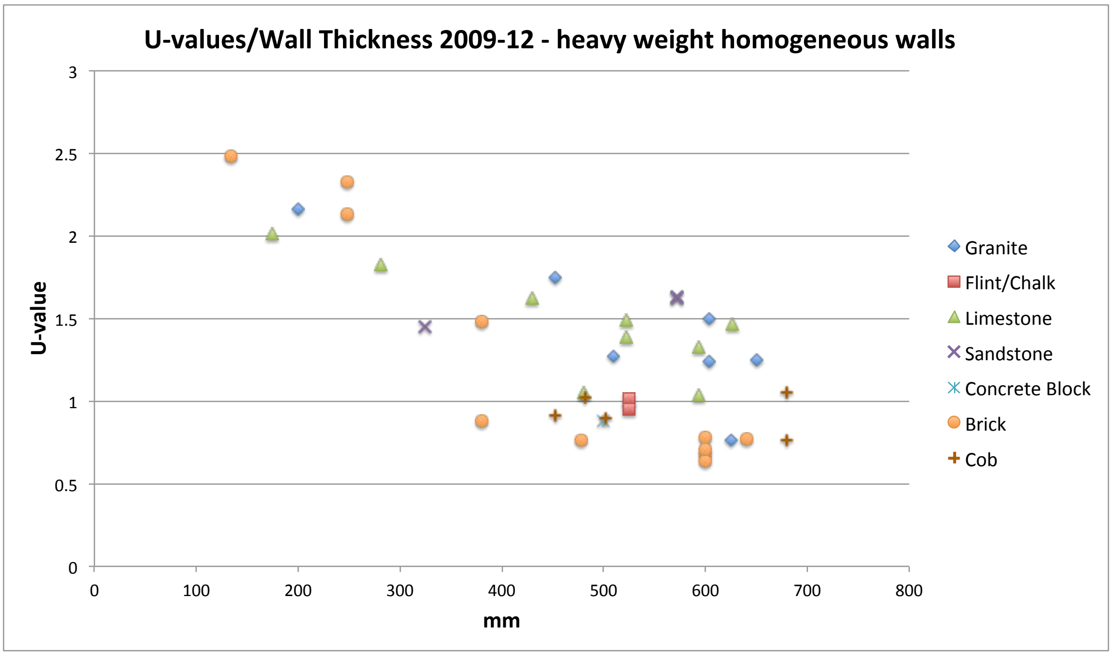

Figure 6. *In situ* U-values for heavyweight homogeneous walls 2012.

In general, in homogenous walls built of heavyweight materials e.g. stone/brick/cob, U-values seem to decline in relation to wall thickness (Fig. 6). From Figure 6 it may also be possible to identify certain 'ranges' of performance for particular materials.

Stone Walls

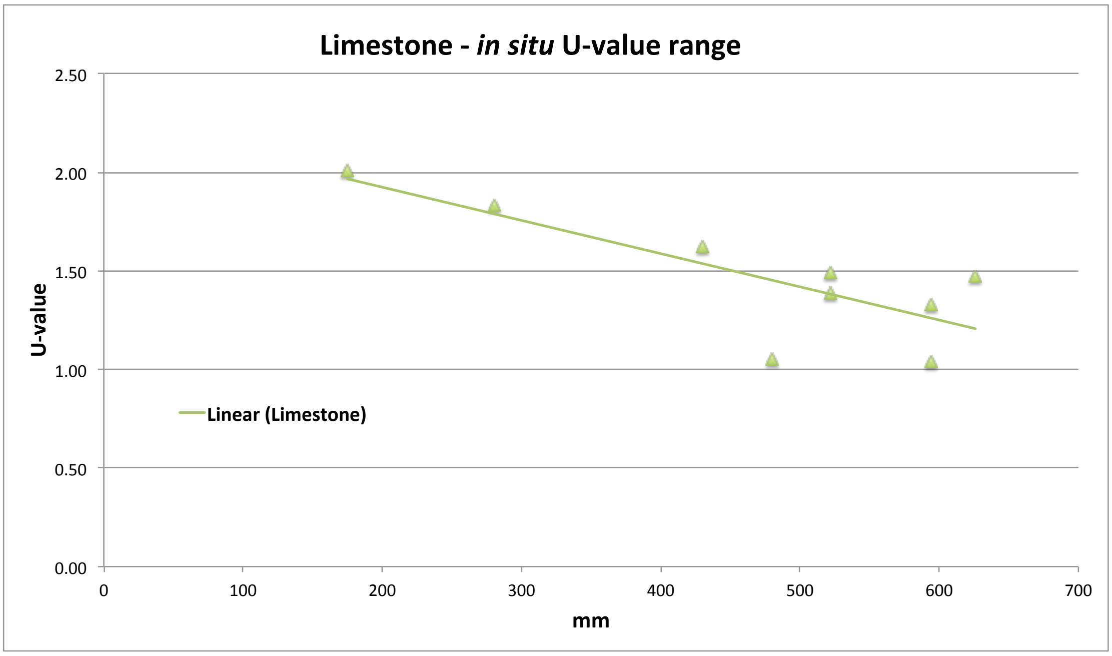

Figure 7. 2009 - 2011 Limestone *in situ* U-values.

For example, if 9b Farringdon (1.05 W/m^{2}K @ 480mm) is treated as an outlier, it is possible to identify a range of values for limestone walls of similar construction. This trend was indicated in the data gathered from the first year's U-value survey (2009-10) and has been strengthened by the addition of more data from the 2010-11 monitoring work (Fig. 7).

Similarly, if 5c Higher Uppacott (0.76 W/m^{2}K @ 625 mm) is treated as an outlier another gradient can be plotted for the results of granite walls. As might be expected for a denser material, this 'range' sits just above the limestone gradient. However, the gradient for granite walls is less satisfactory than the range identified for limestone walls as the points of correspondence with the trend line are fewer and more divergent, therefore, more data for granite walls is required to give more confidence in a performance range for this material (Fig. 8).

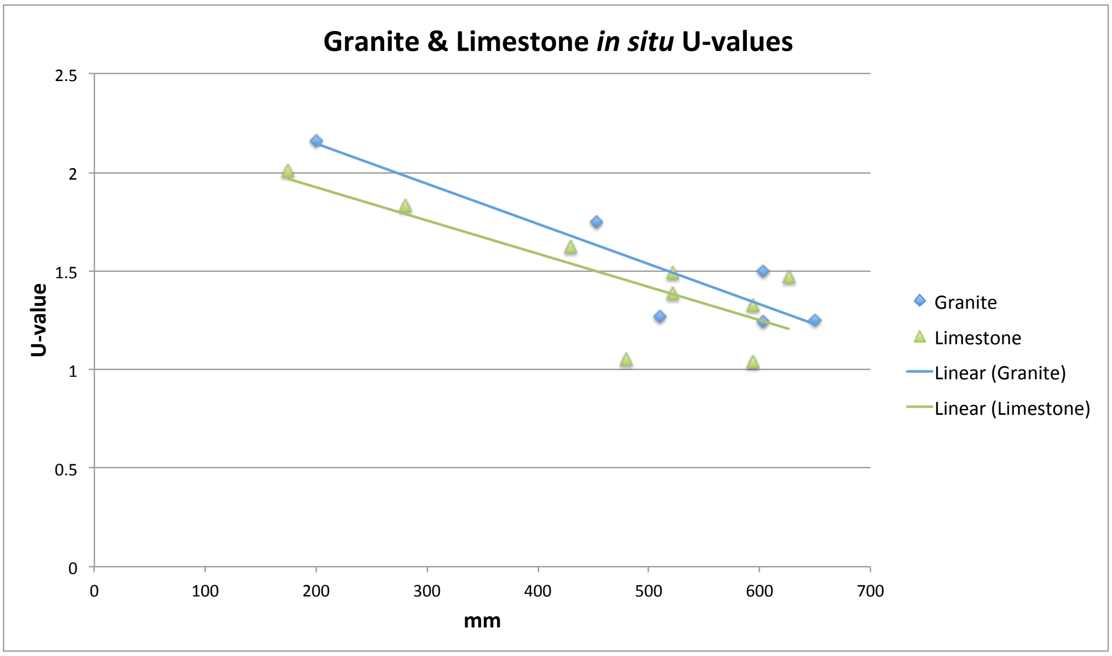

Figure 8. Granite and Limestone *in situ* U-values 2011.

Brick & Cob Walls

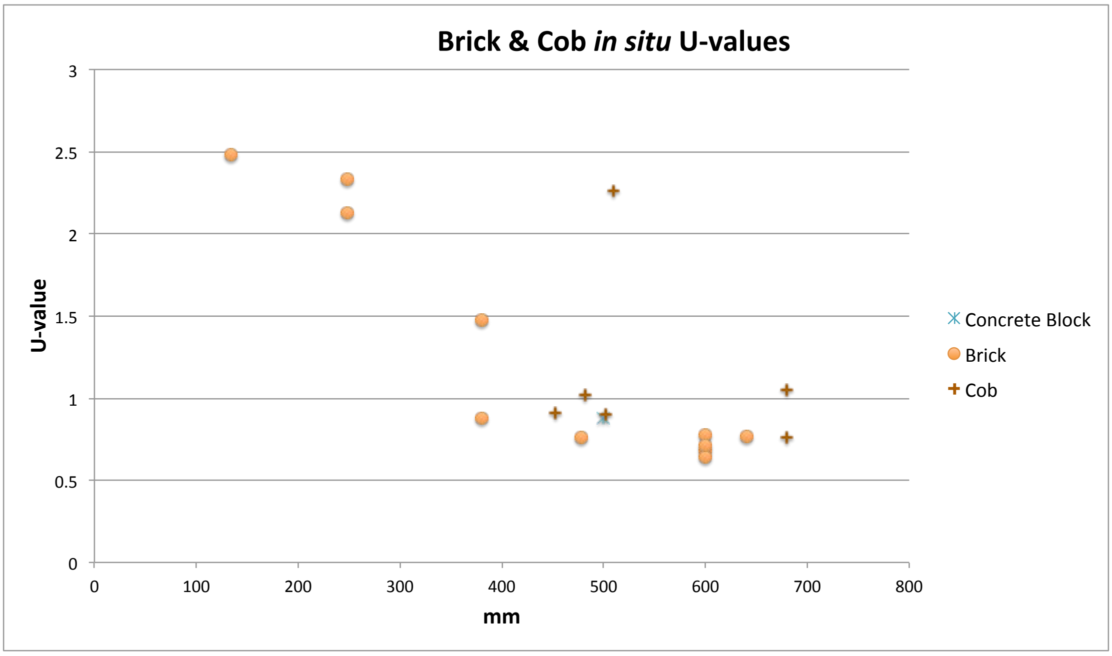

Figure 9. Brick and Cob *in situ* U-values 2012.

Previously it had been thought that the figure for the cob wall from Oxenholm (7b - 2.26 W/m^2K @ 510mm) was questionable due to possible sensor placement error (see page 17.). Subsequently, more *in situ* U-value data has been gathered for cob walls, both earth and chalk, and this would seem to confirm the 7b Oxenholm U-value as erroneous (Fig. 9).

However, the extra data from the 2010-11 survey for walls between 450-500mm shows a cluster around a U-value of 1.00 W/m^{2}K and seems to confirm that a section of wall which had been questionably described as a concrete block repair within a cob walled farmhouse, 4c Burrow Farm, is actually likely to be a cob construction. The other cob U-value which is also around the 1.00 W/m^{2}K mark (1.05 W/m^{2}K, 23a, The Firs, Riddlecombe) is unusual as this wall is considerably thicker, being 680mm wide, than the other walls surveyed. At this property moisture was found within the body of the wall and it may be that this U-value is the product of increased thermal conductivity due to the presence of water within the wall (see SPAB Research Report 2).

The U-values plotted for brick walls shown in Figure 9 once again demonstrate the relationship between increased wall thickness and declining U-values where the highest U-value, 2.48 W/m^{2}K is actually for a brick infill panel within a timber-frame, effectively a wall half a brick thick (1c, Blewbury). Conversely, lower U-values are achieved from a group of much thicker walls measured at New Court, Trinity College, Cambridge. These walls are in total 600mm thick (consisting of 22.5" brick walls with a variety of internal and external finishes) and measured U-values of between 0.64 - 0.78 W/m^{2}K (26a - 26e). With the addition of these measurements from the walls at Trinity College it may be possible to see a range for brick walls emerging (Fig. 10).

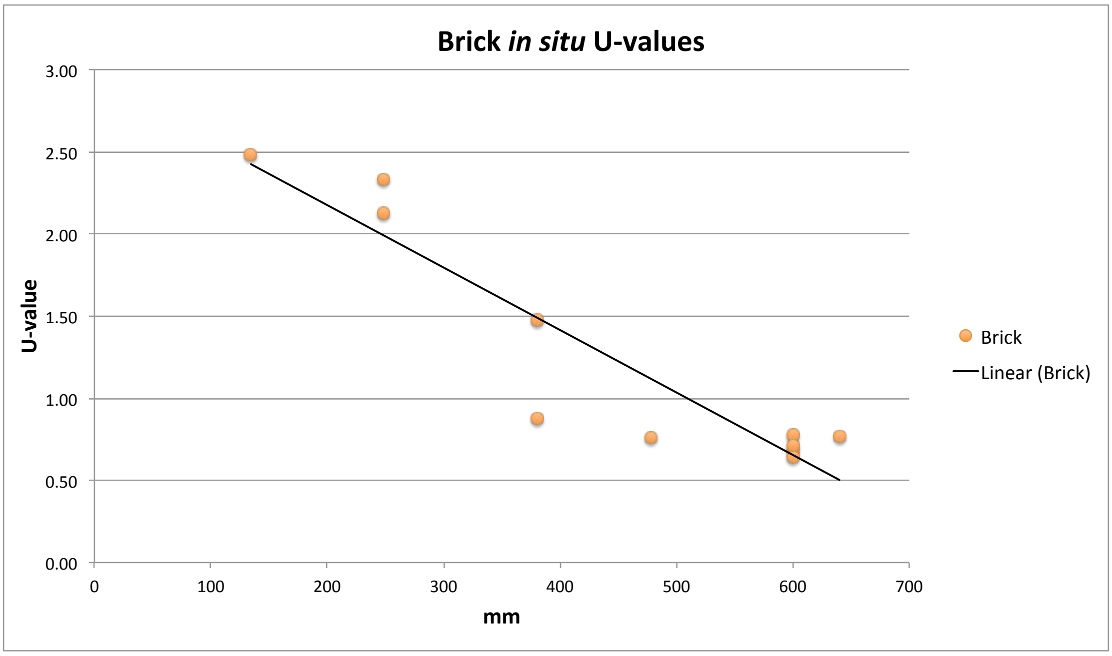

Figure 10. Trend for Brick *in situ* U-values 2012.

The measurements which diverge from the range of U-values described by the trendline plotted in Figure 10 can perhaps be explained by variations in brick density due to methods of manufacture and the raw materials used (both of which are related to age of brick and geographical location) or anomalies within the wall build ups themselves. The two U-values which sit below the trendline (12a, Spital Square, 0.76 W/m^2K & 29a Rectory Grove, 0.88 W/m2) are both taken from buildings in London of a similar age and were noted to consist of quite soft bricks which suggests material of lower density and thus potentially greater thermal resistivity. However, two of the U-values which sit above the trendline are from the gable end wall in Abbeyforegate Street, Shrewsbury of much thinner section, 248mm (20c & 20d - 2.13 W/m^2K & 2.33 W/m^2K). As has been previously mentioned (p. 13.) there is some uncertainty as to the exact dimensions of this gable end wall as well as its build-up as it was formed from what had previously been a partition wall when a section of the terrace was demolished to make way for a by-pass during the 1970s. Therefore given a thinner wall section of around 110 - 120mm (a snapped header for example) the U-values recorded for this wall would straddle the trendline as it is currently plotted. However, as with the previous trend graphs for stone walls, more data is required to provide real confidence in the ranges described for the different wall materials under examination.

There is as yet very limited *in situ* U-value data for flint and sandstone wall materials within this study. The three U-values for sandstones, 1.45 W/m^2K for Malmstone (11b, Huckers Cottage), 1.63 & 1.62 W/m^2K for Millstone Grit (21a & 21b, White House Farm) invert the normal trend as the lower value is for a thinner wall. This reflects the diversity of sandstone materials in general and their widely varying densities which makes establishing a range for this material type, even with increased sample numbers, problematic.

4.3.2 Lightweight Homogeneous Walls

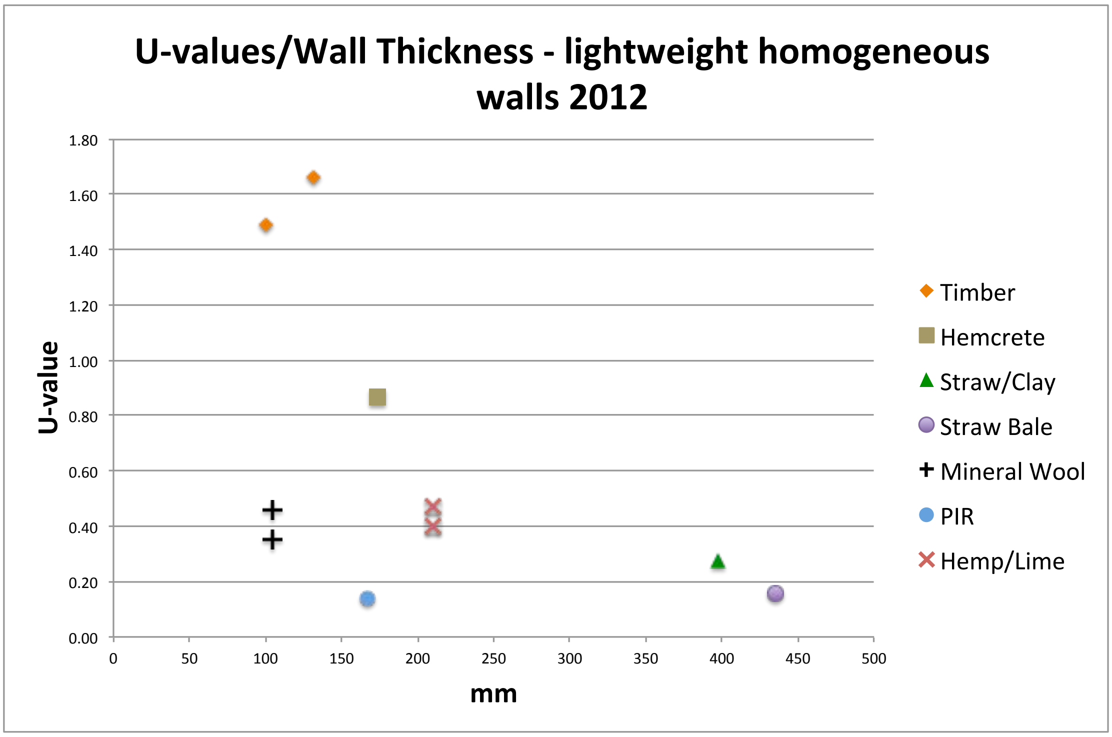

Figure 11. *In situ* U-values for lightweight homogeneous walls 2012.

The other walls contained within the 'homogeneous' grouping could be categorised as 'lightweight' walls constructed of less dense materials some of which may not be typical of traditional walls per se (Fig. 11). These materials are in some cases incorporated as panel infills within timber frame structures, such as the straw/clay example and some are of modern origin, such as the polyisocyanurate and mineral wool walls. There are also two U-values taken from the timber studs of the timber-frames themselves. In general less dense materials incorporate more trapped air and therefore have an insulative effect reducing heat loss. Because of this the relationship of increased wall thickness and decreased U-values found amongst heavyweight walls is not replicated within the lightweight walls in the study. The lowest U-values here come from straw/clay (11b, Huckers Cottage, 0.28 W/m^2K @ 398mm), polyisocyanurate (2a, Blewbury, 0.14 W/m^2K @ 168mm) infills and a Straw Bale wall (16a, The Walled Garden, 0.16 W/m^2K @ 435mm) across a range of wall thickness. Other U-values measured between 0.50 - 1.00 W/m^2K are for mineral wool (24c & 24d, Ashburton, 0.46 & 0.35 W/m^2K) and hemcrete (1g, Blewbury, 0.87 W/m^2K) both used as infills within timber-frames and also two U-values of 0.40 W/m^2K and 0.47 W/m^2K for a solid wall of hemp/lime measured at Haverhill. All these U-values are relatively low in relation to the heavier weight walls, as are the figures for timber studs at Blewbury, 1.66 & 1.49 W/m^2K (1d & 1f) and are a function of the thinness of these walls in relation to the reduced density of their construction material.

4.4 *In situ* results - Heterogeneous Walls

The identification of walls as 'heavyweight' or 'lightweight' becomes more problematic when discussing the heterogeneous walls sampled within this study. This is particularly the case when secondary lightweight additions have been made to existing heavyweight walls to reduce heat loss thus changing the nature of these walls. Perhaps unsurprisingly, given its preeminence as a building material within the UK, there are a substantial number of brick walls within the study, as well as a few stone walls, which feature an additional layer or layers of material, most of which also incorporate some sort of a cavity or air gap. Four of these heterogeneous brick walls with cavities are historic; the wainscot paneled wall at Spital Square and three of the walls measured at New Court, Trinity College which have a lath and plaster lining. A similar lining was found on a thin cob wall at Burrow Farm. Other heterogeneous walls are the result of modern interventions made in order to reduce heat loss through the walls. There are also three examples of stone walls which have both been 'drylined', one at Higher Uppacott which uses a lining for damp-proofing, another at Bradford on Avon which has a plasterboard drylining addition and a test wall installed as part of the SPAB Building Performance Survey on a granite wall at Drewsteignton, Devon. The chart below (Fig. 12) shows the range of brick and stone walls with secondary additions and cavities.

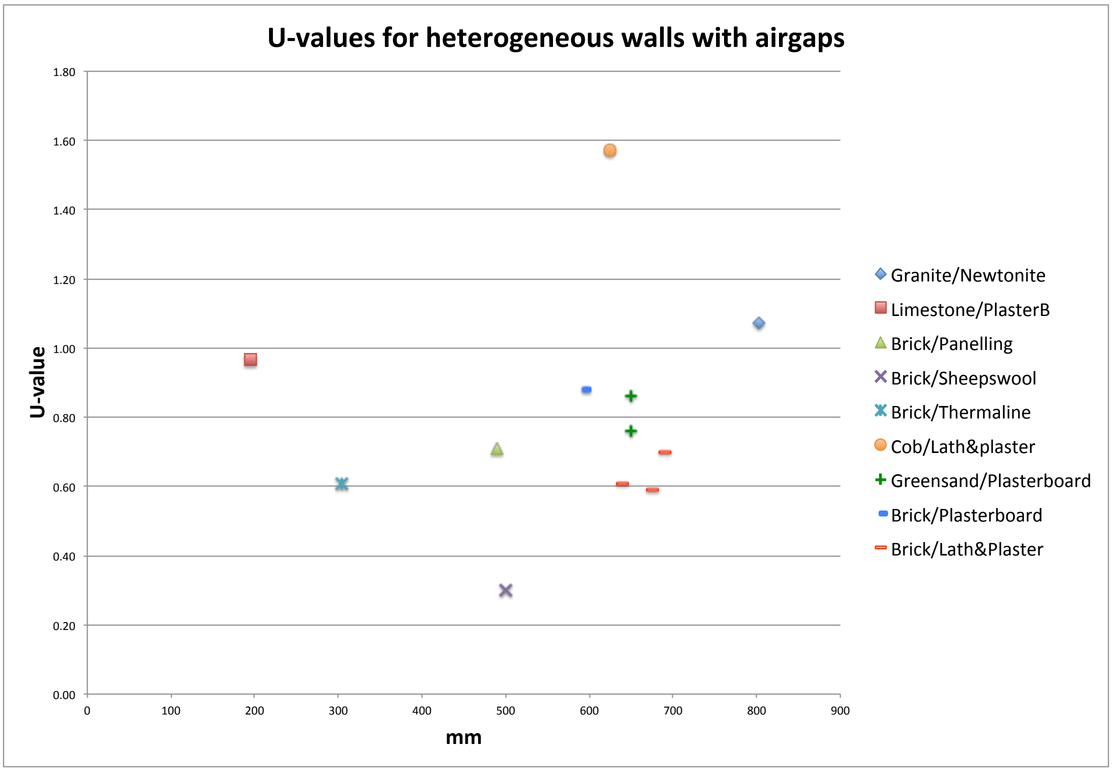

Figure 12. *In situ* U-values for lightweight heterogeneous walls with air gaps 2012.

The historic examples of brick wall linings (timber paneling at Spital Square, 12b = 0.71 W/m^{2}K and lath and plaster at New Court, 26f = 0.59 W/m^{2}K & 26g = W/m^{2}K) all measure fractionally lower U-values than un-lined equivalent walls at the same locations and in general represent some of the lower U-values given in Figure 12. By referring to the U-value ranges plotted for Limestone and Granite walls shown in Figure 8 it is possible to see that the addition of a plasterboard drylining for the limestone wall at Bradford on Avon

(8b, 196mm = 0.97 W/m^{2}K) provides a U-value well below the figure predicted for a wall of equivalent thickness without a drylining, approximately. 1.9 W/mK. However the same cannot be said for the Granite example from Higher Uppacott where the U-value of 1.07 W/m^{2}K recorded for a 803mm wall seems quite high when matched against the trendline plotted for Granite walls in Figure 8.

Overall, variations in the thicknesses of the air gaps found for these walls and crucially whether the air present within them can really be said to be 'still' or otherwise will have a significant influence on the thermal conductivity of the wall as a whole. As will the thickness of any material that is incorporated within the build up specifically for the purposes of insulating the wall. Therefore it is difficult to make meaningful comparisons for this particular sub-grouping of walls.

There are some walls which have received an additional treatment without the incorporation of an air gap or cavity where brick walls have been subject to either external or internal insulation using expanded polystyrene, insulating lime render, reedboard, woodfibre board or hemcrete. Some of the walls that do not incorporate any form of air gap combine two materials as panel infills for timber-frames; one being the traditional treatment of wattle and daub and others more modern interventions such as the addition of reedboard or hemcrete to existing brick and timber stud work or another example where the original panel infill material has been replaced with sheep's wools combined with a woodfibre board (Fig. 12).

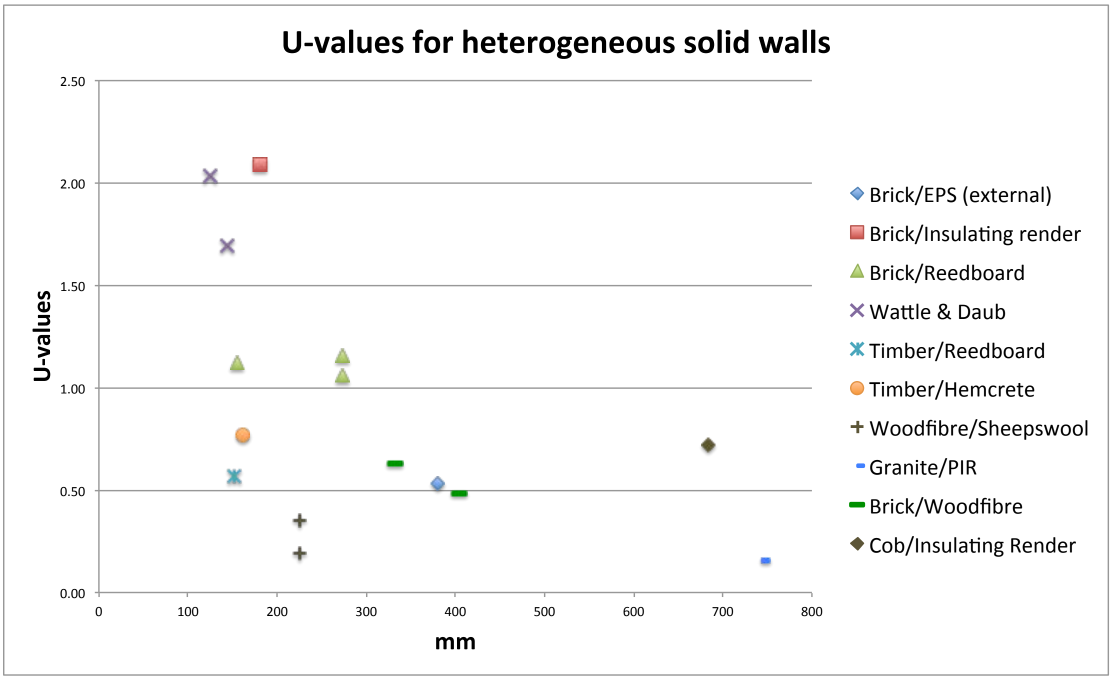

Figure 13. *In situ* U-values for lightweight heterogeneous walls without air gaps 2012.

Although most of the walls shown in Figure 13 feature some form of refurbishment the exception to this are the two measurements for Wattle and Daub infill panels (1e & 3a) which inevitably record quite high U-values (2.03 and 1.69 W/m^{2}K) being of thin wall section and consisting principally of a heavyweight material (clay/daub). The two walls with the lowest U-values either comprise of entirely lightweight and therefore highly insulating materials (13a & 13b, 0.35 and 0.19 W/m^{2}K) or are a combination of a thick granite wall 580mm and a substantial addition of a lightweight insulating material 100mm PIR (25c = 0.16 W/m^{2}K). Once again, however, due to the range of materials involved in the build-ups of these walls and the relative proportions of heavy and lightweight elements comparison between individual walls becomes largely irrelevant. Perhaps of more significance is the consideration of refurbished walls in general and a discussion of these walls is included in the next section of this report.

4.5 *In situ* Discussion

It is not really possible to make precise comparisons between materials and performance due to the diversity of wall thicknesses and variety of treatments featured within the survey. A few measurements have, however, been taken both 'before' and 'after' the addition of insulating layers to a particular wall as part of the SPAB Building Performance Survey (see Research Report 2). Furthermore, this particular study is concerned with the measurement of heat loss through walls and the walls are quantified solely in these terms. There are, however, other factors that effect the performance and behaviour of solid walls, in particular that of moisture and no account of adverse moisture behaviour is made within this analysis either within 'original' or refurbished walls (see, once more, the SPAB Research Report 2 for an analysis that takes account of this). Therefore, where some form of comparison is attempted these limitations should be bourn in mind.

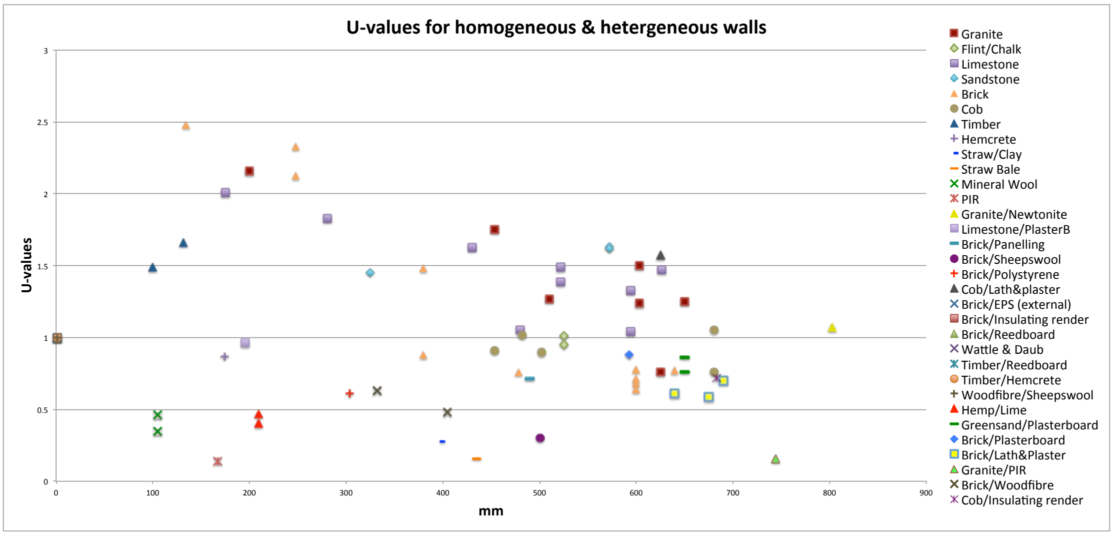

Figure 14. *In situ* U-values for homogeneous and heterogeneous walls 2012.

It is perhaps not surprising that the walls in this study that fall within or under the threshold value of 0.30 W/m^2K from the current Building Regulations *Approved Document L1B Conservation of Fuel and Power* are all recent constructions or refurbishments (Fig. 14). Disregarding wall thickness, the lowest U-value figure achieved overall was from a wall made principally of polyisocyanurate board 0.14 W/m^{2}K (2a) closely matched by a straw bale construction 0.16 (16a). Other walls with very low U-values were a new timber-frame construction with Straw/Clay infill panels, 0.28 W/m^{2}K (11a) and three refurbished walls; a granite wall insulated with polyisocyanurate (PIR) board, 0.19 W/m^{2}K (25c) a brick wall insulated with sheep's wool, 0.30 W/m^{2}K (14a) and sheep's wool as a timber-frame infill material combined with woodfibre board, 0.19 W/m^{2}K (13b).

4.5.1 Refurbished Walls

More meaningful perhaps is an analysis of refurbished walls, that is to say where the interventions have taken place that have resulted in heterogeneous walls, with or without a cavity or air gap, specifically undertaken in order to reduce heat loss through these walls (Fig. 15.).

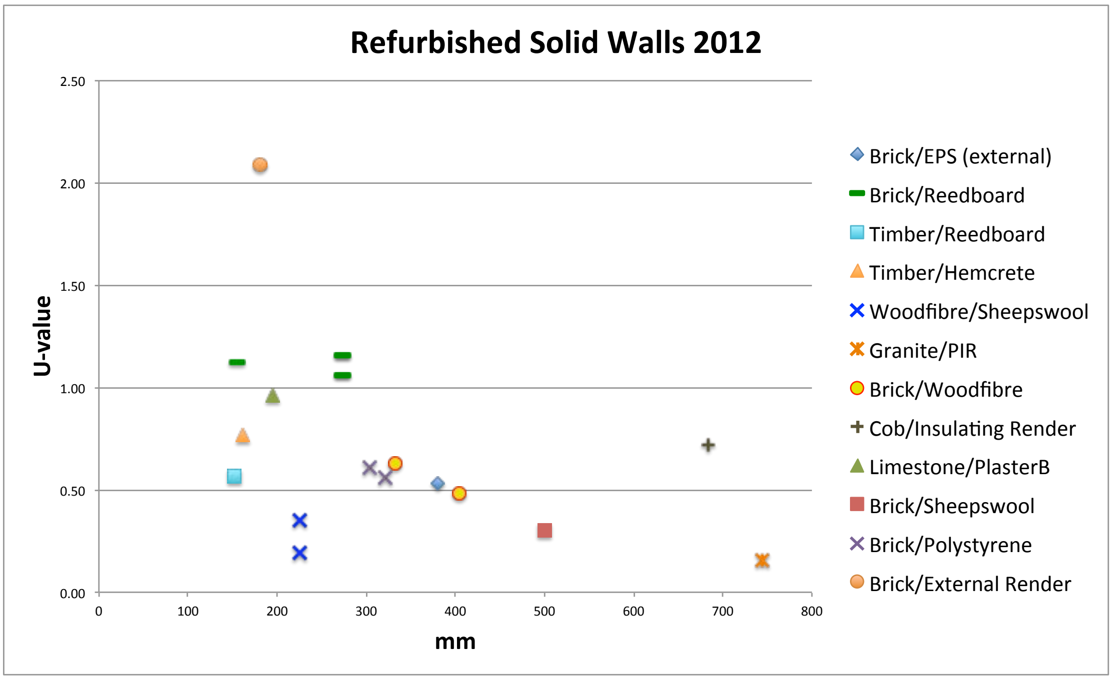

Figure 15. *In situ* U-values for refurbished walls 2012.

In general the same trend of U-values decreasing with wall thickness can be observed, the exception being perhaps the Cob wall at Riddlecombe which despite its thickness would seem to retain a relatively high U-value (23c =

0.72 W/m^{2}K). This is the wall that has been observed to be wet and indeed the pre and post-refurbishment U-values for this wall show little change in measured heat loss. It is possible that the damp condition of the wall is increasing it's thermal conductivity or that the insulation provided by the external render, which is only 40mm thick, is not having a significant effect on the thermal behaviour of the wall, this is discussed in more detail in SPAB Research Report 2. Similarly, albeit for a much thinner wall, the brick wall in Shrewsbury, 20b also treated with an external render would seem to record a U-value (2.09 W/m^{2}K) that sits above the general trend for refurbished walls. The chart shown in Figure 15 contains walls that incorporate both lightweight and heavyweight materials in different proportions therefore there can be a considerable range of U-values seen for walls of similar thicknesses. For example, the 225mm wall from Tyland Farm, which has U-values of 0.19 and 0.35 W/m^{2}K (13a & 13b) consists entirely of lightweight insulating materials used as new infill panels within an historic timber-frame. The 273mm wall recorded at Cholsey consists largely of brick (230mm) and is therefore predominantly a heavyweight wall with the thin addition of lightweight reedboard for insulation, it subsequently provided U-values of 1.06 and 1.16 W/m^{2}K. Therefore no simple equivalences should be drawn between wall thickness and potential refurbished wall U-values as each circumstance will determine the possibilities of what materials can be deployed to best effect taking into account numerous factors including historic fabric, loss of interior room space and general buildablility.

4.5.2 Timber-frames.

It is perhaps also useful to look at performance and treatments for particular *types* of building. Measurements taken within the timber-framed houses in Blewbury, Oxfordshire show poor thermal performance from traditional infill materials: 2.48 W/m^{2}K for 102.5mm brick (1c); and a marginally improved 2.03 W/m^{2}K for 103mm wattle and daub (1e). As is to be expected, the timber stud element of the frame achieves a better performance with a figure of 1.49

W/m^{2}K for a 100mm stud (1f). These U-values are primarily a function of the thinness of the walls (U-values tend to decrease with increased wall thickness) and the relative densities of the materials involved. Mass infill materials, hemcrete and straw/clay, which can be used as infill in timber frame buildings, perform better than the traditional materials; hemcrete with a value of 0.87 W/m^{2}K at 150mm (1g) and Straw/Clay at 0.28 W/m^{2}K @ 300mm (11a). However these materials are used in greater proportions to form thicker walls and are more lightweight (less dense) than traditional infill materials. Other materials that exhibit low U-values within panel infills are modern insulation materials and are extremely lightweight; sheep's wool and woodfibre board, 0.19 & 0.35 W/m^{2}K (13a & 13b), polyisocyanurate (PIR) board, 0.14 W/m^{2}K (2a) and mineral wool, 0.46 and 0.35 W/m^{2}K (24c & 24d) (Fig. 16).

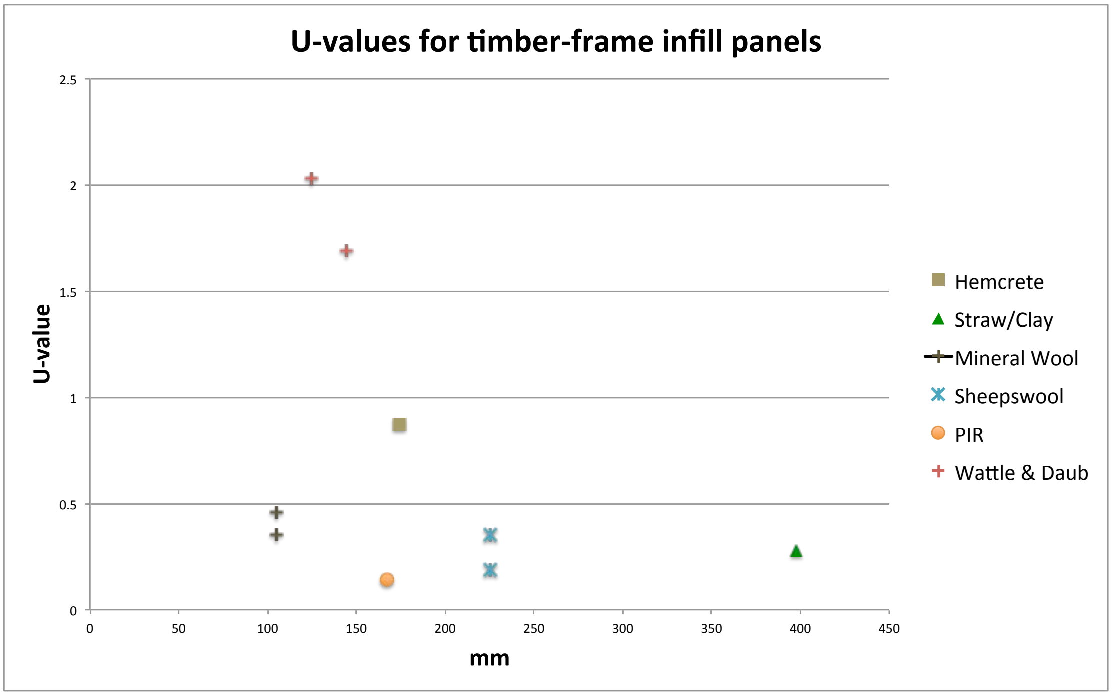

Figure 16. *In situ* U-values for timber-frame infill panels 2011.

4.5.3 Refurbished Timber Frame Walls.

A number of walls within the study group had been subject to some form of 'refurbishment' motivated by concerns of improving the wall's thermal performance. The use of a secondary layer, such as hemcrete or reedboard, in combination with a timber-frame infill of brick or the timber of the frame itself, improves thermal performance. A brick panel at the house in Blewbury recorded an *in situ* U-value of 2.48 W/m^{2}K (1c) whilst a similar panel at the same location which had been covered with 20mm of reedboard provided a U-value of 1.12 W/m^{2}K (1a). With a 100mm timber stud, 20mm of reedboard achieve a figure of 0.57 W/m^{2}K (1b) whilst a similar uninsulated stud measured 1.66 W/m^{2}K (it should be remembered that these U-values have been measured at different locations with the same building and therefore are not directly comparable. Fig. 17).

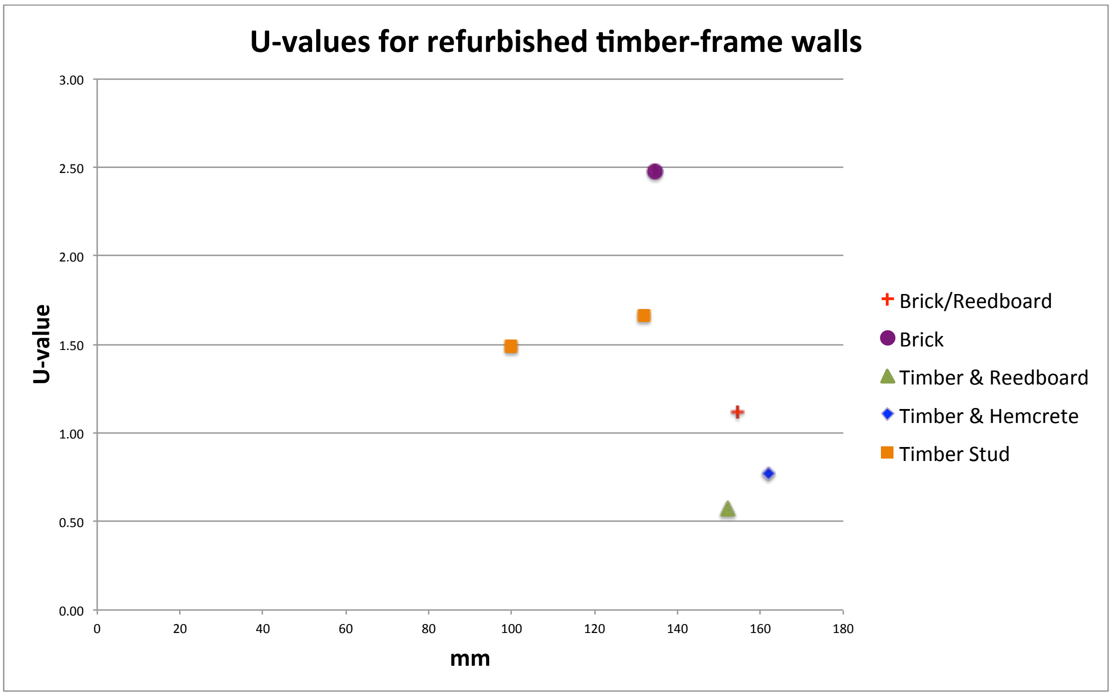

Figure 17. *In situ* U-values for refurbished timber-frame walls 2011.

4.6 *In situ* Average U-values

An average *in situ* U-value of 1.31 W/m^{2}K was calculated for all the 39 heavyweight homogeneous walls in the study, that is to say walls that could best be defined as 'traditional' pre 1919 solid walls made of permeable materials (e.g. solid walls of stone, brick or cob). This U-value sits below the lower end of the range of U-values for unfilled cavity walls of 1.4 - 1.9 W/m^{2}K identified by Hens et al[5] in a study of brick cavity walls. A further average *in situ* U-value of 1.36 W/m^{2}K was calculated solely for the 32 solid stone or brick walls in the study or 1.42 W/m^{2}K for the 21 stone walls and 1.24 W/m^{2}K for the 11 solid brick walls. These figures are lower than the U-values given for stone (2.4 & 2.1 W/m^{2}K) and brick walls (2.1 W/m^{2}K) in *Table S6: Wall U-values for England and Wales* in Appendix S of the Standard Assessment Procedure (SAP) 2009 document used in the calculation of SAP ratings for existing buildings (RdSAP)[6].

4.7 BuildDesk/BR 443 Comparison Results

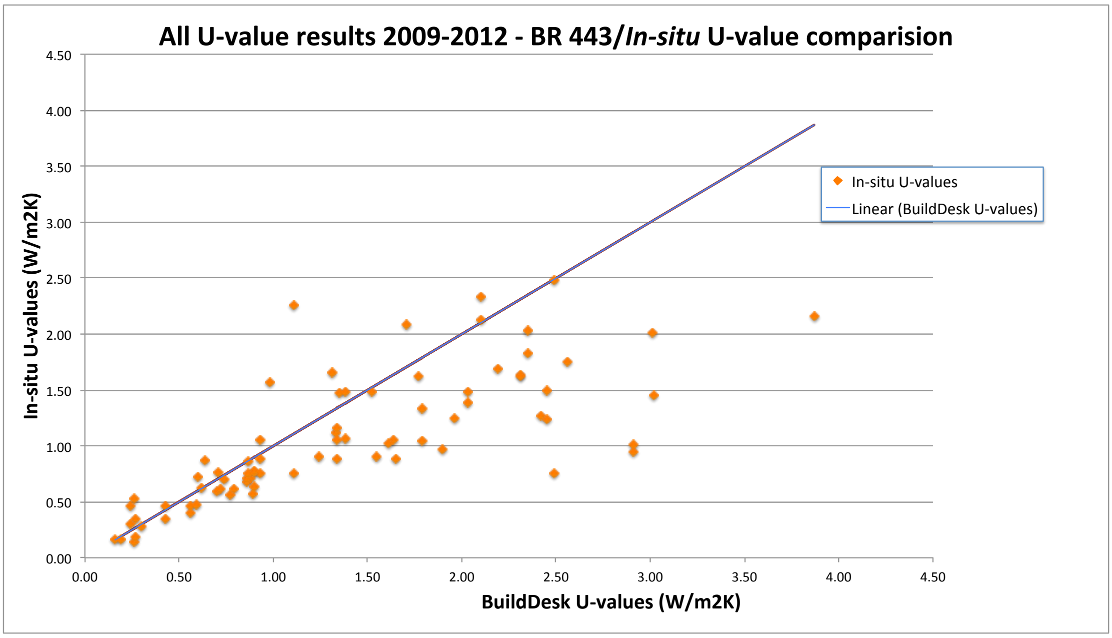

Figure 18. BuildDesk/*in situ* U-value comparison 2012.

When comparing the *in situ* U-value figures for the sample walls with the figures calculated for the same walls using the U-value calculating software BuildDesk v3.4, a significant discrepancy was found. In 77% of cases the BuildDesk software overestimated the U-value in relation to the *in-situ* figure (Fig. 18).

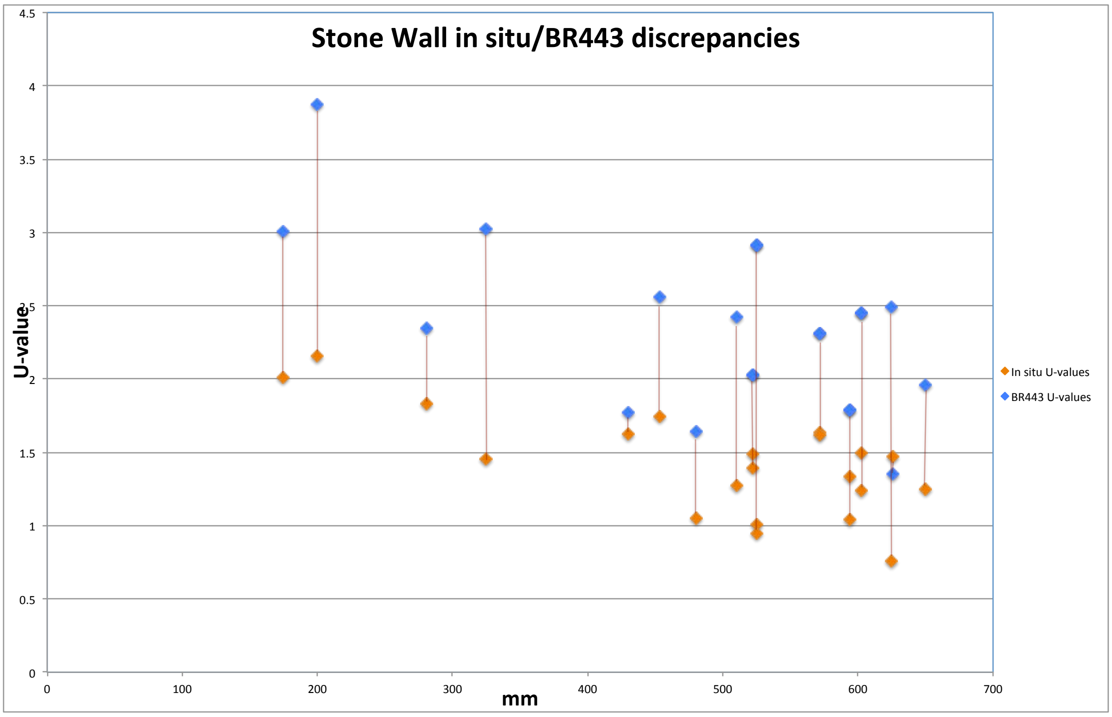

Figure 19. BuildDesk/*in situ* U-value comparison discrepancies for stone walls 2011.

U-values calculated using BuildDesk are mostly widely divergent from the *in situ* figures when calculating solid stone walls, with only two of the sixteen sample walls showing a close correlation (Fig. 19).

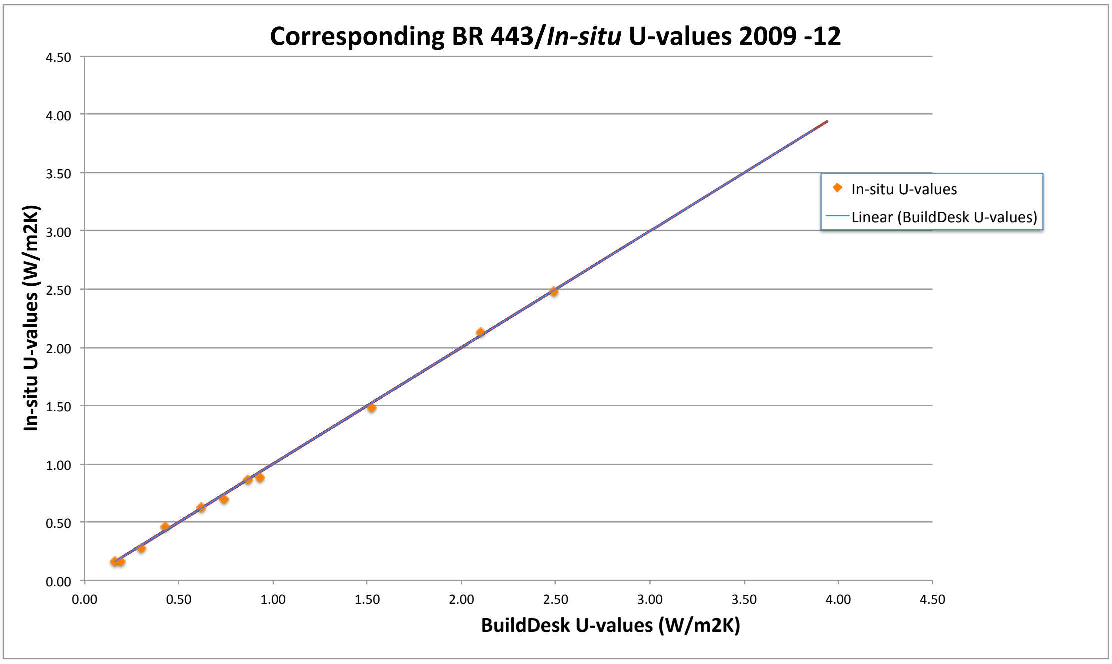

Figure 20. BuildDesk/*in situ* U-value correspondence 2012.

Eleven walls in the survey returned calculated U-values that either matched (in one case) or had close correspondence, i.e. were within 0.05 W/m^2K of the U-value that had been measured for the same wall (Fig. 20). Some close correspondences between BuildDesk BR 443 figures and *in situ* U-values occur when calculating walls consisting of quite simple build-ups. Because these walls are simple to define when they are accompanied by accurate thermal conductivity value for the single principal construction material the result can be a U-value calculation which matches one measured from the same wall. Good correspondence is also achieved for some refurbished walls as, even though in these cases the wall build-ups might be quite convoluted, here the insulating material, as a later addition with a specific measured thermal conductivity, is a known quantity. The same can also be said for some walls that, although they may not specifically include insulating materials the presence of a cavity or air gap of known dimensions that successfully traps air has an insulative effect. In both instances, once again, this allows the wall to be well defined for the purposes of carrying out a U-value calculation and this accurate definition of the principal thermal characteristics of the wall can result in a U-value which closely matches its measured equivalent. Further details of these corresponding walls and their build ups are given in Table 3.

ID	Build Up	mm	*In situ* U-value	BR 443 U-value
1c	Lime Plaster Brick Infill Lime Render	134.5	**2.48**	**2.49**
11a	Lime Plaster Straw/Clay Clay/lime plaster	325	**0.28**	**0.30**
16a	Lime Plaster Straw Bale Lime Render	435	**0.16**	**0.16**
20a	Brick Lime Plaster Gypsum Skim	380	**1.48**	**1.52**
20c	Brick Lime Plaster Gypsum Skim	248	**2.13**	**2.10**
24c	Asbestos Sheet Mineral Wool Plasterboard & Skim	105	**0.46**	**0.43**
29b	Gypsum skim Plasterboard Air gap/battens Lime Plaster Brick	593	**0.88**	**0.93**
28b	Gypsum Skim Plasterboard Air gap/battens Lime Plaster Lower Greensand	650	**0.86**	**0.87**
26h	Lime Plaster Lath & lime plaster Air gap & batten Brick Limestone	690	**0.70**	**0.74**
20e	Lime plaster Woodfibre insulation Lime Plaster Brick Insulating render	332	**0.63**	**0.62**
25c	Gypsum skim Plasterboard Air gap PIR Board Tanking & gypsum Lime Plaster Granite	744	**0.16**	**0.19**

Table 3. Walls with close *in situ* & calculated U-value correspondence 2012.

As can be seen from Figure 20 and Table 3 the ability to provide an accurate definition of a wall element ensures a better correspondence between measured *in situ* and calculated U-values. This is often in contrast to many existing stone walls where, although the overall thickness of the element may be known, the different proportions of materials involved in its construction, including mortar, voids and other non visible characteristics, as well as the random nature of their amalgamation often defy accurate description. The calculation of U-values for traditional walls is further problematised by the lack of basecase thermal conductivity data for most UK vernacular building materials. Furthermore, due to the diverse geology of these Islands such data as does exist may potentially be very location specific. When considered en masse these factors can mean that in some instances there can be significant uncertainty with regard to a calculated U-value for a traditional wall.

5. Conclusions

To date (Nov 2012) this study has looked at the *in situ* U-values of 77 walls built mainly of traditional materials and construction. It has then compared these figures with U-values calculated using the U-value calculating software, BuildDesk v3.4. based on the standard BR 443 Conventions for U-value Calculations

5.1 *In situ* U-values

The study suggests that it maybe possible to begin to build-up a general trend of U-values for walls of traditional construction. A range of U-values for Limestone and Brick walls is developing, however, more data is needed to reinforce the figures already established and provide greater certainty. Likewise, more data is needed in order to reinforce and provide greater certainty for other material types featured within the study, such as granite and cob.

Some materials, often found in thinner wall sections, record high U-values indicating greater heat loss. A secondary layer within a wall which either traps a layer of still air or includes a lightweight (and thus less thermally conductive) insulating material, or both, can reduce the U-values measured for a refurbished wall (see Drewsteignton 25a, 25b, 25c & Shrewsbury 20a, 20b, 20e & 20f). Or result in U-values that sit below a particular expected range for equivalent walls with no additions, such as the examples of the timber paneled brick wall at Spital Square (12b) or the dry-lined ashlar stone wall in Bradford on Avon (8b). However, this study has only looked at the phenomena of heat loss through these walls quantified as a U-value. There are other factors concerning the overall performance of a wall which should be taken into account during the application of a secondary insulating layer to a traditionally-built wall, principally that of moisture transfer. More research work is required in order to better understand this area and this is, in part, the purpose of the SPAB Building Performance Survey (see The SPAB Research Report 2.).

5.2 Measured & calculated U-value comparison

Significant differences between the and the calculated U-value figures were found with the calculating software overestimating the U-value in 77% of cases. In overestimating the U-value BuildDesk/BR 443 *underestimates* the thermal performance of the walls in the sample group, as indicated by their *in situ* figures. Furthermore, averages of the *in situ* U-value data used in this study produced figures that were lower (indicating reduced heat loss) than those shown on U-value Tables used in the assessment of the energy performance of existing dwellings (RdSAP). This is significant as, in part, U-value calculations are the basis for much building energy assessment and building energy legislation and policy. Therefore, this study suggests that conventional industry practices are unable to represent accurately the thermal performance of traditionally built walls. Ultimately, this could have negative consequences for traditional buildings as the poorer calculated U-values may result in misguided priorities with regard to energy saving alterations or suggest the need for interventions which, depending on their manner of execution, maybe deleterious to the fabric and longevity of the building, as well as to human health.

The calculation of U-values for traditionally built stone walls are particularly problematic using the BR 443 calculating method. The reason for this is that features of traditionally built stone walls, including their construction methods and potential ambiguity, are not considered within the BR 443 guidance nor are such things easily incorporated into calculating software programmes such as BuildDesk v3.4. In addition, within the software, there is a paucity of thermal conductivity data for individual stone types. Traditionally built historic buildings tend to be built of the local vernacular material and are therefore of greater geologically diversity than the material types provided for within standard thermal conductivity tables. There is a need to increase the range of available thermal conductivity data to reflect this diversity.

In general, the reason for the discrepancy between measured *in situ* and calculated U-values is likely to be the fundamental difficultly of providing an accurate definition for the purposes of making a calculation for a wall made up of inadequately identified materials, of dubious quantities, with doubtful root thermal conductivity values. Inversely, the calculated figure for a U-value tends to correspond more closely with the *in situ* figure when more information is known about the build-up of that particular wall and a specific thermal conductivity can be given. A correlation between the calculated and *in situ* figure is also more likely when the wall can be described in discrete, known, layers as this construction method corresponds more closely with modern building methods. Therefore, due to the inherent difficulties of defining the precise material properties of traditionally constructed walls an *in situ* figure will in many instances be more representative of actual thermal performance than a calculated one.

6. References

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