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# IN-SITU THERMAL TRANSMITTANCE OF CASE STUDIES IN DUBLIN

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## ABSTRACT

*Thermal transmittance (U-values) of exterior walls represent a source of uncertainty when estimating the energy performance of dwellings. It has been noted in research that the standard calculation methodology for thermal transmittance should be improved. Subsequently, hygrothermal analysis has been used as an accurate building design tool due to its incorporation of climate specific effects on construction assemblies such as moisture retention and release. In-situ measurement of thermal transmittance could also be an effective tool for evaluating the material performance of assemblies of a building. This paper provides the context, research process and analysis of 3 case studies situated in Dublin, Ireland. The case studies offer an account of the in-situ thermal transmittance of exterior walls and link these to hygrothermally simulated comparisons along with more traditional design U-values. The findings of this paper identify discrepancies between in-situ and design U-values, using measurement, hygrothermal simulation and standard method U-value calculations. This study can form the basis for further research on retrofit of the Irish housing stock. Furthermore, the paper offers a source of information for researchers and designers exploring the performance of external walls to anticipate best practice detailing and in-situ thermal performance values.*

## INTRODUCTION

Building envelopes are continually subject to fluctuating internal and external environmental conditions such as temperature, moisture, solar radiation and wind. These variations represent key factors that affect and define the actual physical thermal performance and sustainability of the building envelope. As such, all techniques for the prediction of in-situ hygrothermal behaviour of building components are issues of great interest in building design where the aim of accurate design is vital. The result should be an envelope that anticipates all internal and external environmental conditions allowing the building to perform to its optimum.

As building designs have developed, energy loss analysis has become more important to accurately predict; a key reason being the implementation of these figures to derive CO<sub>2</sub> reduction targets (Kema, 2008). With the understanding that moisture affects the material performance of building assemblies throughout the lifespan of a building, it is vital to implement reliable prediction tools to assess potential thermal performance values.

At present the uniform standard for heat loss definition throughout Europe is the  $U$ -value. This is a calculation which disregards many environmental factors with the exception of wind speed; although as a non-variable. The single method to assess moisture levels of building assemblies within construction assemblies, referred to in Irish building guidance documents, is the Glaser method. The Glaser method is a one-dimensional, steady-state calculation with many limitations including the inability to handle heat and moisture capacity, air transfer through structures and capillary liquid flow. As a result, structures and assemblies may in reality perform entirely different than expected thermally and hygrothermally. Currently, there are two common measurement techniques to evaluate the thermal resistance in existing buildings: direct measurement of the heat-flux (non-destructive method) or direct survey of the fabric layers with direct measure of their thickness (destructive method). The non-destructive method requires the use of a heat flow meter that has to be operated according to ISO 9869.

This paper presents the results of hygrothermal simulations with comparable non-destructive in-situ  $U$ -value measurements and standard calculated  $U$ -values applied to 3 case study buildings situated in Dublin, Ireland. The buildings were selected for analysis based on thermal upgrade methods implemented; uninsulated, full fill cavity and external insulation. For all 3 case studies a process of data collection was adhered to as follows

- a. Interpretation of qualitative information from infrared thermography in accordance with ISO 6781 and collection of various data about the properties.
- b. Calculation of  $U$ -values (thermal transmittance values) using the methods in ISO 6946
- c. Measurement of  $U$ -values (thermal transmittance values) using the methods in ISO 9869 and comparisons between measured and expected  $U$ -values.
- d. Simulation of hygrothermally derived  $U$ -values (thermal transmittance values) using WUFI software in accordance with EN 15026 and ASHRAE 160P.

The calculation method defined in ISO 6946 is the standard for calculating  $U$ -values of exterior walls, principally based on “ideal” conditions. ISO 6946 accounts for thermal conductivities of materials, geometric effects and some types of air voids, however it excludes moisture, variable wind speed or solar related occurrences.

The objective of thermographic imaging was to indicate thermal bridges, cracks or similar sources of irregularities in surface temperatures contra venous to the typical thermal performance of the wall. The result of this was the identification of suitable locations on the wall for installation of heat flux meter (HFM) and thermocouples for in-situ  $U$ -value measurements.

In situ  $U$ -values have been measured by using the heat flow meter (HFM) method performed in agreement with ISO 9869. Accordingly, measurements have been carried on for at least 72h (typically 1 week), with an acquisition time lapse of 1 min. The measurements have been conducted during spring. The 80mm diameter and approximately 5mm thick HFM was temporarily adhered (using masking tape to edges) throughout the period of measurement away from direct influence of either a heating or a cooling device. No protection was required to the HFM to shield from rain, snow or direct solar radiation as it was placed internally. The external thermocouples were fixed within a radiation shield to avoid the effect of direct solar radiation. The measured  $U$ -values are presented alongside the calculated and simulated  $U$ -values of matching environmental conditions and construction type to facilitate comparison.

## **THERMAL TRANSMITTANCE THROUGH IN-SITU MEASUREMENT**

In-situ is a Latin phrase that translates literally to “on site” or “in position” denoting the way a measurement is taken in the same place the phenomenon is occurring without isolating it from other systems or altering the original conditions of the test. The measurement of actual thermal transmittance in building assemblies is known as in-situ  $U$ -value measurement. It uses a HFM in combination with internal and external 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 (Rye, 2010, Rye and Scott, 2012). This method proves to be reliable and can also be used for non-destructive tests of the thermal characteristics of buildings. The thermal transmittance of a building element ( $U$ -value) is defined in ISO 7345 as the “Heat flow rate in the steady state divided by area and by the temperature difference between the surroundings on each side of a system”. However, since steady-state conditions are never encountered on a site in practice, such a simple measurement is not possible. But there are several ways of overcoming this difficulty:

- a. Imposing steady-state conditions by the use of a hot and a cold box. This method is commonly used in the laboratory (ISO 8990) but is cumbersome in the field;
- b. Assuming that the mean values of the heat flow rate and temperatures over a sufficiently long period of time give a good estimate of the steady-state. This method is valid if:
- c. The thermal properties of the materials and the heat transfer coefficients are constant over the range of temperature fluctuations occurring during the test;
- d. The change of amount of heat stored in the element is negligible when compared to the amount of heat going through the element.
- e. Using a dynamic theory to take into account the fluctuations of the heat flow rate and temperatures in the analysis of the recorded data.

### **Previous research involving in-situ $U$ -value measurement**

Early research published from 2000 has investigated the requisite for in-situ measurement to verify calculated  $U$ -values used commonly throughout the construction industry. Doran (2000) suggests an international need for a better understanding of air and moisture movement within opaque building elements while Baker, (2008) and Currie et al., (2013) outlined the basic technique required to implement in-situ analysis. Since then, various publications have analysed numerous wall assemblies

arriving at the conclusion that measurements generally highlight a vast performance gap between design values and in-situ results (Doran and Carr, 2008, Peng and Wu, 2008, Rye, 2010, Byrne et al., 2013, Asdrubali et al., 2014, Evangelisti et al., 2015). Baker, (2011) and Rye and Scott, (2012) reported that within the scope of traditional buildings,  $U$ -value calculations generally overestimate in-situ thermal performance. In other words, uninsulated traditional buildings actually perform better than expected from design values. In contrast to this, Hulme and Doran, (2015) argued that depending on the wall structure and insulation levels, the reliance on in-situ values varied considerably from overestimation to underestimation of design  $U$ -value. Rhee-Duverne and Baker, (2013) then went on to claim that if the thermal conductivity values are known, calculations made using software programs can be in reasonable agreement with the actual measured  $U$ -values, suggesting that much of the unreliability of calculating  $U$ -values lies with the low quality of input data.

With all of the above taken into consideration, in-situ analysis of the  $U$ -value is certainly a practical option to establish the actual performance of external walls. However, the idea within the scope of this research is to establish a method whereby hygrothermal simulation can be verified as a method to predict thermal performance as an accurate reflection of in-situ performance thus replacing ISO 6946 standard method  $U$ -value calculations. To do this, a link between in-situ measurements and hygrothermal simulations was made.

### **Review of Methods & Tools**

Two methods may be used for analysis of the data in accordance with ISO 9869: the so-called average method, or the dynamic method. Ahmad et al. (2014), Li et al. (2015) and Rasooli et al. (2016) have reflected on the average method with proposals to modify this for more precise outputs. For the purposes of this research however, these modified techniques are too undefined and experimental for use at this stage. The measurements in this research are presented as direct comparisons between the simulated  $U$ -values and the  $U$ -values using ISO 6946 standard calculation methodology. This averaging approach is valid if the following conditions apply:

- a. the thermal properties of the materials in the element are constant over the range of temperature fluctuations;
- b. the change in the internal energy of the element is negligible if compared to the amount of heat going through the element.

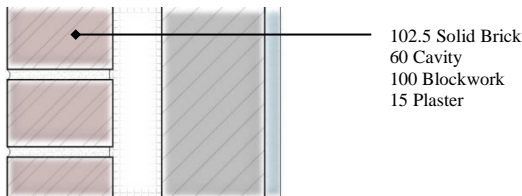
Following analysis of existing literature, the average method is identified as applicable for similar styles of wall construction as those in this research; solid and cavity masonry. It is assumed that the assemblies here are sufficiently homogeneous or made of sufficiently homogeneous layers to use a HFM.

### **METHODOLOGY**

The methodology used in this phase of the research is modelled around multi-methodological design, incorporating some qualitative research to allow a fuller piece of research (Creswell, 2009). Data collection and analysis through past and present research by others, (along with policy design standards, recorded climate data, housing figures, common external wall constructions, standard design calculation methodologies and non-standard design calculation methodologies) corresponds well with and suits the theory of a quantitative methodological approach (Corbetta, 2003, Maxwell, 1998, Maxwell, 2012), the research is structured, performing a series of calculations and recording performance data to produce results which clarify the question. A qualitative approach was used to

develop an understanding of the problem and improve methods for the quantitative element of research.

Searches were undertaken of recognised relevant academic and specialist building conservation literature databases through a number of journals and websites of the statutory bodies responsible for the protection of the Irish, UK and European environment. Using the technical indices and Technical Guidance Document Part L, ISO 6946 is referenced to specify the method of calculating  $U$ -values. The  $U$ -value calculation was then evaluated and the exclusion of environmental conditions was identified as the main fault. This error was identified to be addressed using hygrothermal simulation through WUFI 5.3. Verifying this research, the wall assemblies within the case studies were assessed using in-situ thermal transmittance measurements in accordance with ISO 9869. The existing wall structures were verified through documentation provided and inspection through a bore scope with measurements using the metric system (mm) as an internationally agreed decimal system of measurement. Thus, the following external wall assemblies were assessed for this study (see Fig. 1, Fig. 5 & Fig. 3)



**Fig. 1 - Uninsulated Cavity Wall**  
Case Study 1



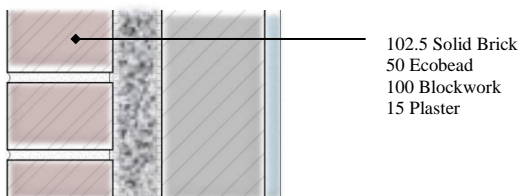
**Fig. 2 – Case Study 1**



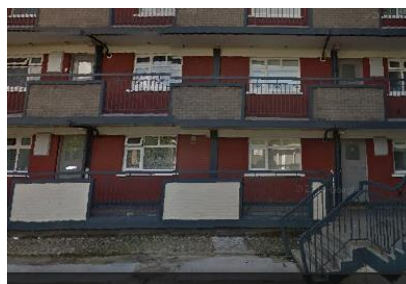
**Fig. 3 – Externally Insulated Solid Wall**  
Case Study 2



**Fig. 4 – Case Study 2**



**Fig. 5 – Cavity Fill Cavity Wall**  
Case Study 3



**Fig. 6 – Case Study 3**

With the aim of measuring the in-situ  $U$ -value of an assembly it is essential to record the heat flow, internal temperature and external temperature continuously over a sufficiently long period of time. In this project, a Hukseflux HFP01 HFM sensor was employed to measure heat flow and RS Pro T Type Thermocouples with a 2m probe were used to record a temperature-dependent voltage to measure internal and external temperatures (see Fig. 7, Fig. 8 & Fig. 9). A Campbell CR1000 datalogger (see Fig. 9) was used to record the measurements of the HFM and thermocouples allowing for cold junction compensation of the latter.



**Fig. 7 – HFP01 HFM**



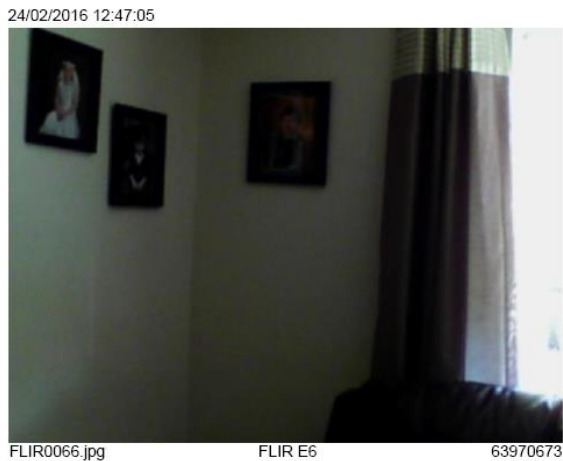
**Fig. 8 –T type thermocouples**



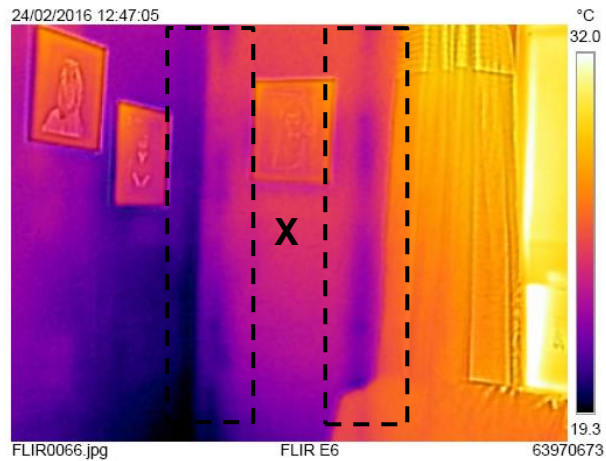
**Fig. 9 - Datalogger rested on window sill for duration of study**

$U$ -values were determined by comparing the heat flow through the element with the temperature difference across it over a minimum 7 day period. In an ideal situation the internal and external temperatures would be constant, giving a stable and accurately determined  $U$ -value. In practice steady state conditions do not arise, however, and attention must to be given to the variations in temperatures and heat flows before the  $U$ -value can be determined reliably. Since most building structures have a significant thermal mass, variations in internal or external temperatures lead to large fluctuations in the heat flow either into or out of the element and it was necessary to measure the heat flows and temperatures over several days in order to arrive at a reliable result.

ISO 9869 recommends thermographic analysis prior to the installation of any HFM. The purpose of the thermography is to establish potential thermal bridges, cracks or similar sources of error in the internal surface temperature near to the potential HFM location. Large variations in surface temperature would indicate that the selected measurement point was uncharacteristic of the typical function of the wall and therefore should not be selected. Multiple thermographic images were taken to ensure accuracy of results and verify that glazing did not distort larger image results. Fig. 10 & Fig. 11 are results from thermographic surveying Case Study 2.



**Fig. 10 – Image of internal wall surface**



**Fig. 11 – Thermographic image of internal wall surface**

Fig. 10 shows the basic image of an internal wall surface, while Fig. 11 is the corresponding thermographic image. While there would not be a significant variation across the wall surface, boxed are what appear to be studs behind the finish plasterboard. The result of this finding was that the sensor was placed between the studs (marked X) to record the typical wall assembly. This typical wall assembly would then relate directly to the calculated and simulated values. The entire schedule of data acquisition composed prior to analysis was invaluable to ensure participants were fully aware of the dates and times associated with each element of research (see Table 1).

**Table 1**

**Schedule of In-Situ Analysis**

Date	Location	Analysis Orientation	Task
18/02/2016	Case Study 1	All	Infrared / thermographic analysis
20/02/2016	Case Study 1	West façade	Application to first wall
27/02/2016	Case Study 1	N/A	Removal of apparatus, extraction of data and formatting
24/02/2016	Case Study 2	All	Infrared / thermographic analysis
29/02/2016	Case Study 2	East façade	Application to first wall
07/03/2016	Case Study 2	South façade	Removal from previous wall and application to next wall
14/03/2016	Case Study 2	West façade	Removal from previous wall and application to next wall
21/03/2016	Case Study 2	N/A	Removal of apparatus, extraction of data and formatting
22/03/2016	Case Study 3	All	Infrared / thermographic analysis
07/04/2016	Case Study 3	West façade	Removal from previous wall and application to next wall
14/04/2016	Case Study 3	East façade	Application to final wall
21/04/2016	Case Study 3	N/A	Removal of all equipment, extraction of data and formatting

In all cases, thermal paste/grease was applied on the wall side of the HFM to ensure full connection to the wall surface. The HFM was then fixed to the wall surface using a masking tape to the edges away from the meter within the plate, to minimize any effect to the heat flux readings.

The probes used for monitoring internal temperatures were usually located approximately 50mm from the internal wall surface and were located at the same height as the adjacent HFM, and positioned to face the room (i.e. to receive a similar radiant temperature to that of the room interior). For the external air temperature, the probes were positioned (housed within a hanging tube shielding to reduce the



effect of direct solar radiation) about 50mm from the external wall surface, fixed to the wall surface using 9mm round cable clips to provide anchoring. For each dwelling the elemental  $U$ -values were determined by recording the heat-flow through the element together with internal surface and external air or surface temperature. This was done by logging differential voltage from the heat flux transducers and temperature from calibrated T-type thermocouples (resistance) continuously over one week. The signals were measured every 60 seconds.



**Fig. 12 – HFM and internal thermocouple fixed**



**Fig. 13 – External thermocouples fixed**



**Fig. 14 – External thermocouples fixed**

## RESULTS & DISCUSSION

In-situ data was administered by means of the progressive average procedure that is based on the idea that the average of instantaneous ratios between heat flux and temperature differences on a gradually increasing time scale levelling out the oscillations leading to the steady-state value of the thermal transmittance (see Equation 1)

### Equation 1

ISO 6891-1 formula

$$U = \frac{\sum_{j=1}^n q_j}{\sum_{j=1}^n (T_{ij} - T_{ej})}$$

### Thermal Performance of the Analysed Walls

For the purpose of this research, the wall types for each case study investigated have been assigned abbreviations for table listings as per below:

**Table 2**

Case study wall type abbreviations

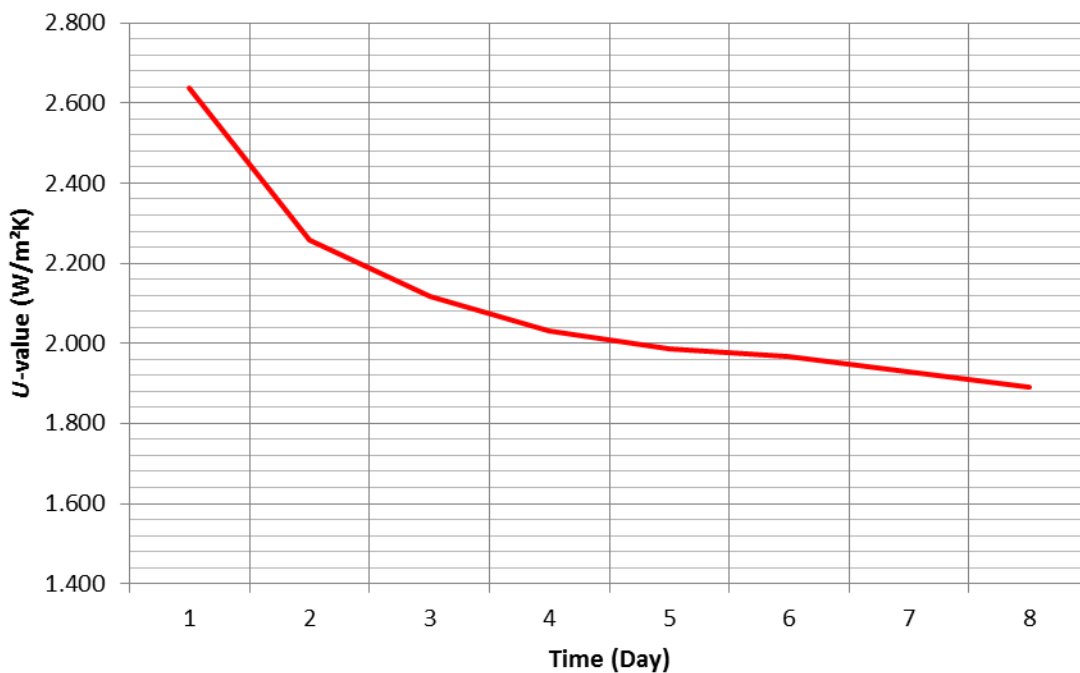
Wall Type	Description	Year of Construction	Year of Thermal Upgrade
WT 1	Case Study 1	1970	N/A
WT 2	Case Study 2	1975-78	2010
WT 3	Case Study 3	1960s/ early 1970s	2012

Standard guidance calculations and simulations were carried out using assembly descriptions and data outlined in Table 3 **Error! Reference source not found.** below:

**Table 3**  
Material Data for Calculations & Simulations

Wall Types	Material (mm)	Conductivity (W/mK)	Specific Heat Capacity (J/kgK)	Bulk Density (kg/m <sup>3</sup> )	Porosity (m <sup>2</sup> / m <sup>3</sup> )	Water Vapour Diffusion Resistance Factor	Insulation Location
WT1	15 Plaster	0.2	850	850	0.65	8.3	Uninsulated
	100 Blockwork	1.33	1000	1900	0.2	15	
	60 Cavity	0.071	1000	1.3	0.999	0.73	
	102.5 Solid Brick	0.77	850	1700	0.24	10	
WT2	15 Plasterboard	0.2	850	850	0.65	8.3	External Insulation
	25 Cavity	0.071	1000	1.3	0.999	0.73	
	215 Concrete	1.6	850	2200	0.18	0.92	
	20Sand-cement render	1.2	850	2000	0.3	25	
	120 Rockwool	0.038	1030	135	0.953	1.1	
10 Render	0.8	850	1900	0.24	19		
WT3	15 Plaster	0.2	850	850	0.65	8.3	Cavity Fill Insulation
	100 Blockwork	1.33	1000	1900	0.2	15	
	50 Ecobead	0.031	1200	11.5	0.95	60	
	102.5 Solid Brick	0.77	850	1700	0.24	10	

In accordance with ISO 9869 the analysis was carried out over a period of 7 days at least. Longer recording times would be ideal, but unachievable in this research project. Fig. 15 is the progressive average *U*-value procedure for WT 1 West façade:



**Fig. 15 - Progressive *U*-value measurement of WT 1 West façade**

WT1-WT3 were all analysed with the same protocol as Fig. 15. These results were then compared with hygrothermal simulations implementing corresponding environmental conditions and ISO 6946 standard method *U*-value calculations. The results of these are assembled in Table 4 below:

**Table 4**

Calculated, simulated and measured thermal transmittance values

Wall Types	Orientation	Calculated (W/m <sup>2</sup> K)	Simulated (W/m <sup>2</sup> K)	Measured (W/m <sup>2</sup> K)
WT1	North		-	-
	South	1.688	-	-
	East		-	-
	West		1.913	1.891
North	-		-	
WT2	South	0.267	0.292	0.315
	East		0.282	0.277
	West		0.297	0.430
	North		-	-
WT3	South	0.508	-	-
	East		0.609	0.603
	West		0.637	0.841
	North		-	-

From analysis of the data, all wall assemblies perform entirely differently depending on orientation, as suggested in previous research by the authors (Flood et al., 2016). It should also be noted that standard ISO 6946 calculations do not align with the in-situ measurements in any case, regardless of orientation. All simulated values align much closer with the in-situ recorded data. For visual contrast, figures within Table 4 have been charted below in Table 5 marking constant ISO 6946 calculations for each wall with red lines.

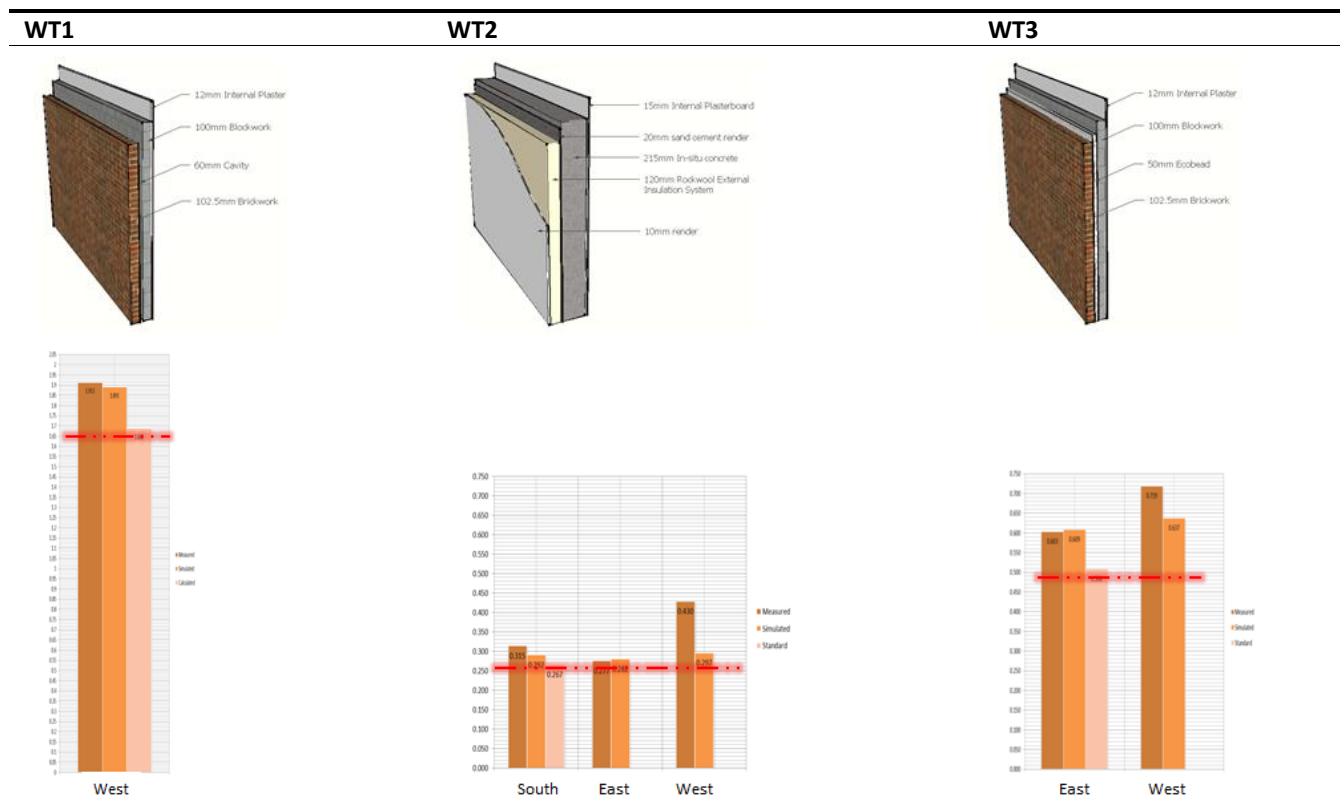
**Table 5**Calculated, simulated and measured *U*-values in chart form

Table 5 confirms the inconsistency between the standard ISO 6946 calculations and in-situ measurements. This discrepancy appears to have been reduced through the use of simulated values,

something linked to orientation – incorporating wind speed, relative humidity, rain and solar transmittance.

## **DISCUSSION**

The findings of this stage of the research confirm that orientation has a significant impact on the thermal performance of an external wall, regardless of the overall assembly as previously suggested through hygrothermal simulation (Flood et al., 2016). Orientation dictates the level of exposure the wall is open to; specifically wind speed, rain count, relative humidity and solar transmittance. This means that when designing an external wall, designers should focus the design parameters around each façade considering the variation in associated external conditions. Hygrothermal performance appears to be a step in the right direction towards a progressive thermal transmittance prediction technique in Ireland. It is clear that the existing thermal transmittance calculation methodology is imbalanced with a number of flaws in its composition. This could be addressed using the knowledge derived from this research.

## **CONCLUSIONS / FURTHER RESEARCH**

This research has reviewed ISO 9869 in-situ  $U$ -value measurement along with hygrothermal simulations and standard ISO 6946  $U$ -value calculations as a method to increase credibility and validity of conclusions resulting from further experimental research. This research is intended to serve as an introduction to issues emanating from a larger research project in order to encourage researchers to understand and further explore the topic.

The realm of heat transfer and building physics is a question throughout the AEC (Architectural, Engineering and Construction) sector, particularly within retrofit and refurbishment. This has been confirmed through an examination of previous research in the field, accompanied by personal experience. The understanding gained regarding the influence of external and internal environmental conditions has already, and continues to enhance the product of this research. Adopting hygrothermal simulations, along with accurate material data analysis has allowed a more concise and defined format of information to be assessed. By searching through previous literature available on AEC research, comparable precedent has been established to set a benchmark for results generated from this research

The findings of this paper identify discrepancies between in-situ and standard method  $U$ -value calculations, proposing to bridge this gap with more representative hygrothermally simulated values. The effect of rain, relative humidity, wind speed and solar radiation may cause the thermal performance gap illustrated in the assemblies. Thus, this research offers a source of information for researchers and designers exploring the performance of external walls to anticipate best practice detailing and in-situ thermal performance values.

Modelled wall assemblies with different porosities, moisture storage capacities and liquid water transport coefficients along with accurate climate data result in different moisture contents and correspondingly; a corrected  $U$ -value. It is clear that if advanced hygrothermal models such as WUFI are to be used to carry out routine assessments of moisture conditions and  $U$ -values in building structures, considerably more construction material data must be made available by manufacturers to achieve realistic simulation results.

## REFERENCES

- Ahmad, A., Maslehuddin, M. and Al-Hadhrami, L. M. (2014) '**In situ measurement of thermal transmittance and thermal resistance of hollow reinforced precast concrete walls**', *Energy and Buildings*, 84(0), pp. 132-141.
- Asdrubali, F., D'Alessandro, F., Baldinelli, G. and Bianchi, F. (2014) '**Evaluating in situ thermal transmittance of green buildings masonries—A case study**', *Case Studies in Construction Materials*, 1(0), pp. 53-59.
- Baker, P. (2008) **Preliminary results** Scotland: Historic Scotland.
- Baker, P. H. (2011) U-values and Traditional Buildings: Historic Scotland Technical Paper 10. **In situ measurements and their comparisons to calculated values**. Edinburgh: Historic Scotland.
- Byrne, A., Byrne, G., Davies, A. and Robinson, A. J. (2013) '**Transient and quasi-steady thermal behaviour of a building envelope due to retrofitted cavity wall and ceiling insulation**', *Energy and Buildings*, 61, pp. 356-365.
- Corbetta, P. (2003) **Social Research: Theory, Methods and Techniques**. SAGE Publications.
- Creswell, J. W. (2009) **Research Design. Qualitative, Quantitative and Mixed Methods Approaches** 3rd edn.: Sage.
- Currie, J., Williamson, J. B. and Stinson, J. (2013) **Monitoring thermal upgrades to ten traditional properties**, Edinburgh, Scotland: Historic Scotland.
- Doran, S. (2000) **Field investigations of the thermal performance of construction elements as built**, Glasgow, Scotland: BRE.
- Doran, S. and Carr, B. (2008) **Thermal transmittance of walls of dwellings before and after application of insulation**, Glasgow, Scotland: Energy Saving Trust.
- Evangelisti, L., Guattari, C., Gori, P. and Vollaro, D. R. (2015) '**In Situ Thermal Transmittance Measurements for Investigating Differences between Wall Models and Actual Building Performance**', *Sustainability*, 7(8).
- Flood, C., Scott, P. L. and Gleeson, W. (2016) '**Application Of Transient Hygrothermal Modelling To Assess Thermal Transmittance: A Case Study In Dublin, Ireland**', *CIB World Building Congress 2016*, Tampere, Finland.
- Hulme, J. and Doran, S. (2015) **In-situ measurements of wall U-values in English housing**, Watford, England: BRE.
- Kema (2008) **Demand Side Management in Ireland: Evaluating the Energy Efficiency Opportunities**: Sustainable Energy Authority Ireland.
- Li, F. G. N., Smith, A. Z. P., Biddulph, P., Hamilton, I. G., Lowe, R., Mavrogianni, A., Oikonomou, E., Raslan, R., Stamp, S., Stone, A., Summerfield, A. J., Veitch, D., Gori, V. and Oreszczyn, T. (2015) '**Solid-wall U-values: heat flux measurements compared with standard assumptions**', *Building Research & Information*, 43(2), pp. 238-252.
- Maxwell, J. A. (1998) **Qualitative Research Design: An Interactive Approach**.
- Maxwell, J. A. (2012) **Qualitative Research Design : An Interactive Approach. Applied social research methods series**; 3rd edn. Thousand Oaks, Calif. ; London: SAGE.
- Peng, C. and Wu, Z. (2008) '**In situ measuring and evaluating the thermal resistance of building construction**', *Energy and Buildings*, 40(11), pp. 2076-2082.
- Rasooli, A., Itard, L. and Ferreira, C. I. (2016) '**A response factor-based method for the rapid in-situ determination of wall's thermal resistance in existing buildings**', *Energy and Buildings*, 119, pp. 51-61.
- Rhee-Duverne, S. and Baker, P. (2013) **Research into the Thermal Performance of Traditional Brick Walls**, London.
- Rye, D. C. (2010) **U-Value Report**, London: SPAB.
- Rye, D. C. and Scott, C. (2012) **U-value Report Revised**, London: SPAB.