Title	The influence of heat transfer and storage in structural precast building components on indoor environments
Author(s)	Hajdukiewicz, Magdalena; Goggins, Jamie
Publication Date	2014
Publication Information	Hajdukiewicz, M; Goggins, J (2014) The influence of heat transfer and storage in structural precast building components on indoor environments Civil Engineering Research in Ireland (CERI 2014) Belfast, Northern Ireland, 2014-08-28- 2014-08-29
Item record	http://hdl.handle.net/10379/4605

The influence of heat transfer and storage in structural precast building components on indoor environments

Magdalena Hajdukiewicz[1, 2, 3], Jamie Goggins[1, 2]
[1]Department of Civil Engineering, National University of Ireland Galway
[2]Ryan Institute, National University of Ireland Galway
[3]Informatics Research Unit for Sustainable Engineering, National University of Ireland Galway
email: jamie.goggins@nuigalway.ie

ABSTRACT: Knowledge about the heat transfer and storage in concrete components of the building envelope is vital in evaluating the environmental and energy performance of buildings. Providing sufficient thermal mass of the building envelope is crucial in delivering optimal indoor conditions while reducing the energy consumption in buildings.
This paper presents a project that focuses on evaluating the thermal performance of precast concrete building structural elements (i.e. twinwall, hollowcore and lattice slab), regarding their thermal properties on indoor environments. The motivation, objectives and method description of the project are described. The analysis proposed in this project will provide (i) better prediction of indoor environmental conditions; (ii) healthier, more comfortable and productive indoor environments; and (iii) reduced/optimised energy consumption in buildings.

KEY WORDS: Buildings, thermal properties, indoor environments, precast concrete

1 INTRODUCTION

Human-induced climate change is occurring globally and has already made a significant impact on the environment and society, due to increased levels of greenhouse gases. The building sector is responsible for 40% of the total final energy consumption and 36% of total CO_2 emissions in the European Union (EU) [1]. Figure 1 shows the energy consumed by residential and commercial buildings in Europe. In Ireland, primary energy use in the building sector is associated with heating/cooling and lighting of buildings. In 2011, primary energy use in Irish buildings accounted for 41% of primary energy supply [2].

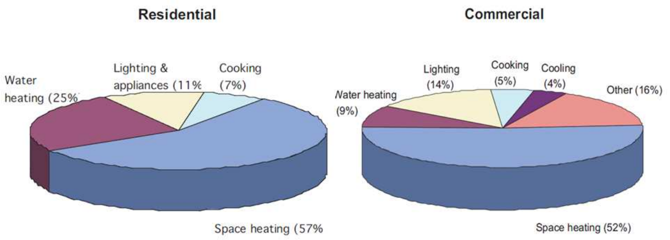

Figure 1. EU building energy consumption for residential and commercial buildings [3].

On May 19th, 2010, the EU adopted the Directive 2010/31/EU [4], which aimed to reduce energy consumed by buildings. Member States are requested to adopt a methodology for calculating the energy performance of buildings (energy performance certification). The objective of the Directive 2010/31/EU is to ensure all new buildings are almost zero-energy consumption buildings by the end of 2020.

At the same time, people spend approximately 90% of their lives indoors [5]. Thus, it is very important to have healthy and comfortable conditions in buildings, including thermal comfort, air quality, or visual and aural comfort. Knowledge about the heat transfer and storage in concrete components of the building envelope is vital in evaluating the occupants thermal comfort and energy performance of buildings. Providing sufficient thermal mass of the building envelope is crucial in delivering optimal indoor conditions while reducing the energy consumption in buildings.

Building regulations and standards incorporate rules for design, construction and operation of existing and new buildings. Those rules are specified in order to ensure safe and accessible buildings that cause limited waste and environmental damage. The compliance with those regulations and standards is crucial for all existing and new buildings. Since, the properties of the building materials are key in building performance, it is essential to accurately assess thermal properties of those materials [6].

2 AVAILABLE METHODS

There are three main evaluation methods that can be used to assess thermal performance of building materials:

- Theoretical design methods.
- Experimental methods.
- Numerical approaches (finite element, finite difference and finite volume methods).

In the theoretical design models thermal resistances of the materials are treated as electrical resistances. However, the design thermal conductivities do not always represent the in situ material properties. Moreover, the design calculations of heat transmission coefficients do not reflect multi-dimensional heat flow conditions [7]. Thus, those theoretical design methods cannot always be used.

The experimental methods such as a guarded hot box or hot plate tests are quite popular. For instance, Kim et al. [8] investigated experimentally thermal properties of lightweight aggregate concrete using a heat flow meter. It was found that the thermal conductivity linearly decreased as the concrete porosity increased, regardless of the location of pores.

Another study measured thermal conductivity of newspaper sandwiched aerated lightweight concrete panels using a guarded hot plate method [9]. It has been known that quartzite, sandstone and other quartzose rocks are the most thermally conductive aggregates. Granite, gneiss, limestone and dolomite have an intermediate thermal conductivity, while basalt and dolerite are the least thermally conductive. Thus, Khan [10] experimentally investigated thermal conductivity of mortar, concrete and its aggregates. The study found the type of aggregate, porosity and moisture content to have a strong influence on thermal conductivity of concrete. Moreover, the study showed that the aggregate type may increase the thermal conductivity of concrete almost twofold.

The numerical methods have been previously utilised in order to investigate thermal performance of building envelope materials. For instance, Lee and Pessiki [11] evaluated the thermal resistance of a three-wythe panel using the finite element method. While, Zhang and Wachenfeldt [12] also utilised this method in order to investigate the effect of air cavities on the heat transfer behaviour and diurnal heat storing capacity of the hollowcore concrete slabs. Furthermore, the study by Del Coz Diaz et al. [13]optimised the lightweight hollow block design for internal floors in respect to energy savings with the support of finite element analysis.

Often, the numerical analysis is supported by experimental data in order to validate the model predictions. Such as in a study that investigated the heat transfer through an in situ constructed, insulated and reinforced (with a truss wire) concrete sandwich wall [14]. This work developed numerical models supported by the laboratory test data (guarded hot box). The computational fluid dynamics (finite volume method), together with experimental tests (guarded hot box unit), facilitated the analysis of heat transfer through a variable aspect ratio cavity wall [15], or a hollow brick wall [16]. The finite difference method supported by experimental tests assisted in the investigation of thermal inertia [17], transient thermal behaviour and surface temperature [18] of aerated lightweight concrete wall panels.

3 PROJECT SCOPE

This paper presents a project that focuses on evaluating the thermal performance of precast concrete building structural elements (i.e. twinwall, hollowcore and lattice slab), regarding their thermal properties on indoor environments.

At the first stage of the project, the real time field measurements are being obtained from the Life Course Studies Institute (LCSI) building at the National University of Ireland Galway. The measurements include monitoring of the (i) weather data with a locally installed weather station, (ii) temperature with thermistors embedded in building's structural precast components (floor/roof slabs and walls), (iii) surface temperature with thermal camera, (iv) indoor air temperature, (v) relative humidity. Next, those measurements will be used to create calibrated CFD models of the precast components design. Those models will be utilised to investigate the heat transfer and storage in precast concrete components. The influence of those phenomena on indoor environmental conditions, including occupants comfort, will be evaluated.

This paper presents the motivation, objectives and method description of the project that investigates the influence of heat transfer and storage in precast building envelope elements on indoor environments. The proposed analysis will provide (i) better prediction of indoor environmental conditions; (ii) healthier, more comfortable and productive indoor environments; and (iii) reduced/optimised energy consumption in buildings.

4 DEMONSTRATION BUILDING

4.1 *Building description*

The LCSI building at NUI Galway is used in this research to analyse the performance of precast concrete building structural elements on indoor environments. The construction of the LCSI building commenced in July 2013 and is expected to be completed by May 2014. The building is partially 3 storey and partially 2 storey with a gross floor area of 3633 m^2 (Figure 2). It is predominately a precast concrete building with the precast elements designed, manufactured and installed by Oran Precast Ltd.

The building accommodates mainly office spaces, seminar rooms and lecture theatres. The building operates with mixed mode ventilation. The part of the building accommodating offices is naturally ventilated, while the seminar rooms and lecture theatres are air conditioned.

Figure 2. The Life Course Studies Institute (LCSI) building © Simon J Kelly Architects.

4.2 *Precast concrete technology*

The LCSI building is mainly built in precast concrete technology, including the building frame, twinwall system, lattice and hollowcore slabs. Precast concrete solutions increase the speed of building erection on site while maintaining the site safer and cleaner when compared to standard construction methods.

Concrete is a long lasting building material that does not require any maintenance, replacement or application of toxic paints or preservatives. Moreover, the thermal capacity of concrete leads to thermal stability and thus offers considerable energy savings and good quality of indoor environment. Hence, concrete is the primary construction material in most of the sustainable developments in Europe [19]. According to the Irish Concrete Society and Irish Concrete Federation '*Exposed concrete acts as a thermal moderator preventing rapid thermal swings, greatly reducing the need to cool office buildings, which is typically the biggest running cost. Only 10% is related to the construction of the building. Designing with energy in mind can reduce in-use energy costs by up to 75% and greatly reduce carbon dioxide emissions'* [20]. The benefits of concrete thermal mass in buildings include [3]:

- Reduction in heating fuel due to solar gains.
- Reduction in heating energy consumption by 2–15%.

- Reduction in the building energy cost.
- Stable indoor temperatures, without high fluctuations.
- Delay in peak indoor temperatures in commercial buildings until the occupants have left.
- Reduction in peak indoor temperatures.
- The possibility of night-time ventilation to eliminate the need for day-time cooling.
- In combination with air-conditioning, concrete thermal mass can reduce the energy used for cooling by up to 50%.

Precast reinforced and pre-stressed concrete is widely regarded as an economic, structurally-sound and architecturally versatile building medium. Controlled and cost-effective manufacturing processes guarantee high quality products at a reduced cost and a minimum design/ manufacturing/ construction time. Despite the popularity of concrete as a building material in Ireland and Europe and its well-known structural properties, there is a dearth of research available on the interaction between the building structure and indoor environments.

4.3 Building instrumentation

Precast concrete technology allows mechanical and electrical products, including sensors to be embedded in the building structure. In order to monitor the thermal performance of structural elements in the LCSI building, over 120 temperature sensors were embedded in the internal and external twinwalls; ground floor hollowcore and in situ slabs; internal and roof lattice slabs. IP68 rated (double insulated, fully encapsulated, protected against water submersion) thermistor sensors (Figure 3) were embedded in the precast and in situ part of the concrete structure. Those thermistors were capable of measuring concrete temperature in the range of between -60/+150°C with a 1% tolerance [21].

a **b**

Figure 3. Thermistors embedded in the (a) precast and (b) in situ concrete in the LCSI building.

This paper describes the details of installation and the initial results of the thermistors embedded in three representative building elements (X0 exposure class – concrete inside buildings with very low air humidity [22]): (i) first floor external twinwall (East facing wall in the West wing), (ii) flat lattice roof slab (East wing), and (iii) suspended ground floor hollowcore slab (0.5 m void, naturally ventilated with external air; East wing with windows facing East).

Figure 4 and Figure 5 show the locations of thermistors in the plan/elevation and across the depth of the precast slab and wall elements, respectively. Thermistors were regularly located at one or two locations and three different depths of each wall/slab in order to measure the temperature distribution profile in the wall/slab. For the external twinwall, at locations 1 and 2, there was one thermistor placed in each of the precast biscuits (T1,2b,t) and one in the middle (T1,2m) of the in situ concrete. For the lattice roof slab, at locations 3 and 4, there was one thermistor placed in the precast biscuit (T4b, *note: T3b & T4t were damaged during the precast manufacturing process*) and two thermistors in the in situ part (T3m,t, T4m). Because of the manufacturing process of the ground floor hollowcore slab, thermistors were embedded into the finished slab by drilling a hole and securing the sensors in locations 5 and 6.

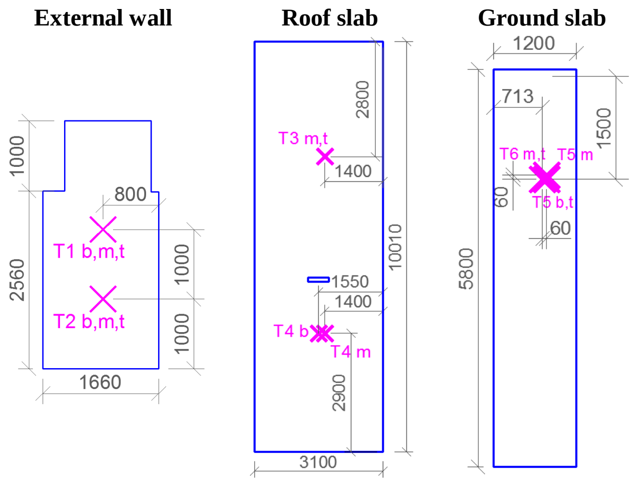

Figure 4. Location of thermistors across the plan of walls and slabs in the LCSI building (dimensions in mm).

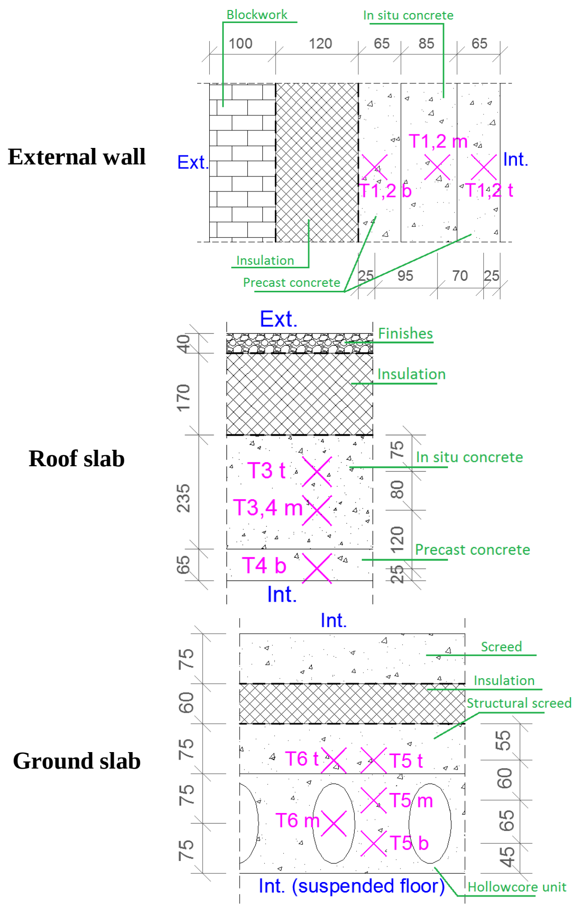

Figure 5. Location of thermistors across the depth of walls and slabs in the LCSI building (dimensions in mm).

4.4 Data acquisition system

The data acquisition system consisting of CR1000 data loggers and AM16/32B multiplexers obtained from Campbell Scientific was employed to collect and store live data measured by the temperature sensors. This system has been automatically logging data from the sensors embedded in the reinforced precast concrete slabs and wall systems since their initial installation. During the construction phase, data is being stored on a flash memory card, which is weekly manually downloaded onto a laptop and backed-up on a server. However, after the building commissioning, data communication will relay on the use of Campbell Scientific's NL115 Ethernet and Compact Flash Module and will allow for data collection over a local network.

4.5 Weather monitoring

The outdoor weather conditions are provided by an automatic weather station [23] at the NUI Galway campus [24]. The station has been continuously reporting weather conditions since July 2010, with a frequency of 1 min. It is located on the roof of one of the University buildings (in the centre of the campus), approximately 1.5 km from the LCSI building. The weather station measures dry-bulb air temperature (^{o}C) and relative humidity (%), barometric pressure (mBar), wind speed (m/s) and wind direction (^{o}), global and diffuse solar irradiance (W/m^2) and rainfall (mm).

4.6 Laboratory experiments

Complementary laboratory experiments will be carried out in order to specify thermal properties of concrete used in the LCSI building, particularly the coefficient of thermal expansion or thermal conductivity. Figure 6 presents the laboratory measurement setup with thermistors embedded in the concrete cylinder, which is placed in a controlled temperature water bath.

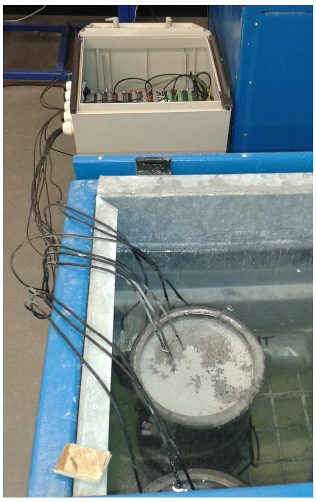

Figure 6. Water bath of the sample concrete cylinders.

5 PRELIMINARY RESULTS

5.1 U-values

The calculation of thermal properties of building materials according to the ISO 6946 standard [25] requires:

- Calculating the thermal resistance of each homogeneous layer of the building component;
- Combining these individual resistances in order to obtain the total thermal resistance of the building component, including the effect of surface resistances;

Calculating the thermal transmittance (U-value) of the building component.

Table 1 shows compliance of calculated *U*-values of the building envelope element in the LCSI building with the current Irish Building Regulations [26].

Table 1. *U*-values of building envelope elements in the LCSI building.

***U*-value [W/m^{2}K]**	**Building Regulations** [26]	**LCSI**
External wall	0.27	0.17 (215 mm cavity twinwall with 80 mm insulation and 100 mm blockwork)
Roof slab	0.22	0.12 (300 mm lattice slab with 170 mm insulation)
Ground slab	0.25	0.24 (150 mm suspended hollowcore slab, 75 mm screed, 60 mm insulation, 75 mm screed)

5.2 Physical measurements

This paper presents the measurements obtained from the thermistors embedded in the external twinwall, roof lattice slab and ground floor hollowcore slab between February 11th, 2014 and March 15th, 2014. The temperature was measured in the external wall every 1 min and in the ground/roof slabs every 6 mins.

During that period, the construction of each considered envelope elements was completed, accordingly to Figure 5. However, the building was not fully enclosed, with many windows and doors yet to be installed (particularly those located on the first and second floor). Thus, Figure 7 Figure 9 compare the temperature distribution in the monitored envelope elements to the outdoor air temperature [24]. It is clear that changes in the outdoor air temperature significantly influenced the temperature distribution in the external twinwall and the lattice roof slab (Figure 7 and Figure 8). There was a clear lag in the wall/slab temperature change in comparison to outdoor air temperature change, i.e. thermal lag. This lag was caused by the thermal mass of the wall/slab, which slowed the heat flow through the element. Figure 7 also shows the temperature of sample concrete cylinder located inside the building. The cylinder temperature profile matched the wall temperature distribution. However, the cylinder temperature was more influenced by outdoor air temperature than wall temperatures. This was due to lack of any insulation on the cylinder.

Temperatures recorded by the thermistors embedded in the suspended ground floor hollowcore slab did not change significantly over the period monitored and were not influenced by the outdoor air temperature (Figure 9). This might have been due to the fact that the hollowcore slab was well insulated from the outdoor temperatures by the underfloor void (with low air exchange) on one side, and 60 mm insulation and enclosed ground floor on the other side.

This suggests that it is not possible to directly utilise the thermal mass of this type of system to regulate the temperature of the space above the floor. However, if designed correctly, it may be possible to take advantage of the relatively constant temperature of underfloor void as part of a heating and/or cooling system for the indoor environment within the building.

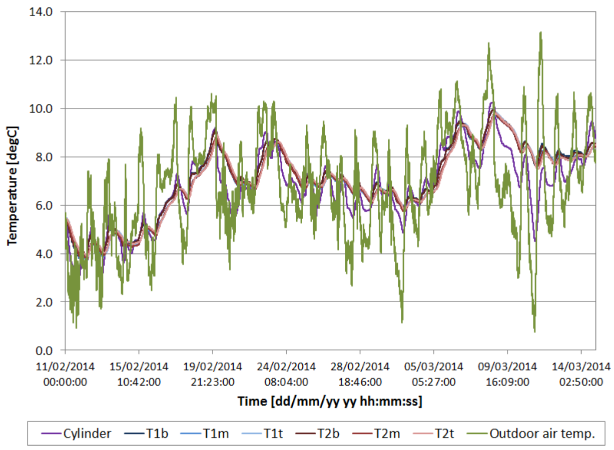

Figure 7. Temperature distribution in the external twinwall.

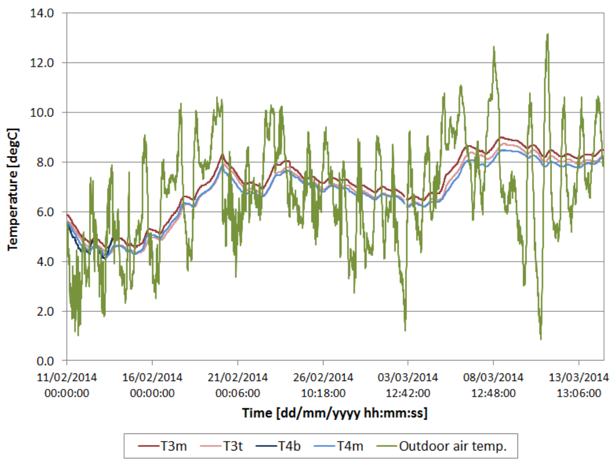

Figure 8. Temperature distribution in the lattice roof slab.

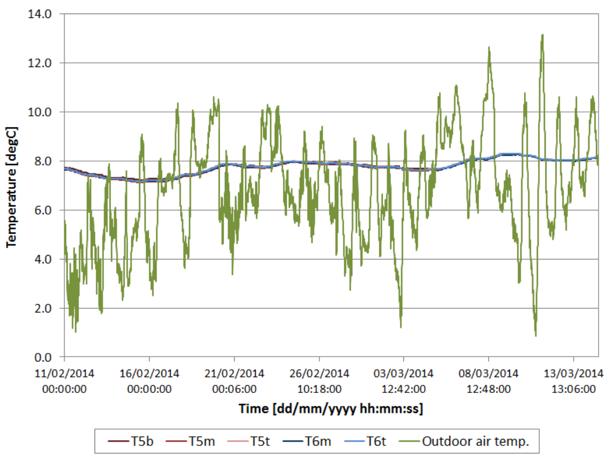

Figure 9. Temperature distribution in the ground floor hollowcore slab.

The correlation coefficients between the outdoor air temperature and the temperatures of the (i) external twinwall, (ii) lattice roof slab, and (iii) ground floor hollowcore slab varied between (i) 0.48 – 0.59, (ii) 0.43 – 0.47, and (iii) 0.20 - 0.28, respectively. Those results reassured previous statements that there was a clear thermal lag in the wall/roof slab temperature change in comparison to outdoor air temperature change and, thus, the correlation coefficient was only ~0.5. Moreover, a good insulation protected the hollowcore ground slab from the influence of outdoor air temperature, resulting in a low correlation coefficient between those two sets of measurements. The correlation coefficient between the outdoor and concrete elements temperature datasets was calculated based on the equation:

$$correl(X,Y) = \frac{\sum(x - x_{ave})(y - y_{ave})}{\sqrt{\sum(x - x_{ave})^2 \sum(y - y_{ave})^2}} \qquad (1)$$

where x_{ave}, y_{ave} are the average values of each data set.

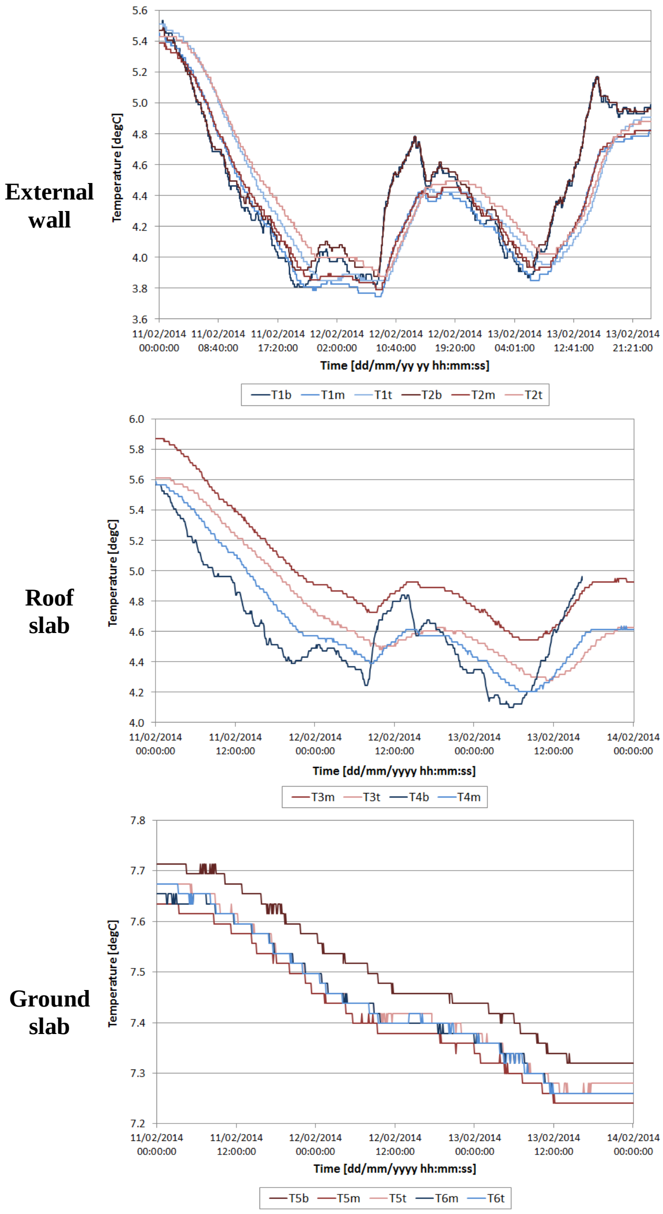

Figure 10. Detailed temperature distribution within the envelope elements (11-14 February 2014).

Figure 10 shows a detailed comparison of temperatures recorded by thermistors embedded at different locations/depths in the envelope elements over a 3 days period. Measured temperatures within the particular envelope element (regardless of location or depth) followed similar profile in time. Generally, there were no significant differences in temperatures at different locations/depths in considered wall and slabs. The reason for that was the fact that the building was not completed at the time of the measurements and there were no significant differences between the indoor/outdoor air temperatures. There were some irregular differences that occurred between different element depths/locations. Those differences might have been caused by localised thermal effects. The sources of those effects were difficult to establish due to ongoing site works. However, the initial results presented here showed a satisfactory performance of installed thermistors and provided an important basis for future thermal performance measurements in the operating building.

6 CONCLUSIONS AND FUTURE WORK

This paper presents the motivation, objectives and method description of the project that investigates the influence of heat transfer and storage in precast building envelope elements on indoor environments. The preliminary results include (i) the measurement setup, both in the operating building as well as the laboratory experiments; (ii) the theoretical analysis of the thermal properties of proposed precast components; and (iii) the early stage measurements from the sensors installed in the LCSI building.

Those results provide the first assessment of the performance of the measurement platform installed in the LCSI building. Moreover, those results together with the measurements taken during the operation phase of the building will support the future generation of CFD models to investigate the heat transfer and storage in precast concrete components and their influence on indoor environmental conditions, including occupants comfort, will be evaluated.

The proposed analysis will provide (i) better prediction of indoor environmental conditions; (ii) healthier, more comfortable and productive indoor environments; and (iii) reduced/optimised energy consumption in buildings.

ACKNOWLEDGMENTS

The authors would like to thank the Irish Research Council and Oran Pre-Cast Ltd. for funding this research. The authors would also like to thank the National University of Ireland Galway and particularly the Department of Civil Engineering for the help with the instrumentation in the demonstration building.

REFERENCES

[1] European Union, “Official website of the European Union” 2014. Available: http://www.europa.eu.

[2] SEAI, *Energy in Ireland 1990-2011*. Dublin, Ireland: Sustainable Energy Authority of Ireland, 2012.

[3] ICF, “Concrete for energy efficient buildings: The benefits of thermal mass” Dublin, Ireland: Irish Concrete Federation, 2008.

[4] European Commission, “Directive 2010/31/EU on the energy performance of buildings” *Off. J. Eur. Union*, 2010.

[5] US EPA, “United States Environmental Protection Agency” 2012. Available: http://www.epa.gov/.

[6] CIBSE, *Guide A: Environmental design*, 7th Ed. London, UK: Chartered Institution of Building Service Engineers, 2006.

[7] L. S. Shu, A. E. Fiorato, J. W. Howanski, “Heat transmission coefficients of concrete block walls with core insulation” in *ASHRAE/DOE-ORNL Conference, Thermal Performance of the Exterior Envelopes of Buildings*, 1979, pp. 421–435.

[8] H. K. Kim, J. H. Jeon, H. K. Lee, “Workability, and mechanical, acoustic and thermal properties of lightweight aggregate concrete with a high volume of entrained air” *Constr. Build. Mater.*, vol. 29, pp. 193–200, 2012.

[9] S.-C. Ng, K.-S. Low, “Thermal conductivity of newspaper sandwiched aerated lightweight concrete panel” *Energy Build.*, vol. 42(12), pp. 2452–2456, 2010.

[10] M. . Khan, “Factors affecting the thermal properties of concrete and applicability of its prediction models” *Build. Environ.*, vol. 37(6), pp. 607–614, 2002.

[11] B.-J. Lee, S. Pessiki, “Thermal performance evaluation of precast concrete three-wythe sandwich wall panels” *Energy Build.*, vol. 38(8), pp. 1006–1014, 2006.

[12] Z. L. Zhang, B. J. Wachenfeldt, “Numerical study on the heat storing capacity of concrete walls with air cavities” *Energy Build.*, vol. 41(7), pp. 769–773, 2009.

[13] J. J. del Coz Díaz, P. J. García Nieto, J. Domínguez Hernández, A. Suárez Sánchez, “Thermal design optimization of lightweight concrete blocks for internal one-way spanning slabs floors by FEM” *Energy Build.*, vol. 41(12), pp. 1276–1287, 2009.

[14] G. . Jones, R. . Jones, “Steady-state heat transfer in an insulated, reinforced concrete wall: theory, numerical simulations, and experiments” *Energy Build.*, vol. 29(3), pp. 293–305, 1999.

[15] D. P. Aviram, A. N. Fried, J. J. Roberts, “Thermal properties of a variable cavity wall” *Build. Environ.*, vol. 36(9), pp. 1057–1072, 2001.

[16] J. M. Sala, A. Urresti, K. Martín, I. Flores, A. Apaolaza, “Static and dynamic thermal characterisation of a hollow brick wall: Tests and numerical analysis” *Energy Build.*, vol. 40(8), pp. 1513–1520, 2008.

[17] S.-C. Ng, K.-S. Low, N.-H. Tioh, “Thermal inertia of newspaper sandwiched aerated lightweight concrete wall panels: Experimental study” *Energy Build.*, vol. 43, no. 10, pp. 2956–2960, Oct. 2011.

[18] S.-C. Ng, K.-S. Low, and N.-H. Tioh, “Newspaper sandwiched aerated lightweight concrete wall panels—Thermal inertia, transient thermal behavior and surface temperature prediction” *Energy Build.*, vol. 43(7), pp. 1636–1645, 2011.

[19] IPCA, “Precast concrete: Frames guide” Dublin, Ireland: Irish Precast Concrete Association, 2005.

[20] ICS and ICF, “The new concrete standards: An introduction to EN 206-1” Drogheda, Ireland: Irish Concrete Society and Dublin, Ireland: Irish Concrete Federation, 2004.

[21] ATC Semitec, “Thermal components” 2014. Available: www.atcsemitec.co.uk.

[22] CEN, “EN 206: Concrete - Part 1 : Specification, performance, production and conformity” Brussels, Belgium: European Committee for Standardization, 2002.

[23] Campbell Scientific, “Campbell Scientific, Inc.” 2014. Available: http://www.campbellsci.co.uk/.

[24] IRUSE, “IRUSE weather website” 2014. Available: http://weather.nuigalway.ie/.

[25] ISO, “6946: 2007. Building components and building elements - Thermal resistance and thermal transmittance - Calculation method” Geneva, Switzerland: International Organization for Standardization, 2007.

[26] Irish Government, “Building Regulations. Part L: Conservation of fuel and energy - Buildings other than dwellings” Environment, Heritage and Local Government, Ireland, Dublin, Ireland: Environment, Heritage and Local Government, 2008.