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Title	The environmental performance of a reinforced precast concrete slab with void forming system
Author(s)	Hajdukiewicz, Magdalena; Lebrene, J; Goggins, Jamie
Publication Date	2014
Publication Information	Hajdukiewicz, M; Lebrene, J; Goggins, J (2014) The environmental performance of a reinforced precast concrete slab with void forming system International Conference on Construction Materials and Structures (ICCMATS 2014) Johannesburg, South Africa, 2014-11-24- 2014-11-26
Item record	http://hdl.handle.net/10379/4608

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The environmental performance of a reinforced precast concrete slab with void forming system

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Abstract. In some climates people spend approximately 90% of their lives indoors. Thus, it is very important to maintain healthy and comfortable conditions in buildings. The building sector is responsible for about 40% of the energy consumption and contributes related CO₂ emissions worldwide. Knowledge about the heat transfer and storage in concrete components of the building envelope and materials that comprise the envelope is vital in evaluating the environmental and energy performance of buildings. Providing sufficient thermal properties of the building envelope is crucial in delivering optimal indoor conditions while reducing the energy consumption in buildings. This paper presents a case study that focuses on evaluating the environmental performance of a reinforced precast concrete slab that incorporates the void forming system. Numerical analysis and field measurements were performed to investigate thermal properties of the floor slab in the operating demonstration Engineering Building at the National University of Ireland Galway in Ireland. Firstly, the numerical finite volume models of the slab in the demonstration building were developed and validated with the ‘real-time’ physical measurements. Those measurements were obtained from the demonstration building, including temperature sensors embedded in the slab, outdoor air temperatures, thermal imaging, etc. Those validated models allowed investigation of the phenomena of heat transfer and storage in the slab and their influence on indoor environmental conditions, including occupants’ health and comfort. The numerical models and ‘real-time’ field measurements were also supported by detailed laboratory experiments regarding the material properties of concrete. The proposed analysis will (i) identify possible design/operation drawbacks; (ii) suggest optimised, cost-effective and sustainable designs; and (iii) allow for the development of new environmentally friendly and energy efficient structural building components.

Keywords. Precast slab, Void forming system, Numerical model, Environmental performance

Introduction

The building sector is responsible for about 40% of the total European energy consumption and related CO₂ emissions in the European Union (EU) [1]. In 2009, EU leaders and the G8 specified a reduction in greenhouse emissions by at least 80% below 1990 levels by 2050 [2]. In addition, the EU adopted the Directive on Energy Performance of Buildings [3], which requires a ‘nearly-zero energy building’ target for

new public buildings from 2018 and from 2020 for all new buildings. This puts pressure on the building sector to consider aggressive energy efficiency measures.

In some climate regions people spend approximately 90% of their lives indoors [4]. While reducing the energy consumed by buildings, consideration must also be given to providing healthy and comfortable indoor conditions for the occupants. Knowledge about the transport of various phenomena through multi-layered building components is vital in evaluating the components' structural and environmental performance. Providing sufficient thermal mass of the building envelope is crucial in delivering satisfactory indoor conditions while reducing the energy consumption in buildings.

In summary, it is vital to give consideration to both the environmental and energy aspects in buildings. This should be done in order to maintain safe, healthy and comfortable environments for the occupants of energy efficient and sustainable buildings.

Numerical methods have been previously used to investigate the thermal performance of building structural components (e.g. [5]–[7]). The most common methods include finite difference, finite element and finite volume numerical analyses. Those methods can help understand and predict phenomena that are often difficult to test experimentally, resulting in cleaner, healthier, better controlled and sustainable internal environments. It is important that numerical simulation tools are validated with physical measurements. However, there is a dearth of measured data for buildings. Experimental investigations in isolation do not provide a comprehensive picture of buildings performance. Furthermore, such investigations may be time consuming and expensive. On the other hand, numerical models can quickly offer rich information about the influence of the building structural elements on indoor environmental conditions. Validated with physical measurements, numerical models allow for many opportunities to test and optimise designs. This is done in order to ensure building owners and occupants enjoy high air quality, thermal comfort, minimal noise levels and energy efficiency.

The European Standards and building regulations for precast building products specify in detail the design and construction of precast elements in terms of their structural and environmental performance. However, there can be a gap between the intended design and the final product. This gap can be bridged by validated numerical models to predict if the designed product may perform as intended.

1. Demonstration building

1.1. A living laboratory

The Engineering Building (EB) at the National University of Ireland (NUI) Galway (Figure 1) is a state of the art academic facility that integrates all engineering activities on campus. The 14 250 m² building has been opened to public in July 2011 and accommodates over 1 100 students and 110 staff. The building provides a learning environment and also acts as a teaching/learning tool. The EB is a 'living laboratory' for engineering, where live data sets from numerous types of sensors are provided to illustrate structural and environmental building performance concepts in undergraduate teaching and in the development of full-scale research. Structural and environmental characteristics of the building are systematically captured, transformed and monitored throughout the building's entire life cycle. Those characteristics include the

measurement of building's (i) structural behaviour (strains, temperatures and movements in the building structure); (ii) energy demands (electrical loads such as lighting, computing and HVAC equipment); and (iii) environmental behaviour (thermal comfort, air quality and water consumption). The information gathered from the building is then used to create interactive tools for students, form the basis for ongoing/future research projects and facilitate the advancement of engineering teaching methods.



Figure 1. Engineering Building (EB) at NUI Galway.

1.2. Void-form concrete slab system

The research presented here investigates the environmental performance, i.e. heat transfer through the void-form concrete slab built in the Cobiax system technology [8]. The Cobiax slabs are the reinforced concrete slabs with implemented high-density polyethylene hollow void formers (Figure 2). Those hollow void formers not only reduce the structural dead load of the slab (resulting in saving on the material cost and allowing larger slab spans), but also increase the thermal resistance of the slab.

The investigated void-form concrete slab was a floor slab located on the third floor in the west wing of the EB. This novel form of flat slab system was implemented for the first time in Ireland in the EB. The slab (12.65 m x 7.50 m) consisted of the precast lattice girder element manufactured off site and the in-situ element (Figure 3). The bottom surface of the slab was exposed (with no finish applied to it), while the top surface of the slab was hidden under the suspended panel floor.



Figure 2. Cobiax voided concrete slab system being installed in the EB (left) and with gauges installed (right) [9].

2. 'Real-time' measurements

There were 164 sensors embedded in the slab, i.e. 64 vibrating wire (VW) gauges (Gage Technique model TES/5.5/T [10] measuring strain and temperature of concrete) and 100 electrical resistance gauges (Tokyo Sokki Kenkyujo model FLA-6-120-11-3LT [11] measuring strain of reinforcement). The aim of embedding sensors in this novel form of slab was to investigate its structural (two-way spanning action) and environmental (heat transfer) performance.

This paper focuses on the measurements taken by the gauges located in the middle of the slab/room (intersection of grid lines 9.5/B) and thus the most representative for the whole slab. At this location there were two gauges (TempX,Y_B) located at the bottom of the slab (100 mm from the bottom surface of the slab), one gauge (TempX_M) in the middle of the slab (227 mm from the bottom surface of the slab), and two gauges (TempX,Y_T) at the top of the slab (354 mm from the bottom surface of the slab).

Data measured by the VW gauges have been collected and stored on a data acquisition system consisting of CR1000 data loggers, AVW200 vibrating wire interface and AM16/32B multiplexers [12]. This system has been automatically logging data from the sensors embedded in the void-form concrete slab since their initial installation. During the construction phase, data were stored on a flash memory card and manually downloaded onto a laptop weekly and backed-up on a server. Since the commissioning of the EB, data communication has been relayed through the use of the NL115 Ethernet and Compact Flash Module [12] and allowed for data collection over a local network. Additionally to the building structure performance measurement, outdoor air temperatures were monitored by the automatic weather station located at the NUI Galway campus [13]. Since, the rooms below and above the slab were both naturally ventilated, it was expected that the outdoor air temperature would influence the temperature distribution in the slab.

This paper presents the measurements taken throughout the full day of July 3rd, 2013. The measurements between 10 am and 4 pm were used to develop the numerical model of the slab (Section 3). Figure 4 compares the profiles of the outdoor air temperature and the slab temperatures. It is evident that with the increase in the outdoor air temperature, the temperature of the slab increased as well, particularly in the lower part of the slab (TempX,Y_B). In the middle (TempX_M) and upper (TempX,Y_T) parts of the slab, the temperature increased with a visible thermal lag. This might have been due to the fact that the room above the slab had the suspended panel floor installed, which provided additional insulation from the influence of the outdoor air.

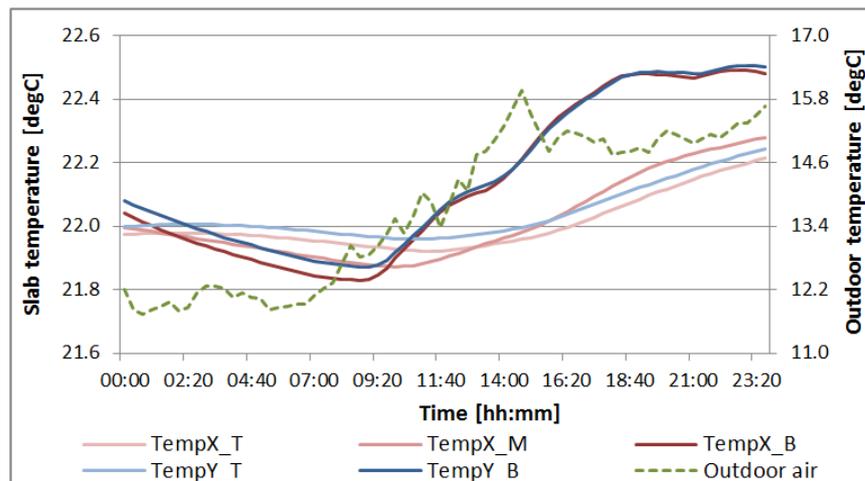


Figure 4. Outdoor air and slab temperature measurements recorded on July 3rd, 2013.

3. Numerical analysis

In this paper, a 3D finite volume model was developed in order to investigate the heat transfer through the Cobiax void-form slab. The commercial finite volume analysis software ANSYS CFX [14] was utilised. The numerical model was then validated with the 'real-time' measurements from the demonstration EB at NUI Galway (Section 2).

3.1. Geometry and mesh

The 3D geometry of the slab was reduced in order to decrease the number of mesh elements to be solved and, thus, minimise the computational time. The geometry consisted of the 450 mm thick reinforced concrete slab with two void formers secured by the light metal mesh (Figure 5). The unstructured mesh of the model contained 2 337 162 tetrahedral elements.

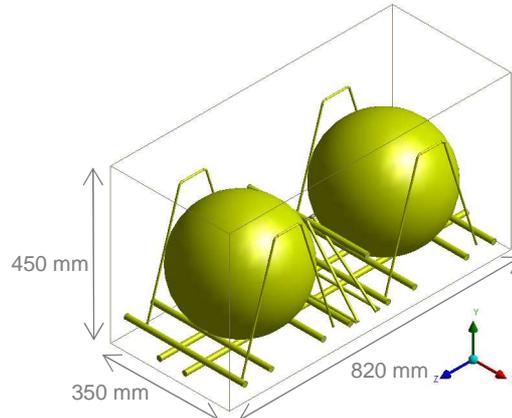


Figure 5. Geometry of the modelled Cobiax slab.

3.2. Material properties and boundary conditions

The steady state conditions were used in the analysis. The mass, momentum and energy governing equations were solved for all mesh elements in the model. The high resolution advection scheme (that denotes a class of numerical discretisation for solving partial differential equations) was applied. The high resolution scheme is essentially a second order accurate scheme, for which values of blend factor vary throughout the domain based on the local solution field. Satisfactory convergence was achieved using the criteria of 0.01% of root mean square residuals for mass, momentum and energy equations, 1% of the energy conservation target and the numerical results at points of interest no longer changing with additional iterations.

The air in the void formers was modelled as an ideal gas with the reference buoyancy density of 1.185 kg/m^3 and the reference pressure of 1 atm. The full buoyancy model was applied (where the fluid density was a function of temperature or pressure) and the Reynolds averaged Navier-Stokes (RANS) eddy-viscosity two-equation standard $k-\varepsilon$ turbulence model [15] was chosen. The other materials described in the model included (i) high-density polyethylene void formers ($\rho = 950 \text{ kg/m}^3$), (ii) steel reinforcement bars (density, $\rho = 7854 \text{ kg/m}^3$), and (iii) concrete

($\rho = 2\,406\text{ kg/m}^3$). The densities of the precast and in-situ concrete were experimentally investigated in the laboratory environment based on the samples taken from the precast manufacturing plant and the building site [9].

The surface temperature boundary condition was set on the top and bottom horizontal surfaces of the model ($t_{top} = 20.40\text{ }^\circ\text{C}$, $t_{bottom} = 22.10\text{ }^\circ\text{C}$). Those temperatures were the average slab surface temperatures, measured with the thermal camera FLIR T335 [16] during the experiment on 3rd July 2013 between 10 am and 4 pm. Since there was no access available to the slab from the room above it, the top surface temperature of the slab was assumed the same as the temperature of the suspended panel floor. The measurement accuracy of the camera was $\pm 2\text{ }^\circ\text{C}$ or 2% of the reading. Despite the fact that the room below the slab and the room above it were both naturally ventilated and operated in the same manner, the temperature of the bottom surface of the slab was higher than the temperature of the top surface. This was due to the temperature stratification inside those rooms and resulted in higher temperature at the ceiling level (in the room below the slab) than the temperature at the floor level (the room above the slab).

The symmetry boundary condition was set at the four vertical surfaces of the model in order to simulate the conditions in the middle of the slab (at the intersection of grid lines 9.5/B). The interface fluxes were set in order to model the heat transfer between the different materials in the model.

3.3. Validated results

Figure 6 shows the temperature distribution in the modelled Cobiax slab. Temperatures in the slab decreased evenly from the $22.10\text{ }^\circ\text{C}$ at the bottom surface of the slab to $20.40\text{ }^\circ\text{C}$ at its top surface. The average temperature of: (i) the air in the void formers was $21.33\text{ }^\circ\text{C}$, (ii) the polyethylene of the void formers was $21.57\text{ }^\circ\text{C}$, (iii) the reinforcement was $21.59\text{ }^\circ\text{C}$, and (iv) the concrete was $21.53\text{ }^\circ\text{C}$.

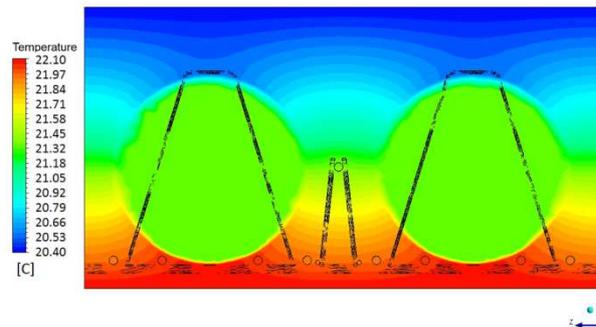


Figure 6. Temperature distribution in the void-form slab.

In order to validate the numerical model, the measurements on 3rd July 2013, taken every 20 min between 10 am and 4 pm were considered. The measurements over this 6-hours period were relatively steady (standard deviation not exceeding $0.13\text{ }^\circ\text{C}$) and, thus, suitable for use in the validation of the steady state numerical simulation. Table 1 compares measured and simulated temperatures in the slab. The numerical results showed a very good agreement with the measurements in the lower parts of the slab (TempX,Y_B) with an error of less than 2%. In the upper part of the slab (TempX,Y_T) the error between measured and simulated temperatures increased up to

6%. This might have been due to the fact that the boundary condition at the top surface of the slab was not specified accurately (it was assumed as the measured surface temperature of the suspended panel floor) and, thus, influenced the modelled temperatures in the upper part of the slab the most.

Table 1. Measured and simulated temperatures in the Cobiax slab at 9.5/B grid lines.

Location	Measured temp. [°C]	Simulated temp. [°C]	Error [%]
TempX_B	22.11	21.77	1.5
TempY_B	22.12	21.75	1.7
TempX_M	21.94	21.19	3.4
TempX_T	21.94	20.68	5.7
TempY_T	21.98	20.69	5.9

4. Conclusions and future work

This paper presents a case study that focused on evaluating the environmental performance of a reinforced precast concrete slab that incorporated the void forming system. The initial field measurements and numerical models were performed to investigate thermal properties of the floor slab in the operating demonstration building.

The proposed analysis, such as presented in this paper, may be utilised to (i) identify possible design/operation drawbacks; (ii) suggest optimised, cost-effective and sustainable designs; and (iii) allow for the development of new environmentally friendly and energy efficient structural building components. Furthermore, validated numerical models can also be used to investigate the thermal behaviour of the void-form concrete slab, including fire resistance and cooling time after extinguishing the fire.

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