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Energy and Buildings 138 (2017) 432–442

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

# Ultra-lightweight concrete: Energy and comfort performance evaluation in relation to buildings with low and high thermal mass

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ARTICLE INFO

*Article history:*
Received 12 September 2016
Received in revised form 9 November 2016
Accepted 16 December 2016
Available online 24 December 2016

*Keywords:*
Themal mass
Ultra lightweight concrete
Building performance simulation
Analytical validation
Monolithic building envelope

ABSTRACT

Ultra-lightweight concrete (ULWC) was recently introduced as a novel building material that combines moderate thermal insulation properties with load-bearing capacity. Its intended use as monolithic building envelope brings new opportunities in building physics, by merging characteristics of both heavyweight and lightweight construction types. This paper investigates the potential of ULWC building envelopes in terms of energy efficiency and thermal comfort. The dynamic thermal characteristics of a monolithic structure of ULWC were first compared to more conventional constructions using EN-ISO-13786 calculation methods. The main contribution of this article lies in the subsequent development and application of a simulation strategy for predicting the energy and comfort performance of ULWC on the whole-building level. The quality of the simulations in EnergyPlus was first ensured in an analytical validation study, and then applied to assess the performance of ULWC for commercial and residential case studies in the Netherlands. Results show that ULWC constructions are comparable to heavyweight buildings in long-term behaviour, whereas they resemble the performance of lightweight building envelopes for short-term heating periods. ULWC can therefore be a suitable construction type in buildings with intermittent operation, but in other cases it can get outperformed by conventional constructions with low or high thermal mass.



## 1. Introduction

### 1.1. Background

Effective use of thermal mass plays a large role in many design concepts for climate-conscious sustainable buildings [1,2,3]. Its importance is becoming more prominent as a result of increasing thermal insulation standards and the need for realizing net-zero energy buildings with a healthy and comfortable indoor environment [4,5]. Constructions with high thermal mass – usually consisting of heavyweight materials such as concrete or masonry at the interior side of the insulation layer – typically result in indoor environments with relatively small temperature fluctuations [6]. This high thermal inertia leads to high radiant temperatures in winter, and a reduced risk for indoor overheating in summer [7,8]. However, buildings with high thermal mass need more time to heat up or cool down, possibly leading to thermal discomfort, and also tend to use more energy for heating and cooling during this process [9]. Considering these possible drawbacks caused by a slow thermal response, constructions with low thermal mass (e.g. timber or steel-frame buildings) can under some circumstances actually lead to higher building performance compared to heavyweight buildings [10].

It is not possible to make unequivocal conclusions about what is better: constructions with high or low effective thermal mass. This is especially the case in cool and moderate climate zones where it is possible to take advantage of the daily and seasonal variation in outside temperature to aid in keeping indoor conditions comfortable [11]. Choosing an adequate amount of thermal mass is always case-specific, and depends on many interrelated factors, such as: weather conditions, occupancy pattern, internal heat gains, HVAC type, building orientation, fenestration and shading system, etc. [12]. Nevertheless, due to the intrinsically opposing effects of thermal mass on the previously described energy and comfort nexus, it is usually needed to make a compromise. It is virtually impossible to select a construction type that, in terms of thermal mass, simultaneously performs optimal considering warm-up behaviour, overheating risk mitigation and overall energy use [9].

This challenge is commonly faced in the building design process, and has therefore led to the search for innovative construction types and new building materials that are able to combine the benefits of high and low thermal mass in a more intelligent way. Among

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http://dx.doi.org/10.1016/j.enbuild.2016.12.049

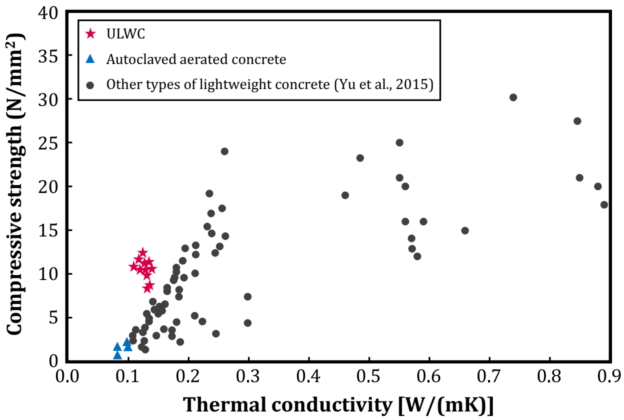


**Fig. 1.** Characterization of various types of concrete, showing the trade-offs between thermal and mechanical properties. ULWC is unique in that it combines high compressive strength with reasonable thermal resistance properties. Adapted from: [17].

the most notable research and development directions are, phase change materials (PCM) [13], hollow block walls [14], ventilated slabs [15] and dynamic insulation systems [16].

### 1.2. Ultra-lightweight concrete

This study is part of the ongoing trend that aspires smarter utilization of thermal mass, and specifically focuses on ultra-lightweight concrete (ULWC). ULWC has recently been introduced as an emerging construction material that can be produced by adding special functional aggregates such as expanded recycled glass [17] or micro-silica [18] to the concrete mixture. The grain size of these aggregates is such that it can replace sand and gravel. The air that is trapped in the small hollow grains represents roughly two-thirds of the total volume. Due to the high air content, concrete with a density of around 800 kg/m$^3$ and a thermal conductivity of $\lambda$ = 0,14 W/(mK) can be obtained, with a relatively high compressive strength of approximately 10 N/mm$^2$ (Fig. 1).

The concept of ULWC shares similarities with aerated autoclaved concrete (AAC) blocks; a construction type that is widely used in many European and Asian countries [19,20]. Both ULWC and AAC aim at combining structural and thermal properties in one construction material. This has benefits for recyclability and reduced use of raw materials. Both construction types also have good sound insulation and fire resistance properties. With bulk densities of 300–500 kg/m$^3$, AAC can reach thermal conductivities as low as 0.08–0.12 W/mK [21]. However, AAC blocks also have a significantly lower compressive strength (usually below 5 N/mm$^2$) (Fig. 1). In cases without reinforcement, this makes it suitable for low-rise buildings up to two storeys only. Recent research activities have aimed at increasing the structural performance of aerated concrete, while keeping low thermal conductivity. Results show that AAC blocks with a compressive strength up to 7 N/mm2 are possible when special additives are used, but this also shifts the thermal conductivity to the same range as ULWC [22]. ULWC is therefore considered to be the material with the lowest thermal conductivity at this range of compressive strength (>10 N/mm$^2$) and density (800 kg/m$^3$) [23]. Another difference between ULWC, with its expanded recycled glass aggregates, and AAC, is that ULWC does not need additional surface finishings to avoid exposition to high moisture straining and freezing of condensed water [24].

The unique combination of insulating and structural properties of ULWC allows for an innovative building concept: monolithic walls. A load-bearing construction with an $R_c$ value of 5 m$^2$K/W can be reached with *only* 70 cm of ULWC. This leads to an unconventional construction, embodying the following paradox: the material ULWC has a low thermal inertia (volumetric heat capacity, $\rho \cdot c_p = 700 kJ/m^3K$), but the equal distribution of thermal resistance and thermal capacitance in the monolithic application – in contrast to a multi-layered construction – also gives it characteristics resembling constructions with high thermal inertia. From the perspectives of architectural integration, production methods and assembly technologies, such a single-layer building envelope brings many promising opportunities. ULWC can moreover reduce the effect of thermal bridges, and allows for airtight constructions because of the lower number of connections and joints.

### 1.3. Performance assessment of ULWC in buildings

ULWC has currently been developed in the form of reduced-scale prototypes that have been tested in a laboratory environment [17]. This corresponds to a Technology Readiness Level (TRL) of 4, whereas the final target of TRL 9 stands for a ready to use building product, fully integrated and tested in actual buildings [25].

Although the potential of ULWC appears promising, there is a need for more information about its performance on the whole building level, before the innovation process can be scaled-up. Experimental campaigns using full-scale buildings with monolithic building envelopes out of ULWC are helpful for this purpose, but are also time-consuming to set-up and monitor, costly, and due to the limited control over boundary conditions, may not be able to deliver the required information. Other evaluation approaches, including commonly used component-level characterization metrics for thermal mass, such as periodic thermal transmittance and decrement factor, also lack powerful capabilities for supporting the R&D process of ULWC because they provide little information about the building integration aspects of the new construction type. To bypass these limitations, this study introduces a simulation-based performance assessment of ULWC. Using a series of tests with *virtual* buildings in whole-building performance simulation models, this study aims at accelerating the R&D process by comparing the performance of ULWC based on performance indicators that are of direct interest to the end user: overall energy use for heating and cooling, and thermal comfort. Simulations have as additional advantage that multiple usage scenarios and environmental conditions can easily be tested, and that it also facilitates insights into the potential of constructions with alternative properties than those already produced in the lab [26].

The 70 cm ULWC construction width that is needed to meet thermal insulation standards may become a barrier, because of the loss in inhabitable space. However, the construction thickness is not undue compared to the walls of thermally heavyweight passive or low energy dwellings in the same climate regions, where structural and thermal performance is ensured by individual construction layers, which commonly leads to construction thicknesses above 50 cm [27,28]. The technical feasibility of making monolithic concrete building constructions has been demonstrated in a number of German projects [18,29]. One of the goals of this research is to explore whether the potential added value in terms of energy and comfort has enough significance to make up for the space loss.

The unique combination of thermophysical properties of ULWC and its application as monolithic structure are not only unconventional for the building sector, but also lead to new questions from the building performance simulation perspective. For example, the complexities associated with this innovative use of thermal mass are not easily captured in readily available quantitative metrics. Furthermore, there is a significant need for quality assurance procedures to ensure that the integration of ULWC in building performance simulation models will lead to sound outcomes. In addition to analysing the performance of ULWC, the development

**Table 1**
Comparison of the material properties of ULWC, a common insulation material and regular concrete.

| | | | ULWC | Insulation material | Concrete |
|---|---|---|---|---|---|
| Thermal conductivity | $\lambda$ | W/(mK) | 0.14 | 0.04 | 2.0 |
| Density | $\rho$ | kg/m$^3$ | 800 | 20 | 2400 |
| Specific heat capacity | $c_p$ | J/(kgK) | 870 | 840 | 850 |
| Thermal diffusivity | $\alpha$ | mm$^2$/s | 0.20 | 2.37 | 0.97 |
| Thermal effusivity | $\varepsilon$ | J/(K m$^2$ s$^{0.5}$) | 312 | 26 | 2019 |

of an appropriate simulation strategy is therefore a main focus point of this study.

### 1.4. Objective and paper outline

The objective of this paper is to present the underlying approach and results of the first simulation-based assessment of the impact of ULWC on energy performance and indoor comfort in commercial and residential buildings. Section 2 continues by describing and characterizing the properties of ULWC in more detail. In Section 3, the unique requirements for computational performance prediction of constructions with ULWC are outlined, together with the simulation strategy that was followed and the results of an analytical validation study. Section 4 provides insight into the performance of ULWC by comparing it to state-of-the-art lightweight and heavyweight building constructions in a representative case study. Finally, Section 5 concludes the paper by summarizing the main findings of this study and providing future perspectives for the development of ULWC.

## 2. Characteristics of ultra-lightweight concrete

### 2.1. Material properties

To analyse the dynamic thermal behaviour of ULWC as a monolithic building construction, it is not sufficient to only consider the most basic material properties, like thermal conductivity, density and (specific) heat capacity. Therefore, other characterization metrics are considered as well.

The thermal diffusivity, $\alpha = \lambda / \left(\rho \cdot c_p\right) \left[m^2/s\right]$ describes the amount of time a material needs to come to a thermal equilibrium with its surroundings. A material of very low thermal diffusivity slowly returns the energy stored in the material to its environment, independent of the amount of energy that can be stored. Table 1 shows a comparison of three different types of materials. The thermal diffusivity of ULWC is almost 5 times lower than of regular concrete. On the other hand, compared to a diffusivity of 13 mm$^2$/s for cast iron or even 113 mm$^2$/s for copper, the values for ULWC and concrete are both low [30]. This actually shows that both materials return stored energy slowly to their surroundings. Insulation has a slightly higher thermal diffusivity, which means that it will faster reach a thermal equilibrium with its surroundings.

Thermal effusivity, $\varepsilon = \sqrt{\lambda \cdot \rho \cdot c_p} \left[J/\left(K \cdot m^2 \cdot s^{0.5}\right)\right]$, sometimes referred to as the heat penetration coefficient, is the rate at which a material can absorb heat. A high value for thermal effusivity indicates that there will be a large heat flux across the surface during the process to establish equilibrium with its surrounding environment. Heavyweight concrete has a much higher thermal effusivity than ultra-lightweight concrete (Table 1). However, the values for metals are again much higher. The values for insulation materials are around 75 times smaller than for regular concrete, which shows that the heat flux and the amount of absorbed heat is lower. Thermal effusivity also gives an indication for the contact temperature, which is the lowest for materials with a high thermal conductivity and a high thermal capacity, resulting in a high thermal effusivity. This explains why ULWC feels warmer when touching it, compared to regular concrete.

In contrast to the thermal diffusivity, where ULWC showed characteristics closer to concrete, with effusivity its properties seem to be more similar to an insulation material (Table 1).

### 2.2. Dynamic thermal characterization

International standard EN ISO 13786 [31] was developed to provide an evaluation instrument that can quantify the dynamic thermal characteristics of different multi-layer building constructions under the influence of variable boundary conditions [32,33]. With the calculation methods in this standard, the periodic thermal transmittance ($Y_{12}$), the internal admittance ($Y_{11}$), the external admittance ($Y_{22}$), the decrement factor ($f$), and the internal as well as external areal thermal capacity ($k_1$ and $k_2$) of ULWC can be compared to alternative wall constructions.

The periodic thermal transmittance combines the properties of thermal transmittance, time shift and decrement factor in one metric. It is a complex quantity that can be defined as: 'the complex amplitude of the density of heat flow rate through the surface of the component adjacent to zone m, divided by the complex amplitude of the temperature in zone n when the temperature in zone m is held constant' [31]. If the periodic thermal transmittance $Y_{12}$ is low, there will be a reduction in outside thermal load impact, particularly from direct solar irradiance on external walls. However, a low $Y_{12}$ value is not capable of reducing the influence of the internal loads, which are the main cause of increased indoor temperatures during summertime, especially in office buildings. Calculations according to ISO 13786 were carried out for a 70 cm monolithic ULWC slab, a multi-layer thermal heavyweight and a multi-layer thermal lightweight structure, following the information in Fig. 2 and Table 2. The construction with high thermal mass is modelled with exposed concrete on the inside, to maximize the heat accumulation effectiveness. All three construction types have a total thermal resistance ($R_c$-value) of 5 m$^2$K/W to comply with contemporary building standards. This equal thermal resistance was chosen to ensure that differences in the results can be attributed to the influence of dynamic thermal storage instead of being confounded by thermal resistance effects. The results of the ISO 13786 calculations are presented in Table 3.

For ULWC, the value of the periodic thermal transmittance is $Y_{12} < 0.001$ W/m$^2$K. For a thermal lightweight construction and a thermal heavyweight construction (from here on referred to as lightweight construction and heavyweight construction), both with the same U-value, the periodic thermal transmittances are $Y_{12} = 0.06$ W/m$^2$K and $Y_{12} = 0.04$ W/m$^2$K, respectively. The value of $Y_{12} < 0.001$ W/m$^2$K for ULWC indicates a periodic heat flow with an amplitude of less than 0.01 W/m$^2$, while for a heavyweight construction this is 0.66 W/m$^2$. This dampening effect is also reflected in the decrement factor $f$, which is a measure for the reduction in cyclical temperature on the inside surface compared to the outside surface temperature.

A value of $f < 0.001$ for ULWC indicates that there is no measurable temperature fluctuation on the inner side of the construction due to temperature variations on the outside. For the lightweight construction, the value is $f = 0.33$, which means that the inner surface temperature varies with almost 10 °C in one temperature cycle if the outside surface temperature fluctuates between 30 °C during the day and 0 °C during night times. The $k_1$ value describes the actual capacity to accumulate heat on the inner side of a multilayer building element. This indicator in interesting to investigate in the present context, because it characterizes the internal thermal mass and its expected effect on thermal performance. The value for ULWC is one-third of the value of the heavyweight construction, but three times larger than a lightweight envelope. The heavyweight

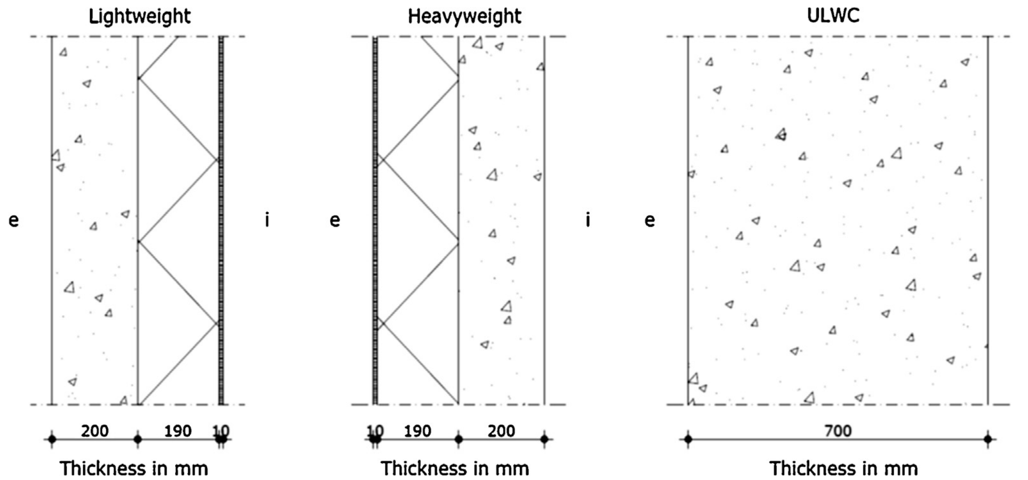


**Fig. 2.** Section of the three construction types that are used in this study: thermal lightweight, thermal heavyweight and ULWC.

**Table 2**
Material properties of the three construction types. Layers are indicated from outside to inside.

| | Thickness [m] | Thermal conductivity [W/mK] | Density [kg/m3] | Specific heat capacity [j/(kgK)] |
|---|---|---|---|---|
| Lightweight | | | | |
| Concrete | 0.2 | 2.0 | 850 | 2400 |
| Insulation | 0.19 | 0.04 | 840 | 20 |
| Plaster | 0.01 | 0.14 | 530 | 900 |
| Heavyweight | | | | |
| Plaster | 0.01 | 0.14 | 530 | 900 |
| Insulation | 0.19 | 0.04 | 840 | 20 |
| Concrete | 0.2 | 2.0 | 850 | 2400 |
| ULWC | | | | |
| ULWC | 0.7 | 0.14 | 870 | 800 |

**Table 3**
Selected dynamic thermal characteristics based on an external temperature (average) of 15 °C, an external amplitude temperature of 15 °C and an internal temperature of (constant) 21 °C. Details of the construction types are given in Fig. 2.

| | ULWC | Thermal lightweight | Thermal heavyweight |
|---|---|---|---|
| Transmittance steady state, U | 0.19 W/m$^2$K | 0.20 W/m$^2$K | 0.20 W/m$^2$K |
| Periodic thermal transmittance, $Y_{12}$ | <0.001 W/m$^2$K | 0.06 W/m$^2$K | 0.04 W/m$^2$K |
| Decrement factor, f | <0.001 | 0.33 | 0.22 |
| Internal areal thermal capacity, $k_1$ | 30 kJ/m$^2$k | 11 kJ/m$^2$k | 94 kJ/m$^2$k |

construction has the highest $k_1$ value, which means that this construction also has the highest potential for heat accumulation on the inner side.

Thus, a monolithic wall of 70 cm of ULWC should be able to almost exclude the influence from outdoor temperature fluctuations on the inner side of the construction. However, due to a lower thermal capacity compared to a heavyweight structure, it will not absorb the same amount of heat generated by internal loads. In an office building, ULWC could induce greater risks for overheating than constructions with regular concrete. On the other hand, ULWC is expected to heat up faster after a cooling down period, e.g. a weekend, because it absorbs less heat. Still, its reaction to temperature changes will be slower and it is able to store more heat than a lightweight construction.

The considerations above are derived from analyses on the building element level. Realistic weather conditions, occupants' interactions, and the integration of ULWC in a three-dimensional building are not taken into account. Moreover, doubts arise about the applicability of EN ISO 13786 for characterizing the unique physical behaviour of ULWC. For example, calculated values of $Y_{12} < 0.001$ W/m$^2$K and $f < 0.001$ for ULWC seem to indicate that the results fall outside the intended application range of the standard. These outcomes reinforce the need for a first-principles based simulation approach, as will be introduced in the next section.

## 3. Modelling and simulation of ULWC

Most of the state-of-the-art building performance simulation tools are generic, in the sense that the user has all freedom to specify thermophysical material properties and the composition of layers in a construction [34,35]. The algorithms in these software tools, however, are based on a number of built-in assumptions that restrict the actual range of construction types it can accommodate without causing numerical instabilities or other types of errors [36,37]. Although the impact of such assumptions and the extent of possibly occurring errors tends to be somewhat hidden, it has been reported that some software programs have difficulties to accurately predict the performance of constructions with unconventional properties, especially for thick insulation layers and very heavyweight constructions [38,39]. ULWC can also be characterized as unconventional, both in terms of its wall thickness and thermophysical properties. It would therefore be fraught with risk to assume that the simulation results for ULWC will invariably be correct, without actually checking the credibility of the results. This section therefore (i) points out the requirements for performance prediction of ULWC, and (ii) presents a way to assure the quality of the simulations by the selecting the most appropriate simulation approach.

### 3.1. Simulation requirements

The focus in this study is on analysing the energy and comfort implications of ULWC. Correct treatment of dynamic heat transfer phenomena, and especially the short-term warm-up and cool-down effects in a whole-building context, are therefore considered to be of high importance. In terms of thermal comfort regulation with thermal mass, long-wave radiant heat exchange between occupants and surrounding constructions plays a large role. Reliable prediction of indoor surface temperatures is therefore also a primary requirement for the simulation approach.

### 3.2. Simulation approaches

Two main categories of methods for predicting transient heat transfer in building constructions can be distinguished in the most widely-used simulation tools: (i) the conduction transfer function (CTF) method, and (ii) the finite difference/volume solution method.

CTF approaches are the default option in many popular simulation tools such as EnergyPlus and Trnsys, because they are optimized for computational performance, while having sufficient accuracy for typical annual energy balance calculations. Only recently, EnergyPlus was extended with a conduction finite difference (CondFD) scheme to be able to accommodate innovative construction types such as PCMs and walls with variable thermal properties [40,41]. Finite difference/volume methods are also available in tools such as ESP-r, IES and IDA ICE [34].

### 3.3. Quality assurance

The results of analytical calculations are used in this study to gain confidence in the quality of simulation results obtained with EnergyPlus v8.3 using both the CTF method and the CondFD method. Three tests were carried out, investigating (i) the effect of spatial discretization, (ii) heat transfer in a semi-infinite solid, and (iii) a temperature step change on two sides of a wall.

By setting up an EnergyPlus simulation model with the same environmental conditions as the analytical calculations, the results can be compared and the impact of different model assumptions and simulation settings can be examined. Since there is no straightforward way in EnergyPlus to simulate a single material/building element, the following procedure was developed to mimic the conditions that apply in the analytical test cases. A cube-shaped building model was created with external walls, floor and roof from ULWC. The constructions were set as adiabatic and not exposed to sun or wind. An internal wall from ULWC was placed to divide the volume into two zones. Depending on the test case, the internal wall consisted of ULWC with a thick layer of insulation on the backside (semi-infinite solid), or of ULWC only, to explore the temperature step response on two sides of a wall. The long-wave emissivity of all construction elements was set to $\varepsilon = 0.001$ to ensure that heat transfer between the wall and its surroundings takes place by convection only.

Unless noted otherwise, all EnergyPlus simulations were carried out with a time step of one minute, using both the CTF and the CondFD methods.

#### 3.3.1. Spatial discretization

First of all, the simulation results for different material layer thicknesses were compared and analysed. It is suggested in literature that the subdivision of a thick material slab into several thinner layers can lead to more accurate results [41]. Various simulations were conducted for a slab of ULWC with an initial temperature of 0 °C on both sides of the material and a sudden increase of 20 °C of air temperature at one side, with the number of material layers in the wall ranging from 1 to 10, always having a total thickness of 70 cm. The predicted surface temperatures on both sides of the material were compared for these different spatial discretization options. The largest difference in surface temperature was found to be only 0.04 °C on the side of the construction with a sudden temperature increase. It can therefore be concluded that the subdivision of the wall into multiple material layers does not significantly affect the predicted thermal behaviour of ULWC. When interpreting this result, it should be noted that one material layer can correspond to multiple nodes, as the CondFD method in EnergyPlus uses its own node space discretization algorithm, apparently resulting in sufficient accuracy for the purpose of this study [42].

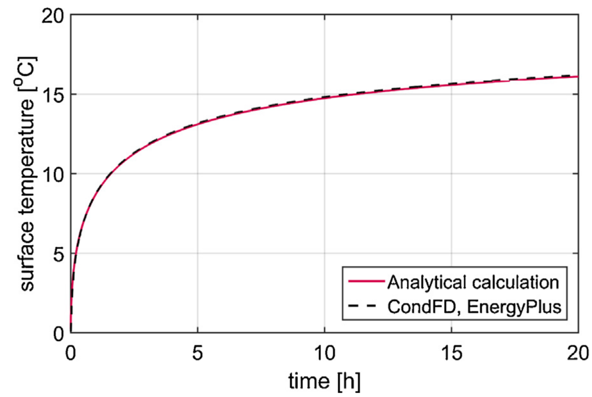


**Fig. 3.** Comparison of the results for the surface temperature after a sudden temperature increase from 0 °C to 20 °C. The red solid line represents the analytical calculations with the equation of a semi-infinite solid and the black dashed line shows the results of EnergyPlus.

#### 3.3.2. Semi-infinite solid

The semi-infinite solid is a classic transient conduction problem for which analytical solutions are readily available. It provides a useful idealisation for many practical situations, such as the transient evolution of temperature in a thick slab [43]. Here, we are interested in analysing how the surface temperature of the solid increases with time, as a result of a sudden increase in ambient temperature from 0 °C to 20 °C. In EnergyPlus, the semi-infinite solid was represented by simulating a construction of ULWC with a thickness of 1 m and by adding 3 m of insulation on the backside of the material to prevent heat loss.

Eq. (1) was used to analytically calculate the temperature within the semi-infinite solid and at its surface [43]:

$$\frac{T(x,t)-T_i}{T_\infty - T_i} = \operatorname{erf}\left(\frac{x}{2\sqrt{\alpha t}}\right) - \left[exp\left(\frac{hx}{\lambda}+\frac{h^2\alpha t}{\lambda^2}\right)\right] \cdot \left[\operatorname{erf}\left(\frac{x}{2\sqrt{\alpha t}}+\frac{h\sqrt{\alpha t}}{\lambda}\right)\right] \quad (1)$$

where: $x$ = position within the construction [m]; $t$ = time [s]; $T_i$ = initial uniform temperature [°C]; $T_\infty$ = temperature of the fluid/air [°C]; $\alpha$ = thermal diffusivity [$m^2/s$]; $h$ = convective heat transfer coefficient [W/($m^2$K)]; $\lambda$ = thermal conductivity [W/(mK)].

Fig. 3 shows the comparison of the results for the surface temperature ($x = 0$) from CondFD simulations performed in EnergyPlus and the analytical results from Eq. (1). The results from the CTF method are not displayed here because they perfectly overlap the CondFD result. Due to the close match between simulation and

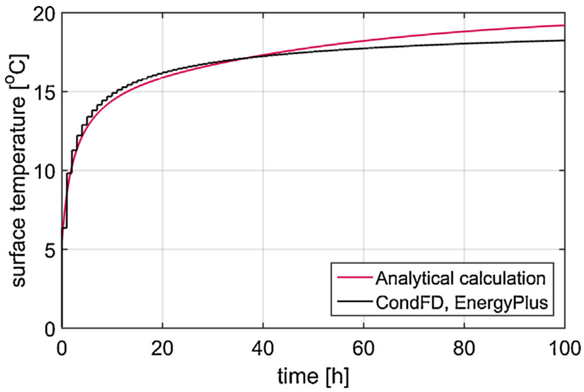


**Fig. 4.** Analytical results of the temperature step response on two sides of a wall compared to the results of the CondFD function used in EnergyPlus with 1 h time step.

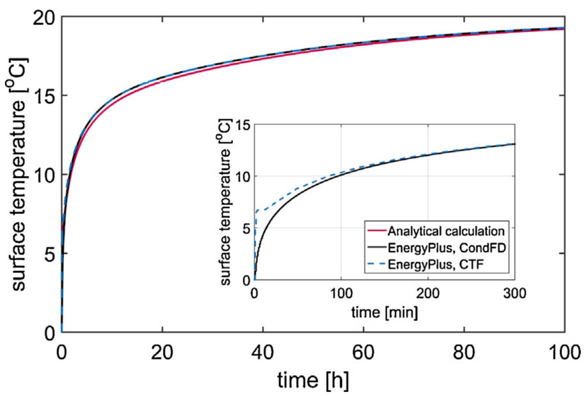


**Fig. 5.** Analytical results of the temperature step response on two sides of a wall compared to results obtained with the CondFD function and CTF method used in EnergyPlus with 1 min time step. The inset zooms in on the first 5 h.

analytical solution, it can be concluded that EnergyPlus is able to accurately predict the surface temperature of ULWC in a one-dimensional semi-infinite problem configuration.

### 3.3.3. Temperature step response on two sides of a wall

The third test case for the validation of EnergyPlus simulations is the *Exact Solution*, which describes the temperature of a plane wall of thickness $x^*$ with an initially uniform temperature, $T(x, 0) = T_i$, and a sudden immersion into a fluid of $T_\infty \neq T$. The temperature at position $x^*$ can be obtained by solving Eq. (2):

$$\theta^* = \sum_{n=1}^{\infty} C_n \exp\left(-\zeta_n^2 Fo\right) \cos(\zeta_n x^*) \quad (2)$$

where:$\theta^*$ = Temperature [°C];$x^*$ = position within the construction [m];$Fo$ = Fourier number$C_n$ = coefficient;$\zeta_n$ = eigenvalues of the transcendental equation describing the Fourier series expansion.

Fig. 4 compares the results of the analytical solution and the CondFD method for a time step of one hour. The CTF results for a one hour time step are not shown, because the simulation reported an instability error and did not proceed. The results show a significant difference just after the step response, and also show an unacceptable difference of more than 1 °C when the system reaches equilibrium. Fig. 5, on the other hand, shows that the simulation with time steps of one minute is more accurate for the simulation with the CondFD and shows temperature deviations falling within an acceptable range. The simulation time step is thus an important simulation setting when predicting the performance of materials like ULWC.

The inset in Fig. 5 zooms in on the first 300 min of the simulation, and shows that the CTF method seems to have difficulties with the sudden temperature increase in the beginning of the simulation. This finding is in agreement with results from literature, which state that CTF has trouble simulating thick slabs and that the results can become inaccurate and unstable for too small time bases and can consequently cause the entire simulation to diverge.

### 3.4. Conclusion

Based on the analytical validation study presented above, the decision was made to continue simulations with the CondFD method in EnergyPlus, using a single layer of ULWC material and a simulation time step of one minute.

An extra advantage of CondFD as opposed to CTF is that it gives insights into the temperature development within the construction. In this way, the dynamic heat transfer through the material can be visualized to gain extra insight into how heat, e.g. solar irradiation on the external surface, is transported and how much reaches and affects the internal surface.

## 4. Case study: performance prediction of ULWC

### 4.1. Case study description

The U.S Department of Energy (DOE) has developed commercial reference buildings, which can act as representative case studies for whole-building energy analysis using EnergyPlus [44]. This study uses the medium-sized office building as the basis for further investigations. The model represents a three-storey commercial building with a window to wall ratio of 33% at all orientations. The windows have U-value of 1.1 W/m$^2$ K and a solar heat gain coefficient (g-value) of 0.39. For this research, only the middle floor level was used, adjacent to conditioned spaces above and below.

Some of the default assumptions for heating, cooling, solar shading and ventilation of the reference building were altered in order to make the building model more relevant for this research. These changes are described below.

First, the building construction was replaced with ULWC, a heavyweight or a lightweight building envelope, according to the details in Fig. 2, Tables 1 and 2. The exterior layer of the building envelope had a solar absorptance of 0.6.

The office space was subdivided into smaller zones with a depth of 4.5 m and a width of 6 m. The rooms are separated by internal walls consistent with the building envelope; thus, lightweight, heavyweight or ULWC internal walls. They were made from gypsum plates, 0.1 m thick concrete blocks, or 0.1 m of ULWC, respectively.

For each occupant, the building provides a floor area of 18.6 m$^2$ with a metabolic rate of 120 W per person, which is the rate for a seated, light-working male adult. Other internal gains consist of the lighting system (10.8 W/m$^2$), and other plug loads (10.8 W/m$^2$). The infiltration of all zones was set to 0.3 ACH. Automated solar shading screens with a control set point of 250 W/m$^2$ incident radiation were assumed.

Night-time ventilation strategies (i.e. night purge) are known to have a major impact on the effectiveness of thermal mass in buildings [45,46]. To study this effect for ULWC, two cases were investigated, with and without night purge. In case of night purge, the ventilation rate increases to 5 ACH in winter and 10 ACH in summer between 09:00 p.m. and 6:00 a.m., if the outside temperature is lower than inside, but warmer than 12 °C, and until indoor temperature reaches the heating set point.

The building is located in Amsterdam, the Netherlands. Heating and cooling set points were chosen in the range of Class B (80%

acceptance) of the new hybrid thermal comfort guidelines for the Netherlands [47], as described in more detail in Section 4.2. The default HVAC system was replaced for an ideal loads system. The design load [W] for heating and cooling was found by simulating the office during design days for Amsterdam with the constructions ULWC, heavyweight and lightweight. The system for all three cases was consequently dimensioned according to the design load of the heavyweight structure, as it required the smallest installed capacity. The system's design load for the building with ULWC had almost the same size as the heavyweight structure, whereas the system for the lightweight structure was noticeably larger. By implementing the same system in all buildings models, the trade-offs between comfort and energy consumption can be rightfully assessed, as all three construction types are compared on the same basis.

### 4.2. Performance indicators

The simulation results are assessed by analysing the annual cooling and heating energy consumption per $m^2$ floor area for different construction types. The primary energy consumption was calculated by including all relevant system efficiencies and distribution losses for heating and cooling systems. For the heating system, an efficiency of $\eta = 0.9$ with a distribution loss factor of $c_{gas} = 1.07$ for gas was used. The primary energy for cooling was calculated with a performance factor of $COP = 3$ for the heat pump system, and $c_{el} = 2.72$ was used as primary energy factor for electricity from the grid.

Indoor comfort is assessed with the new adaptive temperature limits, ATG (Adaptieve Temperatuurgrenswaarden) for the Netherlands [47]. This new guideline is designed to combine the strengths of the static (Fanger) and adaptive approaches for thermal comfort evaluation for different types of building spaces and classes of indoor environmental quality. The ATG method relates the indoor operative temperature to the running mean outdoor air temperature, also called reference temperature ($T_{ref}$).

There are two different building types that describe the comfort ranges; Alpha and Beta buildings (α-type and β-type). Alpha buildings are spaces with at least one effective usable, operable window per façade length of 3 m and no active cooling system. Two types of Beta buildings exist: one without operable windows and one with operable windows and an active cooling system, which is clearly perceivable by the building occupants. The building simulated for this research does have an active cooling system. Therefore, the temperature limits of the β-type are applied for the comfort assessment of the simulation results.

### 4.3. Construction temperature on a typical summer and winter day

Fig. 6a shows the temperature profile within a monolithic wall of ULWC for a warm summer day. Every line represents an instant of the simulation with an interval of 2 h. There is a large temperature deviation of about 35 °C on the exterior side of the façade. Due to solar irradiation on the south-facing wall, the exterior surface temperature reaches a temperature of more than 50 °C. The indoor surface temperature is controlled at roughly 26 °C. At a depth of 25 cm from the outside, the temperature fluctuation due to changing solar radiation and outside temperature is completely attenuated. The small range in daily surface temperatures on the inside indicates that in this situation, the construction is not able to cool down at night through conduction.

For the winter day, a similar situation was observed (Fig. 6b). In contrast to the south façade in summer, there is no direct solar irradiation at this north façade. Consequently, the external temperature fluctuates within a range of only 5 °C. The temperature gradually increases to the heating set point of 21 °C on the inside, and shows little variation around that value during night times. For comparison, Fig. 6c, d and e, f show the temperature profiles of the heavyweight and lightweight construction for the same days. A notable difference between the construction types is that the lightweight building shows the largest temperature fluctuation on the inside surface, although relatively small, with a peak that is almost 2 °C higher in the summer situation. The small influence of the outdoor temperature fluctuation on the inner side of the heavyweight and lightweight construction are caused by the high $R_c$ value of 5 $m^2K/W$ and the way indoor temperature is controlled.

**Table 4**
Annual primary heating and cooling energy use intensity for the three construction types.

| | | Lightweight | Heavyweight | ULWC |
|---|---|---|---|---|
| Heating [kWh/m$^2$] | No night purge | 4.7 | 7.8 | 7.3 |
| | Night purge | 8.3 | 9.0 | 8.4 |
| Cooling [kWh/m$^2$] | No night purge | 33.2 | 22.5 | 23.4 |
| | Night purge | 12.4 | 12.4 | 13.7 |

### 4.4. Dynamic warm-up behaviour

Analysing the thermal response of a construction after a longer unoccupied period is a good way of highlighting the important differences between lightweight and heavyweight buildings. Moreover, it provides a better understanding of the physical characteristics of ULWC. Fig. 7a shows that operative temperature of the lightweight construction rises faster than the other two construction types, because less heat is absorbed in the construction. Furthermore, it shows that during the first few days, the operative temperature in a building with ULWC is always slightly higher than the heavyweight structure. The building with ULWC does not reach the set point temperature of 21 °C during the first two days, whereas in the heavyweight case, it only reaches the set point on the fifth day. Where for the operative temperature, the construction of ULWC is closer to the heavyweight building, the surface temperature of ULWC more closely resembles the lightweight structure (Fig. 7b). The heating energy consumption for ULWC in this period is also closest to a lightweight building structure (Fig. 7c). Because ULWC has the ability to respond much faster to the temperature changes than the heavyweight case, its heating energy use in the first days is markedly lower. Especially in buildings that are used intermittently or for short durations, the impact of this effect can become significant.

### 4.5. Annual energy and comfort assessment

Table 4 shows the annual primary heating and cooling energy use for the three constructions (south-facing office), with and without night purge ventilation.

In this well-insulated office building with fairly high internal gains, cooling energy is the dominant factor. The internally-insulated lightweight construction has less potential to absorb solar and internal heat gains, and has therefore a significantly higher cooling energy use than the heavyweight and ULWC variants. It can be noted that night purge ventilation is very effective for reducing total energy demand for this case study building, even though the energy use for heating slightly increases. Based on these results, it is not yet possible to express a clear preference for either one of the conventional constructions or ULWC.

To get a more holistic view of the potential of ULWC in relation to other construction types, it is important to combine the predicted energy use with information about thermal comfort. Fig. 8 shows the results of the annual comfort assessment for ULWC, heavyweight and lightweight structures for the south orientated office

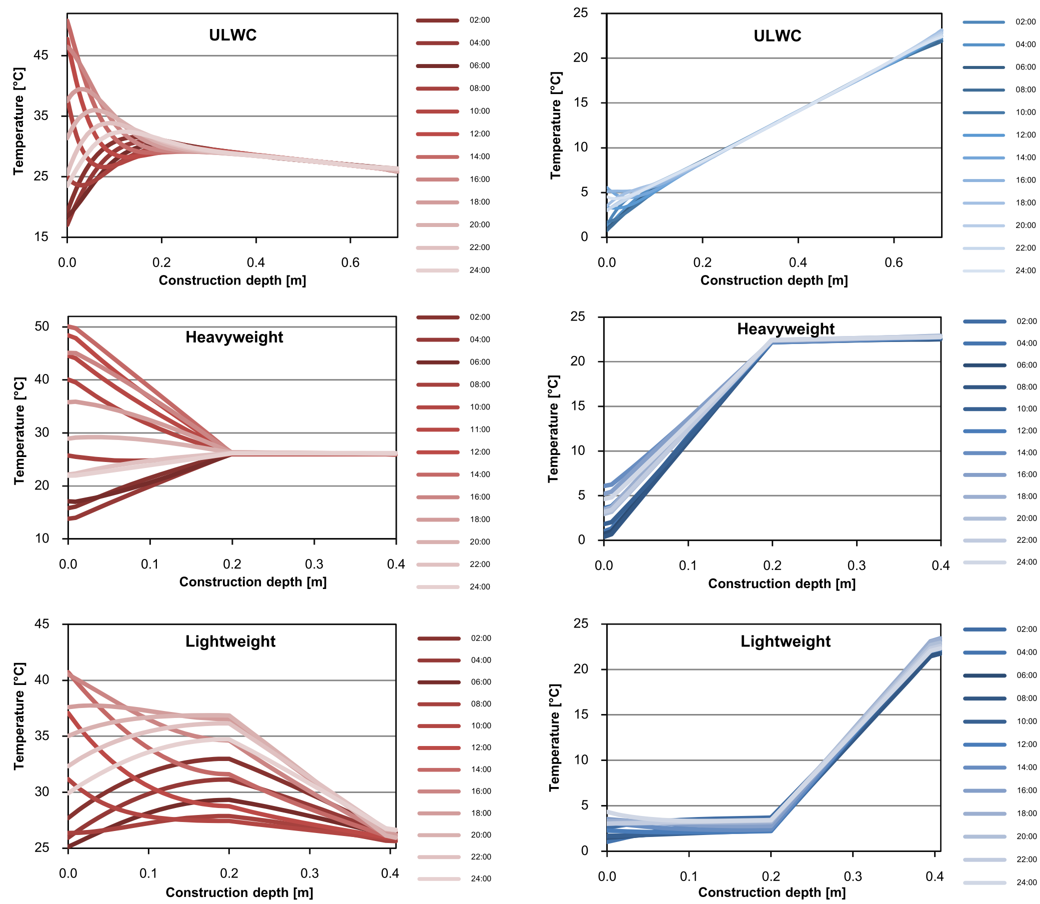


**Fig. 6.** Temperature profiles inside the constructions from outside to inside, showing summer (left = a, c, e) and winter (right = b, d, f).

**Table 5**
Discomfort hours for the south-facing office, with and without night purge ventilation.

| | | Lightweight | Heavyweight | ULWC |
|---|---|---|---|---|
| No night purge | Above Class B | 1156 | 318 | 390 |
| | Above Class C | 129 | 0 | 0 |
| | Below Class B | 43 | 27 | 28 |
| | Below Class C | 14 | 12 | 12 |
| Night purge | Above Class B | 312 | 232 | 269 |
| | Above Class C | 0 | 0 | 0 |
| | Below Class B | 65 | 44 | 46 |
| | Below Class C | 18 | 12 | 12 |

with solar shading and night purge ventilation. The figures show only the occupied hours, since these are relevant for the comfort in a building.

The case with heavyweight constructions shows the smallest temperature swing. Both ULWC and heavyweight remain well inside the boundaries of the upper limit for comfort class C. The lightweight construction has a larger tendency for indoor overheating, especially for high outside temperatures. There are several moments throughout the year when the operative temperature falls below the lower limit for class B. These lower temperature values are a result of the night purge ventilation which is applied the most during the summer months and which causes lower temperatures in the mornings. Table 5 shows a graph that summarizes the discomfort hours for different variants for the south orientation. As can be seen, the lightweight construction shows the most overheating hours, especially for the first configuration without night purge ventilation.

**Table 6**
Discomfort hours for the residential building with two levels of ventilation.

| | | Lightweight | Heavyweight | ULWC |
|---|---|---|---|---|
| ACH = 2 | Above Class B | 179 | 64 | 155 |
| | Above Class C | 37 | 0 | 29 |
| ACH = 5 | Above Class B | 82 | 32 | 79 |
| | Above Class C | 16 | 0 | 13 |

### *4.6. Residential application*

As a final step in the analysis, also the application of ULWC for a residential application (i.e. studio apartments) was explored. The building geometry was assumed to be the same as for the office building, but the following differences were implemented:

- Heating schedule with residential occupancy patterns for the heating periods and different set points: 16 °C during night times and unoccupied hours, and 21 °C during occupancy hours.
- The internal gains were reduced to 5.5 W/m$^2$
- For this application the results were analysed using the α-type building class of the ATG comfort assessment, as residential buildings in the Netherlands normally have operable windows, but do not have an active cooling system.

The operative temperature for ULWC throughout the year in the residential case is lower than the office building due to less internal gains (Fig. 9). There are less overheating hours in the residential building than in the office building. An annual overview of overheating risk for the three construction types is shown in Table 6. By comparing a ventilation rate of 2 ACH and 5 ACH, these results

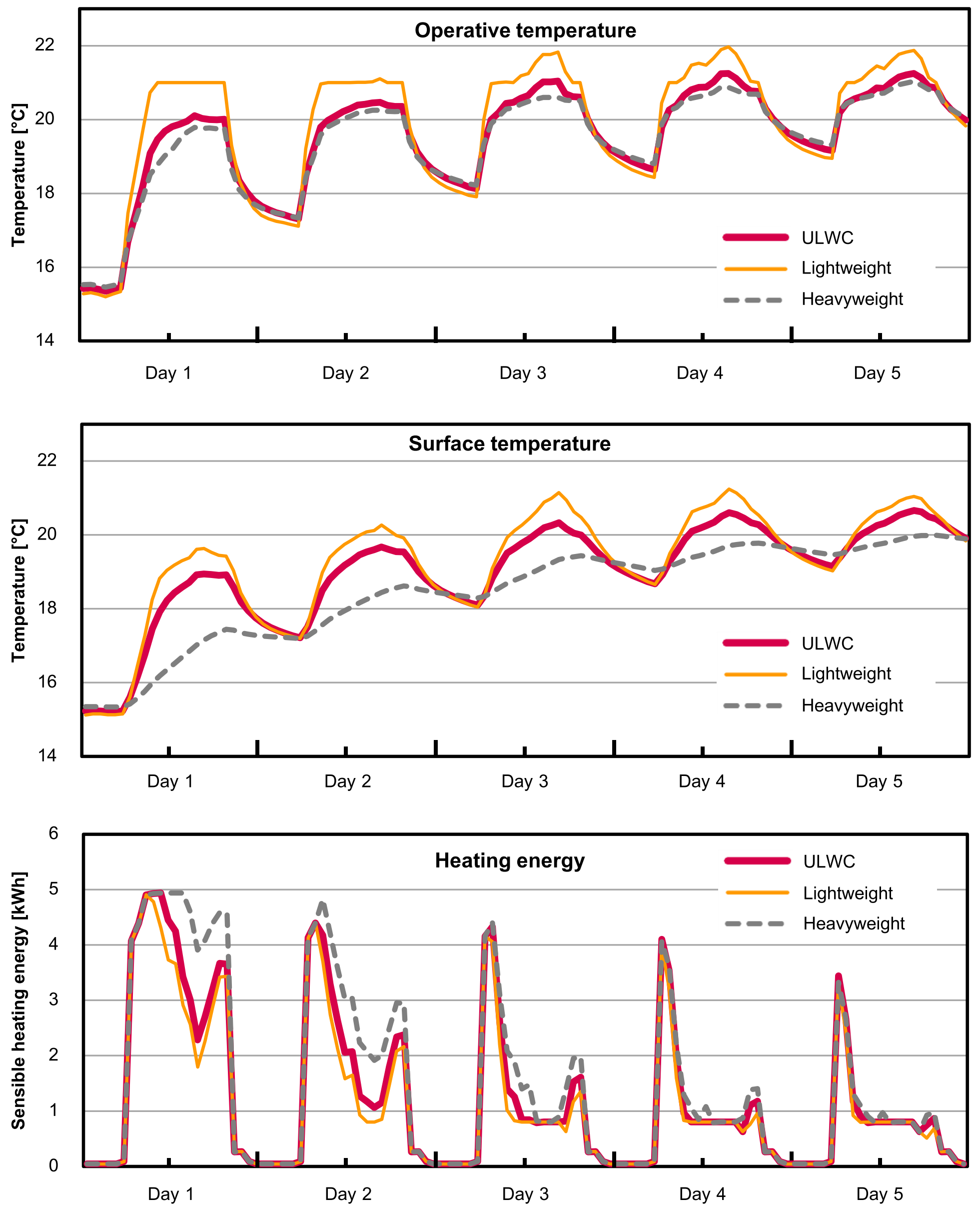


**Fig. 7.** Thermal response during warm-up for the three construction types. (a) operative temperature, (b) surface temperature, (c) heating energy use.

clearly show the interrelationship between heat removal strategies and thermal mass. When applying ULWC in residential buildings, it is important to include sufficient options for ventilative cooling, in order to approach the same comfort level as would be the case for a heavyweight construction.

## 5. Concluding remarks

This study set out to explore the potential of ultra-lightweight concrete in terms of energy and comfort performance. It was found that the use of detailed building performance simulations is very valuable when investigating a construction type with such atypical properties, because conventional characterization metrics such as those described in ISO 13786 can offer only limited guidance when it comes to supporting the R&D process. Building performance simulations generate the possibility to analyse the behaviour of ULWC in a dynamic environment while considering its interactions with building design, climate conditions and occupancy patterns. In this way, the influence of dynamic absorption and release of thermal energy in monolithic ULWC slabs can be studied at a high level of resolution.

Results from an analytical validation study showed that the conduction finite difference scheme (CondFD) in EnergyPlus is able to predict the transient heat transfer phenomena in thick ULWC structures with sufficient accuracy. Simulation users should carefully select an appropriate simulation tool when predicting the performance of ULWC, because this study has also demonstrated that not all transient heat conduction methods that are used in the widely-used software tools are able to predict heat transfer in ULWC slabs without errors.

Even though we note that the performance of ULWC is very case-specific, the following can be concluded from the office case study.

- ULWC has a cooling energy use for an office building that is slightly higher than the heavyweight building, but a heating energy consumption that is slightly lower.
- ULWC behaves as expected with respect to increased risk for overheating, and has around 22% more hours above class B com-

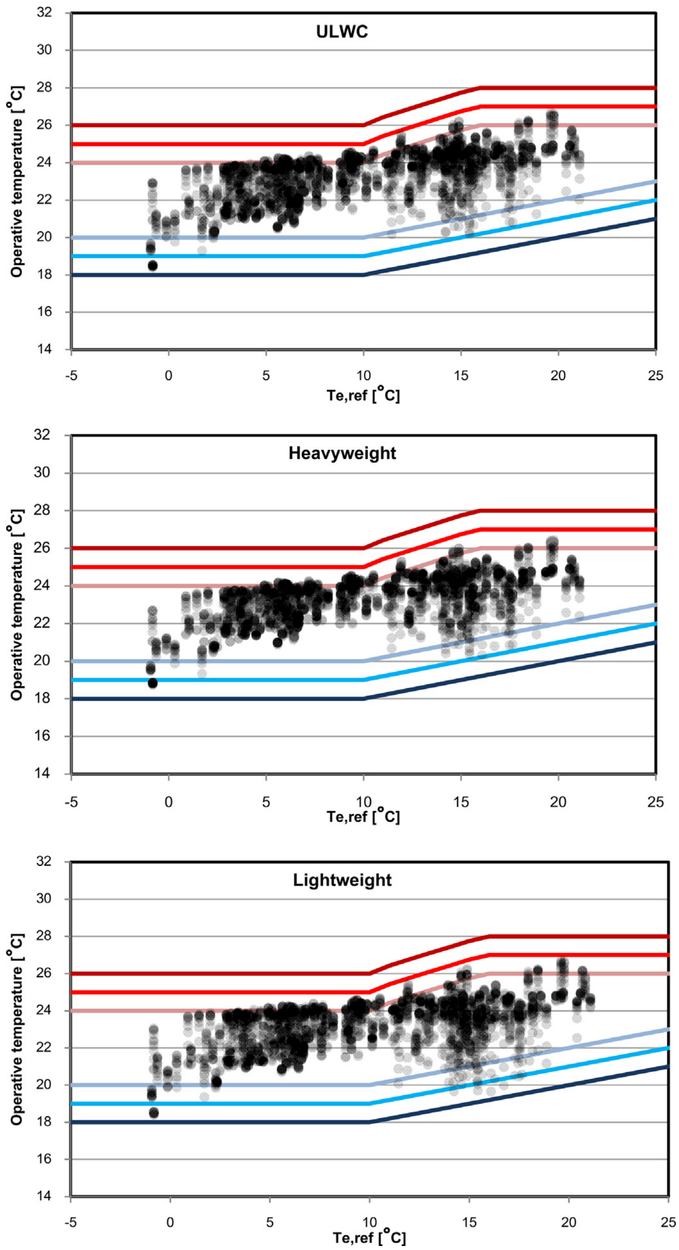


**Fig. 8.** Thermal comfort results for the south facing office zone, showing ULWC (top), heavyweight (middle) and lightweight (bottom) construction types. The blue and red lines indicate Classes B, C and D as a function of running mean outdoor temperature, according to the ATG adaptive thermal comfort standard.

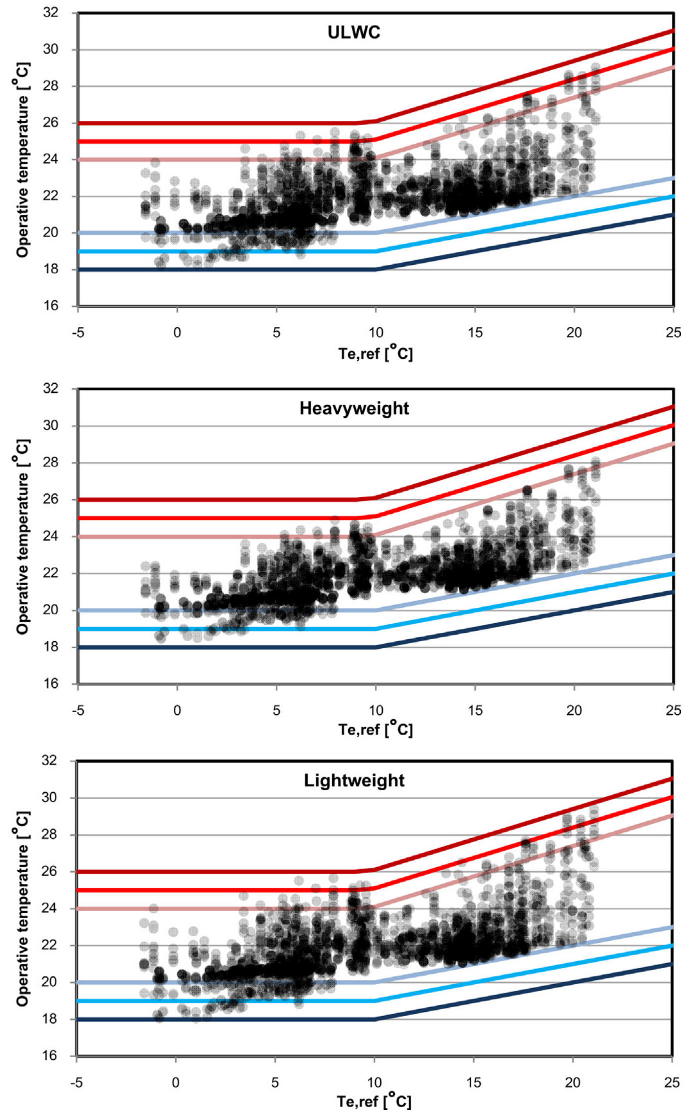


**Fig. 9.** Thermal comfort results for the residential case, showing ULWC (top), heavyweight (middle) and lightweight (bottom) construction types. The blue and red lines indicate Classes B, C and D as a function of running mean outdoor temperature, according to the ATG adaptive thermal comfort standard.

pared to the heavyweight structure in an office building. In terms of overheating risk, it performs better than a lightweight construction.

- ULWC is relatively fast in heating up after a longer unoccupied period, and has an increased surface temperature which more closely resembles the characteristics and behaviour of a lightweight building.
- ULWC is in its long-term behaviour comparable to a heavyweight building, and for short-term heating periods comparable to a lightweight building envelope.

In summary, it was found that operational building characteristics (e.g. occupancy, temperature setpoints, ventilation rates) have a large influence when determining the performance potential of ULWC in relation to other, more conventional, and therefore more established building envelope constructions. Especially in buildings with intermittent operation, ULWC is found to be a suitable construction method for achieving high performance in terms of both energy use and thermal comfort. Continued use of building performance simulation can help to identify building and climate combinations where the properties of ULWC have most potential to transcend the performance of regular construction types.

It should be noted that a construction thickness of 70 cm is needed for a monolithic ULWC wall to meet present-day thermal insulation standards ($R_c = 5\,m^2K/W$). This research has focused on analysing the implications of ULWC from a building physics perspective. Future work should examine whether the thermal and energy-efficiency features of ULWC can make up for concerns about losses in usable floor area.

Another construction type that is present in this niche of the construction market are aerated autoclaved concrete (AAC) blocks. AAC has lower density, and therefore higher thermal resistance, which enables more slender construction types with similar thermal performance. However, a typical characteristic of AAC is it low compressive strength. A unique feature of ULWC is its ability to be used in multi-storey buildings (4–5 floors). Other considerations such as airtightness, need for surface finishings, thermal bridges, ease of construction, embodied energy and life cycle cost will inevitably also play a role in the design decision process. More research into these aspects can form a solid basis for further improvement of the properties of ULWC in the future.

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