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

F. Roberz, R.C.G.M. Loonen*, P. Hoes, J.L.M. Hensen

Unit Building Physics and Services, Eindhoven University of Technology, The Netherlands

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

* Corresponding author.
E-mail address: r.c.g.m.loonen@tue.nl (R.C.G.M. Loonen).

http://dx.doi.org/10.1016/j.enbuild.2016.12.049
0378-7788/

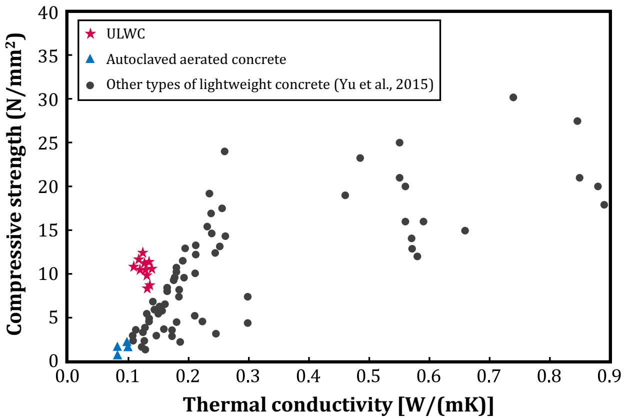

Fig. 1. Characterization of various types of concrete, showing the trade-offs between thermal and mechanical properties. ULWC is unique in that it combines high compressive strength with reasonable thermal resistance properties. Adapted from: [17].

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 λ = 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, $\rho \cdot c_p = 700kJ/m^3K$), 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