Energy and Buildings 156 (2017) 374–389

Contents lists available at ScienceDirect

Energy and Buildings

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

Environmental and spatial assessment for the ecodesign of a cladding system with embedded Phase Change Materials

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ARTICLE INFO

Article history:
Received 26 October 2016
Received in revised form 27 July 2017
Accepted 7 September 2017
Available online 20 September 2017

Keywords:
Ecoinnovation
Phase change materials
Life cycle assessment
Energy efficiency
Building envelopes

ABSTRACT

New building materials and techniques are increasingly developed to respond to the challenges posed by the need of reducing energy demand of buildings while keeping adequate answer to housing needs. The potential of Cement Based Composites (CBCs) panels in which a large amount Phase Change Materials (PCMs) is embedded have been explored in this study. The technological development of the CBCs panel, and the optimization thereof, have been supported by a tailored methodology, combining environmental, spatial and climate-based assessment. Concerning the environmental assessment, Life Cycle Assessment (LCA), at material and component level, has been applied through all the steps of the panel design process to ensure that the use of the innovative product leads to an absolute reduction of the environmental impacts. The assessment of product environmental profile along life cycle stages have been performed covering 15 different impact categories. Based on LCA results, glycerine and fatty acids – if they are secondary material (e.g. from the purification of waste cooking oil) – showed a great potential to be environmentally preferable compared to paraffin. Moreover, the spatial and climate-based assessment has been carried out, considering the climatic conditions of the first 50 most populated cities in the European Union. It allowed identifying the EU cities with the highest potential for PCMs application and the optimal configuration of the CBC panel (single or dual layer). Lastly, when compared to sandwich panels available in the market, environmental benefits are expected from the use of PCMs when the insulating layer can be reduced by 25% without affecting the thermal performance.

1. Introduction

In Europe, buildings account for 40% of the total energy consumption and are responsible for the generation of 36% of the European Union (EU)'s CO_2 emissions [1]. Within a building, the envelope typically impacts 57% of a building's thermal loads [2]. More than 20% of the energy consumed in the EU literally flows out of building envelopes, implying huge emissions of greenhouse gases. Hence, claddings are key building elements on which to act for addressing energy efficiency of buildings. Ecoinnovations of claddings are needed to ensure the decarbonisation of Europe by 2050, where the challenging target of reducing CO_2 emissions by at least 80%, and energy consumption by as much as 50%, should be met [3,4].

The Energy Performance of Buildings Directive (EPBD) [5] and the Energy Efficiency Directive [6] are the EU's main legislation related to the reduction of the energy consumption of buildings. The EPBD requires that EU countries set minimum energy performance requirements for new buildings, for the major renovation of buildings and for the replacement or retrofit of building elements (heating and cooling systems, roofs, walls, etc.). Annex I of the 2010 EPBD indicates the common general framework for the calculation of energy performance of buildings. Although guidelines are provided in the EPBD directive, no specific rules are defined, allowing each Member State to specify its own methodology and values for minimum thermal performance requirements of buildings. The calculation system chosen by most Member States is based on a steady-state analysis, where the *thermal insulation* is the only key parameter for the evaluation of the thermal performance of buildings. Requirements in terms of thermal transmittances are defined to satisfy minimum performance of building components. Transient regimes are usually not considered due to their difficult (and often costly) evaluation with specialised software, such as Energy-

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http://dx.doi.org/10.1016/j.enbuild.2017.09.011

Nomenclature

AC	Air conditioning
CBCs	Cement based composites
CFC- 11	Trichlorofluoromethane
CTU h	Comparative toxic unit – human health
CTU e	Comparative toxic unit – ecosystem
EPBD	Energy performance of buildings directive
HFC	Hydrofluorocarbons
FU	Functional unit
ILCD	International life cycle data system
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LWA	Light-weight aggregates
μe-PCM	Microencapsulated PCM
NMVOC	Non methane volatile organic chemicals
PCM	Phase changing materials
PTt	Phase transition temperature
TES	Thermal energy storage
XPS	Extruded polystyrene
Dfc	Subarctic climate
Dfb	Warm-summer humid continental climate
Cfb	Temperate oceanic climate
Cfa	Humid subtropical climate
Csb	Warm-summer Mediterranean climate
Csa	Hot-summer Mediterranean climate

Plus [7], Trnsys [8] and so on. Hence, the benefits due to the dynamic response of walls with respect to heat fluxes are either neglected or critically simplified ignoring the *thermal inertia*. Therefore, the current legislation is, lacking in the evaluation of benefits from building components, which mainly works in transient regimes.

However, in the last few years, innovative concepts for new insulation materials increasing thermal inertia have been extensively studied [9,10]. This includes the use of Phase Change Materials (PCMs) embedded in building materials and components.

The main property of PCMs is the ability to store heat in a latent form, leading to greater heat storage capacity per unit volume than common building materials. When the ambient temperature rises, the phase changing material changes, from solid to liquid state and vice versa, absorbing or releasing energy at each phase change. Since 1994, more than 1400 articles on PCMs in buildings have been published [11].

The *thermal insulation* of envelopes is a crucial aspect of the energy efficiency of buildings: as a matter of fact, it plays a central role in maintaining indoor comfort conditions by balancing the outdoor climatic variations. Therefore, by increasing the insulation effectiveness it becomes increasingly difficult to transmit heat to and from outside. Accordingly, the thermal insulation, as accounted for using conventional methodologies, considers the heat transfer through a wall only under steady state conditions, namely when the thermal equilibrium is fully established. The dynamic component, also known as transient state, becomes an increasingly relevant aspect with a wider daily temperature range as found in temperate climates.

Thermal inertia allows internal temperatures remaining at comfort levels in spite of wider external variations, not creating a barrier, as is the case of the insulation, but exploiting the dynamics of the process slowing it down. If the slowdown takes several hours, a significant time span with respect to the daily cycle (phase shift), the system would attain an efficiency point, even without reaching a static (thermal) equilibrium. Massive claddings, in spite of their limited insulation properties, have an excellent dynamic transient response, to the point that it may preclude the establishment of steady state conditions during a whole daily cycle.

The dynamic behaviour of building envelopes is important in winter, in particular when heating is discontinuously used in daily cycles. Moreover, in summer, building envelops play a crucial role. Indeed, shading and thermal inertia become crucial when high temperatures and intensive solar radiation occur. In this cases, building envelopes should ensure an adequate indoor thermal comfort especially without air conditioning (AC) systems. The thermal inertia of opaque walls can be measured as the attenuation of the amplitude of internal surface temperature and with the phase shift, namely the decrement of the transmission of external temperature inside.

During the last decades, building techniques have been oriented towards a reduction of the self-weight; the ensuing reduction of the actual mass has also inevitably significantly decreased the thermal inertia. The lightening of buildings is allowed using materials with reduced mass. More than the decrease of the vertical loads, this is especially favourable when the apparent horizontal forces due to seismic excitations are considered.

The objective of this study is to identify an innovative and environmentally preferable solution for claddings produced with advanced concrete containing embedded PCMs, optimising the thermal inertia without increasing the self-weight. The use of light-weight materials with enhanced thermal inertia greatly improves the envelope's behaviour, allowing excellent performance during the hot season, which, to date, has been a critical challenge for traditional light-weight insulation. This integrated approach leads to a strong reduction of energy used for cooling and, – particularly in temperate climates, it might obviate the need for active AC systems in many cases. Conversely, in colder areas using PCMs in light-weight concrete alongside an additional insulation layer enhances thermal properties by combining a lower thermal conductivity with an improved thermal inertia. Thus, fully exploiting the possibility to rely on thermal inertia rather than solely on the traditional concept of thermal insulation. Through the inclusion within concrete panels, PCMs brings other useful properties, namely fire resistance and improved durability, whilst avoiding chemical, UV and biological degradation.

The study presented in this paper has developed in the context of Eco-Energy Efficient Envelopes for innovative Buildings (E4iBuildings) project. The project aimed at designing a product optimized for storing thermal energy within building envelopes, reducing and delaying the peak amplitude of heat fluxes, hence the energy consumption for heating and cooling. The crucial factor in the project lies with the way of exploiting the thermal inertia of building envelope in the transient regime (dynamic). Moreover, one of the main challenges has been to embed as much larger amount of PCMs as possible, up to ten time more with respect to the products readily available on the market. In relation to current state-of-the-art practice, the notable differences are the change of scale in the use of PCM materials (from microencapsulation to macroencapsulation).

On the other hand, to favour resource efficiency [12] and circular economy [13], the use of secondary by-products up-cycled from other industrial processes has been pursued. In fact, industrial processes such as the refining of biofuel from waste oils generates by-products such as *fatty acids* and *polyols* (*glycerol*) which could be used as PCMs (Fig. 1). The development of the research on the building application of PCMs based on natural resources (bio-based) is increasing [14] since they proved to be suitable candidates for low temperature thermal energy storage applications.

Since the beginning of the project, all the options that came up during the design phases have been evaluated through the environmental and spatial assessment.

For the environmental analysis, Life cycle assessment (LCA) has been applied, being recognised as a leading methodology for the