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In situ assessment of the fabric and energy performance of five conventional and non-conventional wall systems using comparative coheating tests

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ABSTRACT

Comparative coheating tests have been carried out in five test buildings with walls constructed of Concrete Block Masonry and timber framed Hemp-lime composite, Polyisocyanurate (PIR), Wood Fibre and Mineral Wool. Five different methods of determining heat loss coefficient (HLC) were applied during the data analysis. While some variability in HLC values was observed between the different forms of construction, the hierarchy of HLC values among the test buildings were consistent, with the Concrete Block Masonry exhibiting the highest and Wood Fibre test building exhibiting the lowest HLC values. Except for the Concrete Block Masonry, there was good agreement between the calculated HLC values and those derived by applying the method 5 where the analysis incorporated both the effects of solar radiation and thermal mass. The in-situ U-value for the Concrete Block wall, determined by the average method, was 32.8% higher than its design value, whilst the other wall systems showed marginally lower U-values than their corresponding design U-values.

1. Introduction

The building sector contributes to approximately 30% of global total energy consumption, of which nearly two-thirds can be attributed to the combined energy use of space heating, space cooling and water heating [1]. In response to this, a number of regulations have been introduced worldwide with the aim of reducing energy use in domestic and non-domestic buildings; these regulations include the Energy Performance Building Directive [2], the Energy Efficiency Directive [3] in the European Union, and Part L of the Building Regulations [4] in the UK.

The aforementioned regulations use certain prediction methods to assess the building energy use during the design stage. Evidences suggest that there is a discrepancy between the predicted and actual energy use in the buildings [5], the mismatch is broadly referred to as the 'energy performance gap' [6]. The 'energy performance gap' between the actual energy use and the calculated energy use of buildings is subject to scores of academic discussions [5–13]. Sometimes the amount of discrepancy is reported as 100% or more [5], e.g., Erhorn [12] reported a performance gap of 300%. The reasons for this 'energy performance gap' is widely attributed to poor prediction of actual energy use (design stage), poor quality of construction, poor service design, discrepancy between design specification and the specification of the construction as-built (construction stage) and user behaviour and 'Rebound Effect' (operational stage) [8,9]. While, user behaviour remains the most reported key reason for energy performance gap [14–16], Gorse et al. [13] observed that poor thermal performance of building fabric could also be an important contributor to unpredicted energy use.

In addition to operational energy, embodied energy of buildings also contributes to their total lifetime carbon emissions. About 6–20% energy use of a conventional building and about 74–100% of that of a nearly zero energy building is attributed to embodied energy [17]. By 2020 all new buildings in the EU countries are required to be nearly zero-energy buildings [2]. It implies that, by 2020, the role of embodied energy will be significant in terms of a building's total energy use. The embodied energy in a building can be reduced by using materials derived from renewable sources as they generally require less 'extraction', processing and transportation energy [18]. In general, locally produced bio-based building materials carry less embodied energy than the fossil fuel and mineral based building materials [19].

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Bio-based building materials, especially insulations and envelope-integrated insulation materials, are produced from renewable sourced and show excellent hygric and good to moderate thermal performance [20–22]. Takano et al. [23], in their study on the energy performance of a hypothetical building model in Finland, observed that the life cycle energy balance of the cellulose fibre insulation was the lowest among all building materials including EPS (expanded polystyrene) and glass wool insulations. Latif et al. [20] studied hygrothermal properties of composite fibrous insulations based on hemp and wood-hemp insulation which are highly sustainable [24] and carbo-negative materials. The insulations demonstrated excellent moisture management capacity and similar thermal conductivity to that of mineral wool insulation. Another important bio-based composite material is hemp-lime which is comprised of hemp shiv, the woody core of hemp plant, and a lime based binder [25]. Hemp-lime can be used in walls, floors and roofs. It has 'Excellent' moisture buffer capacity [21] and moderate thermal properties [26]. Apart from plant sources, bio-based materials are also derived from animal sources. Sheep wool insulation is an animal-based renewable bio-insulation with self-extinguishing capacity [27]. Sheep wool insulation demonstrates high moisture buffering capacity and low thermal conductivity [27]. The following bio-based insulation materials also possess broadly similar hygrothermal characteristics as discussed above: straw, flax, wood fibre.

Recently, as part of the Hempsec Project [28], a new wall system is developed to address the concern with both operational and embodied energy use [29]. The panel is called 'HempCell' and the core materials of the panel are hemp-lime and natural fibre such as wood fibre or hemp fibre. While hemp-lime exhibits excellent hygric and moderate thermal resistance properties [21], both hemp and wood fibre exhibit excellent hygric capacity and good thermal resistance property [20,30]. As a prefabricated and pre-dried system, HempCell is expected to exhibit optimal thermal performance from the very day of its installation as opposed to the unpredictable and poorer initial thermal performance associated with the in situ cast hemp-lime system.

To compare the thermal performance of the 'HempCell' wall system with the other conventional and emerging wall systems, comparative coheating tests were carried out among five test buildings built with the following walls systems: Concrete Block Masonry, HempCell, Polyisocyanurate (PIR), Wood Fibre and Mineral Wool. A coheating test applies a quasi-steady state method for determining the whole building energy performance [31]. It is typically carried out by elevating the internal temperature to 25 °C for a period of 1–3 weeks [32]. The performance is measured in terms of energy use for unit temperature difference between the inside and outside of the building and referred to as heat loss coefficient (HLC). The method for conducting a coheating test is briefly discussed in section 3. In addition to the coheating tests, the wall systems were also compared in terms of the deviation of their in-situ U-value from the corresponding calculated U-values. Assessing the thermal performance of the envelope of an existing building by determining its in situ U-value is a well-established non-destructive method. Desogus et al. [33] compared the results of R value of a wall determined by in situ measurement method and by numerical method. The numerical method used known thermal conductivity of the component materials of the wall as the basis of calculation. They concluded that there was no significant difference between the results obtained as long as the internal and external temperature difference was more than 10 K during the in situ test. In a similar line of study, Evangelisti et al. [34] observed that the calculated U-value of a wall could, however, vary from the in situ U-value of an envelope if the assumption of thermal conductivity of the component materials were inaccurate.

2. Test buildings, wall systems and instrumentation

2.1. The test buildings and instrumentation

Five test buildings, with five different wall systems, were constructed at the Building Research Park, Wroughton, UK, which hosts the HIVE experimental building facility [35] (Fig. 1). The five wall systems are: Concrete Block Masonry; timber framed wall panels containing HempCell; PIR (polyisocyanurate); Wood Fibre; and Mineral Wool insulations. Typical plans and sections of the five test buildings are shown in Fig. 2 with the corresponding dimensions being presented in Table 1. All the timber frame wall systems were designed to achieve the identical U-value of 0.15 W/m^2K using BS EN ISO 6946:2007 [36]. The Concrete Block Masonry was also designed to achieve an U-value of 0.15 W/m^2K but a detailed calculation by the authors using BS EN ISO 6946:2007 [36] and including the effect of thermal bridges through mortar joints and metal ties showed that the design U-value was 0.19 W/m^2K. Floors and ceilings of the test buildings were of identical construction with a design U-value of 0.10 (W/m^2K).

2.2. The wall systems and instrumentation

Some key details of the structure of the wall systems are provided in Table 2.

One of the key objectives of the coheating experiment was to compare the HempCell (Fig. 3) panel with other conventional and emerging wall systems in terms of energy use and thermal performance. As such, a number of test panels of each test building were instrumented with temperature and relative humidity (RHT) sensors (Figs. 4–8). For temperature sensing, Betatherm thermistor [37] sensors with an accuracy of ±0.2% were used. For relative humidity sensing, HIH400 sensors [38] with an accuracy of ±3.5% were used. In the HempCell test building, one panel in each orientation was instrumented. For other test buildings, only wall panels facing North and South were instrumented with RHT sensors. In addition to these, two Hukseflux heat flux sensors [39], with an accuracy of ±5%, were installed on the inner surface of the North wall of each test building.

3. Method

3.1. Coheating test method

To determine the HLC values, the unoccupied test buildings were heated to an elevated mean internal temperature of 25 °C ± 0.5 °C, each building employing an electric resistance heating system rated at 0.7 kW for space heating and energy use was monitored using an energy meter with a pulse output of 2000 impulse per kilowatt-hour (2000 imp/kWh). The interiors of the test buildings were maintained at the aforementioned steady temperature for a period of 18 days during the winter month of February 2016. The key external boundary conditions during the test period are presented in Fig. 9.

By measuring the amount of electrical energy required to maintain the elevated mean internal temperature over the test period, the daily heat input (in Watts) to the dwelling was determined [32]. At its simplest form, the heat loss coefficient (W/K) for