Investigating the potential of adding thermal mass to mitigate overheating in a super-insulated low-energy timber house

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Abstract

Evidence suggests that many UK dwellings are subjected to overheating or will be at some point in the future. Dwellings built using modern methods of construction may have a higher overheating risk due to the low levels of thermal mass associated with most of these methods. The Nottingham HOUSE, a prefabricated timber modular building designed to zero-carbon and Passivhaus standards, was examined in terms of overheating occurrence. The ability of a high-density fibreboard and phase change materials to provide additional levels of thermal mass was examined with the results suggesting that these can help regulate internal temperatures with the benefit of being easy to integrate.

Keywords: modern methods of construction; overheating; thermal mass; phase change materials; energy efficiency

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1 INTRODUCTION

The UK housing construction sector has been unable to meet the demand for housing for a number of years, leading the UK government to set an output target of 2 million houses by 2016 and 3 million houses by 2020 and an expected annual supply of 240 000 houses [1]. However, following the 2007 financial crisis, the house building industry experienced a major decline with build rates decreasing almost by a half and prices falling up to one-third to the pre-crisis levels [2] and only recently, it has started to show signs of recovery [3, 4].

Simultaneously, there is an ongoing increase in demand for dwellings. The number of households in the UK is expected to exceed 27.5 million in 2033 as a result of population growth and a projected decrease in the household size, which corresponds to a mean annual expected rise in the demand of 232 000 houses [5].

The challenge for the UK house building sector becomes even greater within the context of the constantly stricter energy performance requirements set by the building regulations, resulting in higher insulation levels. The UK government set the legally binding target to reduce its greenhouse emissions by 34% in 2020 and by 80% in 2050 compared with the 1990 emissions levels [6, 7]. The government policy regarding newly constructed dwellings requires that all new houses from 2016 onwards should be zero-carbon; this includes emissions associated with the energy use for heating, cooling, lighting and domestic hot water [8]. The framework for achieving zero-carbon standard includes high levels of fabric energy performance, followed by on-site emissions reductions through low and zero carbon technologies and the use of allowable solutions [9]. Furthermore, compliance with level 6 of the Code for Sustainable Homes (CfSH), the national sustainability standard for assessing the environmental performance of new dwellings, requires net zero carbon emissions.

Apart from the high minimum requirements set by the building regulations, other voluntary low-energy building standards, such as the Passivhaus standard, set even stricter requirements through a fabric-first approach. The Passivhaus standard is a popular performance-based standard which requires very low targets to be met for the specific heating and cooling demand (or specific heat load), the airtightness and the specific primary energy demand of a building [10]. The Nottingham HOUSE has been designed to meet most criteria of both zero-carbon and Passivhaus standards.

This paper builds on and extends previous work presented at the 12th International Conference on Sustainable Energy Technologies (SET 2013) (Paper ID: 420).

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Both the building regulations and the low-carbon building standards are setting requirements for very high levels of insulation and air tightness which may be easier to achieve with the use of modern methods of construction (MMC). MMC are expected to play a significant role towards meeting the increased housing demand and have been supported by the UK government in an attempt to achieve high rates of house deliveries built at high standards in terms of quality and energy efficiency [1]. The use of MMC has a number of advantages, including quicker construction, lighter buildings and the possibility of integrating more insulation in smaller overall building envelope thicknesses [11].

The high performance levels set by the UK Building Regulations may be able to reduce the heating load of buildings; however, they also result in buildings with limited ability to reject and dissipate unwanted heat and, hence, increased risk of overheating. Historically, overheating was not taken into account as an issue in the UK. However, recent monitoring studies provided evidence that existing buildings suffer from overheating [12–15]. Thermal mass, a material's capacity to absorb, store and release heat, has been identified as one of the most effective passive measures to help regulate internal temperature, reduce temperature variations and mitigate overheating [16, 17]. Traditionally, thermal mass has been provided by means of concrete, brick or masonry in contact with the internal environment. The low levels of thermal mass associated with most MMC systems suggest that houses built using MMC are more prone to overheating. Numerous simulation studies have examined the overheating potential of dwellings in current and future climate, dwellings with different levels of thermal mass, including various works by the authors which have focused on the thermal performance of super-insulated dwellings constructed with MMC systems [17–29].

Nevertheless, the integration of heavyweight elements in MMC houses may jeopardize some of the benefits of using MMC. Consequently, in this study, the authors investigated the potential of non-traditional lightweight components to provide additional levels of thermal mass and regulate internal temperatures. Rigidur H, a high-density fibreboard that combines gypsum, cellulose fibres from recycled paper and water [30], and the use of phase change materials (PCM) were considered. PCM are materials which have the ability to store and release latent as well as sensible heat. This is done through interchanging state from solid to liquid in specific temperature ranges. The analysis considered the use of two different PCM plasterboards: Rigips Alba®balance 23 and Alba®balance 26. Rigidur H was chosen because it is not only affordable but also for its rigidity, durability and mechanical strength, and for being smooth enough to be decorated without the need for surface treatments. Its performance was examined in another work by the authors under different ventilation patterns and it was found that there is some potential to mitigate overheating [31]. The Rigips PCM plasterboards were chosen in this analysis because they are suitable for use in direct contact with the internal space without requiring the addition of any other element.

2 HOUSE DESIGN

The Nottingham HOUSE (Home with Optimized Use of Solar Energy) is a two-storey L-shaped 'starter home', designed to provide an affordable solution for a first residence for a couple or a new family. The house was designed as semi-detached or as part of a terrace, with the L-shape providing an external courtyard when joined with other houses (Figures 1 and 2). For the purpose of this analysis, however, the house is considered to be stand-alone as it is built. The Nottingham HOUSE was designed by students at the Department of Architecture and Built Environment at the University of Nottingham to enter the Solar Decathlon 2010 competition in Madrid and aspired to provide a solution for the deployment of affordable houses designed and built to zero-carbon standards. The house was first assembled in Nottingham, then in London for the Ecobuild exhibition in March 2010, before being transported and assembled in Madrid for the competition; since 2012, it has been permanently

Figure 1. *External view of the Nottingham HOUSE (left) and view of the interior (right) (Copyright The University of Nottingham).*

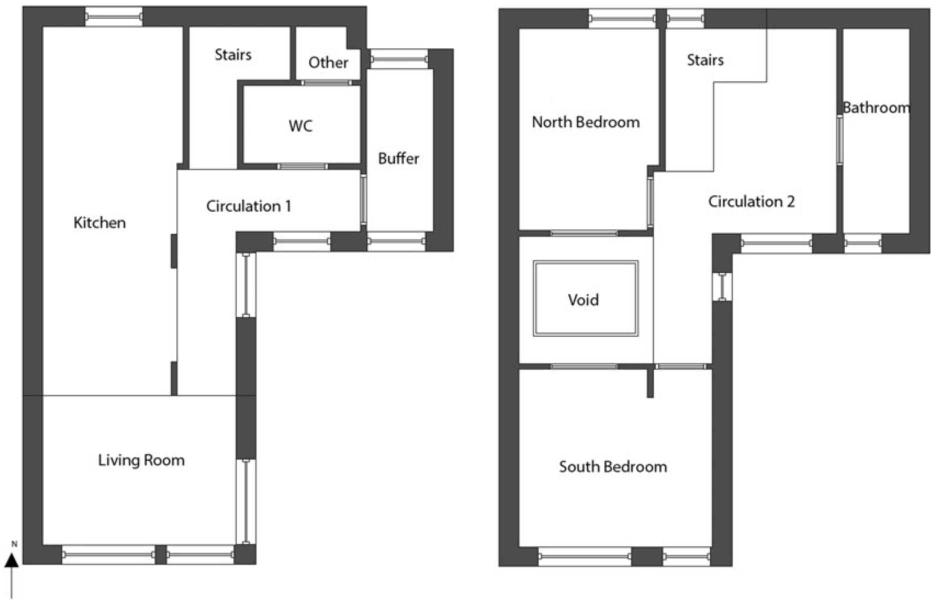

Figure 2. *Ground floor (left) and first floor (right) plans and zones. Model created in EDSL Tas.*

installed at the Creative Energy Homes site at the University Park Campus, University of Nottingham [32]. This is an excellent demonstration of the ease of deployment and the flexibility of the house. The Creative Energy Homes project is a unique research project which involves monitoring seven dwellings built with different MMC and at various specifications aiming 'to stimulate sustainable design ideas and promote new ways of providing affordable, environmentally sustainable housing that are innovative in their design' [23, 32, 33].

The house was built using volumetric MMC; it consists of eight fully prefabricated timber cassette panel structures, filled with glasswool insulation, transported and assembled on-site. It has been designed and built to very high standards and it aims to achieve CfSH level 6 rating and meet the Passivhaus standard certification criteria. The high performance levels are achieved with the use of highly insulated building elements (*U*-value of walls, floor and ceiling ≤ 0.1 W/m^2 K, triple glazed windows with low-e coating and *U*-value of 0.5 W/m^2 K approximately) and low-energy appliances, as well as renewable energy technologies (PV and solar thermal panels installed at the roof). The walls and ceilings were finished with Rigidur H, 10 and 12.5 mm, respectively. Rigidur H for offsite applications has 1200 kg/m^3 density, 1100 J/kg°C specific heat and 0.2 W/m°C conductivity. Heating is provided by a mechanical ventilation and heat recovery (MVHR) unit coupled with an air source heat pump. Ventilation is provided by means of both natural and mechanical ventilation. Window openings in the south and north façade are allowing cross-ventilation. The use of a roof window and a double height space (space between the south and north bedrooms is void) also allows for buoyancy-driven ventilation to take place. In addition, mechanical ventilation is also provided by the MVHR unit by extracting air from the kitchen and the bathrooms and driving fresh outside air to the living room and the bedrooms.

The plans of the ground and first floor are provided in Figure 2. The ground floor, with a heated area of ~37 m^2, consists of a lobbied entrance, WC, circulation area and an open plan area which includes the kitchen, the dining room and the living room. The first floor, with a heated area of ~41 m^2, includes a bathroom, a circulation area and two bedrooms, one facing south and one north.

3 SIMULATION METHODOLOGY

The study investigated the overheating potential of the Nottingham HOUSE and examined the ability of non-traditional lightweight elements to regulate internal temperatures and reduce overheating issues by providing additional levels of thermal mass. Various layers of Rigidur H and Rigips PCM plasterboards were considered and their performance was compared against with that of concrete. A model of the house was built in EDSL Tas (Figure 2) and a series of dynamic simulations was performed to evaluate its performance in current climate conditions in Nottingham. The house was divided in zones according to the expected use of areas: buffer space, WC, circulation areas, stairs, kitchen, living room, south and north bedroom, bathroom, void and other (plant room).

The analysis considered additional layers of material mounted on the walls and ceilings, increasing from one to three layers. The wall area was 260 m^2 and the ceiling area was 80 m^2. A base case was used as benchmark where the walls and ceilings were finished with one layer plasterboard with a 960 kg/m^3 density, 837 J/kg K specific heat and 0.16 W/m K conductivity (Case0-Plast). Then, the performance of Rigidur H was investigated considering one to three layers (Cases 1-Rig to 3-Rig). The wall-mounted layers of Rigidur were 10 mm thick and the ceiling layers were 12.5 mm. In addition, for reasons of comparison, the performance of equal amounts (10 mm on the walls and 12.5 mm on the ceiling) of high-density concrete mounted on the walls and ceilings was examined (Cases 1-Con to 3-Con). The properties of the concrete were 2100 kg/m^3 density, 840 J/kg K specific heat and 1.4 W/m K conductivity. Next, the effectiveness of PCM in regulating the internal temperatures was examined. With the use of the BASF Micronal® PCM utility (Beta) in EDSL Tas, the performance of the Rigips Alba®balance 23 (melting point at 23°C) and Alba®balance 26 (melting point at 26°C) plasterboard was investigated. Alba®balance 23 has latent heat storage capacity of 300 kJ/m^2, while the respective value for the Alba®balance 26 is 330 kJ/m^2. The boards have a density of 1000 kg/m^3 approximately, conductivity of 0.27 W/m K and specific heat of 1132 J/kg K [34]. The performance of each PCM board was investigated using one and two layers on the walls and the ceilings of the house with the thickness of each layer being 2.5 cm. Table 1 provides a summary of the properties for the materials used in this analysis. A summary of the different cases examined and the associated quantities are presented in Table 2.

Table 1. *Material properties.*

	Density (kg/m^3)	Specific Heat (J/kgK)	Conductivity (W/mK)	Latent heat storage capacity (kJ/m^2)
Plasterboard	960	837	0.16	—
Rigidur H	1200	1100	0.2	—
Concrete	2100	840	1.4	—
Alba®balance 23	1000	1132	0.27	300
Alba®balance 26	1000	1132	0.27	330

Table 2. *Summary of cases examined.*

Case	Material	Layers	Volume (m^3)	Mass (kg)
Case0-Plast	Plasterboard	1	3.60	3451.46
Case1-Rig	Rigidur H	1	3.60	4314.33
Case1-Con	Concrete	1	3.60	7550.07
Case2-Rig	Rigidur H	2	7.19	8628.65
Case2-Con	Concrete	2	7.19	15 100.14
Case3-Rig	Rigidur H	3	10.79	12 942.98
Case3-Con	Concrete	3	10.79	22 650.22
Case1-Alb23	Alba balance 23	1	6.10	6104.88
Case1-Alb26	Alba balance 26	1	6.10	6104.88
Case2-Alb23	Alba balance 23	2	12.21	12 209.75
Case2-Alb26	Alba balance 26	2	12.21	12 209.75

The following assumptions were considered for the simulations:

Weather: The CIBSE Design Summer Year Weather Data (DSY) for Nottingham based on the year 2002 was used, which is the recommended climatic file for performing overheating analysis by CIBSE [35].

The following internal gains were assumed:

Occupants: It was considered that two people (adults) live in the house. Heat gains from the occupants were assumed to be 100 W per person, 65 W sensible and 35 W latent. This value was considered to represent an average for residential activity and it was based on recommendations made by ASHRAE for occupant gains in non-residential spaces for different levels of activity [36].

Lighting: Low-energy compact florescent bulbs were considered for lighting. The bathrooms, circulation areas and stairs considered 25 W for lighting, the bedrooms considered 50 W and the kitchen–dining room 75 W.

Equipment and appliance gains: The equipment gains in the living room were caused by the operation of a TV, a hi-fi system, a computer and the use of mobile phone chargers summing up to a total energy consumption of 0.65 kWh/day. The appliances contributing to the kitchen heat gains were a kettle, a microwave oven, a cooker, a washing machine, a dishwasher and a fridge each running at different hours producing total daily energy consumption of 2.45 kWh. The equipment and appliance gains are given in detail in Table 3.

Apertures: All the window types were set to open during the daytime when the occupants were in the house, that is from 6 a.m. until 8 a.m. and again from 6 to 11 p.m. and were kept closed at night for reasons of security, privacy and noise, as the analysis assumed the dwelling in an urban setting. The

Table 3. *Equipment and appliance gains.*

Room	Equipment	Power (kW)	Usage	Frequency	Energy use per day (kWh)
Living room	Hi-fi	0.04	When on	1 h/day	0.04
	TV	0.15	When on	2 h/day	0.30
	PC	0.09	When on	3 h/day	0.27
	Chargers	0.02	When on	2 h/day	0.04
	Total daily energy use in living room				0.65
Kitchen	Kettle	3	1.5 boil	4 times/day	0.60
	Microwave	0.8	When on	0.5 h/day	0.40
	Cooker with hob	0.8	When on	0.5 h/day	0.40
	Washing machine	0.95	Per 1 h cycle	Once weekly	0.14
	Dishwasher	1	Per 1 h cycle	Twice weekly	0.29
	Fridge	226	kWh/year		0.62
	Total daily energy use in kitchen				2.45

bedroom windows were set to start opening when the resultant temperature in the respective bedroom exceeded 23°C and were fully open when the temperature reached 25°C. The non-bedroom windows were set to start open when the resultant temperature of the adjacent zone reached 25°C and were fully open at 26°C. All the windows were also set to close when the outside temperature exceeded the internal or when the wind velocity exceeded 3 m/s.

The MVHR system was set to start providing fresh air when the temperature in the house reached 25°C and fully supply the required ventilation rate when the temperature reached 26°C. Ventilation rate was set to 1 ACH and it was available on a 24-h basis. Mechanical ventilation was working supplementary to natural ventilation during occupancy hours and as the main ventilation system for the rest of the day.

The analysis considered the CIBSE criteria for assessing overheating, i.e. the temperature should not exceed 28°C in living spaces and 26°C in the bedrooms for more than 1% of the occupied time [35]. In addition, since the overheating occurrence in terms of number of occupied hours may lead to varying results according to the selected occupancy pattern [37], the overheating risk was also assessed considering whole-year performance. This stage of the analysis considered the percentage of time over the whole year when the temperature thresholds, 26°C and 28°C, were exceeded in all zones. Furthermore, the maximum temperatures over the whole year were also determined and a degree-hour approach, estimating the degree-hours observed when the two thresholds were exceeded, was followed in order to have a better insight on the ability of thermal mass to regulate internal temperatures.

Table 4. *Zone areas of available thermal mass.*

Zone	Area (m^2)
Living room	25.00
Kitchen	41.74
South bedroom	47.62
North bedroom	40.44

4 RESULTS

4.1 Overheating occurrence during occupied hours

Results were analysed for the main areas of the house, i.e. the living room, the kitchen and the two bedrooms. Table 4 presents the zones examined with the available area of thermal mass in these zones, i.e. the area of walls and ceiling. At this stage of the analysis, the overheating occurrence during the occupied hours for each zone is examined. The percentage of occupied time when temperature in each zone exceeds 26°C and 28°C is presented in Figures 3 and 4 and in detail in Table 5.

With regard to overheating during occupied hours, it can be seen that the bedrooms practically do not present any overheating, since the temperature in the south bedroom exceeds 26°C by only slightly more than 1% (from 1.03 to 1.20%); the temperature in the north bedroom does not exceed 26°C by more than 1% of occupied time in any case. Regarding the living spaces, the kitchen presents overheating with the temperatures being higher than 28°C for 4.84% of occupied hours in Case0-Plast. Increasing the levels of thermal mass reduced the occurrence of overheating in that zone; however, it was not eliminated. Concrete appeared to be slightly more effective than Rigidur H and Alba®balance 26 was found to be more effective than Alba®balance 23. In the living room, overheating was observed to a small degree (1.92% of occupied hours in Case0-Plast) which was reduced with the addition of thermal mass and eliminated when two layers of Alba®balance 26 are used (Case2-Alb26). Again, concrete was found to have a better performance than Rigidur H and Alba®balance 26 was more effective than Alba®balance 23.

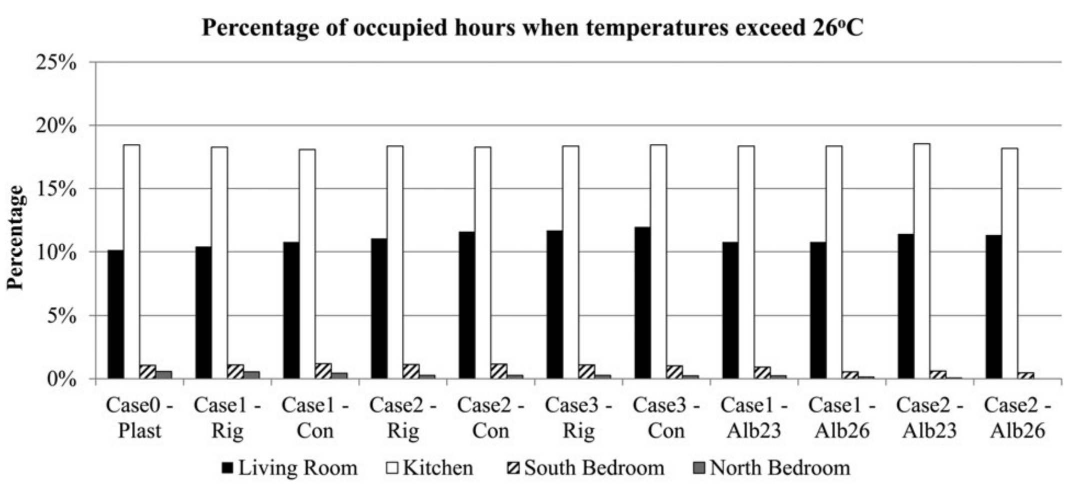

Figure 3. *Percentage of occupied time when temperatures exceed 26°C.*

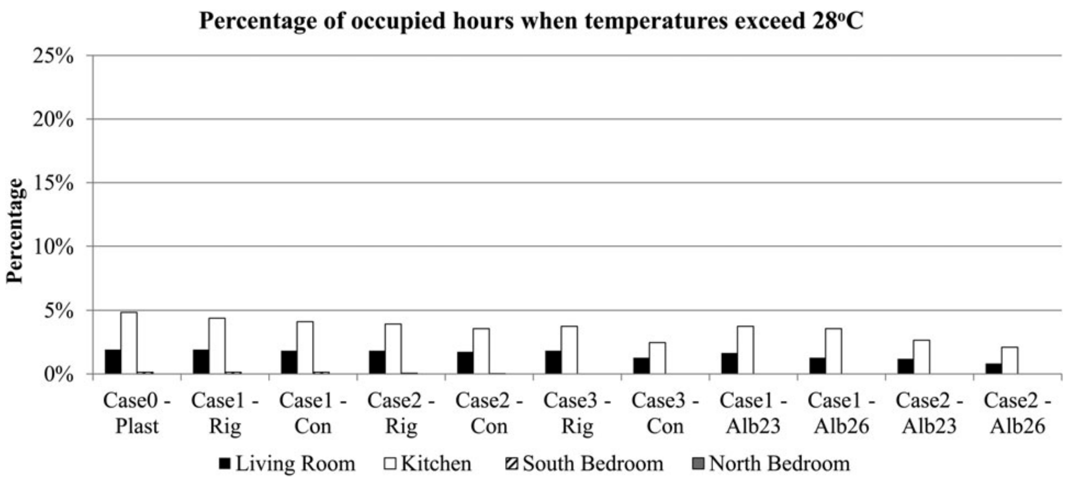

Figure 4. *Percentage of occupied time when temperatures exceed 28°C.*

Table 5. *Percentage of occupied time temperature exceeds 26°C and 28°C.*

	Living room (%)		Kitchen (%)		South bedroom (%)		North bedroom (%)	
	>26	>28	>26	>28	>26	>28	>26	>28
Case0-Plast	10.14	1.92	18.45	4.84	1.06	0.14	0.58	0.00
Case1-Rig	10.41	1.92	18.26	4.38	1.10	0.14	0.55	0.00
Case2-Rig	11.05	1.83	18.36	3.93	1.13	0.07	0.27	0.00
Case3-Rig	11.69	1.83	18.36	3.74	1.10	0.00	0.27	0.00
Case1-Con	10.78	1.83	18.08	4.11	1.20	0.14	0.45	0.00
Case2-Con	11.60	1.74	18.26	3.56	1.16	0.03	0.27	0.00
Case3-Con	11.96	1.28	18.45	2.47	1.03	0.00	0.24	0.00
Case1-Alb23	10.78	1.64	18.36	3.74	0.92	0.00	0.24	0.00
Case2-Alb23	11.42	1.19	18.54	2.65	0.62	0.00	0.07	0.00
Case1-Alb26	10.78	1.28	18.36	3.56	0.55	0.00	0.14	0.00
Case2-Alb26	11.32	0.82	18.17	2.10	0.48	0.00	0.00	0.00

4.2 Overheating occurrence over the whole year

As the number of occupied hours may vary, the overheating occurrence over the whole year was investigated at the second stage of the analysis. The performance of each material in reducing overheating was also examined at this stage in terms of number of layers and material mass applied. When taking into account the overheating occurrence over the whole year, significant levels of overheating were observed in the living room, the kitchen and the south bedroom, while overheating was also observed in the north bedroom albeit to a smaller degree. The results of the whole-year analysis are presented as percentage of time the temperature exceeds 26°C and 28°C in Figures 5 and 6 and in detail in Table 6.

It is apparent that in all cases the living room suffered the most from overheating followed by the kitchen and the south bedroom, while the north bedroom presented the lowest levels of overheating. The performance improvement in terms of temperatures exceeding 26°C, achieved by using one layer of Rigidur H instead of one layer of plasterboard (Case1-Rig over Case0-Plast) ranged from 0.6 to 16.5% in the zones under consideration. The respective performance improvement in terms of temperatures exceeding 28°C ranged from 6.6 to 28.6%. The addition of one and two extra layers of Rigidur H (Case2-Rig and Case3-Rig) decreased further the overheating occurrence in the zones examined and practically eliminated it in the north bedroom. Table 7 presents the performance improvement achieved from adding extra layers of Rigidur H in the zones under investigation, regarding occurrence of temperatures exceeding 26°C and 28°C.

In addition, the performance of concrete and the two PCM boards was investigated. The relative performance of concrete against Rigidur H, namely the materials which act as thermal mass by storing sensible heat, and the relative performance of the two PCM boards, Alba®balance 23 and Alba®balance 26 which have the ability to store latent as well sensible heat, is presented in Table 8.

Concrete was found to be more effective than Rigidur H in reducing the overheating occurrence in all zones. This was particularly the case when increased thickness of material was used and when higher temperature was considered. For example, when three layers of material were considered, the performance improvement of using concrete instead of Rigidur H (Case3-Con over Case3-Rig) ranged from 0.7 to 22.6% in terms of temperatures exceeding 26°C. Regarding the 28°C threshold, the respective improvement achieved from using concrete over Rigidur H ranged from 19.7 to 50.0%. However, care should be taken when interpreting these results; the absolute values of performance should also be taken into account. The higher values of improvement refer to already low percentages of overheating. For example, the relative improvement of Case3-Con over Case3-Rig was found to be 50% in the south bedroom for the 28°C threshold. However, the actual overheating reduction was just 0.3% (from 0.5 to 0.2%). With regard to the performance of the PCM boards, it can be seen that Alba®balance 26 resulted in reduced overheating occurrence in most zones compared with

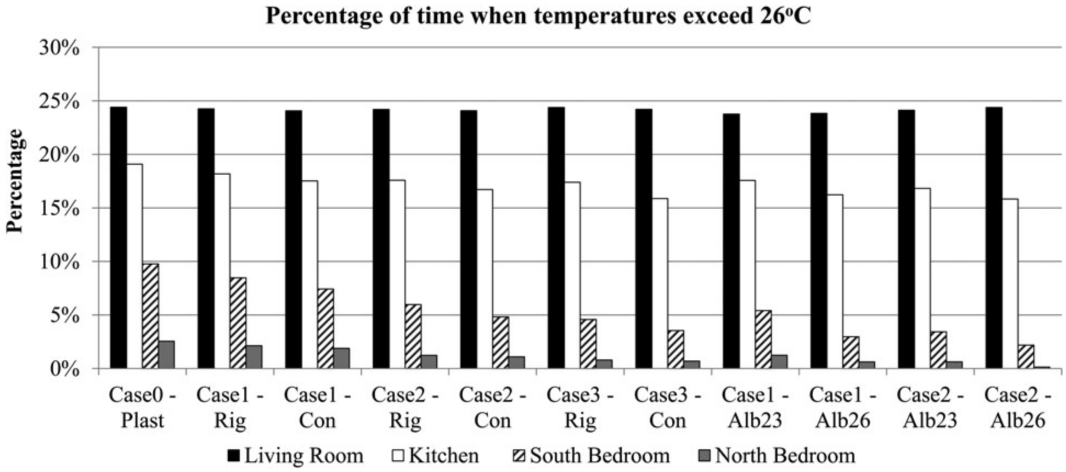

Figure 5. *Percentage of time (whole year) when temperatures exceed 26°C.*

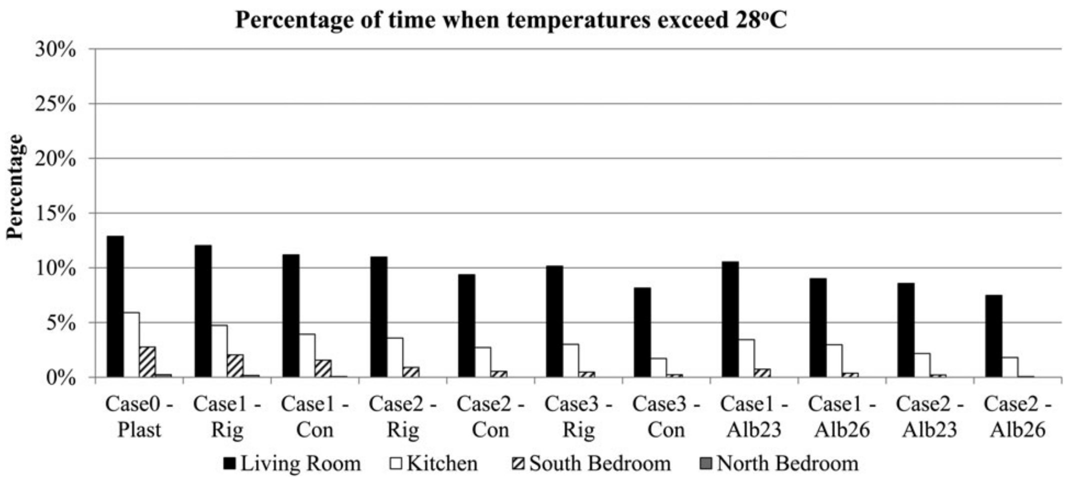

Figure 6. *Percentage of time (whole year) when temperatures exceed 28°C.*

Alba®balance 23 when the 26°C threshold was considered and in all zones for the 28°C limit.

4.3 Effect of material thickness on overheating occurrence

The effect of the thickness of Rigidur H, concrete and the two PCM boards on the overheating occurrence over the whole year in the living room, the kitchen and the south bedroom, was also investigated. As the levels of overheating in the north bedroom were very low and practically eliminated, this zone was omitted from further analysis. Figures 7–9 present the percentage of time when temperatures exceeded 26°C and 28°C for the different number of layers applied in the living room, the kitchen and the south bedroom.

The performance of the materials was investigated considering both thresholds in all zones. In the living room, all materials were found to have similar performance in terms of temperatures exceeding 26°C; increasing the layers of the material did not practically change the overheating occurrence. Regarding the 28°C benchmark, it is apparent that increasing the layers of thermal mass did reduce the percentage of time when temperatures exceeded it. Concrete appeared to be slightly more effective than Rigidur H and the PCM boards were in turn more effective than concrete, with Alba®balance 26, resulting in the lowest percentage of overheating. In the kitchen, increasing the layers of the material resulted in a decrease in the occurrence of temperatures exceeding 28°C, while it did not seem to affect much the occurrence of temperatures higher than 26°C. Again, concrete appeared to have a more significant effect in mitigating overheating than Rigidur. Alba®balance 26 was found to be the most effective considering both thresholds. Finally, in the south bedroom, the results also indicated that concrete was more effective in coping with high temperatures than Rigidur H. The effectiveness of both materials seemed to drop with the increase in the number of layers applied. The PCM boards were found to be significantly more effective and again the Alba®balance 26 had the best performance.

Table 6. *Percentage of time (whole year) when temperatures exceed 26°C and 28°C.*

	Living room (%)		Kitchen (%)		South bedroom (%)		North bedroom (%)	
	>26	>28	>26	>28	>26	>28	>26	>28
Case0-Plast	24.4	12.9	19.1	5.9	9.8	2.8	2.6	0.2
Case1-Rig	24.3	12.0	18.2	4.7	8.5	2.1	2.1	0.2
Case2-Rig	24.1	11.2	17.5	3.9	7.4	1.6	1.9	0.1
Case3-Rig	24.2	11.0	17.6	3.6	6.0	0.9	1.2	0.0
Case1-Con	24.1	9.4	16.7	2.7	4.8	0.5	1.1	0.0
Case2-Con	24.4	10.1	17.4	3.0	4.6	0.5	0.8	0.0
Case3-Con	24.2	8.2	15.9	1.7	3.6	0.2	0.7	0.0
Case1-Alb23	23.8	10.5	17.6	3.4	5.4	0.7	1.2	0.0
Case2-Alb23	24.1	8.6	16.8	2.2	3.4	0.2	0.6	0.0
Case1-Alb26	23.8	9.0	16.2	3.0	3.0	0.4	0.6	0.0
Case2-Alb26	24.4	7.5	15.8	1.8	2.2	0.1	0.1	0.0

Table 7. *Performance comparison of plasterboard against Rigidur H in different quantities.*

	Living room (%)		Kitchen (%)		South bedroom (%)		North bedroom (%)	
	>26	>28	>26	>28	>26	>28	>26	>28
Case1-Rig over Case0-Plast	0.6	6.6	4.8	19.7	13.3	25.9	16.5	28.6
Case2-Rig over Case1-Rig	0.2	8.7	3.3	24.3	29.5	55.6	42.2	100.0
Case3-Rig over Case2-Rig	−0.8	7.6	1.0	15.9	23.3	47.5	36.1	-

Table 8. *Performance comparison of concrete against Rigidur H and Alba®balance 26 against Alba®balance 23.*

	Living room (%)		Kitchen (%)		South bedroom (%)		North bedroom (%)	
	>26	>28	>26	>28	>26	>28	>26	>28
Case1-Con over Case1-Rig	0.8	7.0	3.6	17.1	12.4	23.9	11.8	60.0
Case2-Con over Case2-Rig	0.5	14.7	4.9	24.2	19.3	40.0	11.1	—
Case3-Con over Case3-Rig	0.7	19.7	8.7	43.2	22.6	50.0	13.0	—
Case1-Alb26 over Case1-Alb23	−0.3	14.5	7.7	13.6	45.1	49.2	50.5	—
Case1-Alb26 over Case1-Alb23	−1.1	12.8	5.9	16.8	36.2	63.2	78.2	—

4.4 Effect of material mass on overheating occurrence

Concrete was found to perform better than Rigidur H in all zones. Rigidur H has higher specific heat than concrete; however, concrete has much higher conductivity and much higher density. For the same material thickness, the mass of concrete is by 75% larger than the respective amount of Rigidur H. It can be concluded, therefore, that concrete has the ability to store more heat which can be absorbed and released easier compared with Rigidur H. Alba®balance 26 also performs better than Alba®balance 23 which was expected to a certain degree, as its latent heat storage

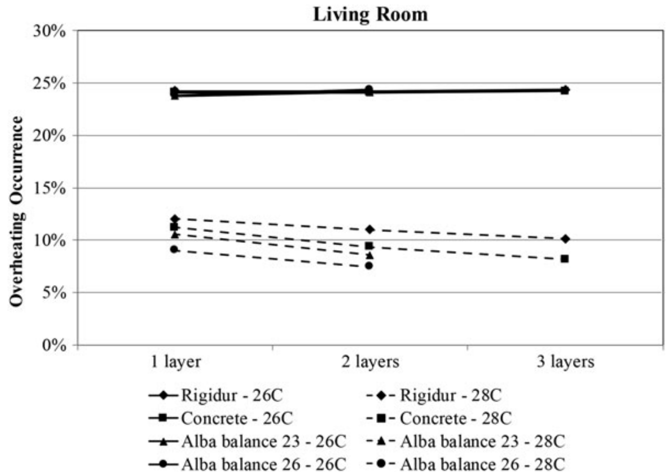

Figure 7. *Overheating occurrence for different layers of material in the living room.*

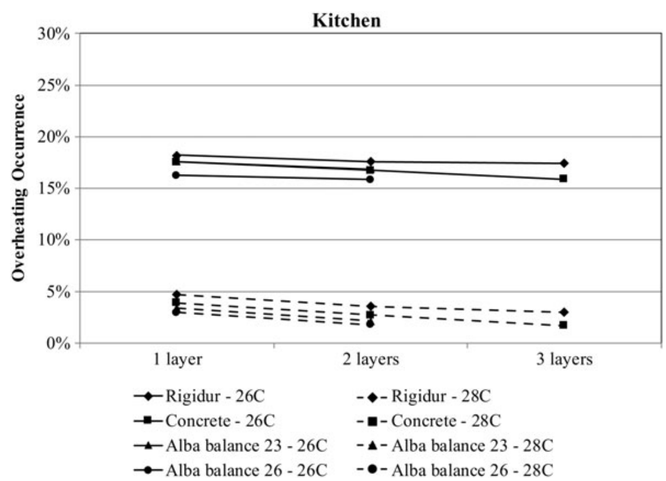

Figure 8. *Overheating occurrence for different layers of material in the kitchen.*

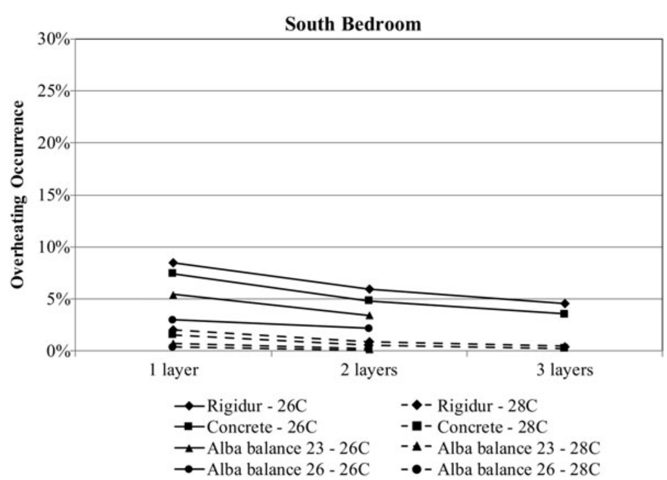

Figure 9. *Overheating occurrence for different layers of material in the south bedroom.*

capacity is by 10% higher. Furthermore, it appears that the temperature ranges occurring in the house are more favourable for the Alba®balance 26 board. It should be noted that the PCM boards are thicker than the layers of Rigidur H and concrete. In order to account for the different densities and thicknesses of the materials, the results were also compared against the material mass available. Figures 10–12 present the performance in terms of material mass for the same zones.

For the same levels of material mass, Rigidur, concrete and Alba®balance 23 presented quite similar performance in the living room and kitchen, where increased internal gains occurred. Alba®balance 26 was found to have slightly better performance in reducing only the 28°C occurrence in the living room and the occurrence of temperatures higher than 26°C and 28°C in the kitchen. In the south bedroom, Rigidur H was found to be more effective than concrete in the south bedroom for the same amounts of mass. Again, Alba®balance 26 board was found to be the most effective.

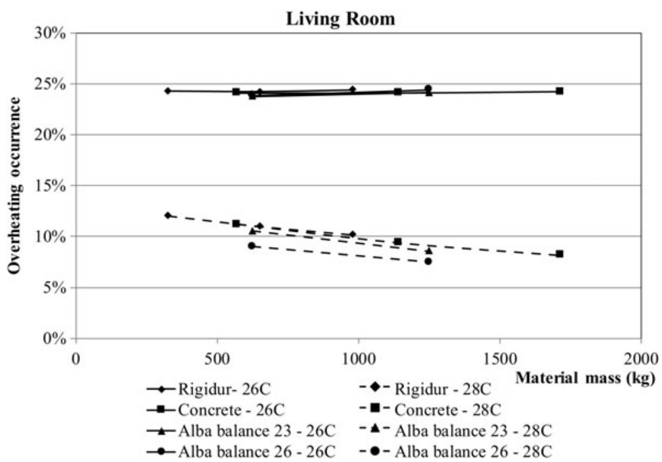

Figure 10. *Overheating occurrence for different amounts of thermal mass of Rigidur H, concrete and PCM boards in the living room.*

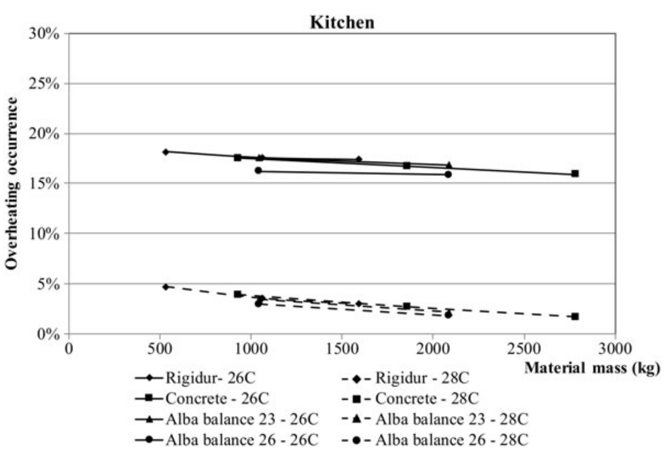

Figure 11. *Overheating occurrence for different amounts of thermal mass of Rigidur H, concrete and PCM boards in the kitchen.*

4.5 Peak temperatures and degree-hours

As it is widely accepted that the number of hours of exceedance of specific temperatures is not an accurate measure for assessing overheating, the effect of thermal mass on the peak internal temperatures of the dwelling was also investigated. The maximum temperatures for each case in the zones examined are presented in Table 9. The relative performance of each material in reducing the peak temperatures, in terms of material mass, is presented in Figure 13. It can be seen that the maximum temperature observed in each zone was reduced when the levels of thermal mass were increased. Concrete, again appears to be more effective than Rigidur H in reducing the peak temperature and Alba®balance 26 is found slightly more effective than Alba®balance 23 in all zones. However, in terms of material mass Rigidur H performs similarly or better to concrete in reducing peak temperatures.

In addition, a degree-hour approach was followed in order to evaluate the magnitude of overheating for the different cases examined. The degree-hours of exceeding 26°C and 28°C were calculated for the three zones where overheating was observed

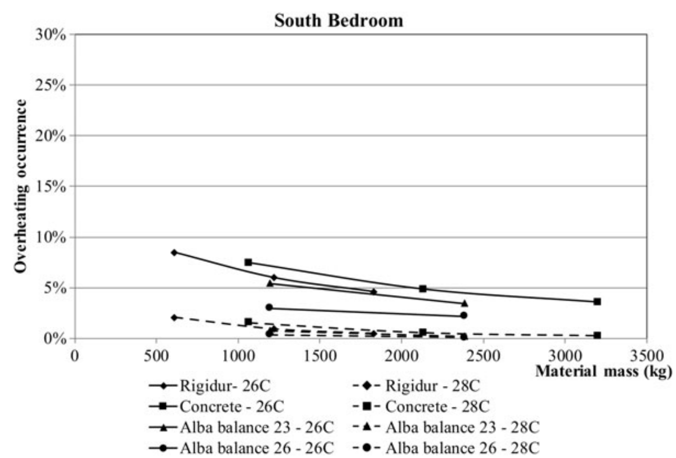

Figure 12. *Overheating occurrence for different amounts of thermal mass of Rigidur H, concrete and PCM boards in the south bedroom.*

Table 9. *Maximum temperature in each zone.*

	Living room (°C)	Kitchen (°C)	South bedroom (°C)	North bedroom (°C)
Case0-Plast	35.47	33.61	32.46	29.53
Case1-Rig	34.80	33.11	31.69	29.05
Case1-Con	34.18	32.62	31.14	28.74
Case2-Rig	33.86	32.24	30.35	27.98
Case2-Con	33.00	31.52	29.79	27.72
Case3-Rig	33.26	31.63	29.64	27.44
Case3-Con	32.29	30.82	29.10	27.21
Case1-Alb23	33.65	32.05	30.09	27.95
Case1-Alb26	33.54	31.94	29.88	27.53
Case2-Alb23	32.49	30.94	29.01	27.14
Case2-Alb26	32.37	30.80	28.71	26.50

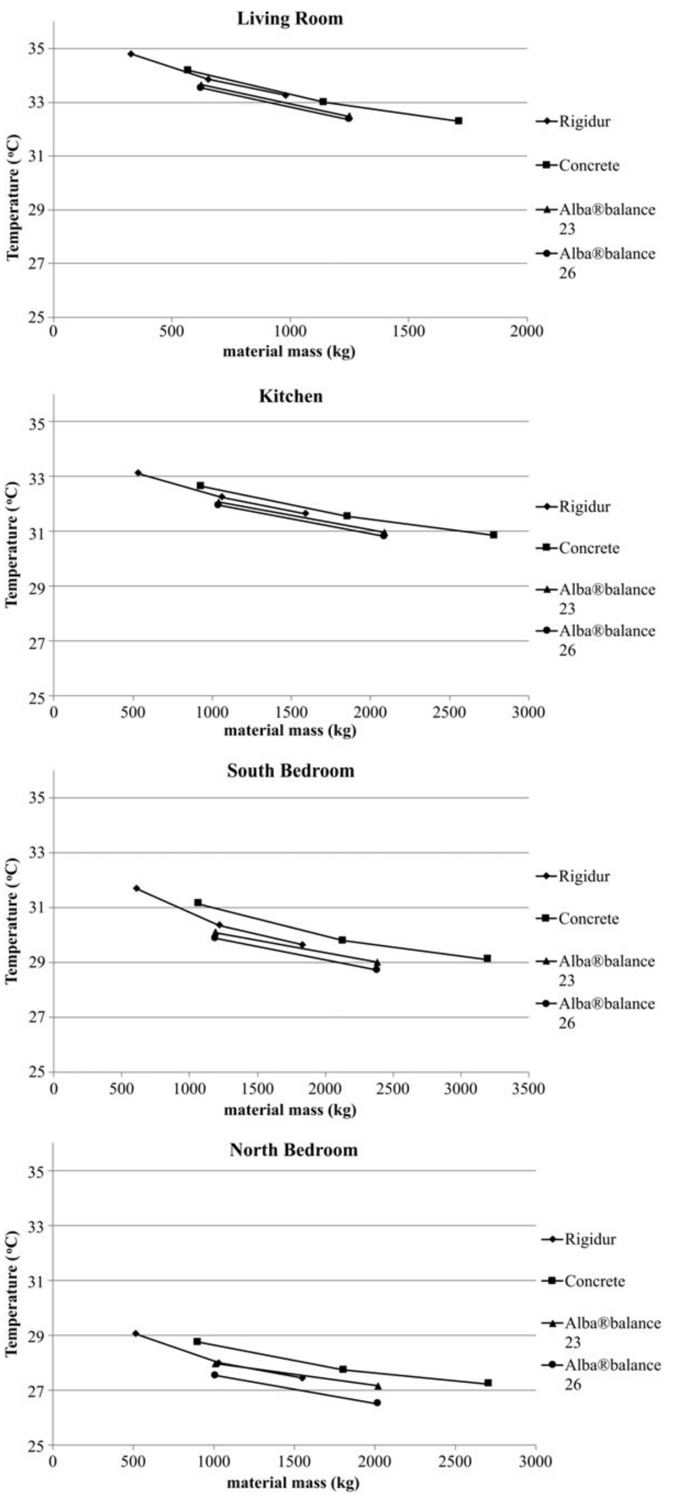

Figure 13. *Reduction in maximum temperatures in each zone for different amounts of material mass.*

and are presented in Figure 14. The results of the degree-hour approach demonstrate the ability of thermal mass to reduce overheating in a manner that the 'number of hours' approach was not able to do. For example, in the living room, it was observed that the use of different materials and the use of additional layers of these materials did not change the percentage of time when temperature exceeded 26°C (Figure 7). However, the results of Figure 14 suggest that increasing the material layers and applying different materials do reduce the magnitude of overheating since the degree-hours above 26°C are decreasing. This suggests that even though the number of hours temperatures exceed 26°C may remain stable, the temperatures were reduced to a certain degree.

5 CONCLUSIONS

The performance of Rigidur H, a high-density fibreboard, and two PCM boards, the Rigips Alba®balance 23 and Alba®balance 26, was examined in this work in terms of their potential for providing thermal mass to help mitigate overheating issues. In order to enable comparison, the analysis also explored the addition of thermal mass through the use of concrete. Rigidur H is an affordable and easy to handle solution which could be easily mounted in most MMC systems in order to provide additional levels of thermal mass without adding too much weight on the structure. PCM boards are also a widely considered alternative to provide extra levels of thermal mass for little weight addition to the structure and are also suitable for most MMC systems. In this work, the materials were used in the walls and ceilings of the Nottingham HOUSE, a super-insulated prefabricated timber house located at the University Park Campus, University of Nottingham.

The analysis assessed the overheating potential of the Nottingham HOUSE in terms of temperatures exceeding 26°C and 28°C during both the occupied hours and over the whole year. The analysis has shown that the Nottingham HOUSE may suffer from overheating in some areas, with the results of the whole-year analysis presenting higher levels of overheating. The use of additional layer of Rigidur H reduced the percentage of time when the temperature exceeded 26°C and 28°C to a certain degree in most zones. Concrete with the same thickness as the layers of Rigidur H examined was found to be slightly more effective at reducing overheating. However, this should be considered in the context of the mass of the material used. The mass of concrete is 75% higher than the mass of Rigidur H. In addition, Rigidur H boards are much simpler to integrate to a wall than concrete. The PCM boards have in most cases lowered the levels of overheating, with the Alba®balance 26 board being more effective than the Alba®balance 23 board.

The results also demonstrated the ability of thermal mass to reduce the maximum temperatures observed in each zone. Furthermore, a degree-day approach was also used to provide a better insight on the performance of the materials used and provide evidence that the overheating magnitude was reduced even in cases when the number of hours of overheating did not appear to be affected.

Overheating was reduced in most cases but not eliminated completely. Nonetheless, the results of the analysis indicate that the use of Rigidur and, to a greater degree, the PCM boards have potential to regulate the internal temperatures and it is believed

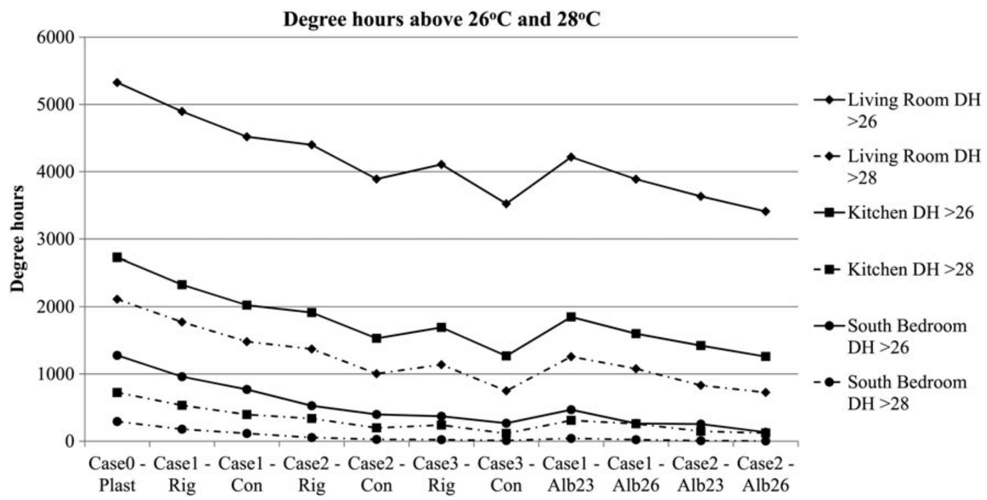

Figure 14. *Degree-hours above 26°C and 28°C.*

that their careful use in combination with other passive technologies is useful to mitigate overheating in highly insulated UK dwellings.

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