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RESEARCH PAPER

General Architecture

Ventilated hollow core slab as a thermal mass strategy and its effect on thermal comfort; (case study: lotion college, England)

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Abstract

Thermal mass is the material's ability to store heat and release it after an amount of time and concrete is considered one of the best thermal mass material. Since concrete has been used widely in many building constructions, by considering the capability of concrete in terms of thermal mass, it is worthwhile to use this ability of concrete in order to build buildings more healthy and comfortable for an increase in the occupants' performance. Ventilated Hollow Core Slab (VHCS) is one of the efficient ways to provide adequate thermal mass within buildings. The present study aimed to assess the thermal performance of VHCS; and its effect on the occupant's thermal comfort of a college building located in Luton, England, using a VHCS system as the exposed thermal mass. Various techniques have been used over two weeks and the recorded data were analyzed. Based on the findings from the review of existing literature in the field and the integrated approach outlined in this paper, results indicate that the application of VHCS as a thermal mass in university buildings decrease not only the daily temperature fluctuation but also the number of times with extreme heat or colds. Results also show the influence of the system on the level of habitants' thermal comfort; though, this influence could be varied hinge on physical and psychological factors.

Keywords: *Ventilated hollow core slab (VHCS); Thermal mass; Thermal comfort; Energy efficiency.*

1. INTRODUCTION

Before introducing mechanical ventilation, cooling and artificial lighting in buildings, several methods were used to change the climate within the buildings. Some of the examples of these methods are the active use of window ventilation, large room volumes or large room heights, the use of thermal mass, and the frame design of window for the maximum use of daylight while minimizing solar gains. During the last few years, several of these techniques have been reintroduced to reduce or eliminate the need for mechanical ventilation and cooling. Moreover, comfort requirements, indoor air quality, and energy efficiency show an increasing trend. Therefore, the previous passive methods need to be improved in modern buildings. Occupants of a well-designed building feel more thermally satisfied when they have control over their thermal environment [1]. The result of having more control and less temperature swing is better health conditions for occupants. Besides, decreased consumption of fuel such as electricity, firewood, and gas can effectively reduce emissions of greenhouse gases, therefore, provide more profits for the environment [2].

Thermal mass is one physical feature that has significant influences on the thermal environment within a building, thus, the thermal comfort of occupants [3]. In this method, the building's surface is used as a thermal energy store. The result is the slow heating of the building in summer when the highest inside temperature is only reached during late hours; when the outside air temperature is already low. Active use of the building mass can significantly increase the total energy saving of the building and keeps the thermal environment within the comfortable range. One of these active strategies is to use Ventilated Hollow Core Slab (VHCS). Ventilated hollow core slab is a precast slab of prestressed concrete, typically used in the construction of multi-story buildings and has tubular voids extending the full length of the slab. In this technique, ventilation air is passed through the hollow

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cores of the floor and ceiling slabs, therefore the airflow will increase the convective heat transfer. This system can be used for heating and cooling buildings [4].

To design buildings more thermally efficient, analysis of thermal comfort can provide useful information. In addition, many problems can arise from an inaccurate analysis of thermal comfort, involving the excessive application of air conditioning and heating units, as well as dissatisfaction with the thermal climate of the building that results in the low performance of the occupants. Many attempts have been made to create a better relationship between indoor climate and performance. However, a large amount of money is lost every year because of the poor indoor climate. For instance, the salaries of office workers are usually higher than the cost of operating a building in developed countries [5]. As a result, even small improvements in human performance, which can partly be achieved by improvements in indoor environmental quality, can result in a considerable financial benefit even greater than a decrease in the energy bill.

Though there are several studies in the field of indoor thermal environment, most of them focused more on variables such as geographical climate, building orientation, material use, and thickness along with their thermal resistance. However, a few studies focused specifically on the performance of the VHCS and its influence on the thermal comfort of an educational building's occupants. Moreover, field investigations with actual occupants in real buildings are rare. This study tries to address the gap assessing the thermal performance of the VHCS; and its effect on the occupant's thermal comfort of a college building located in Luton, England. With a higher understanding of thermal comfort, buildings can be designed more effectively and efficiently [1]. Therefore, this study with an empirical concept could ease the process of designing related studies while actual occupants are involved.

2. LITERATURE REVIEW

Thermal comfort is a psychological state where an individual is satisfied with the body's thermal environment [2,6]. Level of thermal comfort can be affected by social and individual differences of an individual like Personality, culture, and mood. Because of these factors and difficulty in defining thermal comfort, evaluation techniques of thermal comfort are complex [3]. If the surrounding temperature is controlled and maintained constant by proper design, the activity of body organs to normalize the heat would be reduced and the efficiency of physical and mental abilities will increase [7]. Therefore, thermal comfort is described as human mind satisfaction with its surrounding thermal environment [8]. Tahbaz (2013) generalized thermal comfort into physical, physiological, psychological, cognitive, communicative, behavioural, and optional comfort [9].

The building regulations state that the thermal climate should provide acceptable health environments and comfort for the predicted function of the room [10]. Conversely, there is a difference between the comfort level and the highest performance level. Since the comfort level can be changed somewhat by changing the level of clothing or activity. Few, if anyone, would change their clothing to generate higher productivity.

Wyon and Wargocki (2006) studied the influence of temperature on performance. In their research, it has been stated that:

"Room temperature affects the performance by several mechanisms:

Thermal discomfort distracts attention and generates complaints that increase maintenance costs.

Warmth lowers arousal, exacerbates SBS symptoms, and has a negative effect on mental work.

Rapid temperature swings have the same effects on office works as slightly raised room temperatures, while slow temperature swings only cause discomfort" [11].

Various programs such as Smart Schools in the United States of America and The Schools for the Future program in Europe have attempted to provide high-performance learning environments by sustainable site planning and landscaping, good building envelope design, appropriate lighting, and an increased use of daylighting in order to improve student performance and increase comfort levels [12]. Not only do energy-efficient schools reduce the energy use and cost but they also increase thermal and visual comfort and space quality as well as help preserve non-renewable energy recourses [13].

Results from 24 different studies by Seppänen et al. on 21 office buildings and 3 school buildings confirm the growths in performance when temperatures are around 21-22 °C, and drops when temperatures arise more than 23-24 °C. Highest productivity is discovered to be at temperatures around 22 °C [5]. Figure1 shows the relation between standard performance and temperature, based on reports from all of Seppänen's studies (Fig.1).

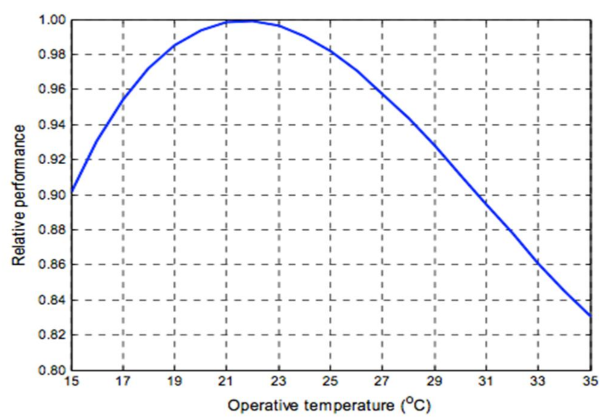


Fig. 1 Normalized performance vs. temperature for typical office work (5)

In former studies, the thermal mass has been described as an effective way of maintaining a stable temperature to provide a thermally comfortable environment for occupants. The scientific definition of thermal mass is solid elements that are used in the construction of buildings; it can absorb energies that are generating from the sun or other sources, store it, and then discharge this energy as heat [14]. The thermal mass of materials is a source of energy conservation and dissipation in buildings [15]. While heat is generating, the temperature peaks can be minimised by the thermal mass. Thermal mass can also moderate or relocate these peaks to a time that is later than the temperature peaks of the outside air [16].

Moreover, thermal mass might have a positive influence on thermal comfort. Primarily, because of the reducing temperature' s swings and the sustainment of a steadier thermal environment provided by the utilization of the high degree of thermal mass [17]; Furthermore, in winter, the air temperature can be lower than the surface temperatures. Lower air temperature will not only reduce heat loss but also improve the perceived indoor air quality [18]. For instance, during the summer, the thermal mass could store heat radiated during the day and gradually release the heat during the night which can then be removed through ventilation when the outdoor temperature is lower. Consequently, air temperature fluctuations for most hours during the day would remain within the comfort range. In winter, because of the similar reason, the stored heat is released into the room during late evening hours, this means the heating of the surroundings when it is needed and avoiding overheating and discomfort conditions during the high solar radiation periods of the day. Therefore, thermal mass produces a positive effect on occupant comfort. Additionally, thermal mass through radiant exchange with the skin has an impact on comfort. As thermal exchanges of the body through radiation represent 62% of the total thermal exchange (convection, conduction, and evaporation) [19], the radiant temperature in one specific point in a room depending on enclosing surface temperatures and the position of this point has the same value as the indoor air temperature.

Concrete has been introduced as a common material to use as thermal mass [20]. One efficient way to provide adequate thermal mass within a building is to use Ventilated Hollow Core Concrete Slab (VHCS). VHCS is a pre-stressed concrete plate with a tubular void stretched along the full length of the concrete slab (Fig.2). This special feature reduces the weight of the structure, therefore reduces the cost of the material; since less concrete is used to produce such a slab. One of the most advanced thermal building slab systems is the patented FES-slab (known by the trade name 'TermoDeck' in the United Kingdom). This slab was first used during the late 1970s in Sweden [21]. The hollow core of the slab is used for ventilation, so the ventilated air is pushed through the core tubes (Fig.3) [22]. The high thermal mass of the hollow core structured buildings allows these buildings to be cooled down, heated and ventilated. This occurs when warmed or cooled fresh air circulates through the slabs [23].

Fig. 2 Hollow Core Concrete Slab (https://oldcastleprecast.com).

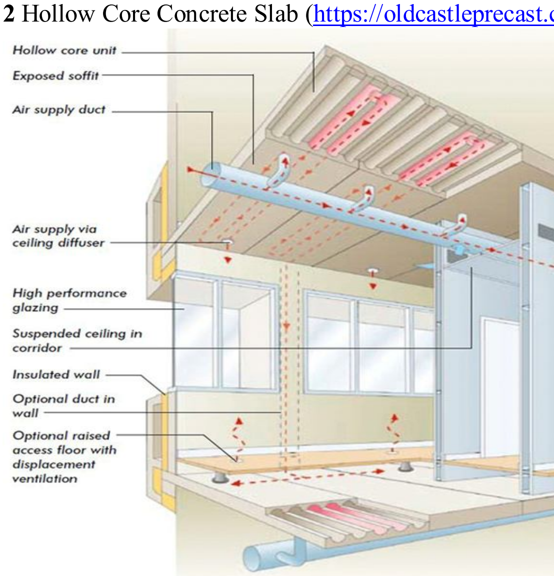


Fig. 3 The ventilated hollow core slab (VHCS) system (http://mesbuildingsolutions.co.uk).

The thermal mass of the ceiling and floor slabs and their large surface acts as energy storage in the VHCS system. The temperature inside the slab remains pretty constant during the change of the environmental conditions. When the winter/summer season changes, the thermal mass of the building stores heat/cold relatively and thermal comfort is achieved [24]. For example, during the summer nights cool air travelling through the slab cools it down and the slab becomes a cool store. Therefore, when the day comes, cool air is released inside the building, which helps to maintain comfortable thermal conditions and save energy consumption (Fig.4). During the hot summer days, warm air passes through the thermal mass of the slab, as it passes with a low-velocity rate, it cools down. Another function of the thermal mass of the slab is to absorb the heat produced by electric appliances and occupants (Fig.5). During the winter, highly insulated building skin stores the heat. Thermal mass absorbs the heat recovered from the extract air and releases it into the room. The exposed ceiling also acts as a low-temperature radiant heating system (Fig.6) [22]. Usually, during the night, all the heating systems inside the building are switched off, so the only source of heating that allows thermal comfort to be retained is the heat from the building envelope mass gradually being released inside.

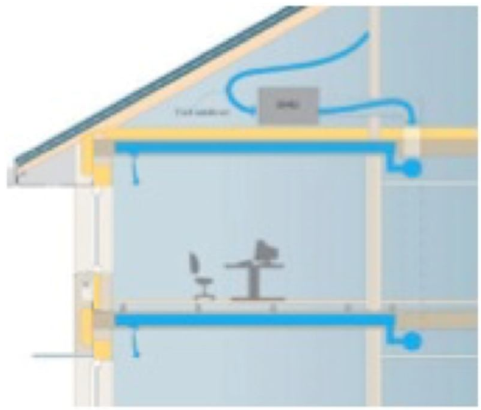


Fig. 4 VHCS system during the summer night, (https://www.termodeck.com).

Fig. 5 VHCS system during the summer day, (https://www.termodeck.com).

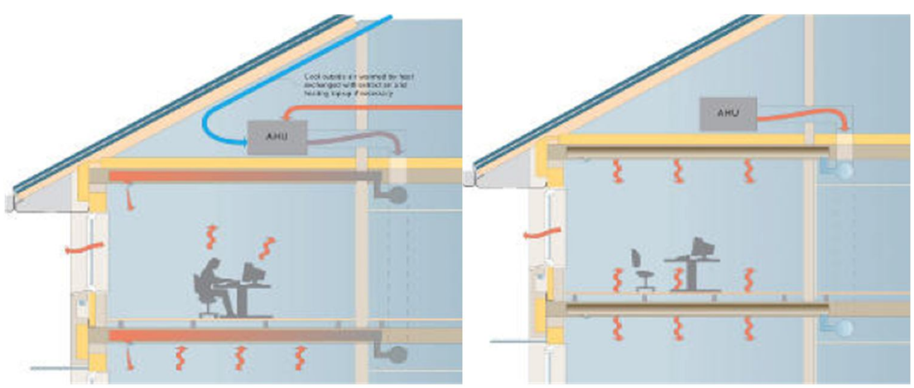


Fig. 6 VHCS system during the day and night in winter, (https://www.termodeck.com).

Kammerud et al. (1984) revealed that during the summer the highest indoor air temperature effectively reduces by coupling the thermal mass with the night ventilation [25]. Shaviv (1989) highlighted that proper use of passive cooling systems can provide spaces with more temperatures within the comfort level. Givoni (1983) studied the performance of a building with high thermal mass and night ventilation. The outdoor air temperature was varied from 19°C to 34°C. He compared the results to an unventilated building. The results showed a reduction of 2.5°C (28.5 C to 26 C) in maximum air temperature measured in the room. Indeed, nightly ventilation pushes the building thermal mass to act as a heat sink and reduce the cooling load during the daytime [27]. The study by Corgnati and Kindinis (2007) accentuate that night ventilation along with activation of thermal mass might lower the average operative temperature and escalate the level of the thermal comfort [24].

To make a building act efficient and maintain thermal comfort inside there has to be a compromise with some features like having a high thermal mass envelope with low U-values, windows with a low infiltration rate and floor /roof slabs being exposed to the room [28]. To predict the thermal comfort of occupants two well-known organizations called the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and the International Organization for Standardization (ISO) have set standards by evaluation of personal and environmental factors. Both models are the continuation of research undertaken by Fanger. He has analyzed the thermal comfort of college students in the 1970s [29]. This study led to the development of a range of thermal comfort standards. Fanger tried to simplify the assessment of thermal discomfort as the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) by establishing an equation to analyze the thermal comfort [29]. Nicol and Humphreys (2007) note that controversy to the Fanger's work, standards based on studies in a real setting can cause excessive use of active heating or cooling systems [30]. ASHRAE Standard 55 was created for the Heating Ventilation and Air Conditioning (HVAC) industry in designing and operating ventilation and air conditioning systems. The standard recommends both a winter indoor temperature and a summer indoor temperature and allows for a buffer zone around each of these temperatures. Humphreys criticizes this standard from different perspectives. It means that thermal comfort zones are constant according to both time and location, which is incorrect as thermal comfort temperatures fluctuate according to geographic location and throughout time; and it applies uniform classifications of 'summer' and 'winter' to all geographic regions. However, these seasons are clearly different with changes in latitude, distance from the ocean, and other geographic variations [1].

There are different ways that levels of thermal comfort can be defined in studies using the adaptive approach. Baker and Standeven [31] defined adaptive opportunity as the ability of the occupants to adapt to their environment thermal condition. That means the occupants of a building should have the opportunity to make themselves comfortable. To determine a range in which an individual is comfortable, thermal neutrality and preferred temperatures can be used; thermal neutrality is defined as an experience when an individual feels neither warm nor cool. Likewise, the preferred temperature is the temperature range within which an individual will identify as being comfortable [14]. It is difficult to set a boundary between comfort and discomfort. This is because there is no temperature at which all people will be comfortable. Therefore, it is recommended to consider thermal comfort as a zone rather than a specific temperature. The conventional temperatures for offices in the temperate climate of the UK were set between 13°C and 30°C. this range depends on levels of physical activity. Nicol defined that if there are levels of thermal discomfort, it is due to the difference between the inside air temperature of the buildings and the comfort temperature which he calculated according to the running mean of outdoor temperature [17].

3. METHODOLOGY

As the subject focuses on the operation of Hollow Core Slab as a thermal mass in further and higher education buildings, one college was selected as a case study. The case study has been surveyed over ten days gathering quantitative and qualitative data to allow the analysis of the subject regarding the thermal environment. Qualitative data were obtained by interviewing the occupants at the beginning of the study. The Building Use Studies (BUS) questionnaire, a collection of information about the background, activities, adaptation behaviour, level of comfort according to the buildings thermal performance, amongst other variables, has been distributed amongst twenty occupants (Appendix2). Analysis of these data delivered appropriate information in terms of thermal comfort, which is described in the paper.

In terms of quantitative data, iButtons(temperature data loggers (Fig.7) was used. Placing a couple of the iButtons in different places inside the building and one of the loggers outside, generated valuable information of hourly indoor and outdoor air temperatures. Additionally, to record the temperature of the hollow core slab iButtons are placed at the ceilings. Data generated during ten days in July has been used to produce several graphs, which indorsed the evaluation of the thermal performance of the building.

Fig. 7 IButtons (https://www.embeddeddatasystems.com)

3.1. Analysis considerations

The accuracy of the iButtons used in the case study has an accuracy of +- 0.5^{o}C.

Thermal Comfort Zone (TCZ) is considered between 22^{o}C and 26^{o}C.

4. GENERAL INFORMATION; LUTON SIXTH FORM COLLEGE

Luton Sixth Form College building sits on the north part of Luton, Bedfordshire, UK, (Fig. 8). Luton has a temperate marine climate with the average annual precipitation around 27 inches. The average maximum dry bulb temperature is 21.4oC and the average minimum dry bulb temperature is recorded at 0.7oC. The eco-tech software is used to produce several pictures giving an overview of the Luton climate. Since there is no weather data of Luton in this software the weather data for Gatwick, which is approximately similar to the Luton climate, is used (Fig. 9-10).

Fig. 8 Luton sixth form collage; (Source: Authors)

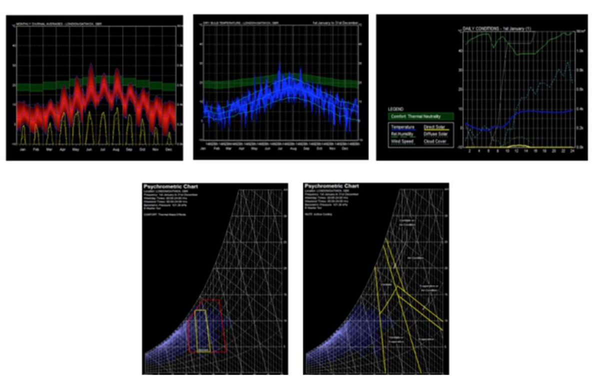


Fig. 9 General climate analysis- eco tech software; (Source: Authors)

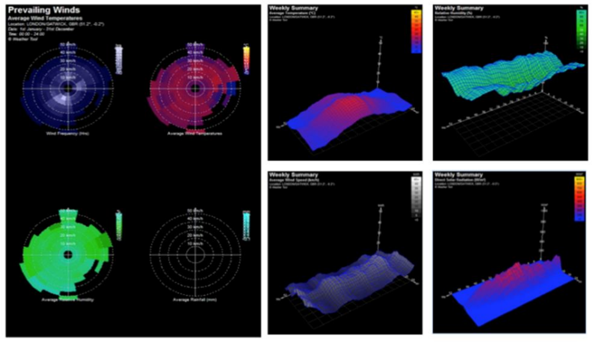


Fig. 10 General climate analysis- eco tech software; (Source: Authors)

In this study, eight classrooms and two offices within the educational blocks of the building with different orientation were studied (south-facing and north-facing). The rooms were selected wisely in order for the study to be able to compare the effect of the orientation in the thermal environment within the rooms. Figure (11) shows the plans of the building and position of the selected rooms in each block. Green areas are the educational blocks using VHCS and the red boxes are the placement of the rooms that were investigated.

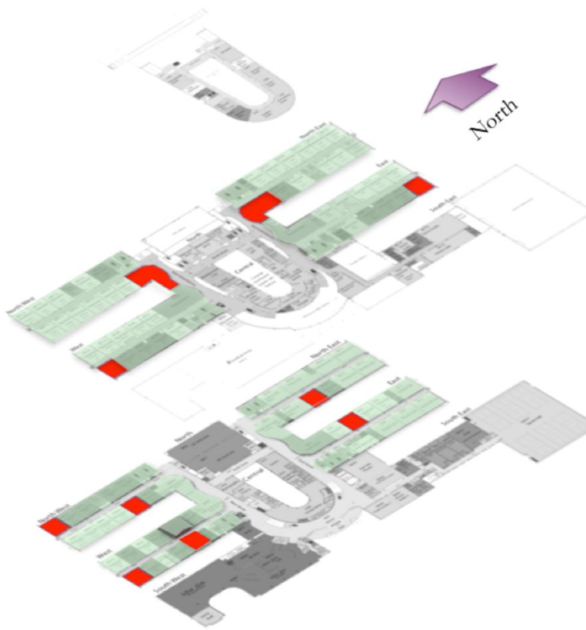


Fig. 11 General plans of the luton sixth form collage; (Source: Authors).

To monitor the temperature, iButtons (temperature data loggers) were used. They have an accuracy of +- 0.5oC and record temperatures between -40°C and +85°C. Measurements were taken at 30-minute intervals (throughout the day and night) and ran for two weeks from June 22th, 2012 to July 2th, 2012. A Blue dot receptor is used to download the temperature recorded by iButtons and transfers the data to the computer (Fig.12). The data was transferred to Excel software, and graphs were created, which have been analyzed. To measure the inside air temperature, the iButtons were placed in the selected rooms in order to be out of direct sunlight and noticeable air currents. To minimize the interference with the occupants, where possible, iButtons were placed out of the vision of the occupants. Moreover, slab temperatures were recorded by attaching the iButtons to the ceiling. This allows the comparison of the slab temperature with the inside air temperature. Placing one iButton outside the building in a sheltered position enabled the comparison of the inside and outside data and in order to examine the effectiveness of the VHCS on the thermal environment. Figure 13 and Figure 14 illustrate the placement of the iButtons in different rooms (Fig. 13-14).

Fig. 12 Blue dote receptor

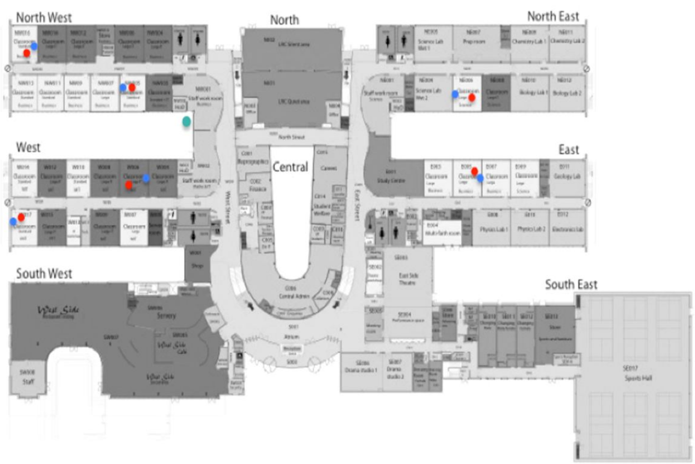


Fig. 13 Ground floor plan, placement of the iButtons; (Source: Authors).

Fig. 14 First floor plan, placement of the iButtons. (Source: Authors).

- iButton measuring the slab temperature.
- iButton measuring the ambient indoor temperature.
- iButton measuring the ambient outdoor temperature.

Figures (15-16) are the keymaps that name each room with an alphabetical symbol. Room A and B are offices and the rest are classrooms.

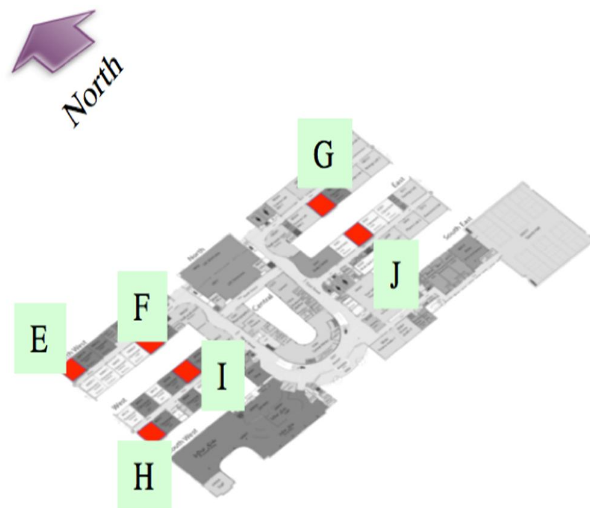


Fig. 15 Key map of the building, showing the monitored room in the ground floor; (Source: Authors).

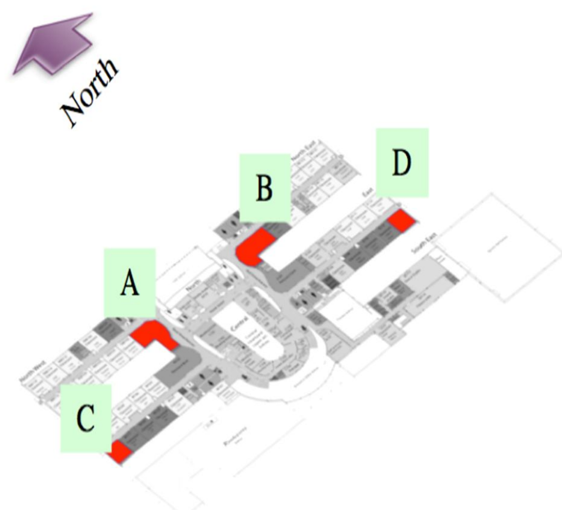


Fig. 16 Key map of the building, showing the monitored room in the first floor; (Source: Authors).

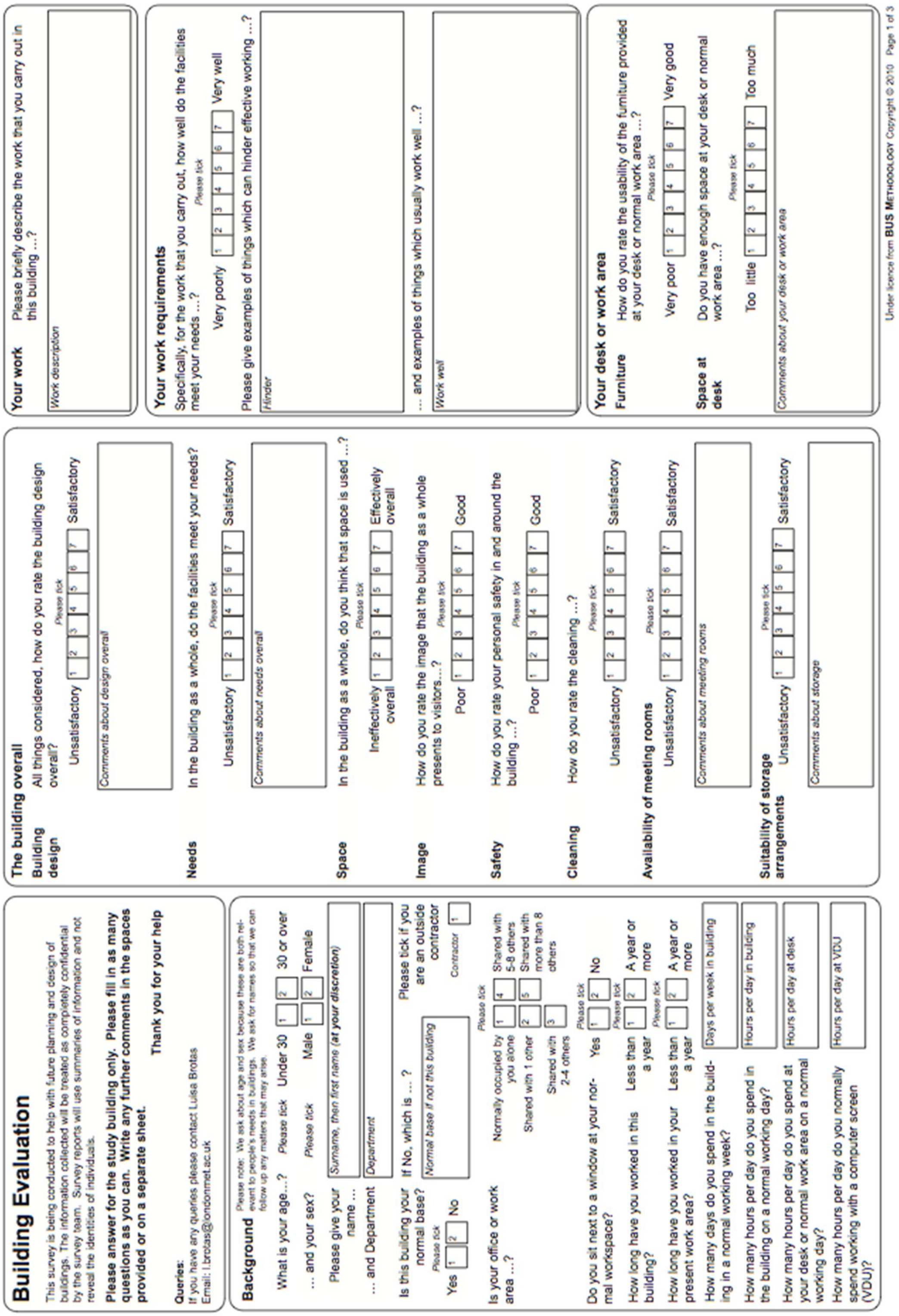
To investigate the comfort level of the occupants conceived by the building, a number of the occupants have been interviewed. Moreover, their general idea regarding the overall comfort concerning the temperature was recorded. Furthermore, the numbers of the Building Use Studies (BUS) questionnaire was distributed amongst the occupants (Appendix1). The BUS questionnaire contains a range of quantitative and qualitative data. The survey data gathered from the BUS questionnaires were typed into pre-formatted Excel data files. This file has been sent to the BUS Company to be analyzed. From those who have answered the questionnaire 85% are over thirty years old and 55% of the participants are male.

List of Abbreviations:

Appendix1: List of Abbreviation

- Ventilated Hollow Core Slab (VHCS)
- The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)
- The International Organization for Standardization (ISO)
- Predicted Mean Vote (PMV)
- Predicted Percentage Dissatisfied (PPD)
- Heating Ventilation and Air Conditioning (HVAC)
- The Building Use Studies (BUS)

Thermal Comfort Zone (TCZ)



Building Evaluation

This survey is being conducted to help with future planning and design of buildings. The information collected will be treated as completely confidential by the survey team. Survey reports will use summaries of information and not reveal the identities of individuals.

Please answer for the study building only. Please fill in as many questions as you can. Write any further comments in the spaces provided or on a separate sheet.

Thank you for your help

Queries:
If you have any queries please contact Luisa Brotas
Email: l.brotas@londonmet.ac.uk

Background Please note: We ask about age and sex because these are both relevant to people's needs in buildings. We ask for names so that we can follow up any matters that may arise.

What is your age...? *Please tick* Under 30 [1] [2] 30 or over

... and your sex? *Please tick* Male [1] [2] Female

Please give your name ... *Surname, then first name (**at your discretion**)*

... and Department *Department*

Is this building your normal base? *Please tick* Yes [1] [2] No

If No, which is ... ? *Normal base if not this building*

Please tick if you are an outside contractor *Contractor* [1]

Is your office or work area ...? *Please tick* Normally occupied by you alone [1]; Shared with 1 other [2]; Shared with 2-4 others [3]; Shared with 5-8 others [4]; Shared with more than 8 others [5]

Do you sit next to a window at your normal workspace? *Please tick* Yes [1] [2] No

How long have you worked in this building? *Please tick* Less than a year [1] [2] A year or more

How long have you worked in your present work area? *Please tick* Less than a year [1] [2] A year or more

How many days do you spend in the building in a normal working week? *Days per week in building*

How many hours per day do you spend in the building on a normal working day? *Hours per day in building*

How many hours per day do you spend at your desk or normal work area on a normal working day? *Hours per day at desk*

How many hours per day do you normally spend working with a computer screen (VDU)? *Hours per day at VDU*

The building overall

Building design All things considered, how do you rate the building design overall? *Please tick* Unsatisfactory [1] [2] [3] [4] [5] [6] [7] Satisfactory

Comments about design overall

Needs In the building as a whole, do the facilities meet your needs? *Please tick* Unsatisfactory [1] [2] [3] [4] [5] [6] [7] Satisfactory

Comments about needs overall

Space In the building as a whole, do you think that space is used ...? *Please tick* Ineffectively overall [1] [2] [3] [4] [5] [6] [7] Effectively overall

Image How do you rate the image that the building as a whole presents to visitors...? *Please tick* Poor [1] [2] [3] [4] [5] [6] [7] Good

Safety How do you rate your personal safety in and around the building ...? *Please tick* Poor [1] [2] [3] [4] [5] [6] [7] Good

Cleaning How do you rate the cleaning ...? *Please tick* Unsatisfactory [1] [2] [3] [4] [5] [6] [7] Satisfactory

Availability of meeting rooms *Please tick* Unsatisfactory [1] [2] [3] [4] [5] [6] [7] Satisfactory

Comments about meeting rooms

Suitability of storage arrangements *Please tick* Unsatisfactory [1] [2] [3] [4] [5] [6] [7] Satisfactory

Comments about storage

Your work Please briefly describe the work that you carry out in this building ...?

Work description

Your work requirements

Specifically, for the work that you carry out, how well do the facilities meet your needs ...? *Please tick* Very poorly [1] [2] [3] [4] [5] [6] [7] Very well

Please give examples of things which can hinder effective working ...?

Hinder

... and examples of things which usually work well ...?

Work well

Your desk or work area

Furniture How do you rate the usability of the furniture provided at your desk or normal work area ...? *Please tick* Very poor [1] [2] [3] [4] [5] [6] [7] Very good

Space at desk Do you have enough space at your desk or normal work area ...? *Please tick* Too little [1] [2] [3] [4] [5] [6] [7] Too much

Comments about your desk or work area

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Comfort This section asks how comfortable you find the building in both winter and summer.

How would you describe typical working conditions in your normal work area in WINTER? If you have not worked here in winter then please leave these questions blank and just complete the questions on Temperature in Summer.

Temperature in winter *Please tick your rating on each scale*

Uncomfortable	1	2	3	4	5	6	7	Comfortable
Too hot	1	2	3	4	5	6	7	Too cold
Stable	1	2	3	4	5	6	7	Varies during the day

Air in winter

Still	1	2	3	4	5	6	7	Draughty
Dry	1	2	3	4	5	6	7	Humid
Fresh	1	2	3	4	5	6	7	Stuffy
Odourless	1	2	3	4	5	6	7	Smelly

Conditions in winter

Unsatisfactory overall	1	2	3	4	5	6	7	Satisfactory overall

How would you describe typical working conditions in your normal work area in SUMMER? If you have not worked here in summer then please leave these questions blank and just complete the questions on Temperature in Winter.

Temperature in summer *Please tick your rating on each scale*

Uncomfortable	1	2	3	4	5	6	7	Comfortable
Too hot	1	2	3	4	5	6	7	Too cold
Stable	1	2	3	4	5	6	7	Varies during the day

Air in summer

Still	1	2	3	4	5	6	7	Draughty
Dry	1	2	3	4	5	6	7	Humid
Fresh	1	2	3	4	5	6	7	Stuffy
Odourless	1	2	3	4	5	6	7	Smelly

Conditions in summer

Unsatisfactory overall	1	2	3	4	5	6	7	Satisfactory overall

Noise How would you describe noise in your normal work area? *This question refers to conditions all year round*

Please tick your rating on each scale

Noise overall	Unsatisfactory	1	2	3	4	5	6	7	Satisfactory
Noise from colleagues	Too little	1	2	3	4	5	6	7	Too much
Noise from other people	Too little	1	2	3	4	5	6	7	Too much
Other noise from inside	Too little	1	2	3	4	5	6	7	Too much
Noise from outside	Too little	1	2	3	4	5	6	7	Too much

Please estimate how you are affected by unwanted interruptions ...

Unwanted interruptions	Not at all	1	2	3	4	5	6	7	Very frequently

Comments about noise and its sources

Lighting How would you describe the quality of the lighting in your normal work area? *This question refers to conditions all year round*

Please tick your rating on each scale

Lighting overall	Unsatisfactory	1	2	3	4	5	6	7	Satisfactory
Natural light	Too little	1	2	3	4	5	6	7	Too much
Glare from sun and sky	None	1	2	3	4	5	6	7	Too much
Artificial light	Too little	1	2	3	4	5	6	7	Too much
Glare from lights	None	1	2	3	4	5	6	7	Too much

Comments about lighting conditions

Overall comfort All things considered, how do you rate the overall comfort of the building environment? *Please tick*

Unsatisfactory	1	2	3	4	5	6	7	Satisfactory

Comments about comfort

Productivity at work *Please try to evaluate this building with respect to your experience of using buildings in general.*

Please estimate how you think your productivity at work is decreased or increased by the environmental conditions in the building?

Please tick one point on the scale

Productivity Decreased by ...	- 40% or less	-30%	-20%	-10%	0	+10%	+20%	+30%	+40% or more	Productivity Increased by ...
	1	2	3	4	5	6	7	8	9	

Comments about productivity

Health Do you feel less or more healthy when you are in the building? *Please try to evaluate this building with respect to your experience of using buildings in general.* *Please tick*

Less healthy	1	2	3	4	5	6	7	More healthy

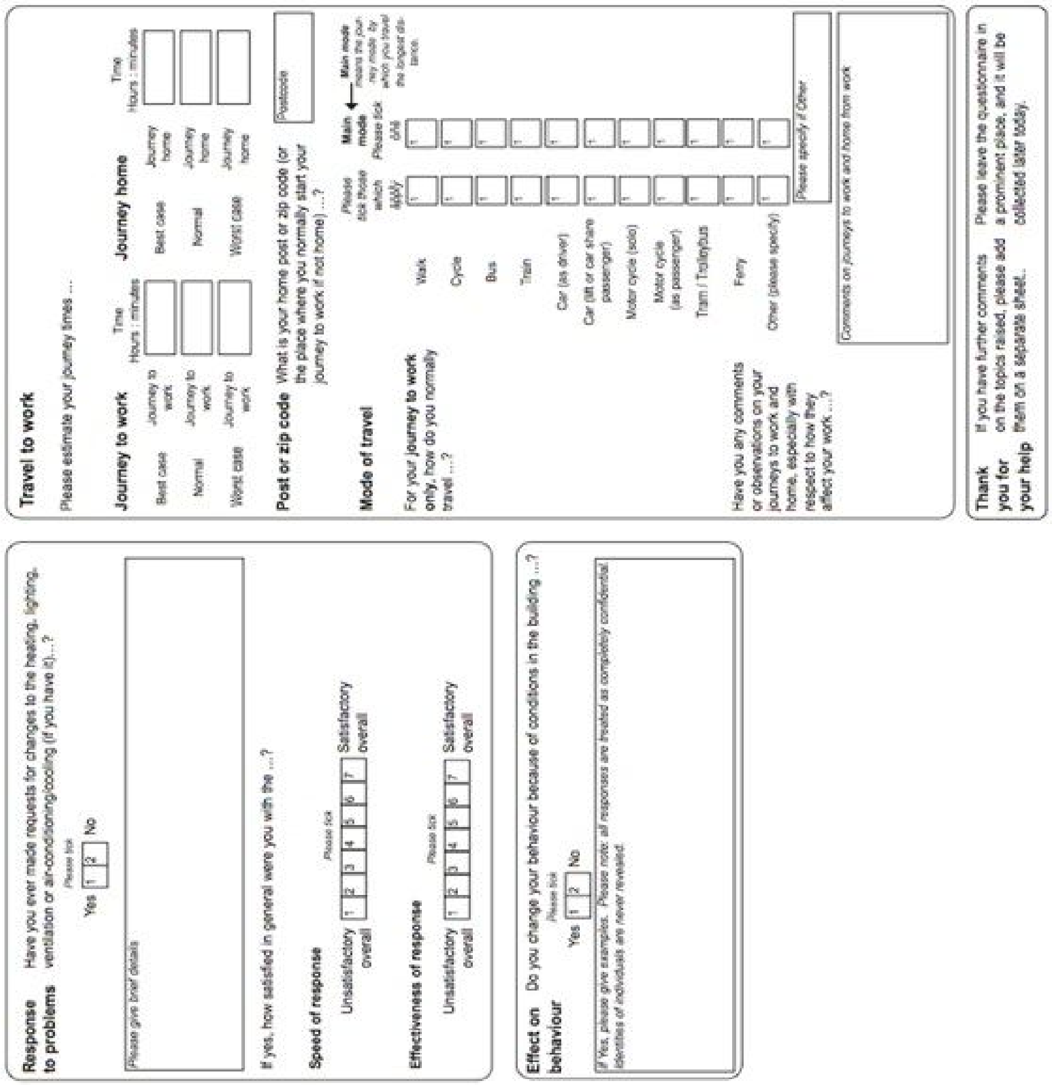
Comments about health

Personal control How much control do you personally have over the following aspects of your working environment...? *Please tick each scale*

										Importance of control *Please tick if important to you*
Heating	No control	1	2	3	4	5	6	7	Full control	1
Cooling	No control	1	2	3	4	5	6	7	Full control	1
Ventilation	No control	1	2	3	4	5	6	7	Full control	1
Lighting	No control	1	2	3	4	5	6	7	Full control	1
Noise	No control	1	2	3	4	5	6	7	Full control	1

Details of method: www.usablebuildings.co.uk/WebGuideOSM/index.html

 Page 2 of 3



Response to problems Have you ever made requests for changes to the heating, lighting, ventilation or air-conditioning/cooling (if you have it)...?

Please tick

Yes 1 2 No

Please give brief details

If yes, how satisfied in general were you with the ...?

Speed of response Please tick

Unsatisfactory overall 1 2 3 4 5 6 7 Satisfactory overall

Effectiveness of response Please tick

Unsatisfactory overall 1 2 3 4 5 6 7 Satisfactory overall

Effect on behaviour Do you change your behaviour because of conditions in the building ...?

Please tick

Yes 1 2 No

If Yes, please give examples. Please note: all responses are treated as completely confidential. Identities of individuals are never revealed.

Travel to work

Please estimate your journey times ...

Journey to work Time Hours : minutes

Best case Journey to work

Normal Journey to work

Worst case Journey to work

Journey home Time Hours : minutes

Best case Journey home

Normal Journey home

Worst case Journey home

Post or zip code What is your home post or zip code (or the place where you normally start your journey to work if not home) ...? Postcode

Mode of travel

For your journey to work only, how do you normally travel ...?

Please tick those which apply / Main mode Please tick one

Walk

Cycle

Bus

Train

Car (as driver)

Car (lift or car share passenger)

Motor cycle (solo)

Motor cycle (as passenger)

Tram / Trolleybus

Ferry

Other (please specify)

Please specify if Other

Main mode means the journey mode by which you travel the longest distance.

Have you any comments or observations on your journeys to work and home, especially with respect to how they affect your work ...?

Comments on journeys to work and home from work

Thank you for your help If you have further comments on the topics raised, please add them on a separate sheet. Please leave the questionnaire in a prominent place, and it will be collected later today.

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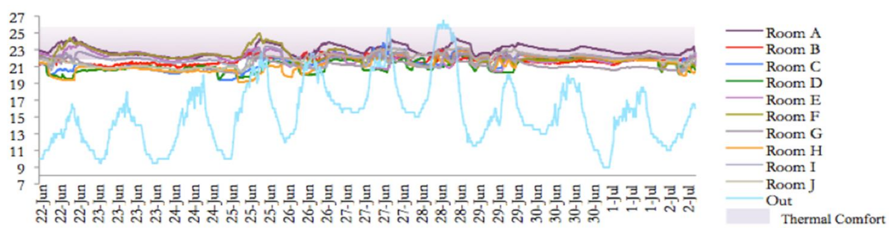
5. RESULTS AND DISCUSSION

5.1. Thermal monitoring, observations, and results

Graphs and tables in the following lines present some of the results obtained in the entire research. Graph 1 highlights the inside air temperature of all spaces with respect to the outside temperature in order to give a general overview of the thermal environment within the building. As can be seen from the graph, although the monitored outside air temperature is fluctuating between the ranges of minimum 9oC and maximum 26o C, inside air temperature of the rooms remained pretty constant with a maximum rise of 24oC in room F and minimum drop of 19 in room H. The highest and lowest outside air temperature occurred in June 28th and July 1st, respectively (Graph1).



Graph 1 General result of the recorded ambient temperatures during the June 22th to July 2th 2012 (Luton Sixth Form Collage); (Source: Authors).

Over the recorded period, during the first week, the slab temperature in room F was higher than room I. As a result, the indoor temperature of room F was warmer. However, from the 29th the slab temperatures for both rooms reached the same level and remained fairly constant in the next following days. During the last three days, the indoor temperature for the room I was slightly higher than room F. This might be either because of the accuracy of the equipment (+- 0.5 oC) or due to the height of the obstructions in front of both rooms. There is a block with a one-floor height obstructing room I, while the obstruction for room F has a two-floor height (Fig.16). The latter may obstruct more solar gains; hence the temperature of the room is lower. The temperatures remain fairly constant as a result of the high thermal mass of the space (Graph 2).

Graph 2 Comparative temperature results room F and room I during 29th, 30th Juneand1th July 2012 (Luton Sixth Form Collage); (Source: Authors).

Table (1) illustrates the results of the monitored temperature in rooms F and I. Results show that compared to the outside temperature, the indoor-recorded temperatures are relatively stable. The average temperatures inside the rooms are similar. Both rooms approximately 50 per cent of the time remained within the thermally comfortable temperature. The ambient temperature inside the room I is more varying than room F with an amplitude of 5oC. Average slab temperatures are very similar and changing over time within the small range.

Table 1 General results of the comparing classroom F and classroom I; (Source: Authors).

July 22th 2012 to June 2th 2012	Classroom F	Classroom I
Ave. Ambient Outside Temp. °C	15.5	
Ambient Outside Temp. Range °C	9 to 26.5	
Time Ambient Outside Temp. within TCZ, as %	6	
Ave. Internal Room Temp. °C	22	22
Internal Temperature Range °C	20.5 to 22	20 to 25
Time Internal Temp. within TCZ, as % Internal Temperature Range °C	48.5	47
Ave. Slab Temp. °C	20.5	21
Slab Temperature Range °C	20 to 22	20 to 23

The results of the recorded temperature in rooms A and B in the building are presented in Table 2. Comparing the indoor and outdoor temperatures, it would reveal that indoor temperatures are considered stable, although the temperature outside the building is fluctuating. The average indoor temperature is similar in rooms A and B. Also, the recorded temperatures are in the same range. The temperature variation during the weekdays is mainly due to the internal gains. Both rooms more than 70 per cent of the time are within the TCZ. The average slab temperatures are very similar and change over time within the small range around 2oC. The average slab temperatures of these rooms are higher than other rooms upon measurement. It can be assumed that when the slab temperature is higher, the indoor temperature is more likely in the comfort zone.

Table 2 General results of the comparing classroom A and classroom B; (Source: Authors).

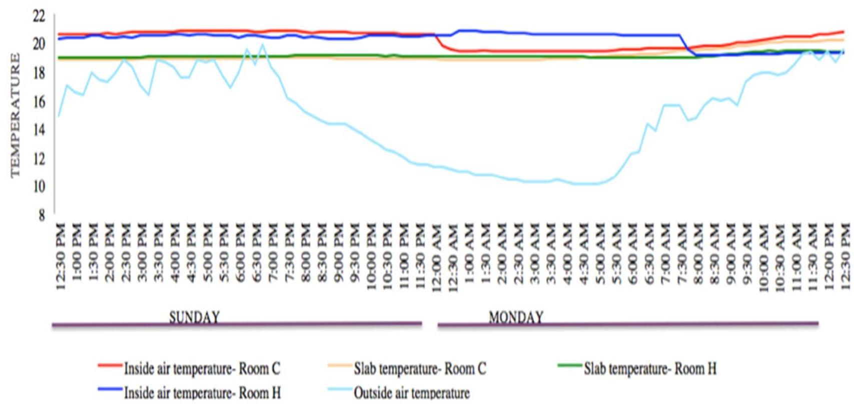
July 22th 2012 to June 2th 2012	Classroom A	Classroom B
Ave. Ambient Outside Temp. °C	15.5	
Ambient Outside Temp. Range °C	9 to 26.5	
Time Ambient Outside Temp. within TCZ, as %	8.8	
Ave. Internal Room Temp. °C	22.5	22.5
Internal Temperature Range °C	20 to 24.5	21 to 23.5
Time Internal Temp. within TCZ, as % Internal Temperature Range °C	72	74
Ave. Slab Temp. °C	22	21.5
Slab Temperature Range °C	20.5 to 23	21 to 22.5

General results from the comparison of classroom C and classroom H are shown in Table 3. The recorded temperatures show that the outside temperature fluctuates widely and only 6 per cent of the time remains within the TCZ. However, indoor temperatures are considered stable. The average inside temperature of room C that is located in the first floor is half a degree higher than room H, but taking into account the accuracy of the equipment, 0.5oC is not relevant in the measurement. Room C and H are 25 per cent of the time within the TCZ (22oC to 26oC) and for the rest of the time, the rooms are overcooling. Slab temperatures for both rooms most of the time remain at the same value.

Table 3 General results of the comparing classroom C and classroom H; (Source: Authors).

July 22th 2012 to June 2th 2012	Classroom C First floor	Classroom H Ground floor
Ave. Ambient Outside Temp. °C	15.5	
Ambient Outside Temp. Range °C	9 to 26.5	
Time Ambient Outside Temp. within TCZ, as %	6	
Ave. Internal Room Temp. °C	21.5	21
Internal Temperature Range °C	19.5 to 24	19 to 23
Time Internal Temp. within TCZ, as % Internal Temperature Range °C	26	24
Ave. Slab Temp. °C	20	20
Slab Temperature Range °C	19 to 22	19 to 21.5

Graph 3 displays the thermal performance of classroom C and H during two days of the recorded data in June 24th and 25th, though the outdoor temperature is fluctuating, the indoor temperatures are fairly constant. In this period the difference between the indoor temperature and Slab temperature is approximately 2oC. Additionally, this graph shows the earlier drop in the indoor temperature in room C that is located on the first floor. Having more external surfaces compared to room H may have caused this. The drop in the indoor temperature, which is about 1.5 oC, occurred at 23:30 PM for room C; while for room H, the temperature dropped at 7 AM the next day morning. This phenomenon illustrates a greater time lag for room H which was produced by the thermal mass.



Graph 3 Comparative temperature results room C and room H during 24th and 26th June 2012 (Luton Sixth Form Collage); (Source: Authors).

5.2. Thermal comfort investigation

The occupants were questioned regarding their general feeling about the thermal environment within their rooms. The overall outcome of the personal interviews was: the occupants were not generally satisfied with the thermal condition of the building and perceived the building during the summer very cold. Most of the participants complained about the drafts produced by the supply air diffuser on the ceiling. Upon questioning the occupants about the quality of the air and temperature during the summer and winter, results are as follow:

The occupants described the air in the summer considerably dry and draughty still acceptably fresh. The occupants also perceived the temperature during the summer varying reasonably but noticeably cold. The participants found the thermal condition of the building generally uncomfortable and rated the overall air quality in the building unsatisfactory (Fig.17).

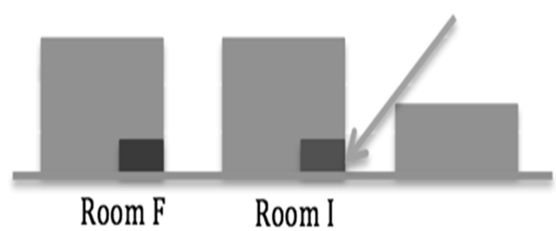


Fig. 17 Schematic sections of the room F and room I; (Source: Authors).

In addition, the occupant perception of the indoor climate during the winter period shows that they found the air within the building draughty. Also, they reported highly variation in temperatures. The results showed that most of the time they felt cold. However, the air is considered neither dry nor humid and reasonably stuffy. In overall both air and temperature are not satisfactory and amongst the hundreds of buildings assessed by the BUS methodology, this college performs relatively poor in terms of the thermal environment during the winter (Fig.18). The response shows that 78 % of the occupants changed their behaviour by adding additional clothing. When questioned about the level of control of overheating, cooling, and ventilation, the answers were completely negative (Fig.19).

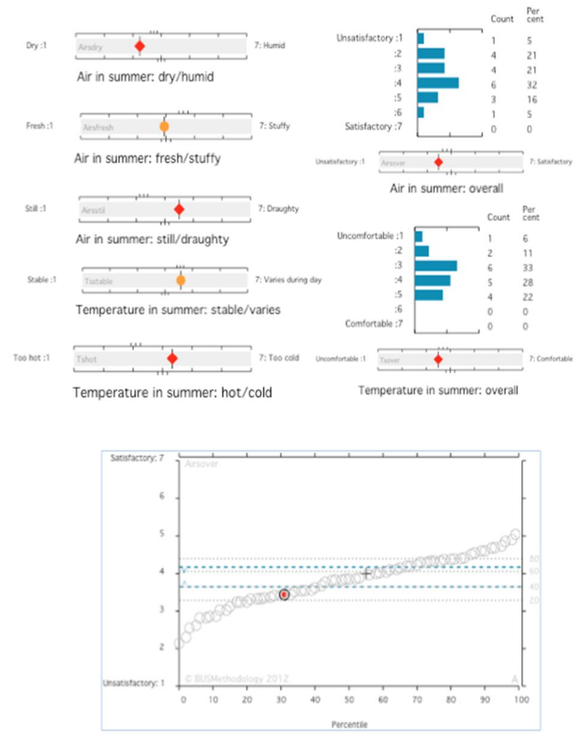


Fig. 18 Perceived overall air conditions in summer; (Source: Authors).

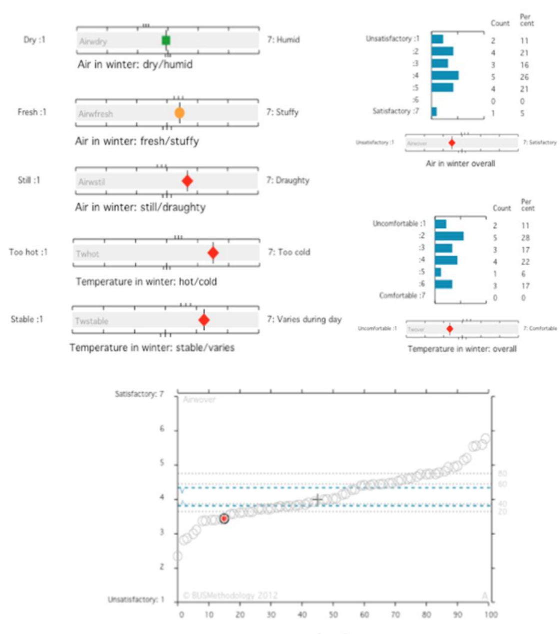


Fig. 19 Perceived overall air-conditions in winter; (Source: Authors).

Analyzing the overall comfort represents the occupants found the building environment generally comfortable. Taking to account all the results, this means although the occupants may have felt unsatisfied to some extent, they still believe this building is better than other buildings. It can be seen that the building is in the normal range compared to hundreds of buildings and around 70% rated it as comfortable (Fig.20).

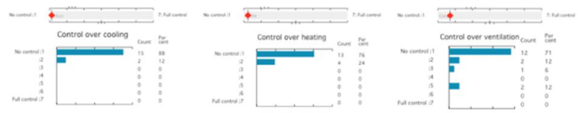


Fig. 20 Control of the occupants over the Cooling, Heating and Ventilation; (Source: Authors).

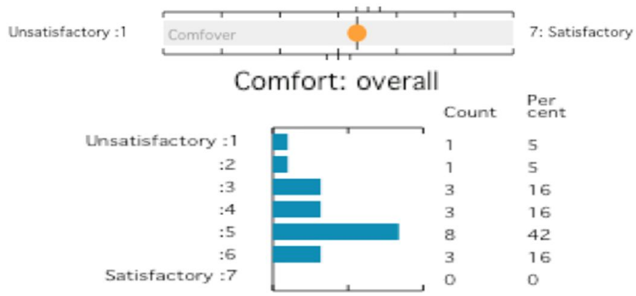


Fig. 21 Perceived overall comfort in the building;(Source: Authors).

5.3. Discussion

Before the studies, numbers of primary measurements were carried out in the Luton Sixth Form College. These approved the effectiveness of the VHCS as the thermal mass by retaining the indoor temperature pretty constant during the variation in environmental conditions. The results are in line with the results of previous studies that focused on this subject [4,7,23-24,32-33]. For instance, Willis and Wilkins (1993), which assessed a ventilated slab system (TermoDeck system) in terms of thermal performance in a section of the BRE Air Conditioning Evaluation (ACE) facility. They concluded that this system offers not only an enhanced alternative to the mechanical ventilation systems but may also match the performance of comfort cooling or conventional air conditioning systems [32]. Furthermore, Shaw et al. (1994) found that ventilated slab systems could considerably control temperatures of the slab surface and maintain the environment within the comfortable range of temperatures [33].

To analyze the comfort level of the occupants, a number of them have been interviewed. 20 of the Building Use Studies (BUS) questionnaires were distributed amongst the occupants. Though this is a very small sample to assess the building performance, some reasons restricted this survey. As this study is conducted during the summer break, the numbers of staff existing in the building were reduced. Besides, it was not allowed to speak with the students. Finally, because of the utilization of the Ventilated Hollow Core Slab only in four of the educational blocks, there were practically only four office rooms available to be surveyed.

The findings indicated that the VHCS could effectively contribute to the thermal perception of the occupants. As the VHCS is a centrally controlled system working with the defined set point, it is not unusual for the occupants to think they do not have enough control over their thermal environment. Referring to (Humphreys, 1995b) lack of control over the environment thermal condition would lead to thermal discomfort [1]. A similar conclusion was reached by Baker and Standeven [31]. They concluded that a higher adaptive opportunity could mean wider ranges of temperatures are possible for occupants in an environment where they can feel comfortable. On the other hand, the diffusers in the ceiling are supplying the air from the top to the rooms; this allows people to feel the draught. Because the air is moving towards crossing them, although the temperature is around 21 – 22 degrees, the occupants perceive the temperature cooler than the actual temperature. This is consistent with what has been found in previous studies [34-35].

There are several possible solutions to increase the comfort level of the occupants. During the summer the challenge is that people are entering the building from the hot outdoor temperature to the VHCS area, which is in the cooling mode, where the set point for the slabs is 21oC; therefore, they will perceive the temperature quite cold. When the body gets used to the temperature, it would reveal that it is not as cold as perceived. As the British Council Offices estimated the thermal comfort temperature between a range of 22oC to 26oC for the mechanical ventilated building this can conclude that potentially by raising the setpoint temperature to 2oC or 3oC the inside temperature can remain within the thermal comfort environment for a longer period of time thus, reducing the effect of the seasonally outside temperature. Another option is using the different types of diffusers to distribute the air to different directions to prevent the drought by blowing the air to the corners rather than downward. Also, it is possible to change the location of the diffusers, for example in the Thomas Pain building the AHU is pumping the air through the slabs and diffuses it inside from the walls.

In General, the results of this study are in line with previous studies that focused on the application of VHCS in buildings and its effect on thermal comfort in different parts of the world [4,7,23-24,33-36]. Thus, it can be concluded that the current study contributes to the knowledge in this field by evaluating the VHCS performance and investigating the thermal comfort of the occupants in the Luton Sixth Form College in England.

6. CONCLUSION

With the aim to investigate the thermal performance of VHCS as thermal mass and its effect on the thermal comfort of the occupants in further and higher education buildings, a college in Luton has been selected as a base case. Through literature reviews, principles, and the development of VHCS in building systems for the levelling the temperature swing inside the building by ventilation air passing the cores, have been explained. From these findings, there are several factors that have a great impact on the efficacy of VHCS, primarily the amount of thermal mass and the type of strategy for ventilation. Moreover, the great role of climate, set-point temperature, occupancy pattern, and ventilation airflow rates should not be forgotten. In site measurements show that due to the uniformity of indoor air temperature, the highest cooling or heating load can be cut down, thereby, resulting in the more satisfaction of the occupants in terms of the thermal environment.

From all of the above mentioned, to provide the maximum comfort, the building and occupants should interact properly. It also should be noted that the occupant's perceptions regarding comfort are largely affected by physical and psychological parameters. Though VHCS can retain the environment within the comfort limits, the building should allow occupants to control their environment. Normally, the occupants do not find the indoor condition satisfactory if they perceive that they do not have much control over it.

As this research is in the category of empirical studies, it should be required to authenticate the results through different seasons and in buildings with other functions. Besides, due to the limited usage of this system, performance evaluations in the actual building systems are also limited. Therefore, more work on VHCS is valuable for further promotional use of these slabs to improve energy efficiency and occupant thermal comfort.

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