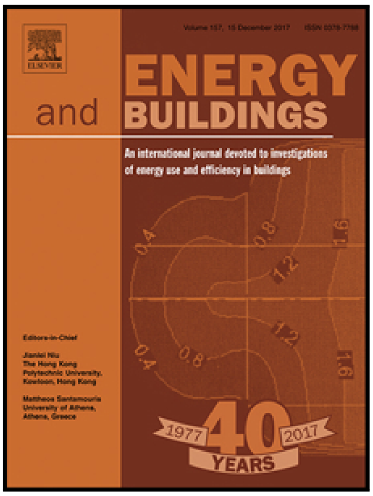
The Rasmaska project: temperature behaviour of three, full scale test cells in hot Mediterranean summer: non-insulated double masonry wall and different insulation locations

Saleh, P., Schiano-Phan, R. and Gleeson, C.P.

NOTICE: this is the authors' version of a work that was accepted for publication in Energy and Buildings. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in Energy and Buildings, DOI: 10.1016/j.enbuild.2018.08.025, 2018.

The final definitive version in Energy and Buildings is available online at:

https://dx.doi.org/10.1016/j.enbuild.2018.08.025



The Rasmaska project: temperature behaviour of three, full scale test cells in hot Mediterranean summer: non-insulated double masonry wall and different insulation locations

Philippe H. Saleh , Rosa Schiano-Phan , Colin Gleeson

PII: S0378-7788(18)31122-8
DOI: https://doi.org/10.1016/j.enbuild.2018.08.025
Reference: ENB 8761

To appear in: *Energy & Buildings*

Received date: 12 April 2018
Revised date: 29 July 2018
Accepted date: 15 August 2018

Please cite this article as: Philippe H. Saleh , Rosa Schiano-Phan , Colin Gleeson , The Rasmaska project: temperature behaviour of three, full scale test cells in hot Mediterranean summer: non-insulated double masonry wall and different insulation locations, *Energy & Buildings* (2018), doi: https://doi.org/10.1016/j.enbuild.2018.08.025

The Rasmaska project: temperature behaviour of three, full scale test cells in hot Mediterranean summer: non-insulated double masonry wall and different insulation locations

1.1 Introduction

Cold climatic zones endeavour to reduce dependency on fossil fuel for winter warmth by recommending or imposing highly insulated construction, which is equivalent to low U-value envelopes. Insulation is being promoted for warm and hot climatic zones as a good material to keep the mechanical coolness inside, and thus reduce the cooling energy loads [1,2]. However, no comprehensive research has identified from the literature to support this claim by investigating the actual temperature performance of un-insulated versus insulated structures in warm or hot climates. Heavyweight construction, the typical choice taken as construction material in many hot climate environments, is usually advised to keep internal temperature lower than outside [3,4,5]. Because of the relatively high conductivity of construction materials such as concrete, construction codes recommend adding variable thickness levels of insulation depending on the exact weather classification [6,7,8,9,10]. While most of studies focus on finding the best location for such insulation layers, the consensus results in promoting an outer location [11,12,13,14] Kiel Moe [15,16] might be among the few voices not convinced by the extensive use of insulation to claim that "*the concept* (of insulation) *has disturbed and disfigured our understanding of energy* [15]". This research is carried out in the coastal climatic zone of Lebanon, on the Easter coast of the Mediterranean, with a **Csa** Koppen-Geiger classification [17] defined as warm temperate with hot summers, no rainfall, and short warm winters [18]. This research recorded and investigated the temperature behaviour of three purpose-built test cells for an entire hot summer season. Each test cell made of double masonry walls had an internal area of 10 sqm where a 25mm layer of expanded polystyrene insulation (XPS) was placed either on the outside, middle, or inside. Observations spanned from late June 2017 to the end of October 2017, and by late August, the middle insulation layer was removed. The aim of the study is to assess double masonry walls with different insulation configurations under the same conditions within a strictly controlled environment, where user-variables such as windows, shutters and lights, occur in all cells simultaneously. The long duration of the monitoring allowed the application of both short-term (three to five days) controlled schedules and to experiment with random changes. The purpose of the former was to test for particular behaviours such as night ventilation, whereas the latter mimicked the randomness of user-variables in actual monitored apartments. In addition, these random schedules with changes in conditions happening simultaneously in all the three test cells allowed for the reduction of biases and errors by calculating an overall temperature performance rank under a wide variety of operating conditions.

Following an overview of previous studies that deal with test cell monitoring and heavyweight construction, the paper describes the process of constructing the three test cells. The internal, external, and internal surface temperatures were recorded on the hour using temperature data loggers. The experiments in all test cells were conducted simultaneously for the same length of time. The effect of different variables on temperature behaviour were studied throughout the period of observation such as the impact of painting the external plastered surface white, different schedules for window and shutter opening and closing, added internal gains from incandescent lamps (operating as heat sources) and the thermal mass storage was also analysed since the construction is heavyweight. After about 10 weeks of observation, the middle insulation of one of the test cells was removed to form an un-insulated test cell which was then compared to outer and inner insulated test cells for another 8 weeks.

The study aims firstly to confirm that outer insulation fares the best in providing the lowest internal temperatures among the three possible locations. Secondly to show that once the middle insulation is removed; the un-insulated cell will perform even better by providing the lowest internal temperatures expressed in terms of degree hours (Dh) of overheating.

1.2 Previous studies

Literature reviews on the dimensions of buildings or test cells for experimentation show a wide range of scales varying from as small as 300mm shoe box dimensions to a full scale of up to 6000mm width x 2500mm internal height. The objectives of the studies also vary from heat flux transfer analysis, to impact on energy load, and temperature output.

Among those studies, few are conducted with parallel comparison to different models. They are commonly based on the temperature difference between inside and outside for one specific model and period, which are later altered and monitored for another period. However, in such cases, confounding factors such as solar radiation and wind are not taken into account, disregarding their major implication on the final outcome.

Scale or size varies from as small as an actual shoe box size with dimension smaller than 1000mm [19,20,21,22], to medium size with dimensions between 1000 to 2000mm [23,24,25,26], and to large scales of more than 2000mm [27,28,29,30,31,32,33]. Most studies include multiple test cells starting by two [22], four [20,21,23,26,27,32] or more [25]. Usually, these go along with simultaneous observations. Some choose random existing structures [33] with different configurations and construction, whereas, others make use of one surface with different alternations [29,30,31,34]. The observations can sometimes be for only short periods [19,21,24,25,26,31,33]. Researchers seldom study both walls and roofs simultaneously [32,33]. The main goal of the studies can vary from heat transfer [23,34] to the impact on energy loads [19], but the larger part investigates temperature: inside/ambient temperature [22,25,26,28]; surface temperature [20,25,29,30], temperature difference between inside and outside [24,26,31], maximum internal temperature [27], cooling degree days [22], and thermal comfort [32,33].

Heavyweight construction such as concrete, stones, and their derivative materials combines high density with high thermal capacity, hence the term "thermal mass" associated with this type of construction. Temperature performance of heavyweight construction in hot climates is described in bio-climatic books and references [3,4,5] as taking longer to warm up when exposed to solar gains and slower to respond to temperature variation. Similarly, it takes longer to cool down and lose the extra heat. This stored heat will dissipate during the night. This situation is ideal to maintain a comfortable indoor temperature when the temperature difference between day and night is considerable. It is a practical free-running (not using mechanical cooling) solution to keep internal conditions within comfortable levels. The recommended practical thickness for such material is between 50 to 120mm [3,4,6] for a minimum diurnal temperature difference of 8 to 10K [3].

The commonly used thermal parameter U-value does not express any thermal mass properties, instead the admittance or Y-value is more appropriate for such materials. Using the same SI units as the U-value, W/m^{2}K, it expresses the ability of thermal mass to store heat within itself. As ambient temperature fluctuates, the larger the admittance, the less internal temperature fluctuation is to be expected [3,35,36,37].

Previous studies dealing with thermal mass [38,39] claim that further thermo-physical specifications, besides the U-value and conductivity, are missing to better understand the expected temperature behaviour of such materials. Another statement [39] adds that there is limited research on actual case studies compared to the larger part based on software analysis. Papers about Cyprus [40,41] and Greece [42] focused on the inevitability of adding insulation and found that the outer layer is the best location.

Software-based research that study the best location of insulation within a wall [11,12,13,14,43,44] find that the outer location is preferable to reduce summer cooling loads or enhance summer comfort [11,12,13,14]. Two cases have found that multi-layered insulation within a wall will perform best [43,44]. Similarly, local, regional or international construction codes aiming to reduce cooling energy loads in hot and warm climatic zones tend to emphasize reducing envelope U-values by adding insulation [1,2,6,7,8,9,10,18].

The construction of the Test Cells

Construction of the three test cells started by mid-May, under the direct and continuous supervision of the researcher. The technical maps of the three rooms on site and with all relevant details and dimensions are shown in figure 1 and construction progress is shown in figure 2.

The finished test cells had the following envelope construction:

a- Concrete slab on grade: 120mm
b- Double masonry walls
  External Hollow Concrete Block walls: 200mm
  Internal walls Concrete Block walls: 100mm
  Air gap in between: 40mm
  Extruded Polystyrene Insulation (XPS): 25mm
  Internal and external cement plastering: 12mm

c- Flat Roof
  Wood planks: 49mm
  Loose fine gravel: 160mm

The finished test cells have the following physical characteristics:

a-	Internal dimension	3450 x 2900 mm
b-	External dimension	4150 x 3600 mm
c-	Internal height	3000 mm
d-	Internal area	10 sqm
e-	Internal volume	30 cu.m

f- The main window is centred on the west elevation and is 1200 x 2000mm, made of 2 horizontally sliding single panels 6mm, transparent glass, U-value 6.1 W/m^{2}K. Sliding rails are located inside.
g- The main west elevation has one white painted louvered aluminium panel of 1300 x 2000mm sliding on horizontal rails located outside and to the right-hand side.
h- The east elevation has a centred small opening of 400 x 300 mm at a height of 2500mm.
i- U-value of walls in test cells 1 and 3 (internal and external insulation) 0.6 W/m^{2}K
j- U-value of walls in test cell 2 varies between (middle insulation) 0.7 W/m^{2}K
k- U-value of non-insulated test cell 1.1 W/m^{2}K
l- U-value of roof varies between 1.5 W/m^{2}K
m- U-value of the slab on grade varies between 4.0W/m^{2}K

On August 23rd, 2017 (day 235), three 100W incandescent light bulbs are added in each of the test cells. They are positioned at a height of 25cm from the floor, in a radial pattern of a 120^o angle and at 900mm from the centre of the room. The light bulbs point towards the walls, with one perpendicular to the window, as seen in figure 3.

During week 34 between August 29 and 31(days 241, 242 and 243) the insulation of the test cell #2 was removed from the middle of the cavity wall. On the afternoon of August 29, a make shift scaffolding was installed between test cell #2 and #3 and the gravel was moved over to this new location, exposing the timber roof. On August 30, the timber logs were moved to allow reaching of the insulation boards. The insulation in test cell #2 was loosely fitted in the 40mm cavity they were also made into long strips of 600mm width and 3000mm length by using adhesive tape to stick two and one-half boards together. Once all the insulations boards were removed, the initial wood planks were repositioned into their location. On August 31, all the gravel was retuned into its initial location and the make shift scaffolds were removed. Thus, the U-value for test cell #2 changed from 0.6 to 1.1 W/m^{2}K.

Following the removal of insulation from test cell #2, data loggers and lighting fixtures were checked for good operation and repositioned into their original positions.

The monitoring instruments

A Davis weather station was installed on a nearby elevated structure and a Data logger for ambient air was installed in the centre of each test cell with a thread linking the timber roof to a nail in the concrete floor at head height some 1600mm from floor level. Furthermore, data loggers were placed in the west wall with the opening for internal and external surface temperature recordings. All used data loggers are Tiny Tags +2 TGP-4500; recording data at the hour including minimums and maximums. They are described as for rugged and suited for outdoors monitoring. They have a 10K NTC thermistor, internally mounted sensor. The reading resolution is at 0.01^{o}C and for temperature ranging between 10 and 50^{o}C, the accuracy is between 0.4 and 0.5^{o}C. The Davis weather station registered all the necessary data such as air temperature, relative humidity, wind direction and velocity, and solar radiation. The weather station was set to record data at half hour intervals, yet the values of hours only are used in the analysis.

The Tiny Tags +2 data loggers are 2 to 4 years old and were not factory calibrated since purchase. However, a comparative analysis of their accuracy was performed as follows: Some 15 data loggers were put to record temperatures every 2 minutes, sequentially put into a fridge, then a freezer and finally in the outside shade for a total length of thirty minutes in each of the different locations. They were all positioned in a row, next to each other with the sensors facing the same direction. All recorded values were evaluated and the three nearest values, among all the values, were noted and given one mark/point. Differences in values are only within second decimals (therefore 100ths of a degree Celsius); the best three with the least difference were used. The same method was applied to the surface temperature evaluation where the surface probe was fixed to the fridge and the freezer's internal surfaces.

Weather in Rasmaska - summer 2017

The weather station installed on site near the test cells in the northern town of Rasmaska recorded the following summer observations (figure 4):

(a) Summer 2017 had a July hotter than August with mean temperatures of 28.1 ^{o}C and 27.6^{o}C respectively.
(b) Hottest **mean** day temperatures are 30.7 ^{o}C and 30.4^{o}C for July and August respectively
(c) Coolest **mean** night temperatures are 25.1 ^{o}C and 24.4^{o}C for July and August respectively
(d) Hottest recorded temperatures are 33.8 ^{o}C and 33.4^{o}C for July and August respectively
(e) Hottest day temperature is usually in the afternoon between 4:00 and 5:00pm, well past the solar noon (around 12:40pm) and a couple of hours before sunset (6:50-7:15pm)
(f) Coolest night temperature is in the hour before or within day break (4:00 and 5:00am)
(g) Wind cycle kicks off in the late morning, around 9:00am, until late afternoon around 6:00pm. Day wind has a faster speed than night wind with a value of 3.66m/s for August
(h) Night wind cycle starts between 9:00 and 10:00pm until the hour before day break at 3:00am with a value of 1.02 m/s for August.
(i) The **mean** diurnal difference between day maximum and night minimum varies at 7.0; 5.6 and 5.9K for June, July and August respectively.
(j) Relative humidity is high with a mean above 70%RH and low near 60 and high above 80

(k) Hourly solar radiation varies between 193 and 235 W/m^2 for July and August.

1.3 Results: Three Test Cells Simultaneous Monitoring

Internal Temperature Results

The early monitoring period, showed that each test cell performed differently with significant day and night temperature differences. All test cells internal temperature are the dry bulb air temperatures, and all outdoor, external, are also dry bulb air temperature.

During the day, test cell #1 (outer insulation) had the lowest internal peak followed by test cell #2 (middle insulation), while test cell #3 (inner insulation) recorded the hottest peak. During the night, test cell #1 maintained the coolest temperature, but test cell # 2 recorded the warmest score.

Initially, during days 172, 173 and 174 on June 21, 22 and 23 (figure 5), before the installation of the shutters, the windows were kept closed for three full days; internal temperate trends with warmest and coolest temperatures rose noticeably, and then dropped as soon as the windows were opened and the shutters closed. Peak temperature of the coolest test cell #1 rose from 28.1^{o}C on day 172 to 28.9^{o}C on day 173 and reached above 29.7^{o}C on day 174, whereas the hottest test cell #3 peak temperature starting at 29^{o}C, rose to 29.9^{o}C and reached 31.4^{o}C on day 174. Accordingly, the peak temperature difference between the hottest (test cell #3) and coolest (test cell #1) peak became larger, starting at 0.9K and reached almost 1.7K. The day's ambient (outdoor air temperature) peak temperature on day 174 (June 23) was 25.9^{o}C whereas the previous day it was 27.1^{o}C with similar solar radiation levels on both days. The continued window closure accompanied with a 1.2K drop in the day's ambient air temperature resulted in a 1.5K rise in the internal temperature in the hottest test cell #3 and 0.8K in the coolest test cell #1. During night, lowest ambient air temperature, starting at 20.8 ^{o}C continued to drop further to 20.3 ^{o}C and then increased back to 21^{o}C. Internal night air temperature rose continuously for the hottest test cell #2 from 23.8 ^{o}C to 25.7 ^{o}C and reached 26.6^{o}C making a positive difference of 2.8K.

Once the windows were installed and the shutters kept closed around the early afternoon of day 175 (June 24) and before the day's peak, all test cells' peak temperature dropped more than 1K from the previous day with values between 30 ^{o}C and 28^{o}C. whereas the day's peak rose 2K, to reach 28^{o}C.

Observation showed that there is a tipping time where one test cell that had a period of cooler internal temperatures than another test cell, shifts to having warmer temperature for another period, than the one compared too. The temperature of test cell #2 and #3 changed during morning, between 9:00 and 10:00am, and in the late evening before midnight around 10:00 and 11:00pm. From morning until late evening, (daytime), the internal temperature of test cell #3 was the hottest, followed by test cell #2. After the tipping time (during night-time), the temperature of test cell #2 becomes the warmest followed by test cell #3.

During week 26 (figure 6), the windows were left open while shutters were opened in a couple of mornings and closed later on. The daily ambient air peaks rose sharply on day 179 (June 28) from 28.9 ^{o}C to 30.1^{o}C and 29.4 to 32.2^{o}C on day 183 (July 2). This abrupt rise resulted in a couple of morning hours where internal temperature was lower than the external in all three test cells. This difference reached up to 3K on day 183, yet the internal peak temperate only increased between 0.8 and 1K.

During night temperatures, dramatic drops in ambient air temperature affected internal temperatures with different degrees. This was evident during the night of day 179-180, where lowest air temperature dropped from 23.1^{o}C (previous night) to

21.9^{o}C with a difference of 1.2K. Accordingly, lowest internal air temperature dropped from 26.2 to 26.1 (0.1K) for test cell #1; from 27.1^{o}C to 26.7 ^{o}C (0.4K) for test cell #2; and from 26.5^{o}C to 25.9^{o}C (0.6K) for test cell #3.

Internal peaks and valleys happened at various times; as a general trend they occurred a few hours after the day's hottest or the night's coolest temperature.

For a few nights, the night's lowest internal temperature was recorded in test cell #3, nonetheless. With only a 0.2 to 0.6K difference than test cell #1. As the monitoring progressed, these exceptions became more and more frequent, until it was adopted as the dominant behaviour at week 31(August) and onwards.

Closing the windows for an extended time might have caused a gradual raise in internal temperature, but the daily short-term usage of shutters and the closure and opening of windows possibly compromised this observation.

During week 28, days 191 through 194 on July 10-13 (figure 7), shutters and windows were closed from noon time until right after sunset in order to see if this method had any impact on cooling the day's peak or the night's temperature. No significant temperature behaviour was observed, or to be more accurate, it was not possible to quantify and compare the results of this modification to an open window scenario. Nonetheless, when both windows and shutters were closed for an extended time (6 days) from day 195 to 200 (July 14-19), the overall internal temperature trend did not show any considerable differences as seen in the previous only closed window scenario.

On a single occasion during which the windows were closed, on, day 209 (July 28), the impact of no ventilation was clearly evident by the sharp drop of ambient temperature from late afternoon to dawn, while the internal temperature drop was more gradual and slow.

So far, the three weeks of monitoring with unpainted external plastering on the three test cells, showed that external insulation has the coolest internal day peaks and temperature, whereas the internal insulation has the warmest.

Impact of white paint

In order to assess the impact of the external white paint on the internal air temperature in the three test cells, similar ambient air temperatures (above 24^{o}C and not more than +/- 1 ^{o}C difference) were recorded before and after the white paint application. Days 217 and 218 (August 5 and 6), the effect of white paint addition was compared to day 202 (July 21) before white paint (figure 8). It should be noted that, on day 217, both windows and shutters were closed during day time from 4:30am until 6:00pm. On day 218, only the shutter was closed from 8:20am and not opened again for the next two days. And on day 203, the shutters were closed from 11:50am until 7:10pm.

The entire day's Degree hours (Dh) of outdoor ambient air temperature (above 24^{o}C) was at 67 and 68 on the painted days (days 217 and 218 respectively) and 68 for the non-painted day (day 202). The full day Dh of test cell #1 (the coolest) was at 104 and 105 for days 217 and 218, whereas it was 117 on day 202. That was the first indication on the significant impact of white paint on internal temperature. The full day Dh of test cell #3 (the warmest) was at 110 and 111 for days 217 and 218, while it was 127 on day 202. This comparison highlights the fact that even with closed windows for the entire day period, the white paint had a cooling effect on the internal temperature. Both these comparisons demonstrate that external white paint had a direct impact on the internal temperature of the three test cells. Furthermore, the combination of the external white paint, and the nil internal gains allowed the internally insulated test cell #3 to have cooler night internal temperature (with one single night exception). This is due to the exposed heavyweight of the other test cell internal walls storing some heat. Test cell #3 is not able to store any heat, consequently is warmer during the day, but cooler during the night.

Internal Gains

The effect of the 300W internal gain produced by the three incandescent lamps was to check whether the ranking of the test cells would be altered following the excess internal gain. No significant changes in ranking occurred, and the day’s coolest peak remained in external insulated test cell #1 while the warmest in internal insulated test cell #3. The most easily recognizable impact of internal gain was on day 272-September 29 (figure 9) when at 11:00am the windows were opened and the lights turned on, while the shutters were kept closed, a clear instantaneous rise in internal temperature occurred from 25.5^{o}C to 26.7^{o}C in test cell #1 and from 26.0^{o}C to 27.0^{o}C in test cell #3. Although the different in between both cells is minimal 0.1K, this actually show the instantaneous ability of the exposed thermal mass in test cell #1 to store more heat compared to no thermal mass of test cell #3.

Removing the middle insulation

Once the middle insulation of test cell #2 was removed, during week 35, the test cells’ temperature performances considerably shifted: while test cell #3 (internal insulation) remained the warmest during the day, test cell #1 (external insulation) came in second, and the un-insulated test cell was now the coolest.

Combined influence of internal gains and ventilation

In addition to the shifting in the internal temperature performance of the test cells, the gap between the peak temperatures was then much more prominent with high internal gains, by either solar gain or lighting gains (figure 10). This was evident on week 40, days 276-278 (October 3-5), when the shutters were left open but the windows were closed (no ventilation), and on week 41, days 279-281 (October 6-8) when the lights were on, the windows and shutters closed. In the case of days 276-278, the temperature difference (Dt) between the warmest and coolest peak was 1.8K, and varied between 1.3K to 1.7K for the coolest and intermediate peak. Similarly, on days 279-281, the Dt between warmest and coolest was 1.3K and 1.4K, and an intermediate between 0.7 and 0.8K between the coolest periods. In regards to other days with ventilation, a frequently occurring Dt between warmest and coolest peak was between 0.7K and 0.8K with less occurrences of lower and higher values from 0.1K to 1.0K.

Shifting the data loggers

Due to minor differences in the temperature behaviour of the different test cells, it was decided to shift the location of the data logger and check if these discrepancies were due to some calibration error in the data loggers. The shift was completed on day 268 (September 25) but the results showed the same temperature behaviour and the same ranking performance for the three test cells.

Thermal mass heat storing

It is typical for the local climate to have heat waves between the months of October and November, after a relatively cool period. A heat wave was registered for one day only this year, on day 292(October 19) when the day’s peak reached 29^{o}C from a temperature of 25.7^{o}C of the previous day (figure 11).

When compared to similar days with air temperature peaks near 29^{o}C, (although higher solar radiation peaks existed) yet, the internal temperature of day 292 was drastically different from all previous cases. The internal temperatures of all three cells were considerably cooler than the dry bulb air throughout the entire day time; an unprecedented behaviour thus far in the experiment.

Ventilation

Fan ventilation started by the end of week 41, when cooler day and night temperatures became the norm. This made it difficult to properly assess if the ventilation had any direct influences on the internal test cells’ temperature. Similar temperature trends started happening from week 38 and onwards but matching the day’s peaks and coolest temperature was only possible for either the peak or the coolest value, but not both at the same time. Furthermore, Dt between internal and external temperature varied between less than 2K up to 4K before and after the addition of fans, making it difficult to be certain of any causative impact in reducing the internal temperature as expected in the literature review.

1.4 Discussion

The most obvious point is the effect of thermal mass in absorbing and storing heat that leads in a few days to an internal morning temperature lower than the outdoors (days 182,184,194,270,273,290,291,292,293,294) observable in all the test cells, thus the thin layer of 12mm internal cement plaster is playing some role in storing heat in the internally insulated test cell.

Similarly, the same effect of storing the heat and releasing it during the night is evident in the night internal temperature loggings which were consistently warmer than the outdoors. Similarly, observable in all test cells. Especially when combined with a relatively low wind velocity during the night which is not enough to flush the heat outside of the test cells.

The low response to the daily changes in the ambient air temperature is visible when external day temperature rises sharply from the previous day. The internal temperature shows minimally warmer temperature compared to the previous day's. Similarly, when the night's external temperature drops sharply, the internal temperature remains as warm as the previous night. This is not due to the effect of insulation slowing the external day time heat from entering, and the accumulated daytime heat from escaping at nighttime, since the effect is observed with the test cell without insulation as well. Furthermore, the different locations of the insulation within the walls would result in different behaviour, which is not the case,

A sudden and limited temperature change (rise or drop) in the external air temperature of 2K to 3K might affect the internal temperature by not more than 0.5K.

The effect of changing the external colour from medium grey to white is well observed and quantified in its effectiveness to reduce the external surface temperature by 10 to 20%. It was also evident by using the degree hours method that this shift in colour had an impact on reducing the internal temperature.

The construction and monitoring of the test cells allowed an accurate insight into the temperature behaviour resulting from the different positions of insulation within double masonry walls. Even with the same calculated thermal parameters, each test cell performed differently when exposed to the following heat gain factors:

(a) thermal transfer from walls and roof;
(b) direct gains from sunlight through the window;
(c) direct gains from the ventilation (though the shutters or the open windows);
(d) direct gains from the three-heat source light bulbs emitting 300W

The wall U-value which does not vary considerably between the different test cells is affecting only point (a), whereas heavyweight property is responsible for acting along the remaining factors (b, c and d).

The externally insulated test cell had the coolest internal temperature peaks during the day, but during the nights, it alternated with only a few nights as the coolest but more frequently as the intermediate night temperature. Based on the literature concerning thermal mass (a) 50-120mm of thermal mass is enough to provide improved temperature performance, and (b) the admittance or Y-value calculation is based on whatever is reached first from (1) half the wall; (2) 100mm of depth from the internal space; and (3) until the insulation layer.

Based on the above, test cell#1 and #2 with external and middle insulation respectively, will bear the same effect by their thermal mass since both are constructed from 100mm internal masonry block and 12mm internal plaster. Their similarity is expected to produce similar internal temperature performances, yet that was not the case in this study.

Within the same line of reasoning, the air gap in test cell #1 extends the depth of thermal mass (of the 100mm masonry) into the external 200mm masonry wall by convective heat transfer, and promotes further heat storage during the day, and similarly during the night, the 100mm masonry wall will continue to release heat into the air gap as well as into the internal room resulting in the coolest day's peak; increasing day time heat storage should result in more heat release during the night. This cannot be blamed on faulty construction where the roof might not seal the air gap properly. The 49mm timber roof planks surpass the 40mm air gap to rest on the outer 200mm walls. Above those planks is a 160mm loose gravel bed.

This middle-insulated test cell got the intermediate day's peak temperature when compared to the other test cells, and the night's warmest temperature. This is due to the limited storage capacity within the 100mm masonry wall during the day; a restricted and one-way storage during the day will result in heat release only into the internal room during the night. When compared to the internally insulated test cell, it has limited heat storage, and hence shows cooler night temperature. The outer insulated, as explained above, shows heat storage into both masonry walls.

The internally insulated test cell got the hottest internal temperature peaks during the day, but ultimately became the coolest during the nights after a few weeks of running the experiment. The reason behind this behaviour is minimal of heat storage in the 12mm of internal plaster that makes the test cell the most vulnerable to direct gains (b, c and d), and the relatively small amount of stored heat to be dissipated during nighttime. whereas when it comes to heat transfer through the walls and roof, the cell has the same U-value (0.6 W/m^2K) as the test cell with the external insulation, hence a similar behaviour is to be expected.

When the insulation is removed from test cell #2, the day peak becomes the coolest among the three cells; the less the test cell is ventilated and is exposed to more internal gains, the more the gap between the coolest and warmest peak stretches.

As for the night coolest temperature, the difference is much less marked, varying only between nil to a maximum of 0.6K. For the night coolest temperature, it is not clear which test cells has the coolest temperature, since the latter tends to alter frequently. Nonetheless, test cell #3 with the internal insulation shows more nights with coolest temperature values.

Thermal mass saturation is related to the already mentioned fact that heat is being stored and released within the thermal mass. This would lead to a saturated and un-saturated mass. This was shown during the experiment at two different instances, although this notion is seldom referred to in the literature however, it is quite a common seasonal term used in Lebanon, to describe the perceivable internal coolness of a given place, in the early hot seasons or whenever a sudden and a few days-long heat wave occurs, usually during the months of May referred to as the *Khamasseen* (the eastern hot and dry wind), and during October referred to as the second summer between October and November. During these sudden and short heat waves, or within the early hot season, due to the construction's thermal mass, internal temperature remains considerably cooler for a few days; it is typically formulated as 'the thermal mass did not saturate yet'.

In the first weeks of observation, from week 25, (as the construction is completed) until week 29, the night temperature of test cell #1 is the coolest, after which test cell #3 becomes the coolest. This is a clear indication of the saturation of both 100mm and 200mm masonry walls of test cell #1 when they no longer are able to store any further heat during the day and release it considerably during the night.

On day 292, when October temperature rose above the previous day's peak, the internal temperature remained much cooler for the entire day period. This is another temperature behaviour that illustrates the de-saturation of the thermal mass: after many days of cooler temperatures, the thermal mass slowly releases the extra stored heat. When a sudden rise in temperature occurs, internal temperature remains cooler for a much longer time span (the entire day time in this example).

Internal gains affected the temperatures, but did not in any way change the ranking of temperature performance among the different test cells.

Since this research is based on simultaneous observations during two periods, it is easy to compare each of the three-different constructions' performance at each period. In order to compare all four over the entire observed period, a small regression application is applied in order to combine the mean minimum temperature, the mean temperature, the max mean temperature, the degree hours of overheating above 30°C, and the hours of overheating (table 1). In all cases, combined day and night temperatures, the un-insulated test cell performed best followed by outer, then middle insulation, while the inner insulation showed the worst temperature performance. Even with its good performing night temperatures.

1.5 Conclusion

The methodology of this paper consisted of building three heavyweight test cells with different insulation configurations within their double masonry walls. These are monitored for a full summer season. This allowed reaching the objective of accurately evaluating and quantifying the summer temperature behaviour of such constructions.

Results show that there is a clear differentiation between day and night temperature behaviour: the day's coolest peak is always well distinguished for the externally insulated test cell when compared to the other locations. However, the night's coolest peak was not so clear. Nevertheless, it tends to be in the internally insulated test cell. Once the middle insulation was removed, the coolest day's peak shifted into the un-insulated test cell, and the shift was clearly observable. While the night's coolest peak was still unpredictable, shifting between the internally insulated and non-insulated test cell.

In regard to overheating using the degree hours above 30°C, the un-insulated test cell with the highest U-values has the least overheating. This is followed by the outer insulation with 40% more overheating, then the middle insulation at 88% more from the non-insulated. The inner insulated has shown the most overheating at 178% and is the only result coherent with the literature (figure 12).

1.6 Acknowledgments

The authors wish to thank all the following for their valuable support: The municipality of Ras Maska, Koura, North Lebanon, its president Mr. Simon Nakhoul, and Mrs Layal Kayrouz for granting us, unconditionally, the land to build the test cells, along with all the logistical support. More so, the construction could not have been done without the generous support of Mr. Ali Ibrahim, and Mr. Raja Khatib. This work was conducted as part of a doctoral research in the Faculty of Architecture and Built Environment, University of Westminster.

1.7 List of references

[1] ASHRAE Standard 90.1 (2004). *Energy Standard for Buildings Except Low-Rise Residential Buildings*, I-P Edition.

[2] *2012 International Energy Conservation Code*, (2011). 1st Edition ed. U.S.A.: International Code Council, Inc.

[3] Szokolay, S.V. (2004). *Introduction to Architectural Science: The Basic of Sustainable Design*, Elsevier Architectural Press.

[4] Littlefield, D. (2007). *Metric Handbook, Planning and Design Data*, 3rd. Elsevier Architectural Press.

[5] Koch-Nielsen, H. (2002). *Stay Cool, a design guide for the built environment in hot climates* James & James Ltd.

[6] California Energy Commission (2014). *Residential Compliance Manuel for the 2013 Building Energy Efficiency Standards*, Title 24; Part 6.

[7] FFEM and ANME (2010). *La Mise en Place de la réglementation Thermique et Energétique en Tunisie.*

[8] French Republic (2006). *Réglementation Thermique 2005 des Bâtiments Confortables et Performants.*

[9] LCEC (2014). *LCEC Guidelines on Preparing Technical Proposal for Non-Certified High Energy Performance Building.* Beirut: LCEC.

[10] Republic of Lebanon (2005). *Thermal Standard for Buildings in Lebanon.* Beirut : UNDP/GEF and MPWT/DGU.

[11] Kossecka, E. and Kosny, J. (2002). Influence of insulation configuration on heating and cooling loads in a continuously used building. *Energy and Buildings.* 34 (4), 321-331.

[12] Balocco, C., Grazzini, G., Cavalera, A. (2008). Transient analysis of an external building cladding. *Energy and Buildings.* 40 (7), 1273-1277.

[13] Al-Sanea, S., Zedan, M.F., Al-Hussain, S. (2012). Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential. *Applied Energy.* 89 (1), 430-442.

[14] Stazi, F., Veglio, A., Perna, C., Munafo, P. (2013). Experimental comparison between 3 different traditional wall constructions and dynamic simulations to identify optimal thermal insulation strategies. *Energy and Buildings.* 60 429-441.

[15] Kiel Moe (2014). *Insulating Modernism* Birkhauser.

[16] Kiel Moe (2010). *Thermally active surfaces in Architecture* Princeton Architecture Press.

[17] Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F. (2006). World Map of Koppen-Geiger Climate Classification updated. *Meteorologishe Zeitschrift.* 15 (3), 259-263.

[18] Order of Engineers and Architects (2010). *Thermal Standard for Buildings in Lebanon.* Beirut: Order of Engineers and Architects of Beirut; LIBNOR; ECOTECH engineering; ADEME; ALMEE; LGBC; ASHRAE.

[19] Alvarado, J.L. and Martinez, E. (2008). Passive cooling of cement- based roofs in tropical climates. *Energy and Buildings.* 40 (3), 358-364.

[20] Halwatura, R.U. and Jayasinghe, M. (2008). Thermal performance of insulated roof slabs in tropical climates. *Energy and Buildings.* 40 (7), 1153-1160.

[21] Hamdan, M.A., Yamin, J., Abdel Hafez, E.M. (2012). Passive cooling roof design under Jordanian climate. *Sustainable Cities and Society.* 5 26-29.

[22] Krüger, E., Fernandes, L., Lange, S. (2016). Thermal performance of different configurations of a roof pond-based system for subtropical conditions. *Building and Environment.* 107 90-98.

[23] Soubdhan, T., Feuillard, T., Bade, F. (2005). Experimental evaluation of insulation material in roofing system under tropical climate. *Solar Energy.* 79 (3), 311-320.

[24] Yu, B.F., Chen, Z., Shang, P.J., Yang, J. (2008). Study on the influence of albedo on building heat environment in a year-round. *Energy and Buildings.* 40 (5), 945-951.

[25] Ong, K.S. (2011). Temperature reduction in attic and ceiling via insulation of several passive roof designs. *Energy Conversion and Management.* 52 (6), 2405-2411.

[26] Kachkouch, S., Ait-Nouhb, F., Benhamoua, B., Limam, K. (2018). Experimental assessment of thermal performance of three passive cooling techniques for roofs in semi-arid climate. *Energy and Buildings.* 164 153-164.

[27] Ogoli, D.M. (2003). Predicting indoor temperatures in closed buildings with high thermal mass. *Energy and Buildings.* 35 851-862

[28] Suman B.M. and Verma, V.V. (2003). Measured Performance of a Reflective Thermal Coating in Experimental Rooms. *Journal of Science and Industrial Research.* 62 1152-1157.

[29] Dimoudi, A., Androutsopoulos, A., Lykoudis, S. (2006). Summer performance of a ventilated roof component. *Energy and Buildings*. 38 (6), 610-617.

[30] Chaiwiwatworakul, P., Chirarattananon, S., Hien, V.D., Rakkwamsuk, P., Tummu, P. (2013). Thermal performance of insulated walls enclosing residential spaces in Thailand. *Energy and Buildings: An International Journal of Research Applied to Energy Efficiency in the Built Environment*. 61 323-332.

[31] Al-Obaidi, K., Ismail, M., Abdul Rahman, A.M. (2014). Design and performance of a novel innovative roofing system for tropical landed houses. *Energy Conversion and Management*. 85 488-504.

[32] Albatayneh, A., Alterman, D., Page, A., Moghtaderi, B. (2016). Assessment of the Thermal Performance of Complete Buildings Using Adaptive Thermal Comfort. *Procidia Social and Behavioral Sciences*. 216 655-661.

[33] Leo Samuel, D.G., Dharmasastha, K., Shiva Nagendra, S.M., Prakash Maiya, M. (2017). Thermal comfort in traditional buildings composed of local and modern construction materials. *International Journal of Sustainable Built Environment*. 6 463-475.

[34] D'Orazio, M., Di Perna, C., Di Giuseppe, E. (2010). The effects of roof covering on the thermal performance of highly insulated roofs in Mediterranean climates. *Energy and Buildings*. 42 (10), 1619-1627.

[35] de Saulles, T. (2012). *Thermal mass Explained,* Surrey: MPA, the Concrete Center.

[36] BRE (2011). *SAP 2009, The government's standard assessment procedure for energy rating of dwellings.*

[37] Balcom, D. and Neeper, D.A. (1983). *Diurnal Heat Storage in Direct Gain Passive Solar Buildings, 21st AICHE-ASME National Heat Transfer.* Seattle, Washington.

[38] Reilly, A. and Kinnane, O. (2017). The impact of thermal mass on building energy consumption. *Applied Energy*. 198 108-121.

[39] Verbeke, S. and Audenaert, A. (2018). Thermal inertia in buildings: A review of impacts across climate and building use. *Renewable and Sustainable Energy Reviews*. (82), 2300-2318.

[40] Fokaides, P.A., Polycarpou K., Kalogirou, S. (2017). The impact of the implementation of the European Energy Performance of Buildings Directive on the European building stock: The case of the Cyprus Land Development Corporation. *Energy Policy*. 111 1-8.

[41] Gaglia, A.G., Tsikaloudaki, A.G., Laskos, C.M., Dialynas, E.N., Argiriou, A.A. (2017). The impact of the energy performance regulations updated on the construction technology, economics and energy aspects of new residential buildings: The case of Greece. *Energy and Buildings*. 155 225-237.

[42] Anastaselos, D., Oxizidis, S., Papadopoulos, A.M. (2017). Suitable thermal insulation solutions for Mediterranean climatic conditions: a case study for four Greek cities. *Energy Efficiency*. 10 1081-1088.

[43] Al-Sanea, S. and Zedan, M.F. (2011). Improving thermal performance of building walls by optimizing insulation layer distribution and thickness for same thermal mass. *Applied Energy*. 88 (9), 3113-3124.

[44] Bond, D.E.M., Clark, W.W., Kimber, M. (2013). Configuring wall layers for improved insulation performance. *Applied Energy*. 112 235-245.

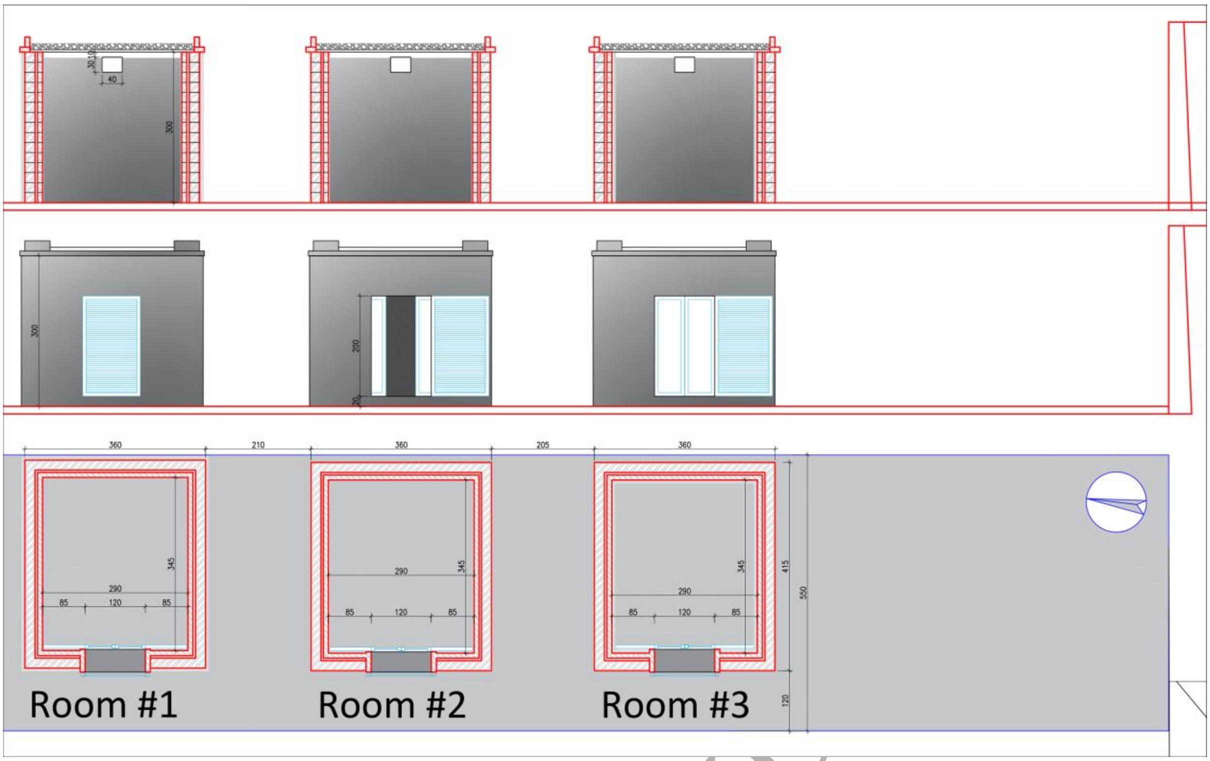


Figure 1: Technical drawings of the 3 test cells, including the plans with the internal dimensions, the section showing the small opening in the back wall, and the elevation with the window and shutters.

Figure 2 overall construction work progress with the corresponding calendar of the three test cells, showing the hollow concrete block walls, the insulation, the plaster finish before and after the white paint, as well as the internal light acting like internal gains.

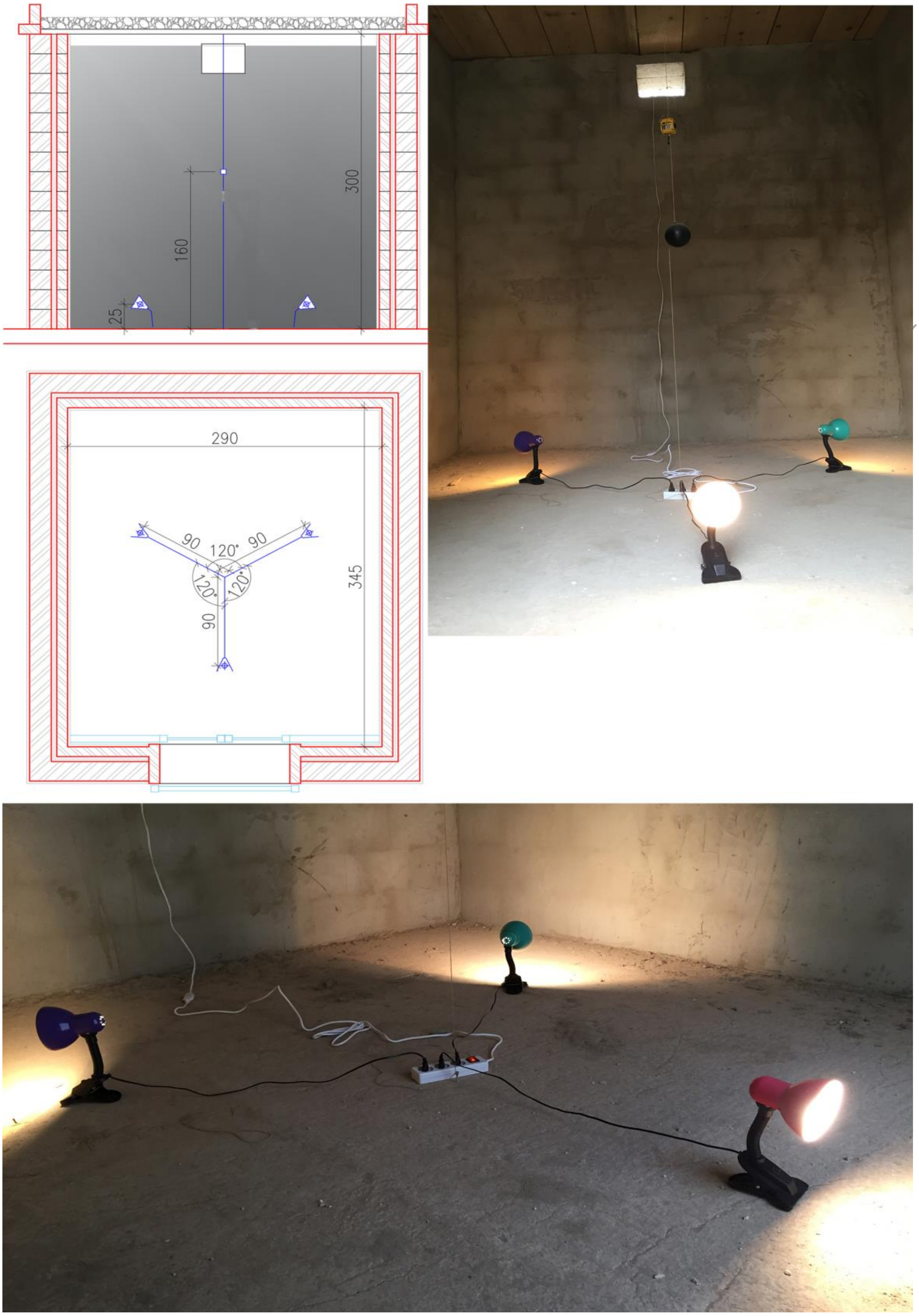


Figure 3, a view of the interior of the test cell, with the configuration of the three light sources and the location of the data logger.

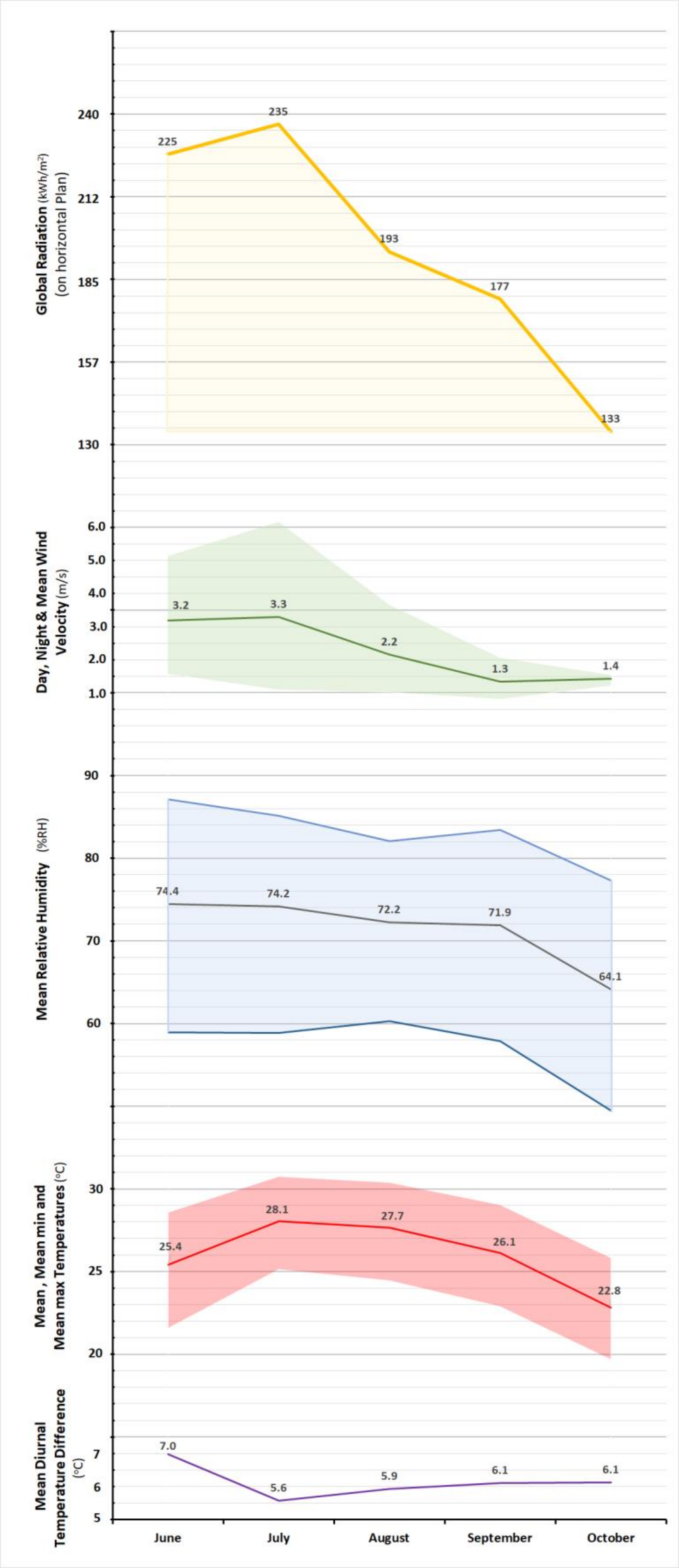


Figure 4. The recorded weather data from the in-situ Davis weather station from June, till October 2017, showing the global solar radiation, the wind velocity, the relative humidity, the temperature and the mean diurnal difference between day and night.

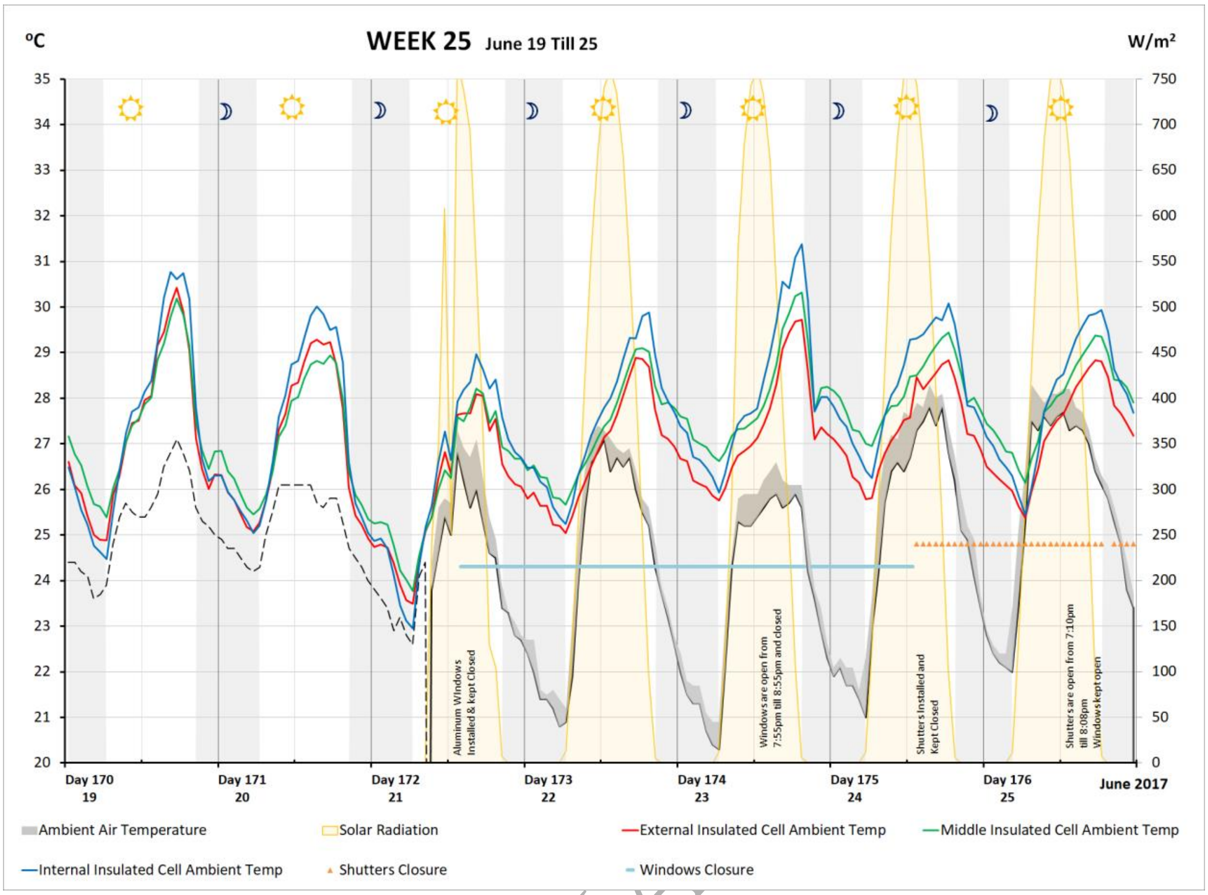


Figure 5. The combined temperature graphs of the first week of observation, week 25 in particular the effect of keeping the windows closed with no shutters during days 172, till 175 174 which results in progressively increasing day peaks. These will drop once the cell is ventilated through open windows and closed shutters.

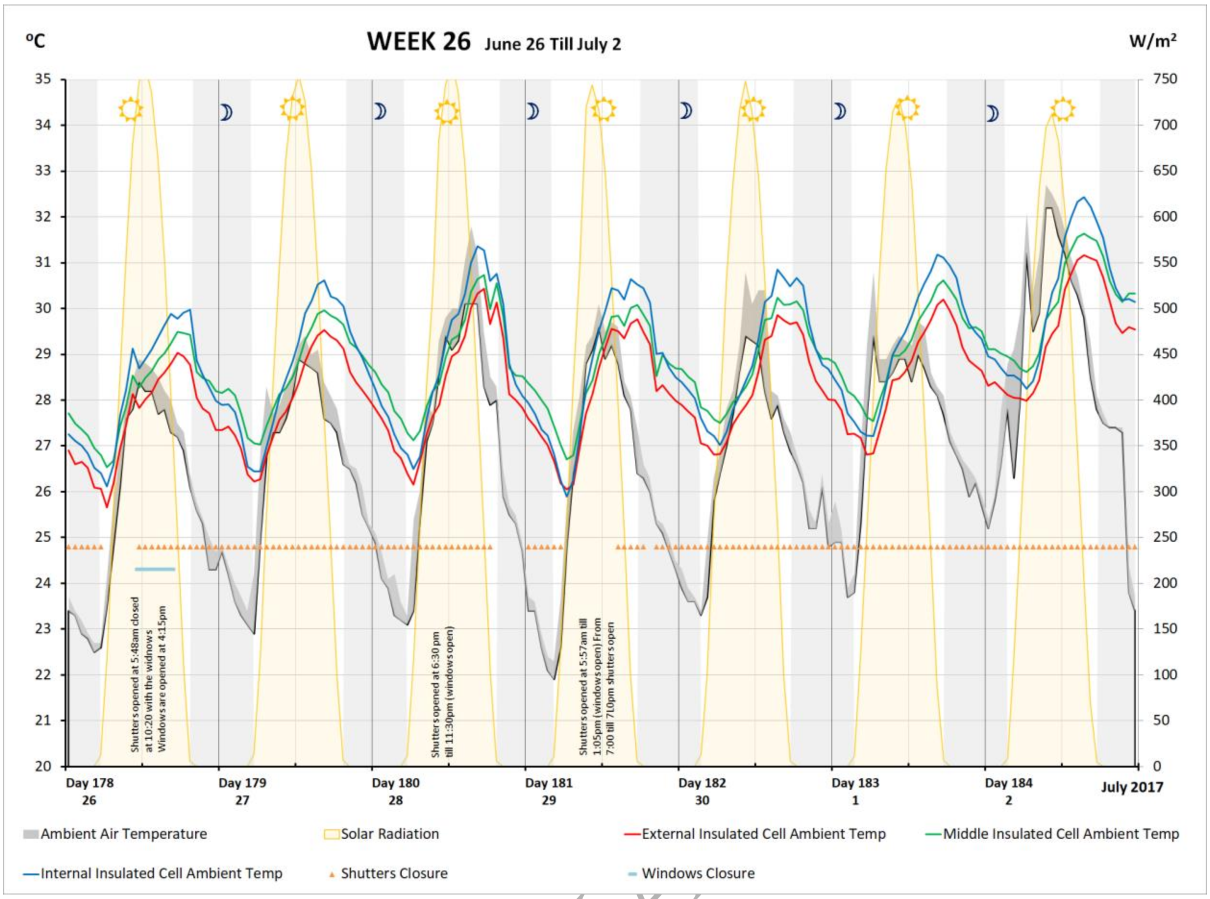


Figure 6. The combined temperature graphs of week 26, with the external insulated cells always with the coolest temperatures. Day 184 is particularly interesting when the surge of about 3k in the day's temperature resulted in all three test cell temperature remaining cooler than the outdoors, even with ventilation through open windows and the closed louvers.

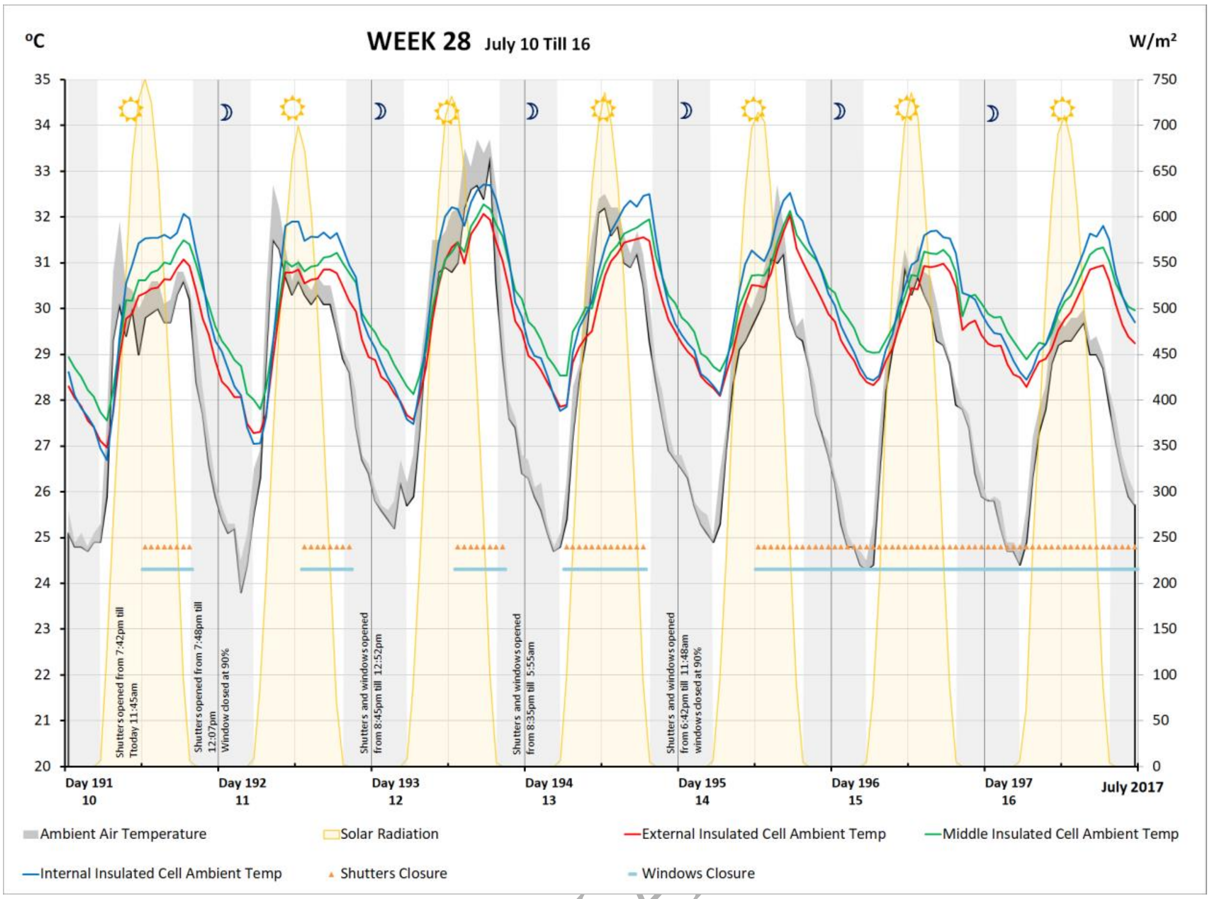


Figure 7. The combined temperature graphs of week 28, with an attempt to study the impact of daily closure of both windows and shutter in the afternoon. Eventually no specific impact is observed.

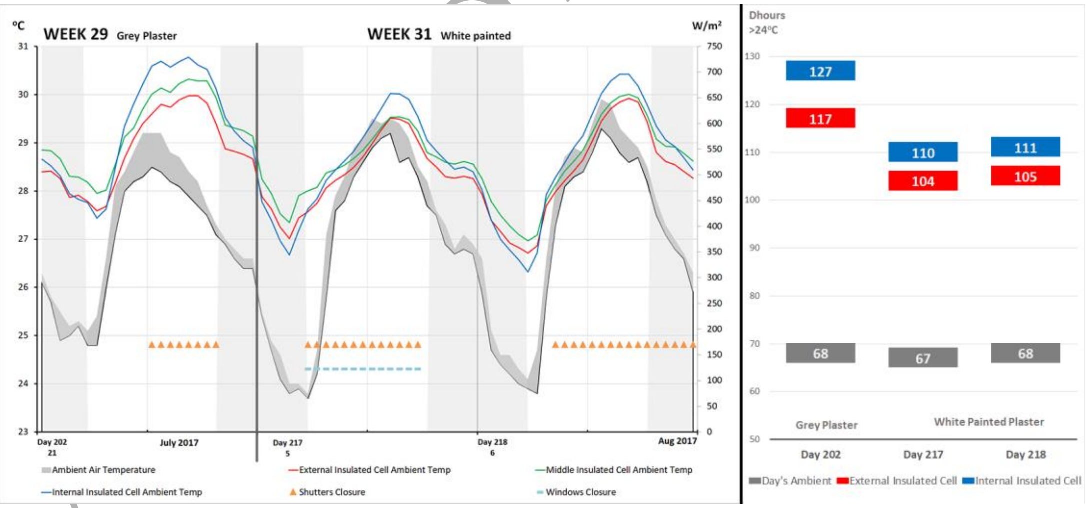


Figure 8. A comparative study between best similar day temperature and total degree hours (Dh)above 24oC. It shows the impact of the white paint (days 217-218) with considerably less Dh than with the not painted plaster of day 202, although with the same full day Dh.

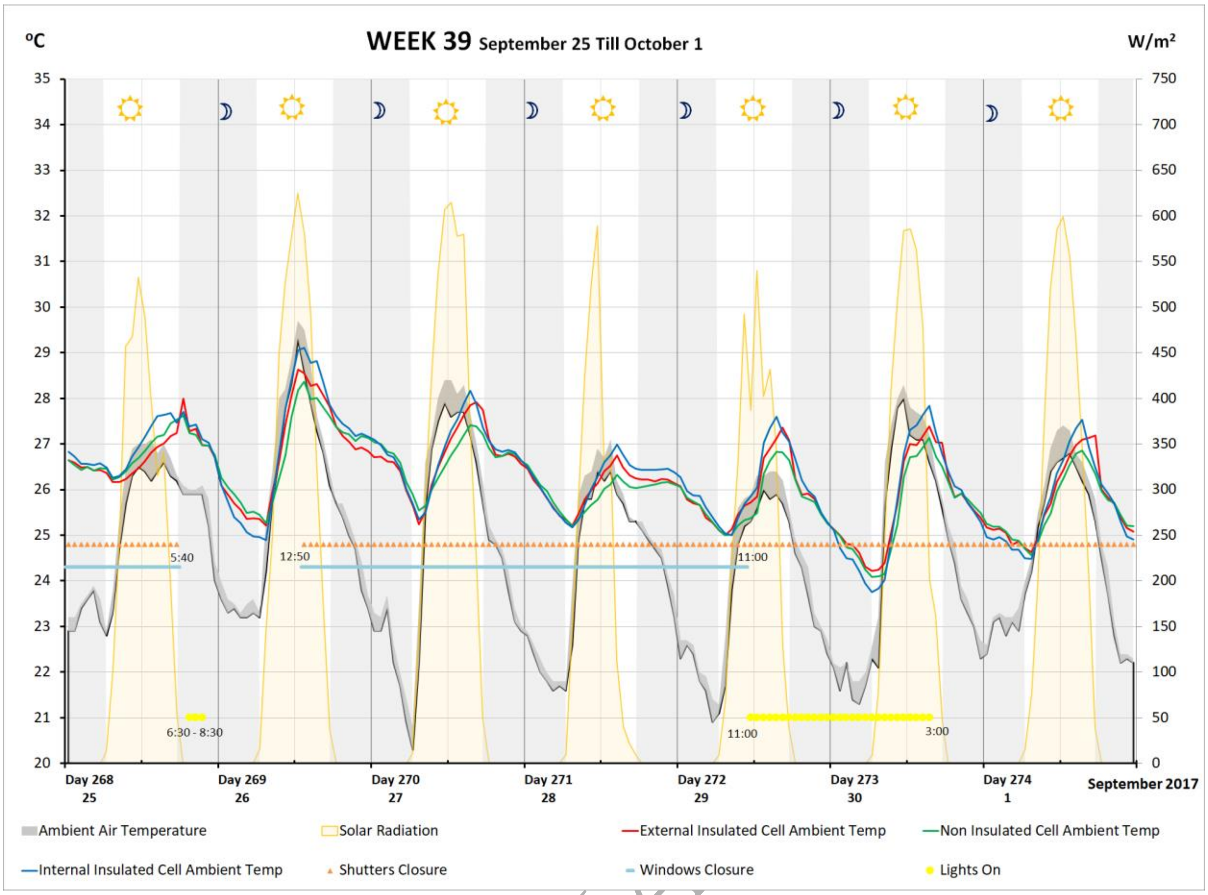


Figure 9. The Combined temperature graph for week 39 where the middle insulation is already removed, and the coolest temperature are for the non-insulated cell. Also on Day 272, the instantaneous effect of internal gains from the combine effect of the 3x100W incandescent light bulb is clear with a sharp rise in the temperature.

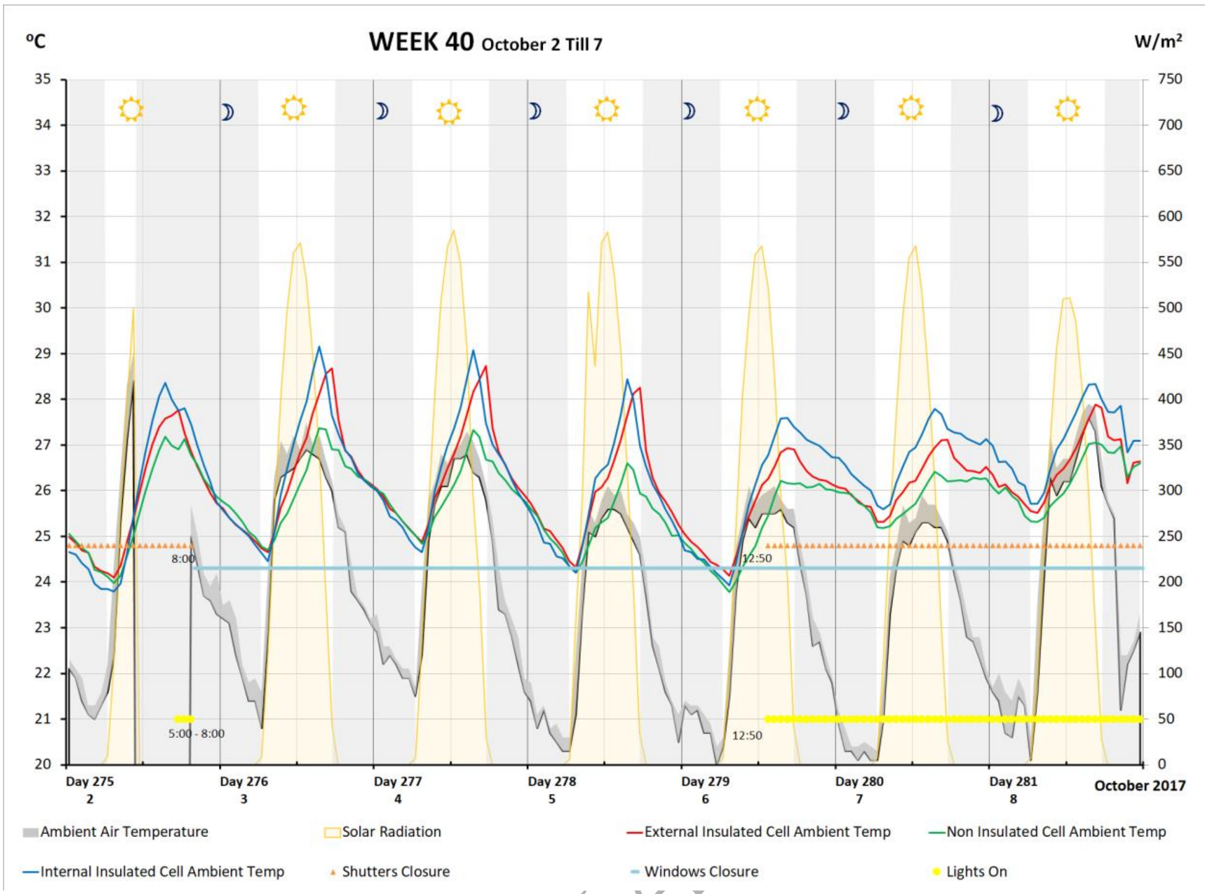


Figure 10. Combined temperature graph for week 40, with the non-insulated cells having the coolest temperatures when windows are kept closed (days 276-278), allowing the solar gains to be prominent inside the room. This resulted in a larger gap between the non-insulated cell and both the outer insulated and the inner insulated. For days 279-281 windows and shutters are closed but the 3x300W incandescent lamps are on, these kept temperatures on the rise, but with a less gap than produced by the solar gains.

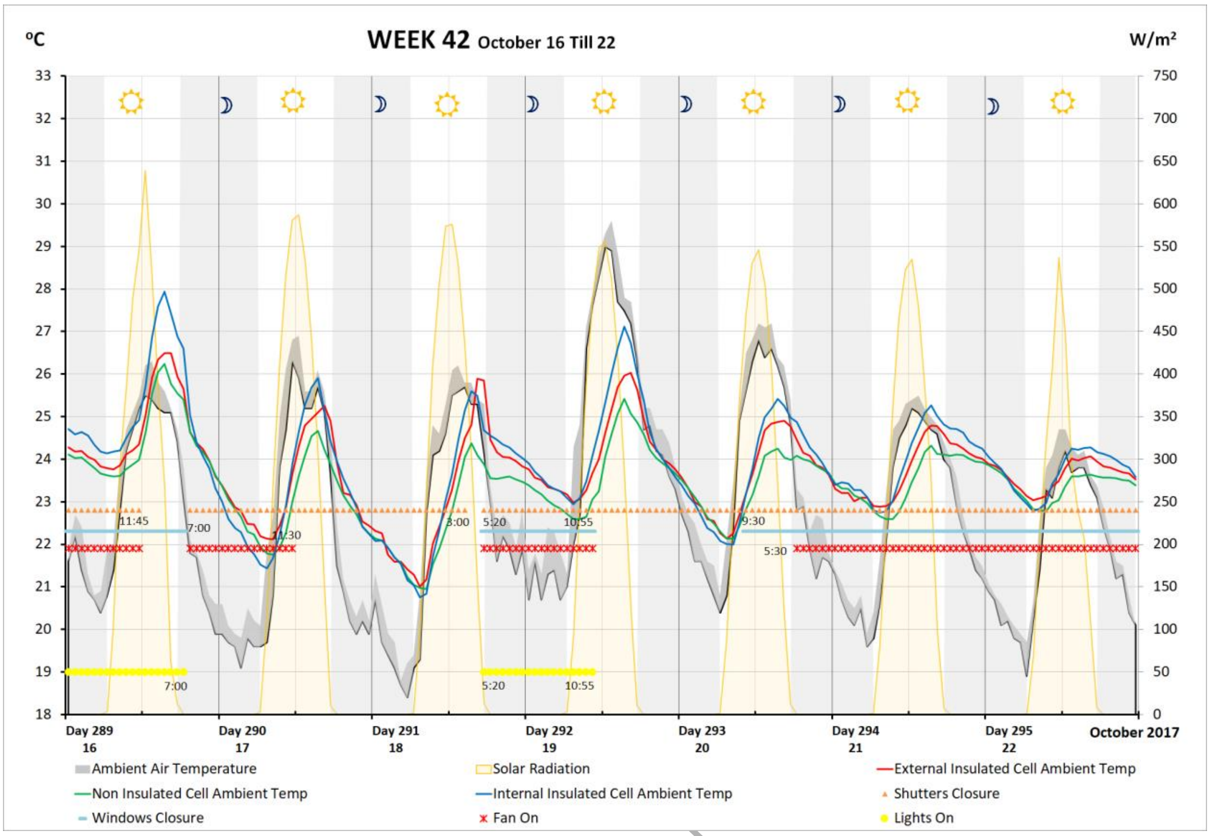


Figure 11. Combined temperature graph of week 42 with the ventilation fan on. No specific effect can be noted from the fans. The same thermal behavior is observed with the non-insulated temperature the coolest during the day, and the inner insulated the warmest.

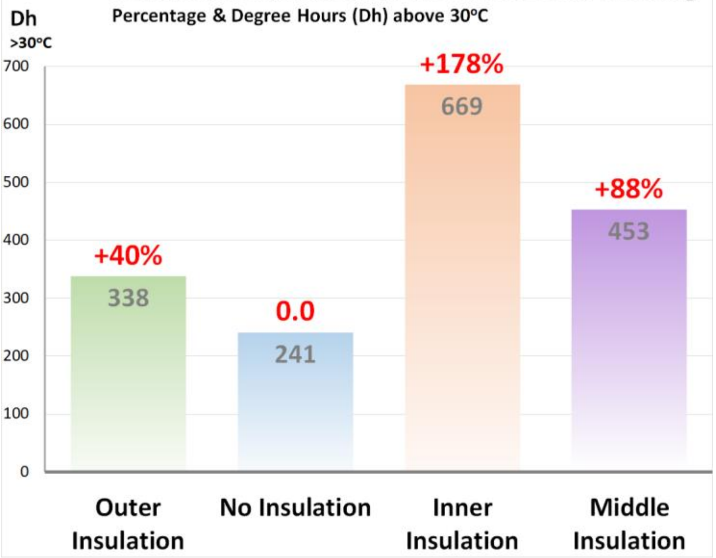


Figure 12. The performance indicator using overheating by degree hours above 30°C for the entire observed period. The lowest is the non-insulated followed by the outer insulation with 40% more overheating.

Combined PHASES 1 & 2, Weeks 25-34 & 36-43

	Weather	Outer Insulation	No Insulation	Inner Insulation	Middle Insulation
Mean Min Temp	22.99	26.16	26.12	26.06	26.61
% Increase from lowest		0.4	0.2	0.0	2.1
Mean Temp	**26.11**	**27.64**	**27.44**	**27.91**	**27.87**
% Increase from lowest		**0.7**	**0.0**	**1.7**	**1.6**
Mean Max Temp	29.00	29.30	28.86	29.76	29.47
% Increase from lowest		**1.5**	**0.0**	**3.1**	**2.1**
Δt Min-Max	**6.02**	**3.14**	**2.73**	**3.70**	**2.85**
Degree Hours Above 30°C	**203**	**338**	**241**	**669**	**453**
% Increase From Weather	**0**	**66**	**19**	**229**	**123**
% Increase From Lowest Test Cell		**40**	**0**	**178**	**88**
Hours Above 30°C	**218**	**435**	**295**	**685**	**556**
% Increase From Weather	**0**	**100**	**35**	**214**	**155**
% Increase From Lowest Test Cell		**47**	**0**	**132**	**89**

Table 1. All the different performance indicators combined. From the mean minimum temperature, to the mean temperature, and the mean maximum temperature. Follows the overheating by degree hours above 30oC as well as the hours of overheating above 30°C, both showing that the best performance is for the non-insulated, followed by the external insulated.