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Research Article

THERMAL RESPONSE TO COLD IN BUILDINGS WITH GREEN COVERS FOR TROPICAL CLIMATE; GREEN FACADES AND GREEN ROOFS

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ABSTRACT

The primary objective of the present study was to demonstrate the benefits that building using natural elements can provide to indoor environments when in low temperatures. For this purpose, an experimental procedure was carried out to enable comparison of the thermal behavior of four systems: a prototype called ‘Control’ (without vegetation), and three different combinations of vegetation (roofs and facades), installed in a tropical climate region. The internal surface temperatures, the internal air temperature, and the external environmental conditions were recorded simultaneously. The results obtained show that the use of plant systems in buildings did not deliver significant results for the type of climate studied. A difference in 1ºC regarding air temperature and in 2ºC for superficial temperatures were registered between the Control test cell and test cells built with vegetation.

INTRODUCTION

Due to the increase in population and the growth in urban centers, there have been significant environmental impacts as a result of the massive concentration of buildings, causing soil sealing, reduction of green spaces, and an increment in air pollution. All this leads to a thermal behavior modification at the microclimate level, generating what is known as an ‘Urban Heat Island’ (VECCHIA, 2005). In other words, the incidence of solar radiation directly on the materials that make up cities causes heating of these materials. In turn, these structures re-emit the captured heat to the atmosphere, which consequently increases air temperature. These factors lead to increased internal temperatures of buildings, resulting in the activation of electronic equipment to relieve the environment and, as a consequence, in the increase in energy consumption. One way to minimize this effect is to discover novel construction models that contain vegetation in their facilities.

The gradual concern regarding these issues has led to greater interest in more sustainable architecture. Green spaces inside cities can be considered indicators of environmental quality. The use of vegetation on roofs and facades is a technique that has a positive impact on urban climate. This result is due to the characteristics of the plants that create shaded areas, absorb some of the incident radiation, and encourage rainwater infiltration, also increasing relative humidity, all factors that minimize the ‘Urban Heat Island’ effect.

According to Dunnett and Kingsbury (2008), the use of vegetation in construction systems is a technique that has been used for centuries throughout the world to improve thermal comfort in buildings. This is one of the reasons why the technology has been currently accepted with keen interest. In addition to the environmental benefits offered, the technique improves interior thermal comfort and, thus, the energy efficiency of buildings. The use of Green Facades with climbing plants may reduce the internal temperature of

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buildings due to shading. Also, in the winter, this system provides protection from the cold and wind by forming a branched structure near the stem of the plant, avoiding losses of internal heat. The present work proposed the study of Green Facades and Green Roofs in a tropical climate area during a critical cold day. Experimental results of four test cells were shown, in which internal surface and internal air temperatures were measured, in order to subsequently compare test cells that presented and lacked vegetation. The final results verified the potential of vegetation on internal heat losses since the reduction of heat loss is one of the most useful parameters in improving indoor comfort conditions.

MATERIALS AND METHODS

The present project regarding plant covers in architecture aimed to evaluate the use of construction methods that cause less impact than conventional buildings and improve the comfort of indoor environments and energy efficiency. To do so, vegetation was planted in four experimental cells on the North (N) and West (W) facades, since those walls receive the most solar radiation during the day, as well as on the roof (Table 1).

Internal surface temperatures (IST) and Dry Bulb temperature (DBT) were measured using Type T thermocouples installed in the test cells. Data regarding solar radiation and other climate variables, such as air temperature, relative humidity, direction and speed of wind, were recorded in the automatic weather station at the Center for Hydric Resources and Environmental Studies (CRHEA) of the São Carlos School of Engineering, at the University of São Paulo (EESC-USP).

Table 1 Summary of test cell types used. Source: Gallardo (2017).

CONSTRUCTION	LOCATION OF VEGETATION
Control Test Cell (CC)	Without vegetation.
Test Cell 1 (GFC)	Green Facades (N & W)
Test Cell 2 (GRC)	Green Roof
Test Cell 3(GF+GR-C)	Green Roof + Green Facades (N & W)

The results of the present study were attained based on the analysis of a single critical cold day in the winter, defined as a day in which an extraordinary form of climate was registered. On that day, the minimum recorded temperature was lower than the absolute minimum temperature reported in historical data, registered in the Historical Climatological Series from 1961 to 1990. This series was published in 1992 by the Ministry of Agriculture and Agrarian Reform, at the National Department of Meteorology, in Brasília.

Data were measured by thermocouples installed on the North and West facades, and roofs of the four test cells, during the period from July 07 to 12, 2015.

Localization and characterization of the study area.

The present study was developed in Itirapina- SP, at the margins of the Lobo Reservoir, at 733m above sea level (Figure 1). Climate characterization in the area is complex since it is located in a transitional region between polar and inter-tropical atmospheric systems, and is considered as being of tropical altitude climate. According to the International Köppen Classification, the area corresponds to a Cwa climate, characterized by warm climate with dry winters, in which the average temperature of the coldest month is less tan 18°C, and the hottest month exceeds 22°C (FERRARI, 2012, p.25) (Figure 1).

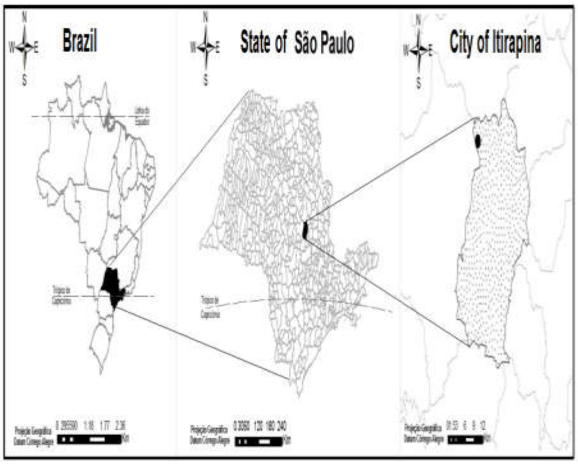

Figure 1 Location of the study area. Source: Gallardo (2017).

The test cells were built *in situ* with cement and sand, and their dimensions were 2.0 x 2.50 x 2.71 m. The roofs consisted of solid brick constructions with dimensions of 10.0 x 20.0 x 5.0 cm, placed on the cells with 1.5 cm thick joints. The cells had wooden doors with eastern orientation, whose dimensions were 2.10 x 0.60 m and wooden windows facing North, with standard measurements of 1.0 x 0.70 m (Figure 2). The test cells were designed in the same orientation, in order to receive equal amounts of solar radiation, wind, and other atmospheric events. This enabled the climatic conditions to act simultaneously and at the same intensity on each cell, as shown in Figure 2. Also, they did not create shadow zones between them.

Figure 2 Experimental cell overview. Source: Gallardo (2017).

Construction system and development of Green Facades and Green Roofs.

Green vegetation was installed on the North and West facades, since those receive more hours of sunlight. The green systems consisted basically of a 2.40 m wide and 3.0 m high metal hexagonal mesh, anchored to the ground and the facades by hooks. In order to not maintain direct contact with the wall, the systems were set up at an angle of 30º, from the ground to the top of the wall.

After placing the mesh to enable upward growth of the plants, and cover the entire surface of the facades, a *Thunbergia grandiflora*, from the family Acanthaceae, was directly sown at the bottom of the mesh from the ground. This plant is a low-maintenance vine from tropical and subtropical areas of the world. It is herbaceous, twining, dark green and simple, and contains opposite and whole green leaves. The *Thunbergia grandiflora* is commonly known as blue Thunbergia (3), blue trumpet vine, and blue Bignonia (MARTINEZ et. al, 2002).

Figure 3 Plant growth on wire mesh Source: Gallardo (2017).

The plant's annual cycle and growth are two critical components to ensure the role of the plant facades. Despite the consequences of working with living creatures, plants still exhibit relatively constant cycles regarding development. However, these guidelines are species-specific and depend on the climate in which the plant is located (PÉREZ, 2010).

Figure 4 Green facades. Source: Gallardo (2017).

The Green roofs were designed *in situ* on a pre-built ceramic slab with pre-constructed concrete beams at a 23% inclination, and 0.40 m parapets of ceramic brick, forming a 'drawer' on which the substrate was settled. As shown in Figure 5 and 6, the Green roofs were composed of a waterproof layer, a drainage blanket, substrate, and vegetation.

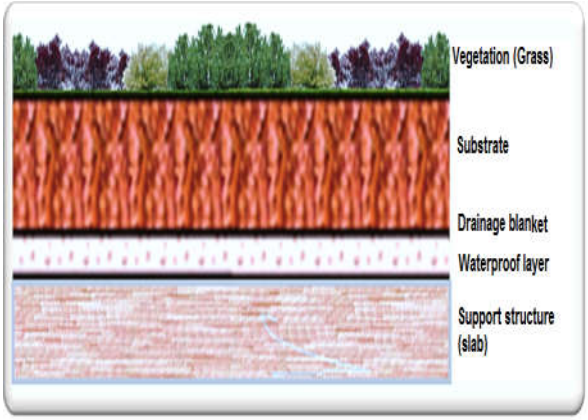

Figure 5 Green roof profile. Source: Gallardo (2017).

Figure 6 Construction of Green Roofs. Source: Gallardo (2017)

Each item that made up the system is described as follows: Geosynthetic blanket and drainage:

The drainage element used was a MacDrain® 2L geosynthetic blanket, used for drainage of highways and other civil constructions. The blanket is a mild and flexible feature, whose draining core consists of a tridimensional geo-mat, composed by filaments of polypropylene, measuring between 10 and 18 mm thick. For drainage, two PVC tubes were placed at the lower ends.Vegetation - Grass.

Paspalum notatum grass was used as vegetation to cover the Green Roofs (Figure 6).

Figure 7 Batatais grass – Forquilha species. Source: Gallardo (2017).

A native grass of the American continent, it is known in Brazil as Batatais grass, Forquilha grass, Mato-Grosso grass, pasture grass and Common grass (LORENZI; SOUZA, 2000), and its leaves are concentrated mainly in the basal part of the plant. One of the outstanding properties of this grass is its ability to quickly cover the ground, forming large mats. For this reason, it is used in football fields and green areas, including protection against soil erosion (KISSMANN, 1997). The species can adapt to poor soils, water deficit conditions, and is resistant to sunlight and treading, although it needs to be frequently cut to maintain good quality (GOATLEY *et al.*, 1998) (Figure 7).

Automatic measuring. Each of the prototypes contained 15 T-type 2x24 WG internal thermocouples, which are characterized as very precise instruments that can measure temperature with an error of ± 0.1-0.2°C (KINZIE, 1973). The measurements were here used to study the thermal behavior of the test cells. For this reason, 64 thermocouples were used, 16 per structure. In each test cell, 15 measured surface temperatures, and one was placed at the geometric center at an approximate height of 1.20 m, to determine the Dry Bulb Temperature (DBT), according to the ABNT NBR 15575-1 Standard, referred to in Annex A. The data was registered at 30-second intervals, and the totals, measured at every hour and recorded by a programmable data logger (CR1000, Campbell Scientific Inc., USA) connected to two 32-channel multiplexers (416AM, Campbell Scientific Inc., USA), which were both regularly calibrated. The battery was powered by a solar panel, which gave the equipment autonomy. Thermocouple distribution is shown in Figure 8.

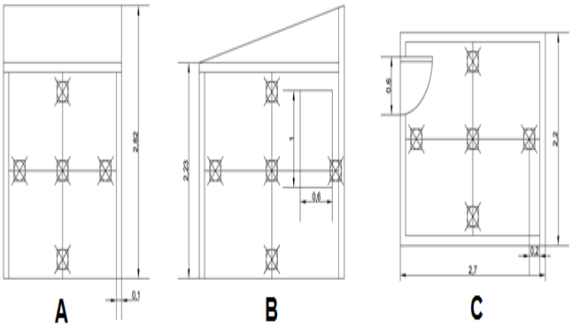

Figure 8 Distribution of type T thermocouples (Copper-Constantan). A- On West Facades. B- On North Facades. C- On roofs. Source: Gallardo (2017) (unscaled).

Experimental Results And Analyses

Climate analysis of the Critical experimental cold day - July 10, 2015.

Regarding the climate perspective used in the present study, the experimental critical day was defined considering the dominant atmospheric state during the testing period. It was used as a reference by the Climatological Norm (1961-1990), which was published in 1992 by the Ministry of Agriculture and Agrarian Reform, of the National Department of Meteorology (historical series of climate data from Brazil). According to VECCHIA (1997), in order to predict climate more accurately, climate analysis using representative episodes or observation periods of climate types is required. In other words, studying the intensity and duration of each dominant air mass in a particular area is related to the phenomena of atmospheric circulation. The consequences of the advance of a cold front over a given locality result in peculiar characteristics on each analysed season (Autumn, Winter, Spring and Summer). The city of Itirapina, from the point of view of dynamic climatology, is characterized as being part of a region of year-round cold front passage. The primary acting masses in the area can be divided into two main stages: Prefrontal and Postfrontal masses; which are, in turn, subdivided into two groups: harbinger and advance masses. These masses, which retain warm features, occur prior to the penetration of the Polar Atlantic Mass (PAM). Afterward, domain and transition phases occur, in which the PAM imposes weather conditions with cold and sometimes wet features (MONTEIRO, 1967).

In face of climate analysis regarding thermal behavior, the mentioned classification is beneficial since it facilitates determining the most appropriate stages in which to conduct experiments (VECCHIA, 2005). Data from external climatic variables used in the present experiment, on the day in question, were collected by the Climate Station of the Center for Water Resources and Environmental Studies (CRHEA), of the São Carlos School of Engineering, at the University of São Paulo (EESC-USP**).**

In the present study case, the episode from July 7 to 12, 2015 was considered for analysis. During this period, the Northwest region of the State of São Paulo was under the domain of a cold mass of air. Climate analysis of the selected day is shown in Figure 9.While analyzing the weather conditions during the month of July, one day was considered the critical experimental cold day (07/10/2015). On that day, the recorded climate was exceptional: 614 W/m^2 of solar radiation, and a minimum hourly temperature of 8.8ºC; less than the absolute minimum temperature described in the historical series (12.1ºC) for that period.

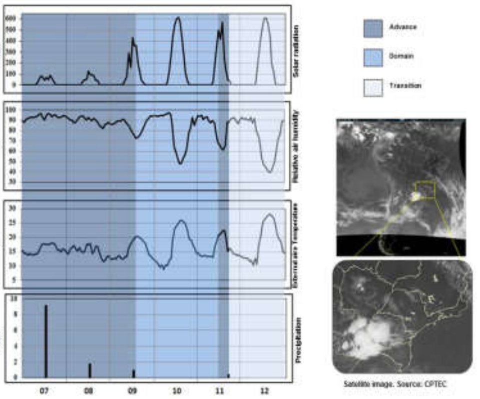

Figure 9 Climate analyses. Episode 7-12 July, 2015. Source: Gallardo (2017).

Thermal behavior: Internal temperature results on the critical experimental cold day: 07/10/2015.

Internal air temperature or Dry Bulb Temperature (DBT):

As indicated in the previous section, the experimental data of the present study, concerning the winter situation, were recorded on July 10, 2015. The graph in Figure 10 shows the internal air temperature (DBT), the external air temperature, and the thermal comfort limits.

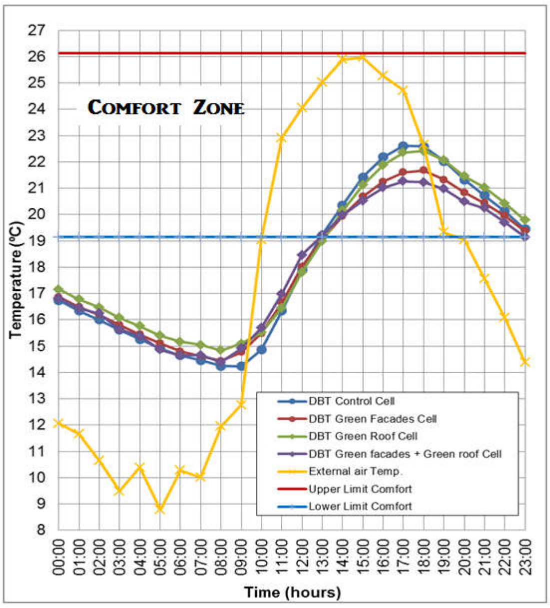

Figure 10 Evolution of internal air temperatures. Source: Gallardo (2017).

The confort limits and the quantification of degrees/hours of discomfort was determined, according to the adaptive method described in the ASHRAE- Standard 55 (2013).
The comfort limits were obtained from the following equations (ASHRAE, 2013):

Upper Limit 80% satisfied = 0.31 $t_{pma(out)}$+21.3 = 26.14ºC
Lower limit 80% satisfied = 0.31 $t_{pma(out)}$+14.3 = 19.14ºC
In the equations, $t_{pma(out)}$ corresponds to the central temperature in the comfort range, calculated as the average of the temperatures of the last 15 days; in this case, an average of 15.6ºC. This methodology sets the comfort limits for each day of the year, for either 80% or 90% of the people living satisfactorily in naturally ventilated buildings. In order to quantify the degrees/hours of discomfort, it was necessary to constantly compare hours, temperature limits (upper and lower), and the operating temperature registered in each of the test cells. The degrees/hour of discomfort parameter is generated when the internal temperature exceeds the limits set by the standard, in which positive numbers represent heat, and negative numbers, cold, as shown in Figure 11.

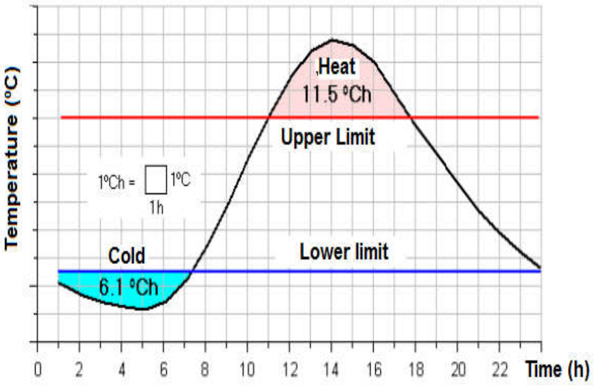

Figure 11 Degrees-hours of discomfort. Source: Roriz, Chvatal and Cavalcanti (2009).

The calculation of the result of hours of discomfort is shown in Table 2. Hours of discomfort by heat were not recorded, however, several degrees/hours of discomfort by cold were observed. The maximum value (47°Ch) was recorded in the Control test cell, and the minimum value (41.41ºCh), in the Green Roof test cell, followed by the test cell with Green Facades and a Green Roof (43.69ºCh). On the critical experimental cold day, as shown in Figure 10, the four test cells followed the same behavior during the early hours of the morning period. When the lowest external air temperature (8.78ºC, at 5 am) was recorded, the minimum internal temperatures (15°C) were registered in the test cell with Green Facades, the Control cell, and the Green Roof cell.

In contrast, at the same hour, higher air temperature was recorded in the Green Roof cell (15.4ºC). Also, it is noteworthy that since the minimum external temperatures were registered until the minimum internal air temperatures were recorded, a thermal delay of 4 hours was considered, since the minimum internal temperatures were recorded at 9 am.

Table 2 Degrees-Hours of discomfort. Source: Gallardo (2017).

DEGREES-HOURS OF DISCOMFORT 07/10/2015

CASES	HEAT	COLD
DBT CC	0.00	-47.3
DBT GFC	0.00	-44.2
DBT GRC	0.00	-41.4
DBT GF+GR-C	0.00	-43.7

The differences between the internal air temperatures during the evening period were not excessive. According to the data, the highest difference between internal air temperatures regarding the 4 test cells (only 2°C) occurred between the Control cell, built with conventional materials (22.6ºC, at 6 pm), and the cell endowed with Green Facades and a Green Roof (21.2ºC, at 6 pm). The behavior of the internal air temperature curves, when the maximum external temperature was registered (25.9ºC, at 2 pm), shows that there was a thermal delay of 4 hours between internal air temperature recordings (Figure 10). While an external temperature amplitude of 17ºC was observed, the indoor environments exhibited an approximate amplitude of 7ºC, regarding all the studied test cells, as shown in Table 3.

Table 3: Variations among internal air temperatures. Source: Gallardo (2017).

INT. AIR TEMP.	DBT (ºC) CC	DBT (ºC) GFC	DBT (ºC) GRC	DBT (ºC) GF+GR-C
Min. TºC	14.3	14.4	14.9	14.4
Max. TºC	22.6	21.7	21.4	21.7
ΔTºC	8.4	7.3	6.6	6.9

Internal Surface Temperature in North Facade cells

The internal surface temperatures (IST) of the North facades, as shown in Figure 12, during the early hours of the morning, when the minimum external temperatures were recorded, exhibited a difference between recorded values in the tested cells of approximately 1°C and 6°C, regarding the external temperature. The behavior of the test cells began to differentiate when the external temperature started to increase, recording, in the Control cell, the maximum measured temperature on the internal surface of the North facades of 25ºC at 5 pm. Subsequently, the next maximum internal surface temperature measured was of 24.1ºC at 5 pm in the Green Roof cell. In other words, both cells exhibited a 2-hour thermal delay when compared to the external air temperature (25.97ºC, at 3 pm).

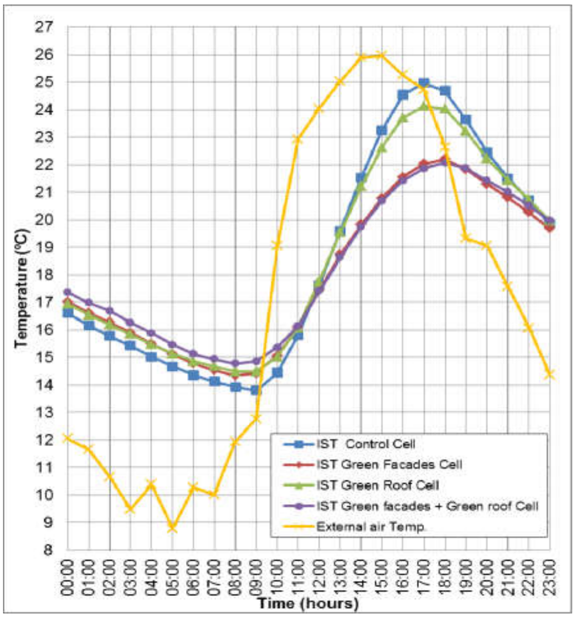

Figure 12 Internal surface temperatures of the North Facades vs. External air temperature. Source: Gallardo (2017).

At 6 pm, the minimum surface temperatures regarding the North facades were recorded in two cells in which the walls were covered with vegetation: The Green Facades cell and the cell with Green facades and Green Roof. The recorded temperature was 22ºC, that is, 2ºC less than the temperatures of the North facades lacking vegetation (Control cell and Green Roof cell). Moreover, regarding the maximum external temperature, the difference was of 3ºC. Given that the external thermal amplitude registered was 17°C, an internal thermal amplitude of 7°C was observed in cells with vegetation on the northern facade, and a thermal amplitude of 11°C in the control cell, it can be assumed that Green facades have more optimal behavior with respect to internal surface temperatures than facades built without vegetation (Table 4).

In summary, it is noteworthy that the highest thermal amplitude record was observed in the Control Cell, and the lowest, in the Green Facades and Green Roof cell (Table 4).

Table 4 Thermal amplitudes in North Facade cells. Source: Gallardo (2017).

NORTH FACADES	IST (ºC) CC	IST (ºC) GFC	IST (ºC) GRC	IST (ºC) GF+GR-C
Min. TºC	13.8	14.3	14.5	14.8
Max. TºC	25.0	22.2	24.1	24.1
ΔTºC	11.2	7.9	9.6	9.3

Internal Surface Temperatures on the West Facades

The West facades displayed similar behavior as the North facades, discussed previously. During the early hours of the day, when the lowest daytime temperatures were recorded, the lowest internal surface temperature was registered in the Control test cell. The remaining test cells showed almost identical temperatures, until the moment when the external temperature began to increase. The highest external temperature (26°C) occurred at 2 pm. On the other hand, the two test cells with no vegetation on their West facades (Control cell and Green Roof cell), exhibited the highest temperatures (22.8ºC) at 6 pm. Thus, an approximate difference of 3°C, with respect to the external temperature, was observed, as well as a 4-hour thermal delay. In contrast, lower temperatures were observed in both test cells with vegetation on their walls (Green Facades cell and the cell with Green Facades and a Green Roof), of 21.5°C at 6 pm. Thus, an approximate difference of 5ºC, with respect to the external temperature, was observed, in addition to a thermal delay of 4 hours.The internal surface temperatures on the West facades, as well as the external air temperature, are shown in Figure 13. In Table 5, the thermal amplitudes recorded in each test cell are shown. It can be observed that the highest amplitudes occur in the Control cell (9°C) (built using conventional materials) and the Green Roof cell (8.2ºC). In contrast, the lowest amplitudes were observed in the Green Facade cell and the Green Facades and Green Roof cell (approx. 7°C).

Table 5 Thermal amplitudes on the West Facades. **Source**: Gallardo (2017).

WEST FACADES	IST (ºC) CC	IST (ºC) GFC	IST (ºC) GRC	IST (ºC) GF+GR-C
Min. TºC	13.9	14.4	14.6	14.8
Max. TºC	22.9	21.6	22.8	22.1
ΔTºC	9	7.2	8.2	7.3

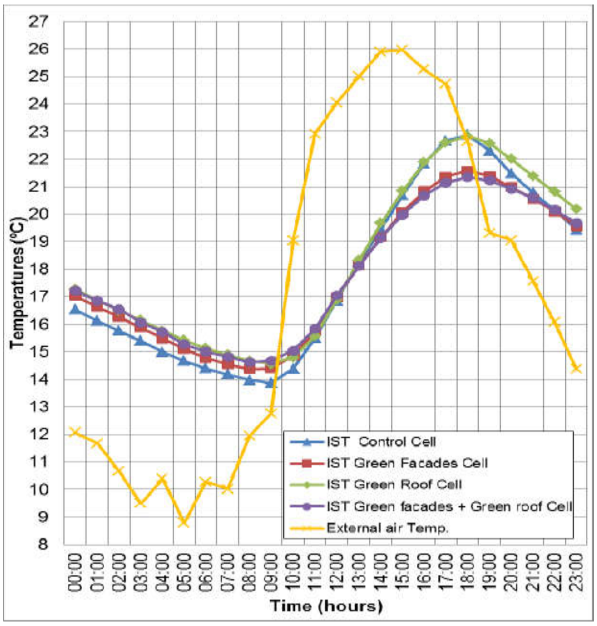

Figure 13 Internal surface temperature of the West Facades vs. External air temperature. Source: Gallardo (2017).

Internal surface temperatures of the Roofs

The evolution of the internal surface temperatures of the four roofs, over the analyzed period, is represented in Figure 14.

In the early hours of the day, when the lowest internal and external temperatures were recorded, the two cells with roofs constructed with ceramic tiles were described as having the lowest internal surface temperatures. In turn, the two cells with vegetation on their roofs had the highest internal surface temperatures, although this difference in temperature did not exceed 2°C. Nevertheless, there is an approximate difference of 8°C in external temperature, regarding the test cells equipped with vegetation on their roofs. In addition, a thermal delay of three hours was observed.

During the part of the day where the recorded temperatures were the highest, corresponding to the afternoon period, the highest internal surface temperature was observed in the test cell constructed with conventional materials (22.8ºC, at 6 pm), followed by the cell equipped with Green Facades (22.1ºC, at 6 pm). In contrast, the lowest temperatures were described in the test cell with Green Facades and a Green Roof (20.6ºC, at 7 pm), followed by the Green Roof cell (21.5ºC, at 7 pm). A thermal delay of 4 hours was described during the evening period between cells built with vegetation on their roofs, while the cells constructed with ceramic tile roofs recorded a thermal delay of 3 hours. The lowest thermal amplitude (~5ºC) was recorded in the test cells covered with vegetation, both on facades and the roof, and the highest thermal amplitude (~8°C) was recorded in the Control cell, built with conventional materials. Table 6 summarizes the indicated thermal amplitudes.

Table 6 Thermal amplitudes on the Roofs. Source: Gallardo (2017).

ROOFS	IST (ºC) CC	IST (ºC) GFC	IST (ºC) GRC	IST(ºC) GF+GR-C
Min. TºC	14.1	14.2	15.9	15.4
Max. TºC	22.8	22.1	21.5	20.6
ΔTºC	8.7	7.9	5.6	5.2

CONCLUSIONS

Regarding the present study on thermal behavior with the use of vegetation in construction systems during cold periods, it can be concluded that in tropical climate areas the use of vegetation in architecture has not exhibited substantial results. Also, we may conclude that plants reduce internal temperature variations. The internal temperature of the cells, in which vegetation was placed on the facades and the roof, displayed fewer variations. During the early hours of the day, in which lower external temperatures were recorded, the internal temperatures were higher.

During the periods in which the highest external air temperatures were recorded, the test cell equipped with Green facades and a Green roof showed lowest thermal amplitude, i.e., it exhibited higher difficulty in transferring heat to the outside environment. The highest internal air temperatures were measured in the conventionally built cell, and the lowest, in the cell equipped with Green facades and a Green roof. The recorded difference between them was of 1.0°C. The internal surface temperatures of the areas with vegetation, on both facades and roofs, remained more resistant to daily temperature variations. The highest difference between the maximum internal surface temperatures recorded occurred between the Control cell's roof and the cell with Green facades and a Green roof, of 2.2ºC.

The internal temperatures recorded in test cells with vegetation displayed lower thermal fluctuations. If the intention of the use of vegetation in buildings is to maintain warmth, and that the temperature come closest to the needs of the inhabitant, according to the results obtained and with respect to the type of climate studied, it would be convenient to design a project that is consistent with the climatic conditions of the area in concern. The existence of different plant species with different types of leaves enables the use of a deciduous type of plant to grow during the summer. In this way the plant would protect the building from solar radiation, and during winter, its leaves would fall, and so the involving structures of the building would receive solar radiation directly and maintain heat in the internal environment. Furthermore, it can be noted that the use of vegetation in architecture is a viable technique with several possible applications in the studied climate. The method contributes, in addition, to environmental benefits, internal thermal benefits and improved thermal comfort for the occupants of the establishment.

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