Energy & Buildings 174 (2018) 31–43

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild

Experimental assessment of the thermal behavior of a living wall system in semi-arid environments of central Mexico

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ARTICLE INFO

Article history:
Received 6 February 2018
Revised 21 May 2018
Accepted 31 May 2018
Available online 19 June 2018

Keywords:
Green façades
Living wall
Semi-arid climate
Experimental measurements
Thermal performance

ABSTRACT

The City of Queretaro is located in a semi-arid region that receives an elevated annual solar radiation (2200 kWh/m^2 in AVG) with high UV factor indices (6+ in AVG) and a low rainfall accumulated throughout the year (550 mm in AVG), which represents a serious problem that affects the environment, buildings and finally people. The aim of this work is to illustrate the behavior of living walls and their beneficial effects under such semi-arid environments in central Mexico.

The present study monitored two experimental huts, built with the most common materials used for Housing in Mexico. In one of them a living wall was placed at the south façade, while the other served as a control bare wall. Temperature and humidity sensors were located inside the huts and between the wall layers. Data about inside and outside conditions of the buildings were collected to evaluate: (a) temperature reduction inside huts; (b) rainfall and water demand of the living wall; (c) temperature and solar radiation transfer on buildings. Results demonstrate that living walls on such climate conditions, help to improve time and percentage of loss/heat gain of the enclosure, increase permeable green surfaces and favor social interaction.

1. Introduction

The construction of social housing in Mexico has historically been determined by budget; the smaller the budget, the smaller the house. The size of the house as a result serves as the principal guiding axis for the design and construction of Mexican social housing, following government guidelines; in 1930 social properties had to meet a minimum floor area of 44 m^2, this then increased gradually to its historic peak of 58 m^2 in 1980 and currently stands at 38 m^2 [1–3]. Moreover, the design and construction is also influenced by the geographic location of Mexico, which falls on the boundary of three tectonic plates, increasing the probability of natural disasters such as earthquakes. As a result, structural safety can be considered as the second most important guiding axis in design and construction. Subsequently, bioclimatic design and thermal comfort conditions are often neglected and not considered to be of great importance to housing developers [4].

The Mexican Institute of the National Fund for Workers' Housing (INFONAVIT) is a public entity which manages a national housing fund, made up of a 5% salary contribution from all private employees in Mexico. With this fund, INFONAVIT then grants mortgage loans, and acts as an intermediary between housing developers and families who are interested in buying a home. To ensure social housing meets a good quality standard, INFONAVIT uses inspection companies, who determine that the properties and housing developments are completed under certain quality parameters. The inspection companies have to certify a "Unique Technical Dictum" of habitability [5], which evaluate the following criteria:

- If the house and the housing development have electricity.
- If the house and the housing development have potable water.
- If the housing and the housing development have drainage and sewerage.
- If the house and the housing development have adequate physical and security conditions.
- Note there is a further section entitled "Report of attributes and ecotechnology solutions for energy saving". Buildings can gain quality points for these features, but, unlike the others, this criteria is not mandatory.

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https://doi.org/10.1016/j.enbuild.2018.05.060
0378-7788/

Furthermore, Mexico is experiencing a period of exponential growth in population which, in turn, is leading to serious housing issues in the cities. There is mass migration of people from rural areas to cities and with this migration a chain effect occurs; more houses are built, the areas around the cities are paved, a lower amount of green areas avoids rain water absorption, temperatures inside the cities are rising causing a heat island effect due to larger amount of non-permeable surfaces. In addition, World Health Organization states that 9 m^2 of green space per inhabitant is needed to prevent chronic respiratory problems. The Metropolitan area of Queretaro City (formed by the municipalities of Querétaro, Villa Corregidora and el Marques) with 1,097,025 inhabitants (2010 census) have only 5 m^2 per inhabitant, meaning that more than 4,000,000 m^2 of green space are needed.

The state of Queretaro is located in a highland (1,820 MASL) semi-arid region (a BSh classification according by Köppen and Geiger scale) in the center of Mexico (20°35′15″N 100°23′34″W). Since 1980 the state has had one of the most important population increases in the country going from having 739,600 inhabitants in 1980 to 2,038,800 inhabitants according to the last population census of 2015 [6]. Particularly the city of Queretaro has experienced a high rate of urban growth of about 33% (more than 360,000 inhabitants) between 1990 and 2010 [7].

The main causes for this population growth are; better quality of life than in most neighboring states, lower rates of delinquency, better and greater public services, direct communication with the Mexican capital (less than 2 h drive), new industrial and technological corridors that demand skilled labor and one of the largest scholar offers (more than 15 universities by 2015) among others [8], Climate change according to Nawrotzki et al. [9] is another cause, as the decrease in precipitation in dry lands in Mexico are forcing people to migrate. Although the good quality of infrastructure and services in Queretaro, the quality of life related with the hygrothermal comfort inside homes is not reached for several reasons:

- Traditional construction materials (e.g. clay bricks and cement bricks/blocks) used for Housing in Mexico, does not contemplate the use of insulation, and therefore "*U* values" (thermal transmittance) goes from 1.6 to 2.0 W/m^2K [10].
- Daily maximum temperatures exceed 28 °C almost all the year, and minimum daily temperature increased at a rate of 0.751 °C per decade during the period 1982–2011 [11].
- Until 2016 thermal comfort has not been contemplated among the objectives for the Federal Housing Bureau neither for the contractor and house builders.

The warmer period of the year for the city of Queretaro goes from April to mid-June (when begins the hurricane season and with it the heavy rain storms period), the annual precipitation is about 500 mm, a solar radiation along the year that goes from 4.0 to 7.5 kWh m^2/day (Fig. 1). UV maximum index range from 6 (for winter season) to 9 (for the rest of seasons). Moreover, according with the findings of Becerril-Piña et al. [12], Queretaro is under extreme risk of desertification with a ratio of 34 km^2/year.

Several studies have demonstrated the use of vegetation in cities represents benefits linked to the ability of plants to use most of the solar radiation received for their biological functions [13–21]. Contrary to what happens with other surfaces exposed to solar radiation, vegetation does not overheat and its temperature remains similar to the temperature of the air [23–27,38] improving hygrothermal conditions. The integration of plant systems therefore, enable the design of envelopes that promote energy savings and respond to specific environmental conditions, in addition to increasing green areas in cities [28–30]. Colunga et al. [31] states that increasing the urban zone canopy cover by 50% would reduce the urban heat island effect (UHI) by 2.05 °C.

The potential of Vertical Greenery Solutions (VGS), improving the thermal conditions of the interior of buildings has been extensively studied in recent years [32–36,47,48], but not for this specific climate under study. An experimental study was implemented to design an ad hoc solution for this climatic zone, looking to improve internal thermal conditions in homes and increasing permeable green areas, for a city that is suffering an effect of desertification due to the increase of its population.

2. Case of study

2.1. Experimental huts

To recreate the real conditions in which people live in the city of Querétaro, two experimental huts (H1 and H2) were built following the construction system most used in the area for the construction of houses. Fig. 2 shows the huts before the insulation and monitoring equipment were installed. Fig. 3 shows the inside of one hut with the sensors of temperature and relative humidity already installed. Both huts have identical dimensions (interior of 2.50 m length × 3.20 m width and 2.30 m height) and same orientation N43 °W, with 15.00 m of separation in between.

In hut H2 a living wall (LW) was installed in the southern façade (Fig. 4) as a bioclimatic strategy to improve inner thermal conditions as well as get better environmental conditions, while the hut H1 served as a control building to monitor the temperature variations of the bare wall (BW) of the southern façade. Huts were built using the same traditional construction system consisting in a monolayer wall made of:

- Annealed clay brick (7.00 × 12.00 × 24.00 cm).
- Cement/lime/sand plastering on both sides.
- Reinforced concrete slab 10 cm thick (with steel reinforcing rods and a concrete compressive strength of 19.60 MPa).
- To provide the slopes in the roof slab a mortar filling of lime-cement was used.

To minimize interior temperature variations due to thermal bridges, 5.00 cm of XPS was installed throughout the interior of the huts except in the ground (Fig. 5). It is necessary to highlight the big difference that exists in thermal transmittance of the huts built with insulation in comparison to traditional homes that don't use this material (Table 1).

The main geometric features of the prototypes are listed in Table 1. Total area of the south façade is 7.13 m^2 (3.10 × 2.30 m) and the total area of the living wall is 5.46 m^2 (2.10 × 2.60 m) which covers an extension of 76.57% of the southern façade. The area of the cover for rainwater recovery is 9.80 m^2. And the total volume inside the hut is 22.54 m^3.

To record the variations on temperature inside the huts, two surface temperatures (ceiling and south façade) were placed as well as a third temperature sensor located between the bare wall and the insulation to measure the contributions of the living wall to the envelope without the insulation (Fig. 6).

3. Sample and methods

3.1. Green module system

There are a vast number of examples to build a living wall [37–42], with different irrigation systems [42,44,45,48] (general or focalized) with or without substrate, different substrate layer size [43–45], different kind of substrate, dosage, fertilizer type and also different kinds and size of plants, etc [14,16–17,22]

The modular living wall system used in this project was formed by two parts: a container module and fastening element. The