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Evaluation of the thermal performance of an industrialised housing construction system in a warm-temperate climate: Morelia, Mexico

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ABSTRACT

This paper examines the performance of a case study of low-income housing situated in a warm-temperate climate (Morelia, Mexico). It represents the first comprehensive evaluation of thermal comfort in a widely used concrete formwork construction system in that country.

The study was conducted in two seasons, determined by climatic analysis identifying the months that presented the most extreme conditions during the year. Indoor thermal conditions were monitored and are compared with the adaptive comfort temperature and comfort zone derived from existing standards.

A thermal comfort field survey was also conducted, including the distribution of questionnaires in both seasons. The findings are compared with monitored data to assess the overall thermal performance of the housing typology.

The results reveal poor thermal performance with houses falling significantly outside the thermal comfort boundaries in both periods due to a number of factors, including the properties of the building envelope, the impact of solar radiation, the number of occupants and their behavior. The results indicate that it is easier for subjects to adapt to cooler rather than warmer conditions. These findings expand existing knowledge of the performance of this concrete formwork system in Mexico as well as other industrialised building systems in similar climates. It demonstrates the urgency of designing viable solutions according to local climate, and questions the use of identical housing prototypes across different climatic regions.

1. Introduction

The National Population Council of Mexico (CONAPO) estimated that in 2010 there would be nearly 30 million households, and by 2030 a total of 45.6 million households in the country, requiring the construction of an average of 780,000 new homes per year [1]. The Federal Government has arrived at a similar figure, proposing to create the necessary conditions to build 750,000 housing units per year [2]. As a result, federal agencies, international aid associations, and other private and public organisations have taken action to expand the housing sector in the country.

Highly capitalised developers control much of the housing market in Mexico, taking a lead role in the process of land acquisition, mortgage allocation, the marketing and delivery of new developments, as well as determining the design quality of new homes [3,4]. Large construction firms have adopted Industrialised Building Systems (IBSs) that allow them to build higher numbers of houses at lower cost through the production of repetitive prototypes and the industrialisation of key processes [5,6]. However, cost-savings are more often than not returned to shareholders rather than invested in improved design [3].

1.1. Energy demand in Mexico

Air conditioning or cooling represents the third largest electricity end use in Mexico with an average share of 24%, after refrigerators and televisions that have an average share of 35% and 26% respectively [7]. A significant number of new housing developments have serious comfort problems, reflected in a high consumption of energy [8]. Since 1996 the use of air-conditioning or other cooling systems has increased considerably, with an

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average annual growth rate of 7.5%, compared with an annual growth in housing stock of 2.7% (see Fig. 1).

The World Bank estimates that electricity consumption from air-conditioning in Mexico might increase ten times by 2030, easily exceeding the current energy consumption of the entire residential sector [9].

Reducing greenhouse gas emissions from the residential sector is therefore a priority in Mexico; but if this is to happen a more viable construction solution to meet housing demand has to be developed. This study contributes to this effort by examining the major issues regarding thermal comfort and energy efficiency that arise from the use of precast concrete systems.

1.2. House construction in Mexico

Mexico has a rich tradition of environmentally responsive vernacular architecture, including the use of heavy weight materials in response to the warm climate. In particular, adobe houses have been constructed in Mexico since the pre-colonial period, and are still found throughout the country, with tiled roofs in mountainous regions characterised by higher levels of rainfall, and *terrados* or flat roofs in drier climates. Lighter weight *Bajareque* construction, comprised of latticework covered in straw-reinforced loam, is found in more humid areas of the country, particularly on the Pacific coast. Both form of construction retain heat during the day, which is released to the environment at night as the indoor temperature falls [10].

The influence of these vernacular traditions can be seen in the bioclimatic strategies evident in the work of Luis Barragán, who also used high capacitive materials, and a range of external spaces such as gardens, terraces, porticoes and courtyards to provide opportunities for adaptation to warmer conditions through a range of indoor-outdoor environments [11].

More recently, the need to increase the volume of housing for low-income families has meant that industrial processes employing new construction materials have replaced traditional building techniques. As with the Concrete Formwork System investigated in this study, these new strategies differ from traditional construction techniques through a more efficient use of materials (e.g. thinner walls), but rarely incorporate energy-efficient solutions such as the use of insulation or double-glazing.

2. Background

Morelia is located in the central area of Mexico (19.7° north, 101.2° west). It is 1,929 m above sea level and has a built area of 1250 km^2. This study examines the largest low-income housing development in Morelia, with around 14,000 homes, constructed between 2007 and 2014. The modularity and repeatability of the construction process, together with the large available sample, provide an opportunity to study the performance of a specific building typology under a variety of orientations and environmental conditions. The involvement of the developer was crucial in this research; providing detailed information about housing design, materials and the industrialised construction system used.

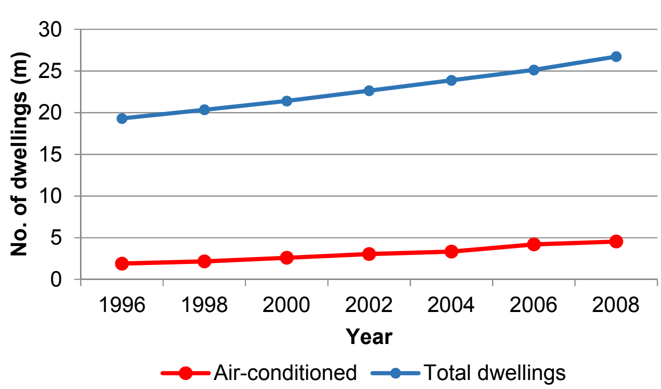

Fig. 1. Number of air-conditioned dwellings in Mexico. Source: (Rosas-Flores et al., 2011).

2.1. Building envelope performance

Previous studies have reported positive findings from the use of multi-layer construction strategies for houses in warm climates such as Turkey [12] and Mexico [13]. Findings indicate that when two construction systems with the same thermal resistance and thermal capacity are compared, the system with more layers results in an improved thermal performance, defined as a reduction in the decrement factor or increase in the time lag (see Section 3.2.). Other studies have investigated the optimum location and distribution of insulation layers, for example in Mexico [14] and Saudi Arabia [15]. Notably, they found that installing the insulation layer on the exterior rather than the interior side of the building envelope also results in an improved thermal performance.

While these studies investigate the relative thermal performance of different configurations of the building envelope, little data has been collected on the thermal comfort of houses constructed employing the industrialised building systems widely used in Mexico today (Fig. 2).

2.2. The concrete formwork system

The Concrete Formwork System uses two main components: concrete and steel or aluminium reinforcement; allowing accurate calculation of material inputs and as a consequence, reduced waste. Working in this way, significant savings can be achieved and higher profits can be achieved [3].

All elements of the house are cast simultaneously by pouring the concrete in the formwork, which is positioned to form walls and ceilings. The uninsulated floor, wall and roof fabric has a u-value of approximately 3–4W/m^{2}K. Prefabricated details are added in a final stage. Aluminium-framed, single-glazed sliding windows (u-value: 5.7 W/m^{2}K) are installed. This systematic process of identical and repetitive actions is a linear method that can be easily replicated, allowing total control of housing production. Typically the houses are constructed without insulation, and the only means of climatic control is cross-ventilation by opening windows (Figs. 3 and 4).

2.3. Thermal comfort studies in tropical and subtropical regions

Over the past couple of decades, numerous thermal comfort studies have been conducted in both tropical and subtropical regions, including China, India, Nepal, Bangladesh, Sri Lanka, Singapore and Mexico. Table 1 reviews some of these thermal comfort studies conducted in naturally ventilated buildings. Neutral temperatures in Aw-type tropical climates range from 28.0 to 30.9 °C. In Af-type tropical climates a similar range is evident, from 28.5 to 32.3 °C. In C-type subtropical climates the range of neutral temperatures is smaller (between 28.0 and 29.1 °C) in the warm season. These studies suggest that occupants in tropical and subtropical regions have a higher temperature tolerance and feel comfortable in warmer environments. The field studies carried out in Mexico are reviewed in more detail in the next section.