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The impact of built environment on thermal comfort in informal settlements. The case of José Carlos Mariátegui, Lima, Perú.

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Abstract

Building energy simulation is little used in Lima, Perú where the generally mild climate means little energy is used for space heating and cooling. This study is the first attempt to explore thermal comfort for marginalised communities living in self-built accommodation and finds a significant thermal comfort gap largely driven by inadequacies in building materials. To carry out the necessary measurements, a meteorological station and 15 data loggers were installed in 3 archetypes identified in the study neighbourhood. The clear link between building materials and internal conditions suggests an important role for urban building energy simulation to enable communities with severely constrained resources to explore the impact of different interventions.

Key Innovations

- The first exploration of comfort or thermal performance of buildings in informal neighbourhoods in Lima or Peru.
- The study was carried out in a pandemic situation, which complicated the creation of a bond of trust with the population, who on some occasions expressed distrust of the measuring devices.
- Dialogue with local assistants, trained during the project, made it possible to develop a technology transfer and mutual transmission of knowledge.

Practical Implications

While building energy simulation has not been much employed in Lima due to the mild climate and low levels of energy consumption for space heating or cooling this study shows a clear thermal comfort gap for the most vulnerable households. This is exacerbated by financial constraints and inaccessibility of dwellings. This study indicates an important role for building energy simulation, particularly at the community level, to enable potential adaptations to be evaluated prior to implementation.

Introduction

This research is part of a larger project which aims to analyse and propose improvements in access to housing and energy in informal settlements in Lima and Ahmedabad within a research-action process. The project takes place over three years and is broken down into four work packages (WPs). The first work package (WP1) focused on governance and planning processes in terms of energy and housing, while the second one (WP2) studied the daily practices of the inhabitants in terms of energy access and consumption and in their influence on the comfort of the home and the spaces used. The findings presented in this document become the link between WP2 and WP3, providing data on the thermal performance of the housing archetypes and their ability to provide comfort. This will allow modelling and simulation at the building and urban level of the study neighbourhoods (WP3). With this, it will be possible to propose improvements in housing and arrive at proposals for archetypes capable of providing thermal comfort in marginal neighbourhoods (WP4). In the case of Lima, work is being done in three emblematic settlements that are in different stages of development: Barrios Altos, El Agustino and José Carlos Mariátegui. Barrios Altos has a unique typology that comes from the colonial era (1500) typically composed of mansions and villas made of adobe and *quincha* (a traditional construction system of walls of the Peruvian coast, made up of a framework of reeds and plastered with mud on both sides), in very precarious conditions today. El Agustino represents a type of consolidated neighbourhood, the result of successive invasions since the 1950s. José Carlos Mariátegui is a settlement of more recent formation (1990) that is similar in its organization and evolution to what happened in El Agustino neighbourhood a few decades back, which is the focus of this article.

It is worth mentioning that there are no previous studies on thermal performance and comfort in dwellings in marginal neighbourhoods in urban areas of Peru, specifically in the coastal region with a subtropical coastal climate. The studies carried out focus on rural areas, where poverty is compounded by the presence of much harsher climates. On the Peruvian coast, the few existing studies were carried out in middle-class homes in warmer cities such as Chiclayo (Perleche, 2019) or Piura (Espinoza, 2020). In all cases, the passive strategies of natural ventilation, solar control and thermal mass end up being the most important strategies to achieve thermal comfort.

Lima climate

The city of Lima has a very particular climate. Despite being located very close to the Equatorial Line (12° south latitude) and at sea level, it has a maritime subtropical climate with relatively mild winters, with temperatures around 14°C in the coldest moments of the night and mild summers, with temperatures around 28°C at the hottest times of the day (Molina, 1999). Solar radiation is very intense in summer due to clear days and the great verticality of the solar path, but in winter the presence of low cloud cover is very common due to the thermal inversion phenomenon; Daily accumulated horizontal global solar radiation is around 5 kWh/m^2 in the summer and 2.5 kWh/m^2 in the winter, even though the difference in the length of the day between seasons is not very marked. Another peculiarity is that, despite the overcast sky, rainfall is practically non-existent, generally in the form of drizzle or drizzle, and it only accumulates around 20 mm per year.

Unlike the central area of the city, which has a flat relief, borders the coast and is more exposed to the sea breeze, the neighbourhood of José Carlos Mariátegui, even though it is part of the urban fabric, is located about 20 km from the sea, 400 meters above sea level and is on the slopes of the first Andean foothills. On the one hand, the climate is noticeably more continental, with a slightly greater daily thermal oscillation -one or two more degrees- with lower relative humidity and greater direct solar radiation almost throughout the year. This situation contrasts with winter, when the humid winds that come from the sea are trapped in the hills, presenting the *lomas* microclimate: extremely humid air, with recurring mist and drizzle, which conditions an environment that makes it difficult to inhabit the place and its time allows the temporary growth of vegetation (Paniagua 2017). In the upper part of José Carlos Mariátegui this phenomenon is clearly presented.

Informal settlements in Lima

The phenomenon of internal migration, from the countryside to the city, which has occurred in the country since the mid-twentieth century, generated an exponential growth in the population of large cities in Peru, particularly in the city of Lima. This phenomenon increased in the 70s and 80s and meant the occupation of a large part of the alluvial plain of the Rímac Valley. Since the 1990s, given the scarcity of habitable land, informal land occupation has been taking place mainly in hillside areas, with the difficulties of accessibility and security that this implies. Several authors have studied the issue of informal settlements in Lima (Matos Mar, 1977; Riofrío & Driant, 1987; Driant, 1991).

The implementation in 1996 of the Organism for the Formalization of Informal Property (COFOPRI) had the mission of achieving the regularization and titling of human settlements, but it indirectly ended up promoting the unplanned invasion of peripheral areas of Lima, in which, to date, of today, the settlers seek to legalize the occupied lands. This logic of land occupation, in which people live first and then urban services and infrastructures are implemented, leads the inhabitants of these areas to live in very precarious conditions for many years, acquiring little by little, thanks to a collective effort, the basic services to live in a minimally dignified way (Fernández Maldonado, A. M, 2015). At the national level, in 2017, approximately 850,000 households were living in inadequate accommodation and 250,000 households were without housing (INEI, 2016). By 2020 this housing deficit had grown to 1.5 million, 500,000 families without housing (and 1 million with poor quality housing) (Fort, R., & Espinoza, A. (2020)).

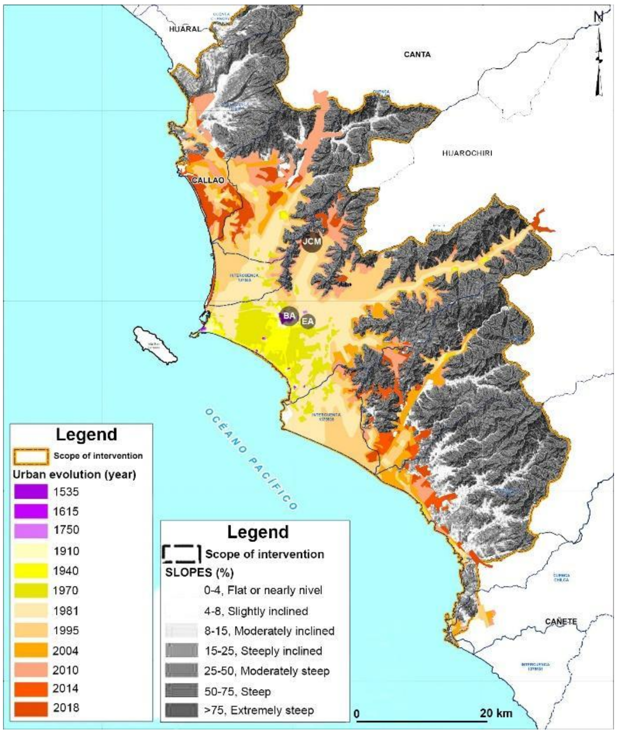

Figure 1. Map of Lima with informal settlements/slums. Locate JCM. Relief information (scale and north).

José Carlos Mariátegui neighbourhood

José Carlos Mariátegui (JCM) is a neighbourhood that emerged from informal occupations and is currently made up of houses in very precarious conditions. It is located on the slopes of San Juan de Lurigancho, the most populated district of the city of Lima with 1.162 million inhabitants (INEI, 2018).

The settlement of JCM has gradually expanded from the lowest slopes of San Juan de Lurigancho upwards. Interviews with community members suggest that JCM was populated little by little since 1985 by the same settlers from the lower zone who began to occupy the land in the upper part. Currently, it continues to grow in the upper part of the hills, where neighbours organize themselves to improve access to energy and services in general (see Figure 2). Most of the land remains untitled, the result of occupations in recent decades by people in search of better living conditions and job opportunities. The situation of the inhabitants is very precarious, many are in areas with steep slopes accessed only on foot via steps built into the hillside. This situation makes it difficult to carry out home improvements, which are generally made with light and cheap materials.

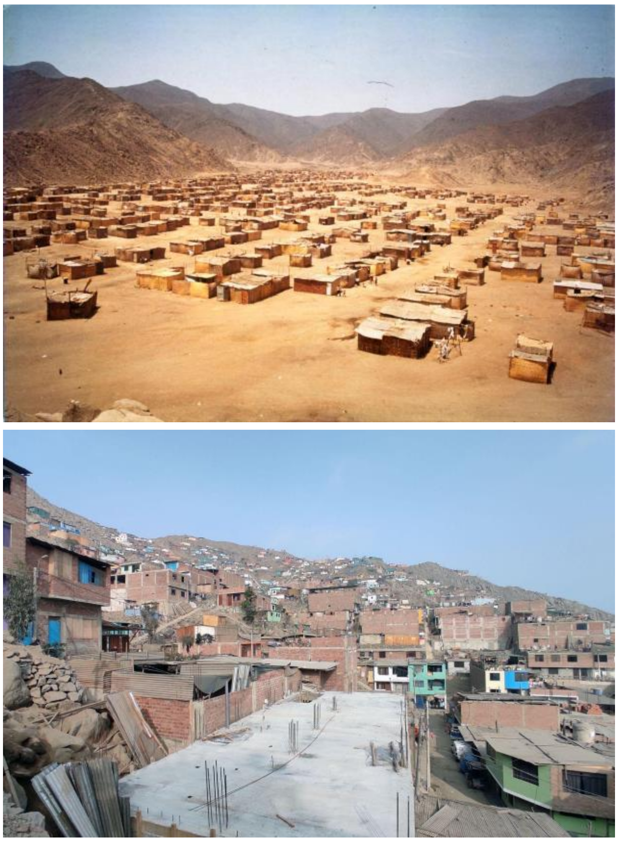

Figure 2. Views of the José Carlos Mariátegui neighbourhood in 1985 (upper) and today (lower).

Source of the photograph below: Documentation and Research Centre of the Place of Memory, Tolerance and Social Inclusion.

Dwelling archetypes in JCM

In JCM, three housing archetypes have been identified, representative of the current situations of the inhabitants. These archetypes correspond to the evolution of housing conditioned to the improvement of the quality of life of the inhabitants over the years (see Figure 3).

The recently settled inhabitants usually live in very precarious dwellings made of lightweight material, generally composed of walls of wooden boards (lightweight archetype). The roof is equally light, usually corrugated sheets of metal or fibre cement. To the extent that the family improves its purchasing power and has the ability to save, the walls are gradually replaced with hollow clay brick, confined with reinforced concrete columns and tie beams, providing increased thermal mass to the envelope.

However, the original lightweight roof of corrugated sheets is retained (intermediate archetype). The final objective of most of the inhabitants, for reasons of safety and comfort, in addition to allowing them to increase living space by extending accommodation vertically, is to replace the roof with a reinforced concrete slab, lightened with hollow bricks (substantial archetype); this ends up providing greater mass and insulation to the whole. To this last archetype an upper floor is usually added that will have a similar evolution, finally adding about 4 or 5 more floors in total. With a few exceptions, these archetypes and their evolution are repeated in the other informal neighbourhoods of Lima and the Peruvian coast.

Figure 3. View of housing archetypes: wood (light archetype, upper) and brick (intermediate and substantial archetypes, lower).

The thermal properties of the construction elements are summarized and presented based on their insulation capacity (thermal transmittance) and thermal inertia with the values of the decrement factor and time lag (see Table 1). The approximate values have been obtained from the Peruvian regulation EM 110 (MVCS 2016) and calculated through the Opaque3 computer tool (Liggett & Milne, 2021).

Table 1. Thermal characterization of the walls and ceilings of the archetypes and traditional architecture.

	Thickness (mm)	**U-Value (W/m^2°C)**	**Decrement factor**	**Time lag (hours)**
Timber wall	12.7	3.625	1	0.20
Brick wall	135	2.205	0.85	3.21
Corrugated metal sheet roof	0.3	4.545	1	0.01
Corrugated fibre cement sheet roof	4	4.199	1	0.07
Lightweight concrete roof	185	1.585	0.74	4.7

Methods

An outdoor weather station and 15 data loggers were installed in homes in the neighbourhood. The houses were chosen based on the construction materials, grouped into the three previously identified archetypes; eight in lightweight archetype houses made of wood or similar, three in intermediate archetype houses with brick walls and light ceilings and four in substantial archetype houses with brick walls and light concrete ceilings. The outdoor equipment was installed on the roof of the community centre, approximately six meters high and free from any immediate obstacles. The measurement equipment, its characteristics, and the conditions it measures can be seen in Table 2 and Figure 4.

Table 2. Measurement equipment

Equipment	Frame and model	Data
Outdoor weather station measurements every hour	Micro Station Data Logger / ONSET HOBO H21-USB Temperature/RH Smart Sensor ONSET S-THC-M00x in Solar Radiation Shield / ONSET RS3-B Silicon Pyranometer Smart Sensor / ONSET S-LIB-M003 Anemometer Smart Sensor / DAVIS S-WCF-M003	Temperature (°C) and Relative Humidity (%) Solar radiation (W/m^2) Wind Speed (m/s) and Wind Direction (°)
Internal sensors Measurements every 15 minutes	ONSET HOBO® U12 Logger ONSET Temperature Probe (6' cable) Sensor plus black sphere	Temperature (°C) and Relative Humidity (%) Radiant temperature (°C)

Figure 4. View of the outdoor weather station (left) and data logger inside a house (right).

For the placement of the interior recorders, the following criteria were considered: place of greatest use of the dwelling by family members, away from the kitchen or other artificial heat source, away from the sun and from least 1 meter from any doors or windows, at a height of approximately 1.20 and that it does not hinder the occupants. Every 3 months the information is collected and takes advantage of a comfort survey (Point in time) at each visit and a satisfaction survey (Building user survey) every two visits, one in summer and one in winter; both to assess the results with greater precision at the end of the measurements.

The measurements were made between January and June 2020 and will continue until the 12 months are completed. The results presented here are preliminary, in which it has been possible to measure the warmest and sunniest months (February and March) and a cold winter month (June).

As comfort surveys are continuing, the partial assessment of thermal comfort presented in this article is based on the CBE Thermal Comfort Tool (Tartarini et al, 2020), based in turn on the ASHRAE Standard 55 -2017 (2017). As mentioned in the tool, the conditions that have been met to identify comfort ranges are: Method is applicable only for occupant-controlled naturally conditioned spaces that meet all of the following criteria: (a) There is no mechanical cooling system installed. No heating system is in operation; (b) Metabolic rates ranging from 1.0 to 1.3 met; and (c) Occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions within a range at least as wide as 0.5-1.0 clo. Under these considerations, the formulas used to define the limits are:

Upper 80% acceptability (°C) = 0.31 x ($t_{pma(out)}$) + 21.3 (1)

Lower 80% acceptability (°C) = 0.31 x ($_{tpma(out)}$) + 14.3 (2)

where $t_{pma(out)}$ is the prevailing mean outdoor air temperature, an arithmetic average of the mean daily outdoor temperatures of the month.

The same ASHRAE Standard 55 allows the identification of the internal operating temperature from the simple average of the air and radiation temperatures, both recorded by the measurement equipment. This as long as the following conditions are met: (a) occupants engaged in near sedentary physical activity, (b) not in direct sunlight, and (c) not exposed to air velocities greater than 0.10 m/s. Once the operating temperatures of the dwellings have been identified and the limits of thermal comfort have been calculated, the thermal performance of the dwellings is assessed, based on the ability to provide thermal comfort at the two representative times of the year.

Results

The external climatic conditions recorded in the José Carlos Mariátegui neighbourhood are presented first (see Figure 5). Even though in the year 2022 the presence of a slightly colder sea has conditioned one of the least hot summers and one of the coldest winters in the last 50 years, the results were quite predictable, around one degree below normal.

As for solar radiation, this has been equally predictable in summer, but singularly high in autumn and winter days, in which there has been an unusual prevalence of days with direct solar radiation. The two two-week periods that are representative of the hottest and coldest times of the year, the first fourteen days of March and the first fourteen days of June, respectively, have also been marked.

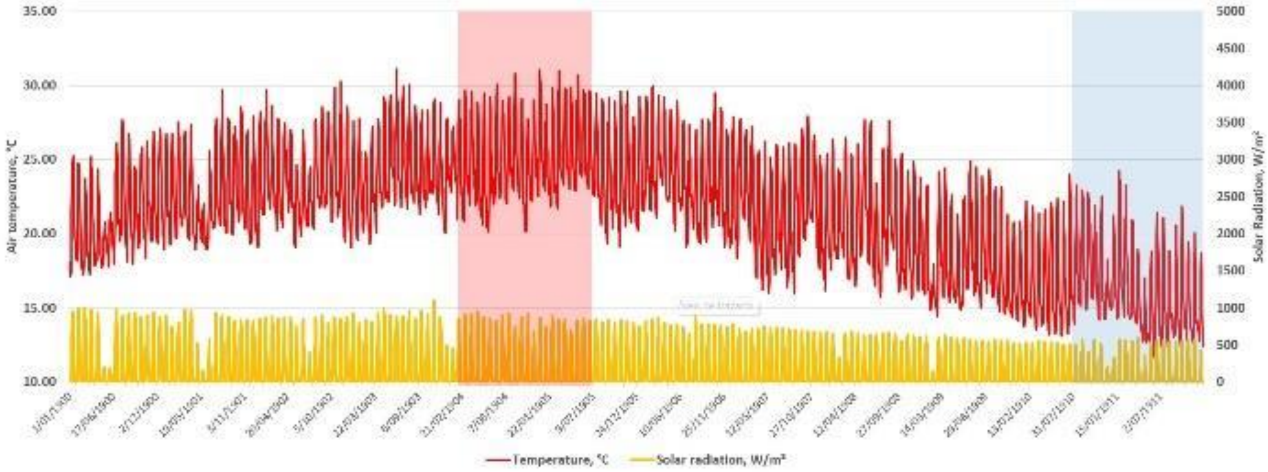

Figure 5. Outdoor conditions of air temperature and solar radiation

Figure 6. Operating temperatures in the dwellings in summer (upper) and winter (lower).

On a typical March day, outside temperatures ranged between 22°C and 30°C, relative humidity between 75% and 47%, and horizontal global solar radiation accumulated around 5 kWh/m^2 per day; In the case of a typical day in June, the temperature ranged between 14°C and 22°C, the relative humidity between 94% and 67%, and the daily radiation around 2.8 kWh/m^2. Wind speed is usually quite weak, although constant, with average speeds slightly below one meter per second.

In relation to the interior conditions of the dwellings, valued according to the registered operating temperatures, the values of average, maximum and minimum average and absolute maximum and minimum temperatures of each of the fifteen registered dwellings are presented first (see Figure 6).

It is clearly observed that the material is the determining condition of the thermal performance of buildings, even when sensitive differences are identified between the performances of the same archetype, associated with other aspects such as ventilation, orientation, size of openings, etc. Except for a house with a brick wall and a light roof that is noticeably warmer in summer, and a brick house that is noticeably colder in winter, the correlation between the construction material and the indoor operating temperature conditions is very noticeable. Also, regardless of the material, the average temperatures in all cases are very similar, but not the minimum and maximum conditions.

The results of the average hourly temperatures in the two representative periods are presented below, grouped and averaged in turn according to the three archetypes presented (see Figure 7). Hourly solar radiation has been added to the graph, evidencing a difference between seasons that responds both to the length of the day and the variation in altitude of the sun, as well as to the lower recurrence of cloudy days in winter. Finally, a strip is added that delimits the thermal comfort zone calculated according to the adaptive method.

It can be seen how the interior temperatures of the lightweight archetype replicate the pattern of the exterior temperature both in the hot and cold periods, being slightly higher at night and noticeably higher around noon. Relating the resulting temperatures to the comfort zone, there is evidence of excessive heat conditions on hot days (around a quarter of the time), as well as conditions of discomfort due to cold in the winter period (around two thirds of the time outside the comfort zone). This pattern is repeated, although with less intensity, in the intermediate archetype with brick walls, in addition to showing a delay in the passage of heat of about three or four hours. The great thermal stability of the substantial archetype with brick walls and ceiling is striking and allows the interior to be kept very stable and practically all the time within the comfort zone.

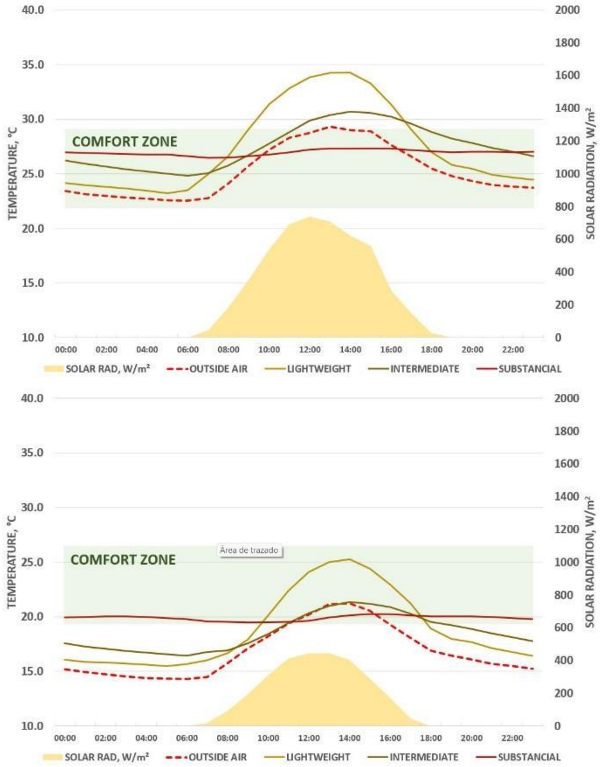

Figure 7. Outdoor air temperature and indoor operating temperatures in summer (upper) and winter (lower).

Discussion

Even though certain conditioning factors that influence the thermal performance of a building, such as ventilation or solar incidence, have not been considered, the individual results of the dwellings have coincided according to the archetypes, which shows that the construction material is decisive in the thermal results. In the case of lightweight archetype, the high conductivity, and the absence of thermal mass results in a very high internal thermal oscillation, without delay and that exposes users to uncomfortable conditions due to heat during the hottest hours of summer days and for cold for much of the night in the winter. The very high temperatures reached in summer are striking, around 34°C inside, even above 40°C in some cases, between 5°C and 10°C above the average outside temperature, which shows the low level of insulation and thermal inertia of the materials and ineffective natural ventilation in the face of high solar radiation. In the case of the cold season, for much of the day the interior conditions are not comfortable (fifteen hours, between six in the afternoon and nine in the morning), again evidencing the low level of thermal insulation, the low mass and a high level of infiltration.

At the other extreme, with a fairly regular performance in terms of operating temperature and thermal stability, the houses with brick and concrete walls and ceilings presented conditions of thermal comfort practically all day long, both in the hot and cold seasons. The houses with brick walls and light ceilings finally had an intermediate performance, with discomfort problems similar to those of the lightweight houses, but during shorter periods and with less extreme temperatures. The results finally allow us to identify a correspondence between the insulation and thermal inertia values presented in Table 1, as well as with the studies already carried out in similar areas and mentioned in the introduction.

Conclusion

It is possible to verify the hypothesis that with relatively low thermal insulation values, and with an intermediate thermal mass in walls and ceilings, comfort conditions are guaranteed in a climate as moderate as that of Lima. This reaffirms the value of the traditional architectures of both pre-Hispanic and colonial period which focus on construction solutions with high thermal inertia such as adobe or rammed earth; including *quincha*, of intermediate mass and good anti-seismic performance, in contrast to more modern approaches which rely on lighter-weight elements. It is important to pay attention to the aspirations of the inhabitants to build with materials such as brick and cement, also known as "noble materials". This aspiration of low-income families to build with these materials should not only be explained based on their association with security against theft and fire, durability and anti-seismic capacity, the ability to allow vertical growth that it implies a form of investment in an informal environment or even the recognition and feeling of social advancement that its use implies. The results show that it is necessary to add to these aspects the evident association that exists between these solutions and the ability to obtain thermal comfort. However, in addition to being relatively expensive for community members, brick and cement have significant environment impacts and are difficult to transport to the parts of the settlement without road access.

The next phase of this study will involve completion of data collection in JCM and two other informal settlements in Lima. This data will be incorporated into community-scale building energy models to allow the evaluation of a range of interventions to improve thermal comfort. The ultimate objective being to identify specific strategies which can be employed by communities to improve living conditions in existing and future homes.

Acknowledgments

[to be included following review]

References

Driant, J.-C. (1991). Las Barriadas De Lima: Historia e Interpretación. Lima: IFEA

Espinoza, L. (2020). Envolvente arquitectónica para la mejora del confort térmico en edificios multifamiliares certificados de la ciudad de Piura (2016-2019) . Lima. URP.

Fort, R., & Espinoza, A. (2020). Mapeo y tipología de la expansión urbana en el Perú.

Fernández Maldonado, A. M. (2015). Planeamiento urbano y producción de vivienda en el Perú. Proyectos urbanos en acción¿ Desarrollo de ciudades para todos?.

Instituto Nacional de Estadística e Informática Perú (INEI) (2016) - Encuesta Nacional de Hogares sobre Condiciones de Vida y Pobreza (ENAHO). Perú.

Matos Mar, J. (1977). Las barriadas de Lima. Lima, Perú: IEP

Ministerio de Vivienda, Construcción y Saneamiento (2016). Reglamento Nacional de Edificaciones. Norma EM.110 Confort Térmico y Lumínico Con Eficiencia Energética. Lima, Perú.

Molina, J. J. C. (1999). Lima, un clima de desierto litoral. In Anales de geografía de la Universidad Complutense (No. 19, pp. 25-45). Servicio de Publicaciones.

Paniagua Guzmán, L. J. (2017). Condiciones microclimáticas en las lomas costeras y riesgos a la salud de los pobladores en Lima metropolitana. Observatorio Geográfico de América Latina, 16, 15.

Perleche, M. P. (2019). Efectos del emplazamiento del módulo típico de vivienda social el confort térmico en la Urbanización Federico Villarreal de Chiclayo, Perú. Paideia XXI, 9(1), 105-125. doi:10.31381/paideia.v9i1.2267

Riofrío, G., & Driant, J.-C. (1987). ¿Qué Vivienda Han Construido?: Nuevos Problemas En

Viejas Barriadas. Lima: CIDAP/IFEA/TAREA.

Standard, ASHRAE (2017). Standard 55-2017 Thermal environmental conditions for human occupancy. Ashrae: Atlanta, GA, USA.

Tartarini, F., Schiavon, S., Cheung, T., Hoyt, T., (2020). CBE Thermal Comfort Tool: online tool for thermal comfort calculations and visualizations. SoftwareX 12, 100563. https://doi.org/10.1016/j.softx.2020.100563

Liggett, R & Milne, M (2021). OPAQUE 3 (Beta 1, Built 6). UCLA Energy Design Tools Group. https://www.sbse.org/resources/opaque