

Thermal characterization of an interior space of colonial architecture in Arequipa, comparative analysis of thermal transmittance of ignimbrite (sillar) envelope and contemporary material (drywall)

Arequipa is characterized by the cyclical occurrence of earthquakes, which has conditioned the construction systems and the application of local materials to its architecture, as is the case of the colonial houses in the historic center that stand out for the use of ignimbrite (sillar) in the thermal envelope, currently the colonial architecture has been replaced by constructions of framed structures, where the enclosures are being carried out mainly by dry construction (drywall). The objective of the study is the thermal characterization of interior environments in an office in a colonial construction with ignimbrite fabric, in comparison with offices made with contemporary materials like drywall construction system. The applied methodology consists: (i) modeling the thickness of the thermal envelopes, (ii) taking surface temperature measurements with a thermographic camera and ambient temperature with sensors, (iii) modeling the evolution of thermal transmittance with measurements of heat and relative humidity; and (iv) development of the comparative analysis of thermal transmittance between the office environments studied. For the colonial construction office, during the rainy season, maximum indoor ambient temperature values of 22,041 °C were obtained and the maximum indoor relative humidity was 59,384 %; on the other hand, in the dry construction it was found that the maximum interior ambient temperature was 23.381 °C, and the maximum interior relative humidity was 57.22 %. The thermal characterization allowed the comparison of the thermal performance between interior environments with ignimbrite factories (sillar) and dry construction (drywall) in order to understand the thermal comfort of the users who inhabit the offices.

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Keywords

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1. Introduction

The city of Arequipa is the second most important city in the Republic of Perú. It is characterized by its Historic Center, declared a World Heritage Site by UNESCO in 2000. The city rises at the foot of the Andes mountain range, bordering three volcanoes, the closest and most representative of which is El Misti (5,825 m.a.s.l.). This proximity to the volcanic mountain range, added to the subduction of tectonic plates along the Peruvian coast, has caused the city to be cyclically subjected to strong earthquakes, which has led to successive reconstructions of the buildings of the old town since its Spanish foundation in 1540 until the mid-twentieth century, a situation that has conditioned and characterized the evolution of the constructive processes of its historic buildings [1].

Its architecture is characterized by the use of white and pink ignimbrite stone (volcanic material known locally as ashlar) in robust walls, arches and vaults, resulting in a type of architecture that represents the integrated response of native labor with European construction techniques and stylistic characteristics.

The constructive evolution in the built heritage of Arequipa is reflected in the colonial architecture developed in the sixteenth, seventeenth and eighteenth centuries by Spanish builders in principle and product of miscegenation in its term, this condition of learning, interpretation and response makes the buildings of architecture "... almost vernacular, if it were not for the attention to the fashions that mark the periods of evolution of the mestizo style" [2].

Arequipa's colonial architecture is a typical regional architecture, which is largely equivalent to saying authentic. Typical architecture obeys constant norms, natural, historical, vital and temporary conditions of the region. The courtyard is the organizing element. It is made up of articulated courtyard, transition spaces (chiflones) that can represent variation in their location. The courtyards have a defined geometric shape and their proportion depends on the dimensions of the lot. The construction system is based on the use of ignimbrite, used for the walls as well as for the interior vaults and existing rail roofs. The architecture is seismic, ignimbrite, with lime-clad roofs and caisson walls consisting of two faces of hewn ashlar filled with lime, boulder or rubble (.90 to 1.20 wide) [3].

The ignimbrite is the material used for the houses in the city of Arequipa. This material, of volcanic origin, is characterized by a thermal conductivity of 0.16 W/m°C, a specific heat of 463.75 J/Kg°C and a density of 1306.96 kg/m³. [4].

On the other hand, there are several studies that analyze the evolution of colonial architecture in Arequipa, from historical, spatial, stylistic and constructive perspectives. However, there are few studies that address the thermal behavior of its interior spaces, allowing the valuation of buildings with heritage value by monitoring and measuring thermal transmittance has become one of the main challenges faced by historic cities such as Arequipa, so we propose a thermal study that allows us to characterize the constructive section of the mansions of Arequipa in comparison with contemporary construction systems such as drywall.

1.1. Backgrounds

As Benavente mentions in "la arquitectura de la vivienda colonial de Arequipa" the mansions are the embodiment of the typology of patio coming from Spain which was formed based on three factors that allowed to realize a model of civil construction that despite the time and the constant earthquakes managed to maintain a unity in its expression, the factors are: geological factor with the presence of earthquakes and ignimbrite volcanic material, the climatological factor dryness, sunshine, winds and temperature, and constructive factor due to the absence of wood; it also mentions that the courtyards become elements of environmental regulation of the mansions, allowing solar gain, wind regulation, as well as the presence of vegetation in second courtyards and orchards, which together with the water channels generate a microclimate [3].

The factors that condition Arequipa's colonial architecture determine its authenticity and mark its

characteristics, Zuñiga mentions that this architecture is "almost vernacular" alluding to its process of miscegenation that was marked by a condition of "learning, interpretation and response" where European fashions and styles were attended to [2].

Burga indicates that the construction system with ignimbrite was used in large houses and popular vernacular housing, characterized by wide walls, narrow openings with railings, gargoyles in the form of canyons and friezes, the ignimbrite is a light material of thick and simple constitution. [5].

Regarding thermal studies we have the work of Luis Carlos Herrerra-Sosa, in his article "Evaluación del desempeño térmico del sillar (ignimbrita) de Arequipa, Perú", in which he thermally characterizes the ignimbrite building material as the sillar soga as 0.78 W/m² K the sillar canto as 1.49 W/m² K [4]. Mention should also be made of the study by José Andrew Zúñiga entitled "Estabilidad térmica de un edificio centenario de sillar (ignimbrita) en clima desértico frío. Hospital Goyeneche", in which he thermally characterizes the Goyeneche hospital by taking temperature and relative humidity both indoors and outdoors with two different data collection over time. [6].

On the other hand, works have been developed whose purpose is the application of knowledge in contemporary architectural design, which focus on the thermal performance of vernacular and traditional buildings.

Martín, Mazarrón, and Cañas monitored two houses, one traditional and one contemporary, built with different materials in Navapalos, Spain. The objective was to analyze and compare the thermal behavior. The results of the field tests showed better conditions inside the traditional houses. [7].

Liu, Wang, Yoshino, and Liu, do something with the same approach in a study in Yaodong, China, on vernacular housing. They made measurements of the internal and external temperatures of the walls; thermal comfort theory was used to assess the indoor environment. [8].

Başaran in Turkey, conducts research on the vernacular house of Harran, characterized by having a dome roof. Inside and outside temperatures and relative humidity were measured, as well as surface temperatures. [9].

2. Materials and Methods

2.1. Study cases

The case studies correspond to offices in two buildings of the Universidad Católica San Pablo de Arequipa - Peru, both environments share the following qualities: (i) They are office environments in constant use. (ii) They are environments without ventilation or direct lighting. (iii) They do not have windows or doors to open spaces. (iv) Both environments have artificial lighting throughout their period of use. (v) The range of use of the environments is from 8:00 to 17:00 hours on average.

The first case study corresponding to the The Center for the Arts of the UCSP, the building is located in the historic center of the city of Arequipa, on Palacio Viejo street. the building that corresponds to the typology of the colonial courtyard house of Arequipa, the structure of the building is composed of ignimbrite (sillar) with walls with a system called "muro de cajón" characteristic of the colonial houses of Arequipa and flat roofs made up of rails, the interior spaces are distributed around two main yards, the entrance has with a "zaguán", a traditional space within the structure of Arequipa's colonial housing that connects the interior of the house with the exterior of the city.

The building has various environments such as exhibition halls (permanent and temporary), souvenir shop, a chapel, a computer room, offices, auditorium and service spaces. The building is frequently used for cultural events. As it is an adapted building, some of the frequently used rooms, such as offices, are left without natural lighting and ventilation. These rooms have artificial lighting throughout their period of use. These spaces do not use artificial air conditioning instruments such as air conditioning or heaters.

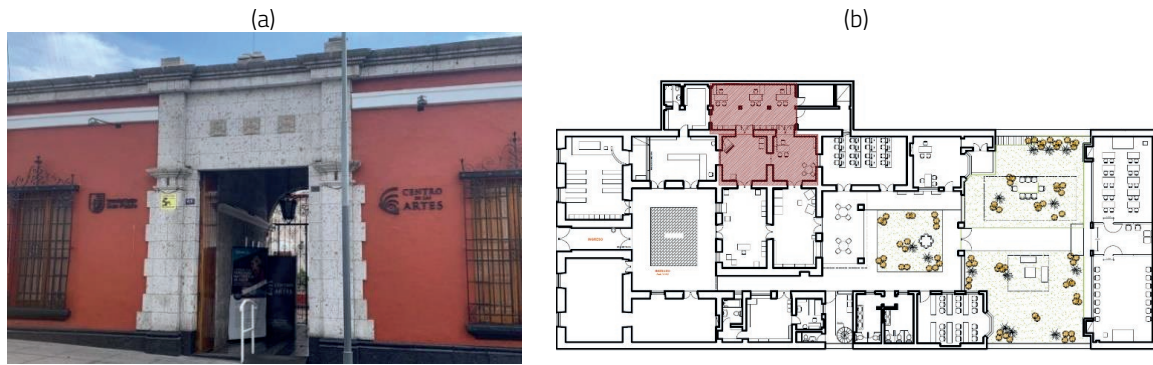


Figure 1. UCSP Center for the Arts, (a) Plan of the building with the office spaces without ventilation or natural lighting marked. (b) photo of the facade of the building. Own elaboration.

The second case study corresponds to the San Pablo Catholic University campus, located in the buffer area of the historic center of Arequipa, on Quinta Vivanco street, the building corresponds to the reuse of a building. The original building was designed for a hotel by the Cooper-Graña-Nicolini firm in the 1970s. Built at the end of that decade, the hotel never came into operation, however, becoming an abandoned place. After a long period in this situation, the San Pablo Catholic University acquired it in 2004 in order to recycle it as an educational facility, a project that was designed by the architect Marcello Berolatti de la Cuba. Since its change of use, the building has had several extensions and remodeling. The original building is the St. John H. Newman was designed for hotel uses and was later adapted to its current educational uses. The rest of the buildings of the university complex are later and their design has better habitable conditions.

Among the main uses of the Newman building are: classrooms, dining rooms, laboratories, office spaces and services. The construction system of the building corresponds to the reinforced concrete frame, and uses the drywall to organize and divide the various environments. Because the uses of the building are adapted, there are environments such as offices that are left without lighting or natural ventilation. These spaces do not use artificial air conditioning instruments such as air conditioning or heaters.



Figure 2. UCSP St. John H. Newman Building, (a) Plan of the building with the office spaces without ventilation or natural lighting marked. (b) photo of the facade of the building. Own elaboration.

2.2. Modeling of thermal envelope thicknesses

The selected environments were surveyed in situ where the architectural qualities of the ignimbrite (sillar) and drywall envelopes are evident, as shown in Figure 3.

The ignimbrite office corresponds to the UCSP Center for the Arts and has walls with an average thickness of 0.65 m. The drywall office corresponds to the UCSP San John H. Newman building and has walls with an average thickness of 0.15 m.

The modeling of the thermal envelope of the selected offices consists of the identification of the layers that make up the enclosing walls that will later be measured to identify their thermal transmittance, as shown in Figure 4.

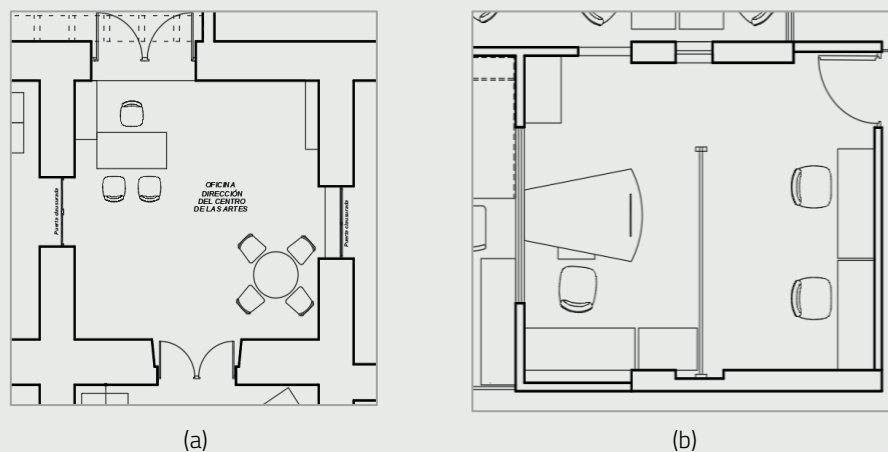


Figure 3. Floor plans of the measured office environments, (a) UCSP Arts Center Office and (b) UCSP St. John H. Newman Building Office. Own elaboration.

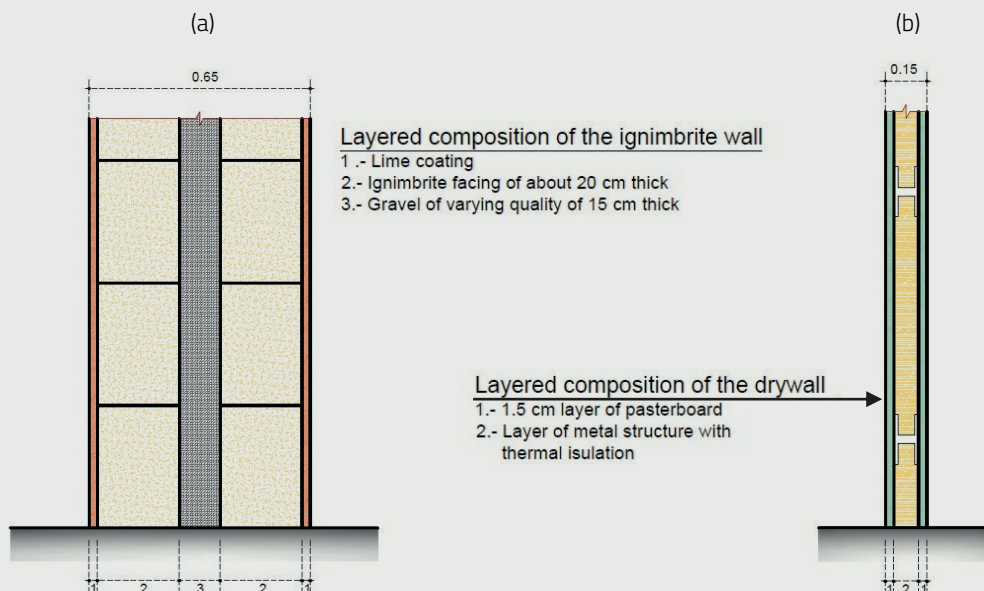


Figure 4. Modeling of the thermal envelope of: (a) Ignimbrite walls with a “Muro de cajón” construction system in offices of the UCSP Center for the Arts (b) Drywall walls in offices of the St. John H. Newman Building Office. Own elaboration.

2.3. Measurements of surface temperature with thermographic camera and ambient temperature with sensors

Surface temperature measurements of the selected office environments were taken with a FLIR 128x96 Compact Thermal Camera, model C3-X, series 9050149613. The measurements consisted of capturing thermal and digital images of both ashlar and drywall walls. The environmental temperature measurements were taken with ONSET Smart 8-meter Temperature and Humidity Sensors, series: 21538572, 21538576, and ONSET wired Data Logger, series: 21549014, the measurement consisted of mounting the equipment in non-visible areas of the selected office environments. Measurements were taken every 30 minutes between March 22 and 30, 2023.

2.4. Modeling the evolution of thermal transmittance with heat and relative humidity measurements.

For the thermal characterization of the constructive section, we must understand that these are composed of three layers, two outer layers of ignimbrite and an inner layer of construction residue, so it is proposed to use the calculation methods of Bienvenido-Huertas [10], that takes the theory of Albatici and Tonelli and Dall'O from the measurements taken of Temperature in order to make an energy assessment of the constructive section. [11,12].

3. Results

3.1. Comparative analysis of modeling of thermal envelope thicknesses

The ignimbrite wall is characterized by having five layers intertwined between them, the first is a lime coating that in many cases has been removed from both the exterior and the interior, the second layer is of ignimbrite facing of about 20 cm thick, the central layer is of gravel of varying quality of 15 cm thick to finish with a layer of ashlar facing of 20 cm thick and lime coating.

The drywall wall is composed of three layers starting with a 1.5 cm layer of plasterboard, a central layer of metal structure with thermal insulation and a layer of plasterboard. Basically, the insulation is centered on the thickness of a material. The material components can be seen in Figure 2.

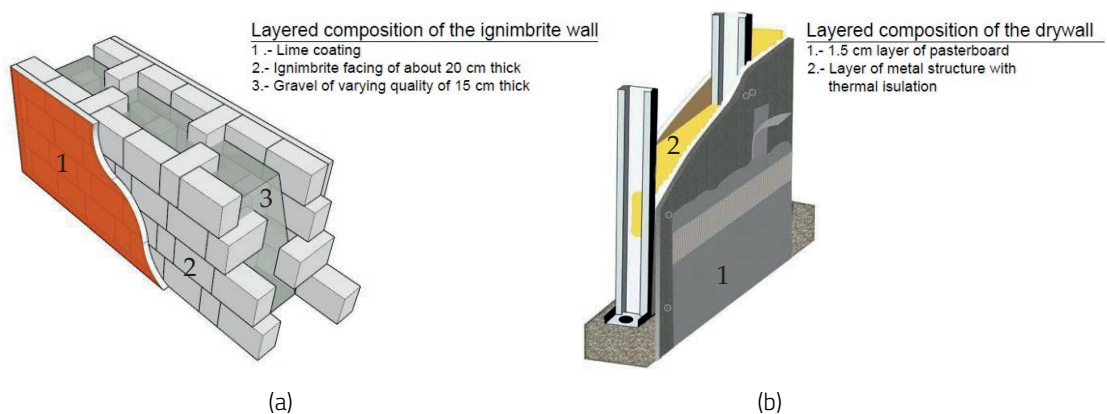


Figure 2. (a) Isometry of ignimbrite wall (b) Isometry of drywall wall. Own elaboration.

3.2. Comparative analysis of surface temperature measurements with a thermographic camera and ambient temperature with sensors.

The following results were obtained from the indoor air temperature and relative humidity measurements of both the office in the Arts Center building and office N220 in the Newman building, as shown in Table 1 and Table 2 .

Table 1. Temperature and Relative Humidity

	Arts Center		N220		Exterior	
	T. Int	HR	T. Int	HR	T. Ext	HR Ext
Min.	31/03	22/03	27/03	23/03	25/03	22/03
	7.30 h.	14.30 h.	5.30 h.	18.00 h.	6.00 h.	14.30 h.
	19.59°C	44.42%	20.85°C	40.64%	13.59°C	32.82%
Max.	30/03	30/03	28/03	28/03	22/03	25/03
	12.00 h.	21.00 h.	17.00 h.	17.00h.	14.30 h.	16.30 h.
	22.04°C	64.41%	23.38°C	57.12%	22.21°C	79.35%

Table 2. Indoor and outdoor air temperature and relative humidity record. Own elaboration.



3.2.1. Air temperature:

The outside temperature ranges from 13.59°C to 22.21°C, which is clearly related to the presence or absence of the sun. The temperature drops considerably during the night, and begins to increase around 9:00 a.m., with the presence of the sun; on the other hand, around 6:00 p.m. the temperature drops again. The highest temperature point is around 14.00 hr. In the interior spaces, we observed that the temperature of the office inside the ashlar house ranges from 19.90°C. to 22.04°C. The drywall office N202 presents a slightly higher temperature, ranging from 20.85°C to 23.38°C.

3.2.2. Relative humidity:

The outdoor relative humidity recorded has been very variable, ranging from 32.82% to 79.35%, it is worth mentioning that the week of measurement had the presence of precipitation, characteristic of the summer months, with an increase in relative humidity during the early morning hours. In the interior spaces the relative humidity is more constant, we observe that in the ashlar office, the relative humidity ranges from 47.02% to 59.38%, on the other hand, in the office N202 these values range from 40.64% to 57.12%, obtaining that the drywall space presents a lower relative humidity.

3.2.3. Thermographic camera:

The photographs taken with the thermographic camera were taken in the spaces adjacent to the offices, either in the corridors or in the adjoining offices. Figure 3 shows the range of temperatures recorded in the walls and openings of the office of the ashlar building, mostly between 15 and 17°C surface temperature (Figure 3). On the other hand, while in the drywall office, the surface temperatures recorded ranged from 17 to 19°C, as shown in Figure 4.

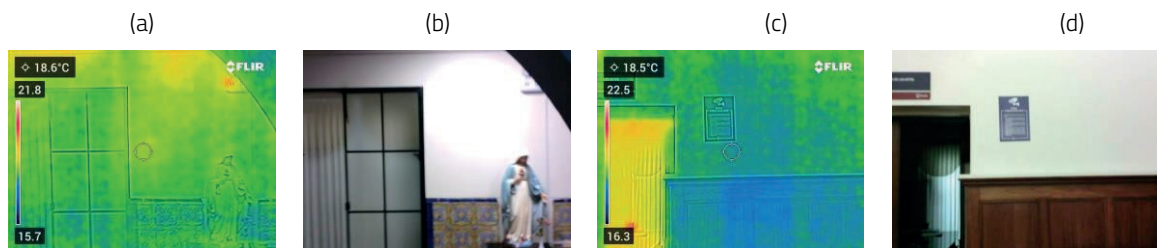


Figure 3. (a) (b) Thermographic photograph 1 of the exterior of the ashlar office;
(c) (d) Thermographic photograph 2 of the exterior of the ashlar office;
(e) Thermographic photograph 2 of the exterior of the ashlar office.



Figure 4. (a) (b) Thermographic photograph 1 of the exterior of room N202;
(c) (d) Thermographic photograph 2 of the exterior of room N202.

3.3. Comparative modeling analysis of thermal transmittance evolution with heat and relative humidity measurements

The results indicate that the data obtained show a thermal transmittance for the vertical walls of between 4.92 and 5.39 W/m²°C for the ignimbrite wall, while for the drywall wall a thermal transmittance of 3.91 and 4.30 W/m²°C was obtained. The study of the floor slabs or vaults shows that the thermal transmittance obtained for the ignimbrite

ceiling at their narrowest point is 4.67 to 5.12 W/m²C, while for the drywall slabs we have a thermal transmittance of 1.89 to 2.10 W/m²C. As shown in Table 3.

Table 3. Comparative calculation between thermal transmittance of ignimbrite and drywall

	VERTICAL WALLS		CEILING	
	IGNIMBRITE 22/03/2023 01:00:01	DRYWALL 22/03/2023 01:00:01	IGNIMBRITE 22/03/2023 01:00:01	DRYWALL 22/03/2023 01:00:01
Q(stefan bolzman)	0.0000	0.0000	0.0000	5.67E-08
E(Emisividad cierre)	0.9500	0.9500	0.9500	0.9500
v (Wind Speed m/s)	0	0	0	0
T(Surface temperature. ext. in k)	292.6000	292.8200	292.4000	290.4000
Ti (Enviromental temperature int in K)	292.8960	294.4650	292.8960	294.4650
Te (Enviromental temperature ext en K)	288.6060	288.0800	288.6060	288.0800
Thermal transmittance (U Albatici)	4.9231	3.9195	4.6717	1.8944
Thermal transmittance (U Dall'o)	5.3998	4.3057	5.1294	2.1074

4. Discussion

It can be observed that the outdoor temperature is lower and much more variable than the indoor temperature, and the outdoor relative humidity is also higher outdoors. This allows us to observe that in both cases of study the construction materials are protected from the exterior climatic conditions.

Both buildings are in the permissible comfort range, being the range established in Givoni's psychometric graph between 20 to 27°C with relative humidity ranges between 20% to 80%. Therefore, during the summer season both offices provide thermal comfort to their occupants. Likewise, the drywall office is slightly more comfortable than the ashlar office.

The results indicate that the data obtained show a thermal transmittance for the vertical walls of between 4.92 and 5.39 W/m²C for the ashlar wall, while for the drywall wall a thermal transmittance of between 3.91 and 4.30 W/m²C was obtained.

The study of the floor slabs or vaults shows that the thermal transmittance obtained in the ashlar vaults at their narrowest point is 4.67 to 5.12 W/m²C while for the drywall slabs we have a thermal transmittance of 1.89 to 2.10 W/m²C.

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