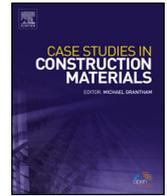




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## Case study

## In situ assessment of superficial moisture condition in façades of historic building using non-destructive techniques

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## ABSTRACT

In historic building the water resistance capacity of their external materials is a relevant property that must be known, because the materials play a fundamental role in the interaction with the external environment. The aim of this research is to evaluate in situ the superficial moisture condition in facades using non-destructive techniques (NDT). Two different moisture measuring NDT was used: Infrared Thermography (IRT) and Electrical Resistance Measuring (ERM); in addition, the Air Temperature and Relative Humidity were measured. The IRT identifies the temperature of the material and offers a thermal image with different temperatures that is interpreted as moisture area. A Moisture Mapping is obtained with ERM, which represents the moisture conditions in the facades. Both techniques give an idea of moisture areas. The results of both graphics shows that the most humid areas correspond to the same areas that obtain by IRT and ERM. In conclusion, using these two NDT at the same time it is possible to acquire usually a quick, qualitative, precise and economic results of: moisture areas in situ, important data to survey and the assessment the historic building for monitoring or preservation project.

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## 1. Introduction

Patrimonial buildings must constantly be monitored and studied to assess their status of conservation, and thus to protect the cultural and historical value of it, since buildings are representatives of the cultural heritage of each country. Moisture detection is one of the most common processes in masonry materials because they are vulnerable to deterioration and decay under the influence of dampness, and it can significantly affect the durability and hygrothermal behavior of the historic building especially on the façades and roofs.

Non Destructive Test (NDT) is one of the suitable methods for historical building inspection, monitorization and evaluation, which can be done in-situ; the results are predicted immediately, can detect the condition of the structures, rank the structures according to present condition, and compare the different properties based on threshold values. They are usually inexpensive, use cutting-edge technology, monument-friendly and high-speed operational instruments [1].

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For that, the aim of this research is to evaluate in situ the superficial moisture condition in façades using non-destructive techniques (NDT). This case analyzes the moisture in façades of Santa Barbara Church located in Colonial City of Santo Domingo, Dominican Republic, using two different moisture measuring NDT: Infrared Thermography (IRT) and Electrical Resistance Measuring (ERM) with moisture maps; in addition, the air temperature and relative humidity were measured. It is important to highlight that the church is closed and the moisture causes serious problems to the building, increasing its deterioration and putting its integrity in risk.

Tavares et al said that a visual inspection is enough to detect pathological phenomena affecting the rendering because of evident and visible symptoms [2]. However, this can produce data that is dubious or difficult to interpret and affected by the education and experience of the technician carrying out the inspection, as well as the accessibility of the area being inspected. The use of auxiliary diagnosis techniques reduces the subjectivity of visual inspections, making it easier to obtain more reliable evaluations. An in-situ technique is more suitable if it is easy/quick to perform and directly provides useful data to in-service performance evaluation [3,4].

Fais et al (2018) states that with NDT it is now possible to obtain all the qualitative and quantitative parameters needed to plan the recovery and preservation of a monumental structure. One of NDT methods applicable to cultural heritage used for diagnosis and inspection is the Infrared Thermography (IRT), because it is a powerful, fast and accurate tool that allows identification of the texture and the structural discontinuity hidden within masonry, crack patterns, detachment, humidity and the problems it entails [5].

IRT has been used in several investigations, in 1996, Cusidó, Devant and Riba, use the IRT and spectro-radiometry in the study over the deterioration of the national architectural patrimony, specifically the Cathedral of *San Salvador de Oviedo* (Spain), where three areas were selected: the "patio" of the kings, the frontal *Rosetón* terrace and the cloister [6]. Two years later, in 1998, Grinzato et al. presented a quantitative methodology for processing IR images to map defects in buildings and they reported example application results including mapping of moisture content [7] and in 2002, Grinzato, Bison and Marinetti, perform a monitoring of the Historical Arsenal of Venice in Italy, using the IRT as one of the thermal methods [8].

In 2010, Grinzato, Cadelano and Bison did several experiments controlled in laboratory conditions on different materials where show the heat and mass exchange between surface and environment [9]. Furthermore, this method is excellent for subsurface investigations through the acquisition of surface thermal patterns: variations of temperature and time can reveal discontinuities below the surface, moisture increase, cracks or other types of defects [10,11]. Lerma, Cabrelles and Portalés in 2011, carried out a multi-temporal thermal analysis to detect moisture in the Arenberg Castle's façade (Leuven, Belgium) based on the differences in thermal behavior of humid masses compared to dry masses over time due to temperature fluctuations [12].

Also, in 2011, Rodríguez Liñan et al. carried out an inspection with NDT of the San Felipe Neri Oratory (Cádiz, Spain), where they used the IRT and ultrasounds to analyze the wooden roof for the detection of different states of deterioration, density drops and defects, with the objective of assessing its conservation status [13]. In 2013, Kordatos et al. used IRT to evaluate the mural of the Monastery of the "*Virgen de la Asunción*" known as "*Molybdoskepastos*", located in the Ioannina (Greece), as well as the characterization of the degradation of historical monuments [14].

While, in 2015, Kilic, employs various NDT, IRT among them, to assess the state of conservation of an historic Ottoman building in Urla, Izmir, Turkey [15]. Also, in 2015, Litti et al. carried out, in a historic building in Amberes (Belgium), an indirect non-invasive monitoring of the envelope, to evaluate the hygrothermal behavior of brick masonry, where they employ passive infrared thermography and environmental monitoring to detect the alteration due to the variation of moisture distribution on the surface [16]. In 2016, Pérez-Sánchez and Piedecausa-García performed the identification and analysis of constructive systems via the application of the IRT on historical domes of temples located in the Province of Alicante (Spain) [17]. In 2017, Hola said that the IRT is very useful for locating damp areas in a wall but there is no possibility to determine the value of the moisture content [18].

Foulks alleged that a moisture meter is helpful, especially in determining or confirming areas of the façades most subject to the action of water where that action is not visibly apparent. Using moisture meters can acquire effective moisture detection and provide a moisture mapping. Also, a detailed and precise visual documentation of the extent of damage, saving time and money in the initial damage assessment stage [19]. According to Dr. Jukka Voutilainen the surface moisture meters are almost the most commonly used tools for measuring moisture conditions in building structures. The device is used to measure the electrical properties inside the material, to interpret the results as moisture and temperature conditions, and to display the results to the user [20].

Larsen (2004) described his experience using various types of moisture sensors to diagnose salt efflorescence on decoration and masonry of an eleventh century church. He noted that the capacitance-type moisture meter gave erroneous results because of the effect of salt in the plaster. It also did not provide a true picture of moisture level in the masonry walls deeper than 50-mm. The neutron-type probe moisture meter provided more reliable results. To obtain the moisture distribution in the masonry wall, Larsen inserted gypsum-blocks and wooden-dowel moisture sensors in various locations in the wall. The range of the electrical resistance measurements of the gypsum-blocks responded to the actual moisture condition of the masonry and they were not sensitive to the effect of salts because the gypsum pores already contain a saturated solution of calcium and sulfate. The variation of the moisture content over the masonry wall cross-section indicated the direction of water movement and aided in identifying the source of moisture [21].

Similarly, some limitations that need to be considered because surface moisture meters usually give only suggestive information about the absolute moisture content and distribution inside structures, thus the acquired readings should be

compared with readings from a dry reference location in the same structure [19]. Sometimes, the moisture quotient readings given by different meters in the same circumstances may differ significantly. Also, the electrical properties of building materials are not constant, and the texture of the material surface can vary (rough or smooth one) and the contact be weaker [22]. In addition, the person performing the measurement may unintentionally or intentionally affect the reading by applying a different force when pressing the device to the structure in different locations [20].

Göller (2013) said that single point measurements at building are not representative for the moisture status of the whole object [23]. In 2017, Balík et al. carried out the application of IRT and moisture mapping in complex moisture inspection of the basement floor of Schebek Palace (Prague, Czech Republic) [24].

Performing tests of the moisture content in the walls of historical buildings do not usually turn out to be an easy task because monument protection authorities only allow intervening in the structure of the historic tissue to a very limited degree. There are many NDT of measuring moisture content described in literature, however, it should be noted that various methods have some restrictions in usage and that there are general conditions for the performance of NDT of moisture content and the portable moisture tester allows in the surface zone and to a depth of about 50 mm to be measured and identify the values of moisture content [27].

## 2. Santa Barbara church description

### 2.1. History

The parish church of Santa Bárbara is located at the Colonial City of Santo Domingo, declared by UNESCO as World Heritage Site, at the neighborhood call Santa Barbara, on the banks of the Ozama river. The origin of the neighborhood is due to the informal settlement of soldiers, stonemasons, masons, carpenters and other related trades that were established in what those moments were the outskirts of the city. The exact date of erection of the church is unknown but it was possibly between 1528 and 1531 under the influence of the Bishop of Santo Domingo, Sebastián Ramírez de Fuenleal.

The primitive parish should have been built around 1534 and was made of wood with a “cana” roof like almost all the island [25]. The current church is made of stone, brick and Rammed Earth, it began its construction in 1573 but it is unknown when it ends since no documents have been found to indicate it, only mentioning that it took a long time for not having money, even the year of his consecration is unknown. Over time, the church has been damaged by earthquakes, fires, hurricanes and storms, highlighting the fire of 1586 caused by the pirate Francis Drake, the storm of 1591 that collapsed the roof and earthquakes of 1673, 1684 and 1751, among others [26].

The church has been intervened on several occasions and not all these interventions have been favorable and had modifications in its architecture and structure. In the middle of the 20th century, the exterior plaster was removed from the whole church, leaving it during environmental effects. However, for the neighborhood the church is a reference and very important place; and for the country is a symbolic building because was baptized Juan Pablo Duarte one of the three Fathers of the Dominican Homeland (Fig. 1).

### 2.2. Description

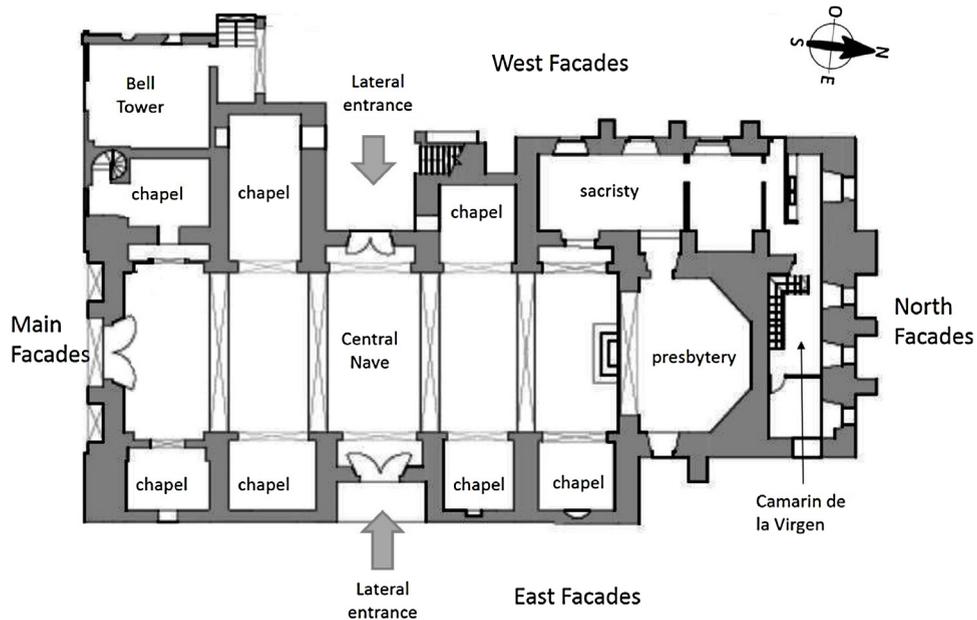
The church has a rectangular plan of five sections with a polygonal apse with five-sided. Church face or he “altar face” is oriented to the North, due to the conditions of the land. The south façade is the main, and the east and west façade are the side chapels are built between buttresses. Main façade has brick arcades with Coralina; north façade is made with Coralina limestone; east façade has four chapels: one of them are made with Coralina and the other three are made with rammed earth; west façade have two chapels and the sacristy made with Coralina. The church is covered by a brick vault, the apse by a vault of stone and brick, and the side chapels are covered by brick domes [28].



Fig. 1. A) Church at the beginning of the 20th century [27] B) Church in 2017.

**Table 1**  
Porosimetry of brick and Coralina [29].

|                        | Rustic Brick |              | Coralina Limestone |              |
|------------------------|--------------|--------------|--------------------|--------------|
|                        | Relative (%) | Absolute (%) | Relative (%)       | Absolute (%) |
| Interparticle Porosity | 9,51         | 31,52        | 17,81              | 73,75        |
| Intraparticle Porosity | 20,67        | 68,48        | 6,34               | 26,25        |
| Total Porosity         |              | 30,19        |                    | 24,15        |



**Fig. 2.** Actual architectural floor plan [30].

The Higroscopicity or Pipette Test (Karsten tube or Rilem tube) in Coralina Limestone showed very low water permeability, after 24 h of applying the pipe, only an absorption of 5 cm<sup>3</sup> of water was observed. While in the rustic brick, the water absorption is not high since after 20 min it stopped and only absorbed 6.90 cm<sup>3</sup>, even though it was left 24 h [29]. Therefore, the measurement of water absorption by pipette method in rammed earth wall indicated that after 60 min it stopped and only absorbed 8 cm<sup>3</sup>, even though it was left for 24 h. All these analyzes were done under the following environmental conditions: average air temperature 28.3 °C, average relative humidity 75%, average wind speed 2.7 m/seg and sky clear.

The analysis by Mercury Intrusion Porosimetry of rustic brick and Coralina Limestone are shown in Table 1.

The interior of the church measures 40.72 m from the apse to the door in the main façade and from chapel to chapel it has 10.92 m. The size of the side chapels on north differs but on south they are all the same. In 17th century, the “Camarin de la Virgen”, a “Dressing room of the Virgin” which is two level building, was added behind the apse. In one of the last interventions were placed metal struts on the north and inside the church were placed some chains to tie the vault. In Fig. 2 the actual architectural plant of the church is shown. The building has been closed for several years and ruinous, which has led to its deterioration presenting many damages.

**Table 2**  
Average environmental conditions (May 2016 to May 2018).

| Year      | Average air temperature (°C) | Average relative humidity (%) | Average Rainfall (mm) | Average wind speed per hour (m/s) | Prevailing of wind direction |
|-----------|------------------------------|-------------------------------|-----------------------|-----------------------------------|------------------------------|
| 2016-2017 | 31.70                        | 58.21                         | 345                   | 35.62                             | ESE (east-southeast)         |
| 2017-2018 | 33.09                        | 50.46                         | 357                   | 33.54                             | ESE (east-southeast)         |

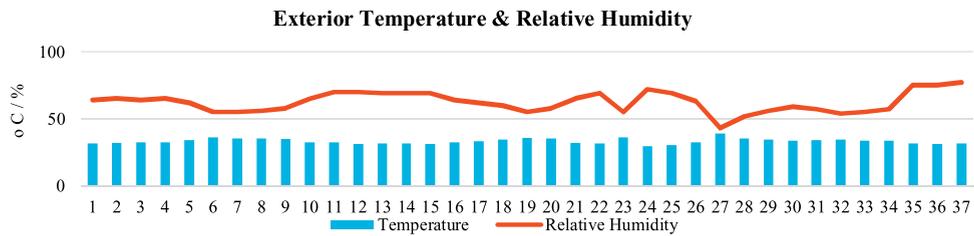


Fig. 3. Exterior temperature and relative humidity (May 2016 to May 2018).

Table 3

Tpi 1010<sup>a</sup> specifications [32].

| Parameters        | Range         | Accuracy   |
|-------------------|---------------|--|
| CO <sub>2</sub>   | 0 to 5000pp   | 10°C-40°C: ±5% of rdg+75ppm <10°C,>40°C: ±10% of rdg+75ppm |
| Air Temperature   | -20°C to 60°C | ±1°C   |
| Relative Humidity | 5% to 95%     | ±1°C   |
| Dew Point         | -44°C to 57°C | Calculation ±1°C   |
| Wet Bulb          | -16°C to 57°C | Calculation  |
| CO                | 0 to 500ppm   | ±3ppm or ±5% of rdg whichever is greater                   |
| % Outside Air     | 0 to 100%     | Calculation  |

### 2.3. General climate conditions

The Santa Barbara parish church is in a tropical weather with wet and dry seasons, with periods of heavy rain and hurricane seasons. Also, the church is located near the Ozama River about 170 m east and 1000 m south from Caribbean Sea. The height above mean sea level (AMSL) is 17 m with few nearby buildings that do not interfere with the behavior and wind speed [31]. For these reasons it was determined to have a wider view of at least two years of the climatic behavior of the zone. The yearly outside air temperature and relative humidity data it was obtained from the Weather Station of the Cathedral of Santo Domingo [36], and the data covered the period from May 2016 to May 2018 as shown in Table 2 and Fig. 3.

### 3. Materials and methods

In this case a series in-situ NDT applies on each façades of the Church based on the measurement of thermal properties and dampness areas, using: Infrared thermography (IRT) and Electrical Resistance Measuring (ERM). In addition, the environmental conditions were measure. The survey was performed a typical tropical sunny day, under normal drying conditions, on June 28th, 2017. IRT was carried out in the morning between 09:30 am and 11:30 am and ERM during 8:00 am to 7:00 pm.

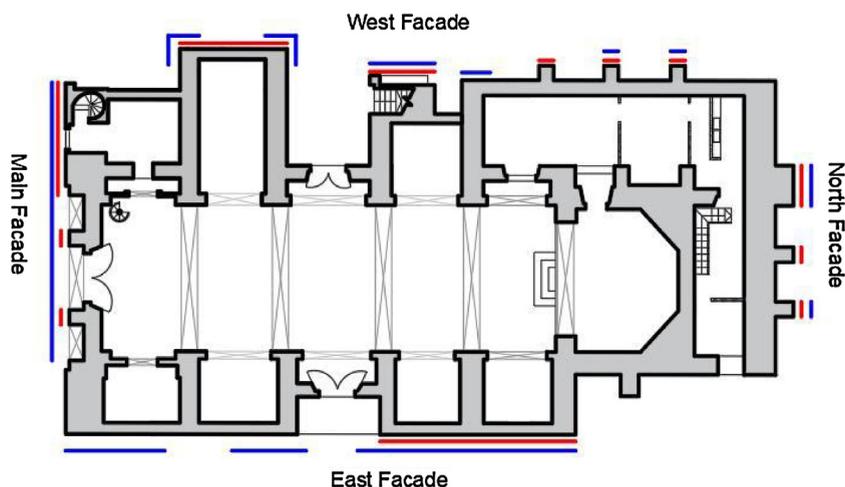
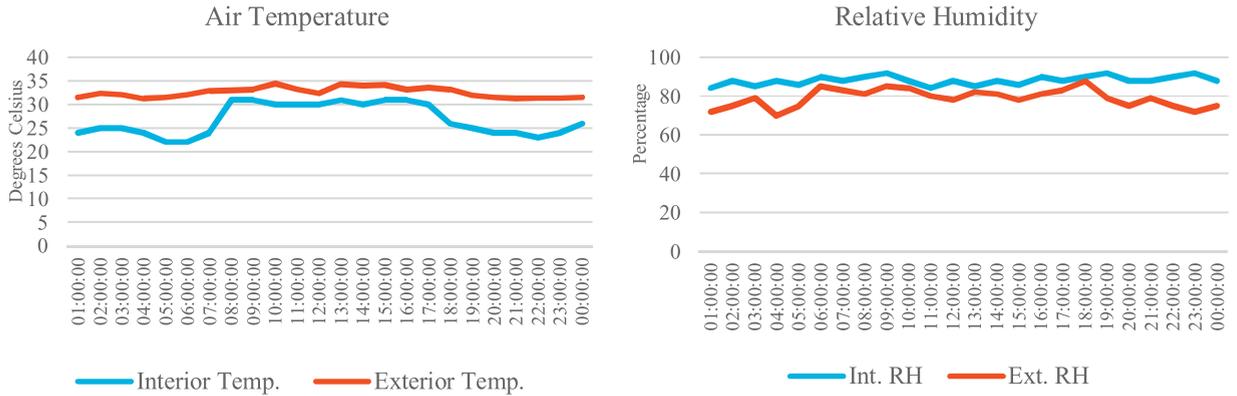


Fig. 4. Study areas with Portable Moisture Tester (Red Lines) and Thermal Camera (Blue Lines).

**Table 4**  
Average environmental conditions on June 28<sup>th</sup>, 2017.

| Ambient CO2 (ppm) | Ambient temperature (°C) | Relative humidity (%) | Atmospheric Pressure (hPA) | Dew point temperature (°C) | Wet bulb temperature (°C) | CO (ppm) | Wind speed per hour (m/s) |
|-------------------|--------------------------|-----------------------|----------------------------|----------------------------|---------------------------|----------|---------------------------|
| 1126              | <b>31.28</b>             | <b>78.52</b>          | <b>1250</b>                | <b>27.1</b>                | <b>30.97</b>              | <b>1</b> | <b>4.16</b>               |



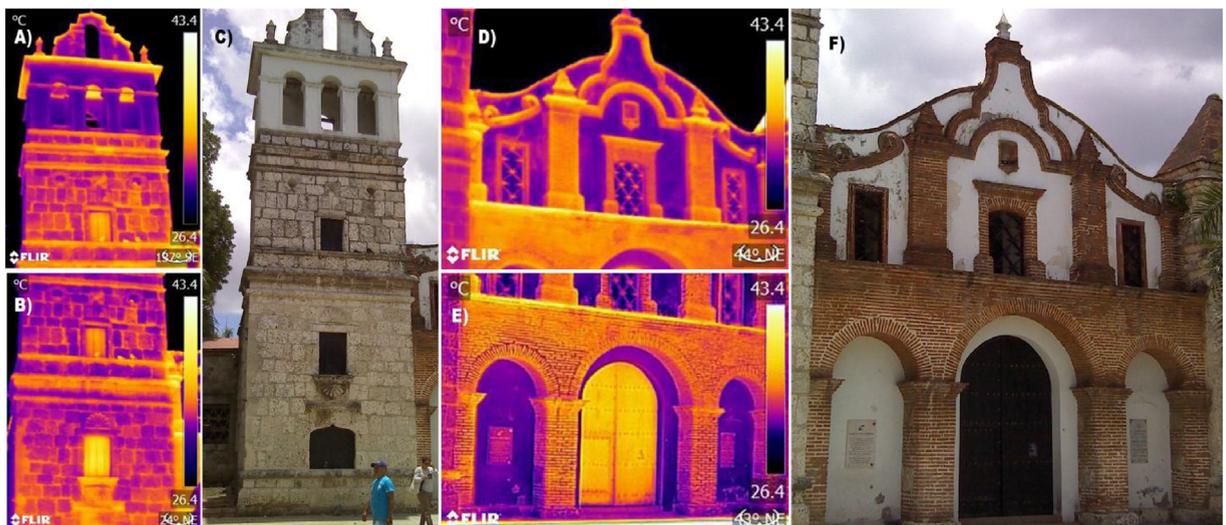
**Fig. 5.** Interior - Exterior Air Temperature and Relative Humidity.

### 3.1. Environmental conditions

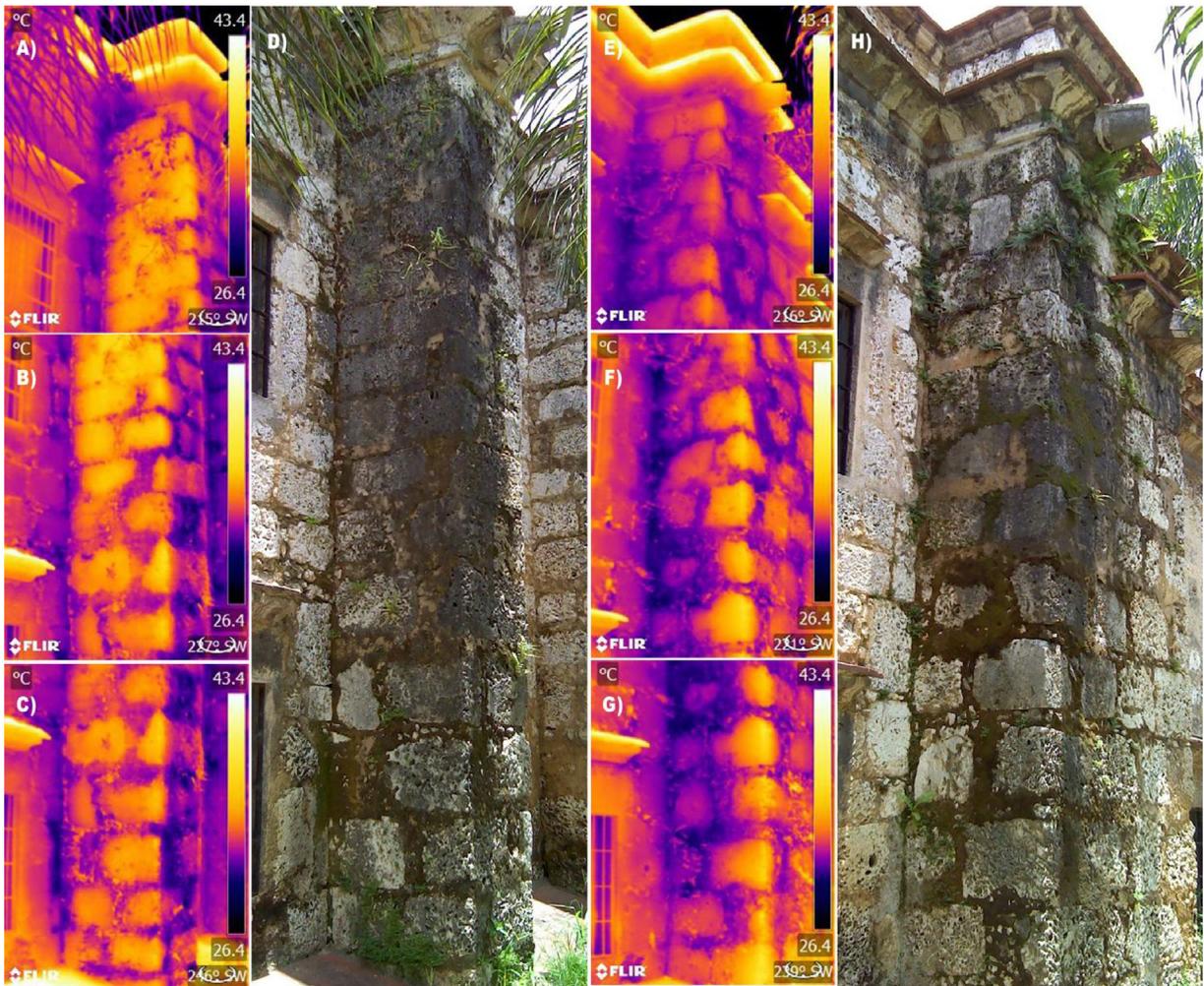
The environmental conditions parameters outside and inside the building were using a Tpi 1010<sup>a</sup> Outdoor/Indoor Air Quality Meter (Table 3), that measure CO<sub>2</sub>, Air Temperature, Relative Humidity, Dew Point, Wet Bulb, CO and Percentage Outside Air. Is a NDT, can use in situ and provide the measurements to monitor and adjust air handling devices [32]. The outdoor air Temperature and surrounding Relative Humidity (T/RH) were correlated with a precision Weather Station Vantage Pro2, Davis Instruments Model 6152 wireless [33], installed in the Cathedral of Santo Domingo, about 800 m from the Santa Barbara Parish Church.

### 3.2. Infrared Thermography (IRT)

The IRT is a thermal-based moisture measurement method that transforms the radiation into a visible image using the change in the temperature of materials caused by the change in moisture conditions, emitted by objects in the infrared band of the electromagnetic spectrum. With thermal images estimating the temperature distribution and detect the problematic



**Fig. 6.** A,B) Thermograms bell tower; C) Visual image of bell tower; D, E) Thermograms of main façade; F) Visual image of main façade.



**Fig. 7.** A,B,C) Thermograms First buttress; D) Visual image first buttress; E,F,G) Thermograms Third buttress; H) Visual image of third buttress in north façade.

areas, considering that lower temperature zones are more humid and those with higher temperatures are less humid. Currently there are two approaches available for thermography inspections: passive and active. The passive approach measures the temperature differences of a structure that are generated under normal conditions, while the active approach generates the temperature differences of the structure using external stimulus [34]. In this research, the study is based on passive thermography.

The thermographic inspection allows observing the temperature differences occurring in the materials. These variations determine possible anomalies such as the presence of moisture, bringing important information for the restoration and conservation of the monuments. Apart from that, these defects must be fixed to avoid irreversible damage to historic buildings.

Likewise, some factors affecting the IRT study during a building cover thermal behavior inspection are, like: climatic conditions (insulation, wind, ambient temperature, relative humidity and greenhouse gases concentration), properties of the material (emissivity/reflectivity, color), surface finish of the building or material (roughness or unevenness, stains and color of the materials or surface, thickness), orientation of building to the path of sunshine during the survey, angle of vision and survey distance and the existence of any nearby elements that produces heat [35–37].

The IRT façades moisture was conducted in accordance with the standards UNE-EN 13187: 1998 / ISO 6781: 1983 modified, "Thermal performance of buildings. Qualitative detection of thermal irregularities in building envelopes. Infrared method" [38]. The infrared scanning camera used was a FLIR SYSTEMS model T420, FOL 18 mm lens and  $240 \times 320$  pixels IR resolution, which transforms an infrared image into radiometric, letting temperature values to be read straight from the image as it has complex algorithms. The camera used for this study having a spectral range  $7.5$  to  $13 \mu\text{m}$  and has a field of view (FOV) of  $25^\circ \times 19^\circ / 0.4 \text{ m}$  and spatial resolution (IFOV) of 1.36 milliradians. The T420 camera has an adjustable thermal

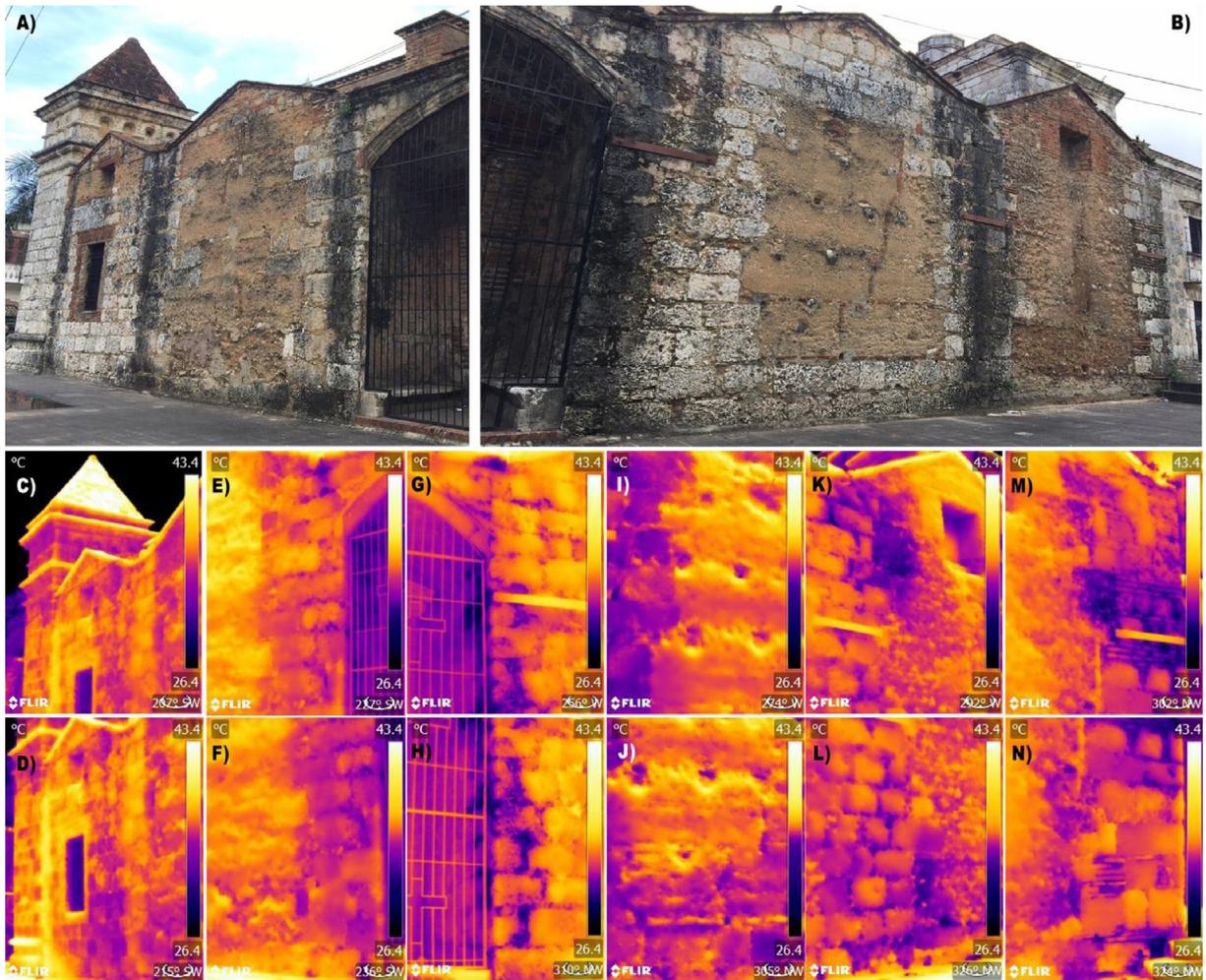


Fig. 8. A,B) Visual images of east façade; C-N) Thermograms of east façade.

range from  $-20^{\circ}\text{C}$  to  $650^{\circ}\text{C}$  and for this project was set at  $-20^{\circ}\text{C}$  to  $120^{\circ}\text{C}$ . The camera used for this survey meets the requirements of UNE-EN 13187:1998.

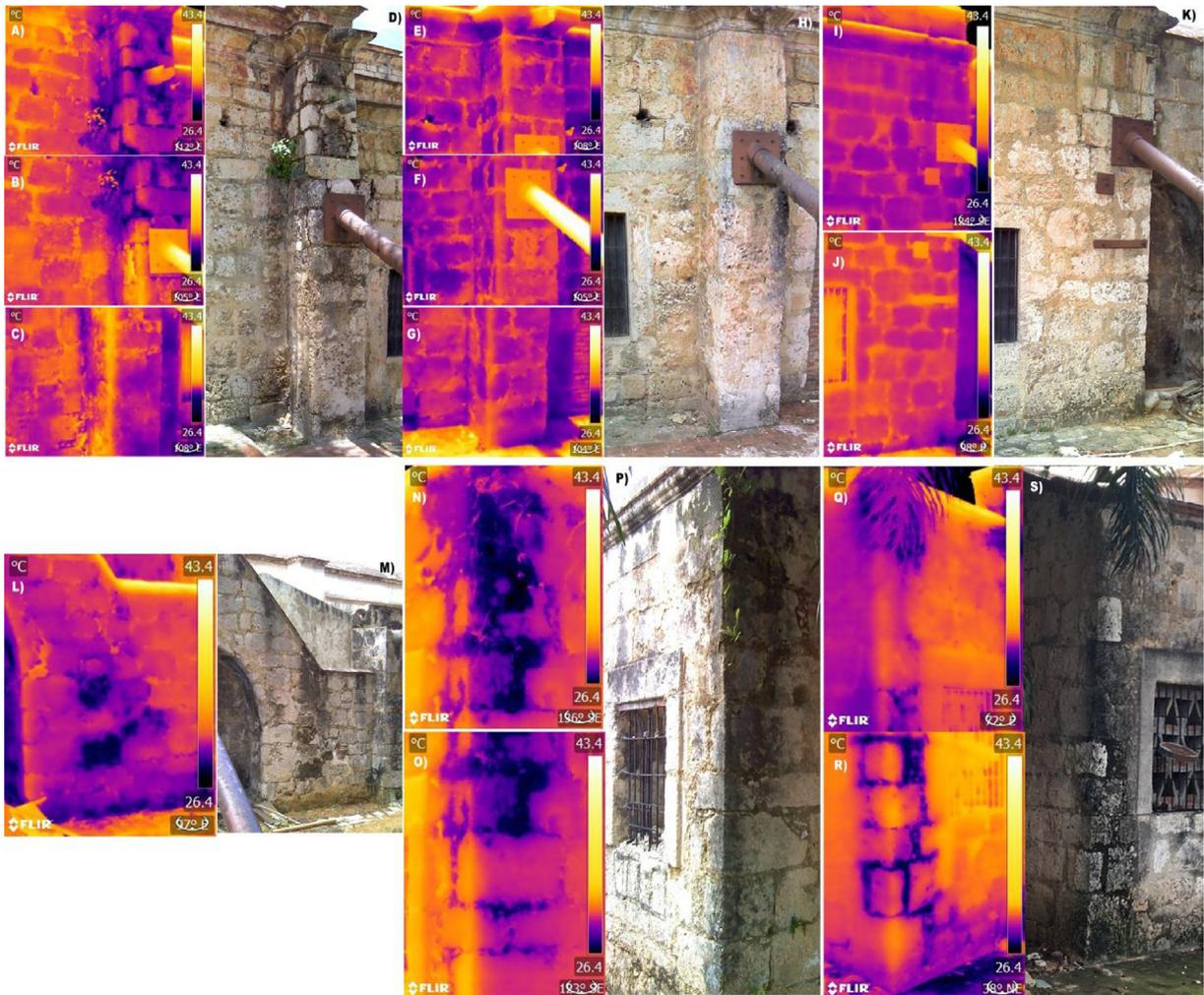
Emissivity values that have been considered for construction materials of the façades are limestone: 0.95, bricks: 0.93, mortar: 0.92 and rammed earth: 0.93 [39], allowing to obtain temperature readings as accurate as possible.

Once the thermal images were taken, they are introduced in the FLIR Tools program (version 6.0.17046.1002), where the parameters of temperature, relative humidity, distance, reflected apparent temperature were adjusted. Also, points are placed in the thermal images to measure the temperature in different areas of the image or rectangles are placed to measure averages, along with maximum and minimum temperatures. For thermal images, an iron color palette mode was used using reference colors: blue for coldest temperature range and yellow for warmest temperature range. This way, the coldest point can be identified on each image.

### 3.3. Electrical Resistance Measuring (ERM)

ERM is another NDT that measure moisture indirectly by measuring the electrical resistance of the material which makes measured resistance dependent on the dielectric property of the material being measured in addition to possible temperature effect [40]. With the data proceed from the moisture meters is that the moisture maps are made using specialized software.

Moisture Mapping (MM) is a documentation tool for diagrams of wet building material locations and key observations of where the moisture is. Moisture Mapping or Humidity Maps [41] are photographs or drawings of affected surfaces with a superimposed grid and corresponding moisture levels for the materials in each location. Is a very useful method for identifying the location and size of the affected areas and the corresponding moisture content values for these affected areas, as compared to the “dry standard” of a non-affected area [40]. It can be used to validate and measure the moisture, detection



**Fig. 9.** A,B,C) Thermograms First buttress; D) Visual image first buttress; E,F,G) Thermograms Second buttress; H) Visual image second buttress; I,J) Thermograms Corner in west façade; K) Visual image of corner; L) Thermograms Stairs; M) Visual image of stairs; N, O) Thermograms Corner in west façade; P) Visual image of corner; Q, R) Thermograms Corner; S) Visual image of corner in west façade.

the presence of the humidity and assess abnormally wet locations of historic buildings, structures and their materials; provide and locate trapped moisture within your existing roofing system.

In this research it was used the DELMHORST BD-2100 with two pins and pin lees meter. DELMHORST BD-2100 is a non-destructive method used to assess and monitor the relative moisture level of building materials. It is a pin type moisture meter that readings through two small pins and displays instant moisture content results on its, measure the subsurface moisture to a depth up to 19 mm. The numerical values represent the actual percent moisture content on brick. These instruments can detect moisture levels below levels that are visible or can be felt. DELMHORST BD-2100 has three scales: #1 Wood Scale, #2 0–100 Reference Scale and #3 Gypsum Scale. We used Scale #2 - 0–100 reference scale for other non-wood materials such as bricks, rammed earth and stone parapet wall to determine a qualitative reading [42]. These readings are shown as a numerical value which we can use to estimate whether that material is “wet” or “dry.” It is important to note that the numbers used in a reference scale are not indicative of a specific percentage of moisture content. Instead, measurements in the reference scale are used as a relative indication of how much moisture a material has in it. [43].

An area was selected on each facade to measure brick and stone (Fig. 4). For the data collection, a 50 x 50 cm mesh was used and it was measured in each of those points with the portable moisture testes along the façades from ground level to the roof. Before the survey the DELMHORST BD-2100 was calibrated. Once the values were obtained, they were introduced in the program Surfer V15 develops by Golden Software [44]. In this program an interpolation of the data is done to obtain the humidity maps of each façades. For moisture mapping we used the blue color to indicate that the surface is too wet (> 95) whereas red color indicates a sufficiently dry moisture level (0–85) and yellow color indicates a borderline situation (85–95) [42].

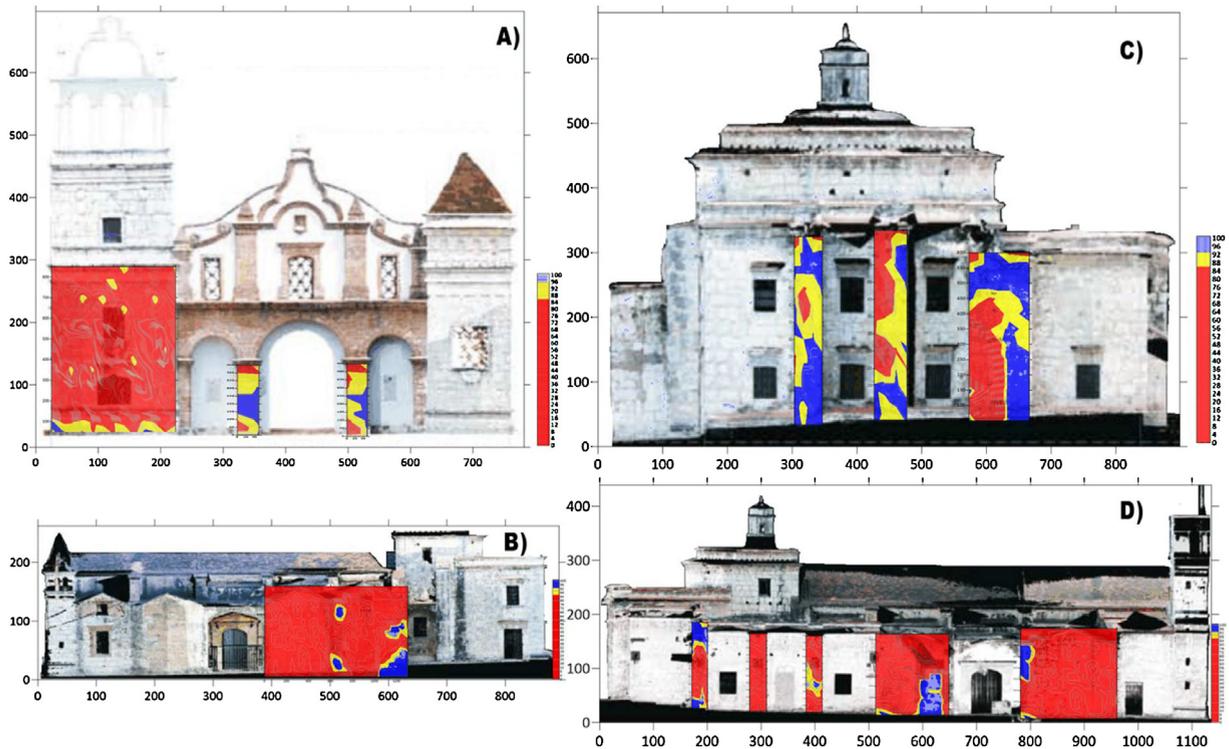


Fig. 10. A) Moisture in Main Façade (South); B) East Façade; C) Back Façade (North); D) West Façade.

## 4. Experimental results and discussion

### 4.1. Environmental conditions

To appreciate the conditions under which the study was carried out, it is important to know the environmental conditions at the time of the assessment because have direct impact on the material condition. Is important in Warm Humid Regions, like Dominican Republic, controlled and managed the humidity and the movement of water because in this kind of weather the continual presence of dampness in the materials and the water vapor present in the air affect the materials. The analyzed parameters were the following: Ambient CO<sub>2</sub>, Ambient Temperature, Relative Humidity, Atmospheric Pressure, Dew Point, Wet Bulb and CO. The average data taken in situ can be seen in Table 4 and Fig. 5 shown the interior – exterior air temperature and relative humidity taken on June 28th, 2017.

The warm-humid climate is characterized by hot, sweaty and sticky conditions. For instance, in this case there is a high relative humidity 78.52%, air temperatures remain moderately high between 22 and 33 °C with little variation between day and night. The construction materials used in this building responded adequate to this climate.

### 4.2. Infrared Thermography (IRT)

#### 4.2.1. Main façade

In the Main Façade (south) the thermal images (Fig. 6E) shows that in the middle of the columns there are an area wet while the base was dry. This humidity is originated when rainwater and runoff water penetrate. Also in the upper part (Fig. 6D) there are moisture in a large area due to a) when rainwater and runoff water penetrate; b) humidity penetrates through cracks and through the loss of the lining or paneling c) rammed earth wall hygroscopicity, even though we can observe this humidity in the visual image (Fig. 6F).

While in the Bell Tower the thermal images indicate: a) Moisture originating from the subsoil due to the capillary action at the base of the bell tower when rainwater and runoff water penetrate; b) humidity penetrates through cracks and through the loss of the lining or paneling in some areas of the bell tower; c) rammed earth wall hygroscopicity. (Fig. 6A, B).

#### 4.2.2. North façade

The North Façade present dampness in both walls and buttresses, caused by: a) ascending capillarity when penetrating rainwater runoff from facades; b) Moisture by filtration when the water penetrates the stone due to poor drainage in roofs, allowing the growth of vegetation and the formation of the black crust. (Fig. 7).

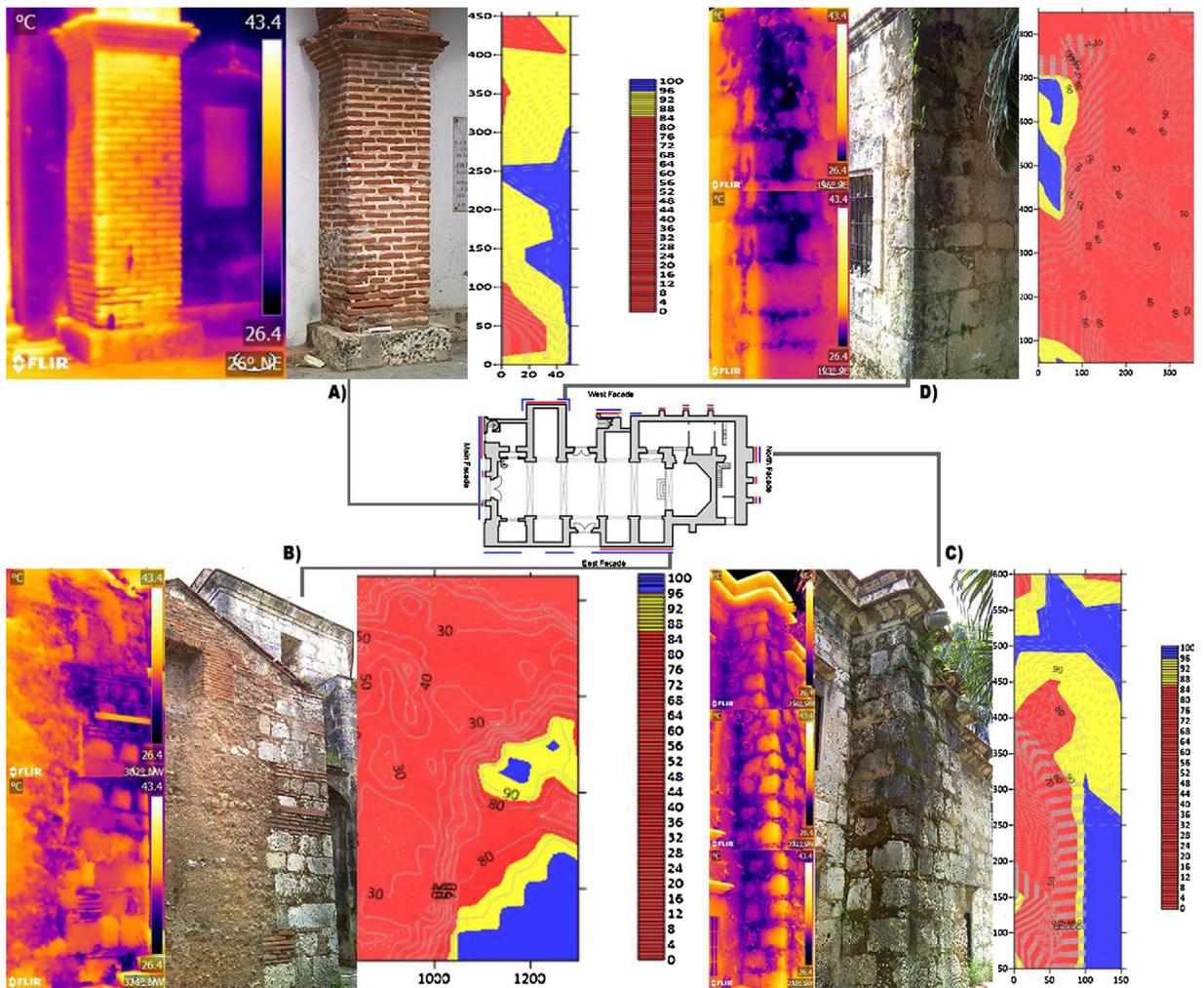


Fig. 11. A) Column in main façade (South); B) Corner in east façade; C) Buttress in back façade (North); D) Corner in west façade.

#### 4.2.3. East façade

In East façade observed a dampness in the walls caused by: a) ascending capillarity when penetrate rainwater runoff from facades; b) Moisture by filtration when penetrating the water through wall due to damage drainage in roofs and by the loss of plaster, allowing the growth of vegetation in some zones and formation of the black crust; c) rammed earth wall hygroscopicity. (Fig. 8). Most of the humidities are identify in the areas where the drainages are located, deteriorating the rammed earth and the coralina limestone.

#### 4.2.4. West façade

In West façade was observed dampness in both walls and buttresses, caused by: a) ascending capillarity when penetrate rainwater runoff from facades; b) Moisture by filtration when the water penetrates the stone due to damage drainage in roofs, allowing the growth of vegetation in some areas and the formation of the black crust. (Fig. 9). This humidities are deteriorating the façade with the consequence of major damages such as structural problems.

### 4.3. Electrical Resistance Measuring (ERM)

The Moisture mapping shows the main façade (south), where the extent of wet and dry areas can be identified with different colors (blue color indicates a surface too wet (>95), whereas red color indicates a sufficiently dry moisture level (0–85) and yellow color indicates a borderline situation (85–95)). Fig. 10A) shows a great area sufficiently dry moisture in the bell tower with a few areas too wet in the base, whereas in the two columns there are an area too wet located in the middle and a few areas sufficiently dry moisture. Fig. 10B) shows a great area sufficiently dry moisture, also we can observe a blue zones located in the base and in some parts of the façade. Fig. 10C) shows a great surface too wet in the three buttress located

in different areas (base, top, middle), also there are areas with borderline situation (yellow) and sufficiently dry moisture (red). Fig. 10D) shows a great areas sufficiently dry moisture, also we can observed some areas too wet located in the base and the top of the façade.

Fig. 11 shows a comparative between IRT and ERM of small part of each façades. Fig. 11A) shows a column located in the main façade where we can observe in both methods that there is a wet area in the middle of the column. Fig. 11B) shows a part of east façade where there are two areas too wet (>95) perfectly identify in the middle and in the base of the corner. Fig. 11C) shows a buttress in back façade where we can observe areas too wet in part of the base and top, also there are areas in the borderline situation (85–95) and others areas sufficiently dry moisture (0–85). Fig. 11D) shows a corner in west façade where we can observe in both methods that there is a wet area located in the top and in the middle of the corner.

Also in Fig. 11 we can observed that there is a difference in the results between both techniques, because of in ERM there is no difference between the joints and the stone or brick pieces, these occur due to the moisture was measured only in the stone and brick.

## 5. Conclusions

In conclusion, by comparison between the IRT and ERM results on façade of the church of Santa Barbara Church (Santo Domingo, Dominican Republic) can reduce the risks of being wrong and give a detailed diagnostic analysis of the materials in historic building that can lead to a successful precise recognition of the behavior of historic external material and is therefore an opportunity to conduct research in any number of measuring points. Integrated various NDT for the analysis can be considered as powerful, simple and low-cost methods for in situ monitoring and assessment cultural heritage monuments.

In the scope of the rehabilitation process in a historical building it is necessary to carry out a complete identification and inspection survey of the buildings. For that reason, locate and map the pathologies is a fundamental tool in the diagnostic phase for studying a building's conservation state, especially with the presence of surface moisture which is one of the major damage that affect the historical buildings.

In a tropical warm humidity climate is very important establish, control, and identify the moisture levels in a historic building because the environment plays a major role in material deterioration. The use of both methods offers supports and monitor the humidity in building because the natural levels of humidity and temperature in the humid tropics keep materials with a small percentage of moisture, so they can be slightly damp while avoiding problems.

Considering the relative steadiness of this tropical climate, it was determined that despite the effect caused by the humid environment, walls are constructed with heavy materials with low porosity and large thermal capacity to absorb much of the heat entering through the outer surface of the wall during the day. Even though the brick absorbed more than coralina limestone both of them confirmed that they do not have communicated pores and this produced the low porosity at the materials.

Both techniques are a fundamental tool for the detection of moistening in walls or any other construction elements and they can do it in situ, making it easier for construction technicians to assessment and identify the affected areas, as to find a solution for the encountered problems, without affecting the authenticity and the historical value of the building. The data obtain by IRT and ERM combined with visual inspection allows to make in situ, easier, inexpensive, precise and quality an assessment of the moisture conditions based on scientific information.

The application of these techniques have similarities and differences, in IRT, surface temperature depends on more variables than humidity, such as exposure to sun and shade, thermal bridges, density and conductivity of materials at each point, while ERM, as measures the electrical resistance of the material, reading data depends on more variables than just humidity, such as dielectric property of the materials, temperature effects (sunlight and shadows, thermal bridges, density and conductivity of materials, among others).

Several moisture sources were identified: moisture originating from the subsoil due to the capillary action; water leaking from damaged water distribution systems; and hygroscopic moisture on the rammed earth wall. With ERM the results show the most humid areas corresponding to the same areas that appear in the IRT, confirming in this way the presence of moisture in large part of the façades. Also, it is important to take into account that there are mosses, lichens and even plants in some parts of the facades that could distort the real temperature of the surface, increasing the moisture in that area. On the other hand, in this church there is no salt efflorescence due to the characteristics of the material, since it has very large pores and when it rains the salts come out of the pores.

## Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and this research is part of the project "Influence of the Environment in the process of deterioration of construction materials in historic buildings and proposals for its conservation", Contract No.165-2013, Code: 2013-285-102 funded by FONDOCYT 2013, MESCYT (Ministry of Higher Education Science and Technology).

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). She is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author and which has been configured to accept email from Letzai Ruiz Valero (l.ruiz@ce.pucmm.edu.do).

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