

High performance thermal properties of natural pumice-based bricks

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ABSTRACT

Aims: Characterization of the thermal properties of natural pumice-based lightened bricks under ASTM standards, analyzing thermal conductivity to promote thermal comfort inside buildings.

Study design: The project had four stages. The first was getting the base material (pumice). The second was developing of lightened test specimens. The third was focused on the characterization and fourth intended for the interpretation and analysis of the test results and conclusions of the project.

Place and Duration of Study: Universidad Autónoma de Querétaro, from January to December, 2012.

Methodology: XRD by powders with a diffractometer Bruker D-8 Advance, Cu anode at 30 KV and 30 mA, Cu Ka radiation $\lambda = 1.54 \text{ \AA}$, from 10 to 90° on the 2 θ scale at 2°/min. Mechanical tests according to ASTM C109/C109M-08, minimum compressive strength at 28 days of 7.8 N/mm². X-Ray fluorescence with Spectrometer SIEMENS fluorescence X-ray SRS 3000. Thermal conductivity using ASTM C177: Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded Hot-Plate Apparatus (2004).

Results: Pumice was identified as pozzolanic material with crystalline phases of significant silica- aluminate content by X-Ray diffraction. X-Ray Fluorescence analysis confirmed the elements of the pumice, therefore this analysis confirmed the presence of Si dominant, followed by Al. Lightened bricks were developed meeting the specifications of resistance of the ASTM standards, and the properties of thermal conductivity are better than traditional sand-cement bricks; density and porosity could create a zone of thermal comfort within buildings. Apparent thermal conductivity of pumice specimens was 0.336W m⁻¹K⁻¹, thermal resistance 0.234W⁻¹m²K and Expanded uncertainty (k=2) 5%.

Conclusion: Due to porosity together with good mechanical comportment, the natural pumice-based bricks have advantages in lighter weight-effort, tensile strength and higher thermal insulation characteristics. The thermal conductivity results 66% lower than hollowed bricks, 59% lower than typical lightweight bricks and lower in 62% than traditional mud brick. The thermal properties of the material are affected by the size of the mineral material form, presence of micro pores, fractures, and humidity.

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1. INTRODUCTION

Due to its relatively low thermal conductivity characteristics and being a local product, pumice aggregate concrete (PAC) blocks are increasingly used as a masonry wall unit [1]. The masonry construction is the most widely used worldwide, and especially in Latin America has a beneficial use; example of this are ancient pre-Hispanic buildings that still standing and preserved both architectural beauty and its goal of structural support [2]. Similarly, public buildings and colonial faithful are clear testimony of the quality and durability that masonry construction systems can provide [3,]. However, the construction industry continues improving the structural building systems according to the available technology, this due to the increasingly demanding requirements for quality and environmental standards for buildings [4]. Technological advances in masonry walls are to reduce the execution times in construction, thermal insulation, sound insulation, fire protection and reduction of coating thickness. Many of these advances are focused in getting a more sustainable building system by reducing costs for energy consumption [5, 8, 24]; however, environmental, development and application of natural materials that meet the nowadays sustainable requirements remain being a problem.

Buildings have resources consumption needs, the electric energy is the most demanding requirement because of high energy consumption required of the heating, ventilation, and air conditioning (HVAC) systems for maintaining internal thermal comfort and hinder the outside temperature due to inside buildings increased temperatures reach up to 2°C [6]. Different kind of masonry walls has been investigated to provide a thermal isolation structure for buildings and lightweight bricks walls have demonstrated this capacity, approximately 70% of total energy consumption is destined to HVAC systems hence savings in air conditioning and heating are a significant cost savings in the maintenance of buildings [7].

Combination of the heat storage capacity and the thermal insulation characteristics of the masonry walls regulate the conditions inside the building. The thermal behavior of masonry walls depends on the conductivity coefficient of the wall material as well as the thermal characteristics of the mass of the wall [9]. The qualities of thermal inertia of the wall slows the response to changes in external conditions and limit changes in internal temperature, so that when constructing walls with bricks, which by their physical properties of the matter have low conductivity coefficient, will be provide to the building a thermal isolation from its conception [10].

According to P. Ihm (2012) it is necessary to make a design optimization in order to achieve the energy efficient [14] but those elements for structural insulation show a high investment cost that most people are not willing to pay. In addition, these novelty elements as lightweight and semi lightweight concretes using materials and construction processes require trained staff and usually are not available skilled labor [15], [16]. Despite the good results that show temperature insulation new materials and methods used to date, these have significant disadvantages, specifically the main is high cost of the material, unusual constructions. For another part, the septum annealing is the leading and most abundant construction material [17] but their process of making has a disadvantage of high cost in ecological terms, it needs a temperature between 950°C and 1050°C for 12 hours, requires 2365 kJ= 657 W/h and the type of fuel used, typically fossil fuel [18]. The benefits of use natural material become evident when considering that for every MW/h of renewable energy generated, the emission of approximately 0.75 T of CO₂ is avoided [25] and a “model” tree can absorb 0.67 T of CO₂ [26].

As a result, this work searches for low-cost new construction materials with better properties of thermal insulation and sufficient availability and accessibility which are one of the main goals for this study.

Natural materials shows the lowest thermal conductivity and the fiber variety contribute significantly to improving the thermal insulation properties to be applied to the exterior of buildings [11, 12, 13]. Furthermore, the coefficient of thermal conductivity depends on the humidity, layer thickness and porosity of the material. A high porosity has considerable impact on the thermal performance of insulation materials.

The walls of lightweight material with pumice have a density between 650 and 685 Kg/m³, the Young's modulus ranges from 6,850-7,580 MPa and a thermal conductivity coefficient between 0.17 and 0.19 Wm⁻¹ K⁻¹ [19]. Although, research shows the potential of the mineral pumice because there has only been applied in the form of wall construction as a structural element, but used as a coating, it has proved that produce thermal qualities essential processes in the area of the baking ovens for isolation of the burn chamber [20]. Despite the knowledge of pumice it is necessary to make a physic-chemical characterization of Queretaro pumice that allows discovering the nature of pumice in this region.

Faced with the consumption of resources for raw materials and excessive air pollution, care for them is increasing to a greater degree than in the past. In recent years, some researches about natural materials have shown to be commensurate with common building materials [11] bricks lightened with natural materials still having the typical disadvantage of low compressive strength, although having good isolation results, some of pumice lightened-bricks investigations [8], [19] evidence the unfortunately the constant failure of mechanical properties. One of the natural materials with the qualities for construction is the pumice; applied both for their physical and mechanical properties [21] to improve the thermal resistance of the structures and lower total loads. The walls made of pumice as material for hollow walls, has proved to be one of the most effective ways to reduce energy consumption and costs due to the non-use of air conditioning systems, providing that proper thickness of material is used [22]. This work deals with lightweight pumice bricks theme which approves the NMX standards for structural bricks and ASTM standards about thermal conductivity properties to provide a thermal isolation material. The principal objective is to create a lightweight pumice-based brick with the characteristics before mentioned.

Hypothesis: the local pumice rock in extraction natural form as aggregated for lightweight bricks provides an efficient isolation natural material with a thermal conductivity coefficient lower than typical lightweight bricks improving the compressive strength required by currently standards.

2. MATERIAL AND METHODS / EXPERIMENTAL DETAILS / METHODOLOGY (ARIAL, BOLD, 11 FONT, LEFT ALIGNED, CAPS)

2.1 Material

In this study was characterized the pumice rock which from the superficial mine of San Clemente, Queretaro.

Pumice is a glassy igneous rock with low density and high porosity ratio, with color tones ranging from white to gray. Contains mainly silica-aluminates and has a visually appearance from crushed texture to vitreous, usually could be found in considerable volumes as a result of volcanic action. Pumice has different applications; can be found in works of art, in the health and beauty industry mainly in construction and decorative materials of low density textured coatings. The pumice is a result of volcanic activity, and may be acidic or alkaline in composition; density varies between 0.5 and 1 T/m³ for acid rock, and between 1 and 2 T/m³ for alkaline pumice. It has approximately 70% porosity.

2.2 Methods

2.2.1 Analysis of the crystalline phases by XRD

Pumice preparation for XRD study according to the methodology of SCT standard M-MMP-1- 03-03. Ten random samples from the bank of San Clemente mine in Queretaro were analyzed in two different conditions. The first was in a natural extraction condition and the second after a calcination process at 450°C during 4 hours into a muffle. Two analyzes were conducted on each sample with the XRD powder process in a diffractometer Bruker D-8 Advance, with Cu anode operated at 30 KV and 30 mA, wavelength of Cu Ka radiation of $\lambda = 1.54 \text{ \AA}$, from 10 to 90° on the 2θ scale at 2° / min. The calcination process was made in order to remove the organic content of the samples.

2.2.2 Compressive strength

Mechanical tests are according to ASTM C109/C109M-08 and NMX-C-036/404 which establishes a minimum compressive force at 28 days of 7.8 N/mm². With the pumice were created 5 gravels with different granulometry. Then three different proportions were analyzed with each kind of gravel. On each mixture were made three bricks and were elaborated to test at ages of 7, 14 and 28 days. The bricks were made in a manual press and the mixture which showed better properties according to this investigation was selected to continue with the thermal conductivity test. The proportions are in Table 1.

Table 1. Proportions used for samples in the compressive strength test

N° of Samples	Cement	Pumice	Gravel
	(%)	(%)	(Type)
9	40	60	
9	50	50	G1 to G5
9	60	40	

2.2.3 X-Ray Fluorescence

X-ray spectrometry is a qualitative and quantitative elemental analysis based on the lengths of wave or X-ray energy, emitted by the sample after primary radiation. X-Ray fluorescence with Spectrometer SIEMENS fluorescence X-ray SRS 3000, method based on ASTM standards [26]

2.2.4 Thermal conductivity

Thermal conductivity using the ASTM C177: Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded Hot-Plate Apparatus (2004)[23]. The primary apparatus GHPA to determine the resistance and the apparent thermal conductivity of insulating materials, Figure 1 shows a picture of the apparatus, provided by the CENAM for this research.

Principle of Operation: the GHPA (Figure 1) is a basic tool that uses the approach of conduction heat transfer in a steady state and to determine the thermal conductivity by the following equation:

$$q \lambda = l / (A \Delta T) \quad (1)$$

Where q is the ratio of heat flow through the sample W , λ is the thermal conductivity of the sample in $W / m K$, ΔT is the temperature difference across the sample $^{\circ}C K$ or L is sample width in m and A is the cross sectional area in m^2 .

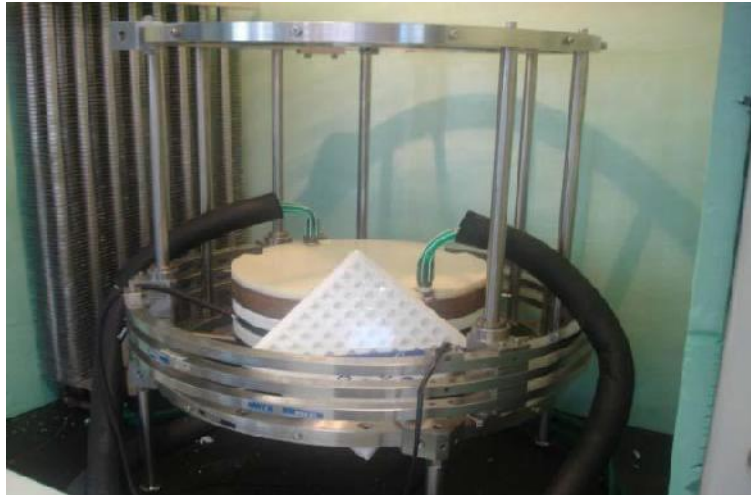


Figure1. Guarded hot plate apparatus (GHPA). National Metrology Center, México.

Procedure for assessment

The procedure for measurement can be summarized in the following stages:

1. Sample selection,
2. Sample preparation and installation in the apparatus,
3. Establishing constant state thermal
4. Data collection and
5. Analysis of results.

Sample elaboration: Samples were made in a cylindrical metallic mold with 19 cm of diameter and 7.86 cm of thick helped by a universal machine. The mixture is poured into the mold and cylindrical mold and the machine's shaft is actuated. The universal machine stops until it feels a slight resistance in the sample. The sample selected for the test were the samples made with the mixture that showed more compress strength resistance using the less amount of cement.

The parameters controlled during the test were the minimum and maximum value for temperature, simulating two extreme ambient conditions in Queretaro.

Sample Selection: the most critical factors in the selection of the sample are the size, width and thickness, flatness and parallelism of the sample. The width is essential to keep the error within the maximum allowed. The diameter should be chosen such that it fully covers at least the size of measurement which is at least 152.4mm. The surfaces of the sample should be flat and parallel to get a good thermal contact with GHPA plates.

Sample Preparation: it is necessary to produce parallel sample surfaces to ensure good thermal contact between it and the GHPA plates. The sample and thermocouples should have rigid contact surface to a better determination of the temperature condition, and the plates with the sample at a temperature close to the temperature of test, for example, placing it in a furnace to prevent the absorption of condensation water.

205 Establishment of Permanent Thermal State: this stage begins after the installation of the
206 sample in the measuring area of the stored items and the insulating necessary to reduce the
207 effect of environmental conditions. The device takes action to fulfill the conditions of
208 temperature at which to perform the test. The time required to reach steady state at a
209 sample thickness of 25.4 mm and uniform insulating items is almost 5 h, this time increases
210 with increasing thickness.
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213 3. RESULTS AND DISCUSSION

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215 Lighten practical building material by replacing a portion or all of the aggregates of the mix to
216 make bricks, adding materials in excess of 5% on the weight of the binder. These additions
217 are lightweight aggregate, which in this case study is pumice. There is lightweight compound
218 when the true density is less than 2g/cm^3 . Advantages of addition: the particle size inclusion
219 improves by more reasonable weight, higher mechanical resistance and better surface
220 hardness. Moreover, the better-quality characteristics improve the performance of blends
221 with binders.
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224 3.1 XRD

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226 From XRD research on pumice samples, Figure 2 shows diffractograms from two natural
227 samples and two samples after a burning process. The signals obtained are inconsistent and
228 the graph shown vague so by XRD study did not support the total pumice formation, mostly
229 due to the nature of their structure; presume result because the material include a vitreous
230 fraction. This was confirmed through X-Ray fluorescence research.
231

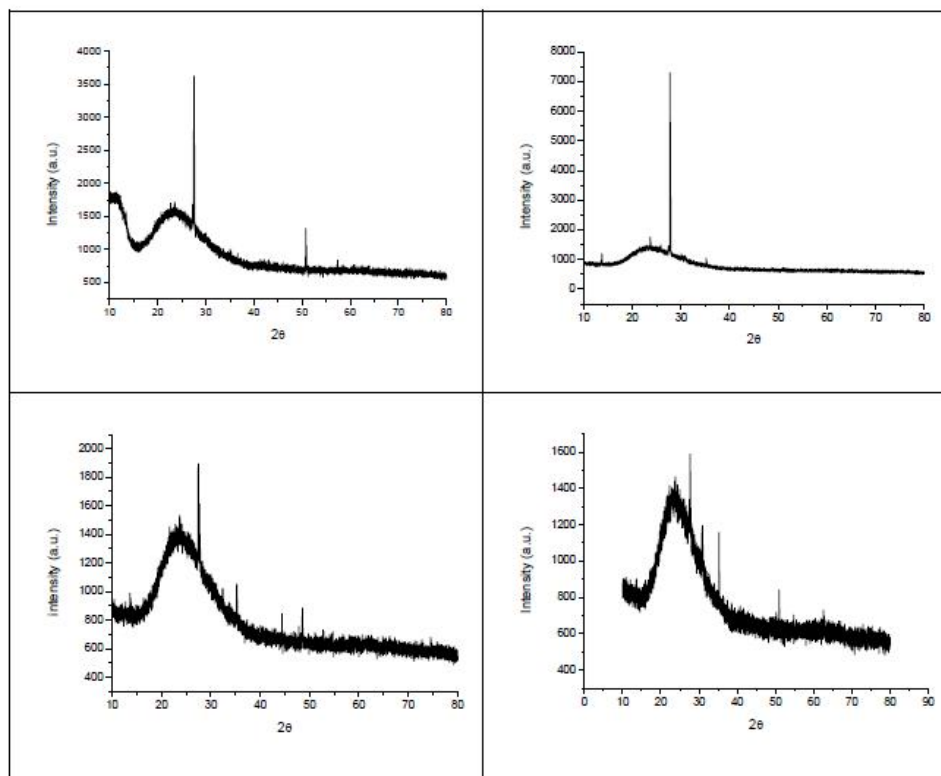


Figure 2. Diffractograms of four of the t 252 en pumice samples showing the main amorphous phase and the crystalline phases of signals which correspond essentially to silicon oxide.

When analyzing the samples after a burning process, diffractograms corresponding to those obtained in the first instance; in contrast, these diffractograms confirmed the amorphous phase of the material due to the presence of feldspar, a volcanic glass and phenol-crystals trace minerals, as hematite, with the remainder **found** in the second analysis of the crystal structures of predominantly silica-aluminates. Clear signals relative to crystalline phases of silicon oxide are in **Table 2**.

Table 2. Crystalline phases detected by XRD.

PDF	2θ	ID	Crystal
086-1562	27.316	Silicon oxide phase 1	Quartz
	41.55		
	70.23		
085-0461	27.599	Silicon oxide phase 2	Quartz
085-0459	27.31	Silicon oxide phase 3	
083-0540	27.31	Silicon oxide phase 4	
081-0069	29.80	Silicon oxide phase 5	Quartz
	41.54		
063-7619	27.59	Silicon oxide phase 1	Low periodicity quartz

3.2 Compressive strength

The goal of this work focus on the property of thermal conductivity; however, proof of appropriate **mechanical** behavior across the study of compressive strength, which was suitable for use in manufacturing pumice bricks according to the typical practices. The compressive strength of specimens for 7, 14 and 28 days was analyzed according to the NMX-C-036-2004- ONNCCE "blocks, bricks - Compressive Strength - Test Method". A total of 135 samples were tested under this NMX standard and samples dimensions are 30 x 15 x 8 cm, length, width and thickness respectively. The finally approved brick for next stage was the one that was made with 40% of cement and 60% of pumice in weight. The area tested was 450 cm², with 3600 cm³ and a density of 0.720 T/m³. Granulometry characteristics are showed in figure 3. The values of compressive strength and average gross section are according to standard NMX-C-404-2005-ONNCCE "Blocks and Bricks partitions for structural purposes - Specifications and methods test". Results are in Table 3. The mechanical characteristics of this lightweight brick are especially relevant when it is take into account that almost any low-density brick reaches the compressive strength required by NMX standards.

Table 3. Results of compressive strength for specimens, averages.

Area (cm ²)	Resistance (kN)			Average resistance compressive strength (N/mm ²)		
	Age (days)			Age (days)		
	7	14	28	7	14	28
450	340.70	473.57	511.46	7.35	10.37	11.20

Table 4. Comparison of compressive strength between pumice-based lightweight bricks and ASTM C109/C109M-08 bricks and NMX- C-404-ONNCCE-2005 standards.

Piece	Compressive strength	Minimum compressive strength on gross area for blocks
	N/mm ²	N/mm ²
Own Lightweight Brick	6.52	
D1	2.80	Concrete block and septum annealing 6
E1	2.626	
E2	2.723	

Values of pumice-based lightweight bricks were taken from reference [19]. The most compressive force per unit of net cross-sectional area, exceed the specified compressive support for masonry; consequently, the material is a good choice for manufacturing lightened bricks.

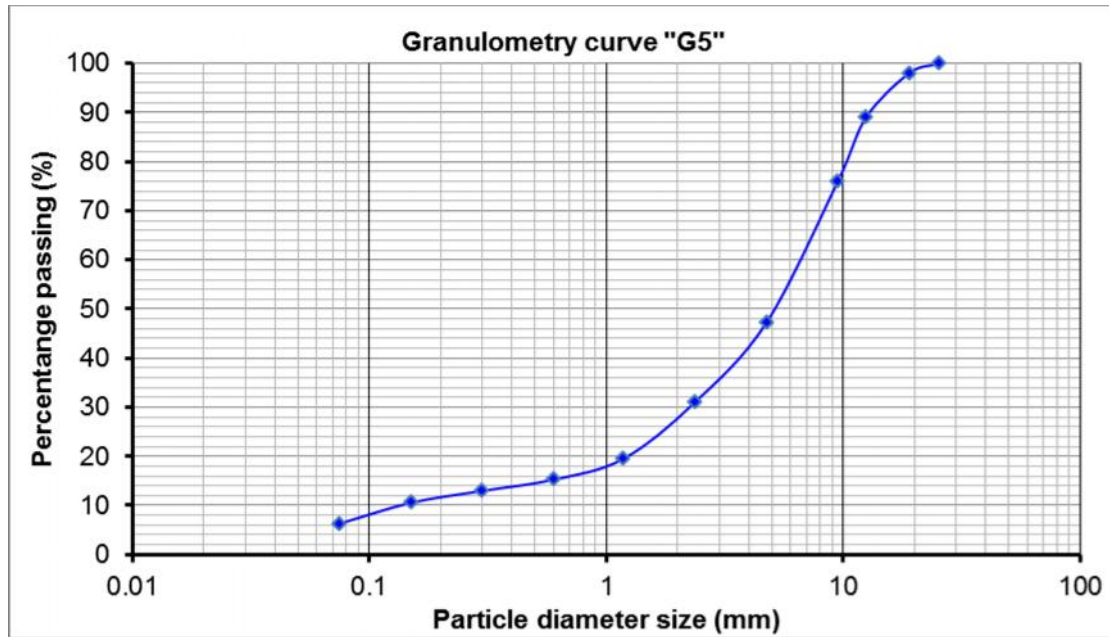


Figure 3. Granulometry curve of gravel used for conductivity coefficient test.

3.3 X-Ray Fluorescence analysis

The elements in the pumice were confirmed, so XRF study by semi-quantitative percentages for each sample. The presence of Si foremost was long-established, followed by Al as shown in Table 5. It can be appreciated that the compound with the largest percentage is silicon oxide, the same as was detected in the past XRD study.

Table 5. Main elements detected by XRF.

Compound	Mass fraction
	(%w/w)
SiO ₂	75.958
Al ₂ O ₃	10.796
K ₂ O	8.537
CaO	2.428

3.4 Measurement of thermal conductivity

One of the most important factors in the thermal behavior of walls is the thermal conductivity of their bricks [25]. Thermal conductivity for samples of building materials to the manufacture of lightweight bricks, consider the national standard thermal conductivity of insulating materials. The result of the thermal conductivity of the studied bricks helps for a more sustainable building. Conventional sand-cement bricks are around $0.930 \text{ W m}^{-1} \text{ K}^{-1}$.

The thermal conductivity coefficient was measured in four samples. These samples were elaborated with the mixture which has the major compressive resistance, lower absorption and the best workability characteristics which ensured the use of the best mixture and the best thermal insulation conditions. To ensure the flatness in the samples, faces were filed

302 until get parallel surfaces in all samples and the flatness and parallel conditions were
 303 confirmed with a surface measurement (Figures 4 and 5).
 304



Figure 4. Pumice-cement sample 1.



Figure 5. Surface measurement

305 The thermal conductivity of a material is a measure of its ability to transfer thermal energy
 306 (heat), by imposing a temperature gradient. Better materials enable delay in put heat and
 307 soften the outside temperatures, with air chambers or low density producing low thermal
 308 conductivity material. Results of thermal conductivity for pumice specimens are on Table 5.
 309

Table 5. Experimental values of thermal conductivity.

NATIONAL METROLOGY CENTER	
Laboratory of Thermal Conductivity	
Operator: SaúlGarcía Duarte	Test Number: One
SAMPLE DESCRIPTION: pumice-cement	
Identification: 1, 2	
Characteristics: solid material	
Dimensions: Samples of 19 cm diameter and 7.86 cm thick	
Notes: construction material	
APPARATUS DESCRIPTION: Guarded hot plate apparatus (GHPA)	
Orientation: Horizontal	
Operation mode: Double side measurement	
TEST PROCEDURE: Guarded hot plate apparatuswith constant heat flux	
Experimental values:	
Variable name:	Average value:
Power dissipation during test / W	3.63
Hot platetemperature/°C	32.0
Coldplatetemperature/°C	12.2
Temperature gradient in the sample /°C	19.8
Average temperature of test /°C	22.1
Ambient temperature/°C	21
Relative humidity /%	32
Samplethickness/mm	78.61
Measurement area/mm ²	21407
Average weight (1)/g	2275.1
Average weight (2)/g	2211.2
Results:	
Apparent thermal conductivity/W m ⁻¹ K ⁻¹	0.336
Thermal resistance /W ⁻¹ m ² K	0.234
Expanded uncertainty (k=2)/%	5

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4. CONCLUSIONS

In this research the objective of create a lightweight pumice-based brick with local pumice for masonry walls was achieved. Was also obtained an important conclusion that paves the way for future industrial exploitation of the Queretaro pumice is that the local pumice is suitable to produce lightweight pumice-based bricks in amounts from 50% to 70%, with the best mechanical performance at 60% of pumice content in weight, proportions that gives 7.35 N/mm² since 7 days and even achieve compressive resistance of 11.20 N/mm² at 28 days and improve resistance 86.67% major than required by NMX standards.

Natural pumice-based bricks produce the expected technical capabilities for the thermal isolation and mechanical properties, according to ASTM and NMX (Mexico) standards. Pumice from San Clemente, Queretaro, México, reduce the thermal conductivity coefficient of lightened ordinary bricks which preferred to the traditional sand-cement bricks for keeping indoor temperatures stationary along climate changes during the year. Lightweight brick elaborated in this work has 0.336 Wm⁻¹K⁻¹ of thermal conductivity coefficient which implies a better isolation material, is 66% lower than hollowed bricks, 59% lower than typical lightweight bricks and lower in 62% than traditional mud brick moreover present a lower density of 0.792 T/m³. Also after finalizing physic-chemical characterization methods, it is confirmed the amorphous nature of pumice as well as its dominant content of Si, Al and K presents at 75.95, 10.796 and 8.537 respectively.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

AUTHORS' CONTRIBUTIONS

Author MGR designed the study, wrote the protocol, and wrote the first draft of the manuscript and managed the literature searches. Author MZG have completed the experiments. Both authors have read and approved the final manuscript.

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