

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.

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 worthy mechanical comportment, the natural pumice-based bricks have advantages in lighter weight-effort, tensile strength and higher thermal insulation characteristics. The analyzed pumice reduces the thermal conductivity coefficient of lightened bricks. Thermal conductivity of lightweight bricks elaborated in this work implies a superior insulation material, comparable to the highest quality insulation materials.

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17 **1. INTRODUCTION**

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19 Due to its relatively low thermal conductivity characteristics and being a local product,
20 pumice aggregate concrete (PAC) blocks are increasingly used as a masonry wall unit
21 [1]. The masonry construction is widely used globally, and it is particularly useful in Latin
22 America; an example of this are ancient pre-Hispanic buildings, that still standing and
23 preserved architectural attractiveness and structural support [2]. Equally important, public
24 buildings and colonial heritage are clear testimony of the durability that masonry construction
25 systems can provide [3]. Otherwise, the construction industry continues improving the
26 structural building systems according to the technological development, due to the
27 increasingly demanding requirements for quality and environmental standards for buildings
28 [4]. The advances in masonry walls reduce the construction execution times; improve
29 thermal insulation, sound insulation, fire protection and reducing coating thickness [5]. Many
30 of these advances are focused in getting a more sustainable building system by reducing
31 costs of energy consumption, [6]. Nevertheless, environmental development and application
32 of natural materials meeting the sustainable requirements remain being a problem [7].

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34 Buildings have consumption needs: the electric energy is the most demanding requirement,
35 because of high energy consumption required by the heating, ventilation and air conditioning
36 (HVAC) systems for maintaining internal thermal comfort, and hinder the outside
37 temperature due to inside buildings increased temperatures reach up to 2°C [8]. Different
38 kind of masonry walls has been investigated to provide a thermal isolation structure for
39 buildings, and lightweight bricks walls have demonstrated this capacity [9]; approximately
40 70% of total energy consumption is destined to HVAC systems; henceforward, savings in air
41 conditioning and heating are a significant cost savings in the maintenance of buildings [10].

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43 Combination of the heat storage capacity and the thermal insulation characteristics of the
44 masonry walls, stabilize the conditions inside the construction. The thermal behavior of
45 masonry walls depends on the conductivity coefficient of the wall material, as well as the
46 thermal characteristics of the mass of the wall [10]. The thermal inertia of the wall slows the
47 response to changes in external conditions and limit changes in internal temperature; as a
48 consequence when constructing walls with bricks have low conductivity coefficient, a thermal
49 isolation will be provided to the building from its conception [11].

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51 It is essential intend a materials design optimization, in order to achieve the energy efficiency
52 [12]. Even though, the insulation materials are usually expensive and most people are not
53 willing to pay. In addition, these novelty elements as lightweight and semi lightweight
54 concretes using materials and construction processes, require trained staff and usually are
55 not available skilled labor [13], [14]. In the same way, the septum annealing is the leading
56 and most abundant construction material [15], although, their processing has the
57 disadvantage of high ecological impact as a result of prerequisite temperatures from 950°C
58 to 1050°C for 12 hours, requiring 2365 kJ= 657 W/h, and the typically fossil fuel used [16].
59 The benefits of natural material use become evident when considering that for every MW/h
60 of renewable energy generated, the emission of approximately 0.75 T of CO² is avoided,
61 and a “model” tree can absorb 0.67 T of CO² [17].

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63 The benefits of natural material use become evident; thermal conductivity and the fiber
64 variety contribute to improve the thermal insulation properties to the exterior of buildings [18].
65 Furthermore, the coefficient of thermal conductivity depends on the humidity, layer thickness
66 and porosity of the material [19]. In the same way, high porosity has considerable impact on
67 the thermal performance of insulation materials [20]. The lightweight pumice bricks could
68 have a density between 650 and 685 Kg/m³, Young's modulus ranges from 6,850 to 7,580

MPa, and a thermal conductivity coefficient from 0.17 to 0.19 Wm⁻¹ K⁻¹ [21]. Afterward, research demonstrate the potential of 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 worthy thermal effects in essential processes of the baking ovens for insulation of the burn chamber. Whereas he widely knowledge of pumice, it is necessary to achieve a physical-chemical characterization of the Querétaro State pumice, providing local pumice properties for better construction practice.

Faced with the resources consumption of raw materials and environment impact, 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 adequate along with common building materials [18]. Lightened bricks made of natural materials still having the characteristic disadvantage of low compressive strength, although having good isolation results, some of pumice lightened-bricks investigations, evidence the unfortunately the constant failure of mechanical properties [21]. One of the natural materials with the quality for construction is pumice; applied both for their physical and mechanical properties to improve the thermal resistance of the structures and lower total loads [22]. The walls made of pumice as raw material have proved to be one of the most effective ways to reduce energy consumption and costs due to the non-use of air conditioning systems. This work deals with lightweight pumice bricks which approves the ASTM standards [23]. The main objective of this paper is the examination of high performance thermal properties of natural pumice-based bricks which provide better thermal insulation properties, appropriate availability and user-friendliness.

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

2. MATERIAL AND METHODS / EXPERIMENTAL DETAILS / METHODOLOGY

2.1 Material

In this study, pumice rock from the mine of San Clemente, Querétaro State was characterized. Pumice is a glassy igneous rock with low density and high porosity ratio, with color tones ranging from white to gray. Mainly contains silica-aluminates and has a visually appearance from crushed texture to vitreous; usually could be found in bulk volumes as a result of volcanism. Pumice can be found in art works, health and beauty industry and in construction, mainly as decorative materials of low density textured coatings. The pumice may be acidic or alkaline; density varies from 0.5 to 1 T/m³ for acid rock, and from 1 to 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 $\lambda = 1.54$ Å, from 10 to 90° on the 2 θ 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 which establishes a minimum compressive force at 28 days of 7.8 N/mm². Formerly, with the natural pumice were produced five gravels with different granulometry. Afterward, three different proportions were analyzed of each kind of gravel. Subsequently were made three bricks in a manual press and were tested at ages of 7, 14 and 28 days. Finally, the mixtures showing appropriate compressive results were selected to proceed to the thermal conductivity test. In Table 1, proportion results are shown.

Table 1. Proportions 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 was done with Spectrometer SIEMENS fluorescence X-ray SRS 3000, method based on ASTM standards [24].

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 (GHPA) [23]. The primary apparatus GHPA provided by the National Metrology Center (México), to measure the resistance and the apparent thermal conductivity of insulating materials is shown in Figure 1.

Principle of Operation: the GHPA 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 °C K or L is sample width in m and A is the cross sectional area in m^2 .

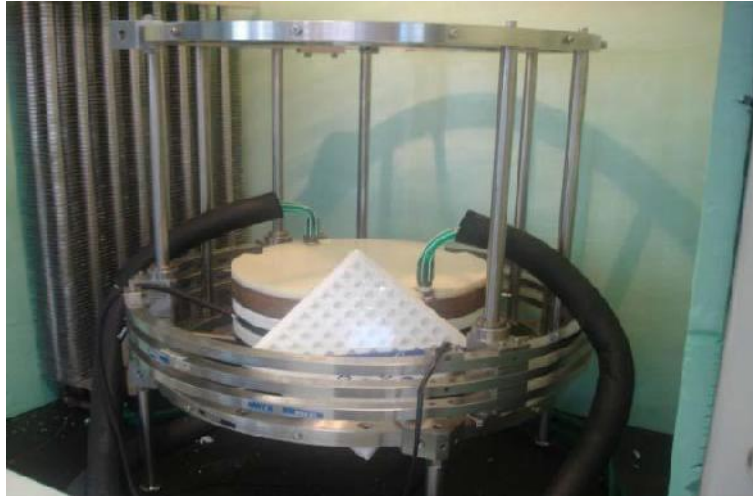


Figure1. Guarded hot plate apparatus (GHPA). National Metrology Center, México.

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 senses a slight resistance in the sample. The samples for the thermal test were the samples approving ASTM compress strength resistance standard, using the less quantity of cement. The parameters controlled during the test were the minimum and maximum temperatures value, simulating two extreme ambient local conditions.

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 as possible, to improve the contact with GHPA plates.

Sample Preparation: it is necessary to produce parallel sample surfaces to ensure good 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. The dimensions and weight were recorded previously to the test; the samples were tested in a dried weight condition and in order to have this condition, the samples were dried in the furnace until get a constant weight. After that, samples were covered with a thin plastic coat and placed in a furnace to prevent the absorption of condensation water. Finally, the samples were placed in an insulating foam mold that helps to reduce the lateral heat leakage and ensure a heat unidirectional flow. The moisture of samples was controlled by this preparation. The relative humidity was maintained at 32% during the test which is controlled by the GHPA as shown in the test report.

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Establishment of Permanent Thermal State: this stage begins after the installation of the sample in the measuring area of the stored items and the insulating needed to reduce the effect of environmental conditions. The device takes action to accomplish the temperature conditions to perform the test. The time required reaching steady state at a sample thickness of 25.4 mm and uniform insulating items is almost 5 h; this time increases if increasing thickness.

3. RESULTS AND DISCUSSION

The foregoing results show advantages of the addition of a lightweight aggregate; the physical characteristics were upgraded by reducing weight, sufficient mechanical resistance and satisfactory surface hardness. Moreover, the better-quality improves the thermal performance of natural pumice-based bricks.

3.1 XRD

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

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 shown in Table 2.

Table 2. Crystalline phases detected by XRD.

PDF	2θ	ID	Crystal
	27.316		
086-1562	41.55	Silicon oxide phase 1	Quartz
	70.23		
085-0461	27.599	Silicon oxide phase 2	
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

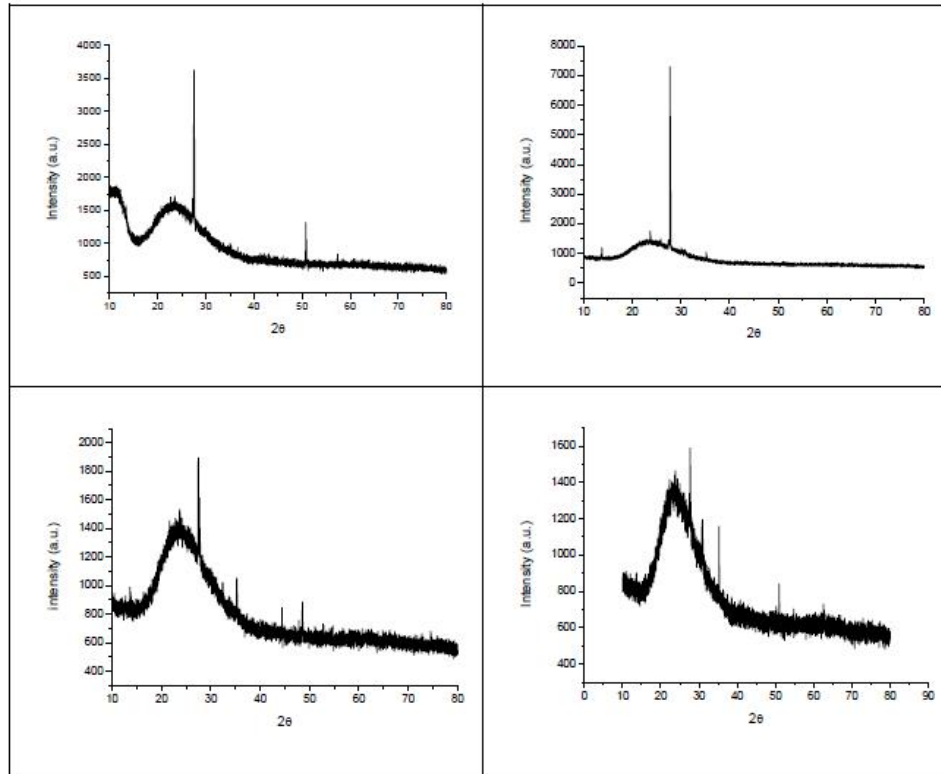


Figure 2. Diffractograms of four of the t 252 en pumice samples showing the main amorphous phase and the crystalline phases of signals which correspond essentially to silicon oxide.

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 ASTM C109/C109M-08 standard. A total of 135 samples were tested under this 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 according to results are shown in Table 3.

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

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

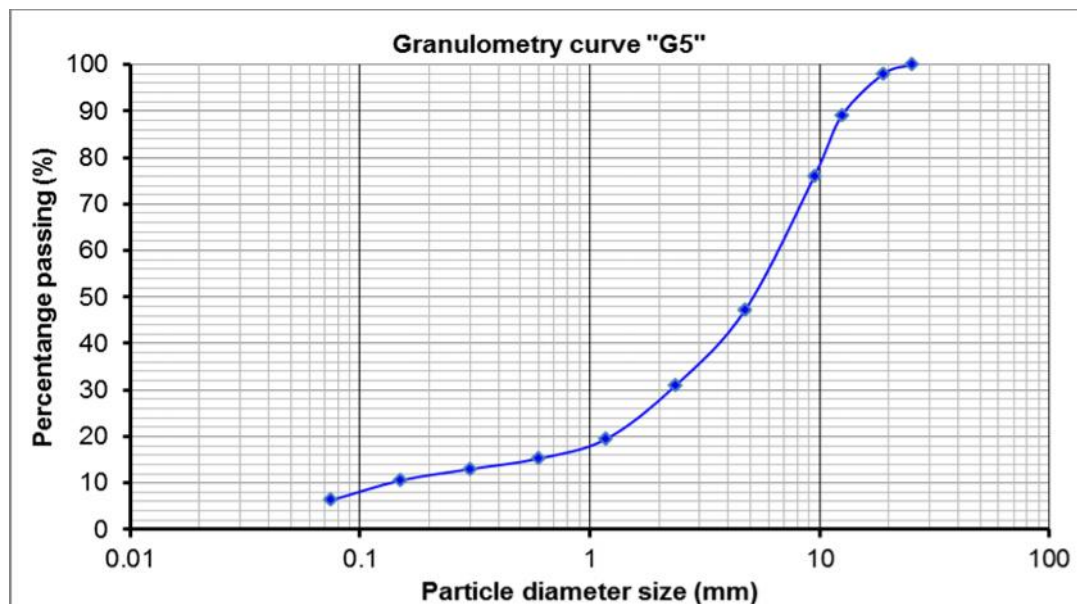
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Table 4 shows values of some pumice-based lightweight bricks taken from reference [19]. The most compressive force per unit of net cross-sectional area, exceed the specified compressive support for masonry; consequently, the material is a good choice for manufacturing lightened bricks.

Table 4. Compressive strength of pumice-based lightweight bricks, ASTM C109/C109M-08 standard.

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
E1	2.626	6
E2	2.723	

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

270 **3.3 X-Ray Fluorescence analysis**

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

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277 **Table 5. Main elements detected by XRF.**

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

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281 **3.4 Measurement of thermal conductivity**

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283 One of the most important factors in the thermal behavior of walls is the thermal conductivity
284 of their bricks [25]. Thermal conductivity for samples to the manufacture of lightweight bricks,
285 consider the ASTM standards. The result of the thermal conductivity of the studied bricks
286 helps for a more sustainable building. Conventional sand-cement bricks are around 0.930 W
287 m⁻¹ K⁻¹ [26].

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289 The thermal conductivity coefficient was measured in four samples. These samples were
290 elaborated with the mixture which has the major compressive resistance, lower absorption
291 and the best workability characteristics which ensured the use of the best mixture and the
292 best thermal insulation conditions. To ensure the flatness in the samples, faces were filed
293 until get parallel surfaces in all samples and the flatness and parallel conditions were
294 confirmed with a surface measurement (Figures 4 and 5).



Figure 4. Pumice-cement sample 1.



Figure 5. Surface measurement.

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

Table 5. Experimental values of thermal conductivity.

NATIONAL METROLOGY CENTER	
Laboratory of Thermal Conductivity	
Operator: Saúl García 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

4. CONCLUSIONS

In brief and according to results, the examination of high performance thermal properties of natural pumice-based bricks providing great thermal insulation properties was achieved as a consequence of thermal conductivity gotten in the experiments, in addition to the 7.35 N/mm² since 7 days and even achieve compressive resistance of 11.20 N/mm² at 28 days, improving the resistance in specimens in over than minimum required by ASTM standards. In the same way, it is confirmed the amorphous phase of pumice as well as its dominant content of Si 75.95%, Al 10.796% and K 8.537% respectively. The low density of 0.792 T/m³ is equally important. High performance thermal properties of natural pumice-based bricks produce the expected technical capabilities for the thermal insulation and mechanical properties, according to ASTM standards. The analyzed pumice reduces the thermal conductivity coefficient of lightened bricks. Lightweight brick elaborated in this work has 0.336 Wm⁻¹K⁻¹ of thermal conductivity coefficient which implies a better insulation material, comparable to the highest quality insulation materials.

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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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