

Research paper

High performance thermal properties of natural pumice-based bricks

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ABSTRACT

Aims: Characterization of the thermal properties of natural lightened pumice-based bricks under ASTM standards, analyzing thermal conductivity on promoting 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, between January and 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 0.336 W m⁻¹K⁻¹, thermal resistance 0.234 W⁻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 and acoustic insulation characteristics. The thermal conductivity depends on the amount of heat from the outside environment, the thickness of the material that conducts heat, the area of material exposed to the heat source and time of exposure to the source. The thermal properties of the material are affected by the size of the mineral material form, presence of micro pores, fractures, and humidity.

Keywords: Natural pumice, bricks, thermal properties, energy efficiency.

1. INTRODUCTION

The masonry construction is the most widely used worldwide, and especially in Latin America has a beneficial use; example of this is the ancient pre-Hispanic buildings that still standing and preserved both architectural beauty and its goal of structural support[1]. Similarly, public buildings and colonial faithful are clear testimony of the quality and durability of masonry systems can provide constructions [2]. However, the construction industry continues to grow structural building systems compatible with the available technology, this due to the increasingly demanding requirements for quality and environmental standards for buildings[3].

These technological advances in building masonry walls are to reduce the execution times in construction, thermal insulation, sound insulation, fire protection and reduction of coating thickness, resulting in a more sustainable building system by reducing costs for energy consumption[4]; however, environmental, development and application of natural materials that meet the nowadays sustainable requirements remain being a problem[5].

Buildings have consumption needs necessary resources for users such as water, ventilation, electricity and fuels by building service. Of the above, the electric energy is the most basic requirement, and these is due to high energy consumption required of the heating, ventilation, and air conditioning (HVAC) system for maintaining thermal comfort within them and hinder the outside temperature [6]. Inside buildings, increased temperatures reach up to 2° C so that it becomes necessary to weatherize the building. The heating, cooling, and lighting, are the most demanding power applications in residential and public buildings. Approximately 70% of the total energy consumption is for use; hence savings in air conditioning and heating are a significant cost savings in the maintenance of buildings [7].

In masonry walls and dividers have a crucial place because their key physical and chemical characteristics coupled to provide different value accommodations to meet architectural, social and requiring use buildings[8]. The 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 the masonry walls coefficient depends on the conductivity 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 construction slow response to changes in external conditions and changes in internal temperature limits, so that when constructing walls with bricks, which by their physical properties of the matter have low conductivity coefficient, the building will provide thermal insulation from conception[10].

The lowest thermal conductivity and the fiber variety of most common materials contribute significantly to improving the thermal insulation properties in the exterior of buildings[11]. 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.

From a comprehensive approach, it is not enough reducing energy consumption, but now must be resolved from an ecologically and socially. México has seen its meetings for the conservation of the environment such as the Vienna Convention for the Protection of the Ozone Layer, the Montreal Protocol on Substances that Deplete the Ozone Layer, the Convention United Nations Framework on Climate Change, among others [12]. In response to the needs of the environment, it becomes necessary to provide a sustainable approach to the construction industry. As one of the biggest economic impacts of buildings, it is essential to promote technologies that optimize the use of natural resources while promoting

environmental protection preventing contamination due to traditional methods of production and use of energy in the construction processes and manufacturing processes for building materials[13].

Common elements for structural insulation show a high investment cost that most people are not willing to pay. In addition, these elements using materials and construction processes require trained staff and usually are not available skilled labor[14].

Similarly costs for ventilation systems are still high, both as to acquisition costs for generating electricity consumption. As a result, it searches for low-cost new construction materials, with sufficient availability and accessibility for use[15]. Despite the good results show temperature insulation materials and methods used to date, these have significant disadvantages that eventually control the property needs. Specifically the main disadvantage is the high cost of the material; placement of individual attachments and unusual constructions for the case of double walls reduce interior volume of the property and the growth of the structures and increased dead load[16].

The septum annealing is the leading and most abundant building material currently applied for part of the soil; it is appropriate, environmentally friendly, resulting in a building material abundant, and availability[17]. Their process of making and has a high cost disadvantage in ecological terms soil calcined at a temperature between 950°C and 1050°C for 12 hours, have a distinctive state of drying is 2591 kJ / kg each partition humidity and requires 2365 kJ=657 W / h, but this value depends on the type of clay, the moisture content of crude septum, the type of fuel used and the construction of traditional oven [18]. This involves the burning of oil and timber, causing deforestation in the region where the septum occurs, so the constant exposure to the gases emitted by conventional ovens generates respiratory diseases in the population near the bricks factory. The replacement of wood by coal provides better ecological and financial results, or the implementation of ceramic furnaces [18], however, this technology is not fully developed so that a more viable solution partitions is preparing uncooked, as presented in this project.

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].

The new approach to energy efficient design reduces energy consumption, also to the disclosure and use of natural and local materials. Environmental responsibility count to energy savings, also addresses green building and pollution generated, which must be part of the production, installation and use of insulation materials. Thus, not only must reduce the size and capacity of cooling systems, small heaters, ventilation and sizes of air conditioners, but means to achieve environmental benefits by reducing pollutants and gases domestic and economic benefit by eliminating the cost of procurement of HVAC systems and benefits to create a healthy environment [4]. 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 and have shown to be commensurate with common building materials[11].

Currently the partitions own quality requirements such as fire resistance, sound insulation, durability, and resistance to environmental conditions and thermal insulation [9], features that are affected when you add a low-cost economic demand. One of the natural materials

with the qualities for construction is the pumice; applied both for their physical and mechanical properties to improve the thermal resistance of the structures and lower total loads [21]. The walls made of pumice as material for hollow walls, which has proved one of the most effective ways to reduce energy consumption and costs due to the climate, the proper use of material type and thickness; optimal materials are factors that provide the lowest total cost including the cost of isolation and energy consumption during the life of the building [22].

The thermal conductivity of a material is a measure of its ability to transfer thermal energy (heat), when subjected to a temperature gradient. The thermal conductivity can be measured through 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 experimental values of the thermal conductivity base their style in more sustainable building practices.

This work, emphasizes sustainable developing using natural materials; gathering ecological and business requirements with environmental benefits.

2. MATERIAL AND METHODS / EXPERIMENTAL DETAILS / METHODOLOGY

2.1 Material

The material characterized in this study, pumice, from a bank in San Clemente, Querétaro. The 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 visually appears from crushed texture to vitreous and usually could be found in considerable volumes as a result of volcanic action. The 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 the standard M-MMP-1-03-03 of the SCT. Ten random samples from the bank of San Clemente mine in Querétaro. 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 2 θ scale at 2° / min. The organic content of the samples was removed with calcination at 450°C for 4 hours in a muffle.

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.

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.

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 $^{\circ}C$ or K or L is sample width in m and A is the cross sectional area in m^2 .

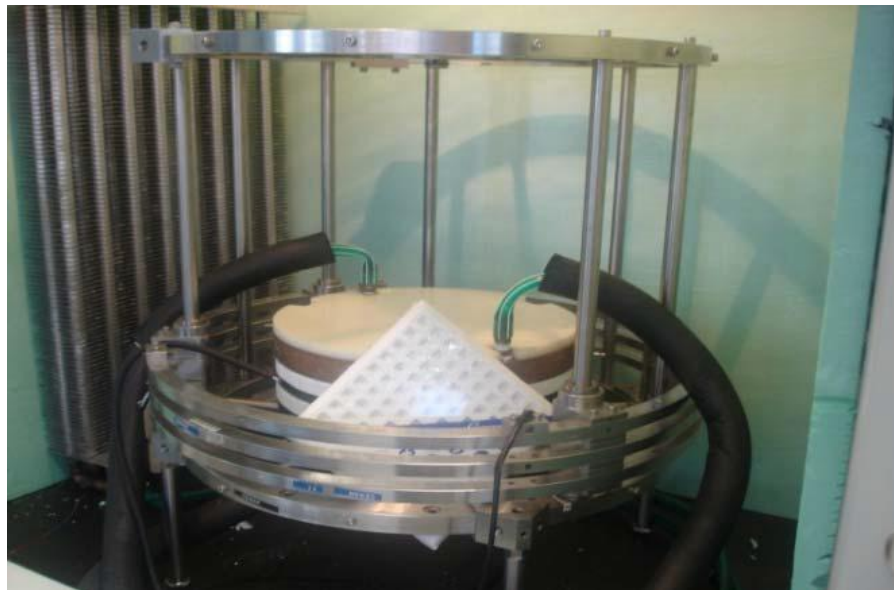


Figure1. Guarded hot plate apparatus (GHPA). National Metrology Center, México.

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.

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

217
218 Sample Preparation: it is necessary to produce parallel sample surfaces to ensure good
219 thermal contact between it and the GHPA plates. The sample and thermocouples should
220 have rigid contact surface to a better determination of the temperature condition, and the
221 plates with the sample at a temperature close to the temperature of test, for example,
222 placing it in a furnace to prevent the absorption of condensation water.

223
224 Establishment of Permanent Thermal State: this stage begins after the installation of the
225 sample in the measuring area of the stored items and the insulating necessary to reduce the
226 effect of environmental conditions. The device takes action to fulfill the conditions of
227 temperature at which to perform the test. The time required to reach steady state at a
228 sample thickness of 25.4 mm and uniform insulating items is almost 5 h, this time increases
229 with increasing thickness.

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232 3. RESULTS AND DISCUSSION

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

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243 3.1 XRD

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

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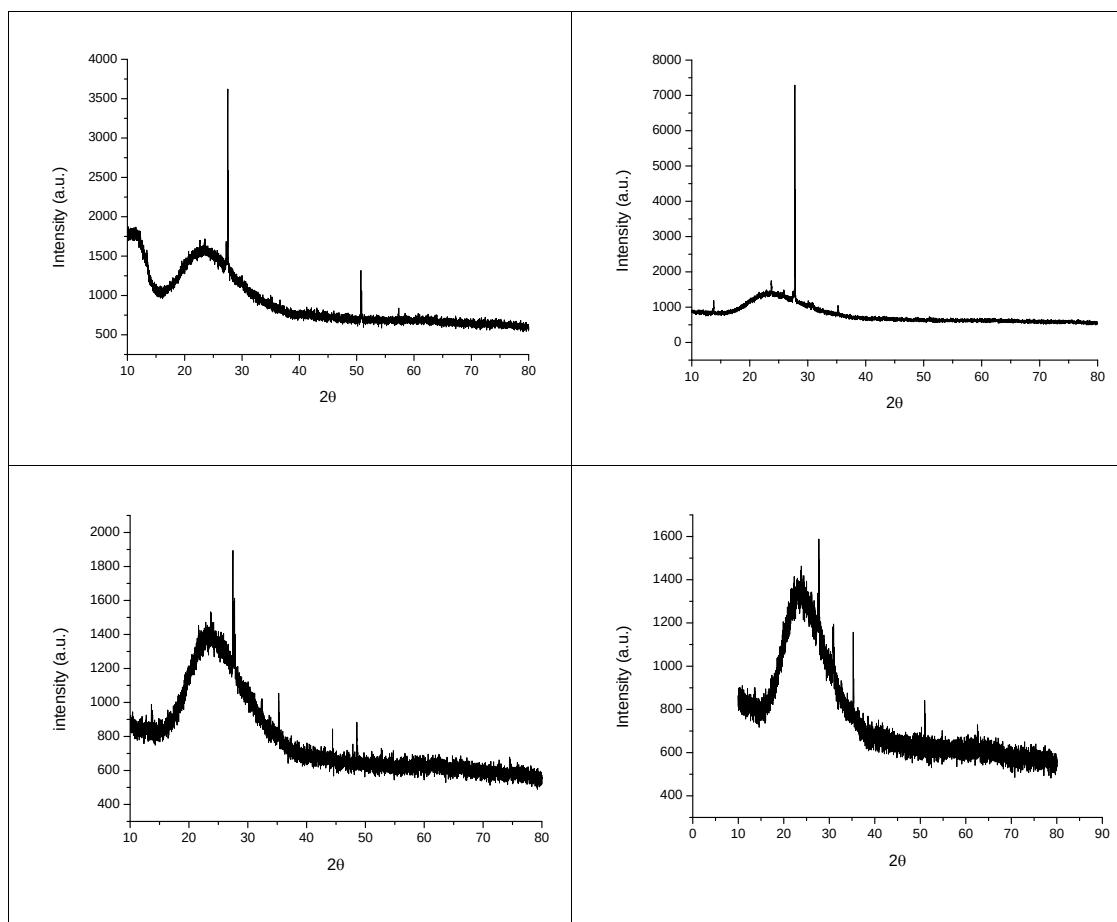


Figure 2. Diffractograms of four of the ten pumice samples showing the main amorphous phase and the crystalline phases of signals which correspond essentially to silicon oxide.

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 1.

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Table 1. Crystalline phases detected by XRD.

PDF	2θ	Element	Crystal
086-1562	27.316	silicon oxide phase 1	Quartz
	41.55		
	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	
	41.54		
063-7619	27.599	silicon oxide phase 1	Low periodicity quartz

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3.2 Compressive strength

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The goal of this work focus on the property of thermal conductivity; however, proof of appropriatemechanical 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 specimensfor 7, 14 and 28 days according to the NMX-C-036-2004-ONNCCE "blocks, bricks - Compressive Strength - Test Method".

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Table 2.Results of compressivestrength for specimens; averages.

Area (cm ²)	Resistance (kN)			Average resistance compression 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

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3.3 X-Ray Fluorescence analysis

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The elements in the pumice were confirmed, so XRFstudy by semi-quantitative percentages for each sample. The presence of Si foremostwas long-established, followed by Alas shown in theTable 3. 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 3. 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

The thermal conductivity for samples (Figures 3 and 4) 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 $0.930 \text{ W m}^{-1}\text{K}^{-1}$.



Figure 3. Pumice-cement sample 1.



Figure 4. Pumice-cement sample 2.

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 input 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 4.

Table 4. 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 apparatus with constant heat flux	
Experimental values:	
Variable name:	Average value:
Power dissipation during test / W	3.63
Hot plate temperature / °C	32.0
Cold plate temperature / °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
Sample thickness / 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. CONCLUSION

Both, solar radiation increase heat (which can only be positive), as the gain or loss of heat by convection and conduction due to the temperature difference between the interior and exterior, be determined by climatic factors in each region and its development cannot be intentionally altered by human beings. Nevertheless, what it can be changed is the building design and characteristics of the materials and building systems for comfort with the most efficient use of energy.

Natural pumice-based bricks produce the expected technical capabilities for the thermal isolation and mechanical properties, according to ASTM and NMX (México) standards. Pumice from San Clemente, Querétaro, 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.

337 ACKNOWLEDGEMENTS

338

339 The authors express their gratitude to Dr. Leonel Lira-Cortez from CENAM and Dr. Rodrigo
340 Velázquez-Castillo from UAQ, for their technical support.

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344 COMPETING INTERESTS

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346 Authors have declared that no competing interests exist.

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349 AUTHORS' CONTRIBUTIONS

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

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