Case Studies in Construction Materials 10 (2019) e00216

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Case study

Study of the properties of the Echerhirhu-Block made with *Opuntia ficus* mucilage for use in the construction industry

Javier Guillen Aparicio[a], Erik García De León Monter[a], Noemí Ortiz Lara[b], Ramiro Escudero Garcia[b], María Neftalí Rojas-Valencia[c,*]

[a] *Research Department, Higher Technological Institute of Tacámbaro, Tecario Tacámbaro, Michoacán, C.P. 61650, Mexico*
[b] *Institute of Metallurgical Research, Michoacán University of San Nicolás de Hidalgo, University City Building "U", PO Box 888, C.P. 58000, Morelia, Michoacán, Mexico*
[c] *National Autonomous University of Mexico, Institute of Engineering, Coordination of Environmental Engineering, Av. Universidad 3000, Mexico City, MX 04510, Mexico*

ARTICLE INFO

Article history:
Received 3 July 2018
Received in revised form 14 December 2018
Accepted 4 January 2019

Keywords:
Block
Construction industry
Mucilage
Mud

ABSTRACT

This research shows the results of mixtures of materials used for making Echerhirhu-Block (mud block, in purépecha) that complies with quality standards, as possible replacement for conventional bricks. The product was made from soil mixtures, cellulose (recycled paper), and *Opuntia ficus* extract (mucilage) used as binder. The process was carried out by grinding soil and waste paper down to a particle size smaller than 3 mm. It was hydrated with water, mixed, its pH was modified through the addition of lime. This led to a stabilization that contributed to the cementation of the particles. Subsequently, mucilage was added and the components were homogenized until a moldable paste was obtained. This was emptied into molds and left to dry for 9 days. Physical tests were performed to determine the properties of the bricks. Compressive strength was determined and compared with some commercial products according to the NMX-C-404-ONNCE-2012 standard. The optimum sample presented a compressive strength of almost 76 kg/cm^2, while conventional bricks for non-structural purpose showed a maximum compressive strength of 60 kg/cm^2. Moreover, a 17% water absorption decrease and a weight reduction up to 25% were observed, at a 10% lower cost since no firing is required.

1. Introduction

Nowadays, the production of ecological materials promotes the conservation of natural resources, the protection of the cities, the improvement of the quality of life of the inhabitants and the reduction of the environmental impact [2]. According to the megatrends, in the next 10–15 years, this type of materials will impact the future of various areas of human activity [3,4]. Additionally, since sustainability is generated by biomimicry, which is based on the study of natural models, systems, processes and elements in order to imitate them and find practical, ecologically sound solutions to human needs, this approach contributes to preserve natural resources and make more efficient use of the financial and human assets of a country [5], with the correlated reduction in environmental pollution [6]. On the other hand, the traditional brick industry is

* Corresponding author. Tel.: +52 55 56173497.
E-mail address: nrov@pumas.iingen.unam.mx (M.N. Rojas-Valencia).

https://doi.org/10.1016/j.cscm.2019.e00216

one of the emitters of the short-lived pollutants that contribute to global warming, degrade air quality and affect human health, such as carbon black (or soot), methane (CH_4), tropospheric ozone (O_3) and some hydrofluorocarbons - HFC - [7].

Some studies have shown that traditional brick firing in kilns has increased gas emissions by up to 12% [8]. It is estimated than in Mexico, about 2 170 fewer deaths would be registered if the standards recommended by the health organization were adopted [9].

On the other hand, in Mexico, technological advances, the presence of important innovation centers, the large amount of research focused on this issue, and widespread technology transfer make it possible to generate regional development. The scientific basis of this type of research allows the development of materials from geopolymerization, a term that was introduced by Davidovits in the 1980s to designate the synthetic inorganic polymers of aluminosilicates which have been investigated in recent years. The production of geopolymers from phyllosilicates contained in the soil is also viable from an environmental point of view, since the level of contamination is relatively low, compared to the Portland cement production process, where energy consumption and CO_2 release to the atmosphere are very high.

The trend towards the development of ecological and sustainable materials creates opportunities for improvements in different fields of engineering and industry, essentially as regards mechanical, thermal and durability properties, leading to a wide range of potential applications, such as the containment and immobilization of toxic waste, prefabricated structures, structural and non-structural elements, concrete products, protective coatings for marine concrete, rehabilitation of concrete infrastructure, fire-resistant composite materials, among others [10,4].

The objective of this research is to develop an ecological material having properties and characteristics appropriate to partially or totally replace conventional bricks.

2. Materials and methods

The experimental development of the present research is shown in Fig. 1 which describes the three main stages:

2.1. Formulation of mixtures

For this purpose, the raw materials, soils and paper waste were crushed down to a particle size smaller than 3 mm. Subsequently, for the preparation of the mixtures, water was added and the volume concentration of each of the components was varied, as shown in Table 1.

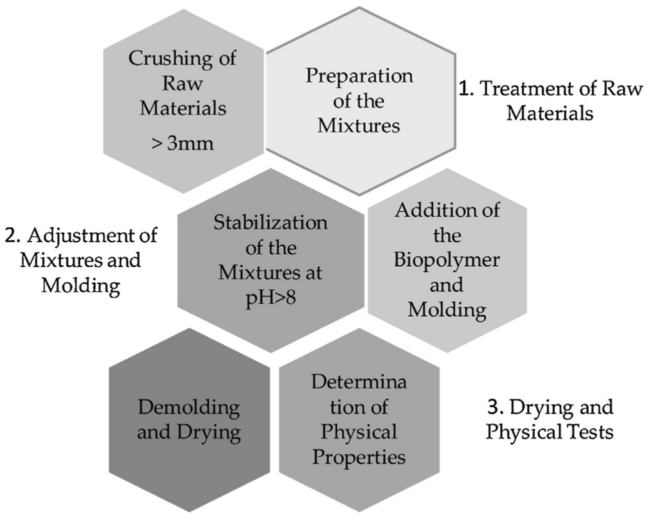

Fig. 1. Flowchart of experimental development for the manufacture of the Echerhirhu-Block.

Table 1
Volume concentration of the components used for manufacturing the Echerhirhu-Block.

Sample	Soils		Paper	Lime	Mucilage
	Sand (%)	Clays			
L1	40	10	30	10	10
L2	25	25	30	10	10
L3	15	35	30	10	10
L4	35	15	30	10	10

2.2. Mixing and molding

This stage consisted of adjusting the pH of the mixtures at >8 through the addition of lime, in order to promote the geopolymerization of the components, mainly the phyllosilicates, i.e. the minerals contained in the soils [11]. Finally, *Opuntia ficus* mucilage prepared according to the proposed methodology [12] was added. The mixture was emptied in the molds. The samples were then left to dry during more than 12 days and their physical properties were evaluated. Fig. 1 shows a flowchart of the methodology.

2.3. Tests

Compression tests were performed using a traction machine (PCE-MtS500), as shown in Fig. 2. The brick samples were subjected to the tests provided for by the NMX-C-404-ONNCCE- [13] and NMX-C-441-ONNCCE- [24] standards, both individually and consecutively. They were also tested as regards the specifications that concrete blocks, red bricks and concrete bricks for structural and non-structural use must comply with. Moreover, their weight and water absorption were determined based on the NMX-C-037-ONNC-CE-2013 standard.

2.4. Extraction of Opuntia ficus mucilage and Production of the Biopolymer

The methodology used for the extraction of the mucilage was based on the process proposed by Rojas and Aquino, [3,4]. The biopolymer was developed and modified according to the technique devised by [15]. Fifteen mL of *Opuntia ficus* mucilage, 5 mL of distilled water, 5 mL of starch and 0.5 mL of glycerol were placed in a beaker, stirred for 10 min at 200 rpm in a magnetic thermostatic stirrer at a temperature of 50 °C, and the resulting suspension was then added (10% v/v) to the L4 mixture.

2.5. SEM and IR analyses

In order to identify the components, morphology of the phases and porosity, the various mixtures were observed with a JEOL JSM-6400 scanning electron microscope. Infrared Spectroscopy was performed using a Bruker Tensor 27 equipment in a range from 4000 to 400 cm^{-1} at a resolution of 4 cm^{-1}.

3. Results and discussion

3.1. Mixtures obtained and their characteristics

Fig. 3 shows the appearance of the various proposed mixtures. The tests performed on each of them and the values obtained are shown in Table 2, highlighting the results of the compression test determined based on the NMX-C-404- [13] and NMX-C-441 [14] standards for structural and non-structural use [16]. The load applied to each of the blocks at the time of the first crack was recorded. After the occurrence of the crack, the test was continued until total fracture, in order to calculate the gross compressive strength of the area [17]. The maximum amount of water absorbed by each of the pieces tested was determined according to the NMX-C-037-ONNC-CE -2013 standard.

3.2. Analysis of the L2 and L3 mixtures

Table 3 offers a comparative analysis of the properties of the Echerhirhu Block, generated with the components proposed in the above described mixture (L2), and the minimum values of the bricks currently on the market, according to the standard

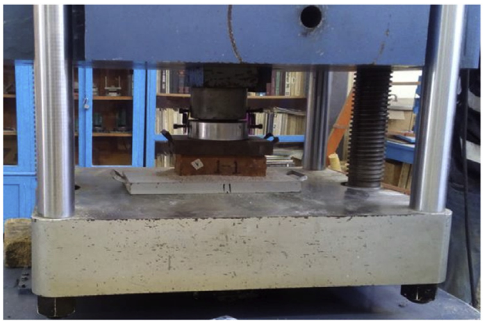

Fig. 2. Compression tests to which the Echerhirhu-Blocks were subjected.

Fig. 3. Appearance and color of the different mixtures prepared for the Echerhirhu-Block.

Table 2
Characteristics of the mixtures and tests performed on them.

Sample	Compressive strength (Kg /m^3)	Water absorption (%)	Density (g/cm^3)	Geometry (cm^3)	Bending Strength (Kg/m^3)
L1	48	18	1.7	7 × 14 × 28	24
L2	76	16	1.7	7 × 14 × 28	20
L3	27	17	1.9	7 × 14 × 28	17
L4	62	1	1.8	7 × 14 × 28	25

Table 3
Comparative analysis of the characteristics of the Echerhirhu-Block and traditional bricks for structural use.

Type of piece	Compressivestrength (Kg /m^3)	Weight (kg)	Water absorption (%)	Density (g/cm^3)	Geometry (cm^2)	Bending Strength (Kg/m^3)
Concrete Brick	70	6.5	12	2.2	7 × 12 × 24	–
Handicraft Brick	60	2.20	23	2.2	7 × 14 × 28	–
Adobe Brick	25	–	28	2.2	–	–
Echerhirhu Block	76	1.7	16	1.7	7 × 24 × 28	20

for structural use and the values obtained with the ecological brick, such as compression strength test, water absorption and weight of the bricks.

Table 4 offers a comparative analysis of the properties of the Echerhirhu Block generated with the components proposed in the above described mixture (L3), and the minimum values of the bricks currently on the market, according to the standard for non-structural use.

Based on the foregoing, it derives from the essays and tests carried out on the L2 mixture that an average value of 76 kg/cm^2 was obtained from 5 samples, compared to a requested minimum compression value of 60 kg/cm^2 for structural red bricks. Thus, the Echerirhu Block shows a compressive strength above the requested minimum compression value for structural red brick and even slightly above the minimum requested value of 70 kg/cm^2 for concrete brick. Table 4 shows a similar situation, with a compression value of 27 kg/cm^2 for the ecological brick, i.e. above the minimum requested value of 24 kg/cm^2 for traditional non-structural brick.

3.3. Compressive strength and binding strength

This is one of the most important tests, because the function of the brick is basically to support compressive stress in masonry buildings. Fig. 4 shows that an average compressive strength value of 76 kg/cm^2 was obtained with the L2 mixture, which is greater than the minimum compressive strength of 60 kg/cm^2 requested for conventional brick according to the provisions of the standard. Generally speaking, it was observed that the bricks that underwent compressive and binding strength tests broke when they developed irregular cracks. This is attributed to the presence of paper waste in the brick. On

Table 4
Comparative analysis of the characteristics of the Echerhirhu-Block and traditional bricks for non-structural use.

Type of piece	Compressive strength (Kg /m^3)	Weight (kg)	Water absorption (%)	Density (g/cm^3)	Geometry (cm^3)	Bending Strength (Kg/m^3)
Concrete Brick	32	6.5	12	2.2	7 × 12 × 24	–
Handicraft Brick	24	2.20	23	–	7 × 14 × 28	–
Adobe Brick	25	–	28	2.2	–	–
Echerhirhu- Block	27	1.7	17	1.9	7 × 24 × 28	17

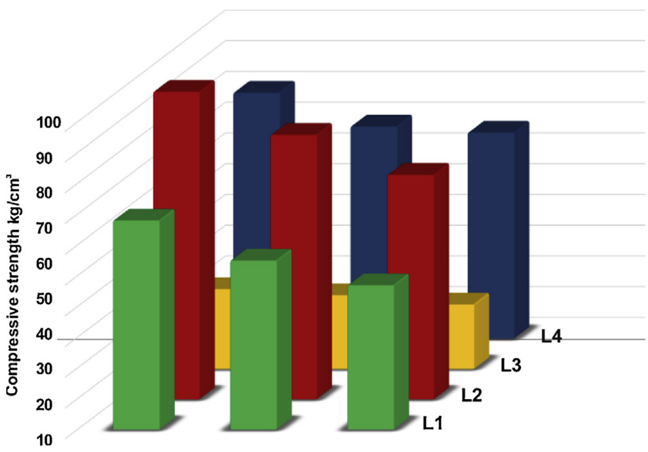

Fig. 4. Compressive strength of various mixtures.

the other hand, binding strength test values in the order of 23 kg/cm^2 have been reported with conventional bricks [19]. Studies carried out on conventional bricks relate the compressive strength to the particle size and the presence of clays. Fine particles can provide a better compressive strength since they offer better compaction characteristics and better load distribution. The above is clearly evident with this mixture that consists of 50% sand and 50% clay. It is moreover improved as a result of the interaction of the cactus mucilage with the components, since its presence interacts within the pores as some researchers have shown [18,20].

3.4. Water absorption

The results show that, on average, the Echerhirhu Block has a maximum water absorption (17%) below the standard requirement for red bricks (21%). This value can be attributed to the interaction of cactus mucilage with brick components, where the calcium oxalate contained in the mucilage [1] forms a film that protects the surface and structure against acidic gases present in all types of atmosphere, responding in turn actively to other atmospheric changes in temperature and

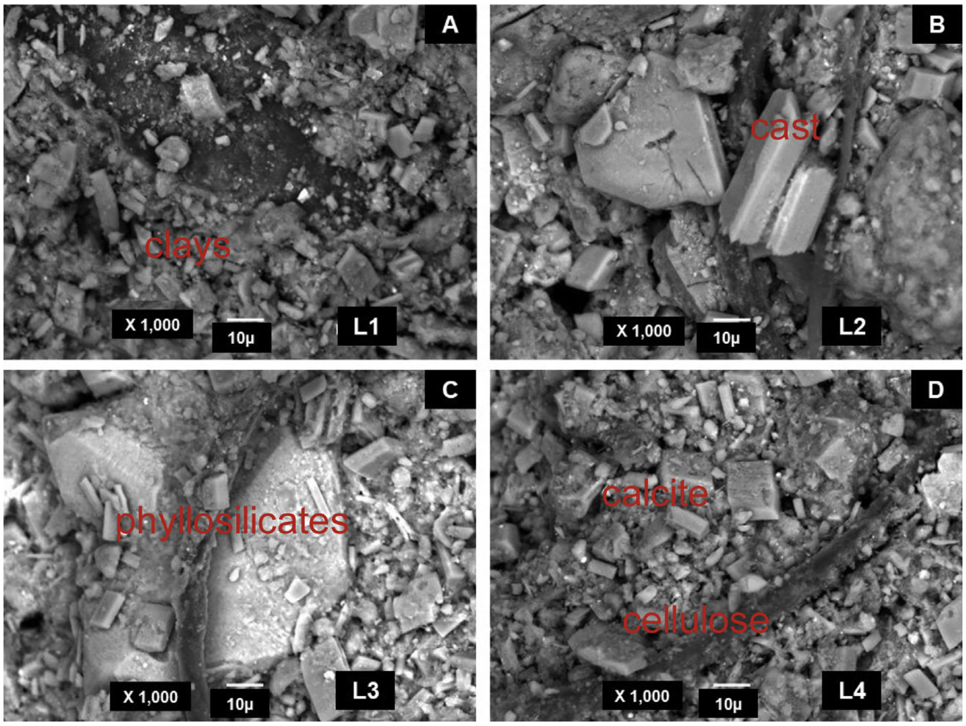

Fig. 5. a) Mixture with clays, b) mixture with silty clay loam, c) mixtures with silt d) with addition of biopolymer.

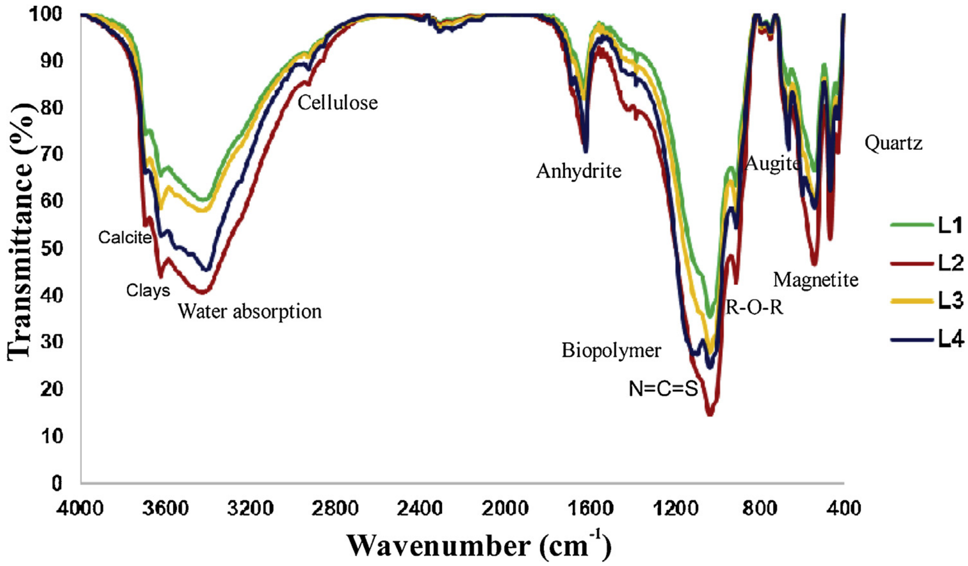

Fig. 6. Infrared spectra of the various mixtures.

humidity [21]. This value indicates the need to moisten the pieces before laying them, to obtain a better adherence. On the other hand, the water absorption reduction shown by the ecological bricks can also be attributed to the fact that the mucilage covers the solid particles and fills the spaces generated by the interaction of the components [22]. In other words, it promotes a better integration of the components Rojas, [4]. The porosity of the microstructure of traditional bricks has been linked to a poor integration [19].

SEM analyzes show the presence of irregular, hexagonal, columnar, tabular and fibrous crystals associated with the phases such as sands, clays, calcite, gypsum and cellulose that are the main constituents of the raw materials used in the manufacture of the various mixtures. In these images, particle sizes ranging from 1 μ to over 100μ can be seen. The homogeneity and distribution of the particles coincide with the results obtained from the compression tests. In the image corresponding to Fig. 1b, a combination of particle sizes ranging from 10μ to 80μ can be seen. Correlating these particle sizes with the compressive strength results, it can be said that the samples show behaviors similar to those reported by [23]. This is because this particle distribution promotes the generation of a ductile-brittle system, which allows small particles to penetrate between the gaps left by the largest particles and these are immersed in an organic matrix (the *Opuntia ficus* mucilage acted as a binding and cementing agent). A ductile-brittle system is obtained with L1 samples, while a brittle-ductile system is obtained with L3. This is due to the heterogeneity of the particle distribution which causes these two systems to have values that differ from the valued observed with the L2 mixture. A ductile-brittle system is obtained with the L4 mixture. However, since a biopolymer is used as cementing agent, the pore size in the mixture decreases, as can be seen in Fig. 5d, leading to low water absorption and compressive strength values greater than L1, L3 and close to L2, with bending strength values greater than the ones obtained in all the samples because of the properties provided by the biopolymer.

Fig. 6 shows infrared spectroscopy analyzes, with wavenumbers of 3650, 3620, 3406, 2924, 1621, 1094, 1035, 912 and 599. In L4, component associations such as calcite, kaolinite, cellulose, anhydrite, bonds N=C=S (associated with the biopolymer), CO, ROR, these two are associated with *Opuntia ficus* mucilage, augite, magnetite and quartz contribute to the very low water absorption and to bending strength values greater than in the other mixtures. C—O, R—O—R, these components coincide with the morphology recorded in the analyzes conducted by scanning electron microscopy.

4. Conclusions

The non-fired Echerhirhu Block offers a competitive advantage because it contains sustainable materials as manufacturing components, is environmentally friendly, and allows energy savings during its manufacturing process. From the tests conducted on the product, it derives that its mechanical characteristics comply with the standard, besides presenting a totally innovative appearance. The compressive strength value showed by organic bricks (76 kg/cm^2) exceeds the requirement for non-structural conventional bricks (60 kg/cm^2) and structural conventional bricks (70 kg/cm^2), and are close to the values obtained with concrete bricks. On the other hand, moisture absorption is reduced by up to 30% and the organic brick is 25% lighter. It can thus be concluded that, when compared with conventional materials, the Echerhirhu Block offers better mechanical properties, only slightly below concrete bricks, without generating CO_2, because of its environmentally friendly manufacturing process. This can contribute to cost reduction because of fuel savings related to the lack of firing process, shorter production time, fewer worker diseases and mitigation of climate change.

Conflicts of interest

The authors declare no conflict of interest.

References

[1] M. Contreras-Padilla, Evaluation of oxalates and calcium in Nopal Pads (*Opuntia ficus-indica* var. redonda) at different maturity stages, J. Food Compos. Anal. (2011) 38–43.

[2] S.J.P. Rovira, Eco innovación y Producción Verde. Una Revisión Febrero de, Comisión Económica para América Latina y el Caribe (CEPAL), Canadá, 2017 (In Spanish).

[3] M.N. Rojas-Valencia, E. Aquino Bolaños, Sustainable adobe bricks with construction wastes, Waste Resour. Manag. 169 (November (4)) (2016) 158–165. Editor: ICE publishing. ISSN 1747-6526 | E-ISSN 1747-6534 http://www.icevirtuallibrary.com/doi/abs/.

[4] M.N. Rojas-Valencia, E. Aquino Bolaños, Recycling of construction wastes for manufacturing sustainable bricks, Proceedings of the Institution of Civil Engineers - Construction MaterialsISSN 1747-650X | E-ISSN 1747-6518 Indizada en Web of Science (2017), doi:http://dx.doi.org/10.1680/jcoma.16.00046. Published Online: October 03, 2017 http://www.icevirtuallibrary.com/doi/10.1680/jcoma.16.00046.

[5] E. Rocha Rangel, Biomimetic: sustainable innovation inspired by nature, Investigación y Ciencia (2012) 56–61 (In Spanish).

[6] B.F. Penades, Tesis Doctoral. Desarrollo de nuevos materiales ecológicos en matrices poliméricas de origen renovable y refuerzos de alga de Posidonia Valencia, España. (Julio de 2017) (In Spanish), (2017) .

[7] E. Floess, Measuring Emissions from Brick Kilns Using a Portable Dilution Samper. 3er Foro Latinoamericano Para el Diseño de Estrategias Transformacionales del Sector Ladrillero, Políticas Publicas, Medio Ambiente, Desarrollo y Economía, 3er FORO PANLAC, Tlaquepaque, Jalisco, México, 2017 (17-20 de Octubre de 2017). (In Spanish).

[8] J.A. Velasco, Tesis. Estudio de Localización y Diseño de Planta en la Asociación de Ladrilleras de Palmira (Coronado) Para el mejoramiento de la Seguridad y Salud en el Trabajo, Pontificia Universidad Javeriana, Cali, Colombia, 2017 (In Spanish).

[9] SEMARNAT, Estrategia Nacional de Calidad del Aire. México, SEMARNAT, México, 2016 26 de Noviembre de (In Spanish).

[10] C.A. Juarez Alvarado, Compuestos Cementantes Fibroreforzados de Bajo Impacto Ambiental Comportamiento Mecánico, Alconpat (2017) 135–147 (In Spanish).

[11] M.A. Henigal, Study on Properties of self-Compacting Geopolymer Concrete, J. Mech. Civil Eng. (2017) 52–66.

[12] S. Ramírez Arellanes, Propiedades de Durabilidad en Hormigón y Análisis Microestructural en pasta de Cemento con Adición de Mucilago de Nopal Como Aditivo Natural, Materiales de Construcción (2012) 327–341 (In Spanish).

[13] Organismo Nacional de Normalización y Certificación de la Construcción y Edificación (ONNCCE), NMX-C-404-ONNCCE-2012, Industria de la construcción mampostería-bloques, tabiques o ladrillos y tabicones para uso estructural-especificaciones y métodos de ensayo, Official Journal of the Federation, City of Mexico, Mexico, 2012 (in Spanish).

[14] Organismo Nacional de Normalización y Certificación de la Construcción y Edificación (ONNCCE), NMX-C-441-ONNCCE-2013, Norma Mexicana-Industria de la Construcción-Bloques, Tabiques o Ladrillos y Tabicones Para Uso No Estructural-Especificaciones, General Direction of Norms-Direction of Normalization: Mexico City, Mexico, 2013 (In Spanish).

[15] X.P. Gonzales, El plástico del nopal (Una alternativa sustentable) (In Spanish), UNAM, Toluca, México, 2011. https://feriadelasciencias.unam.mx/anteriores/feria21/feria118_01_el_plastico_del_nopal_una_alternativa_sustentable.pdf.

[16] M.L. Corona, Normas NMX Para Estructuras de Mampostería. Norma Mexicana NMX-C-404-ONNCCE-2012 Piezas Para Uso Estructural. México, Diario Oficial de la Federación, México, 2015 (In Spanish).

[17] A. Ruiz, G.S. Sibaja, Obtención de Características Geométricas y Mecánicas del Ladrillo de Barro Recocido de Tuxtla Gutiérrez, Chiapas. Que hacer Científico en Chiapas (2011) 14–26 (In Spanish).

[18] Q.H. Contreras, P.H. Trujillo, O.G. Arias, C.J. Pérez, F.E. Delgado, Espectroscopia atr-ftir de celulosa: aspecto instrumental y tratamiento matemático de espectros, e-Gnosis 8 (2010) 1–13.

[19] E.E. Guerrero Gómez, Análisis de Temperaturas Durante la Cocción de Ladrillos Macizos y sus Propiedades Finales, Tecnura (2017) 118–131 (In Spanish).

[20] A. Aguilar-Penagos, J.M. Gómez-Soberón, M.N. Rojas-Valencia, Physicochemical, mineralogical and microscopic evaluation of sustainable bricks manufactured with construction wastes, Appl. Sci. Appl. Sci. 7 (10) (2017), doi:http://dx.doi.org/10.3390/app7101012 1012; Factor Impacto JCR =1.679. Indizada en Web of Science.

[21] M. Pérez Alonso, Desarrollo de un Nuevo Tratamiento Lara la Conservación de Piedras con Alto Contenido en Carbonatos Utilizando la Tecnología de Resinas de Intercambio Iónico, Arqueol. La Arquit. (2013) 235–239 (In Spanish).

[22] Y.G. Aranda-Jiménez, E.J. Suárez-Domínguez, Efecto de la impermeabilidad del Mucélago de Nopal en bloques de tierra comprimidos, Nova scientia 6 (11) (2014) 311–323.

[23] C. Suryanarayana, Mechanical alloying and milling, Prog. Mater. Sci. 46 (2001) 1–184.

[24] Organismo Nacional de Normalización y Certificación de la Construcción y Edificación (ONNCCE), NMX-C-037-ONNCCE-2013. Norma Mexicana-Industria de la Construcción-Mampostería-Determinación de la absorción Total y la Absorción Inicial de Agua en Bloques, Tabiques o Ladrillos y Tabicones Método de Ensayo, General Direction of Norms-Direction of Normalization, Mexico City, Mexico, 2013 (In Spanish).