Thermal properties of fired clay bricks from waste recycling. A review of studies

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Abstract

The large waste volumes globally generated have increased environmental awareness, promoting waste recycling as a sustainable construction material. This study presents a review of researches that analyze the thermal behavior of eco-friendly clay bricks incorporating organic and mineral waste materials as an addition. Many of these works also provide data related to the composition of the material, and its physical, micro-structural and mechanical characteristics. Most of eco-friendly clay units increase the porosity of the ceramic, improving the energy efficiency of masonry enclosures, reducing the clay content and the energy consumption during the fire process. The positive effects of lightweight ceramics are an opportunity to improve the fire resistance inside green buildings.

Introduction

Clay bricks are one of the oldest and most demanded building materials in the world. Technically and economically competitive, these units have good load bearing capacity, durability, fire resistance, thermal insulation, satisfactory bond and performance with mortar, and do not cause indoor air quality problems.[1,2] They are produced from sintered clays at high temperatures and, therefore, incorporate high energy levels in their manufacture.[3]

In an environmental sustainability context, one of the innovation lines in the sector is to incorporate domestic, industrial and agricultural waste in the production of bricks. Eco-friendly bricks do not only reduce waste, but also try to improve their properties or manufacture process, reducing the depletion of clay raw resources and the energy consumption during fire. Numerous researches were aimed to incorporate waste such as shells of seeds, sawdust, straw, fly ash, effluent treatment plants sludges, cotton waste, paper processing residues, cigarette butts, polystyrene foam, plastic fiber, granulated slag, rubber, *etc.*, summarized in previous review works, such as those carried out by Raut *et al.*,[4] Dondi *et al.*,[5] Kadir and Sarani,[2] Zhang,[3] Shakir and Mohamed,[6] Monteiro and Vieira,[7] Muñoz *et al.*,[8] Ardeshir and Ahmadi,[9] and Al-Fakih *et al.*[10]

To improve energy efficiency in buildings, the use of efficient insulation envelopes is promoted. Standards such as CTE DB-HE: 2017[11] and DPR 59/2009[12] establish a limit of thermal transmittance of walls according to their location and climate. This criterion favors the use of materials with low thermal conductivity and the design of constructive solutions based on hollow bricks which reduce the thermal conductivity of the brick with respect to the material. Ceramic thermal conductivity is complexly influenced by many variables that include: apparent density, porosity, pore size and mineralogical components, particularly calcium, quartz and amorphous silicates.[13] Therefore, one way of increasing the insulating capacity of bricks is the use of lightweight clays that reduces thermal conductivity with a homogeneous porosity. Most eco-friendly clay units increase porosity, improving the energy efficiency of masonry.

Thermal conductivity (λ_a) and heat capacity (c_a) of clay bricks vary with temperature (T), mainly influenced by free water evaporation.[14] European Standard EN 1996-1-2[15] includes temperature-dependant thermal properties curves of clay units with a density range of 900-1200 kg/m^3. Heat capacity evolution derives from the evaporation energy peak. Thermal conductivity variation at high temperature is governed by two opposite effects: conductivity of the bulk material that varies due to phase changes, and radiation within the pore network of the material, that contributes once a certain temperature threshold is exceeded and from then on increasing rapidly as a result of the T^4 dependence.[14] In the case of relatively dense ceramic, the contribution of radiative heat transfer has a noticeable influence only at late stages. For concrete units, Eurocode 6 part 1-2[15] provides different curves for autoclaved aerated concrete units that depend on the density of the material. The high volume of pores allows a low thermal conductivity that is an advantage for thermal insulation at ambient temperatures and an asset for resistance against fire.[16] However, Eurocode 6 part 1-2[15] does not consider the existence of lightweight ceramics.

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Thermal conductivity of bricks from waste recycling

Depending on their origin, waste used as additives in eco-friendly clay bricks can be divided into two categories: organic or extracted from renewable sources, such as products or by-products of agricultural, agroindustrial and industrial waste; and minerals or inorganic, such as marble waste, slag, ash, or glass waste.[10] Studies that analyze thermal conductivity of eco-friendly clay bricks employ waste additions, for both organic and mineral, incorporated as pore-forming agents, are reviewed.

Clay bricks with organic waste addition

Ugheoke *et al.*[17] experimentally analyzed insulating firebricks produced by kaolin, rice husk and plastic clay, establishing the optimal ratio of these constituents. Ten brick samples with different compositions were tested, fired at 1200°C. Thermal conductivity of samples ranged from 0.005 to 0.134W/mK, with good insulating characteristics. Results show that a high percentage of rice husk causes a low thermal conductivity, that decreases with the reduction in density and the increase in porosity. Mixing ratio of 4:1:2 gave the optimum performance in terms of refractoriness, thermal conductivity, modulus of rupture, shrinkage and bulk density and the effective moisture content.

Bànhidi and Gömze[18] conducted an experimental investigation to improve the insulation properties of conventional bricks, fired at 900°C, adding agricultural waste materials: sawdust, rice husk and sunflower seed husk; with 0%, 4% and 7% proportions by weight. Thermal conductivity measurement was carried out using a RAPID-K system. The ignition of the waste addition decreased the energy used during brick manufacture by providing additional thermal energy and creating pores during the firing process that improved the insulation properties of the material. Thermal conductivity decreased by between 10% and 31% compared to the control brick with 4% of additives. The greatest reduction was obtained through the addition of sunflower seed husk, followed by rice husk and sawdust. Thermal conductivity value decreased from 0.27W/mK to 0.17 W/mK with 7% of sunflower seed husk additive. In contrast, the compressive strength experimented a decrease to 77-26% of the original value for the 4% of additives and a decrease to 48-25% of the original value for the 7% of additives. In terms of mechanical properties, the most suitable additive was sawdust.

Sutcu and Akkurt[19] developed lightweight ceramic bricks with reduced thermal conductivity, using waste from the paper industry as a pore-forming additive. Mixtures contained brick raw materials and additives in different proportions up to 30% by weight. Brick samples were formed by molding and fired at 1100°C. The performed tests evaluated bulk density, apparent porosity, water absorption, thermal conductivity and compressive strength. Thermal conductivity was analyzed through a rapid thermal conductivity meter, which works according to the hot wire method. The results show that the residue addition causes a reduction in thermal conductivity of more than 50%, 0.83-0.42 W/mK, an increase in apparent porosity and a decrease in compressive strength, which is also influenced by the direction of pressing and the shape of the pores.

Folanrami[20] studied the effect of the addition of ashes from burning dried mango trees and mahogany wood sawdust on clay bricks thermal conductivity. Different percentages of ashes and sawdust were incorporated, ranging from 1% to 30%. Brick samples were fired at 800°C. Thermal conductivity was analyzed using Lee method, obtaining values between 0.180 and 0.250 W/mK in case of bricks with ash addition. This slight decrease is due to the bridges that ashes particles generate between the clay particles. On the other hand, the thermal conductivity of clay bricks with sawdust addition ranged between 0.060 to 0.230 W/mK, due to the presence of pores, generated by their combustion at high temperatures.

Kadir *et al.*[21] analyzed different physical-mechanical properties of fired clay bricks with the addition of cellulose acetate cigarette butts. Cigarette butts were disinfected and mixed with the clay raw material, with 0%, 2.5%, 5% and 10% proportions by weight. The mixture was compacted manually with the optimum moisture content obtained in the standard tests. Brick samples were fired at 1050°C. The results show a reduction of density up to 30%, obtained for a cigarette butts content of 10%. The thermal conductivity performance of bricks was improved by 51 and 58% for additions of 5 and 10% respectively. In this study, thermal conductivity was estimated by the dry density value, using a model based on the results obtained with 256 samples of brick, concrete and aggregates. The compressive strength of the bricks is reduced from 25.65MPa to 12.57MPa, 5.22MPa and 3.00MPa for cigarette butts percentages of 2.5%, 5.0% and 10% respectively, while the flexural strength is not affected by the frequency of this type of residue.

Saiah *et al.*[22] studied the use of different types of vegetal matter: wheat seeds, resinous wood fibers, colza seeds, corn cob, maize seeds, wheat straw, and sunflower seeds; as addition in fired clay bricks. The study analyzed the effect of the different porosities generated during combustion. The clay brick samples contained a percentage of vegetal matter less than 10%. Porosity increased between 11% and 18%, decreasing thermal conductivity up to 32% that could improve in thermal resistance in perforated bricks between 18% and 48%. Porosity obtained using wheat straw provides the best relationship between thermal and mechanical properties.

Cusidó and Soriano[23] analyzed the viability of using wastewater-treatment plants sludges through pelletization, a sintering ceramization process at 1050°C. Obtained material is similar to expanded clay. Although clay matrix is not incorporated, pelletization is similar to the sintering clay process. This new lightweight material with an open porosity of 62% and an average thermal conductivity of 0.09 W/mK, which classifies the material as thermal insulator. Leaching tests revealed undetectable amounts of dangerous metals, with the exception of vanadium. Toxicity tests also have negative results. Combustion emissions were lower than those of clay bricks with sewage sludge additions.

Eliche-Quesada *et al.*[24] investigated the use of biodiesel production residues as an additive in the manufacture of porous clay bricks. The bricks were sintered at 1050°C with two different types of waste addition: spent soil from biodiesel filtration (up to 20% by weight) and glycerin (up to 15% by weight). The results indicated that samples containing soil achieved compression resistance values between 26.1 and 41.2 MPa, the lowest value with the highest residue content due to porosity and other microscopic imperfections. In contrast, the compressive strength increased with the addition of glycerin residues from 41.0 to 78 MPa with additions between 5 and 15%. Thermal conductivity was reduced with the addition. The incorporation of up to 15% glycerin produced a more important reduction in thermal conductivity, up to 40% compared to the reference clay bricks.

Muñoz *et al.*[25] studied the influence of the use of paper pulp as an additive in the thermal and mechanical properties of the ceramic material. The study analyses samples with different percentages of residues, ranged between 0% and 17% by weight, formed by molding and sintered at 942°C. The study concludes that for percentages of paper pulp addition less than 15% the mechanical properties maintain resistance values greater than 10MPa. This amount of paper pulp improved the conductivity properties by 39.69% compared to the clay without additives, registering a minimum conductivity value of 0.45 W/mK. This decrease in the conductivity of the ceramic material results in a 16% improvement in the equivalent thermal transmission for brick walls. The thermal conductivity test was carried out with the stored hot plate method, EN 12664-2001.[26]

Gorhan and Simsek[27] studied the use of rice husks as brick additive. Rice husk was incorporated in two ways, as ground and coarse rice husk, with percentages of 5%, 10% and 15% by volume. Clay brick samples were formed by molding and sintered in the range of 700-1000°C. The compressive strength of the reference samples fired at 1000°C was 17.1 MPa. The resistance decreased with the increase of addition, more pronounced with coarse husk. Compressive strength reaches 7-10Mpa by adding a percentage of rice husk between

5% and 10%. The conductivity of all samples was determined by the hot wire method, increased with the firing temperature. The reference sample showed the maximum thermal conductivity of 0.548 W/mK that decreased to 0.165 W/mK in the case of samples pieces fired at 800°C with 15% coarse rice husk. The coarse rice husk improved the thermal conductivity more than the ground husk, but bricks that contained 15% of coarse rice husk were fragile.

Phonphuak[28] analyzed physical, mechanical and thermal properties of fired clay bricks with charcoal addition with 0%, 2.5%, 5.0% and 10% proportion by weight, fired at 950°C. Apparent porosity results range between 28.96% and 46.85% for 0% and 10% of addition, and the density was reduced by up to 10%, depending on the percentage of charcoal incorporated into the raw materials. Compressive strength of samples was in the range of 78.59-152.66 kg/cm2, decreasing according to the percentage of charcoal included in the mix. Finally, thermal conductivity decreases with the reduction in density and increase in fired clay bricks porosity, ranging between 0.270 and 0.216 W/mK.

Muñoz *et al.*[29] investigated the behavior of fired clay bricks manufactured with the addition of pomace residues from the wine industry. Four mixtures were analyzed: with 0%, 5%, 11% and 17%, and a constant water content of 20%. The samples were formed by molding and after dried, sintered at 980°C. Thermal conductivity was determined according to European standards,[30,31] using the stored hot plate method and the heat flow meter method. The results determined that the optimum additive content was 5%, both for water absorption and for compressive strength. Thermal conductivity for clay bricks without additive was 0.738 W/mK, reduced up to 0.39 W/mK once added. Pomance residues reduced linear shrinkage and bulk density, reaching the 23% with the 17% of waste addition.

Muñoz *et al.*[32] presented a research for lightweight bricks made with the addition of coffee grounds collected from different coffee shops and restaurants to improve the insulation properties, based on the porosity increase due to the combustion of the organic substances during firing process. Several tests have been conducted for different percentages of waste: 0%, 5%, 11% and 17%, for which thermal conductivity range from 0.73 to 0.38 W/mk. The study conclude that it is possible to add 17% of waste maintain the clay bricks compressive strength above 10 N/mm2, reducing thermal conductivity up to 50%.

Adazabra *et al.*[33] studied the addition of shea waste to improve the manufacture of fired clay bricks, investigating its influence on the chemical, mineralogical, molecular bonding and technological properties. Mixtures were composed by yellow clay with a constant white clay content of 25%, and percentages of residues ranging between 0% and 20%. Brick samples were sintered at 900, 1000, 1100 and 1200°C. Waste addition contributed to energy savings, improved pore formation, reduced the thermal conductivity of bricks and improved compressive strength. Thermal conductivity of sintered bricks at 900°C showed values that ranged between 0.36 and 0.21 W/mK, while the reference standards fired at 1000, 1100 and 1200°C recorded values of 0.49, 0.54 and 0.60 W/mK respectively.

Galán-Arboledas *et al.*[34] investigated the incorporation of diatomaceous earth residues in the manufacture of clay bricks. These wastes came from two industrial processes: the refining of vegetable oils and the brewing of beer. Proportions between 3 and 10% by weight were used to obtain clay bricks at three firing temperatures: 850, 950 and 1050°C. The addition improves the behavior of the materials in the drying process, increases the open porosity of the fired pieces and reduces the bulk density by up to 10%. The increase of the porosity is greater in the pieces that incorporated spent diatomites fom oil refining, reaching the maximum value of 37%. The increase of both residues decreased the flexural strength, reaching values greater than 10 MPa, acceptable for construction use. In addition, the energy released during the firing stage is greater than the energy required for drying, and thermal conductivity values decreased, which reduce the energy consumption of the buildings. Thermal conductivity was obtained through an adaptation of the hot wire method, achieving two different trends. In the case of specimens that incorporated waste from the oil industry thermal conductivity is maintained or decreased when the amount of waste increases. On the other hand, if it is used up to 7% waste from the brewing industry causes a slight decrease in thermal conductivity, while if 10% is added, thermal conductivity increases slightly again, in line with the greater vitrification capacity observed in this material in the sintering diagrams.

Results related with thermal behavior of fired clay bricks that incorporate organic wastes are resumed in Table 1.

Clay bricks with inorganic waste addition

Gencel *et al.*[35] investigated the effect of the addition of different combinations of ferrochromium slag, from the manufacture of ferrochromium metal, and natural zeolite, in the physical, mechanical, thermal conductivity and microstructure properties of clay bricks. The semi-dry mixtures, whose percentage of addition ranged between 0% and 30%, were molded and sintered at 900°C. The study characterized the physical, thermal and mechanical properties of fired clay bricks. The bulk density of the bricks with slag increased and with zeolite decreased. Clay bricks with slag addition had a compressive strength of 27.5-32 MPa, slightly smaller than the reference brick, 34.9 MPa, and with zeolite addition showed a strength of 14.3-22.3 MPa. The effect of zeolite on brick porosity dominates due to the porous structure generated by the ignition of the zeolite. Thermal conductivity of samples, obtained through a sensor that uses the modified transient plane source method, increased with the addition of ferrochrome slag and decreased with the addition of zeolite. The brick sample with 30% of zeolite additive had the lowest thermal conductivity value of 0.69 W/mK, and the highest, of 1.26 W/mK, corresponded to the sample containing 30% slag additive.

Sutcu *et al.*[36] analyzed in 2015 lightened fired clay bricks with waste marble powder addition up to 35% by weight, sintered at 950 and 1050°C. The results of the study showed that the use of residual marble dust reduced the bulk density and compressive strength of the samples, which reached 8.2 MPa. The thermal conductivity decreased with the addition from 0.97 to 0.40 W/mK, showing that the marble waste powder could be used as a pore-forming additive and contribute to the formation of crystalline phases in brick production in certain proportions.

Munir *et al.*[37] analyzed the viability of using marble sludge residues from industry in the production of clay bricks. Samples were manufactured under real conditions, sintered at 800°C, using percentages of residues between 5% and 25% by weight. The study analyzed different physical, mechanical and thermal properties, comparing them with other studies using other types of waste. The study showed how the addition of marble mud residues generates a structure with irregularly interconnected open pores, improving thermal insulation properties and decreasing the bulk density and strength of the bricks. With 15% of waste thermal conductivity falls around 16%, and resistance is reduced by almost half, maintaining a value greater than 5MPa.

Kazmi *et al.*[38] studied different physical-mechanical and thermal properties of clay bricks with the addition of waste glass dust, with 5%, 10%, 15%, 20% and 25%

proportion by weight, manufactured in an industrial oven. Units had higher density and compressive strength after the addition of glass dust. Ceramic bricks that incorporated a 25% addition showed a 37% increase in compressive strength. A reduction of apparent porosity and water absorption were also observed by increasing the content of glass waste. The microscopic images showed a dense and homogeneous structure with reduced porosity, which increased the thermal conductivity of the bricks. Control samples showed a thermal conductivity of 0.53 W/mK, which increased to 0.59 W/mK after incorporating 25% residue. According to this study, the use of waste glass dust may be useful to reduce landfills and associated environmental problems.

Results related to thermal behavior of fired clay bricks that incorporate mineral wastes are resumed in Table 2.

Discussion

This review shows the great potential of eco-friendly clay bricks, meeting in many cases the requirements established in standards while improving their isolation properties compared to the reference bricks. The investigations demonstrate the viability of using waste as addition in clay bricks, that not only allows its disposal but also prevents the depletion of resources.

The lack of homogeneity of the clay raw materials and of the standards used to determine the eco-friendly clay bricks properties, especially in case of thermal conductivity, do not allow the comparison of results. The scattering between results with the same addition prevents their use as a reference in future.

Eco-friendly clay bricks made by adding organic wastes improve the thermal isolation behavior, reducing the bulk density and increasing the porosity. In case of inorganic waste, additives can react and melt during the firing process reducing open porosity. In this case thermal conductivity can increase or decrease, the same way than bulk density.

Despite the reduced thermal conductivity values achieved in some of the studies, there are no experimental analysis that determine the fire resistance of clay bricks with waste addition, or their thermal and mechanical behavior at high temperatures. In the absence of these results, the national annexes of EN 1996-1-2: 2005[13] provide diagrams of density, thermal conductivity,

Table 1. Overview of thermal behavior of fired clay bricks incorporating organic wastes.

Researchers	Waste material	Mixing range (%)	Firing temperature (°C)	Density range (kg/m³)	Porosity range (%)	Thermal conductivity range (W/mK)
Ugheoke *et al.*[17]	Rice husk	35-60	1200	1410-1040	56-95.93	0.134-0.005
Bànhidi and Gömze[18]	Sawdust Rice-peel Seed-shell	0-7 0-7 0-7	900 900 900	- - -	- - -	0.27-0.23 0.27-0.20 0.27-0.17
Sutcu and Akkurt[19]	Paper processing residues	0-30	1100	1850-1290	30.8-52	0.83-0.42
Folaranmi[20]	Sawdust Ashes	0-30 0-30	800 800	- -	- -	0.25-0.06 0.25-0.18
Kadir *et al.*[21]	Cigarette butts	0-5	1050	2118-1482	-	1.08-0.45
Saia *et al.*[22]	Vegetable matter	0-9.1	850-1150	2000-1500	24.9-42.9	0.367-0.247
Cusidó and Soriano[23]	Wastewater-treatment plants sludges	100	1050	583.2	62	0.09
Eliche-Quesada *et al.*[24]	Spent soil biodiesel filtration Glycerin biodiesel	0-20 0-15	1050 1050	2052-1641 2052-1847	33-32 22-36	0.17-0.12 0.17-0.10
Muñoz *et al.*[25]	Paper pulp	0-17	942	1684-1412	-	0.737-0.394
Gorhan and Simsek[27]	Rice husks	0-15	700-1000	1890-1262	28-48	0.548-0.165
Phonphuak[28]	Charcoal	0-10	950	1800-1490	28.96-46.85	0.270-0.216
Muñoz *et al.*[29]	Pomance	0-17	980	1700-1300	26-37	0.738-0.39
Muñoz *et al.*[32]	Coffee grounds	0-17	942	1700-1400	22-32	0.73-0.38
Adazabra *et al.*[33]	Spent shea waste	0-20	900-1200	-	-	0.6-0.36
Galán-Arboledas *et al.*[34]	Spent diatomite	0-10	850-1050	1860-1640	28.5-37.5	0.7-0.45

Table 2. Overview of thermal behavior of fired clay bricks incorporating mineral wastes.

Researchers	Waste material	Mixing range (%)	Firing temperature (°C)	Density range (kg/m³)	Porosity range (%)	Thermal conductivity range (W/mK)
Gencel *et al.*[35]	Ferrochromium slag Zeolite	0-30 0-30	900 900	1679-1913 1679-1479	34.9-32.1 34.9-42.8	1.196-1.26 1.196-0.69
Sutcu *et al.*[36]	Marble powder	0-35	950, 1050	2050-1590	22.3-42.8	1.014-0.401
Munir *et al.*[37]	Marble sludge	0-25	800	1300-1150	32-42	0.56-0.4
Kazmi *et al.*[38]	Glass sludge	0-25	850	1350-1377	43.27-35.28	0.53-0.59

specific heat, thermal deformation and stress-strain as a function of temperature for clay bricks with density values ranging from 900 to 1200 kg/m^3, that allow the assessment by calculation with an advanced method based in properties at room temperatures.

Conclusions

This work presents various studies that determine the thermal conductivity of eco-friendly clay bricks incorporating waste materials, classified by the organic or inorganic nature of the waste added. These studies also analyze different physical-mechanical and chemical properties of fired clay bricks according to specific literature and standards.

The reduction in density and thermal conductivity while maintaining compressive strength in permissible values offers an economical option for the design of ecological clay bricks.

The study of the behavior in fire conditions of ceramics with the addition of waste recycled products with low thermal conductivity will change its use as insulating material in sustainable constructions.

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