Introduction to eco-efficient masonry bricks and blocks

1

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1.1 Brief historical considerations on masonry bricks and blocks: past, present and future

The first masonry units were based on dried mud and were used for the first time around 8000 BC in Mesopotamia, an area bordered by the Tigris and Euphrates rivers stretching from Southeast Turkey, Northern Syria, and Iraq reaching the Persian Gulf (Pacheco-Torgal & Jalali, 2011).

Today, earth masonry units (adobe or compressed earth blocks) still represent a large share of the built environment. Between one-third up to 50 percent of the world's population lives in earth-based dwellings (Guillaud, 2008). The majority of earth construction is located in less developed countries, however, this kind of construction can also be found in Germany, France or even the United Kingdom (Hall, Lindsay, & Krayenhoff, 2012).

As to the fired-clay bricks, their use goes back to around 3000 BC (Lynch, 1994). Even the Roman civilization has left several buildings constructed with fired-clay bricks, for example, the library of Celsus in Ephesus built in 117 AD.

The compressive strength and durability to weathering of fired-clay bricks have made them a widely used construction material for thousands of years. An excellent source on brick history can be found in the book *Brick: A World History* by Campbell and Pryce (2003). It's worth mentioning that this book has an excessive focus on brick masonry's grand architectural features and is less focused on the engineered aspects of brick masonry. Common clay-fired bricks still serve as the base of recent and amazing buildings (Figure 1.1), highlighting the notorious words of the architect Louis Khan on this building material (Scully, 1993).

With the appearance of Portland cement in the twenty-first century, masonry concrete blocks emerged as an alternative to fired-clay bricks, although the latter are still predominant to a large extent. For instance in the United Kingdom, concrete blocks represent only around five percent of the total masonry units production (Bingel & Bown, 2009).

Because of the high kiln-firing temperatures, the fired-clay industry has high energy consumption and is responsible for high greenhouse gas emissions (GHG). Creation of fired-clay bricks has an energy consumption that is almost 300% higher than the energy consumption of concrete blocks (Reddy & Jagadish, 2003). Taking into account the lower embodied energy of concrete blocks, it's expected that in the future this material will gain a higher market share. Still, masonry fired-clay bricks and

Figure 1.1 Indian Institute of Management, Ahmedabad (Louis Khan, 1962–1974).

concrete blocks are and will continue to be widely used construction materials around the world, even in highly developed countries. According to a report forecast (Freedonia Group, 2010), US demand for fired-clay brick and concrete block products is projected to increase nearly twelve percent annually from a weak 2009 base to 12.4 billion units in 2014 (66% clay bricks and 37% concrete blocks). This represents just a small proportion of the annual worldwide production. Machine-made brick production, using automated kilns, is approximately 125 billion bricks. China alone is responsible for 100 billion units. Around 91% of the total brick production (1391 billion units) concerns handmade bricks. China and India are the major producers of handmade bricks, respectively, with 700 billion and 144 billion units respectively. The remaining countries are responsible for the production of 422 billion units (Habla, 2014; Sabapathy & Maithel, 2013). This leads to the exploitation of hundreds of millions of tons of nonrenewable resources and, to make things worse, in the next decades the brick (and block) demand will continue to rise just because the building construction industry in less developed countries will also rise steadily (until 2030 urban land cover will increase by 1.2 million km² (Seto, Buneralp, & Hutyra, 2012)) to deal with the dramatic increase of urban population (in the next 40 years, urban population will be about 3000 million people (WHO, 2014)).

1.2 Contributions of masonry bricks and blocks for eco-efficient construction

The concept of eco-efficiency was firstly coined in the book *Changing Course* (Schmidheiny, 1992) in the context of the 1992 Earth Summit process. This concept includes “the development of products and services at competitive prices that meet the needs of humankind with quality of life, while progressively reducing their environmental impact and consumption of raw materials throughout their life cycle, to a level compatible with the capacity of the planet.”

In the last 10 years, around 1000 papers were published in Scopus journals related to masonry units. The terms "eco-efficiency" or "eco-efficient" were mentioned in only 0.3% of those papers, meaning that the eco-efficiency concept has not yet successfully entered in the masonry research field. This is especially disturbing in the context of the major environmental threats faced by our planet and the major environmental impacts of the construction industry. Since energy efficiency improvements have the greatest potential of any single strategy to abate global GHG emissions, a major worldwide environmental problem, from the energy sector (IEA, 2012), and since the building sector is a large energy user responsible for about 40% of the European Union's total final energy consumption (Lechtenbohmer and Schuring, 2011), this means that energy efficiency is a priority for eco-efficient construction. The Energy Road Map 2050 (COM (2011), 885/2) confirmed that higher energy efficiency in new and existing buildings is key for the transformation of the EU's energy system. The European Energy Performance of Buildings Directive 2002/91/EC (EPBD) was recast in the form of the 2010/31/EU by the European Parliament on 19 May 2010. One of the new aspects of the EPBD, which reflects an ambitious agenda on the reduction of the energy consumption, is the introduction of the concept of nearly zero-energy building (Pacheco-Torgal, Cabeza, Mistretta, Kaklauskas, & Granqvist, 2013).

Since walls are the major surface areas of the buildings through which considerable amounts of heat are exchanged between the interior and the external environment, the use of masonry units with improved thermal conductivity contributes to the reduction of heat losses in buildings. Therefore, reducing heat energy needs represents an important contribution for eco-efficient construction. A simple way to achieve that concerns the pore forming technique. It takes advantage of the fact that during the firing stage the combustion of organic matter (sawdust, tobacco residues, grass waste, sawdust, cork dust, paper sludge) leads to the formation of micro-pores. This technique allows for the reduction of the density of fired-clay bricks with organic additions resulting in new bricks with an increased thermal resistance. A more efficient technique encompasses the improvement of the design of the cross-section of masonry units in order to reduce their mass and increase the thermal resistance (minimize their thermal transmittance or U-value). Intense research efforts in this field have turned traditional, thick masonry units into highly perforated ones. This subject is important enough to merit the attention of several chapters in this book. State-of-the-art technology on the cross-section design of fired-clay bricks and lightweight concrete blocks allows single-leaf masonry walls with high thermal performance to be built (Figure 1.2).

In some European countries, these masonry units allow for walls without any additional thermal insulation materials like extruded polystyrene, rigid foam of poly-isocyanurate or polyurethane. These insulation materials are associated with negative impacts in terms of toxicity. Polystyrene, for example, contains antioxidant additives and ignition retardants. Additionally, its production involves the generation of benzene and chlorofluorocarbons. On the other hand, polyurethane is obtained from isocyanates, which are widely known for their tragic association with the Bhopal disaster. Besides, it releases toxic fumes when subjected to fire (Pacheco-Torgal, Fucic, & Jalali, 2012). These masonry units are also specially indicated for

Figure 1.2 Examples of masonry units with enhanced thermal performance. Left: lightweight concrete block; Right: fired-clay brick (Sousa, Castro, Antonio, & Sousa, 2011).

load-bearing structures, even those located in areas prone to seismic risks (Lourenço, Vasconcelos, Medeiros, & Gouveia, 2010).

However, as Sandrolini and Franzoni (2010) recognized, energy savings by means of more efficient thermal insulation is an insufficient approach, further suggesting the inclusion of embodied energy as an important parameter for sustainable construction. A recent review by Cabeza et al. (2013) highlights research efforts to develop building materials with less embodied energy. In a future of a near zero operational energy context, the percentage of the embodied energy in the total energy consumption of the buildings will become increasingly prevalent, and then the use of building materials with lower embodied energy will become a priority area. The energy embodied in construction and building materials (embodied energy) covers the energy consumed during its service life. There are, however, different approaches to this definition, namely: including the energy consumed from the extraction of raw materials to the factory gate (cradle to gate), from extraction to site works (cradle to site) or from extraction to the demolition and disposal (cradle to grave). Berge (2009) considers as embodied energy only the energy needed to bring the material or product to the factory gate (first case), and the transport energy and the energy related to the work execution as being both included in the construction phase of the building. According to this author, the embodied energy represents 85–95% of the material total energy (the remaining 5–15% being related to the construction, maintenance and demolition of the building). As to the third case, the embodied energy includes all energy consumption phases from the production to the cradle. As to the transport energy, it depends on the mode of transport: sea, air, road or rail. Recently Pacheco-Torgal, Faria, and Jalali (2013) studied a 97 apartment-type building (27,647 m²) located in Portugal, concerning both embodied energy as well as operating energy. The results show that the embodied energy in masonry fire brick units represented 16% of the total energy consumption. If the buildings were in the AA+ energy class, this would mean that the embodied energy in masonry fire brick units could only represent more than 60% of the operating energy for a service life of 50 years. An excellent example of low-embodied-energy masonry units concerns

adobe or compressed earth blocks, which consume as much as 15 times less energy than fired-clay bricks (Zami & Lee, 2010).

The replacement of only 5% of concrete blocks used in the UK masonries by earth masonry would mean a reduction in CO₂ emissions of approximately 100,000 tons (Morton, 2008). Unfortunately, climate change impacts (EEA, 2012) like rivers flooding due to extreme precipitation may pose some limitations to the future use of the earth masonry blocks in the major portion of Europe. Since earth construction is labor intensive, this kind of construction is specially indicated for less developed countries in which the higher housing needs will take place and in which the labor is available for a very low cost (Pacheco-Torgal & Jalali, 2012; Sanya, 2007). That's why earth block masonry constitutes the subject of three chapters of this book.

Last, but not least, another positive way for the brick and block industry to contribute to a more eco-efficient construction encompasses the incorporation of wastes from other industries. This option not only prevents an increase of the area needed for waste disposal, but most important, avoids the exploitation of nonrenewable raw materials used in the production of masonry units, thus reducing its environmental impacts such as deforestation, top-soil loss, air pollution and pollution of water reserves. It is worth remembering that around 1.2 billion people live in areas of physical scarcity, and 500 million people are approaching this situation (Pacheco-Torgal & Labrincha, 2013).

According to the Waste Management Acts 1996 and 2001, wastes can be defined as "any substance or object belonging to a category of waste which the holder discards or intends or is required to discard, and anything which is discarded or otherwise dealt with as if it were waste shall be presumed to be waste until the contrary is proved". In Europe, the milestone related to waste recycling can be found in the Roadmap to a Resource Efficient Europe:

By 2020, waste is managed as a resource. Waste generated per capita is in absolute decline. Recycling and reuse of waste are economically attractive options for public and private actors due to widespread separate collection and the development of functional markets for secondary raw materials. More materials, including materials having a significant impact on the environment and critical raw materials, are recycled. Waste legislation is fully implemented. Illegal shipments of waste have been eradicated. Energy recovery is limited to non-recyclable materials, landfilling is virtually eliminated and high quality recycling is ensured.

So far, a wide variety of waste materials have been studied for fired-clay bricks, including fly ash, mine tailings, slags, construction and demolition waste (CDW), wood sawdust, cotton waste, limestone powder, paper production residue, petroleum effluent treatment plant sludge, kraft pulp production residue, cigarette butts, waste tea, rice husk ash, crumb rubber and cement kiln dust (Zhang, 2013).

Because of its high volume, CDW and mine wastes merit a few additional comments. Eurostat estimates the total for Europe to be 970 million tons/year, representing an average value of almost 2.0 ton/per capita (Sonigo, Hestin, & Mimid, 2010). Currently, the average recycling rate for EU-27 is just 47%. The need to recycle at least

70% of nonhazardous construction and demolition waste by 2020, expressed in COM 571, was set by the Revised Waste Framework Directive 2008/98/EC and does not include naturally occurring material defined in category 170,504 (soil and stones not containing dangerous substances) in the European Waste Catalog. Eurostat estimates the total for Europe to be 970 million tons/year, representing an average value of almost 2.0 ton/per capita. As the current average recycling rate of CDW for EU-27 is only 47%, increasing it to 70% in just a decade seems an ambitious goal, further stressing the need for new and more effective recycling methods (Pacheco-Torgal, Labrincha, Tam, Ding, & de Brito, 2013). Besides, in the next decades, waste recycling will be more and more challenging on the zero-waste scenario (Zaman & Lehmann, 2013).

In other parts of the world (especially in Asia) industrial waste reuse will be even more dramatic just because by 2030, urban land cover will increase by 1.2 million km², and that will happen concomitant with an enormous infrastructure boom (Seto et al., 2012).

Mining and quarrying wastes represent a worrying waste responsible for more than 700 million tons/year just in Europe. Mineral waste can be defined as the “residues, tailings or other non-valuable material produced after the extraction and processing of material to form mineral products” (Harrison et al., 2002). Not very long ago, the failure cases of Aznalcollar mine in Spain (1998) which affected 2656 ha of Donana Nature Park with pyrite sludge and Baia Mare mine (2000) in Romania clearly showed that in the short term and environmentally speaking, mine wastes represent a clear and present danger (Pacheco-Torgal & Labrincha, 2013).

Since most mining wastes have toxic substances, research efforts capable of immobilizing these wastes on masonry units would be very important. That is why waste reuse represents an important part of this book, being the subject of five chapters.

Most books already published in masonry have a low-technology approach on this subject, failing to embody any scientific-updated information on masonry units. Those are more suitable for a craftsmanship audience. Others are authored by structural experts and focused on structural details having nothing on masonry units or at maximum a superficial coverage of this issue. The most relevant gap in the literature of masonry units concerns its environmental performance, which is the main reason that led to the making of this book. Assembled by a team of leading international expert contributors, this book constitutes an innovative eco-efficiency approach to masonry units.

1.3 Outline of the book

This book provides an updated state-of-the-art review on the eco-efficiency of masonry units; particular emphasis is placed on the design, properties, performance, durability and environmental performance of these materials.

The first part encompasses an overview on the design, properties and thermal performance of large and highly perforated fired-clay masonry bricks (Chapters 2–4).

Chapter 2 concerns the design and mechanical performance of large and highly perforated fired masonry bricks. The mechanical performance of the units and of the masonry assemblages under distinct loading conditions is discussed. An emphasis is

given to the seismic behavior of hollow, clay brick masonry under combined vertical and lateral in-plane loading, the main seismic performance parameters being discussed.

Chapter 3 addresses the influence of thermal conductivity of clay in the equivalent thermal transmittance of walls built with large and highly perforated fired-clay bricks. The factors that influence heat transfer in single-leaf walls, namely, the geometry of the block (internal voids and vertical joint), the execution of the wall (horizontal joint) and the thermal conductivity of clay are discussed. An equation that enables the calculation of the decrease in the equivalent thermal transmittance of a wall when the thermal conductivity of the clay is decreased is presented.

Chapter 4 covers the influence of several types of clay bricks on the thermal performance of a designed building. These include traditional fired-clay bricks, highly perforated fired-clay bricks without cavity filling and highly perforated fired-clay bricks with expanded polystyrene as cavity filling material. The design, properties and durability of fired-clay masonry bricks containing industrial wastes are the subject of Part Two (Chapters 5–7).

Chapter 5 is concerned with the properties and durability of clay fly ash-based fired masonry bricks. The fly-ash characteristics and its influence on the physical and mechanical properties are analyzed. The durability of the clay-based fired masonry bricks is also covered.

Chapter 6 covers the types of waste, properties and durability of pore-forming waste-based fired-clay masonry bricks. The different types of waste, properties and durability of pore-forming waste-based fired masonry bricks are reviewed.

The different types of waste, properties and durability of toxic waste-based fired masonry bricks are the subject of Chapter 7. It includes a waste classification according to the European Waste List and the distinctive role of wastes in the ceramic process. Its influence on the technical properties of the product as well as on atmospheric emissions are discussed. Its immobilization in the ceramic matrix is also discussed. Considerations on environmental behavior and commercialization are also covered.

Part Three (Chapters 8–11) deals with the design, properties and durability of Portland cement concrete masonry blocks.

Chapter 8 covers the properties and durability of high pozzolanic, industrial by-product content, concrete masonry blocks. The several types of pozzolanic by-products and the fresh and hardened concrete properties, as well as their durability, are reviewed.

Chapter 9 analyses the properties and durability of autoclaved, aerated concrete masonry blocks. It includes an overview on the different types of lightweight concrete, the manufacture and the mechanism of autoclaved, aerated concrete, its physical and mechanical properties, microstructure, thermal conductivity and durability assessed by freeze–thaw resistance.

Chapter 10 covers the design, properties and performance of concrete masonry blocks with phase change material (PCM). Selection criteria, as well as PCM types, are reviewed. The design of PCM-based masonry bricks is discussed. The thermal performance of bricks with PCMs, using either numerical analysis or experimental measurements, is also discussed.

The decrease in thermal transmittance of the optimized units is compared to that of the commercially available blocks.

Chapter 20 addresses environmental performance and energy assessment of fired-clay brick masonry. The use of alternative fuels is analyzed. Process efficiency and environmental impacts are assessed and compared.

Chapter 21 covers the case of energy and carbon embodied in straw and fired-clay masonry bricks. The manufacturing of wall blocks with straw and clay by small enterprises is introduced. Energy and carbon embodied is assessed. Comparisons with energy and carbon embodied of current fired-clay bricks and concrete blocks are included. Thermal resistance comparisons are also included.

Chapter 22 closes Part Six with a case study concerning the assessment of embodied energy and CO₂ of earth-block and concrete masonry-block houses.

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Part One

Design, properties and thermal performance of large and highly perforated fired-clay masonry bricks