Chapter 6
Masonry Units

6.1 General

While stone masonry walls exist since the beginning of human civilization, the first bricks were based on dried mud and were used for the first time in 8,000 BC in Mesopotamia, an area bordered by the rivers Tigris and Euphrates stretching from Southeast Turkey, Northern Syria and Iraq reaching the Persian Gulf. As to the fired-clay bricks, its use go back to 3,000 BC (Lynch 1994). The ceramic glazed bricks of the Ishtar Gate dating from 500–600 BC show that ceramic bricks reached a level of some sophistication. Although the Roman civilization has left numerous constructions made of stone masonry, they also left several buildings constructed with fired-clay bricks, as it happens in the case of the library of Celsus in Ephesus built in 117 AC. Traditional masonry uses mainly hollow clay bricks and concrete blocks. The environmental impacts of the latter are mostly related to the production of Portland cement (an issue analyzed in Chap. 5) and rather lower when compared to the environmental impacts of fired-clay brick production. According to Reddy and Jagadish (2003) fired-clay brick masonry, has an energy that is almost 300% higher than the energy of concrete block masonry. The environmental impacts caused by the fired-clay brick industry, can be summarized as follows:

- Non-renewable resources consumption
- Energy consumption
- Water consumption
- GHGs emissions
- Waste generation

The majority of the environmental impacts associated with the consumption of nonrenewable resources are less related to the availability of clay, but rather on the reduction of the area that should be available for biodiversity conservation purposes. The need for high temperatures for the production of fired-clay bricks means that this is an industry with an high energy consumption. The energy

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sources cover fuel, natural gas and propane. The use of more efficient equipment, the use of biomass or the use of additives in the composition of the bricks acting as calcination enhancers, contributes to reduce the consumption of fossil fuels. The fired-clay brick industry involves the consumption of high water volumes which, however, are considerably shorter than those required for other industries. The pollutant emissions caused by this industry are made up of particles of sulfur dioxide (SO_2), nitrogen oxide (NOx), carbon monoxide (CO), hydrogen fluoride (HF) and carbon dioxide (CO_2). The wastes generated by this industry are composed mostly of raw and fired-clay pieces. Given its characteristics, this wastes are reused again and incorporated in the production process or may be used as by-products for the production of concrete, as already mentioned in Chap. 5.

6.2 Fired-Clay Bricks with Industrial Wastes

The production of fired-clay bricks with the incorporation of wastes from other industries constitutes a positive way for the ceramic industry to contribute to a more sustainable construction. On one hand there is a reduction of the clay extraction and on the other this avoids the landfill of wastes. Lingling et al. (2005) studied the possibility of replacing large amounts of clay by fly ash. They show that clay-fly ash based bricks need a calcination temperature of almost 1,050°C. This represents between 50°C and 100°C above the traditional calcination temperature. These bricks show a high compressive strength, low water absorption and a high freeze-thaw resistance. Table 6.1 shows that increasing the fly ash/clay ratio leads to a reduction both in compressive strength and in density, as well as an increase in water absorption.

Those authors also mentioned that the use of high volume fly ash leads to a reduction in the plasticity index (Fig. 6.1). Since the mixtures with a plasticity index below six make it difficult to cast bricks by plastic extrusion these means that mixtures with a fly ash/clay ratio above 60% are not recommended. Other authors (Cultrone and Sebastián 2009) also studied the performance of fly ash based bricks confirming that its inclusion helps to decrease the density of the mixture. They reported that the use of fly ash can lead to a color change of the bricks. This may hinder their use in certain exposed applications when the bricks come from different manufacturers. Saboya et al. (2007) studied the replacement of clay by marble waste mud, a by-product of the marble processing industry. Those authors obtained bricks with a high compressive strength concluding that the use of a replacement percentage of 15% and a calcination temperature of 850°C are the most recommendable. El-Mahllawy (2008) studied the feasibility of using granite powder, kaolin and blast furnace slag in the manufacture of fired bricks with high acid resistance. This author recommended the use of a mixture with 50% kaolin, 20% granite powder and 30% blast furnace slag. Ajam et al. (2009) studied the performance of ceramic bricks with partial replacement of clay by phosphogypsum noticing that the addition does not reduce the plasticity of the

Table 6.1 Properties of clay-fly ash bricks (Lingling et al. 2005)

Fly ash/clay ratio (vol%)	Calcination temperature (°C)	Apparent porosity (%)	Water absorption (%)	Density (kg/m^3)	Compressive strength (MPa)
50:50	1,000	35.82	22.18	1,610	50.0
	1,050	30.37	17.62	1,720	98.5
60:40	1,000	39.83	26.94	1,480	25.4
	1,050	36.65	23.62	1,550	39.6
70:30	1,000	40.62	28.08	1,440	21.5
	1,050	39.76	27.54	1,440	27.8
80:20	1,000	42.12	31.26	1,350	14.7
	1,050	39.80	27.86	1,430	25.4

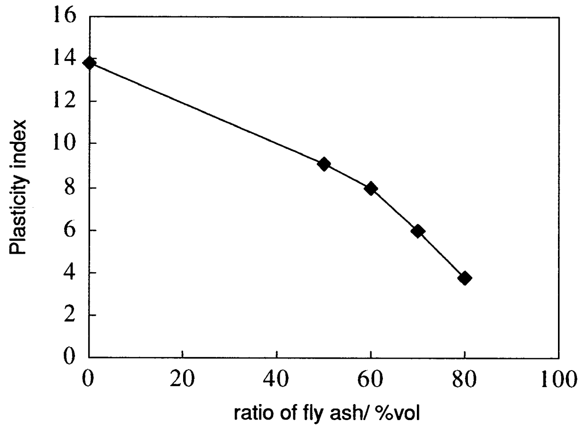

Fig. 6.1 Plasticity indexes of clay and clay-fly ash mixtures (Lingling et al. 2005)

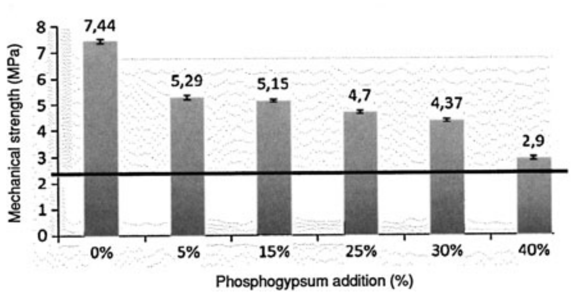

Fig. 6.2 Mechanical strength versus phosphogypsum proportioning (Ajam et al. 2009)

mixture and that the use of substantial amounts of phosphogypsum allows mixtures with enough mechanical strength (Fig. 6.2).

The same authors also noticed that these bricks show a water absorption percentage below the regulatory limits (Table 6.2) and also that the use of phosphogypsum percentages of 5% and 10% lead to a water absorption lower than the one presented by the mixture without phosphogypsum. As to the shrinkage

Table 6.2 Water absorption coefficient of brick samples (%) (Ajam et al. 2009)

$C_{0\%}$	$C_{5\%}$	$C_{15\%}$	$C_{25\%}$	$C_{30\%}$	$C_{40\%}$	Regulatory limits
7.15	5.3	5.7	7.65	11.2	13.4	15

Table 6.3 Shrinkage coefficient of brick samples (%) (Ajam et al. 2009)

$C_{0\%}$	$C_{5\%}$	$C_{15\%}$	$C_{25\%}$	$C_{30\%}$	$C_{40\%}$	Regulatory limits
6.66	6.7	7.2	6.7	7.5	10	8

Table 6.4 Average gaseous emissions (Monteiro et al. 2007)

Gases	Oil wastes (% by weight)	
	0%	10%
SO_2	2 ppm	58 ppm
NO	–	–
CO	5,650 ppm	7,120 ppm
CO_2	3,750 ppm	38,000 ppm
CH_4	–	500 ppm

coefficient (Table 6.3) only the mixture with 40% phosphogypsum show an inadequate behavior.

Monteiro and Vieira (2005) suggest that production of fired-clay bricks can help to solve the problem of oil wastes, thus preventing their disposal. The oil wastes contain water (12.7%), organic matter (33.1%) and some heavy metals. The results show that the use of almost 30% of oil wastes did not alter the density of the fired bricks, nor its water absorption or the linear shrinkage. As to the flexural strength it decreases with increasing percentages of those wastes. Monteiro et al. (2007) also study the use of oil wastes in fired bricks; however they produced the bricks in an industrial facility while other studies were conducted in laboratory using small specimens. These authors show that is possible to produce fired bricks containing oil wastes as long as its percentage does not exceed 5%. They also mentioned that the leaching tests are within the Brazilian thresholds; nevertheless the firing process generates substantial hazardous gaseous emissions (Table 6.4).

More recently Pinheiro and Holanda (2009) confirm that the incorporation of 30% of oil wastes does not impair the physical and mechanical properties of fired-clay bricks. They point out that several authors used different types of waste oil but unfortunately they do not disclose any comment on gaseous emissions. Mekki et al. (2008) studied the possibility of incorporation of olive mill waste water in the fired brick-making process. These wastes have a high organic content and phenols that are toxic and represent an environmental problem. The results showed that the production of fired bricks from the mixture of clay and olive mill waste water allows for a final product with mechanical characteristics identical to bricks without this addition. The new bricks show a 10% increase in shrinkage and a 12% increase in water absorption. The same authors also show that the new bricks can be fired at 880°C instead of the traditional 920°C firing temperature which allows

Table 6.5 Properties of paper processing residues fired-clay bricks (Sutcu and Akkurt 2009)

Properties	Percentage of paper processing residues by weight			
	0	10	20	30
Water absorption (%)	16.7	23.9	31.9	40.4
Compressive strength (MPa)	39.2	15.7	7.5	4.9
Thermal conductivity (W/mK)	0.83	0.59	0.48	0.42

Table 6.6 Total concentrations of heavy metals in raw river sediments in mg/kg on dry material (Samara et al. 2009)

Element	Cadmium	Chromium	Copper	Lead	Zinc
Raw sediment	12.8	413	150.7	1,373	5,032
Level N1	1.2	90	45	100	276
Level N2	2.4	180	90	200	552

for a reduction in the energy consumption. Identical results were obtained by De La Casa et al. (2009) which showed that the reuse of olive mill waste water allows the production of fired bricks with physical and mechanical characteristics similar to traditional fired bricks with the advantage of allowing for energy savings between 2.4% and 7.3%. Cruz (2000) analyzed the performance of fired-clay bricks containing waste sawdust, polystyrene and perlite, mentioning that the new bricks have an increased thermal and acoustic performance. The technique of reducing the density of fired-clay bricks with organic additions takes advantage on the fact that during the firing stage the combustion of the organic matter leads to the formation of micro-pores. This technique has been used by several authors (Kohler 2002; Demir et al. 2005; Demir 2006; Ducman and Kopar 2007). More recently Demir (2008) studied the feasibility of using several organic wastes (sawdust, tobacco residues, grass) to enhance pore formation in fired-clay bricks. The results show that pore formers are not associated with extrusion problems up to 5% weight. A residue addition of 10% weight was found to be unsuitable because of low plasticity and excessive drying shrinkage. Sutcu and Akkurt (2009) used paper processing residues as pore forming agents in fired-clay bricks obtaining new bricks with enhance thermal conductivity (W/m K), high water absorption and adequate compressive strength (Table 6.5).

Samara et al. (2009) studied the use of river sediments in fired-clay bricks. This sediments come from the dredging of river beds that receive effluents from highly polluting industries (coal, iron, steel, glass, chemicals), thus having a high toxic content (Table 6.6).

The levels N1 and N2 are set by the French regulations as toxicity thresholds. Below level N1, the potential impact is regarded, as neutral or negligible. Between levels N1 and N2, further investigations may prove necessary. Beyond N2 level, additional investigations are generally necessary. Since the raw sediment exceeds the level N2 they have been treated with the Novosol® process developed and patented by the Solvay Company. This process encompasses two different phases. A phosphatation phase in which raw sediments are mixed with phosphoric acid

Table 6.7 Results of the leaching test undertaken on brick specimens in accordance with the French Standard AFNOR, XP X31-210 (Samara et al. 2009)

Element	Sediment-amended brick pH 8.9	Standard brick pH 7.6	Limit values for waste acceptable as inert L/S = 10 (l/kg)	Limit values for waste acceptable as non-hazardous L/S = 10 (l/kg)
Cd	<0.02	<0.02	0.04	1
Cu	<0.03	<0.03	2	50
Zn	0.053	0.177	4	50
Ni	<0.07	<0.07	0.4	10
Pb	<0.2	<0.2	0.5	10

Table 6.8 Concentration of heavy metals in the leachates of samples, leached with acetic acid in mg/kg on dry material, according to the American Standard TLCP-USEPA (Samara et al. 2009)

Element	Sediment-amended brick pH 4.92	Standard brick pH 7.6	Regulated TLCP limit
Cd	<0.04	<0.04	1.00
Cu	0.1	0.2	15
Zn	3.7	3.3	25.00
Ni	<0.14	<0.67	–
Pb	<0.4	<0.4	5

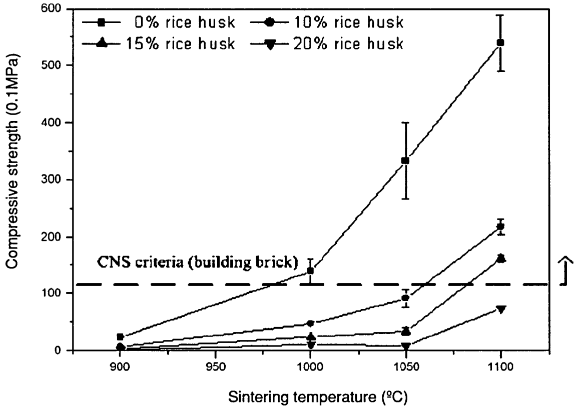

Fig. 6.3 Sintering temperature effect on the compressive strength (Chiang et al. 2009)

H_3PO_4 in the presence of calcite, leading to the formation of calcium phosphates minerals. The second phase implies the calcination of the phosphated sediments at ≥650°C. The treated sediments consisting of an odorless fine powder that were used in fired-clay bricks. The results show that bricks with 15% wastes have increased compressive strength (63%), lower water absorption (13%) and lower porosity (10%). Tables 6.7 and 6.8 shows the leaching performance of the new bricks when using respectively distilled water and acetic acid. The results are within the legal thresholds.

Table 6.9 Chemical composition and heavy metals in TFT-LCD wastes (Lin 2007)

SiO_2	Na_2O	Cu	Zn	Pb	Cr
64%	0.3%	0.27 (mg/kg)	0.23 (mg/kg)	0.65 (mg/kg)	0.18 (mg/kg)

Chiang et al. (2009) studied the reuse of rice husk ash and water treatment sludge to produce light bricks. The results show that the achievement of a minimum regulatory 10 MPa compressive strength implies the use of a calcination temperature of 1,100°C and the use of a rice husk ash percentage below 15% (Fig. 6.3). Water absorption results show that increasing the percentage of rice husk ash leads to high water absorption, which can be reduced by the use of a high sintering temperature.

Lin (2007) studied inert wastes from thin film transistor-liquid crystal display (TFT-LCD) optical waste glass (TVs and computers) incorporated in fired-clay bricks. Estimates about the amount of such waste are around 25,000 m^3/year of PC and TV glass per million people in European countries (Hermans et al. 2001). This represents almost 19 millions of m^3/year. These wastes are composed mostly of glass with some heavy metals (Table 6.9).

The environmental performance of these bricks was examined with the standard TLCP-EPA and all the compositions including those containing 40% wastes met the regulatory limits. The bricks show low water absorption and a high compressive strength both dependent on the firing temperature. The results show that the mixtures with 30% wastes lead to the maximum compressive strength. The reuse of TFT-LCD wastes avoids disposal costs (40 €/ton) and also the cost of raw clay (10 €/ton). Dondi et al. (2009) also studied the inertization of this kind of wastes in fired-clay bricks and roof tiles suggesting the use of only 2%, because higher percentages may be responsible for a plasticity reduction generating extrusion problems, but also for reductions in the compressive strength. These authors used the leaching standard DIN 38414-S4 for the assessment of the environmental performance of the bricks containing TFT-LCD wastes, observing that the metals concentration in the eluates is very low. Loryuenyong et al. (2009) study the reuse of waste glass from structural glass walls in fired-clay bricks. The use of as much as 30% weight waste glass lead to a compressive strength increase of the bricks up to 41 MPa and a water absorption decrease as low as 3%. The use of higher percentages of waste glass lead to a severe decrease in compressive strength and a high water absorption.

6.3 Unfired Units

The use of unfired masonry units allows for low embodied energy units. Unfired-clay units consist of raw clay mixed with sand, compressed and artificially air-dried during one or two-days before being used in construction. The thermal conductivity of unfired-clay bricks follows a linear function related to its density, as it happens for fired-clay bricks (Oti et al. 2010). Usually these units are use to

Table 6.10 Physical and mechanical properties of blocks made with limestone powder wastes and wood wastes (Turgut and Algin 2007)

Mix	Compressive strength (MPa)	Flexural strength (MPa)	Density (g/cm^3)	Water absorption (%)
Ref	24.9	3.94	1.88	12.4
Lw-10	16.6	3.75	1.70	13.9
Lw-20	11.0	3.50	1.66	15.1
Lw-30	7.2	3.08	1.51	19.2

built non-load-bearing walls. According to Morton (2006) the embodied energy of an unfired-clay brick house test is about 14% of the value for fired-clay bricks and 24% for lightweight concrete blocks. Masonry blocks based on hydraulic binders also belong to the unfired units category. Kumar (2000, 2002) mentioned the development of (fly ash + lime + phosphogypsum) based blocks, obtaining a final product with a density between 20% to 40% lower than the fired-clay bricks, but with a compressive strength in the range of 4 to 12 MPa, enough to built masonry walls with a high resistance to aggressive environments. The mixture reproduces the characteristics of a hydraulic binder, the silica in the fly ash reacts with calcium hydroxide to produce calcium silicate hydrates. As to the aluminum in conjunction with calcium hydroxide reacts with gypsum to form calcium tris-sulfoaluminate hydrated. Turgut and Algin (2007) studied the use of limestone powder wastes and wood wastes (10, 20 and 30%), together with small amounts of cement (approx. 10% by mass) in the manufacture of masonry blocks (Table 6.10).

The results show that using a percentage of 30% wood wastes, is responsible for a high reduction of the compressive strength. Still the blocks meet minimum regulatory requirements for materials meant to structural applications, as defined in the BS 6073-1:1981 (Precast concrete masonry units). It is also clear that increasing the percentage of wood wastes leads to increased water absorption and a decrease in the density of the concrete blocks. The same authors (Algin and Turgut 2008) also studied the reuse of limestone wastes and cotton wastes in the production of concrete blocks ($W/C = 0.3$) containing limestone powder and glass wastes (10% to 30%). The results show that increasing the volume of glass wastes means that the compressive strength rises slightly from 27.5 to 30.1 MPa. At the same time the flexural strength increases from 4.15 to 7.76 MPa and the modulus of elasticity increases from 12 to 19 GPa. The results also show that the water absorption remains almost unchanged at about 12%, and that increasing the glass wastes leads to a considerable increase in the freeze-thaw resistance (Fig. 6.4).

Chindaprasirt and Pimraksa (2008) studied the manufacture of blocks based on lime and fly ash (10% + 90%) using an autoclave process (130°C and 0.14 MPa) during 4 h. The fly ash particles were previously submitted to a granulation process that causes a substantial increase in its pozzolanic reactivity because it contributes to an increase of the inter-particle contact. The granulation is obtained by inducing the formation of a water film around the particules. These blocks present a compressive strength between 47 and 62 MPa and a water absorption between 16% and 19%. Pimraksa and Chindaprasirt (2009) used the same

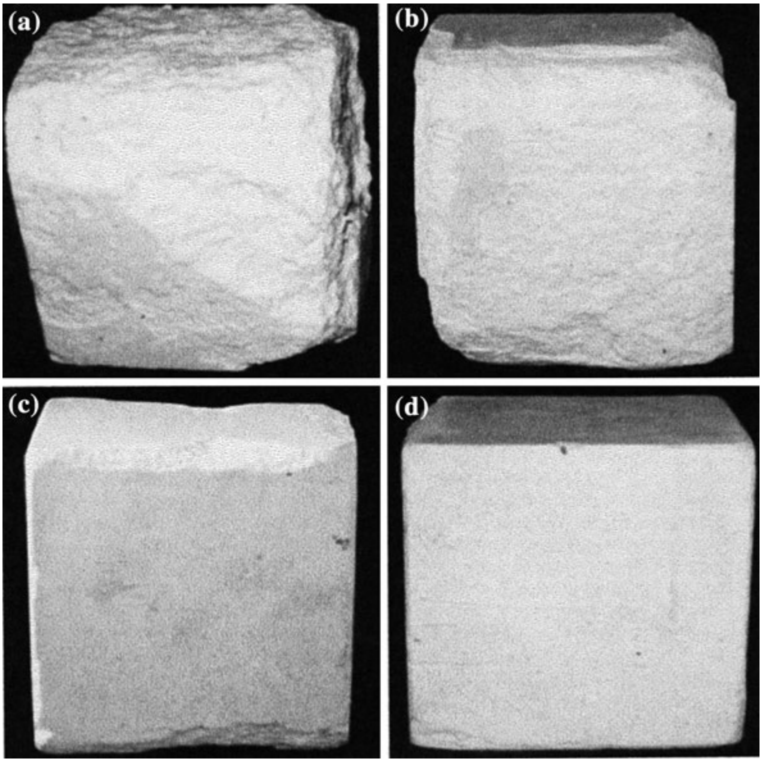

Fig. 6.4 Specimens after 50 freeze-thaw cycles testing: **a** mix without waste glass; **b** mix with 10% waste glass; **c** mix with 20% waste glass; **d** mix with 30% waste glass (Turgut 2008)

autoclave conditions to produce blocks made of diatomaceous earth, lime and gypsum (80% + 15% + 5%) with high compressive strength (14.5 MPa) and low density (880 kg/m^3). Some blocks were made using diatomaceous earth calcined at 500°C showing an increase in the compressive strength (17.5 MPa) and a decrease in their density (730 kg/m^3).

6.4 Shape Optimization

Recent investigations have been carried in order to optimize the shape of masonry units for enhanced thermal and acoustical performance. Dias et al. (2008) present results about the development of highly perforated fired-clay units designated cBloco containing wood wastes as pore formers that allow the construction of single-leaf walls (Fig. 6.5). Table 6.11 presents some of the characteristics of the cBloco unit.

Other authors (Del Coz Diaz et al. 2008, 2011) studied the shape optimization of concrete masonry units in order to reduce its mass and increase its thermal

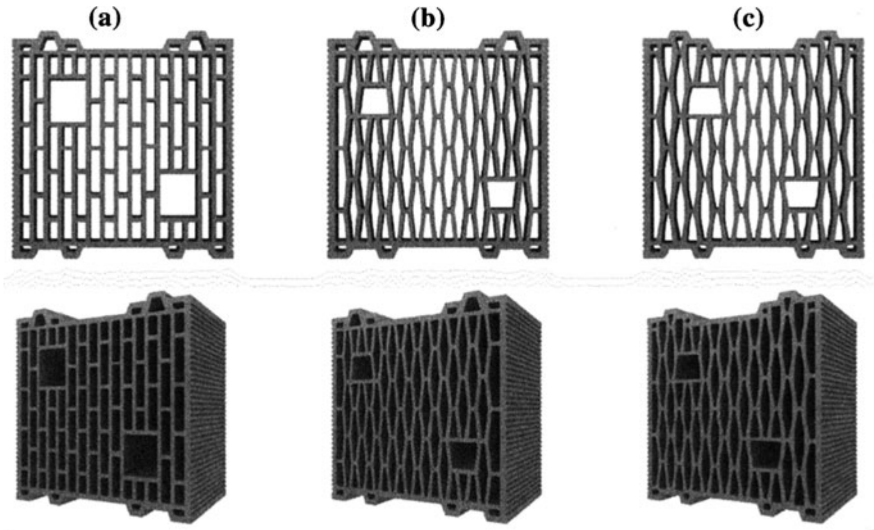

Fig. 6.5 cBloco 30 × 30 × 19 unit: **a** Rectagles; **b** Lozenges; **c** Rice grain (Dias et al. 2008)

Table 6.11 Characteristics of the cBloco unit (Dias et al. 2008)

Characteristics	Value
Dimensions (mm)	300 × 300 × 200
Compressive strengh (MPa)	13
Voids (%)	55
Mass (kg)	14
Real density (kg/m^3)	1,850
Apparent density (kg/m^3)	750
Thermal conductivity-λ (W/mK)	0.50
U-value of the c-Bloco unit (W/m^2 K)	0.60
Acoustic resistance Rw (dB)	44

conductivity. Sousa et al. (2011) studied the shape optimization of lightweight concrete masonry units using a genetic algorithm. The new blocks make it possible to built single walls with a U-value of 0.50 W/m^2 K.

6.5 Conclusions

Traditional masonry units (fired-clay bricks or concrete blocks) without an improved performance in terms of thermal and acoustical insulation are a symbol of a low technology past very far from the demands of eco-efficient construction. The best commercially available solutions for fired-clay bricks and lightweight concrete blocks allow to built single masonry walls with high thermal performance ($U < 0{,}6$ W/m^2°C). Therefore, the eco-efficient choice between these two masonry units will be made in terms of its global environmental impact. However, taking into account the low embodied energy of concrete blocks its expected that in the future this material will gain a higher market share. An increase in the use of unfired-clay bricks will also occur. The reuse of wastes from other industries will increase the eco-efficiency of masonry units.

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