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How to face the new industrial challenge of compatible, sustainable brick production: Study of various types of commercially available bricks

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ABSTRACT

In the view of a sustainable production responding to the important challenges to which industrial research is currently facing, this research is addressed to define the more appropriate brick types, among those here studied, in terms of mechanical resistance and durability, as well as the esthetic qualities. More in detail, five industrial bricks, produced with three types of clay and fired at four temperatures (600, 950, 980, 1050 °C), were analysed with a combined multianalytical approach to determine relationships between mineralogical-textural and physical-mechanical properties and decay behavior. Samples fired at 1050 °C show more complete mineralogical evolution and have the best mechanical resistance, but are the most sensitive to the water absorption. Instead, samples fired at the lowest temperature (600 °C) have the best pore interconnections and the lowest coefficient of capillarity, however, the absence of new silicates and melting make them the weakest under load and decay tests. Lastly, bricks produced at firing temperatures of 950 °C and 980 °C generally show intermediate behavior. These results indicate how bricks produced form the same or similar mix design and fired at different temperatures show different reactions to decay and mechanical resistance, allowing the industry to identify the limit of applicability of these materials in various contexts.

1. Introduction

Brick, a ceramic product used as building material since ancient times, is still valued for its easy availability of georesources, resistance to loading and environmental stress, and its esthetic quality. During firing, the raw materials, generally a mixture of a body of clay minerals and predetermined fractions of silt and sand (temper), is transformed into a new artificial material in which mineralogical changes occur, similar to those which developed during pyrometamorphism; as regards microstructure, new porosity develops and melts form (Riccardi et al., 1999; Aras, 2004; Cultrone et al., 2004). Many works have been published on case studies of historic interest, with specific focus on the mineralogy and texture of fired samples (Cardiano et al., 2004; Cultrone et al., 2005a), the provenance of raw materials (López-Arce et al., 2003; Maritan et al., 2005) and firing conditions (Setti et al., 2012), as well as on the phase transformations during firing of artificial samples (Dondi et al., 1998; Duminuco et al., 1998; Riccardi et al., 1999; Elert et al., 2003; Aras, 2004; Cultrone et al., 2004; Cultrone et al., 2005b; Maritan et al., 2006; Nodari et al., 2007; Fabbri et al., 2014) and have greatly contributed to our knowledge of the physical and mechanical changes according to raw material composition and firing temperature (Cultrone et al., 2001b; Carretero et al., 2002; De Bonis et al., 2014). Porosity and decay have also been investigated, to evaluate the parameters controlling durability, since bricks, like any other construction material, are affected by various and sometimes combined deterioration phenomena (Valluzzi et al., 2002; Valluzzi et al., 2005; Anzani et al., 2010). Examples are interactions with other materials nearby (Larbi, 2004; Cultrone et al., 2007), environmental conditions, and the presence of soluble salts (Cultrone et al., 2000; Rodriguez-Navarro et al., 2000; Benavente et al., 2003) or ice (Grossi et al., 2007a; Ducman et al., 2011). Nevertheless, although extensive studies on ceramic materials have been carried out, little research has focused on the real needs of brick industries. This work aims to close this gap, in collaboration with the personnel of a brick factory and focusing on actual requirements in industrial research, i.e., the creation of new mixes for specific situations (e.g., restoration of historical buildings) and the promotion of sustainable solutions in terms of saving resources and energy. Replacing some particular types of bricks in a damaged historic structure requires caution in operating in a way which is mechanically and chemically compatible with the undamaged materials and in preserving the overall original appearance (Cardiano et al., 2004). The brick industry is also encouraged to ensure quality, to improve eco-friendly brick production, and to optimize firing conditions, while maintaining the characteristics which make brick a traditional material, in which our cultural identity can be recognized (Cultrone and Sebastián, 2009; Eliche-Quesada et al., 2012; Zhang, 2013; Monteiro and Fontes Vieria, 2014).

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Table 1
Labels of raw materials and bricks and their maximum firing temperatures.

Clay	Additive	Brick type	Firing temperature (°C)
LG	-	GP	1050
	Hausmannite	N	1050
LRSS	-	RSS	950
	-	R6	600
LRS	-	RS	980

Table 3
Mineralogical assemblages determined according to XRPD data of clay minerals. Mineral abbreviations: Qz = quartz; I = illite; Chl = chlorite; Kfs = K-feldspar; Pl = plagioclase; Cal = calcite; Dol = dolomite; Hem = Hematite. Relative quantity: **** = very abundant; *** = abundant; ** = medium; * = scarce; + = rare.

	Qz	I	Chl	Kfs	Pl	Cal	Dol	Hem
LGP	****	**	**	*	*	****	***	+
LRS	****	**	**	*	**	**	**	+
LRSS	****	**	**	**	**	*	*	+

Compared with natural stone, brick has the advantage that its technical and esthetic qualities can be modified by changing the composition of raw materials and/or firing conditions to obtain certain properties, depending on the position or function the brick is required to carry out in a given place and environment. Identifying new mix designs for use in historic and modern constructions is a challenge of prime interest for restorers and builders. This work develops a valid multianalytical approach to study the properties of bricks, starting from five different types, four already on the market, in order to have a solid basis on which to tackle the actual industrial challenge of identifying methods and criteria to introduce green solutions to the market and ensure a leadership industry promoting excellence and innovation. Awareness of the close connections among mineralogy, porosity and physical properties can lead to improved quality in the brick industry as a whole, allowing us to take the next steps toward sustainable, compatible production and introducing new materials adapted to particular cultural and environmental contexts.

2. Materials and methods

Three types of clay raw materials largely adopted from the brick factory SanMarco-Terreal (Noale, Veneto, Italy) were studied: LG (*Laminato Giallo*, i.e. “Yellow Laminated”), LRSS (*Laminato Rosso*, “Red Laminated”) and LRS (*Laminato Rosa*, “Pink Laminated”). From these clays, five types of bricks (GP, N, RSS, RS and R6) were prepared by SanMarco-Terreal according to the “soft mud” method: GP (*Giallo Paglierino*, i.e., “Straw Yellow”) obtained with LG clay fired at 1050 °C; N (*Nero*, “Black”) produced with LG clay with the addition of 15 wt% of hausmannite powder (Mn_3O_4), to obtain a dark gray product, and fired at 1050 °C; RSS (*Rosso*, “Red”) and R6 (*Rosso600*, “Red600”) prepared with LRSS clay fired at 950 and 600 °C, respectively; RS (*Rosato*, “Pink”) obtained by LRS clay fired at 980 °C (Table 1). Samples were fired in a tunnel kiln, with the following temperature curve: heated to maximum temperature in 1-h and left at maximum temperature for 1-h (soaking time).

Both clay materials and fired bricks (two specimens per type of bricks) were characterized using a multianalytical approach: type of instruments and instrumental setting for each technique adopted are described in Table S1. Equations used to calculate the physical parameters from instrumental data are reported in Table S2.

Color coordinates (L^*, a^* and b^*) were determined for both clay materials and fired bricks (dry and wet) and color difference ΔE calculated for each brick (UNE EN 15886, 2011). The mineralogical composition of raw materials and bricks was determined from X-ray Powder Diffraction (XRPD). The bulk chemical analysis of raw clays and mixtures (bricks) was performed by X-ray fluorescence (XRF) (we refer to Scott and Love, 1983, for ZAF correction and to Chen and Wang, 1988, for the standards used). Texture, mineral phases and vitrification level were studied under both optical microscopy and field emission scanning electron microscopy (FESEM) on polished thin sections. Hydric parameters (Tables S1, S2) of fired bricks were determined, and free and forced water absorption (UNI EN 13755, 2008), drying (NORMAL 29/88, 1988), capillarity rise (UNI EN 1925, 2000) calculated (Rilem, 1980; Cultrone et al., 2003). The ultrasound propagation velocity of compressional (Vp) and shear (Vs) pulses was measured in the three perpendicular directions on cubic samples (50-mm edge). Once the compressional and shear wave velocities had been determined, the Poisson coefficient (ν) and the Young (E), Shear (G) and Bulk (K) moduli, and the total (ΔM) and relative (Δm) anisotropies were calculated (Guydader and Denis, 1986) (Table S2). Uniaxial compressive strength of bricks was measured according to UNI EN 1926 (2007). Three cubic samples with 40-mm edges of each brick type were tested at a loading rate of 20 kg/s (Table S2). Accelerated aging tests were carried on three cubic samples (50-mm edge) per brick type, to evaluate their resistance to frost (UNI EN 12371, 2010) and salt crystallization (UNI EN 12370, 2001). At regular intervals of 5 cycles during the freeze-thaw test and 3 cycles of salt crystallization, sample compactness was also monitored by ultrasound.

3. Results

3.1. Raw clay materials and dye

Under chemical viewpoint (Table 2) clay LRSS is the richest in SiO_2 and LG the poorest; LG has the highest calcium and LOI, indicating that is rich in carbonate. On the basis of XRPD data, clay materials are mineralogically similar, but differ for the percentages of mineral phases (Table 3). Quartz, calcite, dolomite, feldspars *s.l.*, chlorite and illite occur in all samples. Comparisons of X-ray diffraction patterns confirm the higher carbonate content in LG than in the others, due to higher concentrations of calcite and dolomite. Quartz prevails in clay LRSS, followed by LRS. As regards clay minerals, illite and chlorite occur in all samples with weak reflections at 10.02 Å, and 13.99 and 6.99 Å, respectively, but being both more intense in LRS (Fig. 1). Parameters L^*, a^* and b^* reveal some differences among the three clay materials (Table 4). In particular, GP, the most carbonate-rich, has the highest b^* value, yellow component, and lightness. The dye additive, hausmannite, due to its mineralogical nature, is very different from the clay materials, with low L^*, a^* and b^* tending to gray.

Table 2
Chemical composition of major elements expressed in wt% of oxides for clay materials (LG, LRS, LRSS) and bricks (GP, N, RS, RSS, R6). LOI = Lost on Ignition.

		SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI
Clay	LG	39.81	10.63	3.87	0.08	4.75	17.76	0.54	2.37	0.43	0.11	19.65
	LRS	51.50	12.72	4.43	0.09	3.41	10.45	0.70	2.74	0.54	0.12	13.29
	LRSS	57.77	14.14	4.85	0.10	2.68	6.16	1.09	2.99	0.63	0.13	9.47
Fired bricks	GP (1050 °C)	50.17	13.19	4.80	0.09	5.61	20.39	0.72	2.84	0.49	0.13	1.56
	N (1050 °C)	42.41	11.67	4.93	12.86	4.93	17.63	0.60	2.66	0.52	0.15	1.63
	RS (980 °C)	59.46	14.53	4.94	0.09	3.69	11.06	0.89	2.99	0.59	0.13	1.62
	RSS (950 °C)	63.79	15.28	5.16	0.11	2.87	7.01	0.99	3.20	0.66	0.13	0.78
	R6 (600 °C)	60.32	14.35	4.85	0.11	2.69	6.22	0.93	3.03	0.64	0.13	6.74