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Research paper

## Clays and bodies for ceramic tiles: Reappraisal and technological classification

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## ABSTRACT

The ceramic tile industry is a dynamic sector whose technological innovation and market trends have drawn a complex picture of products and processes. Raw materials have been deeply involved in such an evolution: the flexibility of current manufacturing cycles enables the use of a very wide range of clays, whose chemical and mineralogical composition, particle size distribution and ceramic properties were reappraised. The classical reference schemes are no longer able to properly describe and predict the role of clays in tilemaking. In order to fill this gap, an industry-oriented, technological classification of clay raw materials is proposed on the basis of chemical ( $\text{Fe}_2\text{O}_3$  content) and mineralogical parameters (amount of phyllosilicates and carbonates) together with particle size (fractions  $<2\ \mu\text{m}$  and  $>63\ \mu\text{m}$ ) and plasticity (methylene blue index and Atterberg plastic index). It firstly discriminates light-firing and dark-firing clays according to an iron oxide threshold of 3%. Light-firing clays are distinguished by the amount of kaolinite group minerals and plasticity in “kaolins” (high-grade, low-grade, and raw kaolins, kaolinitic loams) and “plastic clays” (ball clays, pyrophyllitic clays, white bentonites); the distinction of three classes of ball clays with increasing plasticity is envisaged. Dark-firing clays are classified according to coarse-grained fraction and amount of carbonates in carbonate-rich types (marly and carbonatic clays), red loams and red clays; these latter are furtherly differentiated by the relative abundance of clay minerals. Such a classification is essential to draw the guidelines for body formulation and to explain the criteria followed in the industrial practice for each category of ceramic tiles. Key properties are discussed to design batches for porous tiles, vitrified and semi-vitrified red stoneware, and vitrified light-firing bodies. Both the clay classification and the guidelines to body formulation are intended to provide up-to-date tools to assess the ceramic potential and correct use in tilemaking of clay materials, but they cannot substitute a thoroughful technological characterization, adequately simulating the industrial processing.

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## 1. Introduction

The production of ceramic tiles is growing worldwide at a rate of ~300 million  $\text{m}^2/\text{year}$  and has already passed 10 billion  $\text{m}^2$  in 2012 (Baraldi, 2013; Stock, 2012). Such an impressive growth implies an increasing demand for raw materials, whose global consumption can be estimated around 230 million tons/year. The commercial success of ceramic tiles is due to a continuous increase of product quality from both technical performance and esthetic appearance viewpoints. Such a quality improvement stems from the intensive product and process innovation that took place during the last decades and is now widespread in every tilemaking country (Corma, 2008; Nassetti, 1989).

This innovation has completely renovated the manufacturing cycle by introducing technological revolutions like fast firing, which brought about drastic changes in raw materials and eventually gave rise to novel products (e.g., *monoporosa* and *porcelain stoneware*) and to the disappearance of classic tile types (e.g., *majolica* and *calcareous*

*earthenware*). As a consequence, a paradigm shift occurred in the formulation of ceramic bodies and in the selection of raw materials (Becker and Brenner, 1997; Dondi, 2003; Fiori and Fabbri, 1985).

From this standpoint, classical treatises on ceramic raw materials – set up with reference to a picture of manufacturing and products already obsolete – are no longer able to describe the current market or to assess the potential of a given clay in tilemaking (Diaz Rodríguez and Torrecillas, 2002; Harvey and Murray, 1997; McCuiston and Wilson, 2006; Mitchell and Vincent, 1997; Worrall, 1975) or to address the correct design criteria for batch formulation (Fabbri and Fiori, 1985; Fiori et al., 1989; Singer and Singer, 1963).

The aim of this paper is to overview the technological evolution in the ceramic tile sector and its effects on product typologies through: (i) a reappraisal of composition and application of clay materials in tilemaking; (ii) the proposal of a clay classification for ceramic purposes; (iii) the review of compositional ranges for each type of ceramic tile with design criteria and guidelines for their batch formulation. Overall, the main objective is the study of the chemical–mineralogical composition and technological behavior that allows the evaluation of the applicability of the ceramic clays.

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## 2. Experimental approach

As a first step, a classification of ceramic tiles is outlined to introduce both terminology and basic concepts of tilemaking. Criteria followed in tile classification encompass standard prescriptions and commercial issues.

Another fundamental aspect is the continuous change in technological and compositional features of ceramic tiles induced by process and product innovation. The evolution of both manufacturing technology and product types is reviewed in order to draw a picture of how the ceramic tile industry has been evolving during the last decades.

Clay materials used in the industrial practice were selected in order to get a representative picture (1040 samples) of uses, technological features, and geographic provenance. The data sources for the clays here considered are summarized in Table 1. For each clay, chemical and mineralogical composition (with rational calculation when quantitative data were not given) were considered together with particle size distribution, plasticity (Atterberg consistency limits and Methylene Blue Index, MBI) and technological behavior in tilemaking (if available). In particular, MBI is able to summarize the overall technological performance of clays (Chiappone et al., 2004; Kelly, 1984): it can be measured at natural pH (MBI<sub>n</sub>) or in acidic conditions (MBI<sub>a</sub> at pH ~ 4) according to ASTM C837.

The body formulation of different types of wall and floor tiles was taken from literature sources about porous bodies (Bittencourt et al., 2001; Das et al., 2005; Dondi, 1999; Dondi et al., 1999b; Escardino

Benlloch, 1992; Sousa and Holanda, 2005) and vitrified bodies (Beltrán et al., 1996; Lassinanti Gualtieri et al., 2011; Lazaro et al., 2012; Motta et al., 2001; Mukhopadhyay et al., 2009; Zanelli et al., 2011b) as well as from the industrial practice (Brusa and Bresciani, 1996; Lorici and Brusa, 1991; SACMI, 1986, 2001; Sánchez et al., 1997).

## 3. Ceramic tile technology

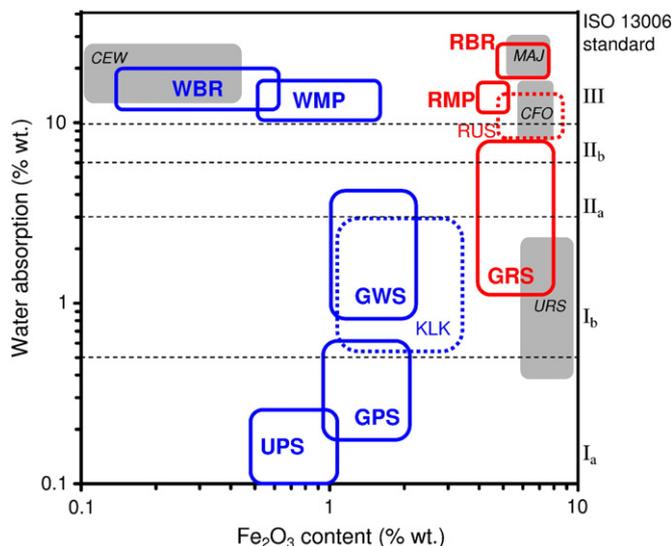
### 3.1. Ceramic tiles: types and classification

Ceramic tiles are classified by the ISO 13006 technical standard on the basis of water absorption: <3% (Group I), 3–10% (Group II) and >10% (Group III); groups I and II are divided in two subgroups each at the water absorption threshold of 0.5% and 6%, respectively (Fig. 1). The group code includes a letter which stands for the shaping technique: A for extrusion and B for pressing (Table 2).

In contrast, tile marketing is based on the end use: wall coverings (Group III and to a large extent II<sub>b</sub>) and floorings (Groups I and II<sub>a</sub>). Along with the end use, tiles are discriminated by the body color (a different product value is usually assumed for colored and colorless bodies). The resulting terminology is somehow related to the tilemaking technology and/or the ceramic material constituting the product, so creating a patchwork of names not easy to be understood (Table 2). Fig. 1 gives a picture of tile products, stemming from the above mentioned commercial and standard issues, by contrasting body color (mostly depending on iron oxide concentration) and body

**Table 1**  
Data sources of selected clay raw materials used in tile manufacturing.

Country	No.	Data sources
Italy	140	Andreola et al. (2009), Bertolani and Loschi Ghittoni (1989), Billi et al. (1992), Dondi (1999), Dondi et al. (1995a, 1995b, 2003), Fabbri and Dondi (1995), ICerS (1995–2010), Ligas et al. (1997)
Brazil	127	Alcântara et al. (2008), Correia et al. (2005), Dutra et al. (2006), Leite et al. (2007), Menezes et al. (2003), Moreno et al. (2009), Motta et al. (2001, 2004, 2008), Silva et al. (2009), Souza Costa et al. (2007), Vieira et al. (2006), Wilson et al. (2006)
Spain and Portugal	105	Bastida (1982a, 1982b), Bastida and Beltrán (1986), Bastida et al. (2006), Beltrán et al. (1996), Boix et al. (1994), Diaz Rodríguez and Torrecillas (2002), Dondi et al. (2003), Enrique and Bastida (1982), García-Tomás et al. (1996), ICerS (1995–2010), Jordán et al. (1999, 2001, 2009), Martin-Martin et al. (2006), Meseguer et al. (2011b)
Turkey	83	Celik (2010), Çigdemir et al. (2010), Dondi et al. (2003), Ece et al. (2003), Erkoyum and Kadir (2011), ICerS (1995–2010), Kadir and Akbulut (2009), Kadir and Kart (2009), Kadir et al. (2011), Karasu et al. (2004), Kartal and Metin (2004), Türkmenoğlu and Yavuz-İşik (2008), Yanik (2011), Yanik et al. (2010), Yavuz et al. (2011)
India, Bangladesh, Pakistan and Sri Lanka	68	Amritphale et al. (2006), Chandrasekhar and Ramaswamy (2007), Das and Mohanty (2009), Das et al. (2005), Das Kshama et al. (1992), Hettiarachchi et al. (2010), Joshi et al. (1993), Manoharan et al. (2012), Manju et al. (2001), Mukhopadhyay et al. (2003, 2010), Parveen and Jahan (2010), Saikia et al. (2003), Siddiqui et al., 2005
Germany	65	Dondi et al. (2003), Fabbri et al. (1989), ICerS (1995–2010), Kitagawa and Köster (1991), Petrick et al. (2011)
Africa	60	Abadir et al. (2002), Abdel-Aziz and Aly (2006), Andji et al. (2009), Bakr (2011), Diko et al. (2011), Djangang et al. (2008), Ekosse (2000), Felhi et al. (2008), Fentaw and Mengistu (1998), Gomes et al. (1994), Gouda et al. (2003), Hachani et al. (2012), Hajjaji et al. (2002, 2010), Heckroodt (1991), Jeridi et al. (2008), Kabre et al. (1998), Khalfaoui and Hajjaji (2009), Mahmoudi et al. (2008), Medhioub et al. (2010), Moussi et al. (2011), Naga et al. (1993), Ngon Ngon et al. (2012), Njoya et al. (2012), Nyakairu et al. (2002), Seynou et al. (2012)
Poland, Slovakia, Czech Republic and Baltic States	46	Daunoravičute et al. (1997), Galos (2011a, 2011b), Galos and Pietrzyk (2008), Galos and Wyszomirski (2006), ICerS (1995–2010), Kirov et al. (2011), Sedmale and Sedmalis (2000), Wilson (1998), Wilson and Jiranek (1995), Wyszomirski and Galos (2009)
Argentina	44	Alló et al. (1997), Alló and Murray (2004), Cravero et al. (1997, 2000), Domínguez et al. (2008, 2010), Dondi et al. (2008), Dristas and Frisciale (2003), Hevia et al. (2006), Zalba (1979), Zanelli et al. (2011a)
Ukraine	42	Dondi et al. (2003), Galos (2011a), ICerS (1995–2010), Il'ina et al. (2005), Naimo et al. (2000), Zanelli et al. (2011b)
Balkan countries	37	Christidis and Scott (1997), Djambazov et al. (2009), Ferrari and Gualtieri (2006), Galán et al. (1996), ICerS (1995–2010), Kirov et al. (2011), Mazza (1973), Petrov and Parvanov (1994), Radosavljevic et al. (1994), Sikalidis and Minopoulos (1994), Tsirambides (2004), Tsolis-Katagas and Papoulis (2004), Vasić and Slobodan (1988)
France and United Kingdom	37	Dondi et al. (2003), García-Tomás et al. (1996), ICerS (1995–2010), McCuiston and Wilson (2006), Scott et al. (1996), Wilson (1998)
Southeastern Asia	35	Ariffin et al. (2008), Aungatchart and Wada (2009), Bordepong et al. (2012), Ngun et al. (2011), Seli et al. (2013), Tontrakoon and Breen (1978), Wilson (1998), Wattanasiriwech et al. (2009), Worasith et al. (2011)
Middle East	32	Almohandis (1993), Ganji and Masoumi (2009), Kuparidze et al. (2012), Marghussian and Maghsoodipoor (1999), Mohsen and El-maghraby (2010), Saqqa et al. (1995), Taj et al. (2006)
Russia, Belarus and Central Asia	26	Gal'perina et al. (1971), Gal'perin et al. (1967), Gal'perina and Tarantul (1990), Goncharov et al. (2006), Il'ina et al. (2005), Kara-sal and Mongush (2005), Karikit and Sennikov (1997), Levitskaya et al. (2002), Levitskii et al. (1996, 1997), Mikhailova et al. (1998), Sergievich et al. (2012), Skidan et al., 1999, Zaykov and Udachin (1994)
China	25	He et al. (2012), Mitchell et al. (1991), Weni and Jianguo (2011), Wilson (2004), Zhang et al. (2013)
other Latino-American countries	22	Bertolani and Loschi Ghittoni (1986a), Guillén et al. (2012), Meseguer et al. (2010, 2011a), Pardo et al. (2011), Vázquez et al. (2009)
USA and Canada	21	Chávez and Johns (1995), Kontak et al. (2004), Wilson (1998)
Korea and Japan	8	Chung et al. (1977), Higashi (2000), Kitagawa and Köster (1991)



**Fig. 1.** Typologies of ceramic tiles (acronyms from Table 2) according to body color (mostly depending on the iron oxide content) and compactness (expressed by water absorption) and their classification in agreement with ISO 13006 standard.

compactness (expressed as typical values of water absorption). It can be seen that standard groups are not homogeneously populated neither as the number of products (much more in Groups III and I) nor in terms of body color (Group II is essentially represented by red bodies, while in Group I<sub>a</sub> there are exclusively colorless bodies).

### 3.2. Ceramic tile manufacturing

Ceramic tiles are currently manufactured by the wet or the dry route. A detailed description of tile manufacturing goes beyond the aims of the present paper. At any rate, a short outline of technology and its evolution is given hereafter (some relevant features are reported in Table 2) with reference to the five basic steps (Various Authors, 2000–2008):

- 1) *body preparation* involving wet ball milling or dry grinding of raw materials and powder agglomeration by spray drying (wet route) or granulation (dry route);
- 2) *tile shaping* mostly by dry pressing, but also extrusion is used;
- 3) *tile drying* by fast cycles in vertical or horizontal driers;
- 4) *tile glazing and decoration* by a large set of technological solutions;
- 5) *tile firing* by fast cycles in roller kilns (rarely chamber or tunnel furnaces).

Additional steps can be present, like end-of-line treatments (e.g., tile polishing, cutting or functionalization), while others may be shifted along the flow-chain (e.g., decoration can be performed during shaping).

A key-point is the technological innovation that has deeply changed each processing step in the last six decades, as it can be appreciated in Fig. 2:

*Body preparation* has been since long time improving starting by the introduction of the wet route: replacing to a large extent conventional hammer mills (#1 in Fig. 2) and granulation (#6) by spray driers (#7) and ball mills with upgrading from discontinuous (#2) to continuous (#3) then to modular mills (#4). Significant improvement has been recently achieved in the dry route too, by developing versatile and more efficient roller and pendular mills (#5) as well as by granulation systems of new generation (#9).

*Tile shaping* gained a great advantage by the adoption of hydraulic presses (#12) instead of mechanical ones (#11); the former have been continuously improved, getting more powerful and reliable machines able to produce even large size slabs. Novel shaping technologies

(e.g. dieless pressing) entered in use especially focused on low thickness and large size, e.g. 3x1 m slabs 3 mm thick (#13). Extrusion (#10) has been recently revitalized to manufacture big slabs with novel wet technology (#8).

*Tile drying* was converted from old-style chamber plants (#14) to vertical driers (#15) that in the last decade made progressively room for multichannel horizontal driers (#16) and even hybrid solutions, including infra-red heating (#17).

*Tile glazing* is still retaining conventional processes (application by bell, disk or doctor blade) that have been gradually automatized and improved, gaining in control and quality, and enriched by dry applications; the introduction of digitalized systems is envisaged. *Tile decoration* moved from traditional screen printing to silicon roller printing and soluble salts, till the recent spreading of ink-jet printing.

*Fast firing* is the trait of ceramic process that has been continuously improved by developing roller kilns (#20) that replaced tunnel furnaces (#18) and early kinds of fast firing plants, like plates or pegs kilns (#19). Roller kilns have gradually gained wider sections, turning multichannel (#21) and able to operate at higher temperatures (up to 1250 °C). Further steps go towards hybrid furnaces, as those fed by methane and electricity (#22).

### 3.3. Evolution of ceramic bodies with technological innovation

Technological innovation has strongly affected the use of raw materials, thus a look at the evolution of ceramic tile technology is fundamental to fully understand the changes occurred in bodies formulation along the last 60 years. Product and process innovation can be perceived through the historical evolution of ceramic tiles, mainly based on data from the Sassuolo district in Italy, that is leading the technological progress in this field (Fig. 3) and the Castellón district in Spain, besides some time lags (Corma, 2008). As a matter of fact, after the World War II a few types of ceramic tiles were on the market (Singer and Singer, 1963): essentially porous and glazed wall tiles (white body: *calcareous earthenware*; red body: *majolica*) while floor tiles were unglazed products mostly destined to industrial and outdoor applications: *stoneware* in its variants (red or white) manufactured by extrusion (*klinker*, *rustic cotto*) or dry pressing (red stoneware and fine stoneware). The main product innovation during the 1960s was the development of *cottoforte*, a glazed porous tile suitable for floorings, which switched the production towards floor tiles. The harsh energetic crisis during the 1970s compelled the ceramic industry to convert its process to a lower energy consumption, fostering the advent of fast firing in roller kilns, that turned step by step the whole tilemaking cycle into a new technology (involving wet milling > spray drying > dry pressing > fast drying and firing).

Such a novel technology, besides being much more flexible and efficient from the energetic point of view, proved to be unable to process the classic body formulations (*i.e.*, *majolica*, earthenware and stoneware) thus imposing drastic changes to batch compositions. This eventually gave rise, through an empirical approach, to new products: *monoporosa* (manufactured by fast single fire) and then *birapida* (by fast double fire) took the place of *majolica* or earthenware and are now dominating the field of porous tiles. As red *monoporosa*/*birapida* derived from *majolica*, white *birapida* arose from *calcareous earthenware* but, curiously enough, white *monoporosa* was developed starting from stoneware formulations.

The evolution of floor tiles was more complicated (Reh, 1991): first a *single-fired glazed red stoneware* was achieved by modifying unglazed stoneware and *cottoforte* batches (and it is still the reference product for semi-vitrified or vitrified red bodies). As the use of ball clays, instead of local red-firing clays, ensured several advantages, a shift to white bodies occurred during the 1980s (Bertolani et al., 1986). By this way, a *single-fired glazed white stoneware* was developed, starting from

**Table 2**  
Classification, basic requirements and firing schedule of ceramic tiles.

Body type	Water absorption % wt.	Class (ISO 13006)	Tile typology (commercial name)	Tile features			Tile type (acronym)	Minimum modulus of rupture MPa	Resistance to deep abrasion mm <sup>3</sup>	Typical firing schedule				
				body color	shaping	glaze				maximum temperature °C	duration cold-to-cold			
POROUS	>10	BIII AIII	Majolica	D	P	G	MAJ	15	no prescription (BIII) ≤2365 (AIII)	960–1050 (biscuit)	30–40 h (b.)			
			Calcareous earthenware Red birapida	L	P	G	CEW			1040–1060 (biscuit)	7–14 h (g.)			
				D	P	G	RBR			960–980 (glaze)	35–40 h (b.)			
				L	P	G	WBR			1030–1140 (biscuit)	12–14 h (g.)			
													1030–1150 (glaze)	30–50 min (b.)
														30–45 min (g.)
			White birapida	L	P	G	WBR		1100–1150 (biscuit & glaze)	40–50 min (b. & g.)				
			Red monoporosa	D	P	G	RMP		1070–1100	35–50 min				
			White monoporosa	L	P	G	WMP		1100–1140	40–50 min				
SEMI POROUS	6–10	BII <sub>b</sub> All <sub>b</sub>	Rustic cotto	D	E(P)	U	RUS	17.5 18	≤649 ≤540	950–1000	40–70 h			
			Cottoforte	D	P	G	CFO			980–1060 (biscuit)	38–40 h (b.)			
SEMI VITRIFIED	3–6	BII <sub>a</sub>	Red stoneware	D	P	G	GRS	18 (BII <sub>b</sub> ) 22 (BII <sub>a</sub> ) 30 (BI <sub>b</sub> )	≤540 (BII <sub>b</sub> ) ≤345 (BII <sub>a</sub> ) ≤175 (BI <sub>b</sub> )	960–980 (glaze)	12–14 h (g.)			
										1120–1160	20–50 min			
VITRIFIED	0.5–3	BI <sub>b</sub> AI	Klinker	L	E	U	KLK	23 30 30	≤275 ≤175 ≤175	1100–1200	40–70 h			
			Red stoneware	D	P	U	URS			980–1000	42–45 h			
			White stoneware	L	P	G	GWS			1170–1200	35–50 min			
HIGHLY VITRIFIED	<0.5	BI <sub>a</sub> AI	Porcelain stoneware	L	P	G	GPS	35	≤175	1190–1220	40–60 min			
			Porcelain stoneware	L	P(E)	U	UPS			1200–1230	45–75 min			
			stoneware											

Body color: D = dark-firing body; L = light-firing body. Shaping: P = pressing; E = extrusion. Glaze: G = glazed tile; U = unglazed tile.

fine stoneware formulations, turning to be the leading product in the 1990s. In the same period, a new floor tile type was launched: the *porcelain stoneware* (Sánchez et al., 2010). Thanks to its outstanding technical performances, it has rapidly got market shares to become now likely the most important tile product worldwide. Such a commercial success drew the implementation of the whole manufacturing route, providing substantial improvements in body preparation, shaping, thermal cycles, end-of-line treatments and particularly decoration. Porcelain stoneware, initially an unglazed floor tile for heavy traffic applications, has progressively gained esthetic value by a wide range of decoration techniques with the creation of glazed porcelain stoneware and special body types (e.g., polished, superwhite, translucent).

#### 4. Ceramic clays: composition and classification

The use of clays in tile manufacturing, hence their commercial classification, depends on the technological and appearance requirements of each kind of ceramic body: firstly the color after firing and secondly the behavior during the tilemaking process, involving properties like slip viscosity, plasticity, drying sensitivity, fusibility, pore-forming ability and so on, which are strictly connected with clay mineralogy and particle size distribution (Bal and Fiederling-Kapteinat, 2007; Dondi, 1999; Dondi et al., 2003; Stentiford, 2005).

First of all, ceramic bodies are distinguished in light-firing (from white to light brown) and dark-firing (from pink to dark brown) on the basis of color after firing. This color depends essentially on the iron oxide content, even if a certain role is played by further components (as TiO<sub>2</sub> and CaO) that may turn the color to yellowish or pinkish shades. Overall, clays used in light-firing and dark-firing bodies are fairly well discriminated by a Fe<sub>2</sub>O<sub>3</sub> content of approximately 3% wt. (Fig. 4). At any rate, such a threshold is somewhat related with technological properties: the iron content of a kaolin utilized to whiten a given body, for instance, is acceptable for values well below the limit (e.g., 1% Fe<sub>2</sub>O<sub>3</sub>); on the other hand, the iron oxide content of a bentonite, introduced in a small amount to improve the green bending strength, is tolerable even if slightly exceeding the limit. Further distinctions,

entailing the technological features of clays (rheological properties and behavior during grinding, compaction, drying and firing) will be outlined in the following paragraphs.

##### 4.1. Light-firing clays (LFC)

Light-firing clays encompass several commercial types going under the general terms of *kaolin* and *ball clay* (including *pyrophyllite* and to some extent *bentonite*) each referring to a wide range of mineralogical and granulometric characteristics. From the mineralogical point of view, they basically consist of phyllosilicates (mostly kaolinite) and silica phases (quartz and exceptionally cristobalite, tridymite and opal), although further components (feldspars, iron and aluminum oxyhydroxides, organic matter) may be present. Among clay minerals, along with kaolinite, also illite, interstratified I/S, halloysite, smectite, pyrophyllite, sericite, dickite, interstratified K/S, vermiculite and chlorite can be found in decreasing order of frequency.

Besides the general distinction between kaolin and ball clay (Harvey and Murray, 1997) these terms are used quite freely for commercial purposes regardless genetic, compositional or technological features (ICerS, 1995–2010). In practice, it often happens that similar raw materials be termed as “kaolin” or “ball clay” depending on the end-use; other clays, very different in composition and particle size, may be classified under the same term. For this reason, we propose a classification based on the following criteria: iron oxide content, amount of kaolinite group minerals (kaolinite, halloysite, dickite); percentage of quartz and other phyllosilicates (particularly pyrophyllite and expandable clay minerals: smectite + interstratified I/S), particle size distribution and plasticity (Atterberg consistency limits and Methylene Blue Index). By this way, low iron oxide clays (hence light-colored after firing) are distinguished by the amount of kaolinite group minerals into the following classes (Figs. 5 and 6):

>75% High-grade Kaolins (HK), characterized by high to very high amount of kaolinite and/or halloysite, may contain low amounts of illite-mica, Al-oxyhydroxides and non plastic

components (quartz, feldspars, rock fragments, titanium dioxide) each below 15%.

50–75% Low-grade Kaolins (LK), besides predominantly kaolinitic, contain from low to significant amounts of illite and/or interstratified I/S along with an always important non plastic portion, made up of quartz, feldspars, etc.

25–75% Ball Clays (BC) have an amount of kaolinite group minerals analogous to low-grade kaolins (although it can be below 50% in case of illite-rich materials). As a matter of fact, the overall mineralogical composition of BC overlaps to a large extent those of kaolins (Fig. 6). The distinction between low-grade kaolins and ball clays is here proposed in terms of plasticity (Fig. 5). Ball clays are distinguished from raw kaolins (when kaolinite content is <50%) by their large particle fraction below 2 μm, at least 40% by weight.

25–50% Raw Kaolins (RK) are basically deeply kaolinized parent rocks (in case of primary deposits) that contain a lot of non plastic components (particularly rock fragments, quartz, feldspars and mica). In any case, the amount of phyllosilicates must be high enough to bestow a sufficient, although low, plasticity on the raw kaolin to act as a clay material. Kaolinitic Loams (KL) are sedimentary deposits where kaolinite is admixed with an abundant non plastic fraction (mainly quartz) frequently accompanied by other clay minerals (smectite, interstratified I/S, illite, chlorite). Both raw kaolins and kaolinitic loams are characterized by a coarse-grained particle size distribution with often a significant sandy fraction (>25% over 63 μm).

<25% Light-firing clays poor in kaolinite and containing more than 20% of pyrophyllite or smectite constitute special cases, being classified as Pyrophyllitic Clays (PC) or White Bentonites (WB) respectively.

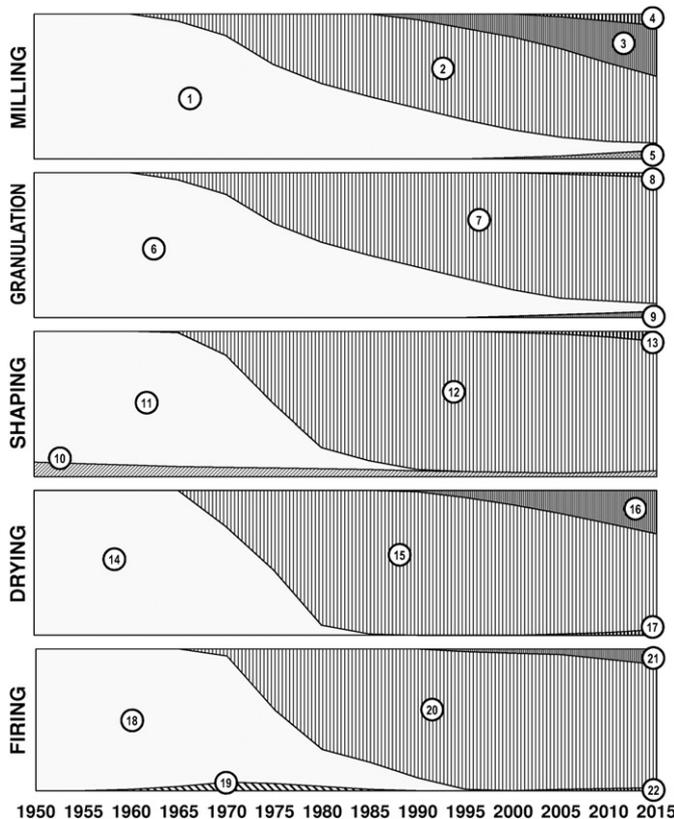


Fig. 2. Technological innovation in the main tilemaking stages (see text for explanation of numbered fields).

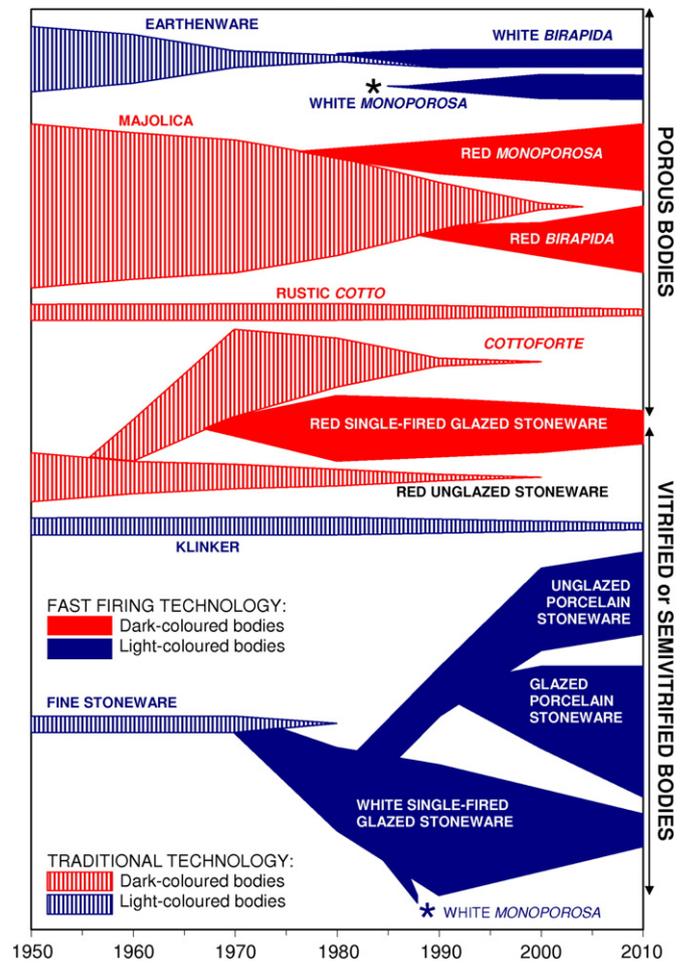


Fig. 3. Evolution of typologies of ceramic tiles with technological innovation.

4.1.1. High-grade Kaolins (HK)

In ceramic tile manufacturing, high-grade kaolins are easily dispersible in water, but difficult to press and highly refractory, enhancing the formation of mullite and whiter shades during firing. More refractory terms often need to be milled in order to exhibit a plastic behavior, so presenting analogies with flint clays (Keller, 1968). HK are typically used in low amounts: a few percent in glazes and engobes (to thicken and stabilize suspensions) and no more than

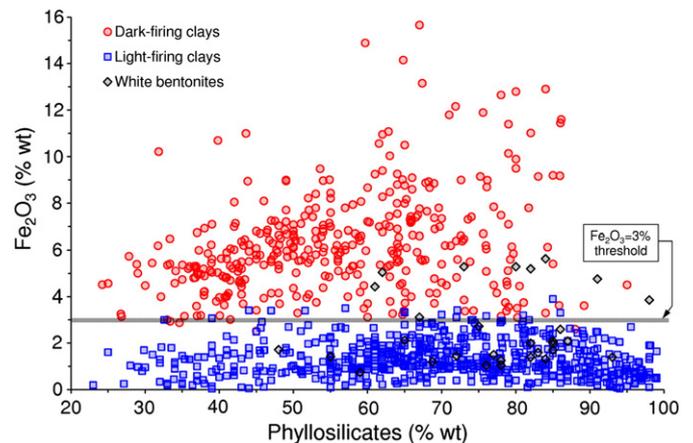


Fig. 4. Content of phyllosilicates and iron oxide in clays whose declared use is in dark-firing and light-firing bodies.

10–15% in porous and vitrified bodies (unglazed porcelain stoneware and white birapida). Examples of HK used in tilemaking are kaolins from Cornwall, UK (Bristow, 1993; Scott et al., 1996) and Bayern, Germany (Keck, 1991; Kitagawa and Köster, 1991) or some grades from Kütahya, Turkey (Kadir et al., 2011; Yanik, 2011).

#### 4.1.2. Low-grade kaolins (LK)

The behavior of low-grade kaolins in the ceramic cycle is influenced by components associated to kaolinite in the plastic and non plastic fractions. For instance, the technological performance of the materials higher in kaolinite and poor in feldspars and expandable clay minerals does not substantially differ from that of high-grade kaolins, although their use is restricted to vitrified and porous bodies (usually in percentages larger than HK) being generally not utilized in engobes and glazes. When the amount of kaolinite group minerals approaches 50%, the technological behavior is clearly different from that of HK, due to the increased non plastic fraction, implying lower plasticity and confirming difficulties in pressing and sintering. However, these limits can be to some extent overcome by the occurrence of feldspars (enhancing fusibility and fostering sintering) and expandable clay minerals (improving plasticity). At any rate, the LK class defines clays with a rather low plasticity ( $MBI_a < 7.5$ ). Examples of LK used in tilemaking are kaolins from Santa Severa, Italy (Costa et al., 1996) or Sinitza and Dedovka, Belarus (Levitskii et al., 1997; Sergievich et al., 2012) and some grades from Muang Ranong, Thailand (Bordeepong et al., 2012; Worasith et al., 2011).

#### 4.1.3. Raw kaolins (RK)

The utilization of raw kaolins in tilemaking is not straightforward, so it is frequently disregarded. As a matter of fact, raw kaolins cannot fulfill ordinary requirements for ceramic clays, especially due to their poor plasticity. However, RK may play as a sort of mix, thanks to comparable amounts of kaolinite, quartz and flux (feldspars, rock fragments) whose technological behavior has to be balanced by the other clays and fluxes making up the body. The addition of raw kaolin turns to be useful particularly when the distance from mine to tile factory is short, so permitting to have a low cost. Examples of RK used in tilemaking are raw materials from Romana (Ligas et al. 1997) and Piloni di Torriella, Italy (Bertolani and Loschi Ghittoni, 1989; Viti et al., 2007) or Michoacán, Mexico (Guillén et al., 2012).

#### 4.1.4. Kaolinitic loams (KL)

Some sedimentary deposits utilized by the ceramic industry contain, as the raw kaolins, an abundant non plastic fraction, mainly consisting of quartz with some feldspars and sometimes carbonates. These clay materials are here named *kaolinitic loams* due to their coarse grain size distribution, strongly affecting their technological behavior. This can be described as a compromise between coarse grain size and relatively high plasticity, due to the frequent occurrence of expandable clay minerals together with kaolinite. Such a peculiar composition turns KL a rather versatile raw material, that can be addressed to vitrified bodies up to 20–25%. Examples of KL used in tilemaking are Italian clays from Lozzolo, Piedmont (Fiori and Fabbri, 1987) and Florinas, Sardinia (Danasio and Di Primio, 1995).

#### 4.1.5. Ball clays (BC)

According to the classical definition “*Ball clay is a fine-grained, highly plastic, mainly kaolinitic sedimentary clay, the higher grades of which fire to a white or near white colour*” (Wilson, 1998). In reality, in ceramic tile production such a definition is stretched to cover a proper (or even a just acceptable) behavior during wet milling, pressing and sintering, regardless of compositional features. As a consequence, an outstanding range of compositions and technological properties goes under the commercial term of “ball clay” (ICerS, 1995–2010). In practice, BC used in tilemaking plot over almost the entire Kaolinite–Illite–Quartz + Feldspar ternary diagram (Fig. 6) implying wide ranges of kaolinite (20–80%), illite (0–60%), quartz (0–60%) and feldspars (0–30%) concentrations. Expandable clay minerals (mostly interstratified illite-smectite and sometimes smectite) are common components that can reach 25% and, although they are not always present, may affect significantly plasticity and behavior during pressing and drying. Other components include iron oxyhydroxides (usually below 2%, even if slightly higher amounts may be tolerated) and organic or carbonaceous matter (commonly in the 0.1–0.7% range). Further minerals (e.g., pyrophyllite, interstratified K/S, chlorite, gibbsite, carbonates) are sometimes present in low amount. Particle size distribution is in most cases fine-grained with the clay fraction over 50% and frequently over 75%. However, some raw materials going under the term “ball clay” exhibit a rather coarse grain size with the silty fraction over 50% (Fig. 7). Overall, these large sets of mineralogical and granulometric data reflect into wide ranges of technological properties of BC, entailing plasticity and behavior during compaction, drying and firing. Ball clays are characterized by a wide range of  $MBI_a$ —going from 8 to 40 meq/100 g (Dondi

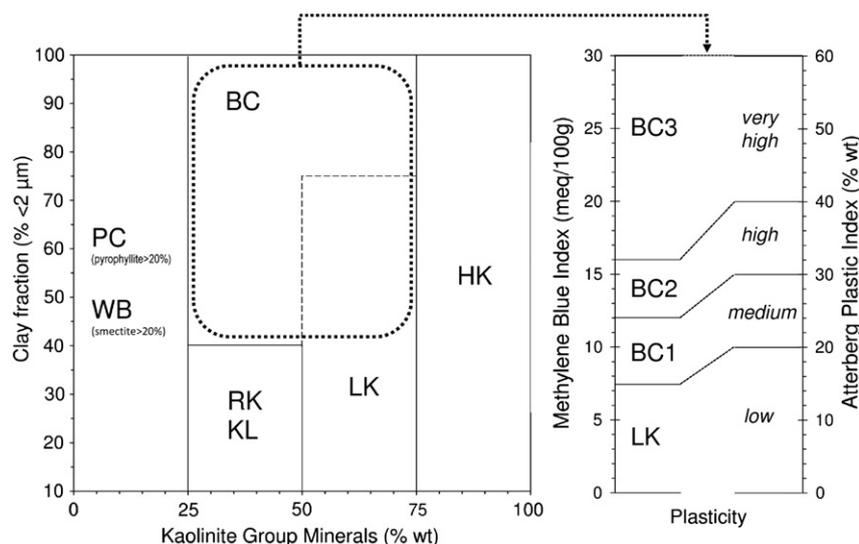


Fig. 5. Classification of light-firing clays according to their amount of kaolinite group minerals and clay fraction as well as their Methylene Blue Index at pH ~ 4 ( $MBI_a$ ) or Atterberg Plastic Index.

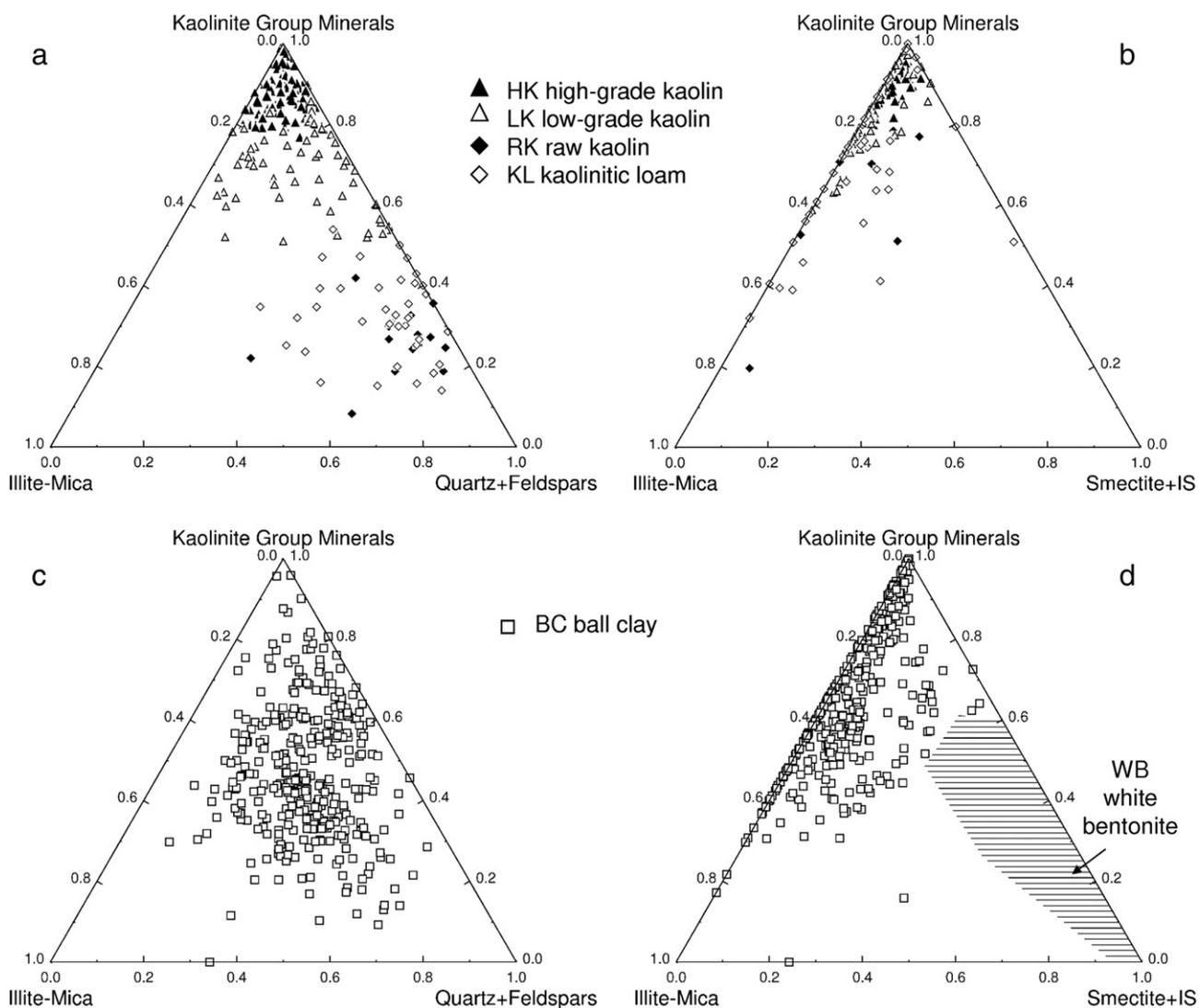


Fig. 6. Mineralogical composition of light-firing clays for ceramic tiles.

et al., 2003, 2008; Wilson, 1998)–with on the whole higher values with respect to LK. This picture allows to classify LFC according to the technological performance (Fig. 5): low plasticity clays (MBI < 7.5; typically kaolins: HK, LK, RK); medium plasticity clays (7.5 < MBI < 12; BC1); high plasticity clays (12 < MBI < 16; BC2); and very high plasticity clays (16 < MBI < 30; BC3 and some WB); extremely high plasticity occurs only in bentonites among ceramic raw materials. These limits are traceable to the technological behavior in tilemaking and differ from established reference schemes (Polidori, 2003 and references therein). There are many examples of BC used in tilemaking (McCustion and Wilson, 2006): clays from Westerwald, Germany (Marx and Henniecke, 1986; Petrick et al., 2011); Donbass, Ukraine (Fiederling-Kapteinat et al., 2000; Naimo et al., 2000); Santa Cruz, Argentina (Domínguez et al., 2008).

#### 4.1.6. Pyrophyllitic clays (PC)

Some clay materials used in ceramic tile production are characterized by the occurrence of pyrophyllite, from a few percent up to 80% wt. Since pyrophyllite has a different technological behavior with respect to kaolinite, it is convenient to classify as *Pyrophyllitic Clays* (PC) the raw materials with a significant amount of pyrophyllite (>20%) as they present commonly lower loss on ignition, easier compaction, and lower refractoriness with respect to kaolins (Mukhopadhyay et al., 2009; Sánchez-Soto and Pérez Rodríguez, 1998). PC are usually claystones of

different origin that, along with pyrophyllite, contain quartz, feldspars and often kaolinite and/or illite or sericite. Pyrophyllitic clays can replace BC in many applications and are used in tilemaking especially in India (Das and Mohanty, 2009; Mukhopadhyay et al., 2010) and Argentina (Dristas and Friscale, 2003; Zalba, 1979), being *roseki* in Japan and Korea (Higashi, 2000; Matsuda et al., 1981).

#### 4.1.7. White bentonites (WB)

Clays with a high amount of smectite (frequently over 50% wt, Fig. 6) and a relatively low iron content ( $\text{Fe}_2\text{O}_3$  at max 6%, but preferably below 2%) are used in tilemaking as additives to enhance plasticity of too lean bodies. This kind of clay materials is commonly referred to as *White Bentonites*, although the firing color of the terms richer in iron is rather dark. Quite complex mineralogical assemblages are common: smectite together with other phyllosilicates (interstratified I/S and less frequently kaolinite or illite), silica phases (quartz, cristobalite, tridymite, opal), feldspars, volcanic glass and rock fragments. The use of WB in tilemaking is substantially addressed to increase the mechanical strength of unfired bodies, though their maximum tolerable amount is constrained by rheological properties during wet milling and spray-drying (smectite induces a sharp increase of slip viscosity and thixotropy) as well as by drying sensitivity (Andreola et al., 2009). These technological constraints make it preferable to have WB with not too much smectite and particularly with a moderate activity

(i.e., Ca-exchanged terms). Examples of WB used in tilemaking are from Italy (Andreola et al., 2009), Greece (Christidis and Scott, 1997) and Argentina (Alló and Murray, 2004; Cravero et al., 2000; Zanelli et al., 2011a).

#### 4.2. Dark-firing clays (DFC)

Red-firing clays are commonly gathered in a single category, so implying a very wide variation range in terms of mineralogical composition, particle size distribution and technological behavior. From the mineralogical point of view, DFC consist predominantly of phyllosilicates (from 35% to over 90%) associated with quartz (up to 50%), carbonates (up to 50%), feldspars and rock fragments (up to 40%), iron oxyhydroxides (up to 15%), and minor components depending on the origin of clay deposits (organic matter, sulfides, sulfates, etc). Particle size distribution can span from silty clays to clay silts and loams, with the <2  $\mu\text{m}$  fraction ranging from 20 wt.% to 80 wt.%.

However, the main parameters considered in the industrial practice are:

- the occurrence of carbonates, which play a complex role during firing, entailing the formation of a small-sized porosity, as of new crystalline phases (e.g., plagioclase, pyroxene, and melilite) controlling firing shrinkage, thermal and moisture expansion, and making the production of net-shaped tiles feasible (Billi et al., 1992; Dagounaki et al., 2008).
- The degree of lithification may affect, depending on the milling process, both particle size distribution and plasticity, therefore the behavior during shaping and sintering. A strongly lithified material (e.g., a shale) may change significantly its ceramic behavior according to its grain size distribution, being classified as *clay* or *loam* depending on the degree of milling (Alló et al., 1997).
- The so-called ‘fusibility’, or more properly the critical temperature at which sintering begins to run by viscous flow of the amorphous phase formed at high temperature. It discriminates easily sintered (self-sintering or vitrifying) clays from more refractory ones.

The criteria followed in the classification of DFC are: iron oxide content (the 3%  $\text{Fe}_2\text{O}_3$  threshold already mentioned for LFC), amount of carbonates, coarse-grained fraction (>63  $\mu\text{m}$ ), amount and type of phyllosilicates (the terms richer in expandable clay minerals are not suitable for the wet route), plasticity by Atterberg consistency limits

(MBI values are just seldom available for DFC). Overall, these criteria allow to distinguish the iron-rich clays in the following classes (Fig. 8):

##### 4.2.1. Marly Clays (MC) and Carbonatic Clays (CC)

Calcite and dolomite are common constituents of many ceramic clay materials and their amount spans from absent to over 40%. A lower threshold is here proposed at 10% carbonates (calcite + dolomite) to define the field of *marly clays*. Although to a certain extent arbitrary, this threshold actually discriminates clay materials whose main use is in wall tiles. However, in the body formulation for wall tiles, particularly in the case of monoporosa technology, the maximum amount of a given clay depends primarily on its content in calcite and dolomite: the lower the carbonates percentage, the higher the amount of clay that can be used. For this reason, it is proposed also an upper threshold at 30% of carbonates that define *carbonatic clays* whose use is generally restricted as a minor component in monoporosa and especially birapida tiles. MC and CC are overall characterized by the most complex mineralogical composition among ceramic clays, where different types of phyllosilicates (commonly illite, chlorite, smectite plus minor kaolinite and interstratified terms), carbonates and quartz are all present in significant amounts (Fig. 9). From the granulometric viewpoint, MC range from silty clays to clay silts with a low sandy fraction (Fig. 10). Typical carbonate-bearing clays used in tilemaking are from Castellón, Spain: for example the Mas Vell (MC) and Araya (CC) clays (Bastida and Beltrán, 1986; Meseguer et al., 2011b; Sánchez et al., 1997) or the Ranzano Fm in Sassuolo for MC (Dondi, 1999).

##### 4.2.2. Red Clays (RC)

Red clays (RC) practically include every iron-rich clay material with  $\text{Fe}_2\text{O}_3$  over 3%, carbonates below 10% and a coarse-grained fraction below 25%. These thresholds define an extremely wide space, both in terms of mineralogical composition and particle size distribution, that as a consequence reflects into different technological behaviors. The phyllosilicates-to-quartz + feldspars ratio can vary greatly, implying that RC can contain a non plastic portion up to 70% (Fig. 9) spread in different way over the silty and sandy fractions (Fig. 10). Furthermore, RC are commonly complex mixtures where 3 to 5 groups of clay minerals (kaolinite, illite, smectite, interstratified terms and chlorite, sometimes pyrophyllite and vermiculite) coexist in the same raw material (Fig. 9). Besides this complicated compositional picture, no distinctions are practiced in the industrial production beyond that of

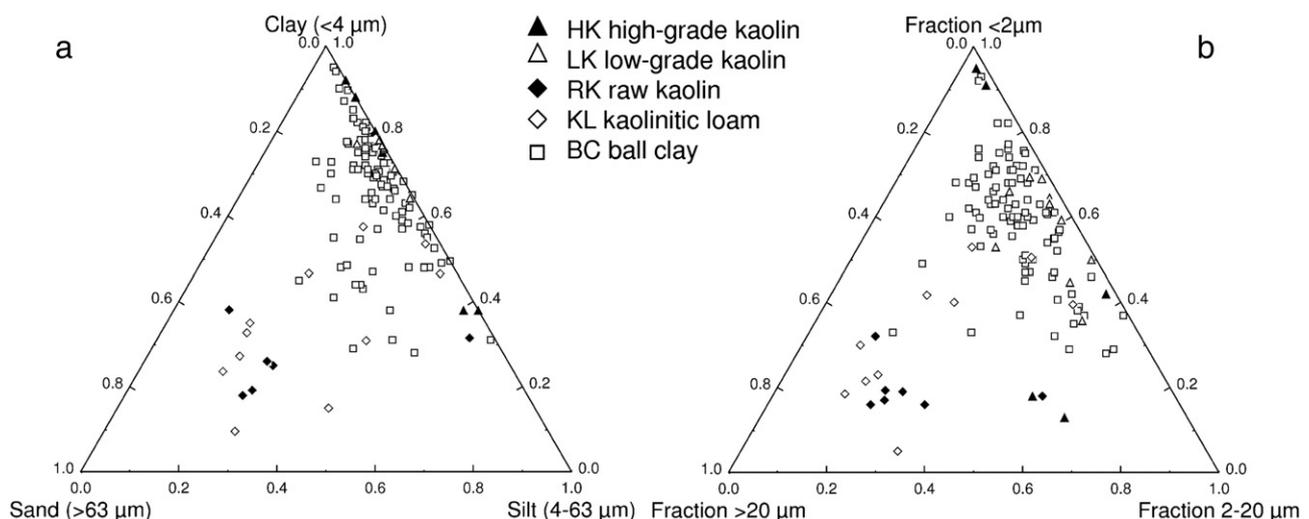


Fig. 7. Particle size distribution of light-firing clays for ceramic tiles.

**Red Clays.** In order to fill this gap, a classification is here proposed in terms of phyllosilicate assemblages (Fig. 8):

- predominantly *kaolinitic red clays* (RC1) where kaolinite group minerals represent over 50% of the total of phyllosilicates; the amount of chlorite or expandable clay minerals is always below 20%.
- Prevalently *illitic red clays* (RC2) where illite-mica terms are over 50% of phyllosilicates and the amount of smectite, interstratified IS and chlorite is within 20%.
- Mixed types like *illite-chlorite red clays* or *illite-smectite red clays* (RC3) where the amount of chlorite and/or expandable clay minerals associated to illite is over 20% of the total of phyllosilicates.

Different technological behaviors are expected for these red clay types: the RC1 grades richer in kaolinite are rather plastic and refractory (somehow approaching the definition of *fireclay*) besides significant amounts of sandy fraction are frequent. Illite-rich RC2 terms are in many cases silty clays, quite fusible but with a poor to moderate plasticity. RC3 are mostly silty clays, highly fusible, with moderate plasticity in case of chlorite-rich terms (Carretero et al., 2002) to high plasticity of the smectite-rich grades. For all types, the plastic behavior is also heavily affected by the amount of non plastic component.

Examples of red clays used in tilemaking are those from Neuquén, Argentina, for RC1 (Cravero et al., 1997); Villar and Chulilla clays from Castellón, Spain, for RC2 (Bastida, 1982a, 1982b; Bastida and Beltrán, 1986); and for RC3 the Corumbataí Fm, Brazil (Christofolletti and Moreno, 2004; Motta et al., 2005) and various red shales from the Sassuolo district in Italy (Dondi, 1999; Fiori, 1996).

#### 4.2.3. Red Loams (RL)

Red loams (RL) represent substantially a special case of red or marly clays with an abundant coarse-grained fraction (over 25% >63 µm, Fig. 10). This sandy component typically consists of quartz, feldspars and rock fragments. The clay fraction is frequently a mix of illite, kaolinite and chlorite, with expandable clay minerals sometimes present. Such a peculiar composition turns RL especially suitable for extruded products and not surprisingly they are extensively used in the manufacturing of heavy-clay products (Fabbri and Dondi, 1995). In tilemaking, RL are typically utilized in the manufacture of rustic tiles, but in proper amounts they may be added practically to every type of red tile bodies in total or partial replacement of filler (Kayaci et al., 2010). Red loams are exploited, for example, in Tuscany and Piedmont, Italy (Bertolani and Loschi Ghittoni, 1986b, 1990; Malesani, 1992) as well as in the Teruel basin, Spain (Bastida et al., 2006; García-Tomás et al., 1996).

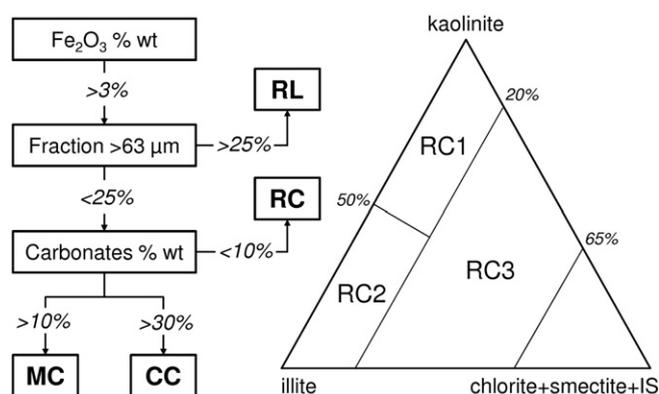


Fig. 8. Classification of dark-firing clays according to their coarse-grained fraction, amount of carbonates and clay minerals.

## 5. Ceramic bodies: formulation and design criteria

In the design of body recipes for ceramic tiles, four basic ingredients are necessary:

- Clay, stabilizing suspensions (in the wet route), ensuring the plasticity necessary for shaping, and bestowing mechanical strength on unfired tiles; during firing clay acts as flux (e.g., illite) or mullite precursor (e.g., kaolinite).
- Flux, forming a liquid phase at high temperature that allows to densify the ceramic body by a viscous flow; feldspars are the typical flux, but sericite, feldspathoids, and further raw materials are utilized too.
- Filler, providing a coarse-grained structure (so-called *skeleton*) contrasting deformations during drying and firing; the most common filler is quartz sand, though chamotte or other sand types are sometimes used.
- Additives, like a *pore-forming agent* which develops porosity during firing and fosters sintering by surface diffusion (role frequently carried out by carbonates); other additives are pigments, opacifiers and sintering promoters.

Technological innovation has been increasing the flexibility of tilemaking processes, so allowing the preparation of ever more complex batches, that usually include up to a dozen different raw materials. It is common in the industrial practice to use more than one source of clay, flux and filler in order to damp any fluctuation in composition and technological properties. Body formulation is focused on both technological behavior and technical performance of finished products, thus it is strictly connected with *key properties* of each typology of ceramic tiles. About the behavior during the tilemaking process, the following key properties are particularly stressed:

- rheological properties of slips, in the wet route, that affect dramatically the efficiency of milling and spray drying (Andreola et al., 2009);
- bending strength of unfired tiles that must be high enough (usually >4 MPa) to withstand wet glazing and mechanical stress of screen printing (this latter requirement can be relaxed in case of non contact decoration, e.g. by inkjet printing);
- porosity and linear shrinkage that must match the target after a proper firing schedule;
- absence of bulk or surface defects (black core, planarity, glaze appearance, etc).

The technical performances refer to the prescriptions of the international standard ISO 13006 for each tile typology; particularly relevant are the following:

- water absorption to fit the window of acceptance for each class (Fig. 1);
- modulus of rupture and resistance to deep abrasion according to each class (Table 2);
- coefficient of thermal expansion (CTE) that ensures the body-glaze thermodynamic matching, so preventing crazing defects;
- resistance to moisture expansion in order to prevent damages to floorings and wallings (Hall and Hoff, 2012).

Furthermore, the body color after firing is an important commercial aspect.

The criteria of body formulation will be outlined, for simplicity sake, by identifying three broad categories: porous bodies (WBR, WMP, RBR and RMP typologies); semi-vitrified and vitrified red bodies (GRS); vitrified light-firing bodies (GWS, GPS, UPS); roughly corresponding to BIII, BII and BI classes of the ISO 13006 standard, respectively. However, account must be taken that multipurpose bodies are sometimes designed by the industry: a single batch can be formulated to produce two different typologies (e.g., BIII or BII<sub>b</sub>; BII<sub>a</sub> or BI<sub>b</sub>) just changing the processing parameters (Brusa and Bresciani, 1996; Dondi et al., 2001; Kara et al., 2006).

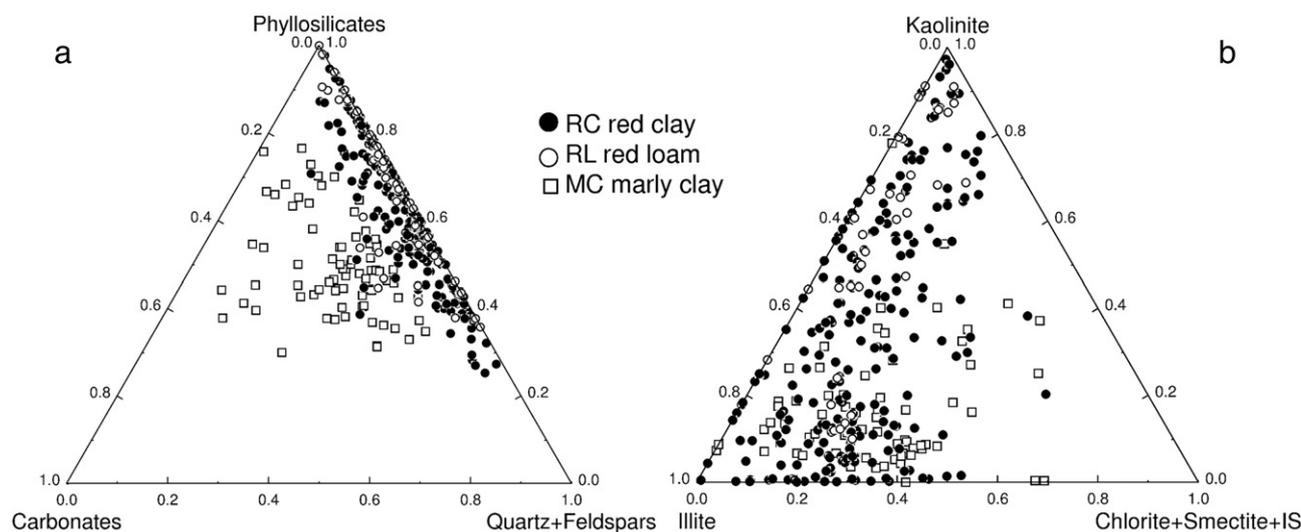


Fig. 9. Mineralogical composition of dark-firing clays for ceramic tiles.

### 5.1. Porous bodies

Porous bodies (water absorption >10%) are addressed to wall tiles that are manufactured by either the *monoporosa* technology (fast single firing) or the *birapida* technology (fast double firing) for both colored bodies (RMP and RBR) and white bodies (WMP and WBR). Industrial firing schedules are typically running at 1000–1140 °C of maximum temperature with 30–45 minutes cold-to-cold.

Porous bodies are designed to get net shape tiles, whose final dimensions are the same of the mold used for pressing. As a consequence, drying and firing shrinkages must be very low, never exceeding 1 cm/m. Porosity is constrained by the minimum bending strength required, that is 15 MPa. As porous bodies are always glazed, special care is needed to ensure the body-glaze thermodynamometric matching, by controlling both CTE ( $\alpha_{20-400}$  °C typically in the 6.5–8.0  $\text{MK}^{-1}$  range) and moisture expansion (recommended <0.1%).

This overall target is easier accomplished with calcium-rich bodies that promoting the formation of Ca–Mg silicates (plagioclase, pyroxene, melilite, etc) during firing result stronger and more stable to moisture than low calcium bodies even with a high porosity. A detailed description of phase transformations occurring during the

thermal treatment of carbonatic clays and porous bodies can be found in the literature (Dondi et al., 1995a, 1998, 1999a, 1999b; González-García et al., 1990; Hajjaji and Mezouari, 2011; Jordán et al., 1999, 2001, 2008, 2009; Kacim and Hajjaji, 2003; Serra et al., 2013; Trindade et al., 2010).

There are three main routes to design proper porous bodies (Tables 3 and 4):

- P1 by using carbonate-bearing clays (MC and CC);
- P2 by adding calcite or dolomite to the batch;
- P3 by introducing Ca or Ca–Mg raw materials different from carbonates.

Route P1 is commonly adopted for red bodies; only when no suitable carbonate-bearing clay is available, route P2 is followed to get RMP and RBR tiles. White bodies are always manufactured by route P2, but when neither calcite nor dolomite are available (or large size, high quality WMP tiles have to be produced without carbonates). In these cases, route 3 opens a wide range of solutions in terms of alkaline-earth oxides-bearing raw materials: wollastonite, diopside, talc, synthetic silicates (including frits and glass–ceramic systems).

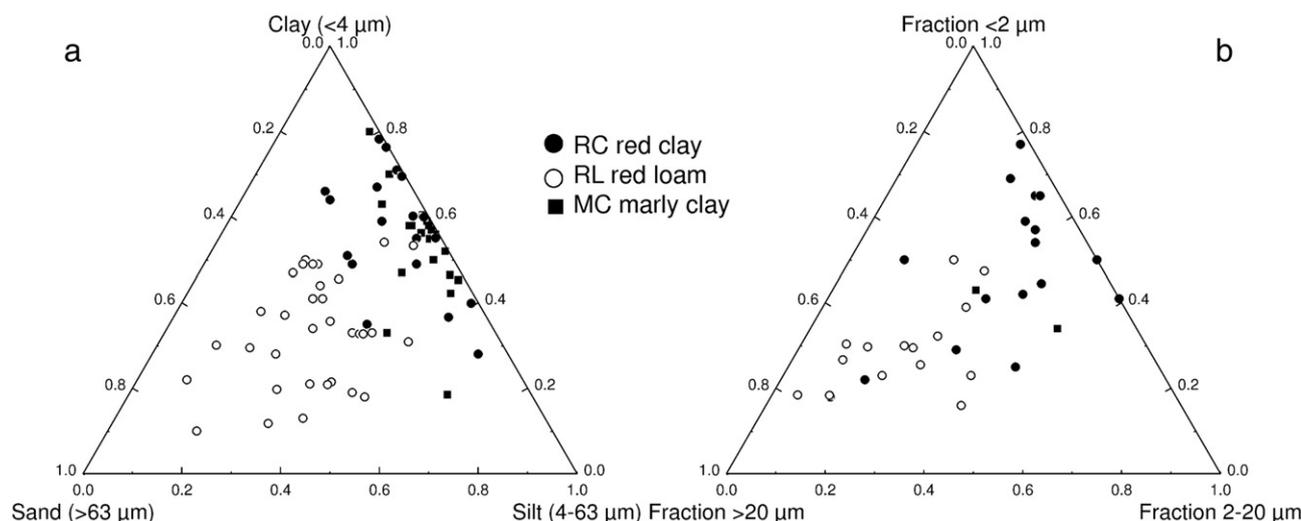


Fig. 10. Particle size distribution of dark-firing clays for ceramic tiles.

**Table 3**  
Examples of batch formulation for light-firing bodies.

Tile typology		Clay raw materials (wt.%)				Other components (wt.%)		
		HK-LK	KL-RK	BC	PC	Pore-forming	Filler	Flux
White Monoporosa	WMP1			50–75		10–15 <sup>C</sup>	10–40	0–10
	WMP2		20–30	30–40		7–10 <sup>C</sup>	15–25	5–10
	WMP3	20–40		30–50		8–12 <sup>C</sup>	0–20	
	WMP4	10–20	10–15	20–30	25–40	5–20 <sup>W</sup>		0–20
White Birapida	WBR1	10–20	10–20	20–30		10–20 <sup>C</sup>	20–30	
	WBR2	10–20	10–20	20–30		5–10 <sup>C</sup>	30–40	
	WBR3	15–35	10–15	15–45			30–40	10–20
	WBR4	0–10		30–50		5–20 <sup>W</sup>	5–10	25–35
Glazed White Stoneware	GWS1	10–20	15–25	10–15			10–15	30–45
	GWS2	0–20	0–20	10–35			10–30	35–50
	GWS3	0–20	0–20	0–30	20–40			30–40
Porcelain Stoneware	PSW1	35–45		12–18			12–18	27–32
	PSW2	12–18		27–32			5–10	42–48
	PSW3			30–40			5–15	45–55
	PSW4	0–10	10–20	10–30			5–15	40–50
	PSW5	0–20	0–20	0–20	20–40		0–10	40–50

Pore-forming agent: C = carbonates (calcite and/or dolomite); W = wollastonite.

In any case, the expected color of fired body is white for WMP and especially WBR ( $\text{Fe}_2\text{O}_3$  of the batch is usually <1%, at most 2% wt dry-basis). Although there is no emphasis on color for RMP and RBR, the  $\text{Fe}_2\text{O}_3$  content of fired bodies is usually from 4 to 6% (at maximum 8% wt). Porous tiles produced by the wet route (particularly white bodies as well as many red monoporosa plants) preclude the use of raw materials with abundant expandable clay minerals (BC3 and some RC3 and MC cannot be utilized as main components).

#### 5.1.1. Monoporosa technology

Monoporosa technology allows to fire at the same time body and glaze, with conspicuous advantages in terms of cost and productivity. However, calcite thermal decomposition occurs, due to the fast firing cycle, at rather high temperatures and may overlap glaze melting; if  $\text{CO}_2$  released from  $\text{CaCO}_3$  breakdown passes through a melted glaze, it will cause defects (pinholes). In order to prevent pinholes, the kinetics of calcite (or dolomite) breakdown has to be accelerated by: i) reducing the carbonate particle size, ii) fostering the gas permeability (lower bulk density of unfired tile by lower load at the press) and iii) limiting the carbonate amount of the batch. For this purpose, carbonates in monoporosa bodies are constrained to 7–12 wt.% (at most 15%). It implies that MC have to be within ~60% of RMP batches (much less in

the case of CC) with some RC together with filler or RL to control gas permeability (Kayaci et al., 2010). Filler is privileged in Italian-style bodies (Fig. 11 and RMP1–2 in Table 4) while RL is preferred in Spanish-style batches (Fig. 11 and RMP3). WMP bodies were derived from stoneware batches and for this reason their formulation may contain low-grade kaolins and kaolinitic loams, along with ball clays or pyrophyllitic clays, together with significant amounts of filler and fluxes (Fig. 12 and WMP3–4 in Table 3).

#### 5.1.2. Birapida technology

Birapida technology was developed to overcome the technological constraints of monoporosa, making simpler – besides the additional cost of a second fire – the production of porous tiles. As the body is first fired without glaze, the amount of carbonates in the batch can be higher than 12–15%, although percentages over 20% (that were common in the traditional majolica and calcareous earthenware industry) are not recommended. RBR batches came from majolica formulations: they are based on 60–80% marly clays corrected by some red clays, with little filler or RL, as there is no gas permeability requirement. If CC are utilized, a higher amount of RC is necessary. The main distinction between RBR and RMP bodies, in fact, is the higher amount of MC and the often lower percentages of filler and flux

**Table 4**  
Examples of batch formulation for dark-firing bodies.

Tile typology		clay raw materials (wt.%)				Other components wt.%)		
		MC	CC	RC	RL	Pore-forming	Filler	Flux
Red Monoporosa	RMP1	50–60		10–20			15–20	0–10
	RMP2		20–40	30–50			20–40	0–10
	RMP3	35–45		40–50	15–25			
	RMP4	20–25	15–20	40–60	0–20			
	RMP5			40–60	20–50	7–12	0–20	
Red Birapida	RBR1	70–80		10–20			0–20	
	RBR2	60–70		20–30	0–20		0–20	
	RBR3		20–40	40–50	0–20		0–20	
	RBR4			60–80	0–20	10–20	0–20	
Glazed Red Stoneware	GRS1			65–80			10–25	15–20
	GRS2			60–80	20–40		0–10	
	GRS3			60–70	10–20			10–15
	GRS4			90–100			0–20	
	GRS5	5–15		65–80			0–20	
Rustic Cotto	RUS1				100			
	RUS2			70–90			10–30	

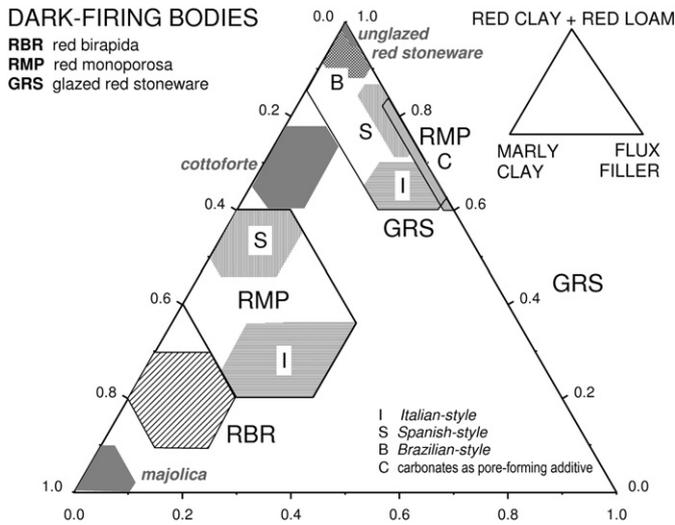


Fig. 11. Batch formulations of dark-firing bodies.

(Fig. 11). On the other hand, WBR derived from calcareous earthenware batches, so still make use of kaolins, large amounts of filler and sometimes fluxes. WBR bodies exhibit both a higher kaolin-to-ball clay ratio and larger amounts of filler with respect to WMP batches (Fig. 12). Pyrophyllite-bearing batches are often fluxed by wollastonite without carbonates (e.g. WBR4 in Table 3).

5.2. Vitrified and semi-vitrified red bodies

Vitrified and semi-vitrified red-firing bodies are utilized for floor tiles that fall in the BI<sub>b</sub> and BII<sub>a</sub> classes (water absorption 0.5–3% and 3–6%, respectively); semi-porous bodies with water absorption 6–10% (BII<sub>b</sub>) are addressed, along with floorings, to wall coverings. This large set of products goes under the commercial name of red stoneware with its variants (glazed, unglazed, rustic) regardless of the BI<sub>b</sub>, BII<sub>a</sub> or BII<sub>b</sub> classification. Red stoneware is manufactured by fast single firing at 1120–1180 °C of maximum temperature in 20 to 50 min cold-to-cold. Sometimes rustic tiles are processed by slow single firing of heavy-clay industry (Table 2). Red stoneware is nowadays produced

by the dry route more frequently than by the wet route (Motta et al., 2004). It is almost always glazed; only rustic tiles and some low porosity tiles for outdoor applications (BI<sub>b</sub>) are unglazed.

Mineralogical transformations occurring during the firing of low porosity red bodies are generally simpler than those of carbonate-bearing batches. In fact, they essentially entail the breakdown of clay minerals (with formation of new crystalline phases: mullite and less frequently sanidine, spinel, olivine) and feldspars (with development of a more or less abundant vitreous phase). Hematite crystallization from Fe-oxyhydroxides is a distinctive feature of these bodies (Hajjaji et al., 2002; Jordán et al., 2008; Khalfaoui and Hajjaji, 2009; Pardo et al., 2011; Trindade et al., 2010).

The main concern in the design of red stoneware bodies is to fit the standard target (water absorption, mechanical strength, etc) with firing schedules that must be as faster (best 40 min or less) and as colder (best 1170 °C or less) as possible. Firing shrinkage must be within 6 cm/m (BII) or 9 cm/m (BI<sub>b</sub>) as firing deformations must be kept under strict control. For this purpose it is useful to have a certain quartzous skeleton (typically 20–30%) which also helps to get the correct CTE (7–8 MK<sup>-1</sup>). Different properties are expected for bodies processed by the wet or the dry route, beyond some convergency of requirements: e.g., highly plastic clays are tolerated in low amounts in both wet milling (as they increase the slip viscosity) and dry cycle (they are difficult to moist by granulation). Generally speaking, expandable clay minerals should be avoided in the wet route (recommended <5% in the batch) as coarse-grained clay materials should not be utilized in the dry route (limiting particularly the silty fraction that is little affected by dry milling). Body color varies from light red to dark brown (when MnO<sub>2</sub> is added to prevent black core) as Fe<sub>2</sub>O<sub>3</sub> amount is usually in the 3–7% range (at maximum 9 wt.%).

The strategies of formulation differ from rustic to glazed tiles, and these latter from semi-vitrified to vitrified bodies. Batches for rustic tiles are simple and often entirely made up of red loam with plasticity suitable for extrusion (Fabbri and Dondi, 1995; Vieira and Monteiro, 2012); in alternative, red clays are corrected with a filler (Table 4).

5.2.1. Vitrified red stoneware

Vitrified red stoneware was developed from the traditional unglazed stoneware by adjusting the technological behavior of red clays to the requirements of fast single firing (Fig. 11). Batches were changed by introducing some flux (to improve sintering kinetics) and some filler (to contrast black core and pyrodeformation) in order to make it

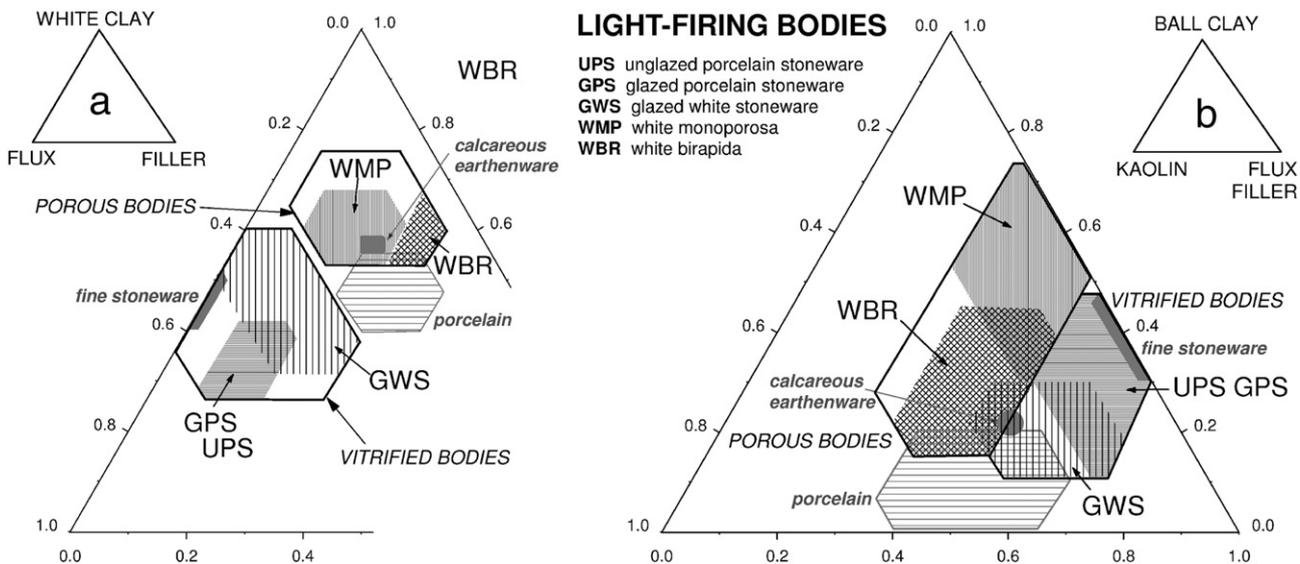


Fig. 12. Batch formulations of light-firing bodies.

possible the fast firing rates (Fabbri and Fiori, 1985; Sánchez et al., 1990). Therefore, the following criteria are applied in the industry to formulate red stoneware bodies (Table 4):

- fine-grained, often plastic and refractory red clays (like kaolinitic types RC1) can be used up to 30%, as they need the addition of both flux and filler, commonly within 20% each;
- raw materials that naturally contain enough feldspars, illite and/or chlorite to be 'self-sintering' (like many RC2 and RC3 clays) can be used in large amounts (35–65%) being adjusted by adding filler, usually below 20%;
- red loams (RL) frequently have enough coarse-grained fraction to replace simultaneously filler and clay (when employed, their amount is 25–40%).

The flexibility in body formulation turned it possible—and in many cases necessary—to combine two or more of the above criteria, mixing different types of red clays and even different kinds of filler and flux.

### 5.2.2. Semi-vitrified red stoneware

Semi-vitrified red stoneware has overall a batch composition close to that of the vitrified bodies, to the point that in several cases the same body can be used to produce BI or BII tiles just modifying the firing cycle. However, BII<sub>b</sub> tiles are easier to be produced, due to their higher water absorption, with bodies containing some carbonates, that can be provided by either calcite-bearing RC (which may contain up to 10% carbonates) or a minor amount of MC to be added to carbonate-free RC (i.e. the *cottoforte* approach, GRS5 in Table 4). A distinctive trait of semi-vitrified tiles is the chance to have bodies based on a single clay able to fulfill all technological requirements (feasible for the rather large window of acceptance: e.g. 6–10% water absorption). It happens for instance with some terms of the Corumbataí Fm that constitute the whole batch of the BII production in the Santa Gertrudes district, Brazil (Boschi, 2004; Masson et al., 2000; Motta et al., 2004).

### 5.3. Vitrified light-colored bodies

Light-colored bodies are utilized to manufacture vitrified (BI<sub>b</sub>) and highly vitrified (BI<sub>a</sub>) floor tiles that correspond to commercial types *Glazed White Stoneware* (GWS) and *Porcelain Stoneware*, respectively. All these products are manufactured by the wet route, with a few exceptions (Melchiades et al., 2010). GWS bodies are typically fired at 1160–1190 °C for 35–50 min cold-to-cold to get water absorption in the 1–3% range. Porcelain stoneware tiles can be either glazed or unglazed and are usually fired at 1190–1240 °C for 50–70 min to fulfill the market requirement of water absorption ~0.1% (although standard limit is <0.5%). The outstanding innovation in porcelain stoneware technology has led to the production of large slabs (up to 360x120 cm<sup>2</sup>) as very thin (0.3 cm) to very thick (2.5 cm) tiles and their combination (large and thin slabs) by uniaxial pressing, dieless pressing, or extrusion (Raimondo et al., 2010). These large sized tiles require a special body formulation with particular care in the choice of clay raw materials and additives.

The firing transformations occurring to LFC and light-colored bodies are the subject of several studies (Aras, 2004; Bastida et al., 2006; Gualtieri, 2007; Hajjaji et al., 2008; Jordán et al., 2013; Lee et al., 2008; Zanelli et al., 2011b) also concerning their effect on the properties of tiles (Bakr, 2011; Carbajal et al., 2007; Ferrari and Gualtieri, 2006; Lassinanti Gualtieri et al., 2011; Mukhopadhyay et al., 2003, 2009, 2010).

Light-colored vitrified bodies are designed to fit the water absorption target by firing schedules achievable with roller kilns, complying all standard requirements in terms of mechanical, abrasion, frost, chemical, stain and thermal shock resistance. This objective is achieved through viscous flow sintering, whose fast densification rates make it

crucial the control on firing shrinkage (recommended <7 cm/m) and pyroplastic deformation, with most technical properties depending on the interplay of residual porosity and phase composition, especially the vitreous phase (Gualtieri, 2007; Zanelli et al., 2011b). Thus, particle size distribution is stressed, since the specific surface area created by milling is the driving force of sintering, like fluxes (sodic, potassic, alkaline-earth and their combination) are strongly concerned, as they directly affect amount and composition of the vitreous phase. Being the more refractory (and expensive) component in light-colored vitrified bodies, along with the richest in iron, clay is kept to a minimum: its role is essentially restricted to govern the technological behavior before firing. The clay contribution during firing is mainly that of mullite precursor (kaolinite, pyrophyllite) or additional flux in case of illite and interstratified IS (Lee et al., 2008). In particular, slip rheological properties (milling and spray-drying), plasticity and compressibility (pressing) and bending strength (glazing and decoration) are the key points for clay raw materials (Bougher, 1995; Dondi et al., 2008). A compromise is necessary to match the slip requirements in terms of viscosity and thixotropy (recommending low amount of smectite and interstratified IS) with the needs of plasticity and strength (satisfied by a relatively high percentage of expandable clay minerals).

### 5.3.1. Glazed white stoneware

Glazed white stoneware was first developed in the early 1980s by SACMI's body No. 17, whose formulation clearly represents a rupture from previous schemes: limited use of conventional clays (25% BC), fluxes (7% sodic feldspar) and fillers (10% quartz sand) but appeal to then uncommon raw materials like low-grade kaolin (8%) and especially "eurite" (50%) that is a sericite-feldspar flux, ensuring fusibility, skeleton and some plasticity (SACMI, 1986). From that moment the doors have been opened for an extensive use of unconventional raw materials that, joined to the flexibility of tilemaking process, offer many degrees of freedom in body formulation. In this framework, basic criteria to design GWS batches are (Fig. 12):

- Fe<sub>2</sub>O<sub>3</sub> amount of the body in between 1% and 2%;
- clay:non plastic raw materials ratio around 50%:50%;
- preferred use of clays with low to medium plasticity (LK, KL, BC1);
- chance to utilize unconventional fluxes with some clay component (e.g., RK);
- priority to multipurpose raw materials (e.g., raw granite acting as both flux and filler).

As an example, typical recipes in the Sassuolo (Italy) and Castellón (Spain) districts are reported in Table 3, together with a pyrophyllite-based batch.

### 5.3.2. Porcelain stoneware

Porcelain stoneware represents the top quality floor tiles with the best technical performances and esthetic appearance; both UPS and GPS can be used in wall coverings and ventilated façades too. The UPS typology was developed starting from recipes inspired to porcelain: not a case if early batches did large use of kaolins and limited amounts of fluxes (i.e. PSW1 in Table 3). However, bodies more suitable for fast firing were formulated during the 1990s and their basic criteria are still valid, though with little adjustments for the GPS typology (e.g., PSW2 and PSW4 in Table 3):

- the Fe<sub>2</sub>O<sub>3</sub> amount of the body (0.7% on average) must be lower than 1.5%; within this threshold, GPS bodies exhibit higher iron contents.
- Non plastic raw materials are more abundant than the clay component; the clay:non plastic ratio usually ranges from 40%:60% to 45%:55%; it can be even lower in special products: e.g. 30–35% of plastic component in superwhite bodies (Tenorio Cavalcante et al., 2004).
- Clays with medium to high plasticity (BC1 and BC2) are preferred; low plasticity clays (KL, LK, PC) are utilized together with highly

plastic additives (BC3 or WB); the use of BC2 with some BC3 is recommended for large sized and/or thin tiles.

- Although conventional fluxes predominate, especially in UPS batches, unconventional types with some clay component, like RK, may be used if their iron content is low (e.g. <1%).
- Multipurpose raw materials are well tolerated, particularly if they contribute to lower cost and iron oxide average content of the batch.

Porcelain stoneware bodies may contain additives with different purposes: e.g., pigments and opacifiers for through-body decoration of UGS; plasticizers (from WB to organic and hybrid binders) especially for large size and/or thin tiles; sintering promoters (talc, glass-ceramic frits, carbonates, etc) to fasten densification kinetics.

Along with typical UGS and GPS recipes, Table 3 reports an example of pyrophyllite-based body. In contrast, batches distinguished essentially by the recourse to special fluxes and additives, like anorthite-based, superwhite or translucent UPS, are not considered here.

## 6. Worked examples

The classification here proposed will be applied to some representative examples of clay raw materials for the ceramic industry, in particular: Miocene clays from the Donbass basin, Ukraine; sedimentary kaolins from Mississippi, Tennessee and Texas, USA; late Paleozoic clays from Argentina; Cretaceous clays from the Oliete-Teruel basin, Spain; Mesozoic to Tertiary clays from Tunisia.

Ukrainian clays are reknown in ceramic tile production for their plasticity and technological properties (Bal and Fiederling-Kapteinat, 2007; Fiederling-Kapteinat, 2005) to the point they are frequently considered a benchmark for high quality ball clays (Galos, 2011b; Zanelli et al., 2011a). The samples characterized by Galos (2011a) are here taken into account as representative of ceramic clays coming from different mines in the Donbass district. As their iron oxide is at most 1.15%, they pertain to light-firing clays and plot into the field of ball clays according to their particle size distribution and kaolinite content (Fig. 13). Depending on their MBI, they are classifiable as medium (BC1) or to high (BC2) to very high plasticity (BC3) implying that not all the Ukrainian ball clays exhibit high plasticity (LK and BC1 terms should be blended with more plastic terms). This classification is in full agreement with the industrial practice, as Ukrainian clays are addressed to porcelain stoneware production (normally 10–30% of

the batch) and secondarily to white-firing bodies for porous tiles, particularly when large slabs have to be manufactured or if it is necessary to improve plasticity of other clay components.

Sedimentary kaolins from southeastern USA are here represented by data taken from Wilson (1998). Overall, they present iron oxide content within light-firing clays; their particle size and kaolinite amount spread from RK to HK with most samples in the field where LK and BC overlap (Fig. 13). Samples with the lowest plasticity and the highest kaolinite percentage are classified as RK-LK and HK, respectively; the MBI values of the other samples indicate ball clays with medium plasticity (BC1) plus two high plasticity samples (BC2) and one smectite-bearing sample of very high plasticity (BC3). Both kaolins and ball clays can be widely utilized in tilemaking (Bougher, 1995; Lombardo, 1996) the former in lower amount (especially in WMP and GWS batches) while the latter as the main clay component of light-firing formulations, particularly for porcelain stoneware.

Late Paleozoic clays from Tandilia, Argentina, are distinguished by rather high amounts of pyrophyllite associated with kaolinite and illite (Dristas and Frisciale, 2003). Half of samples characterized by Zalba (1979) have enough pyrophyllite (20–33%) to be described as PC and a sufficiently low iron oxide (<2%) to be used in light-firing bodies. Another clay with 15% pyrophyllite is likely classifiable as LK, due to the low plasticity of these raw materials, that however depends on the milling degree (Alló et al., 1997). The remaining sample is a pyrophyllite-bearing illitic red clay (RC2). This picture is in agreement with current industrial use: PC (and LK) are components of GWS, GPS and UPS bodies (for instance GWS3 and PSW5 in Table 3); the RC2 clay can be used in GRS batches.

The case-study of the Oliete-Teruel basin in Spain – taking as example the clays characterized by García-Tomás et al. (1996) – offers a wide range of composition and particle size distribution. Iron oxide widely fluctuates from 1% to 9%, with half of samples below 3%, thus classifiable as LFC. According to their relatively low amount of kaolinite and fraction <2 μm, these clays are in many cases classified as KL or LK; two samples plotting in the BC field can be actually defined medium plasticity ball clays on the basis of their Atterberg plastic index (Fig. 13). Overall, these LFC find application in bodies where they play simultaneously the role of filler and plastic component: e.g., GWS1 and PSW4 batches (Table 3). However, their use must be balanced with high plasticity clays like BC2 or BC3 (Sánchez et al., 1997). The iron-rich clays are rather coarse-grained, with half of samples with a

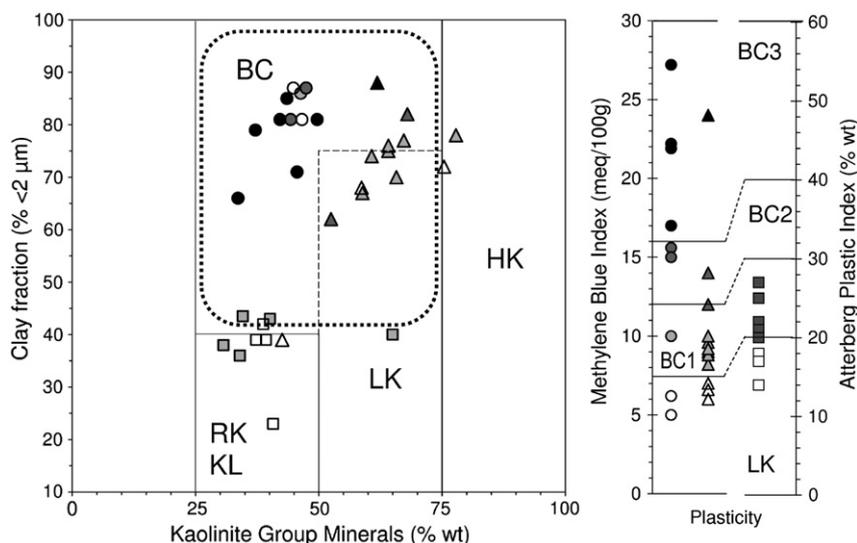


Fig. 13. Examples of classification of light-firing clays: clays from the Donbass basin, Ukraine (circles); sedimentary kaolins from Mississippi, Tennessee and Texas, USA (triangles); clays from the Oliete-Teruel basin, Spain (squares).

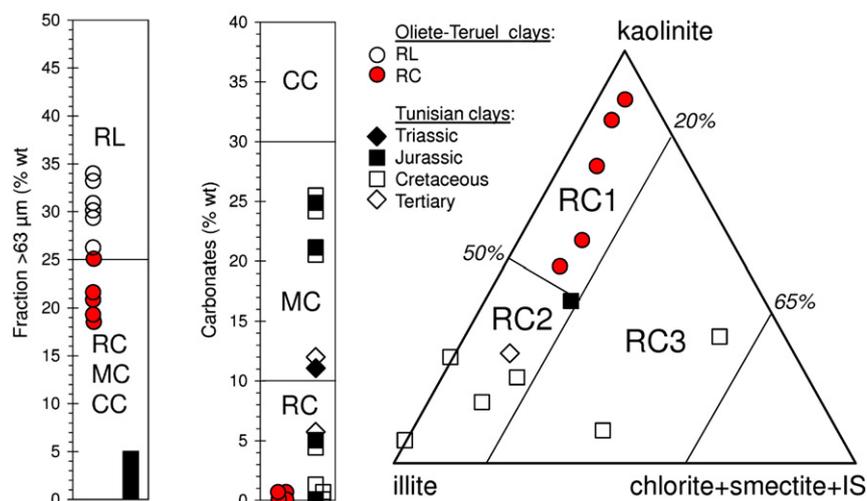


Fig. 14. Examples of classification of dark-firing clays from the Oliete–Teruel basin, Spain and from various Tunisian geological units.

sandy fraction over 25% (thus classified as red loams). The remaining clays are predominantly kaolinitic and so attributable to the RC1 type (Fig. 14). These DFC are currently used (Meseguer et al., 2011b) in both porous and vitrified bodies up to 20% (RL) and up to 30% (RC1).

A wide set of ceramic clays from Tunisia were recently investigated encompassing Triassic (Medhioub et al., 2010), Jurassic (Hajjaji et al., 2010), Cretaceous (Felhi et al., 2008; Hachani et al., 2012; Jeridi et al., 2008) and Tertiary units (Felhi et al., 2008; Jeridi et al., 2008). Common features are their iron amount over 3% (DFC) and their particle size distribution mostly ranging from silty clays to clayey silts. The main distinctive parameters are the amount of carbonates, that discriminates MC and RC, and the clay mineralogy, defining RC2 and RC3 types (Fig. 14). These raw materials appear to be well suited for porous tiles (Azzouz et al., 2011) whose bodies make use of at the same time of MC and RC (that are present in all the geological units). Strategies of batch formulation like RMP3 and RBR2 can be envisaged, entailing the addition of some filler to compensate the rather fine-grained distribution.

## 7. Conclusions

Ceramic tile manufacturing is a dynamic industrial sector where market trends and technological innovation have created a complex picture of products and processes. This technological evolution has directly entailed raw materials: a really wide spectrum of clays – with an outstanding range of chemical and mineralogical composition, particle size distribution and ceramic behavior – is currently utilized in tilemaking. The classical terminology for ceramic tiles and related reference schemes for raw materials are no longer useful to describe and predict the role of clays in tile manufacturing and must be upgraded.

A new and industry-oriented classification has been proposed on the basis of simple chemical, mineralogical, granulometric and rheological parameters of clay materials. It allows a more efficacious and complete evaluation of clay resources (including valuable types not always considered among industrial minerals) along with a realistic assessment of technological potential of clays, readily transferable to the ceramic industry. Although not entailed by this classification, there are chemical features that may affect the suitability of clays for ceramic applications – e.g. F, Cl, S, and further elements mobilized during firing (Domínguez et al., 2012; González et al., 2006) – and must be considered.

The criteria to properly design the batches for wall and floor tiles have been revised, trying to highlight the key properties for each category of ceramic bodies. Besides representative of the industrial practice, the examples of body formulation given with the present guidelines are not exhaustive, as the extreme flexibility of current

technology leaves room for further combination of raw materials (fulfilling anyway the key properties of each tile typology).

At all events, both clay classification and body formulation criteria here proposed cannot substitute a thorough technological characterization of ceramic raw materials, that should be performed simulating as faithfully as possible the industrial tilemaking cycles (the closer to industrial processing, the more reliable the technological results).

## References

- Abadir, M.F., Sallam, E.H., Bakr, I.M., 2002. Preparation of porcelain tiles from Egyptian raw materials. *Ceram. Int.* 28, 303–310.
- Abdel-Aziz, D.A., Aly, M.H., 2006. Effect of non-conventional fluxes on the electrical properties of electro-ceramic bodies. *Interceram* 55, 90–93.
- Alcântara, A.C.S., Beltrao, M.S.S., Oliveira, H.A., Gimenez, I.F., Barreto, L.S., 2008. Characterization of ceramic tiles prepared from two clays from Sergipe – Brazil. *Appl. Clay Sci.* 39, 160–165.
- Alló, W.A., Murray, H.H., 2004. Mineralogy, chemistry and potential applications of a white bentonite in San Juan province, Argentina. *Appl. Clay Sci.* 25, 237–243.
- Alló, W., Domínguez, E.A., Cravero, F., 1997. Precambrian yellow illitic clay from La Siempre Verde pit, Barker, Buenos Aires, Argentina: plasticity improvement by preparation practices. *Proc. 11th Int. Clay Conf., Ottawa, Canada*, pp. 71–74.
- Almohandis, A.A., 1993. Distribution and mineralogy of the clay deposits in Saudi Arabia. *Qatar Univ. Sci. J.* 13, 134–139.
- Amritphale, S.S., Bhasin, S., Chandra, N., 2006. Energy efficient process for making pyrophyllite-based ceramic tiles using phosphoric acid and mineralizers. *Ceram. Int.* 32, 181–187.
- Andji, J.Y.Y., Toure, A.A., Kra, G., Jumas, J.C., Yvon, J., Blanchart, Ph., 2009. Iron role on mechanical properties of ceramics with clays from Ivory Coast. *Ceram. Int.* 35, 571–577.
- Andreola, F., Siligardi, C., Manfredini, T., Carbonchi, C., 2009. Rheological behaviour and mechanical properties of porcelain stoneware bodies containing Italian clay added with bentonites. *Ceram. Int.* 36, 1159–1164.
- Aras, A., 2004. The change of phase composition in kaolinite-and illite-rich clay-based ceramic bodies. *Appl. Clay Sci.* 24, 257–269.
- Ariffin, K.S., Rahman, H.A., Hussin, H., Hadi, K.A.A., 2008. The genesis and characteristics of primary kaolinitic clay occurrence at Bukit Lampas, Simpang Pulai, Ipoh. *Bull. Geol. Soc. Malaysia* 54, 9–16.
- Aungatchart, P., Wada, S., 2009. Correlation between Bigot and Ratzemberger drying sensitivity indices of red clay from Ratchaburi province (Thailand). *Appl. Clay Sci.* 43, 182–185.
- Azzouz, H., Alouani, R., Tlig, S., 2011. Mineralogical characterization of ceramic tiles prepared by a mixture of Cretaceous and Mio-Pliocene clays from Tunisia: factory and laboratory products. *J. Ceram. Soc. Jpn.* 119, 93–100.
- Bakr, I.M., 2011. Densification behavior, phase transformations, microstructure and mechanical properties of fired Egyptian kaolins. *Appl. Clay Sci.* 52, 333–337.
- Bal, M., Fiederling-Kapteinat, H.G., 2007. The Mediterranean clay market for ceramic tile production in the past decade. *Tile Brick Int. Man.* 36–39.
- Baraldi, L., 2013. World production and consumption of ceramic tiles. *Ceram. World Rev.* 103, 42–60.
- Bastida, J., 1982a. Petrografía y mineralogía de arcillas en relación con procesos de cocción rápida. *Bol. Soc. Esp. Ceram. Vidrio* 21, 15–22.
- Bastida, J., 1982b. Significación geológica de la mineralogía de las rocas arcillosas de la provincia de Castellón. *Bol. Soc. Esp. Mineral.* 5, 209–219.
- Bastida, J., Beltrán, V., 1986. Arcillas cerámicas de la provincia de Valencia. *Bol. Soc. Esp. Ceram. Vidrio* 25, 231–235.

- Bastida, J., Lores, M.T., de la Torre, J., Pardo, P., Lopez Buendia, A.M., 2006. Modificación microestructural de minerales arcillosos en ball clays de Teruel mediante tratamiento térmico. *Bol. Soc. Esp. Ceram. Vidrio* 45, 38–45.
- Becker, G., Brenner, P., 1997. Requirements on clays for fast firing from the Westerwald. *CFI/Ber. DKG* 74, 578–586.
- Beltrán, V., Sánchez, E., García-Ten, J., Ginés, F., 1996. Materias primas empleadas en la fabricación de baldosas de pasta blanca en España. *Téc. Cerám.* 241, 114–128.
- Bertolani, M., Loschi Ghittoni, A.G., 1986a. Clay materials from the Central Valley of Costa Rica and their possible ceramic uses. *Appl. Clay Sci.* 1, 239–254.
- Bertolani, M., Loschi Ghittoni, A.G., 1986b. La serie sedimentaria caolinizzata della miniera Bocciole (Boca–Novara): caratteristiche e impieghi nel settore ceramico. *Ceramica* 39 (4), 1–10.
- Bertolani, M., Loschi Ghittoni, A.G., 1989. Kaolin of Piloni di Torniella (Tuscany). *Ind. Miner.* 40 (2), 19–27.
- Bertolani, M., Loschi Ghittoni, A.G., 1990. Aree caolinizzate nel Canavese presso Castellamonte (Torino). *Boll. Ass. Min. Subalpina* 27 (1–2), 63–71.
- Bertolani, M., Fabbri, B., Fiori, C., Loschi Ghittoni, A.G., 1986. Influenza dell'evoluzione impiantistica sull'uso delle materie prime per la fabbricazione di piastrelle. *Ceram. Inf.* 243, 333–336.
- Billi, F., Dondi, M., Fabbri, B., Morandi, N., 1992. Carbonatic clays for the production of porous ceramic tiles by fast single firing. *Geol. Carpathica - Clays* 2, 91–95.
- Bittencourt, E.L., Júnior, J.C.B., Silvestre, M.D.M., 2001. Metodologia experimental para desenvolvimento de uma formulação de revestimento poroso (classificação BIII) em processo de monoporosa através da programação linear. *Ceram. Ind.* 6 (4), 35–40.
- Boix, A., Gargallo, M., Jordan, M.M., Segura, R., Sanfeliu, T., 1994. Mineralogy and technological properties of clays used in the ceramic floor and wall tile sector. *Téc. Cerám.* 224, 404–413.
- Bordeepong, S., Bhongsuwan, D., Pungrassami, T., Bhongsuwan, T., 2012. Mineralogy, chemical composition and ceramic properties of clay deposits in southern Thailand. *Kasetsart J. (Nat. Sci.)* 46, 485–500.
- Boschi, A.O., 2004. O pólo de Santa Gertrudes e a indústria brasileira de revestimentos cerâmicos. *Ceram. Ind.* 9 (3), 7–12.
- Bougher, K., 1995. Ceramic body reformulation procedure with emphasis on ball clay. *Ceram. Eng. Sci. Proc.* 16 (3), 15–20.
- Bristow, C.M., 1993. The genesis of the china clays of south-west England – a multistage story. In: Murray, H.H., Bundy, W.M., Harvey, C.C. (Eds.), *Kaolin genesis and utilization*. The Clay Minerals Society, Boulder, Colorado, pp. 171–204.
- Brusa, A., Bresciani, A., 1996. Floor and wall tile production through a multipurpose body. *Ceram. Eng. Sci. Proc.* 17 (1), 50–59.
- Carbajal, L., Rubio-Marcos, F., Bengochea, M.A., Fernandez, J.F., 2007. Properties related phase evolution in porcelain ceramics. *J. Eur. Ceram. Soc.* 27, 4065–4069.
- Carretero, M.I., Dondi, M., Fabbri, B., Raimondo, M., 2002. The influence of shaping and firing technology on ceramic properties of calcareous and non-calcareous illitic-chloritic clays. *Appl. Clay Sci.* 20, 301–306.
- Celik, H., 2010. Technological characterization and industrial application of two Turkish clays for the ceramic industry. *Appl. Clay Sci.* 50, 245–254.
- Chandrasekhar, S., Ramaswamy, S., 2007. Investigation on a gray kaolin from south east India. *Appl. Clay Sci.* 37, 32–46.
- Chávez, G.L., Johns, W.D., 1995. Mineralogical and ceramic properties of refractory clays from central Missouri (USA). *Appl. Clay Sci.* 9, 407–424.
- Chiappone, A., Marelli, S., Scavia, C., Setti, M., 2004. Clay mineral characterization through the methylene blue test: comparison with other experimental techniques and applications of the method. *Can. Geotech. J.* 41, 1168–1178.
- Christidis, G.E., Scott, P.W., 1997. The origin and control of colour of white bentonites from the Aegean islands of Milos and Kimolos, Greece. *Mineral. Deposita* 32, 271–279.
- Christofoletti, S.R., Moreno, M.M.T., 2004. Características das rochas da formação Corumbataí utilizadas na indústria de revestimento cerâmico. *Geosci. Geociênc.* 23, 79–88.
- Chung, C.-J., Baik, Y.-H., Park, H.-S., 1977. Hampyong, Kyochon clay—its characteristics and effects of clay–organic complexes on it. *J. Korean Ceram. Soc.* 6, 95–103.
- Çiğdemir, G., Kara, A., Kara, F., 2010. Effect of alkaline earth oxides on firing behaviour of porcelain stoneware. *Ind. Ceram.* 30, 177–186.
- Corma, P., 2008. Innovations and innovative processes in the Castellón ceramic district. *Qualicer 2008*. P.BA 59–78.
- Correia, S.L., Curto, K.A.S., Hotza, D., Segadães, A.M., 2005. Clays from southern Brazil: physical, chemical and mineralogical characterization. *Mater. Sci. Forum* 498–499, 447–452.
- Costa, V., Danasino, P., Di Primio, S., Peco, G., 1996. Caolini tradizionali e prodotti innovativi di S. Severa. *Ceram. Inf.* 365, 499–506.
- Cravero, F., Gonzalez, I., Galan, E., Dominguez, E., 1997. Geology, mineralogy, origin and possible applications of some Argentinian kaolins in the Neuquen basin. *Appl. Clay Sci.* 12, 27–42.
- Cravero, F., Keith, K.S., Murray, H.H., Toth, T., 2000. A white bentonite from San Juan Province, Argentina—geology and potential industrial applications. *Appl. Clay Sci.* 16, 31–43.
- Dagounaki, C., Sikalidis, C., Kassoli-Fournaraki, A., Tsirambides, A., 2008. The influence of carbonates on the technological properties of an industrial red clay. *Ind. Ceram.* 28, 181–187.
- Danasino, P., Di Primio, S., 1995. A Sardinian kaolinic clay for different uses in ceramics. In: Palmonari, C. (Ed.), *Floor and wall tiles. IV Euroceramics*, 11. Faenza Ed., pp. 73–84.
- Das Kshama, V., Mohan, B.V., Lalithambika, M., 1992. Sintering studies on plastic clays. *Ceram. Int.* 18, 359–364.
- Das, B., Mohanty, J.K., 2009. Mineralogical characterization and beneficiation studies of pyrophyllite from Orissa, India. *J. Miner. Mater. Charact. Eng.* 8, 329–338.
- Das, S.K., Dana, K., Singh, N., Sarkar, R., 2005. Shrinkage and strength behaviour of quartzitic and kaolinic clays in wall tile compositions. *Appl. Clay Sci.* 29, 137–143.
- Daunoraviciute, D., Petrikaitis, F., Lasys, A., Jarulaitis, V., 1997. Clays for the ceramics industry in Lithuania. *Tile Brick Int.* 13 (1), 34–37.
- Diaz Rodríguez, L.A., Torrecillas, R., 2002. Arcillas cerámicas: una revisión de sus distintos tipos, significados y aplicaciones. *Bol. Soc. Esp. Ceram. Vidrio* 41, 459–470.
- Diko, M.L., Ekosse, G.E., Ayonghe, S.N., Ntasin, E.B., 2011. Physical characterization of clayey materials from tertiary volcanic cones in Limbe (Cameroon) for ceramic applications. *Appl. Clay Sci.* 51, 380–384.
- Djambazov, S., Malinov, O., Yoleva, A., 2009. White halloysitic clay from the east Rhodopian Paleogene depression at Kravevo village, Haskovo district, Bulgaria – a potential raw material for the ceramic industry. *Interceram* 58, 210–212.
- Djangan, C.N., Elimbi, A., Melo, U.C., Lecomte, G.L., Nkoumbou, C., Soro, J., Yvon, J., Blanchart, Ph., Njopwouo, D., 2008. Refractory ceramics from clays of Mayoum and Mvan in Cameroon. *Appl. Clay Sci.* 39, 10–18.
- Domínguez, E., Iglesias, C., Dondi, M., 2008. The geology and mineralogy of a range of kaolins from the Santa Cruz and Chubut provinces, Patagonia (Argentina). *Appl. Clay Sci.* 40, 124–142.
- Domínguez, E., Iglesias, C., Dondi, M., Murray, H.H., 2010. Genesis of the La Espingarda kaolin deposit in Patagonia. *Appl. Clay Sci.* 47, 290–302.
- Domínguez, E., Iglesias, C., Dondi, M., 2012. Environmental suitability of ceramic raw materials: a geochemical approach to volatile emissions and leaching potentials. *J. Environ. Earth Sci.* 65, 517–523.
- Dondi, M., 1999. Clay materials for ceramic tiles from the Sassuolo district (northern Apennines, Italy). *Geology, composition and technological properties*. *Appl. Clay Sci.* 15, 337–366.
- Dondi, M., 2003. Technological and compositional requirements of clay materials for ceramic tiles. In: Domínguez, E.A., Mas, G.R., Cravero, F. (Eds.), *Proc. 12th Int. Clay Conf. Elsevier, Bahía Blanca, Argentina*, pp. 23–30.
- Dondi, M., Ercolani, G., Guarini, G., Marsigli, M., Venturi, I., 1995a. Evoluzione della microstruttura durante la cottura rapida di impasti per piastrelle porose. *Ceramurgia* 25, 301–314.
- Dondi, M., Morandi, N., Zuffi, P., 1995b. Possibile impiego ceramico di vulcaniti acide ladiniche (Prealpi vicentine) e dei loro prodotti argillosi di alterazione. *Miner. Petrogr. Acta* 38, 201–218.
- Dondi, M., Ercolani, G., Fabbri, B., Marsigli, M., 1998. An approach to the chemistry of pyroxenes formed during the firing of Ca-rich silicate ceramics. *Clay Miner.* 33, 443–452.
- Dondi, M., Ercolani, G., Fabbri, B., Marsigli, M., 1999a. Chemical composition of melilite formed during the firing of carbonate-rich and iron-containing ceramic bodies. *J. Am. Ceram. Soc.* 82, 465–468.
- Dondi, M., Ercolani, G., Guarini, G., Raimondo, M., 1999b. Microstruttura delle piastrelle ceramiche a supporto poroso. Influenza della composizione dell'impasto e della tecnologia di processo. *Ceram. Inf.* 392, 849–857.
- Dondi, M., Biasini, V., Guarini, G., Raimondo, M., Argnani, A., Di Primio, S., 2001. Impasti multiscopo per piastrelle ceramiche in pasta chiara. *Ceram. Inf.* 411, 963–968.
- Dondi, M., Guarini, G., Raimondo, M., Salucci, F., 2003. Influence of mineralogy and particle size on the technological properties of ball clays for porcelain stoneware tiles. *Tile Brick Int.* 20 (2), 2–11.
- Dondi, M., Iglesias, C., Domínguez, E., Guarini, G., Raimondo, M., 2008. The effect of kaolin properties on their behaviour in ceramic processing as illustrated by a range of kaolins from the Santa Cruz and Chubut provinces, Patagonia (Argentina). *Appl. Clay Sci.* 40, 143–158.
- Dristas, J.A., Frisciale, M., 2003. Two types of hydrothermal clay deposits in the south-east area of Tandil, Buenos Aires Province, Argentina. In: Domínguez, E.A., Mas, G.R., Cravero, F. (Eds.), *Proc. 12th Int. Clay Conf. Elsevier, Bahía Blanca, Argentina*, pp. 85–92.
- Dutra, R.P.S., Varela, M.L., do Nascimento, R.M., Gomes, U.U., Paskocimas, C.A., de Melo, P.T., 2006. Avaliação da potencialidade de argilas do Rio Grande do Norte – Brasil. *Ceram. Ind.* 11 (2), 42–46.
- Ece, O.I., Nakagawa, Z.E., Schroeder, P.A., 2003. Alteration of volcanic rocks and genesis of kaolin deposits in the Şile region, northern Istanbul, Turkey. I: *Clay Mineralogy*. *Clays Clay Miner.* 51, 675–688.
- Ekosse, G., 2000. The Makoro kaolin deposit, southeastern Botswana: its genesis and possible industrial applications. *Appl. Clay Sci.* 16, 301–320.
- Enrique, J.E., Bastida, J., 1982. Características cerámicas de algunas arcillas del Cretácico inferior del Maestrazgo. *Cuad. Geol. Iber.* 8, 899–912.
- Erkoyun, H., Kadir, S., 2011. Mineralogy, micromorphology, geochemistry and genesis of a hydrothermal kaolinite deposit and altered Miocene host volcanites in the Hallaçlar area, Uşak, western Turkey. *Clay Miner.* 46, 421–448.
- Escardino Benlloch, A., 1992. Single-fired ceramic wall tile manufacture. *Int. Ceram. J.* 111–140.
- Fabbri, B., Dondi, M., 1995. Clays for the heavy-clay industry in Tuscany and Umbria (central Italy). In: Churchman, G.J., Fitzpatrick, R.W., Eggleton, R.A. (Eds.), *Proc. 10th Int. Clay Conf., Adelaide, Australia*. CSIRO Publishing, Melbourne, pp. 122–128.
- Fabbri, B., Fiori, C., 1985. Clays and complementary raw materials for stoneware tiles. *Miner. Petrogr. Acta* 29A, 535–545.
- Fabbri, B., Morandi, N., Nannetti, M.C., 1989. Abundance of chromium and other transition metals in ceramic clays from Westerwald (GFR). *Appl. Clay Sci.* 4, 475–484.
- Felhi, M., Tlili, A., Gaiet, M.E., Montacer, M., 2008. Mineralogical study of kaolinic clays from Sidi El Bader in the far north of Tunisia. *Appl. Clay Sci.* 39, 208–217.
- Fentaw, H.M., Mengistu, T., 1998. Comparison of Kombelcha and Bombowha kaolins of Ethiopia. *Appl. Clay Sci.* 13, 149–164.
- Ferrari, S., Gualtieri, A.F., 2006. The use of illitic clays in the production of stoneware tile ceramics. *Appl. Clay Sci.* 32, 73–81.
- Fiederling-Kapteinat, H.G., 2005. The Ukrainian clay mining industry and its effect on the European ceramic raw materials market. *Interceram* 54 (1), 4–9.

- Fiederling-Kapteinat, H.G., Schetnikov, A.I., Venturelli, B., 2000. Light-firing Ukrainian clays for the world market. *Interclay* 49, 342–343.
- Fiori, C., 1996. Raw materials for the Italian stoneware tile industry. *Ind. Ceram.* 16, 77–83.
- Fiori, C., Fabbri, B., 1985. Technological evolution of the Italian ceramic floor and wall tile industry. *Interbrick* 1 (5), 38–43.
- Fiori, C., Fabbri, B., 1987. Gres rosso "tipo Gattinara". *Ceram. Inf.* 252, 144–146.
- Fiori, C., Fabbri, B., Donati, F., Venturi, I., 1989. Mineralogical composition of the clay bodies used in the Italian tile industry. *Appl. Clay Sci.* 4, 461–473.
- Gal'perina, M.K., Aleinikova, T.N., Saffronova, Z.N., 1971. Use of Voronovo clays for the production of ceramic sanitary ware. *Glass Ceram.* 28, 50–52.
- Galán, E., Aparicio, P., Miras, A., Michailidis, K., Tsirambides, A., 1996. Technical properties of compounded kaolin sample from Griva (Macedonia, Greece). *Appl. Clay Sci.* 10, 477–490.
- Galos, K., 2011a. Composition and ceramic properties of ball clays for porcelain stoneware tiles manufacture in Poland. *Appl. Clay Sci.* 51, 74–85.
- Galos, K., 2011b. Influence of mineralogical composition of applied ball clays on properties of porcelain tiles. *Ceram. Int.* 37, 851–861.
- Galos, K., Pietrzyk, W., 2008. New white-firing clays from Bolesławiec vicinity—mineralogical and technological characteristics. *Mater. Ceram./Ceram. Mater.* 60, 64–70.
- Galos, K., Wyszomirski, P., 2006. Clayey raw materials for the domestic industry of the fine and technical ceramics. Part I. Domestic white and light firing clayey raw materials. *Mater. Ceram./Ceram. Mater.* 58, 58–63.
- Gal'perin, M.K., Pavlov, V.F., Aleinikova, T.N., 1967. Use of Ust'Kyakhta quartz-sericite shale in production of ceramic sanitary ware and acidproof goods. *Glass Ceram.* 24, 327–328.
- Gal'perina, M.K., Tarantul, N.P., 1990. Ceramic tiles from pyrophyllite bodies for internal wall facing. *Glass Ceram.* 47, 285–287.
- García-Tomás, F., Bastida, J., de la Torre, J., Esteve, V., Lores, M.T., Serrano, F.J., 1996. Plasticidad y características composicionales de arcillas industriales de la zona minera de Teruel (España). *Bol. Soc. Esp. Mineral.* 19, 101–117.
- Gomes, C., Velho, J., Guimarães, F., 1994. Kaolin deposit of Mevaiela (Angola), alteration product of anorthosite: assessment of kaolin potentialities for applications in paper. *Appl. Clay Sci.* 9, 97–106.
- Goncharov, Y.I., Rudenko, T.S., Sysa, O.S., Zakabluk, Y.I., 2006. Use of "blue clay" from the Maloarkhangel'skoe deposit in the production of ceramic tiles. *Glass Ceram.* 63, 62–63.
- González, I., Galán, E., Miras, A., 2006. Fluorine, chlorine and sulphur emissions from the Andalusian ceramic industry (Spain)—Proposal for their reduction and estimation of threshold emission values. *Appl. Clay Sci.* 32, 153–171.
- González-García, F., Romero-Acosta, V., García-Ramos, G., González-Rodríguez, M., 1990. Firing transformations of mixtures of clays containing illite, kaolinite and calcium carbonate used by ornamental tile industries. *Appl. Clay Sci.* 5, 361–375.
- Gouda, A., Abdel-Marouf, S., Aboud, G., Ibrahim, D.M., 2003. Ceramic cooking ware. *Silic. Ind.* 1–2, 7–10.
- Gualtieri, A.F., 2007. Thermal behavior of the raw materials forming porcelain stoneware mixtures by combined optical and in situ X-ray dilatometry. *J. Am. Ceram. Soc.* 90, 1222–1231.
- Guillén, J.A., Bribiesca, S.V., Escudero, R.G., 2012. Caracterización y evaluación de un depósito de caolín de "Los Azufres" Michoacán, México, para su uso industrial. *Bol. Soc. Esp. Ceram. Vidrio* 51, 329–336.
- Hachani, M., Hajjaji, W., Moussi, B., Medhioub, M., Rocha, F., Labrincha, J.A., Jamoussi, F., 2012. Production of ceramic bodies from Tunisian Cretaceous clays. *Clay Miner.* 47, 59–68.
- Hajjaji, M., Mezouari, H., 2011. A calcareous clay from Tamesloht (Al Haouz, Morocco): Properties and thermal transformations. *Appl. Clay Sci.* 51, 507–510.
- Hajjaji, M., Kacim, S., Boulmane, M., 2002. Mineralogy and firing characteristics of a clay from the valley of Ourika (Morocco). *Appl. Clay Sci.* 21, 203–212.
- Hajjaji, M., Belkadir, A., Berrada, S.H., 2008. Peraluminous rocks of Bou-Azzer region (Morocco): Geology and firing transformations. *J. Afr. Earth Sci.* 52, 114–120.
- Hajjaji, W., Moussi, B., Hachani, M., Medhioub, M., Lopez-Galindo, A., Rocha, F., Labrincha, J.A., Jamoussi, F., 2010. The potential use of Tithonian-Barremian detrital deposits from central Tunisia as raw materials for ceramic tiles and pigments. *Appl. Clay Sci.* 48, 552–560.
- Hall, C., Hoff, W.D., 2012. Moisture Expansivity of Fired-Clay Ceramics. *J. Am. Ceram. Soc.* 95, 1204–1207.
- Harvey, C.C., Murray, H.H., 1997. Industrial clays in the 21st century: A perspective of exploration, technology and utilization. *Appl. Clay Sci.* 11, 285–310.
- He, H., Yue, Q., Qi, Y., Gao, B., Zhao, Y., Yu, H., Li, J., Li, Q., Wang, Y., 2012. The effect of incorporation of red mud on the properties of clay ceramic bodies. *Appl. Clay Sci.* 70, 67–73.
- Heckroodt, R.O., 1991. Clay and clay materials in South Africa. *J. South. Afr. Inst. Min. Metall.* 91, 343–363.
- Hettiarachchi, P., Motha, J.T.S., Pitawala, H.M.T.G.A., 2010. Identification of an appropriate body composition for red clay products. *Cerâmica* 56, 285–290.
- Hevia, R., Inocencio, A., Barrachina, E., Gómez, J., Gil, C., Carda, J.B., 2006. Manufacture of porcelain tile with selected raw materials from the Argentine Republic. *Qualicer* 2006. Pos, pp. 125–134.
- Higashi, S., 2000. Ammonium-bearing mica and mica/smectite of several pottery stone and pyrophyllite deposits in Japan: their mineralogical properties and utilization. *Appl. Clay Sci.* 16, 171–184.
- ICeRS, 1995–2010. Handbook of Ceramic Raw Materials, five editions: 1995, 1999, 2002, 2006 and 2010. Italian Ceramic Society, Bologna, Italy.
- Il'ina, V.P., Ozerova, G.P., Lebedeva, G.A., 2005. Facing tiles based on feldspar material and Cambrian clay from Chekalovskoe Deposit. *Glass Ceram.* 62, 84–86.
- Jeridi, K., Hachani, M., Hajjaji, W., Moussi, B., Medhioub, M., Lopez-Galindo, A., Kooli, F., Zargouni, F., Labrincha, J., Jamoussi, F., 2008. Technological behaviour of some Tunisian clays prepared by dry ceramic processing. *Clay Miner.* 43, 339–350.
- Jordán, M.M., Boix, A., Sanfeliu, T., de la Fuente, C., 1999. Firing transformations of Cretaceous clays used in the manufacturing of ceramic tiles. *Appl. Clay Sci.* 14, 225–234.
- Jordán, M.M., Sanfeliu, T., de la Fuente, C., 2001. Firing transformations of Tertiary clays used in the manufacturing of ceramic tile bodies. *Appl. Clay Sci.* 20, 87–95.
- Jordán, M.M., Montero, M.A., Meseguer, S., Sanfeliu, T., 2008. Influence of firing temperature and mineralogical composition on bending strength and porosity of ceramic tile bodies. *Appl. Clay Sci.* 42, 266–271.
- Jordán, M.M., Martín-Martín, J.D., Sanfeliu, T., Gomez-Gras, D., de la Fuente, C., 2009. Mineralogy and firing transformations of Permo-Triassic clays used in the manufacturing of ceramic tile bodies. *Appl. Clay Sci.* 44, 173–177.
- Jordán, M.M., Sanfeliu, T., Meseguer, S., Pardo, F., González, I., 2013. Mineralogical transformations of kaolins from Cauquenes (region of Maule, Chile). *J. Geogr. Geol.* 5, 9–15.
- Joshi, C.K., Malkan, V.G., Bhatt, J.V., 1993. Ceramic raw materials of India. Seminar on Ceramic Industry Raw Materials and Essential Inputs. INDEXTb, Ahmenabad, pp. 3–44.
- Kabre, T.S., Traore, K., Blanchart, Ph., 1998. Mineralogy of clay raw material from Burkina Faso and Niger used for ceramic wares. *Appl. Clay Sci.* 12, 463–477.
- Kacim, S., Hajjaji, M., 2003. Firing transformations of a carbonatic clay from the High-Atlas, Morocco. *Clay Miner.* 38, 361–365.
- Kadir, S., Akbulut, A., 2009. Mineralogy, geochemistry and genesis of the Taşoluk kaolinite deposits in pre-early Cambrian metamorphites and Neogene volcanites of Afyonkarahisar, Turkey. *Clay Miner.* 44, 89–112.
- Kadir, S., Kart, F., 2009. The occurrence and origin of the Söğüt kaolinite deposits in the paleozoic Sarıcakaya granite-granodiorite complexes and overlying neogene sediments (Bilecik, northwestern Turkey). *Clays Clay Miner.* 57, 311–329.
- Kadir, S., Erman, H., Erkoyun, H., 2011. Mineralogical and geochemical characteristics and genesis of hydrothermal kaolinite deposits within neogene volcanites, Kütahta (Western Anatolia), Turkey. *Clays Clay Miner.* 59, 250–276.
- Kara, A., Özer, F., Kayaci, K., Özer, P., 2006. Development of a multipurpose tile body: Phase and microstructural development. *J. Eur. Ceram. Soc.* 26, 3769–3782.
- Kara-Sal, B.K., Mongush, A.D., 2005. Majolica products based on raw material from Tuva. *Glass Ceram.* 62, 317–318.
- Karasu, B., Kaya, G., Sevim, C., Sen, E., 2004. Utilisation of a natural stone with fluxing ability in floor tile body as a Na-feldspar replacement. *Key Eng. Mater.* 264–268, 1705–1708.
- Karklit, A.K., Sennikov, S.G., 1997. Clays of the Kholm deposit. *Glass Ceram.* 54, 20–22.
- Kartal, A., Metin, S.O., 2004. Investigation on the use of a brick clay in the floor tile body. *Key Eng. Mater.* 264–268, 1645–1648.
- Kayaci, K., Kucuker, A.S., Genc, S.C., Kara, A., 2010. Utilization of a sandy clay in double-fired wall tile bodies. *Ind. Ceram.* 30, 7–15.
- Keck, E., 1991. AKW kaolins and feldspars for the ceramic industry. *Ceram. Forum Int.* 68, 146–150.
- Keller, W.D., 1968. Flint clay and a flint-clay facies. *Clays Clay Miner.* 16, 113–128.
- Kelly, W.J., 1984. Review of the methylene blue test. *Ceram. Eng. Sci. Proc.* 5, 886–894.
- Khalifaoui, A., Hajjaji, M., 2009. A chloritic-illitic clay from Morocco: temperature-time-transformation and neoformation. *Appl. Clay Sci.* 45, 83–89.
- Kirov, G., Šamajova, E., Nedialkov, R., Stanimirova, T.S., 2011. Alteration processes and products of acid pyroclastic rocks in Bulgaria and Slovakia. *Clay Miner.* 46, 279–294.
- Kitagawa, R., Köster, H.M., 1991. Genesis of the Tirschenreuth kaolin deposit. *Clay Miner.* 26, 61–79.
- Kontak, D.J., Finck, P.W., DeWolfe, J., 2004. Pyrophyllite Occurrences in the Coxheath area, Cape Breton Island. Open File Rep. ME 2004–1. Nova Scotia Natural Resources, Halifax, Canada, pp. 1–18.
- Kuparidze, D., Pataridze, D., Bertolotti, G.P., 2012. Clays of Georgia for ceramic applications. *Interclay* 4, 178–183.
- Lassinanti Gualtieri, M., Romagnoli, M., Gualtieri, A.F., 2011. Influence of body composition on the technological properties and mineralogy of stoneware: a DOE and mineralogical-microstructural study. *J. Eur. Ceram. Soc.* 31, 673–685.
- Lazaro, A., García Portillo, C., De la Torre, J., Bastida, J., 2012. Características físicas y composicionales de pastas de gres porcelánico con arcillas de Teruel. *Bol. Soc. Esp. Ceram. Vidrio* 51, 201–210.
- Lee, W.E., Souza, G.P., McConville, C.J., Tarvornpanich, T., Iqbal, Y., 2008. Mullite formation in clays and clay-derived vitreous ceramics. *J. Eur. Ceram. Soc.* 28, 465–471.
- Leite, J.Y.P., Veras, M.M., Santos, E.P., Lima, R.F.S., Paulo, J.B.A., Pinheiro, M., 2007. Technological characterization of kaolin tailing from small-scale mining in RN and PB states—Brazil. *Min. Eng.* 20, 959–961.
- Levitskaya, Y.F., Omel'chenko, Y.A., Englund, A.E., 2002. Deposits of clay in Russia. *Glass Ceram.* 59, 63–68.
- Levitskii, I.A., Gailevich, S.A., Dyatlova, E.M., 1996. Floor tiles fabricated from polyminerale clays from mineral deposits of the Republic of Belarus. *Glass Ceram.* 53, 332–336.
- Levitskii, I.A., Dyatlova, E.M., Minenkova, G.Y., 1997. Clay tile from the mineral and secondary raw materials available in the Republic of Belarus. *Glass Ceram.* 54, 12–16.
- Ligas, P., Uras, I., Dondi, M., Marsigli, M., 1997. Kaolinitic materials from Romana (north-west Sardinia, Italy) and their ceramic properties. *Appl. Clay Sci.* 12, 145–163.
- Lombardo, C.A., 1996. Effect of ball clays on tile body formulations. *Ceram. Eng. Sci. Proc.* 17 (1), 156–162.
- Loric, L., Brusa, A., 1991. Porous and vitrified single-fired tiles. *Ceram. Eng. Sci. Proc.* 12 (1–2), 183–221.
- Mahmoudi, S., Srasra, E., Zargouni, F., 2008. The use of Tunisian Barremian clay in the traditional ceramic industry: Optimization of ceramic properties. *Appl. Clay Sci.* 42, 125–129.

- Malesani, P., 1992. Cotto dell'Impruneta: distribuzione areale della risorsa e caratteristiche mineralogico-petrografiche, chimiche e fisiche della materia prima. *Ceram. Inf.* 313, 223–225.
- Manju, C.S., Nair, V.N., Lalithambika, M., 2001. Mineralogy, geochemistry and utilization study of the Madayi kaolin deposit, north Kerala, India. *Clays Clay Miner.* 49, 355–369.
- Manoharan, C., Sutharsan, P., Dhanapandian, S., Venkatchalapathy, R., 2012. Characteristics of some clay materials from Tamilnadu, India, and their possible ceramic uses. *Cerâmica* 58, 412–418.
- Marghussian, V.K., Maghsoodipoor, A., 1999. Fabrication of unglazed floor tiles containing Iranian copper slags. *Ceram. Int.* 25, 617–622.
- Martin-Martin, J.D., Sanfeliu, T., Gómez-Gras, D., de la Fuente, C., Jordán, M., 2006. Caracterización litológica y mineralógica de los materiales permo-triásicos de Castellón utilizados como materia prima cerámica: la arcilla de Moró. *Bol. Soc. Esp. Ceram. Vidrio* 45, 239–244.
- Marx, T., Hennicke, H.W., 1986. Die Westerwälder Tone: Genese, Gewinnung, Eigenschaften. *Keram. Z.* 38, 195–198.
- Masson, M.R., Cristofaletti, S.R., Thomazella, H.R., Fugie, A., Zanardo, A., Alegre, V., 2000. Mapeamento e caracterização geológica/tecnológica da formação corumbataí com vistas ao seu emprego na indústria de revestimentos cerâmicos. Parte I – Geologia e correlação entre as minas e jazidas estudadas. *Ceram. Ind.* 5 (6), 24–33.
- Matsuda, T., Nagasawa, K., Tsuzuki, Y., Henmi, K., 1981. Regularly interstratified dioctahedral mica-smectite from Roseki deposits in Japan. *Clay Miner.* 16, 91–102.
- Mazza, G., 1973. Esperienze di utilizzazione di un granito caolinizzato jugoslavo in alcuni impasti bianchi da alta temperatura. *La Ceramica* 26 (2), 21–28.
- McCouston, J., Wilson, I.R., 2006. *Ball Clays, Industrial Minerals and Rocks*, 7th edition. pp. 343–356.
- Medhioub, M., Baccour, H., Jamoussi, F., Mhiri, T., 2010. Composition and ceramic properties of triassic clays from Tunisia. *J. Ceram. Process. Res.* 11, 209–214.
- Melchades, F.G., Daros, M.T., Boschi, A.O., 2010. Porcelain tiles by the dry route. *Bol. Soc. Esp. Ceram. Vidrio* 49, 221–226.
- Menezes, R.R., Ferreira, H.S., Neves, G.D.A., Ferreira, H.C., 2003. Characterization of ball clays from the coastal region of the Paraíba state. *Cerâmica* 49, 120–127.
- Meseguer, S., Pardo, F., Jordán, M.M., Sanfeliu, T., González, J., 2010. Ceramic behaviour of five Chilean clays which can be used in the manufacture of ceramic tile bodies. *Appl. Clay Sci.* 47, 372–377.
- Meseguer, S., Jordán, M.M., Pardo, F., Sanfeliu, T., 2011a. Geology and application of clays used in Castellon ceramic cluster (NE, Spain). *J. Geogr. Geol.* 3, 132–140.
- Meseguer, S., Pardo, F., Jordán, M.M., Sanfeliu, T., González, J., 2011b. Ceramic behaviour of some kaolins from Cauques Province (VII Region of Maule, Chile). *Appl. Clay Sci.* 52, 414–418.
- Mikhailova, N.A., Gryadkina, E.A., Martem'yanova, Z.S., Kolesnykova, T.Yu., 1998. Ceramic mixtures for manufacturing floor tile. *Glass Ceram.* 55, 119–120.
- Mitchell, D., Vincent, A., 1997. Exploration and appraisal of plastic sedimentary clays for the fine ceramics industry. *Appl. Clay Sci.* 11, 311–327.
- Mitchell, D., Stentford, M.J., Vincent, A., 1991. The geology, mineralogy and ceramic properties of clays of the Pearl river delta area. *Key Eng. Mater.* 53–55, 536–542.
- Mohsen, Q., El-maghraby, A., 2010. Characterization and assessment of Saudi clays raw material at different area. *Arab. J. Chem.* 3, 271–277.
- Moreno, M.M.T., Bartolomeu, D., Lima, R.H.C., 2009. Análise do comportamento de queima de argilas e formulações para revestimento cerâmico. *Cerâmica* 55, 286–295.
- Motta, J.F.M., Cabral, M.J., Tanno, L.C., Zanardo, A., 2001. As matérias-primas cerâmicas. Parte II: os minerais industriais e as massas da cerâmica tradicional. *Ceram. Ind.* 7 (1), 33–40.
- Motta, J.F.M., Cristofaletti, S.R., Garceza, L.L., Florêncio, R.V.S., Boschi, A.O., Moreno, M.M.T., Cuchierato, G., Zanardo, A., 2004. Características do pólo de revestimentos cerâmicos de Santa Gertrudes – SP, com ênfase na produção de argilas. *Ceram. Ind.* 9 (1), 1–6.
- Motta, J.F.M., Cristofaletti, S.R., Garceza, L.L., Florencio, S.R.V., Boschi, A.O., Moreno, M.M.T., Del Roveri, C., Zanardo, A., 2005. Raw materials for ceramic tiles in the Santa Gertrudes pole, Brazil. *Intereram* 54, 190–194.
- Motta, J.F.M., da Luz, A.B., Baltar, C.A.M., Becerra, M.S., Cabral, M.J., Coelho, J.M., 2008. Argila para cerâmica branca. CETEM, Rochas e Minerais Industriais: Usos e Especificações, 34 771–791.
- Moussi, B., Medhioub, M., Hatira, N., Yans, J., Hajjaji, W., Rocha, F., Labrincha, J.A., Jamoussi, F., 2011. Identification and use of white clayey deposits from the area of Tamra (northern Tunisia) as ceramic raw materials. *Clay Miner.* 46, 165–175.
- Mukhopadhyay, T.K., Das, M., Ghosh, S., Chakrabarti, S., Ghatak, S., 2003. Microstructure and thermo mechanical properties of a talc doped stoneware composition containing illitic clay. *Ceram. Int.* 29, 587–597.
- Mukhopadhyay, T.K., Ghatak, S., Maiti, H.S., 2009. Effect of pyrophyllite on the multilamination in triaxial porcelain system. *Ceram. Int.* 35, 1493–1500.
- Mukhopadhyay, T.K., Ghatak, S., Maiti, H.S., 2010. Pyrophyllite as raw material for ceramic applications in the perspective of its pyro-chemical properties. *Ceram. Int.* 36, 909–916.
- Naga, S.M., Sallam, E.M.H., Abd Elaziz, D., 1993. Assessment of some Egyptian basalt and low-grade clays for ceramic tiles manufacture. *Ind. Ceram.* 13 (3–4), 143–148.
- Naimo, D., Imperato, M., Monetti, V., Ponzana, L., Stanzione, D., 2000. Caratteristiche geochimiche e mineralogiche di argille caolinistiche di Donietzk (Ucraina) e il loro uso nel gres porcellanato. *Ceramurgia* 30, 173–176.
- Nassetti, G., 1989. Technological and productive innovations in the ceramic industry with particular reference to ceramic floor and wall tiles. *Mater. Sci. Eng.* A109, 417–425.
- Ngon Ngon, G.F., Yongue Fouateu, R., Lecomte Nana, G.L., Bitom, D.L., Bilong, P., Lecomte, G., 2012. Study of physical and mechanical applications on ceramics of the lateritic and alluvial clayey mixtures of the Yaoundé region (Cameroon). *Constr. Build. Mater.* 31, 294–299.
- Ngun, B.K., Mohamad, H., Sulaiman, S.K., Okada, K., Ahmad, Z.A., 2011. Some ceramic properties of clays from central Cambodia. *Appl. Clay Sci.* 53, 33–41.
- Njoya, D., Hajjaji, M., Njopwouo, D., 2012. Effects of some processing factors on technical properties of a clay-based ceramic material. *Appl. Clay Sci.* 65–66, 106–113.
- Nyakairu, G.W.A., Kurzweil, H., Koeberl, C., 2002. Mineralogical, geochemical, and sedimentological characteristics of clay deposits from central Uganda and their applications. *J. Afr. Earth Sci.* 35, 123–134.
- Pardo, F., Meseguer, S., Jordan, M.M., Sanfeliu, T., Gonzalez, I., 2011. Firing transformations of Chilean clays for the manufacture of ceramic tile bodies. *Appl. Clay Sci.* 51, 147–150.
- Parveen, S., Jahan, S.A., 2010. Investigation on physico-chemical properties of vitreous china sanitary ware from local clays. *Bangladesh J. Sci. Ind. Res.* 45, 387–392.
- Petrick, K., Diedel, R., Peuker, M., Dieterle, M., Kuch, P., Kaden, R., Krolla-Sidenstein, P., Schuhmann, R., Emmerich, K., 2011. Character and amount of I-S mixed-layer minerals and physical-chemical parameters of two ceramic clays from Westerwald, Germany: implications for processing properties. *Clays Clay Miner.* 59, 58–74.
- Petrov, P., Parvanov, B., 1994. Clay deposits in Bulgaria. *Bull. Geol. Soc. Greece* 30, 295–300.
- Polidori, E., 2003. Proposal for a new plasticity chart. *Geotechnique* 53, 397–406.
- Radosavljevic, S., Stojanovic, M., Brankovic, A., 1994. Ceramic clays of Tamnava tertiary basin (west Serbia). *Ind. Ceram.* 14, 155–158.
- Raimondo, M., Dondi, M., Zanelli, C., Guarini, G., Gozzi, A., Marani, F., Fossa, L., 2010. Processing and properties of large-sized ceramic slabs. *Bol. Soc. Esp. Ceram. Vidrio* 49, 307–314.
- Reh, H., 1991. Steps in development of floor tile technology. *Ceram. Eng. Sci. Proc.* 12 (1–2), 1–12.
- SACMI, 1986. Technological notes on the manufacture of ceramic tiles (Imola, Italy).
- SACMI, 2001. Applied ceramic technology (La Mandragora, Imola, Italy).
- Saikia, N.J., Bharali, D.J., Sengupta, P., Bordoloi, D., Goswamee, R.L., Saikia, P.C., Borthakur, P.C., 2003. Characterization, beneficiation and utilization of a kaolinite clay from Assam, India. *Appl. Clay Sci.* 24, 93–103.
- Sánchez, E., García, J., Sanz, V., Ochandio, E., 1990. Raw material selection criteria for the production of floor and wall tiles. *Tile Brick Int.* 6 (4), 15–21.
- Sánchez, E., Barba, A., Feliu, C., García, J., Ginés, F., Sanz, V., 1997. *Matérias primas para la fabricación de soportes de baldosas cerámicas*, 1st ed. Instituto de Tecnología Cerámica, Castellón, Spain.
- Sánchez, E., García-Ten, J., Sanz, V., 2010. Porcelain tile: almost 30 years of steady scientific-technological evolution. *Ceram. Int.* 36, 831–845.
- Sánchez-Soto, P.J., Pérez Rodríguez, J.L., 1998. Características generales, propiedades, yacimientos y aplicaciones de pirofilita. II. Yacimientos, aplicaciones y utilización como materia prima cerámica. *Bol. Soc. Esp. Ceram. Vidrio* 37, 359–368.
- Saqa, W.A., Dwairi, I.M., Akhal, H.M., 1995. Sedimentology, mineralogical evaluation and industrial applications of the Pleistocene Al-Yamaniyyah clay deposits, near Aqaba, Southern Jordan. *Appl. Clay Sci.* 9, 443–458.
- Scott, P.W., Hart, F.W., Smith, D., 1996. The quantitative mineralogy of ceramic grade kaolin from the St. Austell granite and its relationship to chemistry and physical properties. *Proc. Ussher Soc.* 9, 91–96.
- Sedmale, G.P., Sedmalis, U.Ya., 2000. Sintered ceramic materials produced from hydromica clays. *Glass Ceram.* 57, 26–28.
- Seli, H., Bujang, J., Ahmad, Z.A., 2013. Preliminary evaluation of Mukah clay deposits. *Adv. Mater. Res.* 620, 458–463.
- Sergievich, O.A., Dyatlova, E.M., Malinovskii, G.N., Barantseva, S.E., Popov, R.Yu., 2012. Particulars of the chemical mineralogical composition and properties of kaolins from Belorussian deposits. *Glass Ceram.* 69, 94–98.
- Serra, M.F., Conconi, M.S., Suarez, G., Aglietti, E.F., Rendtorff, N.M., 2013. Firing transformations of an argentinean calcareous commercial clay. *Cerâmica* 59, 254–261.
- Seynou, M., Millogo, Y., Quedraogo, R., 2012. White paste for stoneware tiles for pavement using raw clay material from Burkina Faso. *Mater. Struct.* 46, 755–763.
- Siddiqui, M.A., Ahmed, Z., Saleemi, A.A., 2005. Evaluation of Swat kaolin deposits of Pakistan for industrial uses. *Appl. Clay Sci.* 29 (2005), 55–72.
- Sikalidis, C., Minopoulos, P., 1994. Chemical, mineralogical and technical characteristics of natural clays from Macedonia, N. Greece and their evaluation for ceramics. *Bull. Geol. Soc. Greece* 30, 581–589.
- Silva, F.A.N.G., Luz, A.B., Sampaio, J.A., Bertolino, L.C., Scorzelli, R.B., Duttine, M., da Silva, F.T., 2009. Technological characterization of kaolin: study of the case of the Borborema-Seridó region (Brazil). *Appl. Clay Sci.* 44, 189–193.
- Singer, F., Singer, S.S., 1963. *Industrial Ceramics*. Chapman & Hall, London.
- Skidan, B.S., Mosienko, N.A., Zemlyakova, Z.F., Ermakova, V.B., 1999. Use of kaolin from the Zhuravlinyi Log deposit in the production of high-voltage insulators. *Glass Ceram.* 56, 184–186.
- Sousa, S.J.G., Holanda, J.N.F., 2005. Avaliação das propriedades físico-mecânicas de uma massa cerâmica para revestimento poroso (Bill). *Cerâmica* 51, 70–76.
- Souza Costa, D.M.N., Zanardo, A., Torres Moreno, M.M., 2007. Características químicas mineralógicas e cerâmicas das argilas da mina Granisso, Cordeirópolis-SP. *Ceram. Ind.* 12 (1/2), 22–26.
- Stentford, M.J., 2005. Industrial applications of kaolins and clays: General considerations and markets. *Int. Ceram. J.* 49–53 (June).
- Stock, D., 2012. World production and consumption of ceramic tile. *Tile Today* 77, 30–37.
- Taj, R.J., El-Maghraby, M.S., Maddah, S.S., Hegab, O.A., Basyoni, M.H., Serry, M.A., 2006. Assessment of some Saudi kaolin-bauxite deposits for ceramic industries. *Ind. Ceram.* 26, 1–9.
- Tenorio Cavalcante, P.M., Dondi, M., Ercolani, G., Guarini, G., Melandri, C., Raimondo, M., Rocha e Almendra, E., 2004. The influence of microstructure on the performance of white porcelain stoneware. *Ceram. Int.* 30, 953–963.

- Tontrakoon, J., Breen, D., 1978. Quantitative analysis of a ceramic clay. *J. Sci. Soc. Thailand* 4, 113–126.
- Trindade, M.J., Dias, M.L., Coroado, J., Rocha, F., 2010. Firing tests on clay-rich raw materials from the Algarve basin (southern Portugal): study of mineral transformations with temperature. *Clays Clay Miner.* 58, 188–204.
- Tsirambides, A., 2004. Genesis and physical characteristics of the neogene red beds from the Cedar Hills of Thessaloniki, Macedonia, Greece. *Bull. Geol. Soc. Greece* 36, 708–716.
- Tsolis-Katagas, P., Papoulis, D., 2004. physical and chemical properties of some Greek kaolins of different environments of origin. *Bull. Geol. Soc. Greece* 36, 130–138.
- Türkmenoğlu, A.G., Yavuz-Işik, N., 2008. Mineralogy, chemistry and potential utilization of clays from coal deposits in the Kütahya province, Western Turkey. *Appl. Clay Sci.* 42, 63–73.
- Various Authors, 2000–2008. Raw materials preparation and forming of ceramic tiles. Drying and firing of ceramic tiles. Glazing and decoration of ceramic tiles. The end-of-line system and complementary activities, 4 vol. SALA, Modena.
- Vasić, R.M., Slobodan, M., 1988. Possibility of the use of tuff as a potential and cheaper raw material in the production of ceramic floor tiles. *Mater. Sci. Forum* 34–36, 937–940.
- Vázquez, F., Torres, L.M., Garza, L.L., Martínez, A., López, W., 2009. A Mexican kaolin deposit: XANES characterization, mineralogical phase analysis and applications. *Mater. Constr.* 59, 113–121.
- Vieira, C.M.F., Monteiro, S.N., 2012. Firing behaviour of a clayey ceramic body for rustic floor tiles. *Mater. Sci. Forum* 727–728, 959–964.
- Vieira, C.M.F., Peçanha Jr., L.A., Monteiro, S.N., 2006. Effect of kaolinitic clays from the State of Rio de Janeiro in the composition of whiteware floor tile bodies. *Cerâmica* 52, 138–145.
- Viti, C., Lupieri, M., Reginelli, M., 2007. Weathering sequence of rhyolitic minerals: the kaolin deposit of Torriella (Italy). *N. Jb. Mineral. (Abh.)* 183, 203–213.
- Wattanasiriwech, D., Srijan, K., Wattanasiriwech, S., 2009. Vitrification of illitic clay from Malaysia. *Appl. Clay Sci.* 43, 57–62.
- Wenli, Z., Jianguo, J., 2011. A Method for the determination of ceramic paste plasticity. *Adv. Mater. Res.* 177, 594–597.
- Wilson, I.R., 1998. The constitution, evaluation and ceramic properties of ball clays. *Cerâmica* 44, 88–117.
- Wilson, I.R., 2004. Kaolin and halloysite deposits of China. *Clay Miner.* 39, 1–15.
- Wilson, I.R., Jiranek, J., 1995. Kaolin deposits of the Czech Republic and some comparisons with south-west England. *Proc. Ussher Soc.* 8, 357–362.
- Wilson, I.R., de Souza Santos, H., de Souza Santos, P., 2006. Kaolin and halloysite deposits of Brazil. *Clay Miner.* 41, 697–716.
- Worasith, N., Goodman, B.A., Neamp An, J., Jeyachoke, N., Thiravetyan, P., 2011. Characterization of modified kaolin from the Ranong deposit Thailand by XRD, XRF, SEM, FTIR and EPR techniques. *Clay Miner.* 46, 539–559.
- Worrall, W.E., 1975. *Clays and Ceramic Raw Materials*. Applied Science Publishers, London.
- Wyszomirski, P., Galos, K., 2009. Polish clayey raw materials for the production of ceramic tiles. *Clay Miner.* 44, 497–509.
- Yanik, G., 2011. Mineralogical, crystallographic and technological characteristics of Yaylayolu kaolin (Kütahya, Turkey). *Clay Miner.* 46, 397–410.
- Yanik, G., Esenli, F., Uz, V., Esenli, V., Uz, B., Kulah, T., 2010. Ceramic properties of kaolinized tuffaceous rocks in Kesan region, Thrace, NW Turkey. *Appl. Clay Sci.* 48, 499–505.
- Yavuz, O., Kayaci, K., Kucuker, A.S., Ozdamar, S., Uzun, M., Yanik, G., Kara, A., 2011. Characterization of underclays from Agacli-Kemberburgaz region of Istanbul/Turkey and their evaluation for porcelain tile production. *Ind. Ceram.* 31 (3), 183–191.
- Zalba, P.E., 1979. Clay deposits of Las Aguilas Formation, Barker, Buenos Aires Province, Argentina. *Clays Clay Miner.* 27, 433–439.
- Zanelli, C., Dondi, M., Guarini, G., Raimondo, M., Iglesias, C., Domínguez, E.A., Ullmann, R., 2011a. Improving the technological performances of Argentinian ball clays: A case study from Patagonia, Argentina. *CFI/DKG* 88, E1–E4.
- Zanelli, C., Guarini, G., Raimondo, M., Dondi, M., 2011b. The vitreous phase of porcelain stoneware: composition, evolution during sintering and physical properties. *J. Non-Cryst. Solids* 357, 3251–3260.
- Zaykov, V.V., Udachin, V.N., 1994. Pyrophyllite and pyrophyllite raw materials in the sulfide-bearing areas of the Urals. *Appl. Clay Sci.* 8, 417–435.
- Zhang, L., Xiao, S., Chen, S., Chen, X., Dong, C., Zhang, Y., 2013. Performance study of composite clay instead of a single plastic clay. *Adv. Mater. Res.* 652–654, 294–297.