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Chemical, mineralogical and ceramic properties of kaolinitic materials from the Tresnuraghes mining district (Western Sardinia, Italy)

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Abstract

Kaolinitic materials crop out in the Tresnuraghes mining district (Western Sardinia, Italy). Three main kaolinitic deposits, located in the Patalza, Salamura and Su Fongarazzu areas, respectively, were investigated in order to assess their potential in the ceramic industry. The parent rock-types of this raw material are the Oligocene-Miocene rhyolitic-rhyodacitic ignimbrites. Chemical and mineralogical analyses were performed on representative samples of each deposit, by XRD and XRF methodologies. The chemical analyses generally show high silica and low alumina contents in all samples, typical of weakly kaolinized materials. The main mineralogical association consists of kaolinite and cristobalite with quartz and smectite as the minor components. Alunite may be present as a main mineral in the Salamura and Su Fongarazzu deposits, making these clay materials unsuitable for ceramic applications. The Patalza deposit exhibits low iron and sulphur contents, but low plasticity and excessive refractoriness. The Patalza materials can be used as unconventional raw materials to replace both kaolin and silica in white-firing bodies. Results show that the introduction of the Patalza "kaolins" was well tolerated in bodies for tableware, wall and floor tiles, without significant changes in porosity, bulk density, pore size distribution and coefficient of thermal expansion. The main drawback of using the Patalza material is the slight increase of firing shrinkage, while the main advantage is a systematic increase in mechanical resistance.

Key words: applied mineralogy, ceramics, kaolinitic materials, Miocene, Oligocene

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1. Introduction

The main Sardinia kaolinitic mining districts (Fig. 1) are located in the Northern and Western (Romana and Tresnuraghes) and Southern zones of the island (Serrenti-Furtei).

At present, only the Romana kaolin district (Ligas et al., 1997), was characterized both for the composition and the technological behaviour of its material. The Serrenti-Furtei district has been not studied because of the presence of pyrite, widespread in all deposits cropping out in the area (Asunis et al., 1983; Marini et al., 1992) and making these materials unsuitable for an use in the ceramic industry.

The investigations of the Tresnuraghes mining district conclude the studies on the composition and ceramic properties of the kaolinitic materials of Sardinia.

The Tresnuraghes area includes three main kaolinitic deposits (Salamura, Su Fongarazzu and Patalza) which have been mined in the past by open pits. These deposits have been investigated by several authors (Carboni et al., 1984; Garbarino and Palomba, 1990;

Garbarino et al., 1991; Garbarino et al., 1994) from the geological and chemical-mineralogical standpoints.

Several bulk samples were collected from each deposit for their chemical-mineralogical and technological characterization, in an attempt to highlight the relationships between the ceramic behaviour and the composition of clays.

2. Geological setting

Figure 1 shows the geological setting of the investigated area and the location of the kaolinitic deposits studied. A Tertiary volcanic formation consists of an alternance of ignimbrites and products related to other explosive phenomena, these latter represented by breccias and tuffs. The Oligocene-Miocene rhyolitic-rhyodacitic ignimbrites can be distinguished into two lithotypes, as far as regards their macro- and microscopic characteristics. The older lithotype consists of reddish or pinkish rocks, characterized by a fluidal texture due to an alternance of thin white, pink and red layers of variable thickness. The overlying lithotype is violet-pink in colour and characterized by the presence of the "piromeridi", spherical structures with diameter ranging from a few μm to a few mm (Garbarino and Palomba, 1990). The "piromeridi" originated by a radial growth of cristobalite and kaolinite minerals around a core, ranging from microscopic size to 5-6 mm in diameter. The most important kaolinization phenomena, for intensity and extension, are restricted to the former lithotype because of the texture and porosity of the rocks (Garbarino et al., 1991).

The Langhian-Helvetian marine sediments (Carboni et al., 1984) overlie the volcanic formation. An older facies consists of a polygenic conglomerate with carbonate cement and fossil ostree; the later facies mainly consist of sandstones, arenaceous marls and grey fossiliferous limestones (Cherchi, 1985). The basaltic Pliocene-Pleistocene volcanic rocks, in association with breccias and tuffs, close the geological succession.

The Tresnuraghes area was affected by the Tertiary and Quaternary extensive tectonics with regional E-W and NW-SE trending structures (Cherchi and Montadert, 1984). Fractures and faults make up a thick network. The fluvial network of the area is strongly affected by the tectonics. The structural network enhanced the kaolinization process, favouring the permeation and circulation of the fluids within the rocks (Carboni et al., 1984; Padalino et al, 1999).

3. Sampling and methods

Representative big samples from the Salamura and Su Fongarazzu deposits, were collected (SA and SF respectively). Taking into account the heterogeneity of Patalza materials (Carboni et al., 1984), three samples, representing three different grades of alteration (PB, PM and PS), were collected. A composite sample was also made by mixing the three Patalza samples (PX). All samples were ground, homogenized, split and analyzed in order to assess their ceramic behaviour and composition.

Mineralogical analyses were performed by X-ray diffraction analysis, utilizing a Rigaku diffractometer operating with Cu tube at 30 kV and 30 mA. Mineral identification was carried out by comparison with the Powder Diffraction File (JCPDS, 1995). Quantitative mineralogical composition was obtained using the method of Fabbri et al. (1986). Chemical analyses were carried out by a Philips PW 1400 XRF spectrometer, operating with Rh tube at 30kV and 60 mA.

The ceramic properties were studied on a laboratory scale using the same processing procedures as that the ceramic industry. For this purpose, the samples were wet ground in porcelain jar with alumina grinding media. Powders of ground materials were characterized by particle size analysis (Micromeritics SediGraph 5100), humidified and pressed in bars (30 MPa, 110 x 55 x 5 mm). These bars were then dried in oven (105 ± 5℃) and fired with an electric roller kiln (maximum temperature of 1200℃; 60 minutes cold-to-cold). Unfired samples were characterized measuring pressing expansion, drying shrinkage, green and dry bend strength (standard EN 100), and compressibility index (ratio between the thickness of the powders in the mould and the thickness of the pressed specimen). Fired samples were characterized determining firing shrinkage, water absorption (EN 99), and bend strength (standard EN 100). Pressing expansion ($100 (L_g – L_m)L_m^{-1}$), drying shrinkage ($100(L_g – L_d)L_g^{-1}$) and firing shrinkage ($100(L_m – L_f)L_m^{-1}$) were determined considering L_m the length of the mould, and L_g, L_d and L_f the length of the green, dry and fired bars respectively. The coefficient of linear thermal expansion (CTE) was determined by thermodilatometry (gradient 10℃ · min $^{-1}$) in the range 20 – 400 ℃. Phase composition of the ceramic materials was performed by XRD with the RIR method (Dondi et al., 1997).

4. Mineralogical and chemical composition and its importance for ceramic applications

The Salamura material consists mainly of kaolinite and cristobalite with a minor amount of alunite. The Fongarazzu material shows cristobalite and kaolinite as main minerals; alunite and quartz are minor. The Patalza material is free of alunite. These results confirm the previously published information about these materials (i.e. Carboni et al., 1984; Garbarino et al., 1991). The less altered sample from Patalza (PS) consists mainly of cristobalite with minor kaolinite and traces of smectite. The medium altered sample (PM) has a similar mineral composition, but with a lower content of cristobalite. The more altered sample (PB) shows a slight increase of kaolinite with respect to cristobalite; quartz and smectite are minor. The composite sample (PX) shows cristobalite and kaolinite as main minerals; quartz and smectite are minor (Table 1).

Table 2 lists the chemical composition of the studied materials compared to the average chemical data (Tab. 2) obtained by previous studies (Carboni et al., 1984; Garbarino et al., 1991). The Salamura and Su Fongarazzu materials show higher content in Al_2O_3 than the Patalza materials. They contain 4.0 and 2.7 wt% SO_3 respectively, indicating the presence of alunite. Na_2O content could be related to the presence of minor amounts of natroalunite. This feature makes these raw materials unsuitable for ceramic applications. In fact, alunite induces many problems during processing. For example, it is detrimental for the rheological properties of slips, it produces efflorescence after drying, and it releases SO_x during firing.

The Patalza samples are characterized by higher silica and lower alumina contents than a typical kaolin (Ligas et al., 1997) or commercial ball clay (Fabbri and Fiori, 1985). On the other hand, the Patalza materials contain lower amounts of iron, titanium, alkaline-earth and alkaline elements than those of typical ball clays (Figure 2). Overall, the mineralogical and chemical composition of the Patalza kaolins shows both favourable and adverse aspects for ceramic applications.

The favourable characteristics are:

- a simple mineralogical association, mainly represented by kaolinite plus silica phases;
- the prevalence of kaolinite to smectite;

- the considerably low iron amount, particularly if referred to a clay material, which allows these kaolins to be potentially used in white body production (Fiori et al., 1989).

Nevertheless, the most relevant limitations, which could cause many problems in the ceramic manufacturing, can be summarized as follows:

- the abundance of silica phases, prevailing on clay minerals, making these materials poorly plastic and unsuitable to be used as ball clays;
- the abundance of cristobalite, which can cause two different drawbacks: (1) an undesired increase of the coefficient of thermal expansion of the ceramic products and (2) occurrence of cracks during firing, due to the stress deriving from the $\alpha \leftrightarrow \beta$ polymorph transition of cristobalite around 250℃ (Stevens et al., 1997).

5. Technological properties

5.1 Tests on kaolins

The results of technological testing are summarized in Table 3. The behaviour during the pressing and drying processes is highlighted as follows:

- quite high pressing expansion (0.6 – 0.8 $cm \cdot m^{-1}$);
- slight expansion after drying;
- very low mechanical strength, both of green (0.1-0.6 MPa) and dry bodies (0.3-1.6 MPa).

These characteristics are consistent with the mineralogical composition, poor of plastic components and rich of silica phases. The amount of smectite is clearly too scarce to contribute significantly to the mechanical performances, as the relatively fine particle size distribution (Fig. 3).

As far as the firing behaviour is concerned, it can be emphasized that the Tresnuraghes kaolins present:

- a high porosity after treatment at 1200℃ (35-40% water absorption);
- a relatively high linear shrinkage (1.7-2.2 $cm \cdot m^{-1}$) if referred to the porosity of products;
- a very low mechanical resistance (<3.5 MPa) largely depending on the high porosity of fired specimens;
- strong emissions of SO_x during the firing of the Salamura and Su Fongarazzu kaolins;
- a very high coefficient of thermal expansion (17-21 MK^{-1}).

Overall, this refractory behaviour is explained by the phase composition of the fired kaolins: essentially cristobalite (68-75%), mullite (16-18%) and minor residual amounts of quartz (Tab. 4). The amorphous phase is scarce (8-12%) due to the limited amounts of fluxing impurities in the kaolins (iron oxides, alkaline and alkaline–earth elements). The considerable increase of cristobalite after firing is resulted from the reactions (a) kaolinite → mullite + cristobalite and (b) quartz → cristobalite.

In conclusion, the Salamura and Su Fongarazzu materials cannot be used for ceramic applications. The Patalza kaolins are unsuitable to be used as ball clay substitute in ceramic bodies, however, they may be utilised as unconventional raw materials to partially replace kaolinitic clays and/or silica.

5.2 Tests on ceramic bodies

In order to assess the possibility of using the Patalza kaolins as unconventional raw materials, three different ceramic products were taken into account:

- porous wall tiles: the so called “white monoporosa” (Biffi, 1989; Lorici and Brusa, 1991);

- sintered floor tiles: porcelain stoneware (Dondi et al., 1999);
- porous tableware: white earthenware (Singer and Singer, 1963).

Starting from three classical industrial formulations (MB0, GP0 and TF0 of Tab. 5), three new bodies were designed, introducing a moderate amount of the Patalza kaolin (10 wt%) in contemporaneous replacement of both quartzite and kaolin or ball clay (MB3, GP3 and TF2 of Table 5). These new formulations were designed as closer as possible to the mineralogical and chemical composition of the reference bodies (Tab. 6). The results of technological tests aimed at reproducing at a laboratory scale the industrial manufacturing of tableware, wall and floor tiles, are summarised in Table 7.

The introduction of the Patalza kaolin had significant effects on the technological properties of both semi-finished and fired products. Overall, the bodies containing this kaolinitic material, with respect to the reference ones, exhibit the following properties:

- slightly higher values of pressing expansion, however within the current technological requirements (Lorici and Brusa, 1991);
- higher mechanical strength, maybe connected with the better compressibility of powders and partly with the slightly higher working moisture;
- limited increase of the firing shrinkage, which appears to be negligible for porcelain stoneware and in any event tolerable for *monoporosa* and earthenware;
- substantial stability of the values of porosity, bulk density and pore size distribution;
- modest changes of the coefficient of thermal expansion, always within the usual product requirements.

These variations of the technological properties seem to be justified to a large extent by the changes in the phase composition of ceramic materials (Tab. 6).

In the wall tiles, there is a balance between the amounts of quartz in the reference body and the sum of quartz + cristobalite in the body MB3. This circumstance can explain the almost identical coefficient of thermal expansion. The presence of the Patalza material, on the other hand, seems to promote the formation of anorthite during firing, which would justify the increased values of both firing shrinkage and bend strength (Ibanez et al., 1992; Yekta and Alizadeh, 1996).

As porcelain stoneware is concerned, the introduction of the Patalza kaolin brought to a reduction of residual quartz after firing, probably promoting its dissolution into the liquid phase (Demidova, 1978). This could explain the decrease of the coefficient of thermal expansion and porosity as well as the increase of shrinkage and mechanical strength registered for the body GP3.

The variations of the properties of the two tableware bodies are often within the uncertainty range of measurements. This situation probably reflects the very similar phase composition of the products TF0 and TF2.

6. Conclusions

The kaolinitic materials in the Tresnuraghes District are characterized by cristobalite, kaolinite and smectite. The presence of significant amount of alunite make the Salamura and Su Fongarazzu kaolins unsuitable as ceramic raw materials.

Very low iron amounts give Patalza raw materials some interesting potential for ceramic applications in white-firing bodies. A high level of cristobalite is detrimental to the technological properties. For example, the Patalza kaolinitic material has insufficient plasticity and an excessively refractory behaviour during firing.

Nevertheless, Patalza raw materials could be used in small amounts (about 10 wt% of the ceramic body) replacing simultaneously more expensive industrial minerals, such as

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kaolin and quartzite. The introduction of the Patalza materials in three industrial bodies for tableware, wall tiles and floor tiles proved to be well tolerated, without significant changes of the porosity, bulk density, pore size distribution and coefficient of thermal expansion. The main drawback appears to be a slight increase of the firing shrinkage, which is compensated by the advantage of a systematic increase of the mechanical strength, both in fired and unfired bodies.

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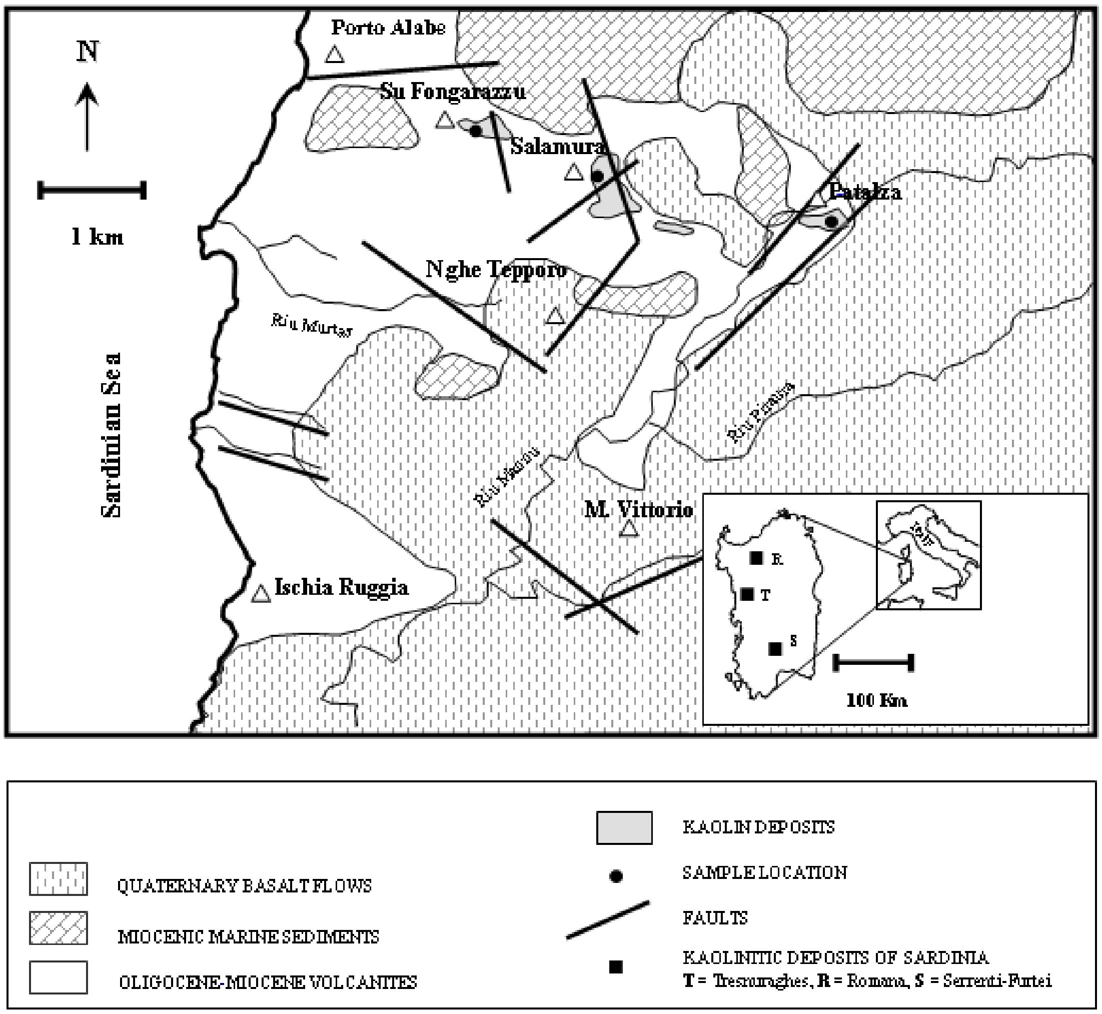

Fig. 1. Geological map of the Tresnuraghes mining district (modified after Padalino et al., 1999) and location of the main occurrences.

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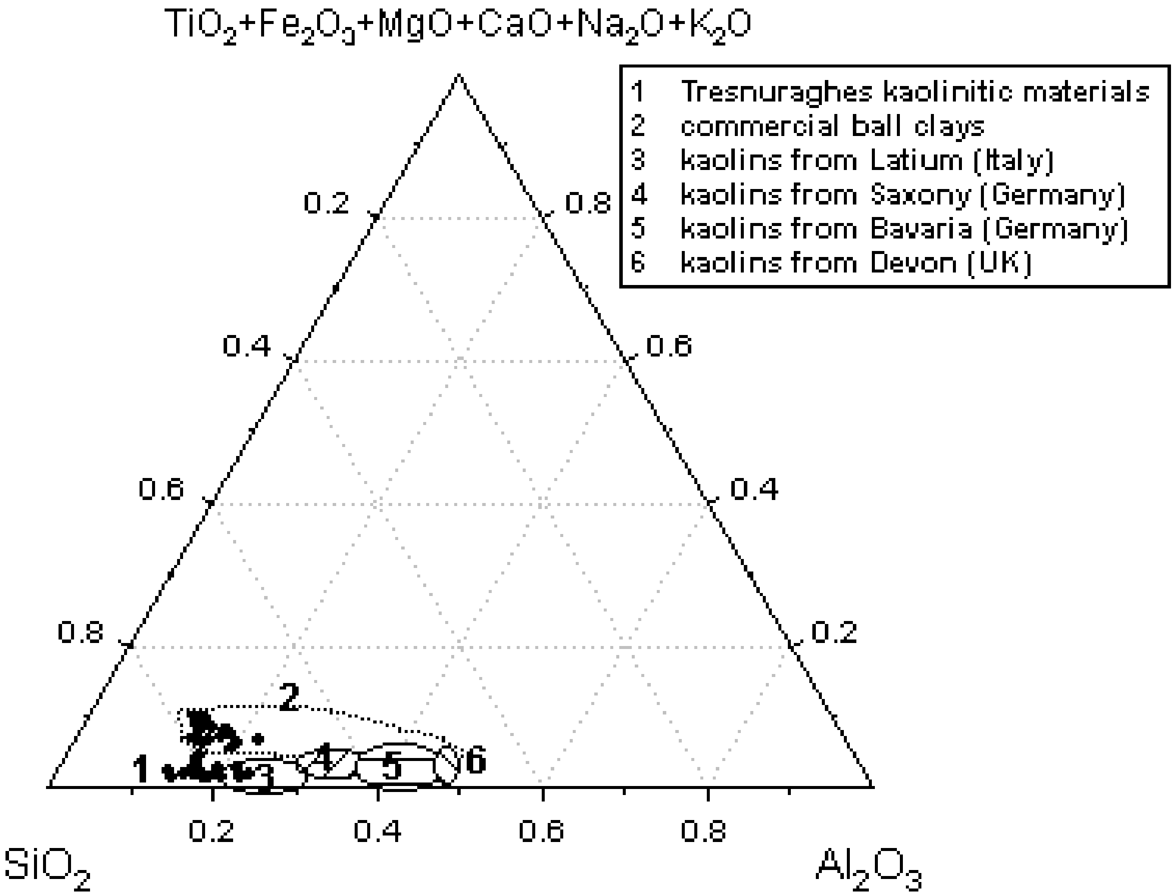

Fig. 2. Ternary diagram SiO_2-Al_2O_3-other oxides of the kaolinitic materials from the Tresnuraghes district and comparison with the chemical composition of commercial kaolins (Ligas et al., 1997) and ball clays (after Fabbri and Fiori, 1985).

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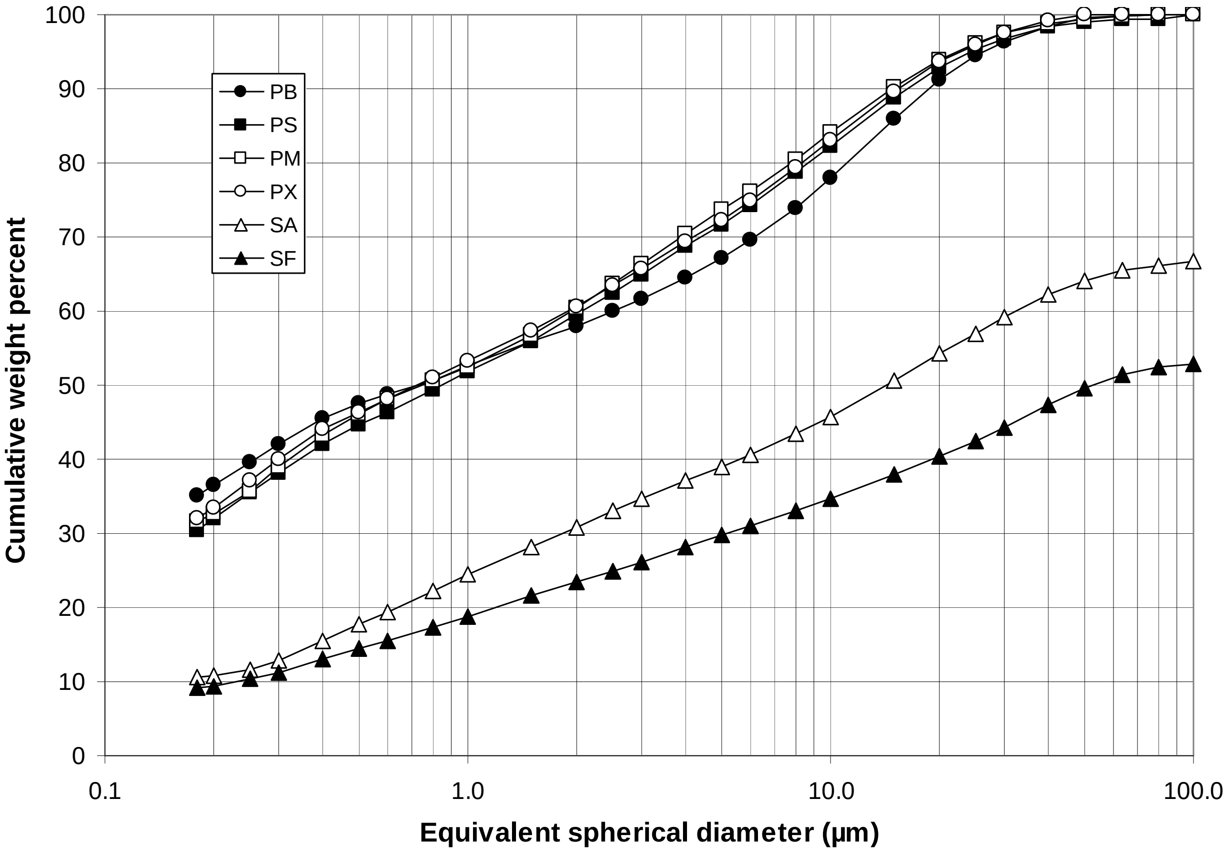

Fig. 3. Particle size distribution of kaolinitic materials from the Tresnuraghes district. The Patalza samples are wet ground, while the Salamura and Su Fongarazzu kaolins are dry ground.

Table 1
Mineralogical composition of the kaolinitic materials from the Patalza deposit.

wt%	PB	PM	PS	PX
Kaolinite	35	35	36	35
Smectite	9	10	9	8
Cristobalite	43	49	51	50
Quartz	11	3	2	5
Accessories	2	3	2	2

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Table 2
Chemical composition of the kaolinitic materials from the Tresnuraghes district.

wt%	Salamura			Su Fongarazzu			Patalza					
	Garbarino et al. (1991)		this work	Garbarino et al. (1991)		this work	Carboni et al. (1984)		this work			
	average (n = 30)	std.dev.	SA	average (n = 11)	std.dev.	SF	average (n = 45)	std.dev.	PB	PM	PS	PX
SiO_2	69.53	3.83	66.95	69.25	3.25	68.38	74.45	2.74	74.80	73.42	74.30	75.42
TiO_2	0.15	0.02	0.16	0.15	0.01	0.16	0.11	0.05	0.09	0.08	0.13	0.05
Al_2O_3	16.80	1.09	18.65	18.09	1.68	19.12	15.89	2.31	16.18	16.69	16.55	16.03
Fe_2O_3*	1.37	0.66	0.59	0.85	0.47	1.00	0.80	0.35	0.67	1.04	0.63	0.54
MnO	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.03	0.01	0.01	0.01	0.01
MgO	0.44	0.28	1.29	0.29	0.17	0.23	0.19	0.17	0.37	0.43	0.33	0.24
CaO	0.11	0.03	0.06	0.16	0.08	0.18	0.18	0.08	0.18	0.36	0.21	0.13
Na_2O	0.65	0.41	1.28	0.54	0.38	0.31	1.10	0.73	0.32	0.36	0.33	0.26
K_2O	1.51	1.09	0.96	1.46	1.27	1.01	2.73	2.30	0.30	0.28	0.31	0.28
P_2O_5	0.04	0.04	0.03	0.03	0.01	0.02	0.02	0.01	0.03	0.19	0.03	0.02
SO_3	4.04	2.85	4.03	3.11	2.32	2.74	<0.01	-	<0.01	<0.01	<0.01	<0.01
L.o.I.	5.46	0.66	5.99	6.08	1.06	6.82	4.53	2.29	7.06	7.13	7.10	7.03

*total iron as Fe_2O_3

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Table 3
Technological properties of the kaolinitic materials from the Tresnuraghes district.

Technological property	Unit	Salamura	Su Fongarazzu	Patalza Quarry			
		SA	SF	PB	PM	PS	PX
Working moisture	wt %	11.6	10.2	6.9	5.9	6.3	5.6
Compressibility index	adim.	2.5	3.0	2.3	2.5	2.5	2.4
Pressing expansion	$cm \cdot m^{-1}$	0.7	0.6	0.6	0.8	0.6	0.8
Green bend strength	MPa	0.2	0.1	0.4	0.6	0.6	0.5
Drying shrinkage	$cm \cdot m^{-1}$	-0.2	-0.2	-0.4	0.0	-0.2	-0.1
Dry bend strength	MPa	0.5	0.3	0.9	1.5	1.6	1.2
Firing shrinkage‡	$cm \cdot m^{-1}$	1.9	0.7	2.2	1.8	1.7	2.0
Water absorption‡	%wt	34.3	29.8	39.8	35.5	34.9	37.0
Fired bend strength‡	MPa	1.8	1.3	2.3	3.2	3.3	3.0
CTE* (25-400 °C)	MK^{-1}	n.d.	n.d.	17.2	21.3	21.1	20.0

‡ Maximum temperature 1200 °C, cycle 60 min cold-to- cold. *Coefficient of linear thermal expansion.
n.d. = not determined. adim. = adimensional.

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Table 4
Phase composition of the fired products obtained from the Patalza kaolinitic materials and the experimental bodies.

		Firing cycle		Phase composition (wt%)					
		Maximum temperature	Time cold-to-cold	Quartz	Cristobalite	K-feldspar	Plagioclase	Mullite	Amorphous
Kaolins	Patalza B	1200 ℃	60 min	7 ± 1	68 ± 5	-	-	17 ± 2	8 ± 3
	Patalza M	1200 ℃	60 min	-	71 ± 5	-	-	17 ± 2	12 ± 4
	Patalza S	1200 ℃	60 min	-	75 ± 5	-	-	16 ± 2	9 ± 3
	Patalza X	1200 ℃	60 min	3 ± 1	71 ± 5	-	-	18 ± 2	8 ± 3
Ceramic bodies	Monoporosa MB0	1150 ℃	50 min	44 ± 4	-	6 ± 1	18 ± 2	6 ± 1	32 ± 6
	Monoporosa MB3	1150 ℃	50 min	39 ± 4	5 ± 1	4 ± 1	27 ± 3	8 ± 1	25 ± 6
	Porcelain stoneware GP0	1200 ℃	75 min	25 ± 3	-	-	2 ± 1	6 ± 1	66 ± 7
	Porcelain stoneware GP3	1200 ℃	75 min	15 ± 2	4 ± 1	-	3 ± 1	6 ± 1	72 ± 7
	Earthenware TF0	1170 ℃	30 h	23 ± 2	22 ± 2	-	17 ± 2	16 ± 2	22 ± 5
	Earthenware TF2	1170 ℃	30 h	24 ± 2	21 ± 2	-	17 ± 2	17 ± 2	21 ± 5

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Table 5
Formulation of the experimental bodies for ceramic tiles and tableware

Raw materials (wt %)	White Monoporosa Tiles		White Stoneware Tiles		Earthenware Tableware	
	MB0	MB3	GP0	GP3	TF0	TF2
Ball Clay A	10	10	-	-	-	-
Ball Clay E	-	-	-	-	30	30
Ball Clay T	-	-	10	10	-	-
Ball Clay U	30	30	30	26	-	-
Kaolin C	10	7	-	-	25	23
Sodium Feldspar	-	-	40	40	-	-
Potassic Pegmatite	20	20	10	14	-	-
Quartzite	20	13	10	-	35	32
Synthetic Cristobalite	-	-	-	-	5	-
Calcium carbonate	10	10	-	-	5	5
Patalza X	-	10	-	10	-	10

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Table 6
Chemical and mineralogical composition of the raw materials and the experimental bodies for ceramic tiles and tableware.

wt%	Ball Clays				Kaolin	Feldspars		Quartzite	Patalza	Experimental bodies					
	A	E	T	U	C	Na	K		PX	MB0	MB3	GP0	GP3	TF0	TF2
SiO_2	68.5	48.3	64.5	65.8	48.2	69.2	72.0	99.1	75.4	65.6	64.8	71.0	68.9	66.2	64.8
TiO_2	1.3	0.9	0.5	1.2	0.2	0.2	0.1	<0.1	0.1	0.5	0.5	0.5	0.5	0.3	0.3
Al_2O_3	18.1	31.8	22.2	21.0	35.6	18.6	17.0	0.7	16.0	15.2	15.7	17.7	19.1	18.7	19.5
Fe_2O_3	2.8	1.0	1.4	1.2	0.8	0.1	0.8	<0.1	0.5	0.9	0.9	0.6	0.7	0.5	0.6
MgO	0.6	0.3	0.9	0.6	0.3	0.1	0.4	<0.1	0.2	0.4	0.4	0.3	0.4	0.2	0.2
CaO	0.2	0.2	0.6	0.5	0.4	0.6	0.1	<0.1	0.1	5.8	5.8	0.5	0.4	3.0	3.0
Na_2O	0.2	0.3	0.3	0.4	0.1	10.4	0.6	<0.1	0.3	0.3	0.3	4.4	4.4	0.1	0.1
K_2O	1.9	1.7	0.9	2.2	1.1	0.2	5.5	0.1	0.3	2.1	2.1	1.4	1.5	0.8	0.8
L.o.I.	6.6	15.1	8.5	6.8	13.0	0.5	3.5	0.2	7.0	9.1	9.4	3.5	4.0	10.0	10.5
Quartz	40	5	31	32	3	5	35	99	7	41	34	28	20	37	35
Plagioclase	2	3	2	-	-	91	6	-	-	tr.	tr.	36	36	tr.	tr.
K-Feldspar	-	2	-	-	-	-	33	-	-	7	7	4	5	tr.	tr.
Illite-Mica	24	18	12	29	15	-	-	-	3	13	13	10	9	9	9
Kaolinite	29	66	47	32	81	3	23	-	38	26	27	18	21	40	42
Chlorite	2	-	-	-	-	-	2	-	-	tr.	tr.	tr.	tr.	-	-
Smectite	-	-	7	5	-	-	-	-	3	2	2	2	2	-	-
Calcite	-	-	-	-	-	-	-	-	-	10	10	-	-	5	5
Cristobalite	-	-	-	-	-	-	-	-	48	-	5	-	5	5	5
Accessories	3	6	1	2	1	1	1	1	1	3	4	1	2	4	4

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Table 7
Technological properties of the experimental bodies for ceramic tiles and tableware.

Technological property	Unit	White Monoporosa Tiles		White Stoneware Tiles		Earthenware Tableware	
		MB0	MB3	GP0	GP3	TF0	TF2
Working moisture	wt %	5.0	5.9	4.9	5.8	5.8	5.8
Compressibility index	adim.	4.0 ± 0.2	3.9 ± 0.1	3.8 ± 0.1	3.5 ± 0.1	4.3 ± 0.2	4.1 ± 0.2
Pressing expansion	cm·m^{-1}	0.46 ± 0.01	0.48 ± 0.01	0.50 ± 0.01	0.52 ± 0.01	0.55 ± 0.01	0.60 ± 0.01
Dry bend strength	MPa	1.0 ± 0.2	1.5 ± 0.3	0.7 ± 0.1	1.0 ± 0.12	1.3 ± 0.1	2.0 ± 0.2
Maximum firing temperature	℃	1150	1150	1200	1200	1 170	1170
Firing time (cold-to-cold)	min	50	50	75	75	1800	1800
Firing shrinkage	cm·m^{-1}	0.4 ± 0.1	0.9 ± 0.1	7.2 ± 0.1	7.4 ± 0.1	0.9 ± 0.1	1.4 ± 0.1
Bulk density	g·cm^{-3}	1.75 ± 0.01	1.74 ± 0.01	2.23 ± 0.01	2.24 ± 0.01	1.74 ± 0.01	1.75 ± 0.01
Open porosity	% vol.	26.6 ± 0.9	27.6 ± 0.9	2.6 ± 0.5	2.4 ± 0.5	28.4 ± 1.0	27.6 ± 1.0
Mean pore diameter	μm	2.5 ± 0.1	2.2 ± 0.1	0.4 ± 0.05	0.1 ± 0.05	1.4 ± 0.1	1.3 ± 0.1
Fired bend strength	MPa	9.2 ± 1.8	11.1 ± 1.0	15.0 ± 1.6	16.8 ± 1.3	9.7 ± 1.0	10.8 ± 1.0
CTE* (25-400 ℃)	MK^{-1}	7.42 ± 0.07	7.40 ± 0.07	7.86 ± 0.08	7.29 ± 0.07	8. 65 ± 0.09	9.08 ± 0.09

*Coefficient of linear thermal expansion. adim. = adimensional.