

## Evaluation of the Incorporation of Waste Generated from Titanium Dioxide Manufacturing in Red Ceramics

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Rotary-vacuum-filter mud (RVFM) is waste generated during the manufacturing process of titanium dioxide. In this work, RVFM and ceramic bricks containing different ratios of this waste are investigated. The mud samples were characterized using thermal analysis (TG/DTG). The aim of the present work was to determine the effect of adding RVFM on the ceramic properties of clay, such as apparent porosity, water absorption, linear shrinkage and flexural strength, used to produce red ceramics (bricks and roofing tiles). Samples were dried out at 110°C and fired at 800°C, 950°C and 1100°C. The addition of RVFM tends to increase the apparent porosity and water absorption and to decrease the flexural strength of the ceramic specimens. Based on the results, ceramic specimens with 20% RVFM content that are burned at 800°C can not be used as bricks, and ceramic specimens with 20% RVFM content that are fired at 800°C and 950°C can not be used as roofing tiles, according to Brazilian standards.

**Keywords:** waste recycling, mud (RVFM), titanium dioxide, red ceramic

### 1. Introduction

Titanium (Ti) is the ninth most abundant element in the earth's crust. Ti has a strong affinity for oxygen, and most of the titanium in the lithosphere is in an oxide form. Oceanic and continental crusts contain approximately 8,100 ppm and 5,300 ppm titanium, respectively<sup>1</sup>.

The largest producers of titanium ore in the world are Norway, Australia, Canada, the United States, India, China, Italy, South Africa and Brazil. The largest deposit of titanium in Brazil is located in Paraíba, in the city of Mataraca. The mine has an estimated annual production of approximately 120,000 tons of ilmenite per year and has a service life of approximately 18 years. Ilmenites (FeO·TiO<sub>2</sub>) are valuable natural sources of titanium compounds. Brazil holds 16% of the world market for titanium dioxide<sup>1</sup>, and the current mineral production has stabilized to a level of 130,000 tons per year throughout Brazil<sup>2</sup>. According to Brazilian Ministry of Mines and Energy (MME) records<sup>2</sup>, the mineable reserves of titanium as ilmenite and rutile are on the order of 7.2 Mton.

The titanium dioxide (TiO<sub>2</sub>) processing factory owned by Millennium Inorganic Chemicals (MIC) in Camaçari,

Bahia, Brazil, has a nominal production capacity of 60,000 tons of TiO<sub>2</sub>/year. This factory is the largest Brazilian producer and the world's second largest manufacturer of white pigment, which is widely used to provide whiteness and opacity to a wide range of products, such as paints, varnishes, plastics, paper and cosmetics, among others.

Worldwide, approximately 38,000 tons of Rotary-vacuum-filter mud (RVFM) are generated annually. Millennium Inorganic Chemicals (MIC) generates approximately 2,500 tons of RVFM each year, and this waste is currently disposed of in industrial landfills at CETREL, the Company Wastewater Treatment in the Camaçari Industrial Complex.

Rotary-vacuum-filter mud (RVFM) is a non-hazardous waste (class II-A) generated by the titanium dioxide manufacturing process. Titanium dioxide is a pigment used as raw material in the manufacture of paints and varnishes. This waste is produced during the filtration process of unreacted ilmenite. RVFM is similar in physical-chemical characteristics to the materials used in civil construction, such as plaster and cement; thus, RVFM has a high potential for use in civil construction. In a recent study, Gázquez et al.<sup>3</sup> performed a physico-chemical characterization of a

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TiO<sub>2</sub> slurry, and it was found to be promising for use as insulation and as a cement additive.

In recent years, there has been a growing interest in the use of industrial waste as the raw material for the manufacture of ceramic products, such as bricks and roof tiles<sup>4,5</sup>. Industrial waste, as such as welding waste<sup>6</sup> and flue waste<sup>7</sup>, are promising raw materials for the manufacture of ceramic bricks.

However, despite the great potential for RVFM use, there is no information available in the literature about RVFM's incorporation into traditional red ceramics.

The objective of this work is to characterize RVFM and ceramic bricks containing different percentages of this waste and to identify the technical possibilities of its incorporation into red ceramic products.

## 2. Material and Methods

### 2.1. Materials

In the present study, two basic raw materials were used: clay and neutralized RVFM. The clay was supplied by Ceramic Igarapé and was extracted from their quarry located in Camaçari-Bahia.

Because of the high silica (SiO<sub>2</sub>-62.92%) and alumina contents (Al<sub>2</sub>O<sub>3</sub>-17.99%), the clay that was used was characterized as predominantly kaolinitic in the literature<sup>8,9</sup>; is widely used in the production of traditional ceramics, such as bricks and roofing tiles.

The neutralized RVFM was present as a powdered solid with irregular particle size. The RVFM was collected directly from the generation stage at Millennium Inorganic Chemicals (MIC) in Camaçari, Bahia, Brazil, using waste sampling procedures specified by the Brazilian standard NBR 10007/04<sup>10</sup> ("Sampling of solid waste").

### 2.2. Methods

#### 2.2.1. Materials characterization

The particle size analysis of the clay sample was performed according to NBR 7181-84<sup>11</sup> ("Soil: Granulometric Analysis"). The real particle density was determined according to NBR 6508-84<sup>12</sup> ("Soil: Real Specific Mass"). The plasticity was determined using the Atterberg method according to NBR 6459-84<sup>13</sup> ("Soil: Determination of the Liquid Limit") and NBR 7180-84<sup>14</sup> ("Soil: Determination of the Plastic Limit") standardized procedures.

The kaolinitic clay and RVFM were characterized using chemical composition (XRF), mineralogical (XRD), microstructure (SEM) and thermal analyses (TG/DTG).

The overall chemical compositions of the clay samples and RVFM were expressed as oxide percentages. The samples were digested in an acid medium. The constituents that were present were quantified using optical emission spectrometry with induced plasma using a I VISTA Varian (IT AQ-158 version 009) spectrometer.

The mineralogical composition of RVFM was determined using X-ray diffraction (XRD) with a Philips X'Pert MPD Diffractometer configured with CuK $\alpha$  radiation, 40 KV voltage, 100 mA current, 2 $\theta$  scanning and a scanning speed of 4°/min.

The microstructures of the clay and RVFM were observed using a Scanning Electron Microscope (SEM) Philips XL-30 and an EDAX microprobe.

TG/DTA analysis was performed on a Shimadzu TGA-51 thermogravimetric analyzer with a dynamic N<sub>2</sub> atmosphere (50 mL.min<sup>-1</sup>). The heating rate was 10°C/min, and the samples were heated from 25°C to 1100°C.

#### 2.2.2. Dosage and molding of specimens

The ceramic bricks were made from a mixture of clay and water. Different amounts of RVFM was added (0%, 5%, 10% and 20% in weight), according to Table 1. To evaluate the physical-mechanical behavior of the ceramic bricks and roofing tiles containing the different levels of RVFM, prismatic specimens (220 x 21 x 7 mm<sup>3</sup>) molded by extrusion were used. An extruder screw-feeding Bonfanti with a cutting device was used.

After molding, the specimens were dried out at 110°C and fired in an electric furnace at a rate of 200°C/h until reaching their final temperatures (800°C, 950°C or 1100°C). The specimens remained at this temperature for 2 hours, at which time the process of cooling the furnace to room temperature began.

#### 2.2.3. Specimens characterization

The samples were characterized using thermogravimetry analysis (TG) and differential thermal analysis (DTG) using a Shimadzu TGA-51 thermogravimetric analyzer. The effects of the addition of RVFM on the physical and mechanical properties of the ceramic specimens were examined, including effects on apparent porosity, water absorption, linear shrinkage, and flexural strength results. For each property measurement, 5 specimens were obtained.

The apparent porosity and density were verified using a technique based on the Archimedes principle. The samples were left immersed in water for 24 hours until they became fully saturated, after which the immersed mass ( $M_i$ ) and the wet mass ( $M_w$ ) were determined. Thus, the apparent porosity ( $P_A$ ) and water absorption ( $W_A$ ) were calculated according to Equations 1 and 2, respectively<sup>8,15</sup>:

$$\%P_A = 100 \times (M_w - M_d) / (M_w - M_i) \quad (1)$$

$$W_A = 100 \times (M_w - M_d) / (M_s) \quad (2)$$

The flexural strength ( $F_s$ , kgf.cm<sup>-2</sup>) of the fired specimens corresponded to the average of 5 values for each ceramic composition and was determined using the three-point bending test (Instron model 5582) at a loading rate of 0.5 mm/min according to the following equation:

**Table 1.** Ceramic mixtures.

RVFM Contents	Clay Mass (Kg)	LRFV Mass (Kg)	H <sub>2</sub> O Mass (Kg)
0%	4.500	0.000	0.930
5%	4.500	0.236	1.000
10%	4.500	0.500	1.100
15%	4.500	0.794	1.170
20%	4.500	1.125	1.350

$$F_s = (3.P.L) / (2.b.d^2) \quad (3)$$

where P is the maximum applied load (Kgf), L is the material span length between the points in the test setup (cm), b is the width of the material sample (cm) and d is the average specimen depth (cm). Prismatic specimens (220 x 21 x 7 mm<sup>3</sup>) that exhibited an error of more than 5% were excluded and replaced by others.

The linear shrinkage was determined using the following Equation 4:

$$RL(\%) = (L_s - L_q) / (L_q) \quad (4)$$

where L<sub>s</sub> is the length (cm) of the sample after drying at 105 ± 5°C, and L<sub>q</sub> is the length (cm) of the sample after burning.

#### 2.2.4. Leaching and solubilization tests

Wastes and composites containing wastes are classified as “hazardous” (class I) or “non-hazardous” (II-A non-inert, and II-B inert) according to the Brazilian standard NBR 10004<sup>16</sup> (“Solid waste - Classification”).

### 3. Results and Discussion

#### 3.1. Materials characterization

The kaolinitic clay powder sample exhibited a wide range of particle sizes (1 to 180 μm), in which the major size ranges were clay (<2 μm) at 29%, silt (2 ≤ x < 63 μm) at 54%, and sand (>63 μm) at 17%. The plasticity of the clay sample was evaluated using Atterberg’s consistency limits. The plasticity values for the clay sample were within the acceptable range for the industrial processing of red ceramics (Table 2).

Table 3 shows the composition of the RVFM and kaolinitic clay, which was obtained by XRF, and Figure 1 shows the microstructure, which was determined using SEM analysis.

The iron oxide (Fe<sub>2</sub>O<sub>3</sub>) and titanium dioxide (TiO<sub>2</sub>) reduce the plasticity of the clay, as well as their refractoriness. Thus, the solid mixture was manually homogenized and an increasing amount of water (Table 1) was added until they reach the point of plasticity for extrusion.

The main chemical compounds detected in the clay and RVFM, obtained by XRD, are shown in Figure 2 and are summarized in Table 4.

The XRD results shown in Figure 2a confirm that the typical composition of the clay was predominantly kaolinite. Figure 2b confirms the expected phases of RVFM according to the chemical composition shown in Table 3

Figure 3 shows the TG/DTG curves of the RVFM samples with the corresponding mass loss and peak temperature in the DTG. Three peaks can be observed, and each peak is associated with a mass loss step.

The first mass loss step is observed in Figure 3 and occurs up to temperature of 100°C; this step is most likely related to the exit of the adsorbed water<sup>8</sup>. The second mass loss step is most likely related to the dehydration of the calcium sulfate hydrate (CaSO<sub>4</sub>·2H<sub>2</sub>O) present in the RVFM. According to the literature, during the process of calcium sulfate dehydration, 1.5 molecules of H<sub>2</sub>O are lost between

**Table 2.** Characteristics of the red clay used (wt%).

Characteristic	Result
Color	Reddish
Density (g/cm <sup>3</sup> )	2.63
Liquid Limit (%)	61.9
Plastic Limit (%)	29.1
Plastic Index	32.8

**Table 3.** Chemical composition of rotary-vacuum-filter mud (RVFM) and kaolinitic clay, estimated by XRF.

Oxide	RVFM	Clay
	Content (%)	Content (%)
Al <sub>2</sub> O <sub>3</sub>	2.55	17.99
Fe <sub>2</sub> O <sub>3</sub>	8.88	6.54
CaO	16.79	0.08
SO <sub>3</sub>	4.70	---
MgO	3.76	1.29
Na <sub>2</sub> O	0.17	0.08
K <sub>2</sub> O	0.49	2.58
TiO <sub>2</sub>	29.81	0.98
MnO	0.39	---
SiO <sub>2</sub>	13.05	62.92
ZrO <sub>2</sub>	0.68	---
LOI <sup>a</sup>	13.49	6.98
Humidity (%)	5.90	18.4

<sup>a</sup>Loss on ignition.

0°C and 65°C. At approximately 70°C, 0.5 molecules of water remain and are tightly bound within the structure of CaSO<sub>4</sub>·2H<sub>2</sub>O. However, at approximately 95°C, this molecule is lost<sup>4</sup>.

The third stage of weight loss (at 700°C) may be related to the dissociation of carbonates due to CO<sub>2</sub> elimination. The decomposition of CaCO<sub>3</sub>, reported in literature<sup>9</sup> at temperatures close to 700°C, and the possible presence of this compound in RVFM indicate that the weight loss observed at 700°C could have been caused by the decomposition of CaCO<sub>3</sub>.

CaCO<sub>3</sub> forms during the manufacturing process. Hydrated lime is added to RVFM, bringing the final concentration of CaCO<sub>3</sub> to 85%; thus, calcium oxide (CaO) and calcium hydroxide [Ca(OH)<sub>2</sub>] are introduced into this waste.

It is possible that the residual lime [Ca(OH)<sub>2</sub>] reacts with the residual CO<sub>2</sub> in the atmosphere and promotes the formation of a carbonate superior to that associated with the contamination of commercial lime. The analysis of the RVFM sample demonstrated the presence of 2.13% carbon. This carbon content is due to the presence of the cationic flocculant FLONEX 9092 (polyacrylamide) in the RVFM, which is added to the process stream at a ratio of 5% by volume. Thermal decomposition of this flocculant may produce carbon oxides.

Table 5 presents the results of the leaching and solubilization tests. No element was present in a quantity greater than the maximum value allowed by the leaching

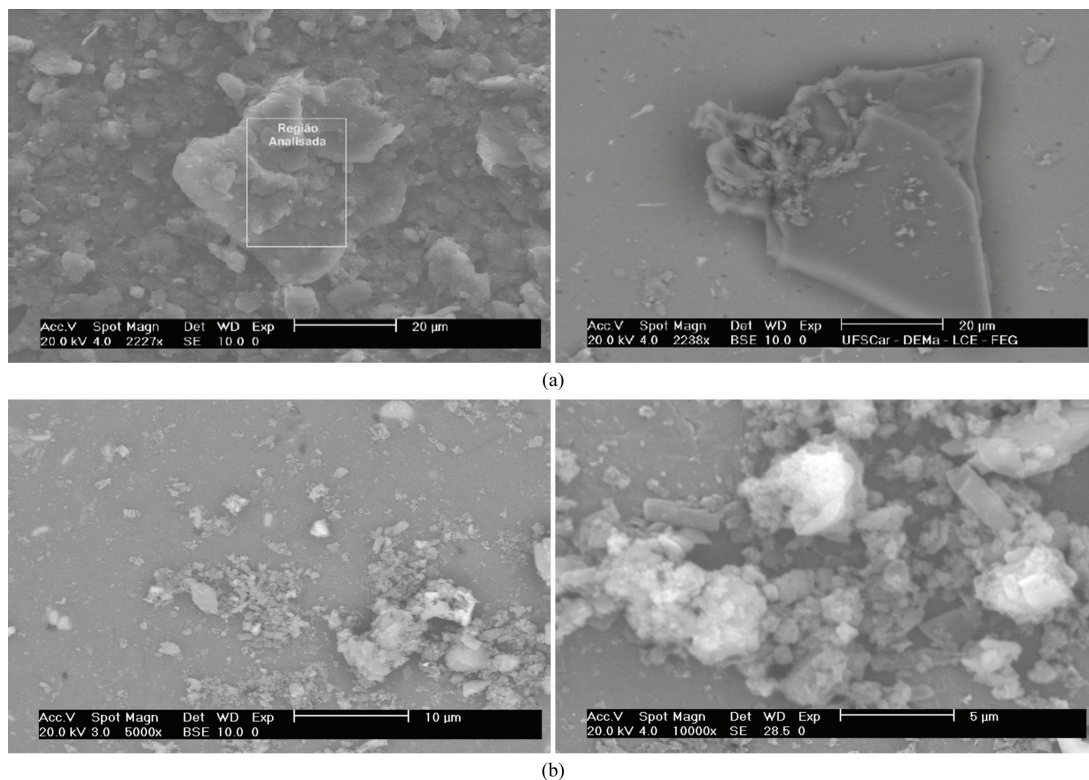


Figure 1. SEM of (a) kaolinitic clay and (b) RVFM.

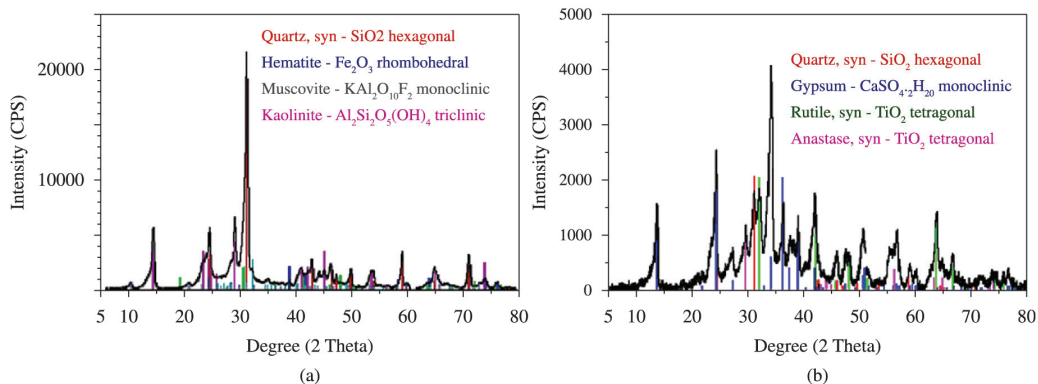


Figure 2. XRD of (a) kaolinitic clay and (b) RVFM.

test, classifying the RVFM as “non-hazardous, non inert” waste (class II-A). The main problems associated with this waste are its sulfate content, which is approximately six times higher than the maximum value allowed, and the arsenic content (35.1%), which is much higher than the maximum value allowed in the solubilization test, according to the NBR 10004/2004 standard<sup>16</sup>.

### 3.2. Specimens characterization

Figure 4 shows the apparent porosity and water absorption results of the samples containing different amounts of RVFM that were fired at 800°C, 950°C and 1100°C.

The data in Figure 4 show that apparent porosity and water absorption increases with the addition of RVFM at the three burn temperatures.

A decrease in water absorption was observed with increasing burn temperature. This behavior is common in ceramics because of the vitrification that begins between 950°C and 1225°C for this type of clay. This is due to the release of SiO<sub>2</sub>, which then reacts with free metal oxides (alkali, alkaline earth and iron) to form glass<sup>17,18</sup>.

According to NBR 15310/2004<sup>19</sup> (“Ceramic Components - roofing tiles: Terminology, requirements and test methods”), the maximum value of allowable water absorption for roofing tiles is 20%. Thus, the samples fired

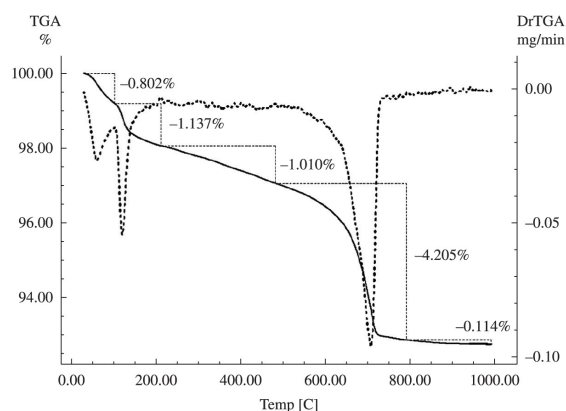


at 800°C and 950°C with 20% RVFM are not suitable for this use.

The water absorption permissible for ceramic bricks, according to Brazilian NBR 15310/2004<sup>19</sup> standard, is 25%. Therefore, the ceramic samples that contain different RVFM

**Table 4.** Mineralogy of the kaolinitic clay and rotary-vacuum-filter mud (RVFM), estimated by XRD.

Kaolinitic Clay		RVFM	
Compound	Chemical	Compound	Chemical
Quartz	SiO <sub>2</sub>	Quartz	SiO <sub>2</sub>
Hematite	Fe <sub>2</sub> O <sub>3</sub>	Gypsum	CaSO <sub>4</sub> ·H <sub>2</sub> O
Muscovite	H <sub>2</sub> KAl <sub>3</sub> Si <sub>3</sub> O <sub>12</sub>	Rutile	TiO <sub>2</sub>
Kaolinite	Al <sub>2</sub> Si <sub>2</sub> O <sub>5</sub> (OH) <sub>4</sub>	Anastásio	TiO <sub>2</sub>



**Figure 3.** TG/DTG curves of sample RVFM in an N<sub>2</sub> (50 mL/min) atmosphere with a heating rate of 10°C/min.

contents and were fired at 800°C, 950°C and 1100°C can be used for Brazilian ceramic bricks in accordance with the standards (Figure 4).

As expected, the results for apparent porosity (Figure 4b) exhibit the same behavior that was observed for water absorption once those properties were dependent. The low porosity of the specimens fired at 1100°C can also be attributed to the effect of vitrification, as discussed above.

The chemical composition of RVFM also contains approximately 3.76% MgO content. However, it has been observed that the apparent porosity and, consequently, the water absorption of the samples increase as the RVFM content increases. It is possible that MgCO<sub>3</sub> and/or CaCO<sub>3</sub> are present in this residue, but these compounds were not identified by XRD.

The presence of calcium and/or magnesium carbonates in clays causes irregularities in the surfaces of the extruded products, including scratches and swells. During the ceramic firing process, the carbonates are dissociated, thereby releasing CO<sub>2</sub> in the furnace atmosphere, while the respective oxides remain inside the product and may react with other substances. After ceramic firing, discontinuities, such as holes and cracks, may arise as a result of strong degassing<sup>20</sup>. This consequently increases the water absorption in the ceramic. Calcium carbonate dissociates above 800°C, and magnesium carbonate decoupling occurs at approximately 600°C, with reasonable heat absorption.

According to Barba et al.<sup>21</sup>, the presence of carbonates in a ceramic matrix alters the course of reactions that occur at high temperatures, producing crystalline phases that are otherwise not formed in the absence of these carbonates. Therefore, the addition of alkaline earth carbonates has a bleaching effect on the cooked products. An increase

**Table 5.** Results of the leaching and solubilization tests according to the NBR 10004/2004<sup>16</sup> standard, which classified the RVFM as a non-hazardous waste (class II-A).

Parameters	Leaching			Solubilization		
	Clay (mg/L)	RVFM (mg/L)	MVA <sup>b</sup> (mg/L)	Clay (mg/L)	RVFM (mg/L)	MVA <sup>b</sup> (mg/L)
Aluminum (Al)	0.000	0.000	#	5.300	0.000	0.200
Arsenic (As)	0.000	34.000	1	0.000	35.100	0.010
Barium (Ba)	0.900	0.700	70.000	0.160	0.013	0.700
Cadmium (Cd)	0.000	0.000	0.500	0.000	0.028	0.005
Lead (Pb)	0.019	0.013	1.000	0.000	0.000	0.010
Cooper (Cu)	0.224	0.104	#	0.011	0.010	2.000
Chrome (Cr)	0.140	0.080	5.000	0.000	0.000	0.050
Iron (Fe)	0.000	0.000	#	0.840	0.000	0.200
Selenium (Se)	0.000	0.008	1.000	0.000	0.000	0.010
Sodium (Na)	x	x	#	2.740	48.900	200.000
Manganese (Mn)	0.180	0.070	#	0.000	0.000	0.100
Zinc (Zn)	x	x	#	0.120	0.000	5.000
Fluorides	0.190	0,000	150.000	0.000	0.000	1.500
Chlorides	x	x	#	0.000	90.900	250.000
Sulfates	x	x	#	34.300	1570.00	250.000
pH (1:1)	4.82	9.47	2.0-12.5	8.38	11.14	#

<sup>b</sup> MVA = Maximum Value Allowed by the NBR 10004/2004 standard. x = not required by the NBR 10004/2004 standard. # = absence of a limit established by the NBR 10004/2004 standard.

in the  $\text{CaCO}_3$  content, according to these authors, carries an increased water absorption and a delay in the onset of sintering for the formation of the liquid phase. At temperatures of 800-900°C, decarbonation of  $\text{CaCO}_3$  occurs, forming calcic crystalline phases (silicates and calcium aluminates)<sup>21</sup>.

The high content of crystalline phases formed during firing and the consequent glass phase shortage at temperatures up to 1100°C result in high ceramic porosity and high coefficients of expansion. In small amounts,  $\text{MgCO}_3$  can act as a flux and lower the firing temperature.

$\text{TiO}_2$  (titanium dioxide) falls into the class of oxides called chromophores, which reduce the plasticity and the refractoriness of the clay. This reduction in plasticity can also result in a ceramic with a higher porosity because of the increased difficulty in obtaining an extruded sample with high compression.

According to Shan et al.<sup>22</sup>, differences in fluidity might resulted from the formation of a different network structure. Titanium ions exist in  $[\text{TiO}_4]$  tetrahedrons by acting as a network former and in  $[\text{TiO}_6]$  octahedrons by acting as a network modifier.  $\text{TiO}_2$  would normally be expected to have a coordination number of six due to the high field strength

of titanium ions (0.68Å). However, to be a part of the glass network structure and to be compatible with the silicate network at high temperatures, some titanium ions might have a coordination number of four. The  $[\text{TiO}_4]$  tetrahedrons enhance the glass formation ability without inducing the formation of any non-bridging oxygen ions.

The results showing the effects of RVFM addition on linear shrinkage and flexural strength are exhibited in Figure 5. For the samples fired at 950°C, the linear shrinkage tended to increase with RVFM addition. However, this was not observed for the samples fired at 800°C and 1100°C.

The high shrinkage of samples fired at 1100°C can also be a consequence of the high MgO content found in the RVFM. At higher temperatures, decomposition occurs, forming MgO or CaO and releasing  $\text{CO}_2$ . Beginning at approximately 1100°C, there is an increase in the liquid phase. This liquid phase will progressively fill the open pores and consequently lower the distances particles, resulting in the shrinkage of the ceramic bodies as the sintering temperature increases<sup>23</sup>.

Typically, high linear shrinkage is associated with a reduction in porosity, as described above. However, despite a reduction in linear shrinkage, there was an increase in

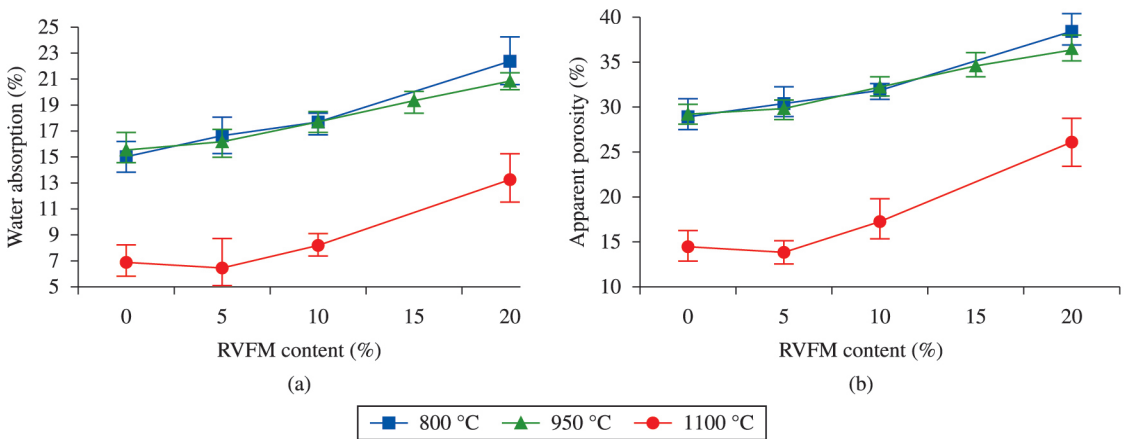


Figure 4. Effect of RVFM on water absorption (a) and porosity (b) of the ceramic block.

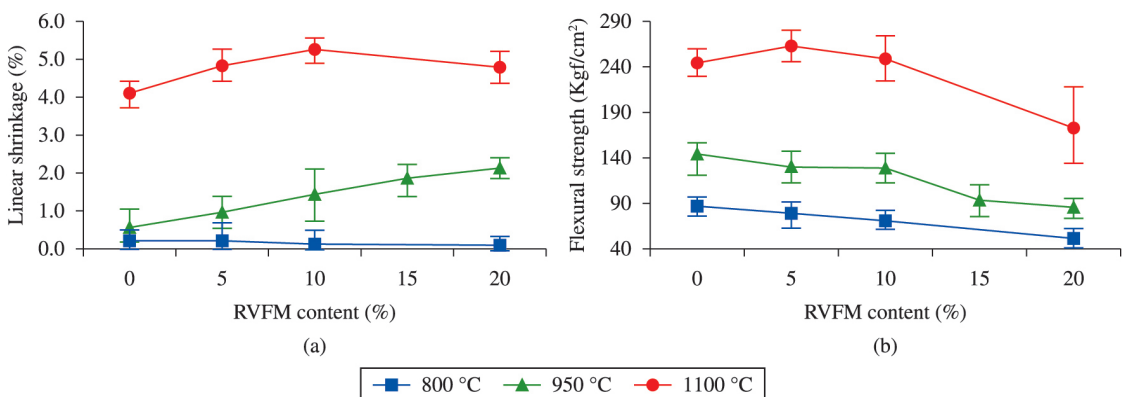


Figure 5. Effect of RVFM addition on linear shrinkage (a) and flexural strength (b) of ceramic bricks fired at varying temperatures.

**Table 6.** Evaluation of the technical feasibility of the ceramics sintered at different temperatures and containing different amounts of RVFM, according to the Brazilian standard NBR 15310/2004<sup>19</sup> (“Ceramic Components - roofing tiles: Terminology, requirements and test methods”).

Properties	Brazilian Specification	Sintering Temperature											
		800°C				950°C				1100°C			
		RVFM content	0%	5%	10%	20%	0%	5%	10%	20%	0%	5%	10%
Flexural Strength (Bricks)	55 Kgf/cm <sup>2</sup>	A	A	A	R	A	A	A	A	A	A	A	A
Flexural Strength (roofing tiles)	65 Kgf/cm <sup>2</sup>	A	A	A	R	A	A	A	A	A	A	A	A
Water Absorption (Bricks)	25%	A	A	A	A	A	A	A	A	A	A	A	A
Water Absorption (roofing tiles)	20%	A	A	A	R	A	A	A	R	A	A	A	A

A – Approved, R – Reproved.

the porosity of the ceramic samples. It is believed that the CO<sub>2</sub> was released into the furnace atmosphere, and the consequent appearance of discontinuities in the samples, such as holes and cracks generated by strong degassing, may be the reason for this unexpected increase in porosity.

The recommended values of linear shrinkage after firing the extruded specimens should be less than 14% when fired at 950°C<sup>8</sup>. Therefore, with the addition of RVFM, all of the contents have satisfactory values of linear shrinkage, as shown in Figure 5.

The decrease in flexural strength with the incorporation of RVFM is likely related to the fact that this additive increases the porosity of the specimens. Figure 4b shows that the addition of RVFM from 5% to 20% raised the apparent porosity of the ceramic block, and this effect was more significant for the increase from 10% to 20%. The increase in apparent porosity decreases the cross-sectional area through which a load can be applied, thereby reducing its flexural strength. Moreover, under flexural loading, the material is subjected to a tensile stress component. The pores would then act as a stress factor concentrator. This also contributes to the reduced flexural strength.

Furthermore, higher flexural strength of the samples with increasing burn temperature was observed. This is related to two factors: i) the formation of crystalline phases (silicates and aluminosilicates of calcium and/or magnesium) of high mechanical strength<sup>24</sup> and ii) the formation of a low viscosity liquid phase such that it progressively fills the open pores with the increasing burn temperature<sup>25</sup>. The recommended values of flexural strength for use in hollow red ceramic bricks is above 55 Kgf/cm<sup>2,8</sup>. Therefore, following the incorporation of RVFM, only specimens fired at 800°C that contain 20% RVFM would not be suitable.

The Brazilian standards NBR 15310/2004<sup>19</sup> (“Components Ceramic - roofing tiles: Terminology, requirements and test methods”) specifies a minimum flexural strength of approximately 65 kgf/cm<sup>2</sup> in roofing tiles. Figure 4b shows that a brick with 20% RVFM content

that was fired at 800°C performed poorly, which makes these mixtures unsuitable for use in the manufacture of roofing tiles.

A summary of the technical evaluation concerning the use of RVFM as an additive to traditional ceramics (roofing tiles and bricks) is presented in Table 6.

#### 4. Conclusions

Based on an analysis of the results, the following conclusions can be drawn:

- RVFM can be classified as a “non-hazardous, non inert” waste (class II-A), according to Brazilian standards;
- The addition of RVFM tends to increase the water absorption and porosity, which is likely caused by the decomposition of carbonates and by the thermal decomposition of the cationic flocculant also present in the RVFM;
- According to the water absorption results, only samples fired at 800°C and 950°C that contain 20% RVFM are not suitable for use as roofing tiles;
- The samples display increased flexural strength as a function of increasing firing temperature, which can be related to the formation of crystalline phases of high mechanical strength and the formation of a low viscosity liquid phase that reduces open porosity at high temperatures;
- According to flexural strength results, only specimens fired at 800°C that contain 20% RVFM cannot be classified as suitable for use as bricks;
- The high shrinkage of the samples fired at 1100°C is attributed to an increase in the liquid phase, which progressively fills the open pores and consequently results in lower distances between the particles. This, in turn, results in shrinkage of the ceramic bodies as the sintering temperature increases.

## References

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