Ternary diagrams SiO$_2$-Al$_2$O$_3$-K$_2$O as tool for the analysis of ceramic materials behavior

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Abstract. The present study about ternary diagrams of SiO$_2$-Al$_2$O$_3$-K$_2$O has been conducted from the determination of two possible optimal clay mixtures through hydrometric tests of a company dedicated to the manufacture of masonry products for construction in the North region of Santander in Colombia; this work is the continuation of others carried out previously. In this raw material (clay) the dominant minerals are silica, alumina, iron, potassium, among others, which provide the plasticity and adequate granulometric distribution. Two optimal m7 and m8 mixtures were selected from 5 samples (M1, M2, M3, M4 and M5) of clays from different points of the company's mine, these mixtures were analyzed by Fluorescence and X-ray diffraction tests with the purpose of determining the chemical elements in their maximum percentage and to be able to graph them in ternary diagrams with the help of FACTSAGE software and finally determine their cooking behavior. The results of the investigation showed that the physical characterization of the clays provides a broad view on the technological behavior of the raw material and consequently the quality of the final product.

1. Introduction
The application of the diagrams of phases balance is remarkable in all the industrial states to design the materials, also to comprise and predict its behavior in service, being of big importance in the ceramic sector. On the other hand, nowadays, the diagrams of balance are valid not only to determine the thermodynamic tendency of balance during the cooking of the ceramic material, but also to predict the final state of balance and, with a good understanding of the relations of balance, also is possible to know the way through which the system evolves to the final state during its application. In consequence, the diagrams of balance are a powerful tool for the design of new ceramic materials exposed to different temperatures, being possible to improve the conditions of processing of a product [1].

The computer package FactSage consists of a series of modules of information, computation and manipulation that allow to access and manipulate databases of different elements of the periodic table in function of two-phase and three-phase diagrams, with what it is possible to realize a wide variety of thermochemical calculations generating tables, charts and figures of interest for the industrial states [2-4]. With the purpose of obtaining the diagrams of phases balance, it is very important to realize
experimental designs through different composed which may offer a solution to any problematic based on the improvement of some material by means of its elementary composition by elements [5]. In order to validate the behavior of the ternary diagrams it is necessary the application of the chemical characterization techniques by X-rays fluorescence (XRF) to determine the existent elements in its higher compositions to do the graphic of the elements and later apply the X-rays diffraction (XRD) to some specific conditions in order to determine the present phases in the system [6-9].

It is for the above, that the present investigation is based on the analysis of a mix of clay obtained from different samples of clay realizing an experimental procedure aimed at improving the characteristics of the final product through different essays of laboratory with which it may predict the prime matter behavior (clay) and in a certain way, the resources of the company.

2. Materials and method

For the development of the project it was established a mixed investigation (Qualitative – Quantitative) of experimental character [10], due to the fact that it required to characterize the clay under the different technological methods such as: physical analysis by hydrometry, Fluorescence and Diffraction of X-rays, aimed at comparing the results with the bibliographic references studied, incidentally the stages of the productive process defined by means of the interviews realized to staff that works in the company [11].

Later, it was initiated with the taking of five (5) prime matter samples (Clay) of one of the companies devoted to the manufacture of products of masonry for the construction, in which later they carried out analysis of hydrometry to determine the composition in percentage of weight of sands, silts and clays, data that were graphed in a ternary diagram based with these compositions to determine the type of texture and product that can be produced with the prime matter [12]. Taking into account that the particles with values until 100 millimeters corresponds to gravels, between 100 and 0.08 millimeters correspond to sand, between 0.08 and 0.005 millimeters correspond to silt and the particles with diameter between 0.005 until 0 millimeters correspond to clay. From them it was obtained the following results.

![Figure 1. Granulometric graph of sieving and hydrometry for the classification of the soil of all the samples.](image-url)

From the previous Figure 1, it is observed that the clays come from the cotton formation given to the sedimentation of the soil as established in the research carried out by Garcia-León [13], which expresses that the clays have a percentage lower than 30%, from which results the following Table 1 of results taking into account the size of the particles for each sample.

The data gathered in the Table 1, were analyzed with the diagram of Winkler, in which they are located the points to characterize the clays, and besides it is necessary to check whether they are apt for the current production that realized in the company [12-14]. Likewise, they identified the textures of the clay and types of products that can be obtained [15,16], taking into account the previous, it was determined that the samples are of soils franco-sand-clay, that their use in a large extent for the manufacture of bricks massifs and perforated blocks. In addition, the samples that will be used to
formulate an optimum mix were the sample M1, M2 and M5; due to the fact that the sample M3 presents very low plasticity and the sample M4 presents similar characteristics to the sample M2. The results of texture according to the diagram of percentages of Winkler, reveal that 2 of the samples selected (M1 and M2) are inside the group 2, which is recommended for the manufacture of perforated blocks.

| Sample | % Sands | % Silts | % Clays |
|--------|---------|---------|---------|
| M1     | 58.0    | 18.0    | 24.0    |
| M2     | 61.0    | 17.8    | 21.2    |
| M3     | 56.3    | 38.1    | 5.9     |
| M4     | 59.7    | 31.1    | 4.6     |
| M5     | 58.0    | 27.0    | 15.0    |

Table 1. Data hydrometry by granulometry.

In order to formulate the ideal mixture of clay, this has to possess a composition of a region found in the zone two (2). Where the central point of that region is (58.5% Sand – 20.1% Silt – 21.4% Clay), and can vary in ± 2% from each component (Sand, silt and clay), ensuring whenever they do not go out of the region as it may be observed in the following, rank of sand 58-61%, rank of silt 18-23% and rank of clay 20-24% for the samples studied but for the zone 2 of Winkler rank of sand 50-65%, rank of silt 10-30% and rank of clay 20-40%. Some of the samples, presented thick grains of in its majority like sands, which would have to be grinded so that they do not modify the technical properties and aesthetics of the final product, as they can be breaks or main absorption of water. Then for the mineralogical characterization the following procedure was carried out.

The preparation of the samples for FRX analysis consisted of the grinding according to the ASTM C323-56 standard, performing the sieving of the material by 400 mesh, until obtaining a particle size of 38 μm, (if the particle size of the sample is greater than 63 microns); Six grams of the original sample were taken to a hydraulic press at 15 tons for 1 minute, obtaining a 30 mm diameter pellet to analyze in the Bruker S4 Explorer fluorescence equipment with Detector Pro4 and X-ray tube. Rh at a voltage of 40KV and 25mA.

Afterwards it was subjected to the process of calcination, which consists in carrying the sample to 1000ºC, and keep it to this temperature for 1 hour, to evaluate the percentage in stray weight during the treatment, after weighting the sample before and afterwards, to 105ºC. These losses by calcination (L.O.I. By his acronyms in English loss of ignition) represent the quantity of volatile components (H₂O, CO₂, F, Cl and S) and organic matter no detected with the team of fluorescence.

Likewise, the preparation of the samples to carry out the process of DRX consists of a setting in dust for quantification of the main mineralogy. The teams used for the realization of this analysis were: A Bruker diffractometer axs D4 Endeavor with detector LYNXEYE, Tube of X-rays Cu 1.9 Kw (K alpha λ =1.5406) with Filter of Nickel to 40 KV 40 mA. It admits samples in dust: 2θ 70° (setting dust), 5° (aggregated oriented) with a size of step: 0.014. The speed of scanning: 0.4 seconds by step for the settings of aggregated oriented [17].

Afterwards of the setting preparation of aggregated oriented, the patterns obtained in the diffraction of the setting in dust are studied with the purpose to identify whether the sample presents oxides and/or organic matter, due to the fact that these compounds affect the identification of the minerals of the clay. The samples analyzed for this analysis do not contain oxides neither organic matter, by what additional procedures to withdraw these compounds were not required.

3. Results and discussions
The chemical and mineralogical characterization was made by means of X-rays fluorescence and X-rays diffraction [18-20]. For the realization of these analyses used 20 grams of the samples (M1, M2 and M5) and mixes selected (m7 and m8) [21-23]. This analysis carried out with the purpose to determine qualitative and quantitative of the chemical composition of a sample and of this way can
obtain a ternary diagram with the present elements in his higher compositions [24]. The results of this analysis are possible to be observed in the Table 2.

Table 2. X-ray fluorescence for the three pure samples (M1, M2 and M5) and the optimal mixture (m7 and m8).

| Chemical formula | Element Name | M1   | M2   | M5   | m7   | m8   |
|------------------|--------------|------|------|------|------|------|
| SiO₂             | Silicon oxide| 55.395 | 55.695 | 57.811 | 54.743 | 56.582 |
| Al₂O₃            | Aluminium oxide | 20.649 | 20.568 | 18.521 | 20.670 | 20.565 |
| Fe₂O₃            | Iron oxide   | 6.613  | 6.011  | 6.344  | 6.567  | 6.691  |
| K₂O              | Potassium oxide | 3.053  | 3.235  | 3.311  | 2.926  | 3.301  |
| CaO              | Calcium oxide | 1.656  | 1.593  | 1.609  | 1.845  | 1.274  |
| MgO              | Magnesium oxide | 0.867  | 0.834  | 0.963  | 0.898  | 0.803  |
| TiO₂             | Titanium oxide | 0.831  | 0.953  | 0.990  | 0.871  | 0.930  |
| Na₂O             | Sodium oxide  | 0.547  | 0.589  | 0.608  | 0.626  | 0.388  |
| P₂O₅             | Phosphorus oxide | 0.449  | 0.472  | 0.499  | 0.448  | 0.452  |
| LOI              | Lost by Ignición | 8.998  | 9.021  | 8.392  | 9.187  | 8.599  |
| SiO₂/ Al₂O₃      | Molar relation | 2.683  | 2.708  | 3.121  | 2.648  | 2.751  |
| Total            |              | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |

In the previous table it may be observed the highest percentages of some compounds that cause a specific influence in the properties of final product that for the specific case of the zone Norte de Santander is the block H-10, from which it is possible to interpret: Silica (SiO₂) of 54.743 and 56.582% for the two mixes respectively, that causes a fast process of dried, in cooking a descent in the contraction; the alumina also finds in high percentages for the two mixes. Taking into account that characteristic chemists recommended for the construction are of 50 to 60%. Alumina (Al₂O₃) of 20.670 and 20.565% for the two mixes respectively, conferring him a resistance to high temperatures and a decrease of breaks in cooking. Taking into account that characteristic chemists recommended for the construction is 20 to 30%. Clays montmorillonite due to the fact that his chemical composition is: SiO₂: 48-56%, Al₂O₃: 11-22%, MgO: 0.3-0.8%. Oxide of iron (Fe₂O₃) of 6.567 and 6.691% for the two mixes respectively, are normal for being minors to 10%. This oxide will confer him a red color after burns it [25]. Because of his percentage possibly do not appear the effect of black heart. The bases contained of alkaline oxides (sodium and potassium) and of oxides alkaline earth (magnesium and calcium), makes possible that the clay generate the vitreous phase to temperatures relatively high (Elder to 900°C), conferring it properties of semi-refractority. The presence of a high content of oxide of potassium (K₂O) of 2.926 and 3.301 %, above the other alkaline oxides and alkaline earth, classifies it such as an illicit material, the other elements find in low proportions that did not affect the structure of the final product [26].

With the purpose to determine the temperatures from which obtains the phase mullite in function of the components in his higher percentages, was realized an analysis of the elements obtained to generate a ternary phase diagram (A-B-C). To initiate this analysis, it took three compounds of the mixes m7 and m8 and the samples M1, M2 and M5 with higher percentages that were: SiO₂ - Al₂O₃ - K₂O, but it was obtained a value of temperature using these compounds, as it is possible to be observed in the Table 3.

Table 3. Chemical composition of the m7 mixture, as well as samples M1, M2 and M5.

| Chemical formula | Element Name | Mix 7  | Mix 8  | Sample 1 | Sample 2 | Sample 5 |
|------------------|--------------|--------|--------|----------|----------|----------|
| Al₂O₃            | Aluminium oxide | 20.670 | 20.649 | 20.568   | 18.521   | 20.565   |
| K₂O              | Potassium oxide | 2.926  | 3.053  | 3.325    | 3.311    | 3.301    |
| Fe₂O₃            | Iron oxide   | 6.567  | 6.616  | 6.011    | 6.344    | 6.691    |
| SiO₂             | Silicon oxide | 54.743 | 55.395 | 55.695   | 57.811   | 56.582   |

Temperature according to the diagram (°C) 1550.0 1499.5 1500.0 1499.5 1485.3
Likewise, there were situated the points of the compositions in the diagram of triangular phase by means of the utilization of the software FactSage free version obtaining the following Figure 3. To attain that these samples obtain the phase mullita, the cooking temperature has to achieve roughly 1600°C. With the current technology of most companies in the region would not attain to achieve to arrive to this request. Incidentally according to the bibliography [22], the temperatures used for the blocks do not have to surpass the 950°C. But taking into account the diagram biphasic of the Figure 2, exists the presence of the constitutive elements to temperature of 900 to 2100°C by which the temperature found in the serious ternary diagram the optimum to obtain products of better quality. On the other hand, it was graphed the compositions of silica, alumina and potassium, being this last as one of the compounds in main proportion as it can be found in the Figure 3. Also, it is observed the points in shape of triangle (▲) and rectangle (■) invariants in the diagram of balance of ternary phases SiO$_2$-Al$_2$O$_3$-K$_2$O, possess the high temperature of 1500°C. Considering the rank of temperatures more used in the ceramic industry (850°C-1000°C) and the characteristics of the oven of the company that only achieves temperatures of 950°C [7]. On the other hand, it may be evident that the best mix is the m7 because of his low content of oxide of potassium K$_2$O no influence to a large extent in the product gresification in the stage of cooking. Likewise, this figure arises of the following Table 5 with the values of SiO$_2$, K$_2$O and Al$_2$O$_3$ it is possible to find the cooking temperature established by the software FactSage for the ternary diagram [2].

On the other hand, in the Figure 3, it shows that the temperature of fusion average for the type of mix formulated has to achieve the 1500°C roughly for the forming of the final product. The points situate on the zone Mullita, which presents the following characteristic: it is a ceramic of aluminosilicates with good stability to high temperatures, this composition uses in the industries of the steel and the glass in shape of bricks and refractory blocks. It uses like an alternative of lower cost to the alumina, with better properties of resistance to the thermal crash [23]. The material cans extrude in shape to circulate and be pressing to create products of masonry for the construction. It presents good resistance to the wear and to the deformation. It has thermal conductivity drop. It can be used until the

![Figure 2. Biphasic Diagram FactSage Al$_2$O$_3$ and K$_2$O. Modified from [2].](image)
1700ºC of temperature roughly. Taking into account the analysis of results of the software in FactSage, the phases that would appear to the temperature of 1500ºC roughly with + 0 mole, with the following formulation chemical SiO$_2$-Al$_2$O$_3$-K$_2$O the phase corresponding is mullite – nepheline.

![Figure 3. Ternary diagram FactSage SiO$_2$, Al$_2$O$_3$ and K$_2$O.](image)

They found temperatures diagram of similar phase to the found by segades, which select the same ternary diagram SiO$_2$, Al$_2$O$_3$ and K$_2$O to analyses the phases behavior of the mixes selected [24]. After, they took into account investigations realized to the Hoffman oven of the company, which achieves temperatures of until 920ºC, with the end to propose to the company that adopt the measures to increase the temperature so that the process proposed in the curve of gresification was until 1050ºC [25]. The results indicate a ternary system of feldspars due to the presence of albite, anortite and potassium feldspar. The albite is of high type due to the low order of Al-Si considering that it appears at temperatures between 700 ºC and 980 ºC.

The X-rays diffraction in a sample allows to tackle the identification of crystalline phases both clayey and non-clayey [26]. This technique realizes the structural characterizations and identifications of crystalline phases. With the end to determine which treatment has to apply to separate the clayey minerals, the rocks can be classified inside one of the following four groups: Clastic rocks, limes, rocks containing sulphates and unconsolidated material. The samples treated in this analysis correspond to unconsolidated sediments.

With this setting identified the present phases in the specimens selected before cocking to a temperature of 1000 ºC because of the characteristics of the team, likewise carried out the comparison of the profiles observed with the reported in the database PDF-2 of the International Centre for Diffraction Dates (ICDD), in addition to the quantitative analysis without determination of amorphous, of what obtained the following results in the Figure 4 and Figure 5 for the mixes m7 and m8. The composition of feldspars constituents of rocks corresponds to a ternary system composed of Quartz (SiO$_2$), Muscovite K$_{0.86}$Al$_{31.94}$[(Al$_{0.96}$Si$_{20.895}$O$_{10}$)((OH)$_{1.744}$F$_{0.256}$)] and Kaolinite Al$_2$(Si$_2$O$_5$)(OH)$_4$. Obtaining the diffractogram of the Figure 4 and Figure 5.
Equally they present the diffractogram of the mix m7 and m8 from which was obtained the following Table 4 and Table 5 of the quantitative analysis.

**Table 4.** Mineralogical structures of the DRX analysis, for the m7 mixture.

| Reference code ICDD | Mineral name     | Chemical formula                                                                 | Percentage (%) |
|---------------------|------------------|----------------------------------------------------------------------------------|----------------|
| 000-89-8934         | Quartz           | SiO₂                                                                             | 38.1           |
| 000-86-1385         | Muscovite        | K₀.₈₆A₁₁.₉₄(Al₀.₉₆Si₂₀.₈₉₅O₈₀)₀.₇₄₄F₀.₂₅₆                                             | 19.1           |
| 000-78-1996         | Kaolinite        | A₁₅(Si₅O₁₈)(OH)₄                                                              | 16.2           |
| 000-70-3752         | Albite           | (Na₀.₀₉Ca₀.₀₂)(Al₁₂Si₂₀.₉₈O₈0)                                                   | 13.7           |
| 000-77-0135         | Microcline       | K₂(Si₀.₇₅Al₀.₂₅)OH                                                             | 10.3           |
| 000-13-0135         | Montmorillonite  | Ca₀.₂(AlₙMg₂)₄Si₁₀(OH)₄H₂O                                                   | 2.6            |
| 000-86-1385         | Muscovite        | K₀.₈₆A₁₁.₉₄(Al₀.₉₆Si₂₀.₈₉₅O₀.₇₄₄F₀.₂₅₆)                                             | 5.9            |
| 000-75-0306         | Halite           | NaCl                                                                            | <1             |
| 000-87-1166         | Hematite         | Fe₂O₃                                                                            | <<1            |

**Table 5.** Mineralogical structures of the DRX analysis, for m8 mixture, before cooking.

| Reference code ICDD | Mineral name     | Chemical formula                                                                 | Percentage (%) |
|---------------------|------------------|----------------------------------------------------------------------------------|----------------|
| 000-85-0795         | Quartz           | SiO₂                                                                             | 27.5           |
| 000-89-6427         | Albite           | Na₆(Al₂Si₅O₈)                                                               | 18.6           |
| 000-74-1784         | Kaolinite        | Al₂(Si₂O₅)(OH)₄                                                              | 16.7           |
| 000-77-0135         | Microcline       | K₂(Si₁₀.₇₅Al₀.₂₅)O₈                                                              | 9.4            |
| 000-13-0135         | Montmorillonite  | Ca₀.₂(Al₂Mg₂)₄Si₈(OH)₄H₂O                                                   | 1.5            |
| 000-86-1385         | Muscovite        | K₀.₈₆A₁₁.₉₄(Al₀.₉₆Si₂₀.₈₉₅O₀.₇₄₄F₀.₂₅₆)                                             | 5.9            |
| 000-75-0306         | Halite           | NaCl                                                                            | <1             |
| 000-87-1166         | Hematite         | Fe₂O₃                                                                            | <<1            |
In general, the clays that are used in construction are called ceramic clays or common clays; which are composed of two or more clay minerals, generally illite, kaolinite and smectite, with significant amounts of other minerals that are not phyllosilicates (carbonates, quartz, etc.) and are generally used for the manufacture of building materials and aggregates.

The samples have a diverse composition, of which certain tendencies are appreciated. Some clays find their main field of application in the absorptive sector because they can retain water or other molecules in the interlamellar space (smectites) or structural channels (sepiolite and paligorskite) [27]. The hydration and dehydration of the interlamellar space are characteristic properties of the smectites, and their importance is crucial in the different industrial uses. For this reason, smectites in the form of montmorillonite are considered to absorb a large amount of water between their interlamellar spaces, which are their main characteristic. As for the clay minerals, it is observed that the majority of the samples is constituted by the illite in an important proportion (it is generally the second most important mineral after the quartz).

Also, the diffractograms indicate that the clay minerals are constituted mainly by silica and hydrated aluminosilicates with the presence of some impurities, such as Na, Fe, K and Ca. The diffractograms reflect the phases present in the materials and highlights the high content of microcline and muscovite, which justifies its yellow color. Also, this type of analysis is fundamental to determine the quality of the same depending on the content of $\text{SiO}_2$ and $\text{Al}_2\text{O}_3$. These results, both with the experimental analyzes, allow us to conclude that the company uses natural sediments that can be considered as good to medium quality plastic clays to prepare its masonry products for construction.

The chemical analysis of fluorescence made to the raw material used for the mixture of the pulp is indicated in Table 2. Taking into account the bibliography, the clays suitable for the manufacture of ceramic bricks should contain $\text{SiO}_2$ between 64.1-83.1\%, $\text{Al}_2\text{O}_3$ between 21.6-27.1\% and $\text{Fe}_2\text{O}_3$ between 3.0-6.1 according to Duitama [28]. For the results obtained, these values are between 54.73-56.52\% $\text{SiO}_2$, $\text{Al}_2\text{O}_3$ between 20.56-20.67\% and $\text{Fe}_2\text{O}_3$ between 6.56-6.61\%, so the values are found very similar.

4. Conclusions
In general, the evaluated samples have high sand contents, greater than 25\%. Low contents of sand are considered to be those less than 10\%, medium contents between 10\% and 25\% and highs above 25\%. The ideal percentages of sand for the production of extruded ceramic products range between 16\% and a maximum of 35\%. Taking into account the above, the mixtures do not need the extra addition of sand to be able to extrude properly.

It can indicate a significant presence of free silica because in the peak of intensity of the quartz and the molar ratio is low $\text{SiO}_2/\text{Al}_2\text{O}_3$. According to the results of the chemical analysis by fluorescence shown in Table 2, $\text{K}_2\text{O}$ content of the samples reaches a value of 2.926\% and 3.301\%, fact that suggests the existence of micaceous in relatively high proportions, although the existence of other minerals in layers it can not be discarded. The $\text{Fe}_2\text{O}_3$ content seems to indicate the presence of iron oxides and the low content of alkaline oxides such as sodium and potassium that give the clay the possibility to generate the glass phase at relatively high temperatures, taking into account the diffractogram.

It may be affirmed that a good clay to be used in the production of masonry products are those samples that work at low temperatures, that is between 950 °C and 1050 °C. In addition, they present water absorption values that comply with the finished product standard that is to be produced. Taking into account the ternary diagrams and the results of the diffractograms, it was possible to show that the Mullite phase was not obtained due to the fact that it reaches 1500 °C and the company's furnace achieves a temperature of 950 °C. Therefore, the albite, microcline and anorthite phases were presented.
References

[1] De Aza A H, Pena P, Caballero A and De Aza S 2011 Los diagramas de equilibrio de fases como una herramienta para el diseño y comprensión del comportamiento en servicio de los materiales refractarios Bol. Soc. Esp. Ceram. Vidrio 50(6) 279–290

[2] Bale C W, Belisle E, Chartrand P, Decterov S A, Eriksson G, Heribei A E, Hackett K, Jung I H, Kang Y B, Melanço J, Pelton A D, Petersen S, Robelin C, Sangster J, Spencer P and Van Ende M A 2016 FactSage thermochemical software and databases, 2010-2016 Calphad 54 35–53

[3] Tejada V and Plé D 2016 Estudio de formulaciones cerámicas para aisladores eléctricos Revista de la Sociedad Química del Perú 81(1) 72–86

[4] De Aza A H 1996 Corrosión de materiales refractarios por escorridas y vidrios fundidos Bol. Soc. Esp. Ceram. Vidrio 35(2) 87–101

[5] Méndez L, Delvasto P and Quintero Sayago O 2007 Diseño y fabricación de moldes para solidificación direccional en aleaciones de aluminio Revista Latinoamericana de Metalurgia y Materiales 27(2) 73–82

[6] Albert E B, Pla J L, Abad M D N and Castelló J B C 2016 Potencialidad de un residuo de frita procedente del sector cerámico como materia prima para la producción de material vitrocérmico Bol. Soc. Esp. Ceram. Vidrio 54(1) 101–108

[7] Zuo O, Zhai S, Liu J and Wang J 2016 Microstructure of the directionally solidified ternary eutectic Ceram. Int. 42(1) 8079–8084

[8] Konar B, Hudon P and Jung I 2017 Coupled experimental phase diagram study and thermodynamic modeling of the Li2O–Na2O–SiO2 system J. Eur. Ceram. Soc. 38(4) 2074-2089

[9] Muñoz R, Muñoz J, Mancilla P and Rodríguez J 2007 Caracterización fisicoquímica de arcillas del municipio de Guapi-costa pacífica caucana Colombiana Revista de la Academia Colombiana de Ciencias Exactas, Físicas y Naturales 31(121) 537–544

[10] Hernández-Sampieri R, Fernández-Collado C and Baptista-Lucio P 2006 Metodología de la Investigación (Mexico: McGrawHill)

[11] Garcia-León R, Flórez-Solano E and Medina-Cárdenas Y 2018 Caracterización física de las arcillas utilizadas en la fabricación de productos de mampostería para la construcción en Ocaña Norte de Santander Respuestas 39(3) 1–6

[12] Garcia-León R and Bolívar R 2017 Caracterización Hidrométrica de las Arcillas Utilizadas en la Fabricación de Productos Cerámicos en Ocaña, Norte de Santander Inge CUC 13(1) 53-60

[13] Garcia J, Medina M and Núñez D 2008 El método del hidrómetro: influencia de los tiempos de lecturas en el cálculo de la distribución del tamaño de partículas en suelos de la Habana Cultiv. Trop. 29(2) 21–26

[14] Fernández A, Sánchez J, Parras J and Acosta A 1996 Caracterización Tecnológica de las matrizes primas Cerámicas de la Sagrada (Toledo) Geogaceta 3(1) 4-10

[15] Rozo S, Sánchez J, and Gelves J 2014 Evaluación de minerales alúminos silicatos de Norte de Santander para fabricar piezas cerámicas de gran formato Revista Facultad de Ingeniería 24(38) 53–61

[16] Selmani S, Essaidi N, Gouziz F, Soussen E, Driss A, Siddi A and Rossignol S Physical-chemical characterization of Tunisian clays for the synthesis of geopolymers materials J. African Earth Sci. 103(1) 113–120

[17] Perales N and Barrera M 2013 Análisis estructural por DRX de una arcilla natural Colombiana modificada por pilarización Revista de Investigaciones Universidad del Quindío 24(1) 100–106

[18] Ramírez R, Andrade G, José J, Juárez J and Carmen M 2002 Caracterización de arcillas del Estado de Guanajuato y su potencial aplicación en cerámica Acta Universitaria 12(1) 23–30

[19] Garcia-León R, Flórez-Solano E and Acevedo-Peñaloza C 2018 Clay surface characteristics using atomic force microscopy Rev. Fac. Ing. Univ. Antioquia 87(2) 9–20

[20] Vieira C, Sánchez R and Monteiro S 2008 Characteristics of clays and properties of building ceramics in the state of Rio de Janeiro, Brazil Constr. Build. Mater. 22(5) 781–787

[21] Amado J, Villafrades P and Tuta E 2011 Caracterización de arcillas y preparación de pastas cerámicas para la fabricación de tejas y ladrillos en la región de Barichara, Santander DYNA 78(167) 50–58

[22] Garcia-León R and Flórez Solano E 2016 Determinación de la ventilación del proceso productivo en la fabricación de bloques H-10 en Ocaña Norte de Santander y la región Revista Ingenio UFPSO 9(1) 35–43

[23] Junkes J, Carvalho M, Segades A and Hutz D 2011 Ceramic tile formulations from industrial waste InterCeram Int. Ceram. Rev. 60(1) 36–41

[24] Shorten J 2006 Identification and Quantitative Analysis of Clay Minerals Developments in Clay Science 1 765–787
[26] García-León R, Flórez-Solano E and Acevedo-Peñaloza C 2018 Caracterización térmica de mezclas de arcillas utilizadas en la fabricación de productos de mampostería para la construcción Revista Colombiana de Tecnologías de Avanzada 31(1) 22–30

[27] García-León R, Flórez-Solano E and Rodríguez-Castilla M 2019 Application of the procedure of the ISO 50001:2011 standard for energy planning in a company ceramic sector DYNA 86(209) 113-119

[28] Duitama L, Espitia C and Mojica J 2004 Composición mineralógica y química de las arcillas empleadas para cerámica roja en las zonas de Medellín Revista de la Academia Colombiana de Ciencias Exactas, Físicas y Naturales 34(1) 555–564