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Recycling of Mine Wastes as Ceramic Raw Materials: An Alternative to Avoid Environmental Contamination

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1. Introduction

Solid waste management has moved to the forefront of the environmental agenda. Nations are considering restrictions on packaging and controls on products in order to reduce solid waste generation rates. Local and regional governments are requiring wastes to be separated for recycling, and some have even established mandatory recycling targets. However, industrial and everyday activities continue discarding vast amounts of material, some of which contains toxic and environmentally harmful substances. Such substances are not always disposed of in a manner with the avoidance of environmental contamination. Despite the existence of environmental standards, and in spite of the ethical implications of such actions, negligence, cost-cutting and accidents cause contamination of the soil, sediments, water and air. In the last few years, numerous industrial sectors have been mentioned as sources of environmental contamination and pollution due to the enormous quantity of wastes they generate. Mineral extraction and processing are good examples of waste production.

On the other hand, reuse and recycling of waste materials after their potentialities have been detected is considered an activity that can contribute to diversify products, reduce production costs, provide alternative raw materials for a variety of industrial sectors, conserve non-renewable resources, save energy, and especially, improve public health.

The insertion of waste materials into an alternative productive cycle might represent an alternative recovery option, which is interesting from both an environmental and an economical perspective. Recovery and recycling is the best environmental solution to save raw materials and to reduce the amount of industrial waste materials produced, and consequently the contamination of environment.

Considerable research work of our research group has recently focused on the recovery and safe, useful application of waste materials originating from the mining and mineral processing industry. Most of these studies report that such waste can be considered important alternative raw materials to the ceramic industry.

Traditional ceramics, such as bricks, roof and floor tiles, other constructions materials, and technical ceramics, such as porcelain and mullite bodies, are usually highly heterogeneous due to the wide compositional range of the natural clays used as raw materials. Therefore, there is a great incentive to use large amounts of suitable waste products as raw materials. Today it is a well-known fact that some waste materials are similar in composition to the natural raw materials used in the ceramic industry and often contain materials that are not only compatible but also beneficial in the fabrication of ceramics. In view of the huge amounts of non-renewable mineral resources that the ceramic industry consumes, this similarity is of even greater significance.

Studies conducted by the authors observed that kaolin processing wastes and granite sawing waste present a high potential to use as raw material for building materials. Kaolin is an important raw material in various industries, such as the ceramic, rubber, plastic, ink, chemicals, cement, and paper industries. However, the kaolin mining and processing industry generates large amounts of waste. The kaolin industry, which processes primary kaolin, produces two types of waste materials. The first type derives from the first processing step (separation of sand from ore), which represents about 70% of the total waste produced, and is also known as china clay sand. The second type of waste is resulted from the second processing step, which consists of wet sieving to separate the finer fraction and purify the kaolin. Granite processing industry produces large amounts of waste materials worldwide. Granite-sawing waste contains feldspar, quartz and mica as major constituents and metallic dust and lime (used as abrasive and lubricant, respectively) as residual materials, and various studies have studied its recycling in ceramic industry. In this scenario, this chapter will address the use of these mine wastes as raw material for the production of ceramic materials as building materials, ceramic brick and tile, roof tiles, mortars, etc.

2. Recycling and mining wastes

The pollution of ground and surface waters began as soon as industry began producing manufactured goods and wasting liquids and solid matter simultaneously. In the 1930s, industries began to be aware of the eventual danger of their wastes when sent untreated into waterways. It was natural for industry at that time to follow the lead of municipalities in using similar treatments to attempt to resolve their pollution problems. In the World War II there is an accelerated industrial production activity (Nemerow, 2006), and two developments in the post-World War II era led to significant escalation in the problems of managing waste. First, a new phenomenon called "consumerism" emerged. A long period of prosperity, combined with improvements in manufacturing methods led to rapid growth in the number and variety of consumer goods. In addition, new marketing and production practices were introduced, such as planned obsolescence and "throw-away" products. The growth of advertising, along with the electronic media, played an important role in the evolution to our society's current level of overconsumption. The end result was a dramatic increase in the amount and variety of consumer goods—and, hence, wastes (The waste crisis). The second development was the birth of the "chemical age," which resulted in a dramatic change in the composition of the waste stream. The petrochemical industry has grown explosively since that time, yielding a vast array of new synthetic organic compounds, a kind of pollution that had never existed before entered the environment, exhibiting toxicity as well as non-biodegradability (Tammemagi, 1999; Nemerow, 2006).

Radioactivity, petrochemical, and synthetic organic chemicals were largely developed and surfaced in the environment in the 1940s and 1950s. During this period, major environmental problems surfaced with rapid and serious consequences. Hence was born the advent of what was to become the pollution problems of the twentieth century (Nemerow, 2006).

Historically, waste was simply dumped in depressions, ravines, and other handy locales that were close to the population centers producing the waste. Even though recycling was commonly practiced by all households during pre-industrial ages, large-scale recycling programs did not arise until the twentieth century. The first organized programs were created in the 1930s and 1940s, when a worldwide depression limited people's ability to purchase new goods and the outbreak of World War II dramatically increased demands for certain materials. Throughout the war, goods such as nylon, rubber, and various metals were recycled and reused to produce weapons and other materials needed to support the war effort. However, after the War there was a drastically decrease in the recycling efforts (Miller, 2010).

It was not until the environmental movement of the 1960s and 1970s that recycling once again emerged as a popular idea. This movement began in 1962 with the publication of Rachel Carson's book *Silent Spring*, detailing the toxic effects of the chemical DDT on birds and their habitats. The book raised the consciousness of many people about the dangers to the environment from chemicals and other toxins produced by modern industries (Miller, 2010). Thereafter, the increase in the environmental awareness and consciousness required industry to meet tighter environmental standards on a global basis. In many countries, such requirements generally cannot be met by using conventional disposal of residual solid wastes in landfills (Wang et al., 2010). Accordingly, much more emphasis has to be placed on waste reduction and recycling technologies as a necessary first step to reduce to a minimum the extent of the waste treatments to be provided.

In recent years there has been growing concern about the negative impacts that industry and its products are having on both society and the environment in which we live. The concept of sustainability and the need to behave in a more sustainable manner has therefore received increasing attention. With the world's population growing rapidly the consumption of materials, energy and other resources has been accelerating in a way that cannot be sustained (Hester, R. E. & Harrison, 2009).

In this scenario, solid waste management has moved to the forefront of the environmental agenda, with the amount of related activities and concern by citizens and governments worldwide reaching unprecedented levels. Nations are considering restrictions on packaging and controls on products in order to reduce solid waste generation rates. Local and regional governments are requiring wastes to be separated for recycling, and some have even established mandatory recycling targets. Concerns about emissions from incinerators and waste-to-energy plants have resulted in imposition of state-of-the-art air pollution controls. Landfills are being equipped with liners, impervious caps and leachate collection systems, and gas and groundwater is being routinely monitored. As a result, the costs of solid waste management are increasing rapidly (Goumans et al., 1994).

In this context, arise the industrial ecology. Industrial ecology is now a branch of systems science for sustainability, or a framework for designing and operating industrial systems as sustainable and interdependent with natural systems. It seeks to balance industrial production and economic performance with an emerging understanding of local and global ecological constraints (handbook of industrial and hazardous). The idea of industrial ecology is that waste materials, rather than being automatically sent for disposal, should be regarded as raw materials—useful sources of materials and energy for other processes and products (Wang et al., 2006).

Waste management strategies that focus on source reduction and resource recovery, reuse and recycling have proven to be more cost effective over the long run, and they are less damaging to the environment simply because they prevent or minimize waste generation at the source. Disposal and treatment technologies require major long-term investments in capital equipment and have ongoing costs. But in addition, the waste and pollution that are treated and disposed of still persist, posing continuous and future threats to the public and environment (Cheremisinoff, 2003).

Recycling of waste materials will conserve decreasing resources and avoid the environmental and ecological damages caused by their disposal in the environment. Recycling saves energy, preserves natural resources, reduces greenhouse-gas emissions, and keeps toxins from leaking out of landfills.

Successful research and development on using wastes as raw material, is a very complex task. This task comprehends a multidisciplinary approach involving knowledge from different areas, such as materials science, marketing development, performance evaluation and environmental sciences. As a rule, the best application for the waste is the one that will use its true characteristics and properties to enhance the performance of the new product and minimize environmental and health risks. Waste applications should not be made on a preconceived basis. This requires creativity and a wide range of both scientific and technical knowledge and for the best results will require the collaborative work of a multidisciplinary team (Woolley et al., 2000).

However, attention should be given to environmental contamination risk evaluation due to leaching of hazardous components is mandatory. New product must satisfy toxicity leach test criteria. But it is not sufficient. Other environmental impacts like greenhouse gases emission, human toxicity, acidification, energy use, etc. are also important and good technology for recycling frequently allows significant reduction on these impacts (Woolley et al., 2000; Rao, 2006).

On the other hand, public are became more accepting of purchasing manufactured goods with recycled content. Manufacturers recognized this acceptance, that using recycling content in their products developed more innovative ways to use waste material. Manufacturers learned that recycled content yielded economic and marketing benefits, and consumers realized they could buy recycled-content products with confidence (Winkler, 2010).

Mining, alongside agriculture, represents one of man's earliest activities, the two being fundamental to the development and continuation of civilization. In fact, the oldest known mine in the archaeological record is the Lion Cave in Swaziland, which has a radio carbon age of 43 000 years. There Paleolithic humans mined hematite, which they presumably ground to produce the red pigment ochre. Moreover, the dependence of primitive societies on mined products is illustrated by the terms Stone Age, Bronze Age and Iron Age, a sequence of ages that indicate the increasing complexity of the relationship between mining and society (mining and its impact). With time, the use of minerals has increased in both volume and variety in order to meet a greater range of purposes and demand by society, and the means of locating, working and processing minerals has increased in complexity. Today, society is even more dependent on the minerals industry than in the past (Bell & Donnelly, 2006).

Mining is first and foremost a source of mineral commodities that all countries find essential for maintaining and improving their standards of living. Mined materials are needed to construct roads and hospitals, to build automobiles and houses, to make computers and satellites, to generate electricity, and to provide the many other goods and services that consumers enjoy. In addition, mining is economically important to producing regions and countries. It provides employment, dividends, and taxes that pay for hospitals, schools, and public facilities (Committee on Technologies for the Mining Industries et al., 2002).

The consequence of the importance of the mining industry to the world economy is not only the large volume of materials processed but also the large volume of wastes produced. Mine wastes represent the greatest proportion of waste produced by industrial activity. In fact, the quantity of solid mine waste and the quantity of Earth's materials moved by fundamental global geological processes are of the same order of magnitude – approximately several thousand million tonnes per year (Lottermoser, 2007).

Mining, and associated mineral processing and beneficiation, does impact on the environment. Unfortunately, this frequently has led to serious consequences. The degree of impact can vary from more or less imperceptible to highly intrusive and depends on the mineral worked, the method of working, and the location and size of the mine. The environmental impact of mining industry is strongly felt in two areas. The first is the volume of industrial waste, effluents, tailings and sludge. The second serious environmental concern is the emission of carbon dioxide, a major green house gas, which has been implicated in gradual climate change round the world.

Operations of the mining industry include mining, mineral processing, and metallurgical extraction. Mining is the first operation in the commercial exploitation of a mineral or energy resource. Mineral processing or beneficiation aims to physically separate and concentrate the ore mineral, whereas metallurgical extraction aims to destroy the crystallographic bonds in the ore mineral in order to recover the sought after element or compound. All three principal activities of the mining industry produce wastes. Mine wastes are defined as solid, liquid or gaseous by-products of mining, mineral processing, and metallurgical extraction (Lottermoser, 2007).

Mining wastes include overburden and waste rocks excavated and mined from surface and underground operations. Mining wastes are heterogeneous geological materials and may consist of sedimentary, metamorphic or igneous rocks, soils, and loose sediments. As a consequence, the particle sizes range from clay size particles to boulder size fragments. The physical and chemical characteristics of mining wastes vary according to their mineralogy and geochemistry, type of mining equipment, particle size of the mined material, and moisture content (Lottermoser, 2007).

Mineral processing encompasses unit processes for sizing, separating and processing minerals, including comminution, sizing, separation, dewatering, some types of chemical processing. Processing wastes the portions of the crushed, milled, ground, washed or treated resource deemed too poor to be treated further. The physical and chemical characteristics of processing wastes vary according to the mineralogy and geochemistry of the treated resource, type of processing technology, particle size of the crushed material, and the type of process chemicals.

Metallurgical wastes are the residues of the leached or smelted resource deemed too poor to be treated further, and are generated by hydrometallurgical extraction and electro- and pyrometallurgical processes.

Mine wastes result from the extraction of metalliferous and non-metalliferous deposits. In the case of metalliferous mining, high volumes of waste are produced because of the low or very low concentrations of metal in the ore. In fact, mine wastes represent the highest proportion of waste produced by industrial activity, billions of tonnes being produced annually. Such wastes can be inert or contain hazardous constituents but generally is of low toxicity. The chemical characteristics of mine waste and waters arising from them depend upon the type of mineral being mined, as well as the chemicals that are used in the extraction or beneficiation processes. Because of its high volume, mine wastes historically have been disposed of at the lowest cost, often without regard for safety and often with considerable environmental impacts (Bell & Donnelly, 2006).

Usually the metalliferous and non-metalliferous wastes (from mining and processing operations) are placed in the postmining topography. In the case of mountain top removal and contour mining methods, waste materials are often used to fill adjacent canyons or hollow areas. When associated with canyon fills, these anthropogenic land forms may be flat or gently sloping on top, but often have steep side slopes and tend to be very erosive. Also, because of the nature of the material (i.e., unconsolidated, non-homogeneous) water penetration can cause instability thus enhancing mass wasting and the formation of seeps containing high levels of various elements that could impact down slope sites (Marcus, 2007).

Another very important concern to the mining industry is particulate matter, which is emitted in relatively large amounts in almost all aspects of mining operations (mining environmental). Particulates can affect human health adversely, as well as damage animals and crops. At high enough levels, particulates can contribute to chronic respiratory illnesses such as emphysema and bronchitis and have been associated with increased mortality rates from some diseases. In addition, particulate matter may cause irritation of the eyes and throat, and it can impair visibility.

As processing technologies move toward finer and finer particle sizes, dust and fine particles produced in the mineral industry are becoming an important consideration Fine particles and dust can represent a health hazard, an environmental concern, and an economic loss. The amount of waste dust and fine particles is increasing significantly as more rock is mined and processed. Research should be focused on minimizing the generation of unwanted fine particles and dust or on using these materials as viable by-products.

Moreover, large volumes of water slurries containing fine particles are produced by all types of mining facilities. The management of these slurries as they are dewatered and disposed of can present significant environmental issues. Whether slurries are produced as tailings from milling operations, spoils in coal mining, or as clay slimes in the phosphate industry, they are often slow and difficult to dewater and dry because of their colloidal nature (Committee on Technologies for the Mining Industries et al., 2002).

There are other problems faced by the mining industry, as closure and reclamation of dump-leaching and heap-leaching operations and tailings impoundments. Upon the cessation of production, dump-leaching and heap-leaching piles and tailings impoundments must be closed in an environmentally sound manner. Depending on the chemical characteristics of the wastes and reagents used, as well as on atmospheric precipitation rates, piles and tailings may contribute poor-quality seepage or runoff to surface and/or groundwater through the release of residual solution or from infiltration of or contact with atmospheric precipitation. The released solution may be acidic or may contain cyanide or other contaminants, such as selenium, sulfates, radionuclides, or total dissolved solids (Committee on Technologies for the Mining Industries et al., 2002).

However, not all mine wastes are problematic wastes and require monitoring or even treatment. Many mine wastes do not contain or release contaminants, and pose no environmental threat. In fact, some waste rocks, soils or sediments can be used as raw materials for a series of industries. , and a few are suitable substrates for vegetation covers and similar rehabilitation measures upon mine closure.

Therefore, the development of innovative, environmentally friendly technologies will be extremely important. Minimizing waste generation and using wastes to produce useful by-products while maintaining economic viability must be a goal for new technologies. For instance, the processing of metallurgical wastes and recovery of valuable components and in some cases converting them into useful compounds not only help to reduce pressure on ponds and landfills but also it, at least in part, offsets the cost of environmental protection (Rao, 2006).

Sustainable development is a concept which attempts to shape the interaction between the environment and society, such that advances in wellbeing are not accompanied by deterioration of the ecological and social systems which will support life into the future. The management of mining and minerals processing wastes is therefore a fundamental sustainable development issue.

The reduction, reuse, recycling and treatment of mining and minerals processing waste are increasingly receiving greater research and development attention for their contribution to improving the sustainability of the minerals industry (Franks et al., 2011) Recent trends outlined the new mining culture: management of resources on a local basis (water, building materials, etc.), prevention of dissipative uses by improved recycling, and promotion of efficiency in production processes (better recovery means less pollution), etc.

It is very important to be aware of the fact that almost the same kind of material, depending on its characteristics, could be regarded as a waste (that may have to be treated) or a secondary raw material (environmental aspects of construction). This implies that close cooperation between society players (in both public and private sectors) dealing with waste recycling technology to replace raw materials by mining wastes.

The quantity of industrial minerals recycled or reused in some way is still minor compared to the total global consumption of industrial minerals obtained by mining and quarrying (resource recovery). However, manufacturers began to look at recycled waste as a more reliable and cost-effective supply source for raw material, and altered existing products or developed new ones to better use recycled products (Winkler, 2010). In this sense mining wastes have being used in resin cast products, glass, ceramics, glazes as well as building and construction materials.

Thus, mining waste can no longer be considered solely a useless material, but, it is must first analyzed (scientifically and technically) the potential usefulness of the wastes as alternative raw materials, reducing the demand for virgin materials and the environmental impacts associated with extraction and processing of virgin resources.

3. Granite sawing waste and kaolin processing waste: Alternative ceramic raw materials

The industry of the ornamental granite is included in the natural stone industry sector, more specifically in the sub-sector of the ornamental rocks comprising the extraction and processing of rocks for ornamental applications. This economical activity represents an important sector in the worldwide economy. However, a less known aspect of the exploration of the ornamental rocks is the great volume of produced residues, specifically, solids (generated during the extraction) and sludges (produced during the transformation process) (Torres et al., 2009).

After mining, the granite blocks are submitted to primary dressing, which consist of sawing (Figure 1 depicts the sawing operations), to obtain semi finished pieces such as plates and strips. This is followed by secondary dressing in which the sectioned pieces undergo polishing and surface finishing. During primary dressing, an estimated loss of 20–35% of the blocks occurs in the form of powder. This leftover powder is removed in a mixture with water and other residual materials such as metallic dust and lime, used as abrasive and lubricant, respectively, producing a sludge.

Hence, granite waste, as described elsewhere (Menezes et al., 2002a, 2002b; Torres et al., 2004; Menezes et al., 2005) is basically composed of quartz, mica, potassium feldspar ($KAlSi_3O_8$), sodium feldspar ($NaAlSi_3O_8$), iron (or iron oxide and iron hydroxides) and lime (or calcite ($CaCO_3$)) and has a large particle size distribution.

This material has been deposited as dry particles with large particle size range or as fine particles in aqueous environment, generally deposited by sedimentation. It is also common to deposit filter-pressed sludge in surface landfill. Although not considered dangerous, incorrectly planned deposition of these residues can cause accidents and environmental impact like, for instance, the increase of the turbidity of the courses of water. The dried mud is easily dragged by the wind and becomes harmful to humans and animals through its inspiration or to plants when deposited on their leaves. The sludge generated during the processing of stone have no specific practical applications and have been managed as waste. Figure 2.

Thus, the search for new recycling technologies is of high technological, economic and environmental interest. In this regard, interesting opportunities are found in the traditional ceramics industry, particularly the sector devoted to the fabrication of building products. Natural raw materials used in the fabrication of clay-based ceramic products show a wide range of compositional variations and the resulting products are very heterogeneous.

Fig. 1. Sawing operation of granite blocks.

Granite sludge is a mixture of debris residue of cut granite rocks with wear remains of cutting steel blades, abrasive metallic shot, and hard materials from the polishing bricks. In the common granite cutting practice, the abrasive metallic shot is dispersed in $Ca(OH)_2$ aqueous slurry for cooling. This slurry is continuously pumped and wets all around the granite block slits (Figure 1).

Therefore, such products can tolerate further compositional fluctuations and raw material changes, allowing different types of wastes to be incorporated into ceramic tiles and bricks. Various studies (Menezes et al., 2002a, 2005, 2007, 2008a) have demonstrated the viability of using granite sawing waste in the production of building materials.

Studies of our research group demonstrated that is possible to incorporate high amounts granite sawing waste in ceramic formulations for the production of ceramic bricks and roof tiles. Figure 3 illustrate the mechanical behavior of ceramic bodies, fired at 1000°C, with the rise of waste content. Small additions of these wastes, up to 20%, improved the mechanical performance of the bodies. Granite wastes present a non-plastic character and, therefore, it was also observed that they can play an important role as plasticity-controllers during fabrication. Figure 4 displays ceramic bodies produced incorporating granite sawing.

For the production of ceramic bricks, the predominant raw material used is mineral clay. Any good brick clay should have low shrinkage and low swelling characteristics, consistent firing color, and a relatively low firing temperature, but at the same time produce an adequately dry and fire-strength brick. The guiding rule of choice on wastes and by-products must rest on their compatibility with the original (host) raw material being used, whereas they must not degrade the final product by focusing simply on making it a repository for wastes (Insam & Knapp, 2011). Granite sawing waste reaches all the requirements to be a versatile raw material for the production of ceramic brick and roof tiles.

Granite sawing waste can also be used in the production of soil-lime bricks. Figure 5 shows a soil-lime brick containing granite waste and a construction developed using this kind of brick.

In ceramic technology there is a large range o firing temperatures. After 1100°C granite sawing waste can be classified as fluxes, as they have the potential to act as glassy phase formers during the sintering process, improving the sinterability of the clay material. The effect of small additions of such rejects in compositions for the production of ceramic tiles has been investigated (Menezes et al., 2005, 2008a), and it was observed that the final properties of the fired products do not change drastically. According to the composition to be manufactured it is possible incorporate high amounts of waste, up to 50%.

Figure 6 depicts the water absorption and mechanical behavior of ceramic tiles (produced with different composition) fast fired at 1175°C, containing distinct amounts of different granite wastes. It can be observed that there is no a directly correlation between these properties and waste content. This is due to the fact that each granite wastes present particular characteristics, as amount of fluxes and particle size distribution. But also, because the influence of granite wastes will be close associated with the characteristics (and amounts) of the other raw materials used in the formulation of ceramic masses. Thus, it is possible incorporated 38% of waste and reached high mechanical performance, and in other situation using 21% of waste the modulus of rupture achieved was just above the strength limit required.

The current optimization procedure for developing ceramic compositions using waste materials consists of an experimental rather than a comprehensive approach. In general, the approach involves selecting and testing a first trial batch, evaluating the results, and then adjusting the mixture's proportions and testing further mixtures until the required

Fig. 2. Disposal of granite sawing waste in the environment: in aqueous environment and in open air

properties are achieved. The conventional method of optimization is time consuming and does not allow the global optimum to be detected, particularly due to interactions among the variables. In contrast, statistical design methods are rigorous techniques both to achieve desired properties and to establish an optimized mixture for a given constraint, while minimizing the number of trials. This methodology when applied in the recycling of wastes in the ceramic technology has led to greater efficiency and confidence in the results obtained and has simultaneously optimized the content waste materials with a minimum of experiments.

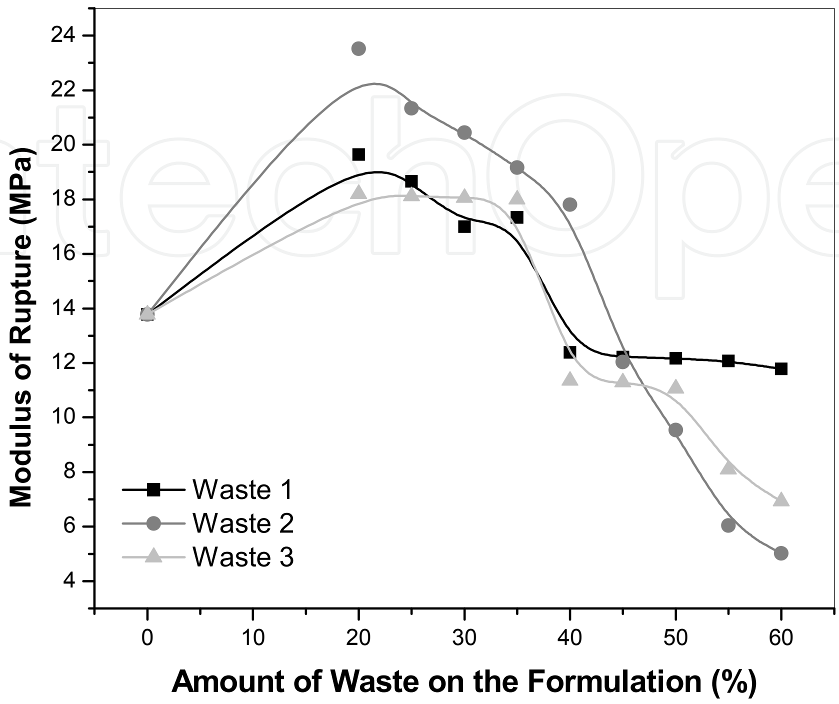

Fig. 3. Modulus of rupture of ceramic bodies fired at 1000°C (formulations for the production of ceramic bricks and roof tiles)

Fig. 4. Ceramic bodies containing granite sawing waste

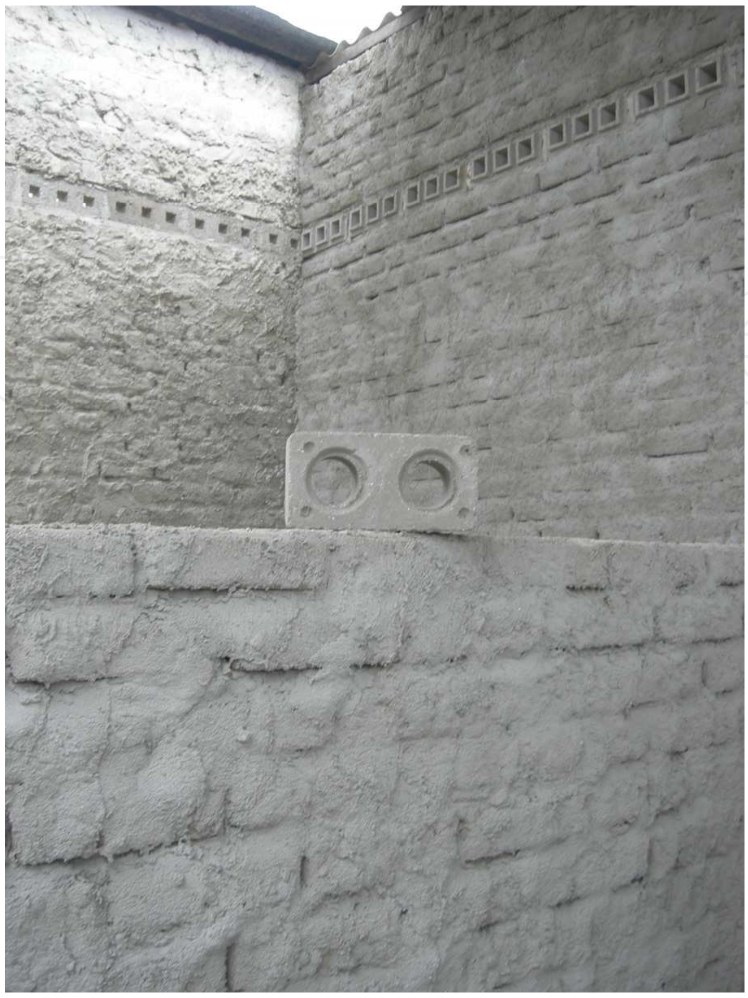

Fig. 5. Soil-lime brick containing granite sawing waste and a construction developed using this kind of brick.

In the development and manufacture of ceramics using waste materials, the properties of fired bodies are basically determined by the combination of raw materials and process parameters. When the processing conditions are kept constant, a number of properties of dried and fired bodies are basically determined by the combination (or mixture) of raw materials. This is the basic assumption in the statistical design of mixture experiments to obtain a response surface using mathematical and statistical techniques. To this end, it is necessary first to select the appropriate mixtures from which the response surface might be calculated. Then, form the calculated response surface, the property value of any mixture can be predicted based on the changes in the proportions of its components. In this sense authors had applied this mathematical tool in several studies developing ceramic formulations containing high amount of granite wastes with great efficiency and a minimum of experiments.

Figure 7 shows the calculated response surface plots and their projections onto the composition triangle for the modulus of rupture ceramic bodies containing granite sawing waste after firing at 1150^{o}C. According to the Figure it is possible to quickly realize the real influence of granite waste on the property of ceramic body and also optimize raw materials composition, increasing the content of waste and, in the same time, improving the performance of the final body. In this case in particular it is clear that the maximum value of the modulus of rupture was achieved when using at around 50% of granite sawing waste.

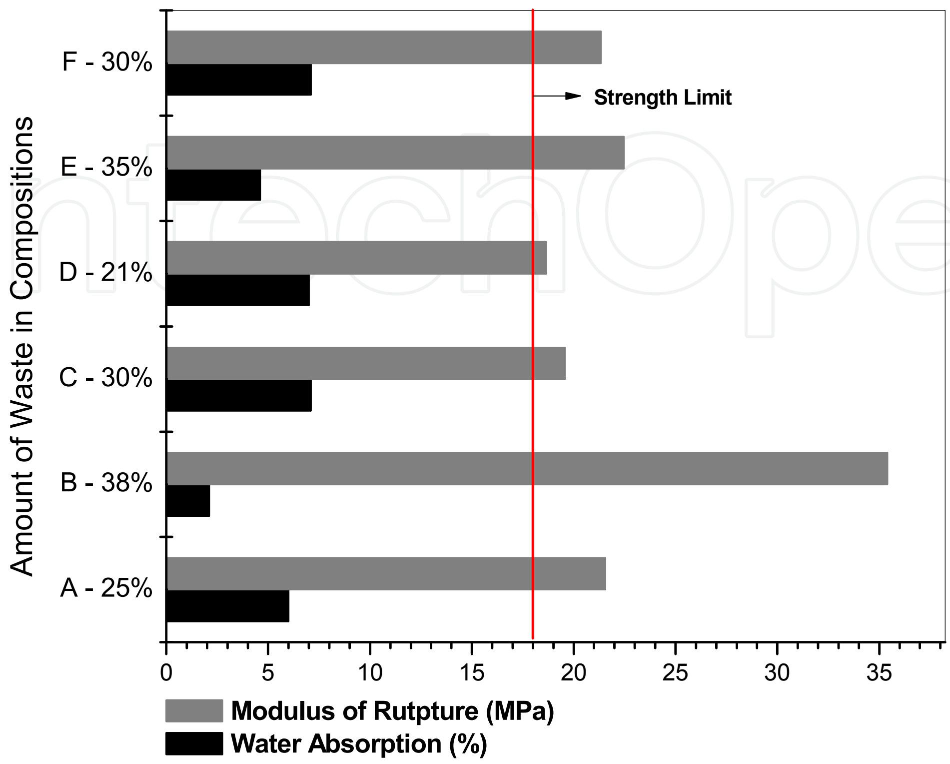

Fig. 6. Water absorption and modulus of rupture of ceramic tiles fired at 1175°C containing granite sawing waste

Kaolin is an important raw material in various industries, such as the ceramic, rubber, plastic, ink, chemicals, cement, and paper industries. However, the kaolin mining and processing industry generates large amounts of. The kaolin industry, which processes primary kaolin, produces two types of wastes. The first type derives from the first processing step (separation of sand from ore, generally by wet sieving). The other type of waste results from the second processing step, which consists of a wet sieving to purify the kaolin. Figure 8 display the second step of the kaolin processing, the sedimentation tank.

Traditionally, these wastes have been disposed of in landfills and often dumped directly into ecosystems without adequate treatment. This can seriously damage the environment through soil and water contamination, and is potentially harmful to flora, fauna and human health. Figure 9 depicts the dispose of these wastes directly in open air. Nowadays, because of more stringent environmental laws and the market's increasing demand for environmentally friendly products, manufacturers are concerned with developing studies aimed at reducing the environmental impact of these wastes. Thus, possible reuse or recycling alternatives should be investigated and implemented.

Physical and chemical characterizations of kaolin processing wastes can be found elsewhere (Menezes et al., 2007, 2008b). According to those reports, kaolin wastes are basically composed of kaolinite ($Al_2Si_2O_5(OH)_4$), mica ($KAl_2(Si_3Al)O_{10}(OH)_2$) and quartz ($SiO_2$) and has a very large particle size distribution. The composition and particle size distribution of the two types of waste are very different. The first one contain a high amount of quartz and coarse particle size (reaching particles of 5, 10mm), while the second one, presents a high amount of kaolinite and a large particle size distribution with a high mount of fine particles (because of this the second waste are known as fine waste and the first waste as coarse waste).

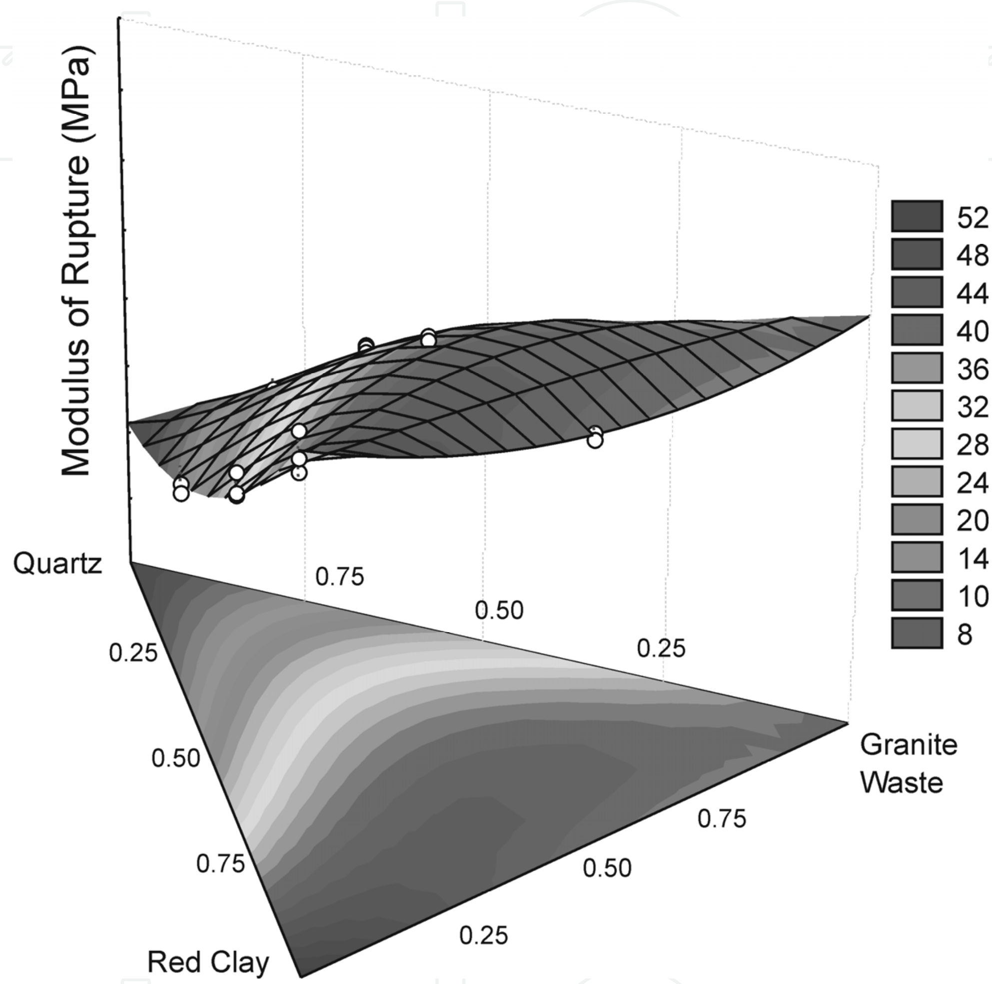

Fig. 7. Response surface plots and their projections onto the composition triangle for modulus of rupture of ceramic bodies containing granite sawing waste after firing at 1150°C

Mineral fillers are used in a wide range of commodities such as paper, paint, plastics, membranes, ceramics, plasterboard, geo-textiles, rubber, pet food, chicken feed, electrical cables and several construction materials. Such fillers are marketed at a relatively high cost, as the total production costs. However many applications such as ceramics and some construction materials, do not require fillers of such a high grade. In this sense, the fine kaolin processing waste was studied by our research group to be used as filled in mortars for the construction industry. The waste replaced the lime and the cement in several mortars formulations presenting very interesting results. Figure 10 shows the compression strength of mortars, which had the lime replaced by kaolin processing waste (fine waste). Addition of waste improved the performance of the mortar due to the filler effect of the material.

Fig. 8. Sedimentation tank used in the second step of kaolin processing

Kaolin processing waste after be fired display pozzolanic activity (capacity to react chemically with the lime and form hydrated calcium silicates, phases similar to those produced with the cement hydration). Thus, calcinations of this waste can improve its applicability and incorporation in construction materials. The compression strength of mortars that had part of cement replaced by fired kaolin waste (50% of coarse and 50% of fine) is depicted in Figure 11. This result illustrates the potential of this waste as agglomerate material after firing. The increase in the compression strength when using waste in natural is due to the filler affect. Because of the high fineness, their particles can fill the voids between the cement particles, increasing the soil density and strength.

Kaolin processing waste (fine waste) can also be used in other ceramic industries. Studies (Menezes et al., 2008b, 2009a, 2009b) have pointed up its application in production of porous ceramics, mullite bodies and porcelains. The waste acts as alternative raw material replacing part of the kaolin and of the quartz used in the formulation. Bodies obtained presented high strength and excellent performance, similar to those of bodies produced using conventional raw materials. The outstanding performance of the produced bodies was close associated with the development of high amount of mullite, as a consequence of the presence of fluxes and kaolinite on the waste (Figure 12).

The potential use of granite waste in combination with kaolin processing waste to produce ceramic bodies was also investigated by our research group. Regression models used to optimize the waste content in ceramic compositions displayed that ceramic bricks containing up to 40% of wastes (kaolin waste + granite waste) can be manufactured without trouble and the final bricks presented physical and mechanical properties similar to those of conventional bricks. Figure 13 illustrates this potential using the surface plot projection onto the composition triangle. The area highlighted on the triangle indicates the possible compositions (according to limitations imposed) to be used for ceramic brick production.

Fig. 9. Piles of wastes directly disposed in the environment

Use of kaolin waste in association with granite waste was also very efficient for the production of ceramic tiles containing high amount of wastes, at around 60%. Figure 14 displays the synergism of the wastes, while the granite waste improves the mechanical behavior of the body, the kaolin waste act in a manner similar to the clay. The combination of both wastes make possible improves the performance of the body and save clay material, using high amount of kaolin waste and granite waste.

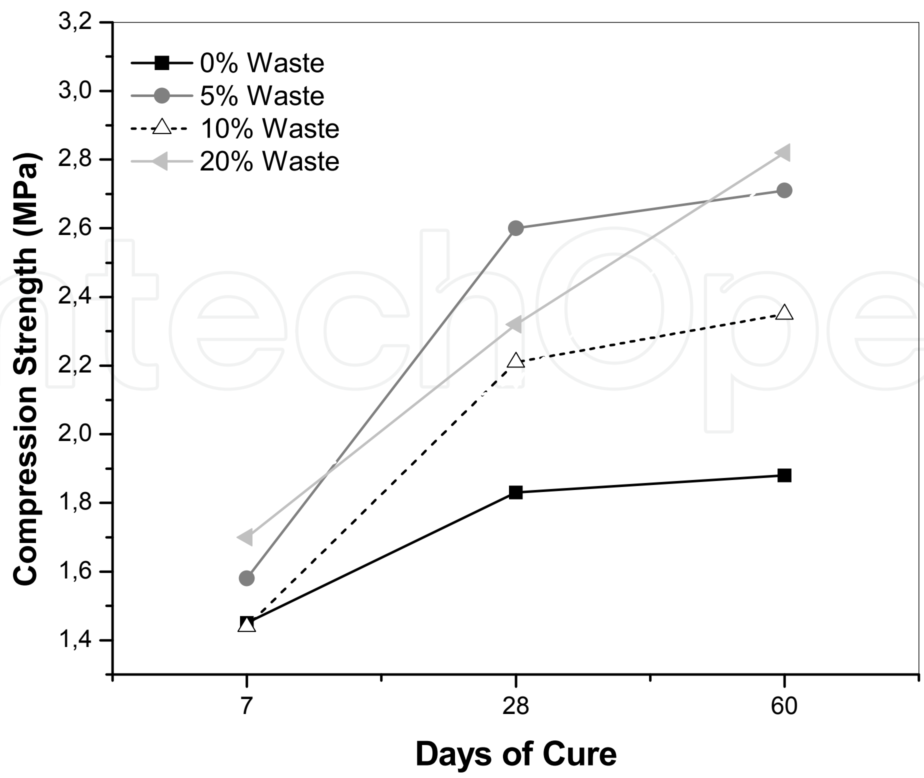

Fig. 10. Compression strength of mortar (cement:lime:sand), which had the lime replaced by kaolin processing waste

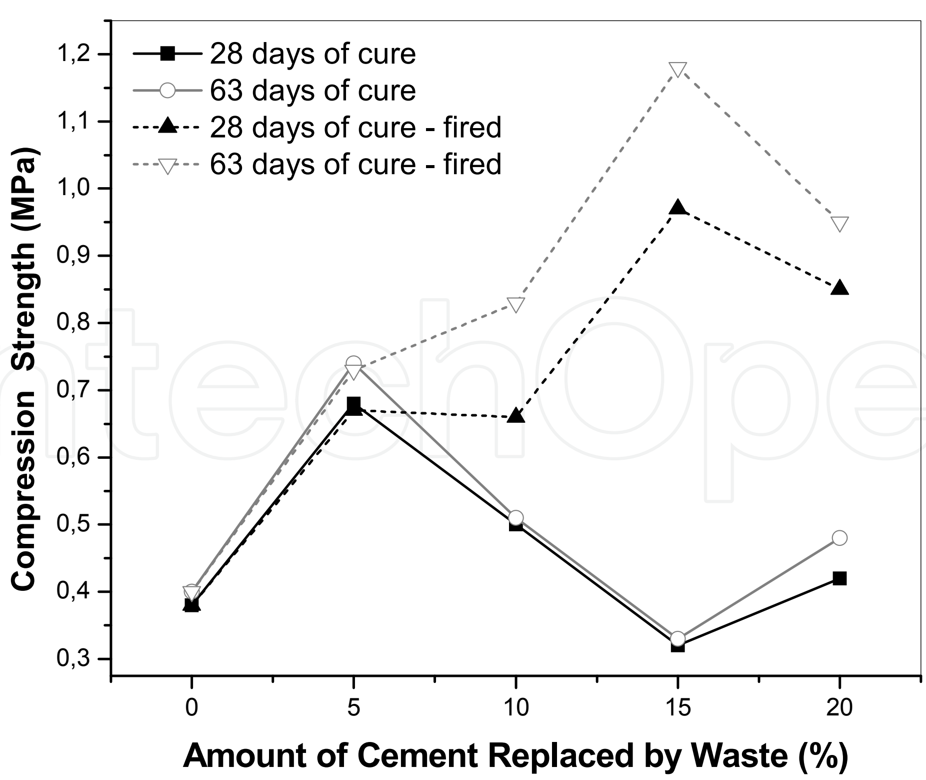

Fig. 11. Compression strength of mortar (cement:sand), which had part of the cement replaced by kaolin processing waste

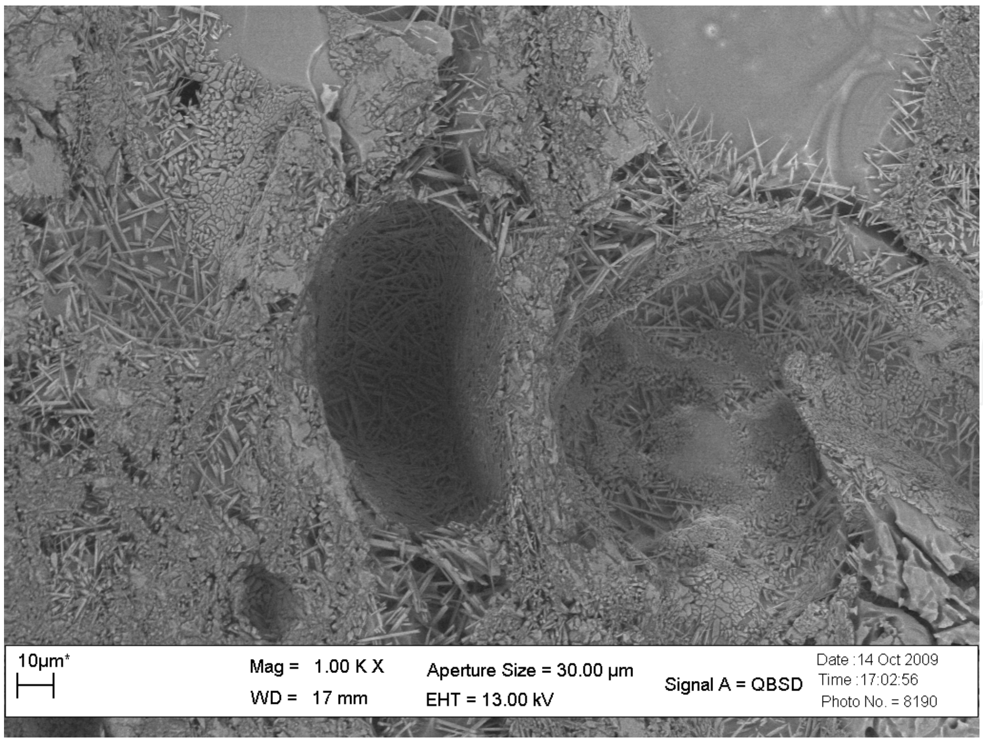

Fig. 12. Scanning electron microscopy micrograph of mullite body produced using kaolin processing waste (fine waste)

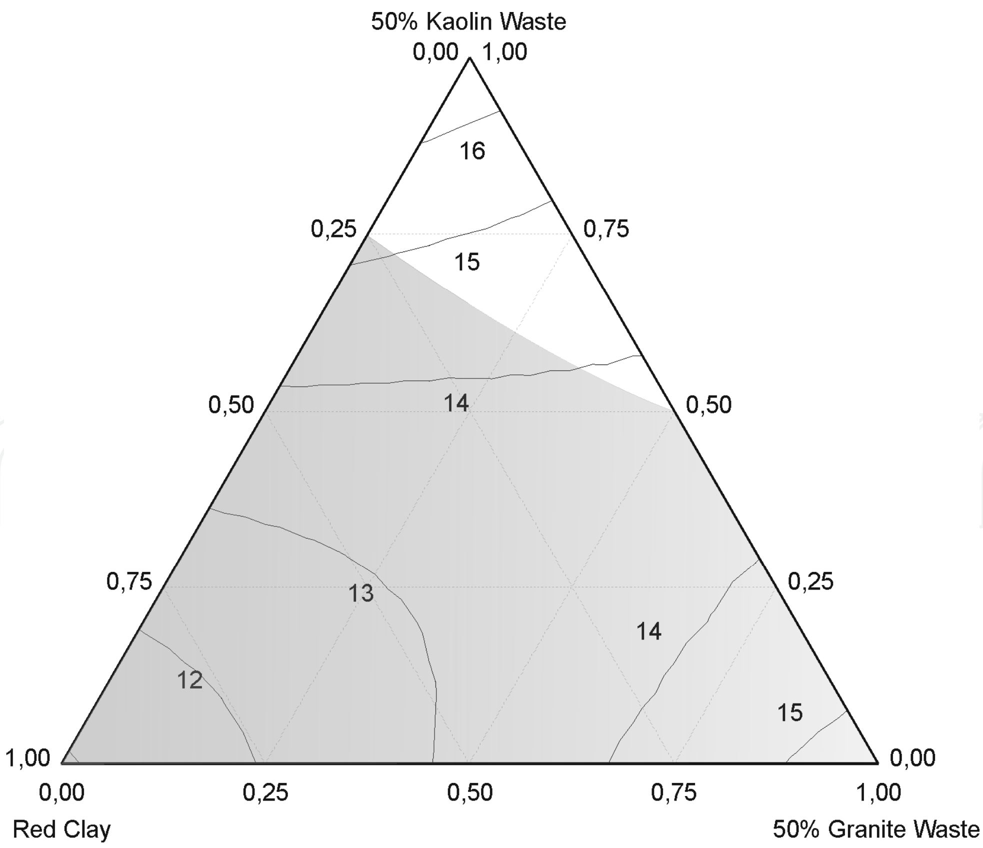

Fig. 13. Surface plot projection onto the composition triangle of compositions containing kaolin processing and granite sawing wastes

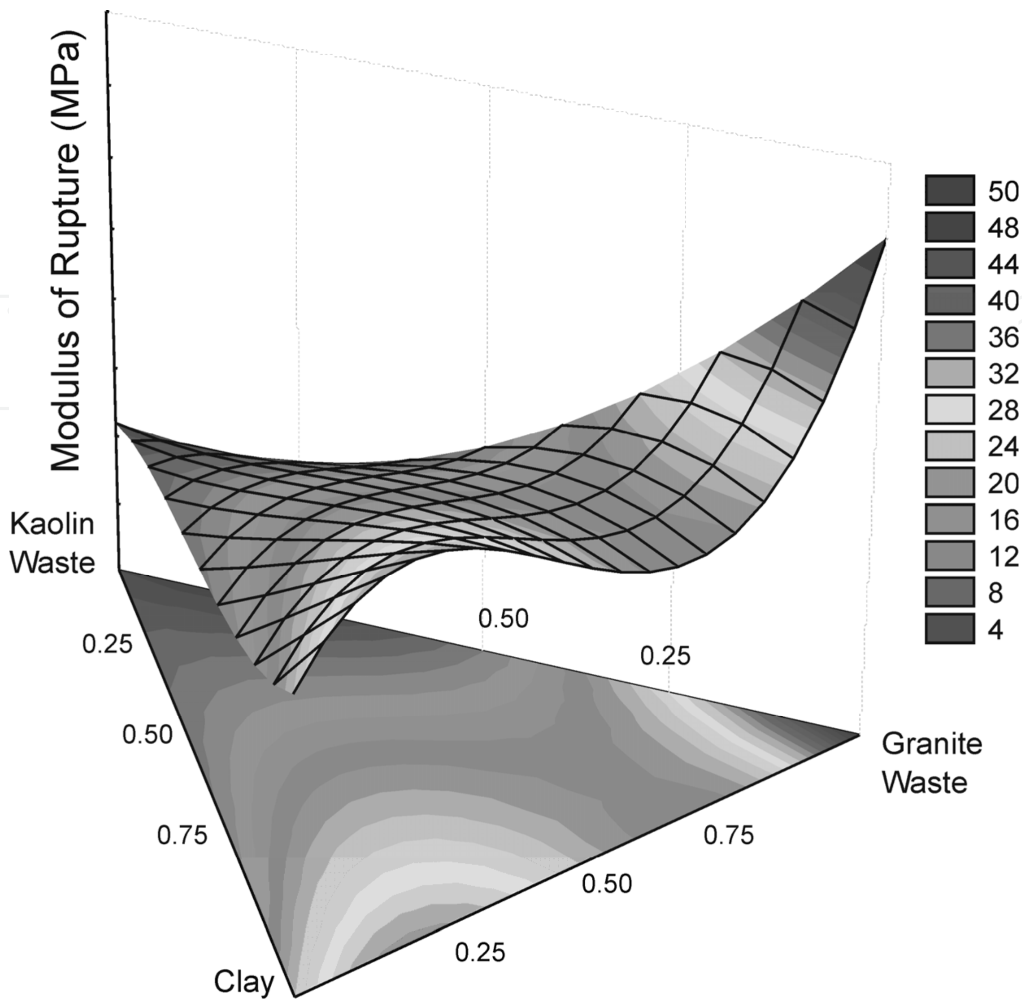

Fig. 14. Response surface plots and their projections onto the composition triangle for modulus of rupture of ceramic bodies containing kaolin processing and granite sawing wastes after firing at 1100°C

While recycling of low added-value residual materials constitutes a present day challenge in many engineering branches, attention has been given to low-cost building materials with similar constructive features as those presented by materials traditionally employed in civil engineering. Developing countries usually face grave housing deficits. Aiming at lowering costs, scientific attention has been given to non-conventional building materials with similar features as those presented by construction materials traditionally used in civil engineering. Quest for such surrogate materials can be two-fold interesting as (*i*) it may help to reduce dwelling deficits (particularly in developing countries) inasmuch as cheaper houses become economically feasible and (*ii*) it can be environmentally friendly as low-value wastes can be recycled or exploited. (Ashworth & Azevedo, 2009).

On the other hand, these results on recycling of granite sawing and kaolin processing wastes highlight that these wastes recycling contributes to diversify products, reduces production costs, provides alternative raw materials for a variety of industrial sectors, conserves non-renewable resources, saves energy and, improves public health. Thus, upgrading these wastes to alternative ceramic raw materials has become interesting, not only technically, but also environmentally and socially.

4. Conclusion

Studies of our research group displayed that kaolin processing and granite sawing wastes can serve as alternative raw materials for the production of ceramic materials, and that not only construction materials (as ceramic bricks and tiles, roof tiles, mortars, etc.) but also ceramics like porcelain, mullite bodies, membranes, etc. The correct use of the wastes produces lower firing temperature or improves the performance of the final bodies. Correct characterization, physically and microstructurally, and application of mathematical tools permit incorporation of high amounts of waste in ceramic formulations, exceeding 50% of the raw material used in the composition. Our results highlighted that the use of mine wastes in the production of building materials can be successfully carried out, allowing the reduction of both the consumption of natural resources and the cost of waste disposal while protecting the environment.

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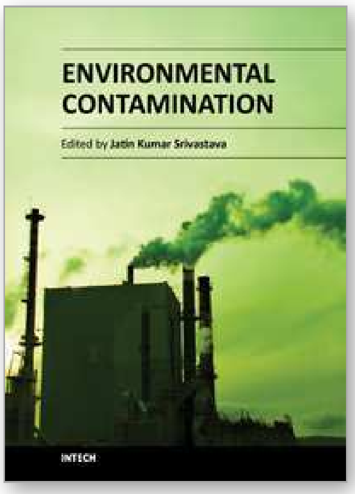

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