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Evaluation of the Ceramic, Mechanical, and Structural Behavior of Traditional Ceramic Pastes Incorporating Coconut Husk Fibers for Tile Manufacturing in Construction

Evaluación del comportamiento cerámico, mecánico y estructural al incorporar fibras de la cáscara del coco en pastas cerámicas tradicionales en la fabricación de baldosas para su uso en la construcción

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Abstract

Environmental degradation has accelerated as a consequence of rapid industrialization. Among the factors that contribute to this deterioration are the production of ceramic tiles and waste generation. Ceramic tile production has become consolidated on the global market, growing at annual rates of nearly 8.5%, while waste generation has increased at an estimated annual rate of 11.7%. Consequently, recent research has focused on developing waste-management strategies to mitigate these impacts. This study evaluated the performance of an unglazed extruded ceramic product incorporating coconut fiber into its ceramic matrix. The material was evaluated at coconut fiber contents of 5%, 10%, and 20% by weight, and fired in a downdraft (beehive) kiln at 950 °C, 1000 °C, and 1050 °C, thermal profiles commonly used by the ceramic industry in Norte de Santander. The methodology included the characterization of the mineralogical, chemical, physical, thermal, and technological properties of the raw materials, ceramic pastes, and fired products. The results revealed limitations in the mechanical and technological performance of ceramic tiles. Nevertheless, the incorporation of 5% and 10% coconut fiber combined with firing temperatures above 1000 °C established conditions that favored the manufacturing products with high regional demand and complying with national requirements for interior wall and floor coverings in low-traffic environments. In addition, mixtures containing up to 20% coconut fiber achieved the regulatory requirements for wall tiles. Overall, the findings demonstrate the potential for incorporating agro-industrial waste into conventional ceramic pastes while maintaining acceptable ceramic, mechanical, and structural performance.

Keywords

Agro-industrial waste valorization, coconut fiber, composite materials, extruded ceramic tiles, firing temperature.

Resumen

El deterioro ambiental se ha incrementado de manera acelerada por la rápida industrialización de la sociedad. Entre los diversos factores que han afectado este deterioro han sido la producción de baldosas cerámicas y la generación de residuos. El primero se ha consolidado en el mercado mundial, creciendo a tasas anuales de casi el 8.5 %, el segundo ha crecido a un ritmo acelerado de casi el 11.7 % anual. Por ello, en los últimos años se han intensificado los esfuerzos para encontrar nuevas estrategias de gestión de residuos que permitan minimizar este problema. Esta investigación tuvo como objetivo evaluar el comportamiento de un producto cerámico extruido sin esmaltar al incorporar fibra de coco en su matriz cerámica. Se evaluó el desempeño del material con adiciones del 5 %, 10 % y 20 % en peso, y desarrollando el proceso de cocción en un horno de llama invertida (horno de colmena) a diferentes temperaturas (950 °C, 1000 °C y 1050 °C), temperaturas frecuentemente utilizadas por las empresas cerámicas del Norte de Santander. La metodología empleada consistió en la evaluación de propiedades mineralógicas, químicas, físicas, térmicas y tecnológicas de las materias primas, las pastas cerámicas y el producto terminado. Los resultados demostraron una limitación en las propiedades mecánicas y tecnológicas de las baldosas cerámicas; no obstante, la incorporación de fibra en porcentajes del 5 % y 10 % y con temperaturas de sinterización superiores a 1000 °C, desarrolló condiciones que favorecieron la fabricación de productos de alta demanda regional y que cumplen con las normativas nacionales para revestimientos para usos en ambientes interiores de bajo tránsito. Incluso, con adiciones hasta de un 20 % en fibra de coco, alcanza la conformidad normativa requerida para baldosas de pared. En conclusión, esta investigación busca ofrecer al sector cerámico regional la oportunidad de incorporar residuos agroindustriales en pastas cerámicas convencionales sin comprometer su comportamiento cerámico, mecánico y estructural.

Palabras clave

Valorización de residuos agroindustriales, fibra de coco, materiales compuestos, baldosas cerámicas extruidas, temperatura de cocción.

1. INTRODUCTION

The ceramic industry is an important sector in Colombia, generating substantial demand for construction materials [1]. Countries such as the United States and Vietnam have recently made significant progress in the development, production, and export of ceramic products [2], [3].

Since ancient times, the ceramic industry has contributed to improving living conditions, making innovation and technological development in this sector increasingly important. Colombia has a substantial production of clay-based ceramic materials. According to available records, the construction-materials sector, including ceramic tiles, experienced significant export growth, with a 24% increase in 2023. This trend reflects increased consumption of non-renewable resources such as clay and the associated environmental impacts [4].

In Norte de Santander, particularly in Cúcuta and its metropolitan area, the production of clay-based materials is widespread. Consequently, research has focused on improving material properties while seeking sustainable solutions that minimize the environmental impact of these processes [1], [5], [6], [7], [8]. The composition, performance, and applications of these products are influenced by the high energy consumption required during manufacturing, particularly because the materials and auxiliary agents must reach elevated temperatures to develop the desired properties. These processes may generate pollutant emissions and are also associated with variability in the quality of construction materials [9], [10].

Accordingly, recent studies have investigated the incorporation of organic and inorganic materials as partial substitutes for clay in traditional ceramic pastes, supporting initiatives aimed at reducing environmental impacts and the consumption of natural resources [1], [5], [7], [11], [12], [13], [14]. These residues can modify and improve specific properties, producing materials with technological characteristics comparable to, and in some cases better than, those of conventional ceramic products. Plant-based natural fibers are particularly attractive because they can reduce production costs [15], [16], [17]. Most are obtained from agricultural residues, increasing their potential availability in substantial quantities and at low cost [18], [19].

The use of organic residues can contribute to improving environmental performance through reuse and by reducing the amount of material that would otherwise be disposed of or burned, thereby potentially decreasing CO_2 and other pollutant emissions [20], [21]. Natural fibers are renewable, generally require less energy per unit of production, are widely available, exhibit

favorable mechanical properties and elasticity, are less abrasive during processing, can provide thermal insulation, and are biodegradable. They may also be two to three times less expensive than other fiber types [22], [23], [24], [25]. In this study, natural fibers obtained from the mesocarp of coconut husks were selected. These fibers are frequently disposed of in landfills or burned, creating environmental concerns [26], [27].

In this study, coconut fiber and clayey soil were mixed at different proportions to evaluate the performance of an unglazed extruded ceramic product incorporating coconut fiber into the ceramic matrix and fired at different temperatures in a beehive kiln. The study also assessed whether the resulting mixtures comply with applicable construction standards. The overall aim was to provide the regional ceramic sector with an alternative for incorporating agro-industrial waste into traditional ceramic pastes without compromising their ceramic, mechanical, and structural performance.

2. METHODOLOGY

Two natural raw materials were used: coconut mesocarp, commonly known as coir and hereafter referred to as CF, and clayey soil, hereafter referred to as AR. The CF was obtained from the mesocarp of coconut husks supplied by a food and derivatives company in Santa Marta, Colombia. To facilitate fiber extraction, the husks were soaked in water for 24 h, as shown in Figure 1. The CF was manually extracted using a coir cutter and dried at 60±5 °C. It was then dry-milled manually using a low-hopper tabletop mill equipped with an internal auger that presses the material against two high-hardness steel grinding discs. The material was passed through the mill until a particle size below 2.00 mm (ASTM No. 10 sieve) was obtained. This particle size was selected because preliminary tests with larger particles produced mixtures with insufficient cohesion for proper molding. A total of 15 kg of coconut fiber was obtained, of which 10 kg was used for preliminary tests and for preparing the final experimental formulations.



Figure 1. Extraction of coconut fiber from the shell. Source: own elaboration.

The AR raw material was obtained from a regional quarry in Villa del Rosario, Norte de Santander, Colombia. It is a plastic material from Guayabo Formation and is used by several regional companies in ceramic pastes for manufacturing construction products such as tiles, bricks, and roof tiles. AR was dried at 110±5 °C for 24 h in a drying oven with an 80 L internal chamber, a temperature range of 5-200 °C, a resolution of 0.01 °C, and a stability of 1 °C. Drying was considered complete when the mass loss was no greater than 0.2 % [28]. The material was manually crushed to below 4.75 mm (ASTM No. 4 sieve) and then ground in a fixed-head laboratory hammer mill to obtain a particle size below 2.00 mm (ASTM No. 10 sieve). The mill can process materials with hardness up to 7 on the Mohs scale, has a capacity of up to 150 kg/h,

operates at 1500-1800 rpm, and produces an average particle size of approximately 140 µm, depending on the material. The ground material was homogenized until a uniform color was obtained and then quartered. Finally, AR was used as the matrix and CF as the discontinuous phase, and the components were mixed using laminar geometry.

Because no specific theoretical background was identified for firing mixtures of AR and CF, and the references consulted mainly addressed clay-fiber mixtures with other raw materials or unfired masonry products, preliminary mixtures were prepared to evaluate the behavior of AR and CF during firing. CF contents of up to 35% by weight were initially tested. Although these mixtures could be prepared, cohesion was insufficient and CF agglomerates formed during mixing, preventing adequate molding. Therefore, 20% by weight was established as the maximum CF content that could be incorporated while maintaining sufficient cohesion. The final formulations contained 5%, 10%, and 20% CF. Intermediate percentages were not included because preliminary tests indicated similar behavior: mixtures containing 1%-4% CF behaved similarly to the 5% formulation, while those containing 6%-9% behaved similarly to the 10% formulation, with the same trend observed at higher contents.

The ceramic pastes, including the reference formulation, were prepared at the following proportions: L (100:0), U (95:5), N (90:10), and A (80:20), expressed as AR: CF. All mixtures underwent routine controls used in traditional ceramic processing. Characterization included Atterberg consistency limits (liquid limit, plastic limit, and plasticity index), determined according to the standard procedure using the Casagrande cup; particle-size distribution; and textural fractions determined by hydrometer sedimentation (ASTM 152H). Technological properties, including density, shrinkage, and mass loss in the dry and fired states, were also evaluated. Mass was measured with an OHAUS digital balance with a capacity of 6000 g and a resolution of 0.01 g, while specimen dimensions were measured with a 300 mm digital Vernier caliper with a resolution of 0.01 mm. Density was calculated as the ratio of mass to volume. The selected formulations were moistened according to their plasticity parameters (Table 1), using 1 kg of water per kilogram of dry paste, homogenized for 24 h to ensure uniform wetting, and manually kneaded to remove trapped air and minimize poor cohesion after extrusion [29], [30], [31].

Table 1. Formulations. Source: own elaboration.

Formulation	Clay	Coconut fiber	Plasticity index (%)
L	100	0	27
U	95	5	31
N	90	10	38
A	80	20	48

Forming was performed using a semi-industrial, non-vacuum Reinaltech extruder at pressures ranging from 30 to 55 kgf/cm² (2.94-5.39 MPa). For pastes N and A, the pressure was increased because of the higher water content required by these mixtures. The molded products were unglazed ceramic tiles, locally known as “tablilla,” with the nominal manufacturing dimensions specified in the original formulation of 25 cm × 8 cm × 1 cm. Fifty specimens were produced for each formulation. The specimens were initially dried at approximately 30 °C until mass loss was below 15%. This gradual drying stage was used because the rapid removal of intrinsic water from the natural polymeric CF could generate internal stress and cracks; no such defects were observed. The specimens were subsequently dried for 24 h in an electric oven, starting at 60±5 °C until the moisture content reached 10%. The temperature was then increased at 5 °C/min to 100±5 °C, completing the drying process and ensuring a residual moisture content of approximately 1 % before firing [32], [33], [34]. No cracks or fissures were observed after drying, possibly because of the gradual water removal and the contribution of the fibers to structural stability. Firing was carried out in an industrial downdraft beehive kiln under an oxidizing atmosphere at 950 °C, 1000 °C, and 1050 °C. The process included 44 h of preheating until the target temperature was reached, an-8 h soaking period

at the peak temperature, and 72 h of cooling until 400 °C. All pastes were fired simultaneously, with 16 specimens placed at each temperature. Paste mass and specimen dimensions (length, width, and thickness) were recorded at each stage of the process [1], [5], [6], [7], [8].

To evaluate paste homogeneity and verify the measurements for each property, five replicates were used for each test. Analytical precision was assessed using the standard deviation and d2s. Because the standards for structural, mechanical, and tribological properties do not specify a maximum acceptable difference, a coefficient of variation below 10% was adopted as the precision criterion. Physical characterization, including shrinkage, mass loss, and density, was performed using a Mitutoyo Vernier caliper with 0.01 mm resolution and an OHAUS digital scale with a capacity of 6000 g and a resolution of 0.01 g. Structural properties were evaluated by water absorption using the boiling-water method: specimens were immersed in boiling water for 2 h and then cooled to ambient temperature for 4 h ± 15 min before their saturated surface-dry mass was measured, in accordance with NTC 4321-3:2021. Mechanical properties were determined by flexural-strength testing using a 1000 N-capacity testing machine equipped with three cylindrical metal bars (two fixed and one loading bar) coated with rubber with a hardness of 50±5 IRHD (Gabbrielli Technology), at a loading rate of 1.0±0.2 MPa/s, following NTC 4321-4:2020. Tribological performance was evaluated using a Gabbrielli Technology CAP 3 abrasimeter by measuring the volume removed from each specimen surface after 150 rotations of a steel disc using corundum as the abrasive material.

3. RESULTS AND DISCUSSION

3.1 Mineralogy and chemical composition

The raw materials were characterized by X-ray diffraction using a Bruker D8 Advance powder diffractometer with DaVinci geometry. Mineralogical phases were quantified by Rietveld refinement. Chemical composition was determined by quantitative analysis of major oxides using wavelength-dispersive X-ray fluorescence spectrometry; oxide concentrations were calculated using the general-oxide and UniQuant methods. Loss on ignition was determined by calcination at a heating rate of 3.08 °C/min to 1000 °C, followed by a 1 h holding period. Table 2 shows that AR contains quartz, kaolinite, and muscovite as the predominant mineralogical phases, together with smaller amounts of cristobalite, hematite, and anatase. These results are consistent with regional studies of clay materials from the Guayabo Group; differences in concentrations may be associated with the specific extraction location in Villa del Rosario [5], [6], [7], [29]. In addition, [8] reported similar concentrations for clays from the same area. The presence of quartz and phyllosilicates such as kaolinite contributed to moderate thermal resistance, as indicated by firing shrinkage below 3 % at temperatures above 1000 °C. The specimens developed a light-orange color, consistent with the presence of hematite and anatase. Muscovite also contributed to the plastic behavior and shaping characteristics of the ceramic pastes.

Table 2. Mineralogical composition. Source: own elaboration.

AR		CF	
Mineral phase	%	Mineral phase	%
Quartz	49.5	Cellulose I	39.4
Kaolinite	17.2	Cellulose II	15.2
Hematite	1.0	Hemicellulose	10.3
Anatase	1.1	Lignin	28.9
Muscovite	23.5	Pectin	3.2
Cristobalite	7.6	Quartz	3.0

The mineralogical composition of CF showed phases commonly reported for natural fibers (Table 2). The predominant crystalline phase was cellulose I, which has a well-defined crystalline structure and is a fundamental component of plant cell walls, wood, and natural fibers. Cellulose I contributes to mechanical stability and may provide strength, rigidity, and dimensional control during drying [18], [35], [36]. Cellulose II was also detected; this phase can result from recrystallization of cellulose I and is more thermodynamically stable and less soluble. Hemicellulose, lignin, and pectin were also identified and may explain the higher amount of water required during mixing and molding. A small amount of quartz was detected, which may have contributed to compatibility between CF and AR during forming and to control of drying shrinkage, consistent with the shrinkage results. Previous studies have reported that small amounts of mineral phases such as kaolinite, talc, or quartz in natural residues can contribute to dimensional stability and reduce cracking [37], [38]. Table 3 presents the chemical composition of AR and CF. AR contains SiO_2 and Al_2O_3 as the predominant oxides, followed by Fe_2O_3. The SiO_2/Al_2O_3 ratio was 3.04, higher than the value of 1.18 reported as characteristic of clay soils [31]. Although the relatively high silica content may increase the risk of dimensional changes during quartz allotropic transformation and because of free silica, no cracks were observed in the specimens. No black cores or dark spots were observed, despite their frequent occurrence in products containing natural waste [39], [40], [41]. The Fe_2O_3 and TiO_2 contents are also consistent with the XRD observations and explain the orange coloration of the fired specimens.

Table 3. Chemical compositions of raw materials. Source: own elaboration.

AR		CF	
Analyte	%	Analyte	%
SiO_2	62.79	CaO	2.75
Al_2O_3	20.67	SiO_2	1.26
Fe_2O_3	4.00	Al_2O_3	1.01
K_2O	1.43	Na_2O	0.25
TiO_2	0.92	MgO	0.17
MgO	0.70	Fe_2O_3	0.14
Na_2O	0.20	Cl	0.09
CaO	0.14	SO_3	0.19
Others	0.30	TiO_2	0.11
Loss on ignition	8.82	K_2O	0.04

The chemical composition of CF showed a high CaO content, which may contribute to pore formation. Although carbonates were not detected by XRD, the material should be considered carefully within the 750-950 °C range [31], [42]. CF contained only small amounts of SiO_2 and Al_2O_3. The presence of SiO_2 may have contributed to compatibility with AR during mixing and firing, while the dimensional stability observed during drying was supported by the absence of deformation, fissures, or cracks.

3.2 Ceramic aptitude

The relevance of this research lies not only in determining whether waste can replace conventional raw materials in traditional ceramic pastes, but also in evaluating its effect on ceramic suitability during manufacturing and on the properties of the final product. Accordingly, the physical and technological characteristics of the pastes were evaluated, including plasticity, particle-size distribution, shrinkage, mass loss, and densification. Figure 2 illustrates the plastic behavior of the formulations and its influence on extrusion and forming.

As shown in graph A of Figure 2, the addition of CF modifies the behavior of AR by shifting the position of the L formulation (100% clay). With 5% CF, formulation U enters the acceptable extrusion zone, improving the difficult extrusion behavior observed for formulation L. The addition also improves cohesion and produces a plastic mass suitable for molding (Figure 3). This is an important processing advantage because comparable forming conditions were not observed with some other wastes having similar characteristics.

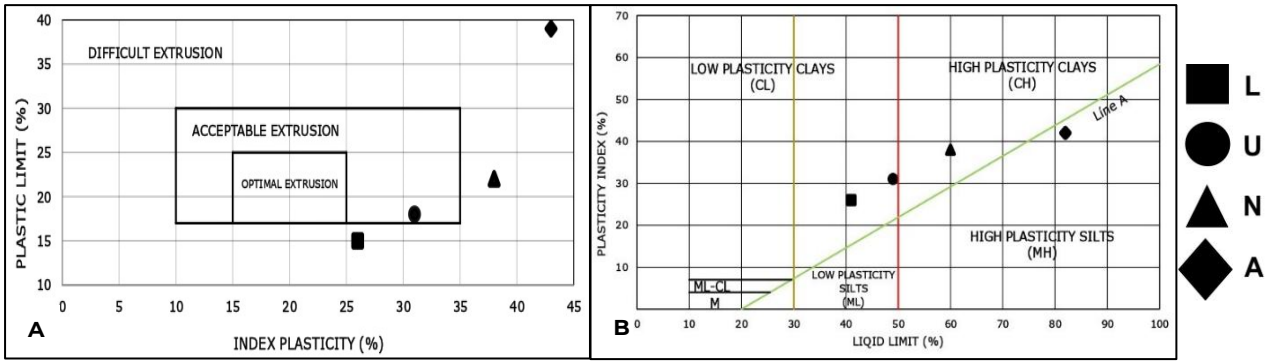


Figure 2. Plasticity (A. Extrusion forecast; B. Plasticity chart). Source: own elaboration.

At higher CF contents, however, the pastes move back into the difficult-extrusion zone. As shown in graph B, additions above 5% modify the plastic characteristics of the soil, shifting it from low-plasticity behavior toward a highly plastic condition that makes extrusion more difficult.



Figure 3. Kneading the formulations. Source: own elaboration.

The same trend is observed in the Winkler texture triangle (Figure 4), confirming the plasticity results. Increasing CF shifts the position of formulation L and modifies both its texture and its suitability for traditional ceramic processing. This behavior may be associated with the non-clayey nature of CF, which acts as a tempering or degreasing material and modifies particle packing within the paste. As CF content increases, the AR texture changes from silty clay in formulation L, which is relatively resistant to plastic deformation, toward a more clay-rich texture in formulation A. This change increases water retention and may hinder drainage, potentially extending drying times.

Similarly, CF additions of up to 10% modify the AR texture toward a clay-loam condition. This produces greater cohesion and may favor kneading before extrusion and subsequent molding. However, the associated increase in water retention can slow drainage and therefore requires greater control during drying.

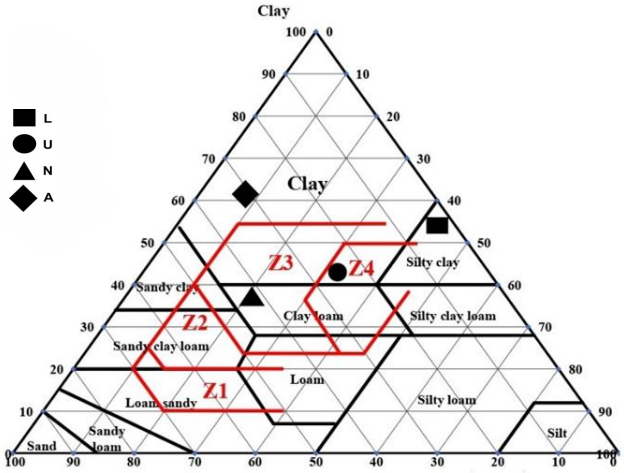


Figure 4. Winkler's Ceramic Aptitude Triangle. Source: own elaboration.

Regarding ceramic suitability, two formulations fall within the zones defined by Helmut Winkler for structural ceramics, whereas two are outside these zones [43], [44]. Formulations L and A are outside the zones of influence, while U and N are located in zones 4 and 3, respectively. Formulation U is suitable for producing horizontally perforated bricks and thin-walled, large-format units known as “bloquelón” [45], whereas formulation N is suitable for structural masonry, tiles, and roof tiles. Thus, CF contents below 10% can adapt the pastes to applications relevant to the regional ceramic sector, provided that forming and drying are carefully controlled [1], [5], [8], [46].

3.3 Physical characterization

Physical characterization included technological parameters such as density (Figure 5), which is particularly relevant because of the limited cohesion of the CF-AR mixtures. Shrinkage and mass loss were also evaluated.

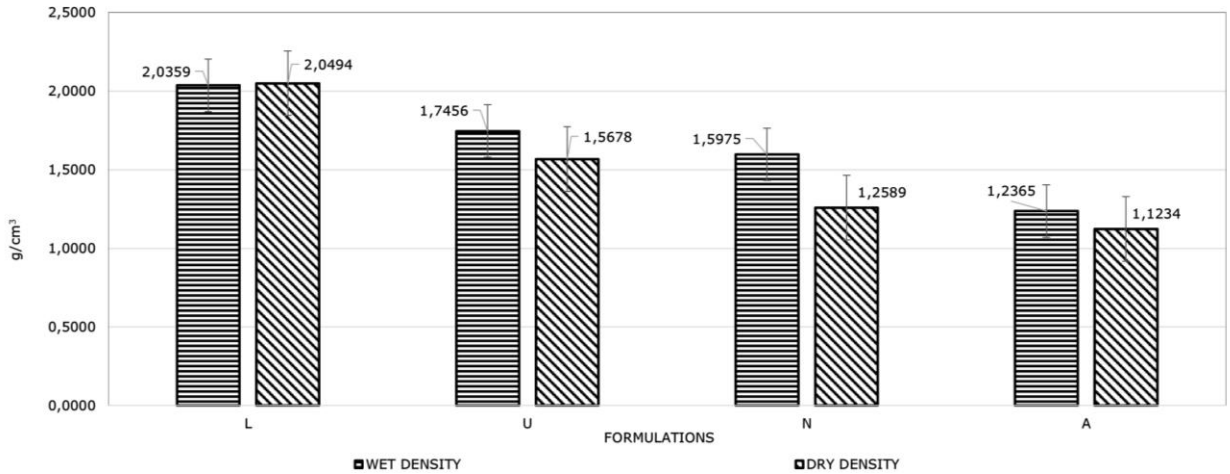


Figure 5. Density (Wet and Dry). Source: own elaboration.

As shown in Figure 5, the density of both the wet and dry materials decrease as CF content increases, with a reduction of up to 39.3% in the wet state. A similar trend was observed in the dry state, where reductions ranged from 23.5% to 45.2%. This behavior may be attributed to the

water absorbed by CF during mixing, consistent with the plasticity results. However, the reduction from the wet to the dry state did not exceed 21.2%, suggesting that the slower drainage associated with the increased water retention was not necessarily detrimental. Instead, it may have moderated the removal of absorbed water through internal migration, diffusion, and evaporation, promoting particle accommodation and limiting the development of internal porosity.

Figure 6 shows shrinkage and mass loss during drying. Shrinkage decreased as CF content increased, which may help control internal stresses and reduce the risk of fissures and cracks, common defects during drying. This behavior differs from that reported in some studies using other natural wastes. For example, [5] reported shrinkage values ranging from 0.55% to 2.61% for molded cellulose; [47] reported increases of 4.55% and 18.18% with 5% and 10% kraft-pulp production waste, respectively; and [23], citing [47], reported increases of up to 16% with paper-pulp waste. In the present study, shrinkage remained below 8%, which is favorable for crack control during drying.

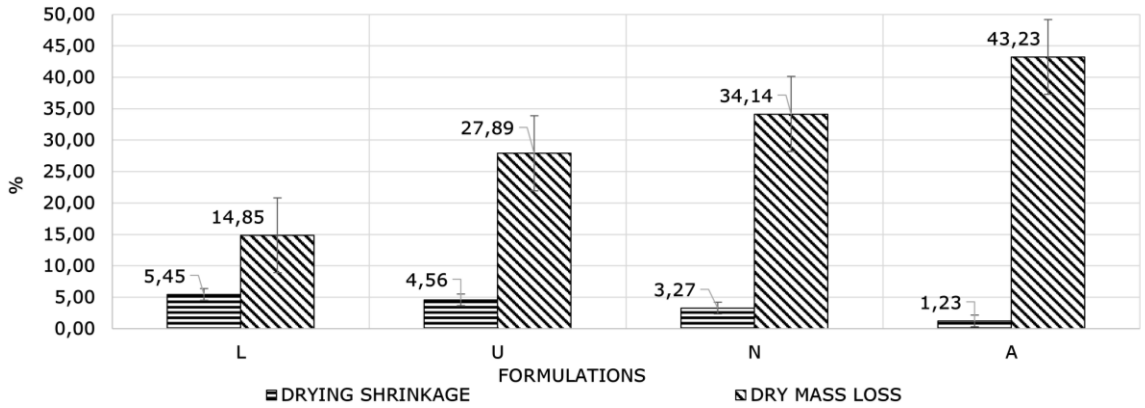


Figure 6. Dry Technological Aspects (Shrinkage; Mass Loss). Source: own elaboration.

Mass loss increased with increasing CF content, as commonly observed when this type of waste is incorporated. Two factors may explain this behavior. First, the greater amount of water required for forming increases the amount of interstitial water removed during drying. Second, the lower densification of the mixtures contributes to greater mass loss, consistent with the observations reported by [48], who associated low densification with increased mass loss. Although these drying characteristics are comparable to those reported in previous studies, CF may offer an advantage because it reduces the risk of fissures and cracks, which are among the most common defects when high water contents are used in extrusion processes [49], [50].

3.4 Technological characterization

Most of the references consulted in this study focused on mixtures of waste and clay for masonry products such as bricks. In addition, relatively few studies evaluated properties beyond manufacturing conditions in the wet and dry stages. Consequently, limited information was available regarding the thermal treatment of these mixtures. Nevertheless, the available literature indicates that thermal processing modifies ceramic raw materials and that, when non-clayey materials such as CF are incorporated, combustion up to approximately 450°C can generate expansion and gaseous products, producing a pore structure with capillaries of different sizes, increasing porosity, and reducing density and mechanical properties [7], [51]. Therefore, during firing, the heating rate was reduced to 10 °C/min between 350°C and 650°C to facilitate complete combustion of the organic material. The effectiveness of this procedure was indicated by the absence of cores or black spots in the fired specimens, defects commonly associated with incomplete combustion and residual organic matter [52], [53].

One of the main limitations of regional ceramic production is the firing stage, as approximately 95% of companies use older kiln technologies such as downdraft (beehive) kilns. For this reason, the firing temperature and technical performance of the mixtures containing CF were evaluated within the temperature range used in regional production. As shown by the vitrification curve (Figure 7), the theoretical firing ranges for U (980-1000°C), N (1020-1040°C), and A (1000-1020°C) fall within the temperatures commonly used in regional ceramic processes [32], [54]. The firing shrinkage of the three formulations was also within the reported permissible ranges. According to [55] and [56], linear firing shrinkage for these processes is approximately 1.0%-3.5%, whereas Yuan et al. reported typical values of 5%-6% for stoneware tiles. Considering these ranges and the firing results, CF incorporation appears feasible for controlling final product dimensions and reducing deformation and cracking. This behavior may be related to the pores generated during CF combustion, which limit particle rearrangement and consequently reduce shrinkage [57].

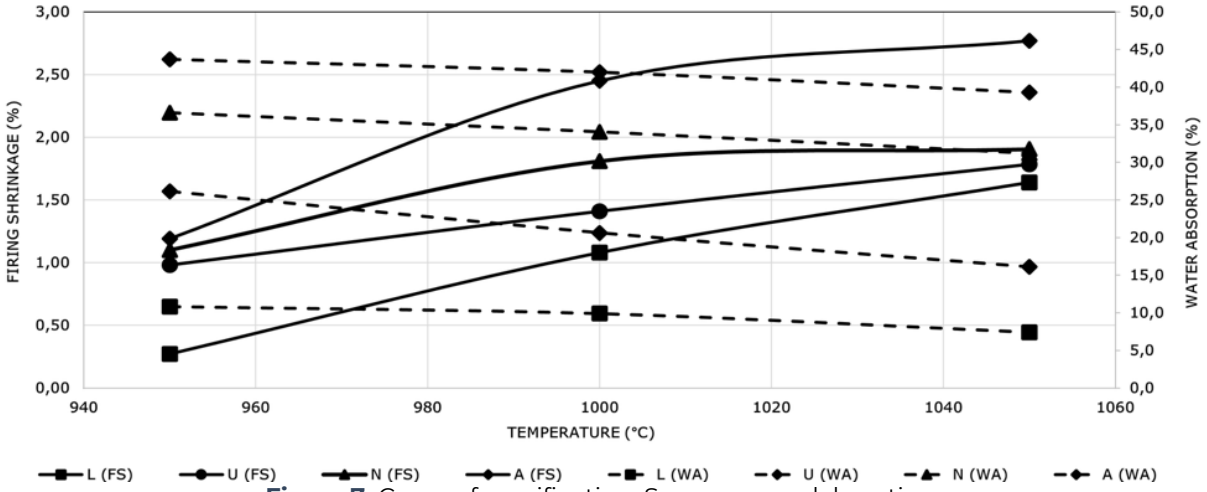


Figure 7. Curve of gresification. Source: own elaboration.

Figure 7 also shows that increasing CF content increases porosity, while increasing the firing temperature reduces it. Although the resulting absorption values are not favorable for wall-covering products, particularly floor tiles, because they exceed the maximum values established by Colombian standard NTC 919:2022 and the 15% limit indicated for wall products [58], [59], the porosity may be advantageous for other applications. For example, formulation U fired at 1050°C can be used to manufacture common or unexposed bricks (NV), for which water absorption of up to 17% is permitted [60]. Another potential application is the incorporation of CF into more refractory soils to manufacture products with higher technical specifications and commercial value, such as insulating bricks or slabs [61]. Initial results from this line of work are described as promising in the present study. The absorption results are also comparable with those reported for other agricultural wastes. For example, [62] reported values of approximately 25% using 5% rice husk at 1050 °C, while [63] reported 25.1% using 5% peanut waste at 950 °C; the latter value is 3.9 percentage points below the value obtained with CF.

Figure 8 presents the density and flexural-strength results. Density followed the same general trend as water absorption, decreasing as CF content increased. Although similar behavior has been reported for other agricultural wastes, the density obtained with CF was lower than that reported for some other residues. This may be related to the relatively large volume occupied by CF within the composite structure and, in particular, to the lower density of coconut fibers compared with other natural fibers [9], [64].

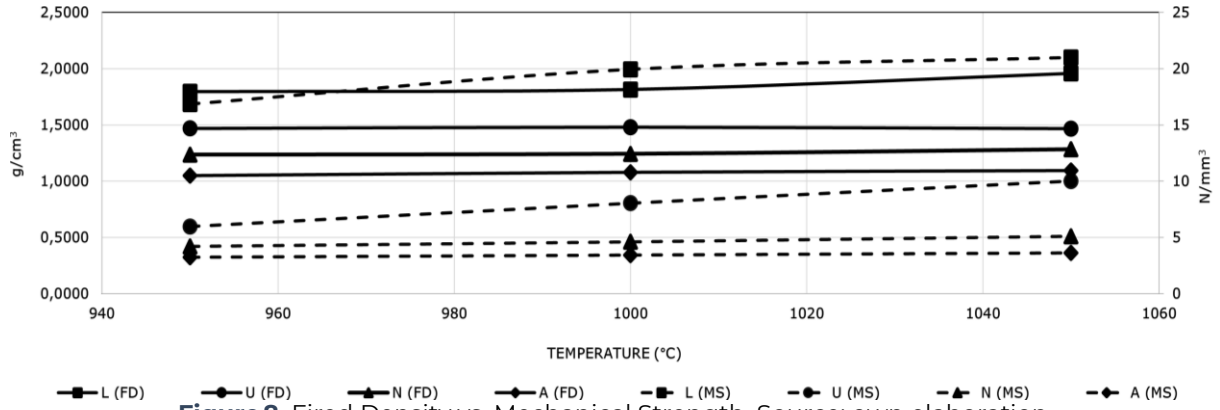


Figure 8. Fired Density vs. Mechanical Strength. Source: own elaboration.

Flexural strength is a critical parameter for determining the technical specifications and potential applications of ceramic coverings because it is directly related to compliance for wall and floor tiles intended for interior or exterior use. Accordingly, its characterization is essential when evaluating ceramic products. The results show that flexural strength at firing temperatures below 1000 °C, particularly with 10% and 20% CF, is insufficient for tile manufacturing because the reduction in mechanical performance may compromise durability. In contrast, a 5% CF addition combined with firing temperatures above 1000 °C achieves the requirements for tiles intended for low-traffic residential indoor environments without outdoor exposure, such as bathrooms and bedrooms, and areas with limited daily use such as living and dining rooms [59].

Another important property of ceramic tiles is tribological performance because erosion, abrasion, and friction can cause material loss and affect long-term service performance. Figure 9 presents the deep-abrasion results for the formulations. The test was based on the volume removed from each specimen surface after 150 rotations of a steel disc using corundum as the abrasive material [65].

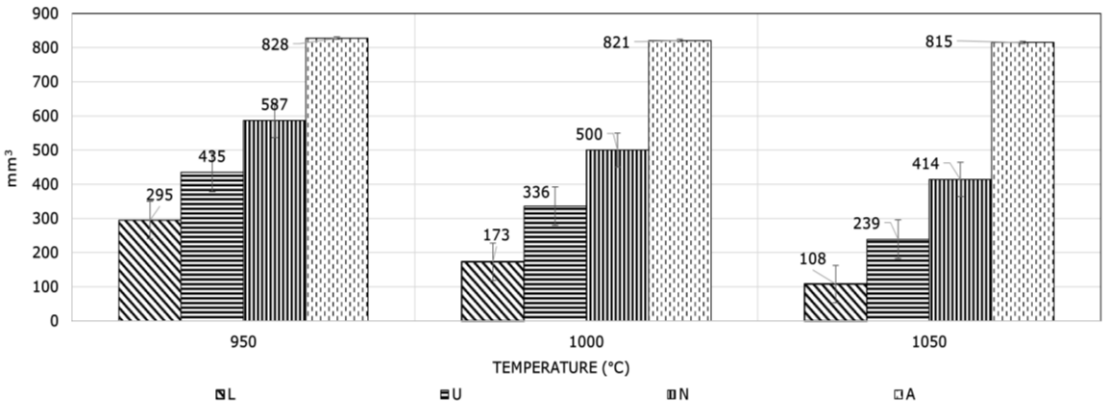


Figure 9. Tribology (Deep Abrasion). Source: own elaboration.

Wear resistance decreased as CF content increased. Nevertheless, two aspects are relevant from a microstructural and technological perspective. First, the tribological response of each formulation improved as firing temperature increased, indicating that the mixtures can be processed using conventional thermal systems in the region, including beehive kilns. As shown in Figure 7, the final firing temperatures are compatible with the thermal behavior of the pastes. Second, the tribological performance remained within the regulatory ranges for tiles exposed to medium-wear environments, such as corridors, balconies, and terraces with frequent pedestrian traffic. However, from the perspective of technical compliance and commercial viability, flexural strength is the principal limiting factor, outweighing the favorable

wear results and restricting application in more demanding environments. Even with 20% CF, the material met the regulatory requirements for wall cladding [58], [59].

The AR-CF mixtures containing up to 20% CF and fired at 950 °C exhibited lower wear volumes than those reported by Belfiore et al. for mixtures containing chamotte and fly ash, with reductions of up to 17.39% and 39.98%, respectively [11]. This result supports the potential use of CF in regional tile manufacturing and suggests a broader range of applications than some other waste-derived formulations, with possible benefits for product life-cycle performance.

4. CONCLUSIONS

This study evaluated the physical, mechanical, tribological, and structural behavior of ceramic tiles fired at different temperatures using mixtures containing 5%, 10%, and 20% coconut fiber and clay. The results indicate promising opportunities for incorporating this low-value agro-industrial residue into ceramic pastes. The main conclusions are as follows:

The AR used in this study is a fine material from Villa del Rosario, Norte de Santander, belonging to the Guayabo Formation. It is composed primarily of quartz (49.5%), kaolinite (17.2%), and muscovite (23.5%), and exhibits a clay-silt texture with low plasticity (ML), which makes extrusion difficult. Coconut fiber is rich in cellulose I and II, hemicellulose, and lignin, characteristics that influence its behavior during processing and drying.

The incorporation of 5% and 10% coconut fiber acts as a textural modifier in the clay matrix and provides favorable physicochemical and ceramic-processing conditions, not only for tile manufacturing but also for products with high regional demand, such as blocks, bricks, and roof tiles.

Coconut fiber improves drying behavior by moderating the rate of water removal through internal migration, diffusion, and evaporation. It reduces drying shrinkage and helps control internal stress, thereby lowering the risk of fissures and cracks.

Coconut fiber modifies the technological behavior of traditional ceramic pastes, and additions above 10% adversely affect compliance with the evaluated requirements. However, a 5% CF addition combined with firing temperatures above 1000°C meets the national requirements for manufacturing tiles intended for low-traffic indoor environments without outdoor exposure. These conditions also meet the technical specifications for non-facing (NF) bricks, which are among the main products manufactured by family-owned enterprises in the region.

With respect to wear resistance, the incorporation of coconut fiber provides adequate performance and meets the requirements evaluated for tiles exposed to medium-traffic conditions. Nevertheless, for regulatory compliance and commercial viability, mechanical strength remains the primary limiting property, restricting the use of these products in more demanding environments.

Overall, the findings support the feasibility of further research on coconut fiber incorporation, both at the 5% level and in combination with highly refractory raw materials. These results contribute to research aimed at replacing conventional raw materials with agro-industrial by-products in ceramic processes, promoting waste valorization and helping to mitigate soil degradation associated with clay quarrying.

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CONFLICT OF INTEREST

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AUTHORSHIP CONTRIBUTION

Angie J. Manrique: Experimental work, Conceptualization, Methodology, and Original draft.
Leonardo Cely-Illera: Conceptualization, Methodology, Validation, Supervision, Analysis, Investigation, and Original draft.
Jairo Cely-Niño: Conceptualization, Review, and Editing.