TecnoLógicas

Mortar Characterization of Granite Polishing Waste as a Partial Substitute for Cement

Caracterización de mortero con residuo de pulido de baldosas como sustituto parcial de cemento

Andrés Felipe Múnera Yepes[1]; Andrés Felipe Conejo López[1]; Carlos F. Herrera[1]; Alba Gallego Hernández[1]

[1]Universidad de Antioquia, Medellín, Colombia

Correspondence: alba.gallego@udea.edu.co

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Abstract

Hydraulic cement is an essential construction material; however, it is associated with environmental pollution due to CO_2 emissions generated during its production. Therefore, strategies to reduce cement use per cubic meter of mortar can help lower emissions. This study evaluated the effects of using granite polishing waste as a partial replacement for cement on the mechanical properties of mortars. The methodology involved preparing mixtures with cement replaced by granite polishing waste at 0%, 10%, 20%, 30%, 50%, 70%, and 80% by weight. The granite polishing waste had a moisture content of 47% and was used without any treatment or modification. The mixtures were tested in both fresh and hardened states, with flow measured per ASTM C1437-20 and compressive strength tested per ASTM C109/C109M-24. Additionally, petrographic analysis of each mixture was performed using optical microscopy on thin sections per ASTM C856/C856M-25 and electron microscopy techniques. Results showed that both flow and compressive strength decreased as the replacement level increased, with reductions of over 12% in flow and 33% in compressive strength after 20% replacement. Petrographic analysis indicated that significant cement replacements led to decreased adherence and increased voids. In conclusion, replacements of 20% or less have potential for non-structural applications. Using granite polishing waste as a partial cement replacement in mortars offers an alternative disposal method.

Keywords

Alternative materials, construction materials, mortar, mortar petrography, polishing waste.

Resumen

El cemento hidráulico es un material indispensable para la construcción; sin embargo, se encuentra asociado con problemas de contaminación ambiental por las emisiones de CO_2 generadas durante su producción, lo que hace necesario buscar estrategias que reduzcan la cantidad de cemento por metro cúbico de mortero y, de este modo, reducir las emisiones. Esta investigación tuvo como objetivo evaluar cambios en el comportamiento mecánico de morteros con residuos como sustituyente parcial del cemento. La metodología empleada consistió en preparar mezclas con sustituciones de cemento por residuo de pulido de baldosas de granito en porcentajes del 0, 10, 20, 30, 50, 70 y 80 %. El residuo presentó una humedad del 47 % y se utilizó sin ningún tratamiento o modificación adicional. Estas mezclas fueron caracterizadas en estado fresco y en estado endurecido mediante pruebas de fluidez ASTM C1437-20 y de resistencia a la compresión ASTM C109/C109M-24, respectivamente. Además, se realizó un análisis petrográfico de cada tipo de mezcla mediante microscopía óptica, con el uso de láminas delgadas ASTM C856/C856M-25 y microscopía electrónica. Los resultados permitieron observar que la fluidez y la resistencia a la compresión disminuyen con el aumento de la sustitución respecto al mortero sin sustitución, experimentando, a partir de la sustitución del 20 %, reducciones superiores al 12 % en fluidez y al 33 % en la resistencia a la compresión. El análisis petrográfico permitió identificar que, con el aumento de la sustitución, disminuyó la adhesión del cementante y aumentaron los espacios vacíos. Finalmente, se concluye que sustituciones iguales o inferiores al 20 % de cemento representan un gran potencial de uso en morteros con aplicaciones no estructurales. La factibilidad de incorporar el residuo de pulido de baldosas de granito en morteros como sustitución parcial del cemento brinda una alternativa de disposición.

Palabras clave

Materiales alternativos, materiales de construcción, mortero, petrografía de mortero, residuo de pulido.

1. INTRODUCTION

In Colombia and other countries around the world, the waste generated by the construction industry is often left unused and ends up in landfills [1]-[3]. An example of this is Granite Polishing Waste (GPW), which comes from the grinding of granite tile floors during civil works or at tile production factories [4], [5]. This GPW is discarded in large land areas, causing significant financial and environmental costs [4]–[7]. The granite tile manufacturing process is an ancient activity that has spread to countries all over the world, such as Spain, Iraq, India, Turkey, Brazil, Cuba, and Colombia, among others [5], [8]-[12]. Granite tiles are widely used to construct floors in institutional and commercial buildings [5], [7]. These tiles consist of a layer of mortar as a base and a surface composed of cement, marble, pigments, granite, and water, which acquire a finish and shine when polished, wet, or dry [4], [7].

Granite Polishing Waste (GPW) is a mixture of cement, sand, marble, and granite, consisting of fine particles that tend to agglomerate when moistened [4], [5]. As a result, GPW could serve as a potential substitute for cement in hydraulic cement mortars [7], [13]. Studies incorporating GPW into construction materials have focused mainly on replacing aggregate [4], [5], [7]. Several studies explore the use of waste materials as partial substitutes in hydraulic cement mortars, such as replacing part of the aggregate with GPW [5], [14]-[17]; substituting some of the binding material with granite sludge [14]; and using ceramic polishing residues of various granulometries to replace part of the cementitious material [13], [18].

On the other hand, cement is a vital material for the infrastructure sector, but it also requires a large amount of energy during production [14], [15], [19], [20]. Studies show that cement production, along with concrete and mortar, accounts for about 8% of global CO_2 emissions [14], [20]-[24]. Therefore, it is crucial to explore alternative materials that reduce cement use in civil construction, thereby lowering emissions [2], [3], [15], [22], [25]-[28].

Studies that aim to incorporate waste into construction materials have found that material performance depends on the mix design and the type of waste substitution (such as aggregate or binder) [2], [13], [14], [29]-[32]. Managing waste as a raw material in the production of other materials not only reduces demand for natural resources [1], [15], [20], [25], [29], [32], [33] but also helps cut production costs, lower emissions, dispose of waste properly, and support the implementation of the circular economy [6], [15], [21], [25].

This research aimed to assess the changes in the mechanical behavior of hydraulic cement mortars with partial replacement of cement by GPW. Therefore, this study analyzes GPW in hydraulic cement mortar mixtures with GPW substitutions of 0%, 10%, 20%, 30%, 50%, 70%, and 80% by cement weight, using flow tests, compressive strength tests, and petrographic analyses. This type of research enables the use of alternative materials in aesthetic applications and non-structural elements, thereby reducing cement consumption.

2. METHODOLOGY AND EXPERIMENTS

The experimental research methodology comprises physical characterization of GPW followed by physical, mechanical, and petrographic analyzes of hydraulic cement mortar mixtures with and without GPW.

2.1 Granite Polishing Waste (GPW)

The GPW used in this study was collected from a company that produces granite tiles in Medellín, Antioquia, Colombia. The GPW residue was obtained directly from the final stage of the sludge treatment, which is part of the water-management process used to polish granite tiles. Treatment features include enhanced sedimentation with a polymer that promotes particle agglomeration. The characterization of waste involved the analysis of physical properties, including color, size, texture, shape, and granulometry.

Physical characterization was conducted by visual inspection using a Boeco stereomicroscope (model BST606) with a B-Cam 16 Boeco camera, located in the laboratory of hydrobiology sanitation of the Universidad de Antioquia. The shape, color, and texture of the GPW in both dry and wet states were described, and the material was then compared macroscopically with hydraulic cement. The specific gravity of the GPW was determined according to ASTM D854-23 [34], and the gradation of the GPW was evaluated by the granulometry sieve test ASTM D6913/D6913M-17 [35] and sedimentation analysis ASTM D7928-21 [36]. The Atterberg limits of the GPW were defined in accordance with the liquid and plastic limits specified in ASTM D4318-17 [37]. In addition, qualitative X-ray diffraction (XRD) analysis was performed on a Malvern-PANalytical diffractometer equipped with a 3D Pixel detector and a Cu source (λ = 1.541 Å), operating at 45 kV and 40 mA; the goniometer had an Omega/2 theta and a platform configuration with standard reflection. The step size was 0.05° and the time per step was 50 seconds.

2.2 Dosage, preparation, and characterization of mortars

The materials used to prepare the mortar mixtures, with and without GPW, included Granite Polishing Waste, Argos reference cement ASTM C150/C150M-24 [38], Argos reference sand and drinking water ASTM C1602/C1602M-22 [39].

The sand used in all mixtures was standardized to meet the limits specified in ASTM C778-21 [40]. This involved mechanical sieving of the sand to separate the correct percentages and sizes, then mixing them in the proportions required by ASTM C778-21 [40]. The goal was to fully comply with the requirements set by ASTM C778-21 [40], thereby reducing potential influences from variations in granulometry across mixtures that could otherwise cause differences in the physical behavior of the mortars, both in their fresh and hardened states. Additionally, the standardized sand was compositionally characterized using observations with a Boeco stereomicroscope. Some mineral phases were identified and described in terms of size, shape, and crystal habits to monitor possible physical changes or chemical reactions.

The mixture was prepared according to ASTM C109/C109M-24 [41], maintaining a binder-to-sand ratio of 1:2.75. In these mixtures, GPW replaced cement, producing seven types of mixture with GPW replacement of cement ranging from 0% to 80% (Table 1). The replacement was increased in 10% steps up to 30%, as literature reports indicate minimal changes in physical behavior for replacements below 30% [1], [21], [26], [42]. Given the limited data on higher replacement levels and the potential of waste as a cementing material, it is important to evaluate the physical properties of mixtures with 50%, 70%, and 80% replacement.

Table 1. Relation among percentage weight, cement weight, GPW, and water (*M=Mortar 0=replacement substitution). Source: own elaboration.

Mortar	M0*	M10	M20	M30	M50	M70	M80
Cement, wt% %	100	90	80	70	50	30	20
GPW, wt% %	0	10	20	30	50	70	80
Cement, g	250	225	200	175	125	75	50
GPW_{wet}, g	0	25	50	75	125	175	50
Water, g	220	220	220	220	220	220	220
Water/(Cement +GPW_{wet})	0.88	0.88	0.88	0.88	0.88	0.88	0.88

The dosage for each type of mixture, including the amounts of cement in dry weight and GPW in wet weight, was designed to assess the applicability of GPW directly from the production process without drying (Table 1). Each GPW addition was taken from material with the same moisture content, which means a constant moisture level (w% = 47%) was assumed throughout all mix preparations. A water-to-binder ratio of Water/(Cement + GPWwet) of 0.88 was used in all mixes, as shown in Table 1. The binder consists of cement and GPWwet. The behavior of GPW is particularly complex in the mixture because it easily shifts from a fluid to a hard state; therefore, it was decided to use GPW under the conditions in which it was collected to ensure a controlled fluidity of 110 ± 5% (sample M0, ASTM C109/C109M-24 [41]) and to maintain suitable initial workability in the mixes shown in Table 1. Additionally, due to the consistency of GPW, using lower Water/(Cement + GPWwet) ratios did not allow adequate mixing.

The GPW is an industrial residue with unique behavior. When the unmodified waste is collected from its source, it appears as an agglomerated material composed of very fine particles. However, these aggregates reach block sizes and seem to exhibit solid block behavior. However, when manipulated, the aggregates quickly lose their cohesion. For mortar mixes, the GPW aggregate used in different mixtures had a diameter of less than 4.75 mm, as ensured by mechanical sieving. Mortar preparation was performed according to ASTM C-305-20 [43]. As an initial step, GPW was mixed with water at each dosage in a Hobart mixer to promote its disintegration. Once the material disintegrates in water, the process continued according to ASTM C-305-20 [43]. Three mortar cubes were prepared for each dose to ensure statistical control of the results of physical property.

The physical and mechanical properties of the mixture types were assessed by measuring the flow in the fresh state and the compressive strength of the hardened cubes. Flow was measured using the procedure described in ASTM C230/C230M-23 [44]. Fluidity was calculated as the average of four measurements of the expansion diameter of the mixture in its fresh state, according to ASTM C1437-20 [45]. For each type of mixture, three 50 mm cubes were removed from the formwork after 24 hours and cured using the dry curing method. All cubes were covered with plastic wrap and kept moist for 24 hours in an isolated room. Compressive strength tests were conducted after 28 days of curing, according to ASTM C109/C109M-24 [41]. These tests were performed using a Control model C5014 compression press located in the soil laboratory at the Universidad de Antioquia. The compressive strength was measured for each of the three mortars in each mixture, for a total of 21 mortar cubes.

2.3 Petrography of mortar

Petrographic analysis of the mortar characterization allowed us to identify and describe microstructural effects and their connection to macrostructural performance. This research project aimed to study how GPW functions as a substitute for cement within the mortar matrix.

2.3.1 Optical microscopy

Petrographic analyzes were conducted on thin polished sections 20 µm to 30 µm thick. After the compressive strength test failed, thin sections were prepared from the mortar cubes according to ASTM C856/C856M-25 [46]. Seven sections were taken from the center of each cube, representing each mortar type (M0, M10, M20, M30, M50, M70, and M80). In each polished thin section, 30 visual fields were examined with an Olympus BX40 petrographic microscope located in the geoscience department of Universidad EAFIT; the visual fields were recorded with a cellphone camera for statistical counting and analysis. The study of each thin polished section involved quantifying the voids, the agglomerating matrix (Cement + GPW), and the aggregates. Using ImageJ software, visual fields covering areas of 2.12 mm were analyzed to determine the areas corresponding to voids, aggregates, and paste (Cement + GPW).

2.3.2 Electronic microscopy

Electron microscopy analysis was performed on fragments from mortar cubes that failed the compressive strength test. The analysis was conducted with a JEOL JSM 6490 LV electron microscope located at the Research Center of the Universidad de Antioquia. The samples were mounted on slides, and a thin gold (Au) coating was applied to each fragment using the Denton Vacuum sputtering technique. The samples were examined with a high-vacuum electron microscope to obtain high-resolution images. The backscattered electron detector was used to evaluate the morphology and topography of the samples. Elemental analysis was performed with an X-ray Microprobe-EDX (reference INCA PentaFETx3, Oxford Instruments). Samples M0 and M30 were selected for electron microscopy analysis to assess the quality of the binder material and its relationship to the aggregates at the microstructural level. Additionally, the percentage of M30 was chosen as the limit based on the strength test, which indicates that percentages above 30% significantly alter the physical and mechanical properties.

3. RESULTS AND DISCUSSION

Characterizing granite polishing waste and cement in the mortar mixture provides insight into their physical and mechanical properties on different scales and under various hardening conditions.

3.1 Characterization of Granite Polishing Waste (CPW)

The initial inspection of the GPW at the generation site revealed solid consistency fragments, ranging in size from 75 mm to pieces smaller than 4.75 mm, as shown in Figure 1a. Under a stereomicroscope, the GPW appeared as particles smaller than a millimeter, mostly gray in color (Figure 1b), including agglomerated fragments (Figure 1b). Black particles were also observed. Based on the materials used to make the tiles, the black dots seen in Figure 1c, within the red square, are rock fragments produced during polishing; however, the shape and texture of the particles are not distinguishable at the stereomicroscope level. GPW tends to agglomerate when moistened, similar to hydraulic cement (Figure 1b).

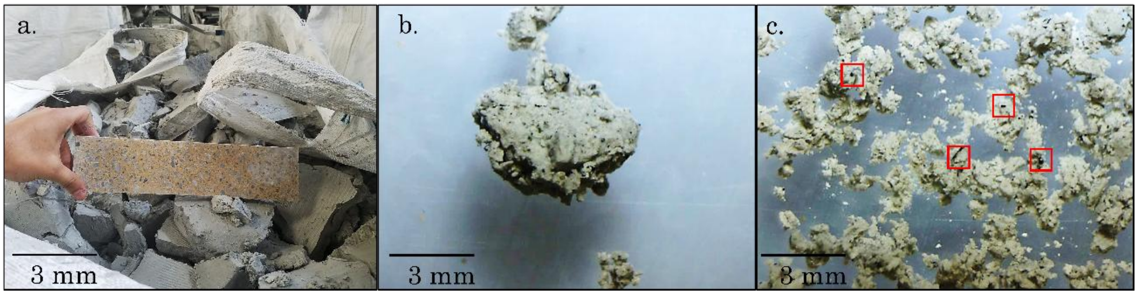


Figure 1. Granite Polishing Waste (GPW): a) GPW at the generation site, b) dry GPW sample viewed under a stereo microscope, and c) GPW aggregates. Source: own elaboration.

XRD analysis of the GPW confirmed that its primary composition is calcite, with smaller amounts of quartz (Figure 2).

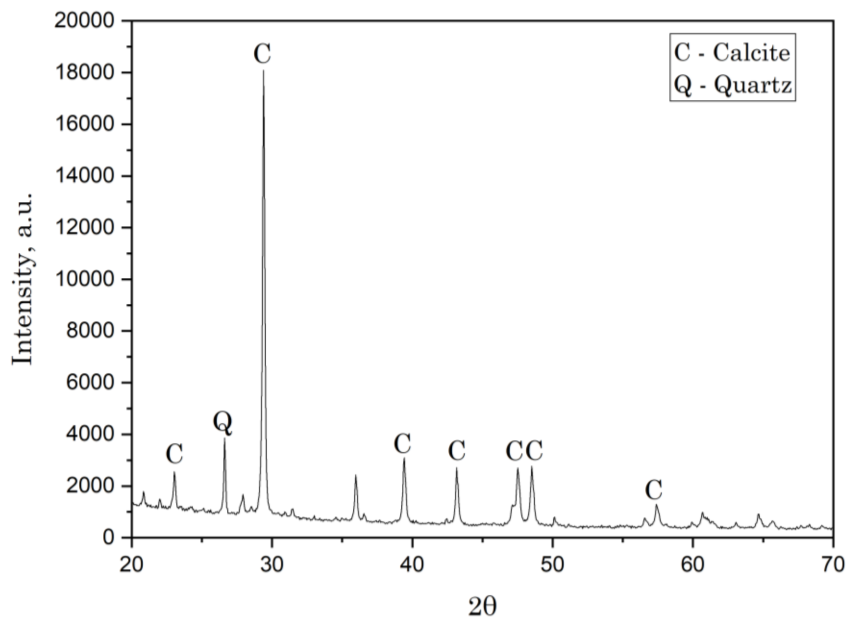


Figure 2. Diffractogram of GPW. Source: own elaboration.

The granulometry test shows that 93% of the GPW has a particle size smaller than 0.075 mm (sieve No. 200). Hydrometer analysis indicates that the sample contains 64.86% of particles between 0.0408 mm and 0.0013 mm, classifying it as a fine-granular soil according to the Soil Unified Classification System (SUCS), ASTM D2487-17 [47]. The Atterberg limits indicate that GPW has a semi-solid or solid consistency at moisture levels below 28.97% (LP). GPW has plastic consistency when moisture is between 28.97% (LP) and 39.97% (LL), and displays liquid behavior when moisture exceeds 39.97% (LL). The GPW used for the experimental work had a moisture content of 47% and a solid consistency, which created a discrepancy with the Atterberg limits. Additionally, the GPW has a specific gravity of 2.69.

The particle-size characteristics defined for the GPW in this study are similar to those reported in another research worldwide [4], [5]. These studies in GPW have focused mainly on analyzing chemical and physical properties through moisture tests, sieve analysis, and clay content detection [4], [5], [7]. As a result, literature currently provides only data on these properties.

Regarding the size of the GPW particles, [5] found that GPW has a fine texture and is mainly composed of silt. This aligns with the results of this study, which also identified a fine silty granulometry with particle sizes below 75 µm. [4] classified the GPW as sludge and reported a moisture content of 73.67%, whereas the present study indicates that GPW can be classified as a solid with a moisture content of 47%. Consequently, GPW did not exhibit the behavior expected from the consistency states identified by the Atterberg limits. According to these limits, a moisture content of 47% should yield a viscous, liquid-like consistency; however, a solid, deformable consistency is observed instead.

Therefore, GPW consistency indicates that, when calculated using Atterberg limits according to ASTM D4318-17 [37], it does not provide meaningful information about the behavior of waste in relation to its moisture content. GPW, due to its granulometric characteristics, resembles silty soil; however, because its chemical reactivity with water is unknown, it cannot be guaranteed that the Atterberg limit test accurately reflects the consistency states of the waste. Therefore, because GPW is obtained after a sedimentation process using a coagulant, traces of this substance in the residue could be inferred from the Atterberg limits, leading to non-representative results.

3.2 Elaboration of the mortar mixture

In Figure 3, the line with black squares shows the granulometric curve of the Argos reference sand. Lines with white circles indicate the upper and lower limit granulometric curves as specified in ASTM C-778-21 [40]. The line with black triangles shows the granulometric curve of the sand after the standardization process.

The standardized sand was examined using a stereomicroscope; quartz (Qz), plagioclase (Pl), and biotite (Bt) were identified as part of its mineral composition (Figure 3). The particles are light and dark in color and are present in similar proportions, leading us to conclude that there are equal amounts of ferromagnesian and non-ferromagnesian minerals.

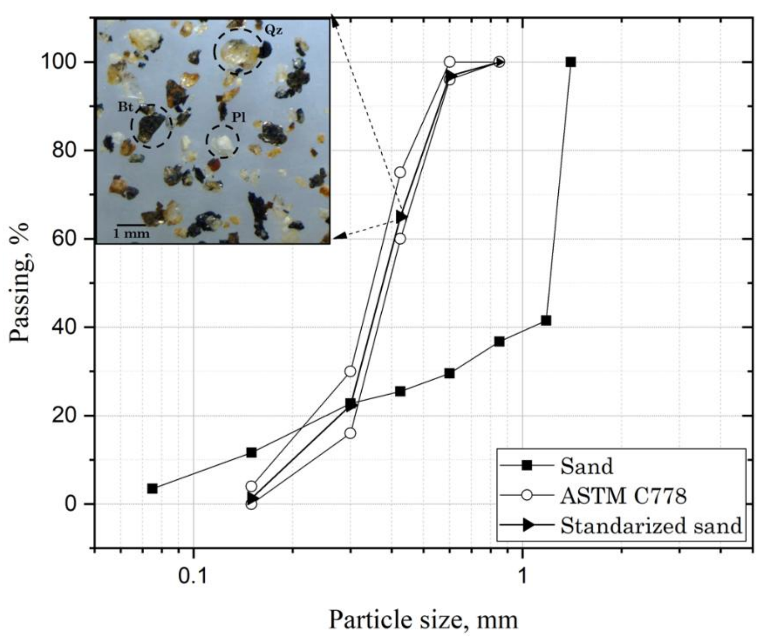


Figure 3. Standardized granulometric curves, sand, standardized sand, and ASTM C778-21[40] Limits. Source: own elaboration.

The GPW was incorporated in its original form, including agglomerate fragments, and no issues were encountered during the mixing process. Because GPW was incorporated in its original state at 47% moisture and already contained water, the Water/(Cement+GPW) ratio decreased as the substitution increased, since the water content of the GPW remained constant. The mixtures account for the added water, including both liquid water and water added for GPW moisture. As a result of keeping the Water/(Cement + GPW_{wet}) ratio constant, both Water/(Cement + GPW_{dry}) and Water/(Cement) increase significantly when analyzing their relationships (Table 2).

Table 2. Comparison of the relationships between Water, GPW, and cement. Source: own elaboration.

Mortar	M0	M10	M20	M30	M50	M70	M80
GPW_{dry}, g	0,00	13,25	26,50	39,75	66,25	92,75	106,00
Water/(Cement +GPW_{dry})*	0,88	0,92	0,97	1,02	1,15	1,31	1,41
Water/(Cement)	0,88	0,98	1,10	1,26	1,76	2,93	4,40

3.3 Physical characterization of the mortar

For each substitution percentage listed in Table 2, the flow of the mixture decreased as the amount of cement replaced by GPW increased. Figure 4 shows the variation in the flow of the mixture. For the control mix, M0, the samples M10 and M20 showed flow decreases of 4.71% and 11.43%, respectively. In contrast, the M30 and M50 mixes experienced decreases in flow of 29.82% and 38.57%, respectively. Furthermore, at 70% and 80% substitution of cement with GPW (M70 and M80), the mixes lose roughly 50% of their flow and show no workability. Figure 5 presents the flow test results for M0, M20, and M50, indicating a decrease in workability with increasing GPW addition.

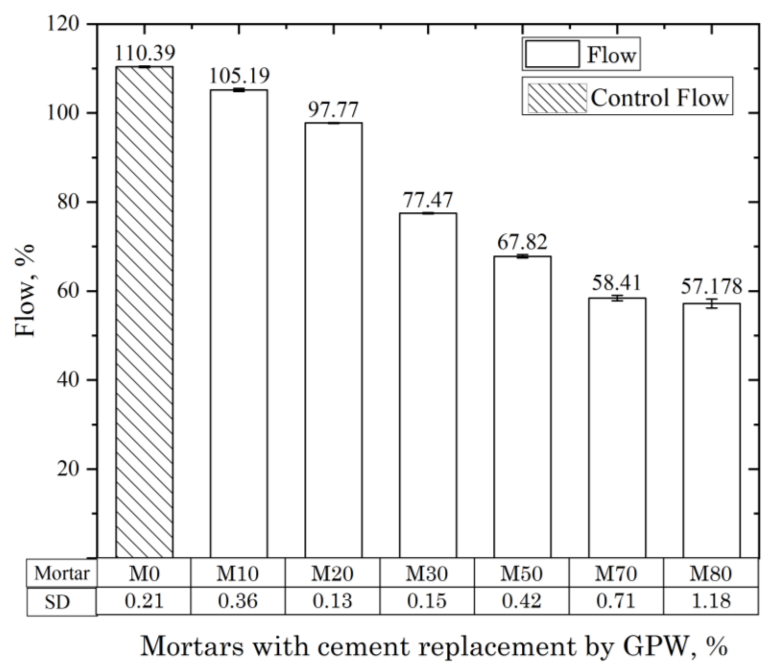


Figure 4. Flow test results for mortar mixes with and without GPW. Source: own elaboration.

Figure 5. Flow decreases as GPW increases. The photographs show the changes in workability for mixtures M0, M20, and M50. Source: own elaboration.

The compressive strength of the mortar cubes decreased with increasing replacement level (Figure 6). M10, M20, and M30 mixes showed reductions in compressive strength of approximately 25%, 33%, and 50%, respectively, compared to the control cubes (M0). At substitution levels above 30% (M30, M50, M70, and M80), compressive strength dropped by more than 50% compared to the strength of the mix without substitution. The reduction in strength is also linked to the water/cement ratio (Figure 7), which decreased as substitution increased. As cement replacement with GPW increased, cubes with substitution levels above M50 tended to fail explosively. The types of failure observed in some of the cubes are shown in Figure 8.

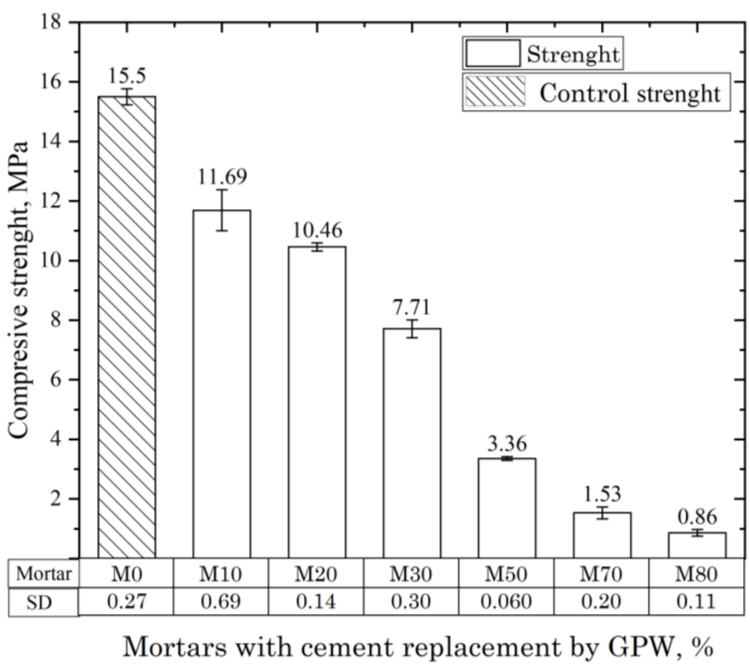


Figure 6. Compressive strength test results for mortar mixes with and without GPW. Source: own elaboration.

Replacement of hydraulic cement with GPW in mortars reduced both the compressive strength and the flowability of the mixes, consistent with the results of other studies using similar waste binders [4], [5], [7], [15], [29]. Figure 9 shows the decrease in compressive strength and flowability for each mix type relative to the control mix, M0, which does not contain substitutions. As substitution levels increased, flowability decreased, which was associated with waste levels and changes in the water-to-cementitious ratio (Cement + GPW).

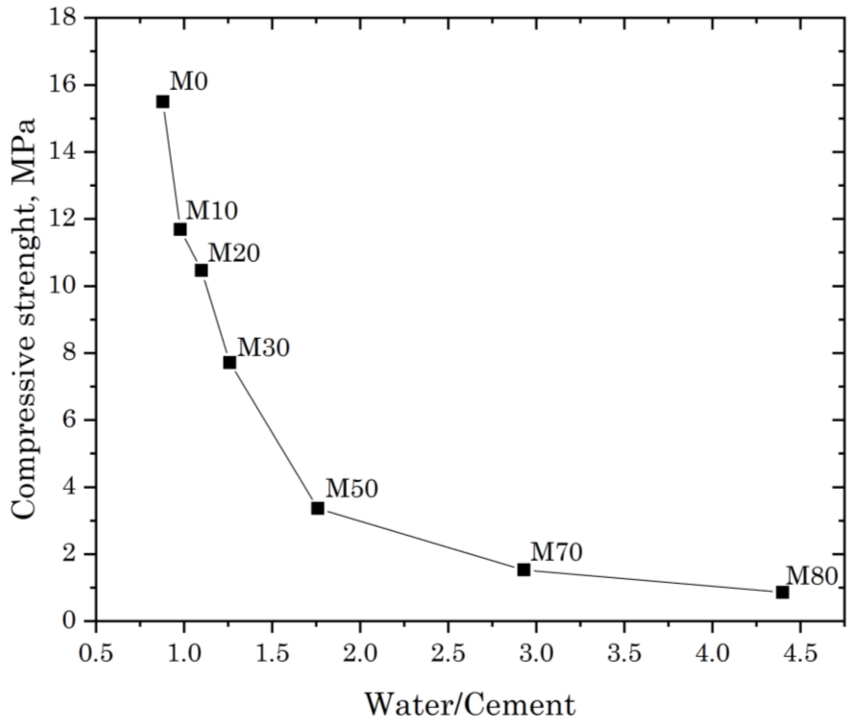


Figure 7. Compressive strength and water/cement relationship. Source: own elaboration.

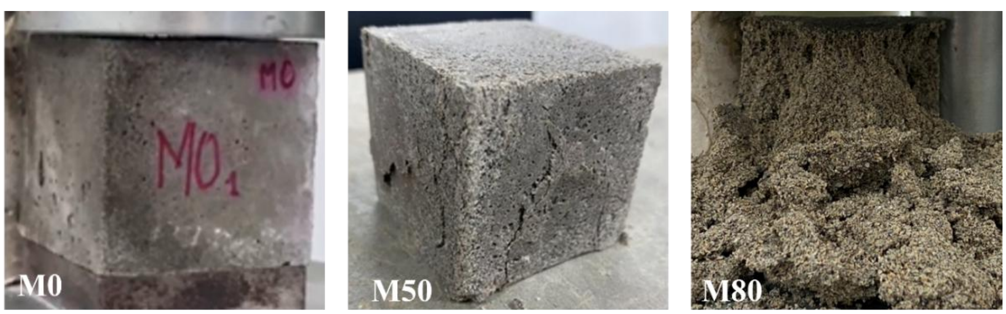


Figure 8. Compressive strength test failure: The photos show the failure of M0, M50, and M80. M0 exhibits a non-explosive failure, whereas M50 tends to fail explosively. M80's response to compression destroys the mortar cube. Source: own elaboration.

According to [48] and [42], the addition of substances to the mixes of construction materials is limited by their fineness, because the addition of fine residues increases the amount of water required to maintain workability.

In general, the effectiveness of a residue as a partial cement substitute and a binding agent depends on the amount used and its pozzolanic properties, especially its chemical composition [29]. Additionally, directly adding GPW as produced in industry resulted in a moisture content that did not match the dry weight of the cement, thus increasing the water-to-cement ratio and reducing the compressive strength [49].

Despite this, the fluidity of the mixes and the compressive strength of the mortars did not show significant decreases compared to other studies, such as those of [50] and [51]. Some studies suggest that substituting cement with industrial waste in construction material production does not allow for high substitution levels due to non-compliance with standards resulting from loss of mechanical properties in the produced materials [1], [4], [50], [52], [53]. Other researchers, such as [54] and [55], have achieved higher substitution levels, but only after subjecting the residue to a chemical transformation (chemical reaction).

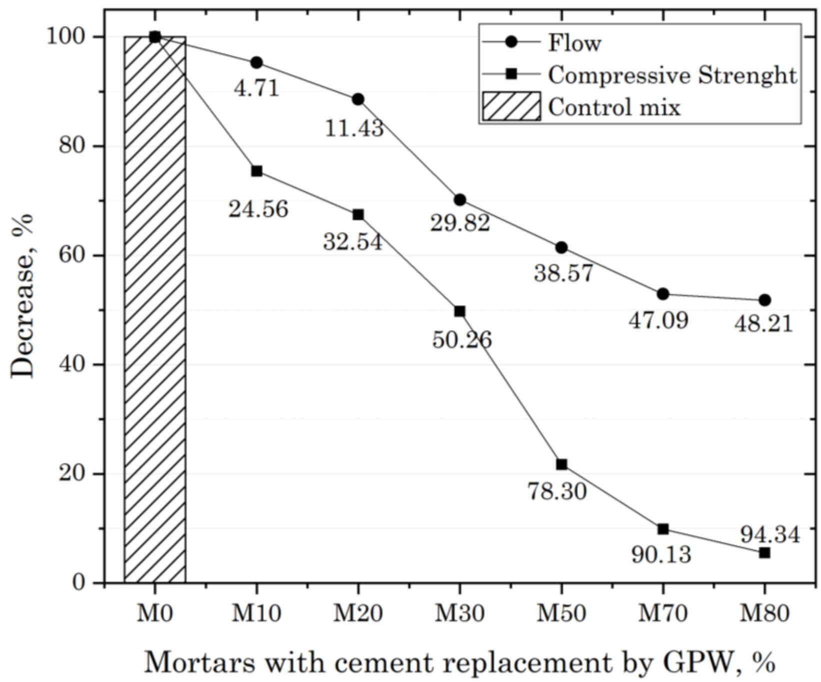


Figure 9. Changes in physic-mechanical properties related to the reference M0 of the mortar.
Source: own elaboration.

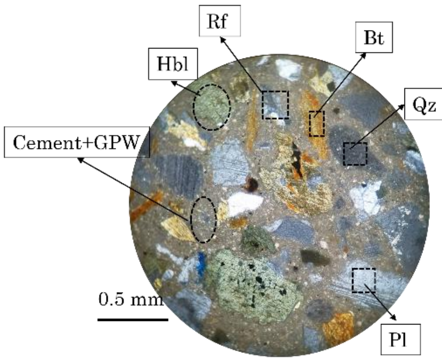
Therefore, although compressive strength and flow decrease compared to the mortar without substitution (M0), this does not indicate that GPW, in small proportions, loses its value as a binding agent in mortars. Other studies incorporating GPW-like waste in the production of building materials have shown that these wastes do not consistently improve the mechanical properties of the resulting materials; however, they can still meet regulatory specifications [1]. Specifically, [5] substituted stone powder with GPW in the production of tile adhesive mortar and exceeded regulatory standards, even though it did not reach the compressive strength of the mortar without substitution.

According to Colombian standards, the results of the compressive strength indicate that the M10, M20, and M30 mortars can be classified as types of N or O mortars, according to ASTM-C270-25 [56] and NSR 10 [57]. Similarly, in terms of flow, the M10 mixture met the criteria for plastic mortar, while the M20 mixture met the requirements for rigid mortar, as specified in the national norm, Table D.3.4-1 of NSR 10 [57]. Therefore, a mortar with less than 20% cement substitution by GPW can be used for coatings, floor leveling, bonding brick walls, wall plastering, architectural applications, and minor construction work [58].

3.4 Characterization of mortar physics

The petrographic study identified the primary mineral phases present in the sand. The sand consists of quartz (Qz), biotite (Bt), plagioclase (Pl), and hornblende (Hbl). Additionally, rock fragments (Rf) and some amorphous grains did not show optical properties under the microscope. Figure 10 illustrates the physical and optical properties of each mineral phase [59].

Seven thin polished sections were observed and analyzed to complete the optical identification. Thirty visual fields were examined in each thin section; with the data collected, it was possible to determine the percentage relationships of sand to cement and GPW to voids (Figure 11). The distribution of cementitious material (cement + GPW) and aggregate material showed that the extent of the cementitious matrix decreased as the substitution of cement with GPW increased. In addition, an increase in the number of voids between the cementitious phase and the aggregate material was observed.



Quartz (Qz): most fragments are colourless (PP*) and have an undulating extinction (XP**).Crystals exhibit an anhedral shape and prismatic habit and are mainly subrounded to rounded. Their distribution is random along the samples, and the adhesion quality is good.
Biotite (Bt): its brown colour is characteristic with variations associated with pleochroism, perfect extinction at 90°. Grain shapes are mainly anhedral, tabular, and elongated. The adherence of the paste and grains is poor, especially on those planes parallel to the exfoliation.
Plagioclase (Pl): grains are colourless (PP). Most of the crystals reveal their characteristic cleavage. Particles with anhedral and tabular shapes are common; some grains showed alterations, and the adhesion quality is good.
Hornblende (Hbl): it is green colour (PP). Most crystals are anhedral with surrounded borders, intense pleochroism in shades of green, and intermittent extinction (XP), , and the adhesion quality is good.
Rock fragments (Rf): there are several rock fragments with a surrounded borders and anhedral shape.
Amorphous: the presence of several fragments with black color under (PP) y (XP), subrounded to rounded shapes is common.
* Polarized Light ** Cross Polarized Light

Figure 10. Sand composition: recognition and key optical features of mineral phases under the microscope. Source: own elaboration.

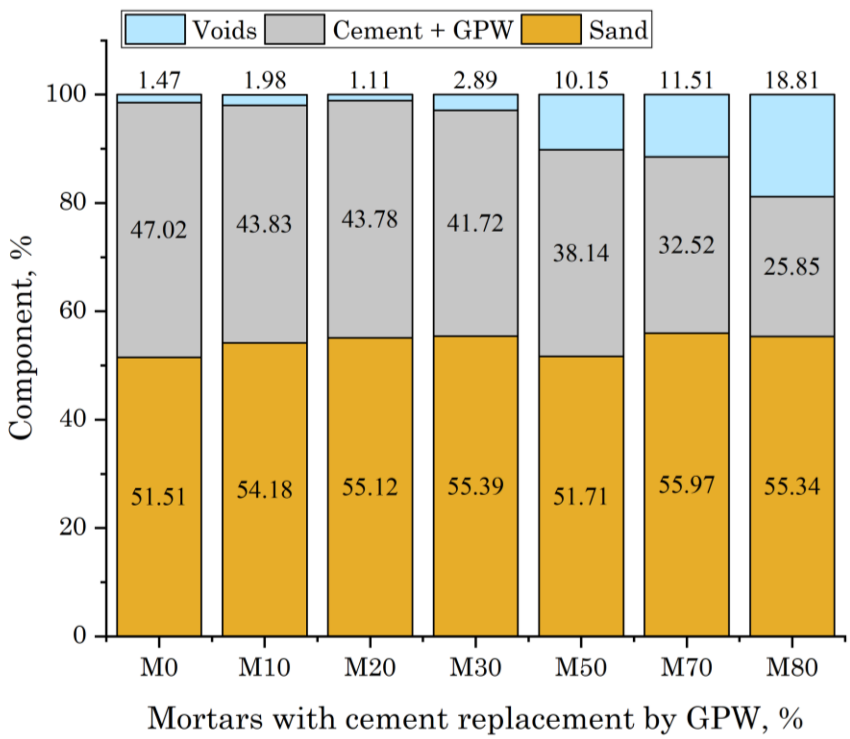


Figure 11. Component variations among mortar mixtures (%), Sand: Cement + GPW: Vacuums. Source: own elaboration.

According to the central limit theorem, which states that samples tend to follow a normal distribution across thirty visual fields, the validity of this assertion is supported. Additionally, phase identification and counting enabled us to determine the percentage distribution of mineral phases and rock fragments in the sand of M0 mortar as follows: quartz (Qz) 24.26%, plagioclase (Pl) 18.16%, biotite (Bt) 11.36%, hornblende (Hbl) 8.73%, rock fragments 37.08%, and amorphous material 0.40%.

From the thin-section analyzes, no distinctive feature in the cementitious matrix was identified that could be directly linked to the GPW. The cementitious phase at each substitution level exhibited a uniform color, suggesting that the GPW did not undergo harmful chemical reactions during its interaction with hydraulic cement.

The adhesion between the cementitious material and the aggregate decreased as the amount of GPW increased. Substituting more than 30% of hydraulic cement with GPW increased voids in the interstitial zone, which is associated with a loss of adhesion between the matrix and the aggregates. Furthermore, petrographic analyses indicate that substitutions up to M20 are suitable for producing non-structural mortars [60]. Figure 11 shows that M20 and M10 interact similarly between the cementitious and aggregate phases.

Figure 12 compares the adhesion of a biotite grain in the M0 mixture with that of a biotite grain in the M80 mixture. Similarly, petrographic analyzes suggest that as residue substitution increases, the number of voids and adhesion issues in the cementitious phase also increases, which accounts for the loss of strength in the cementitious phase [60].

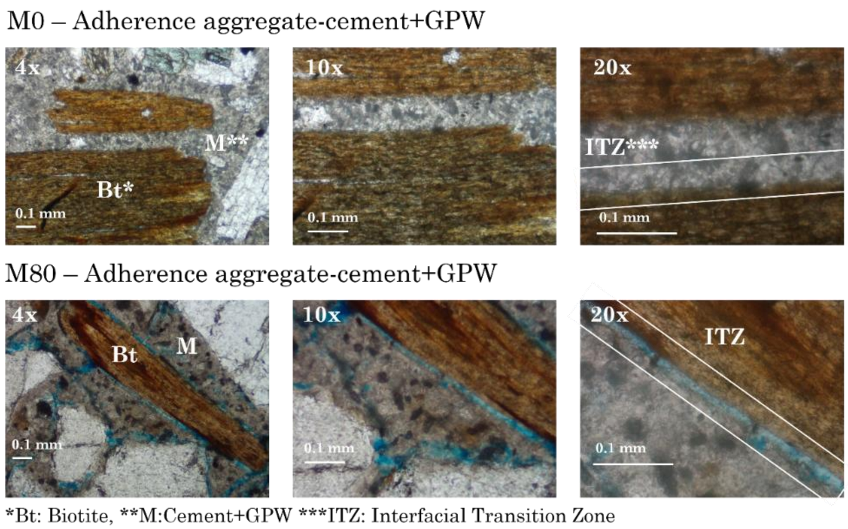


Figure 12. Illustration of the contrast effect on biotite grain adhesion between M0 and M80.
Source: own elaboration.

The petrographic analyzes allowed us to identify various mixtures that do not contain reactive or hazardous aggregates. According to [61], reactive aggregates interfere with the hydration process of cement or cause changes in the volume of aggregate and paste. Petrographic analysis showed a light brown color in the cementitious phase, indicating an effective cement hydration process [60]. The correlation between the loss of adhesion observed in the thin films and the micrographs demonstrates the effect of adhesion loss between the paste and the aggregates, which seems to contribute to the reduction of compressive strength.

3.5 Scanning Electron Microscopy SEM

The surface of the M0 mixture is compact, without visible voids or flaky grains, and the paste adheres fully to the sand particles (Figure 13a). In addition, the cement mineral phases, including ettringite, portlandite, and CSH, develop continuously throughout the examined area (Figure 13b). The surface of sample M30 shows microcracks in the interstitial zone, along with aggregates (Figure 13c). Compared to the M0 mixture (Figure 13b), the 2000x micrograph shows more pores, and the CSH phases in M30 appear to be discontinuous and sparse (Figure 13d).

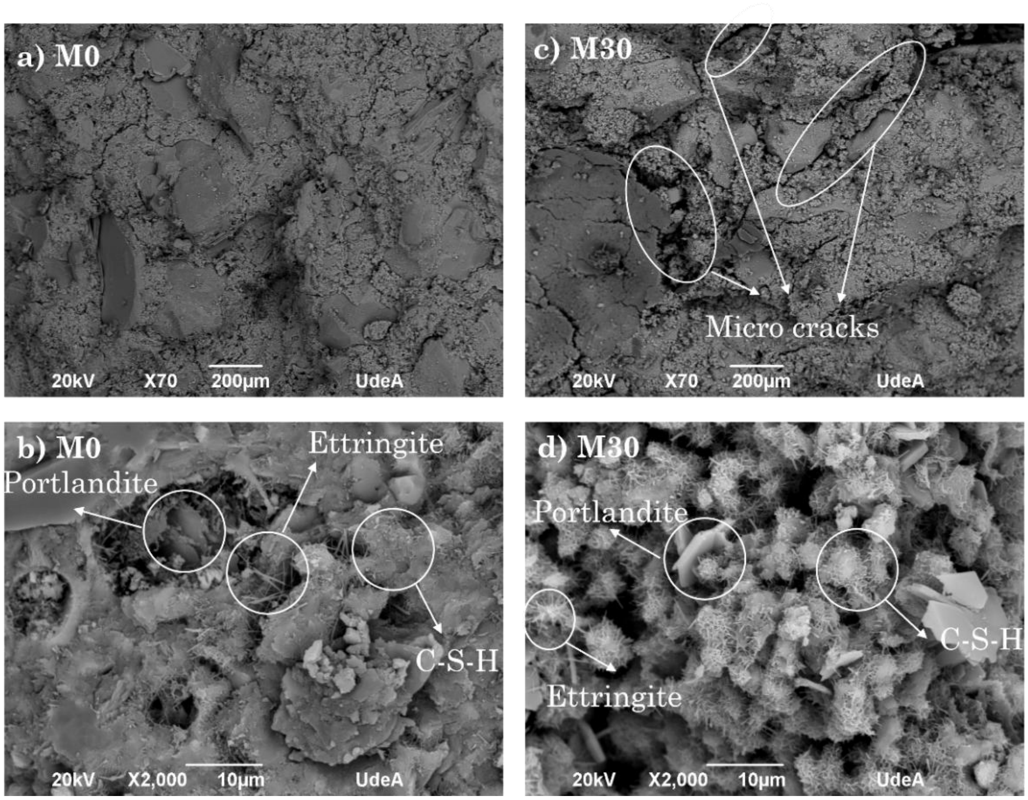


Figure 13. The figure shows morphological differences observed in backscattered electron images of mortars M0 and M30. Images 13a) and 13c) display their morphological features, while images 13b) and 13d) show the cement mineralogy. Source: own elaboration.

Mortars made with GPW substitution were produced from the original residue without additional treatment, thereby avoiding higher energy costs and facilitating their incorporation at the construction site. Other studies, such as those of [4] and [5], which replaced part of the cement with GPW, agree to use GPW in a dry state. However, this method incurs energy costs and complicates on-site integration. The need to dry and crush waste on-site reduces interest in its use, as the necessary processing tools are often unavailable.

Integrating waste into construction materials involves reintroducing industrial waste into the production process, which reduces waste management costs and the expense of producing construction materials [1], [30], [62]. Therefore, the primary aim is not to improve the physical and mechanical properties of the materials [63], [64]. Using GPW in hydraulic cement mortars as a partial replacement for hydraulic cement offers potential economic savings in civil construction and reduces the harmful environmental impacts associated with cement manufacturing and use on construction sites.

Therefore, if the GPW is used as a binder rather than an aggregate, as shown in the research of [4] and [5], it would produce greater economic savings and a lower environmental impact. This would enable the construction industry to adopt sustainable designs and participate in the circular economy.

4. CONCLUSIONS

This study shows that GPW waste has potential as a cement substitute due to its composition, although it presents challenges to handle. Characterization of GPW indicates that a chemical reaction occurs during the sedimentation of the waste, which affects the physical properties of the material related to the moisture content. Despite a high moisture level (47%), the consistency of the material before mixing resembles a solid with plasticity, suggesting low workability in a cement mixture.

The analysis of mortars using the design employed in this research shows that the addition of waste directly from the production process is feasible without additional economic or energy costs for preparing the waste.

Physical-mechanical characterization tests for the fluidity and strength of mix designs with less than 20% cement substitution by GPW demonstrate adequate performance for using this type of mixes in non-structural applications, in accordance with Colombian regulations.

Petrographic analysis identifies the aggregate composition and indicates that there are no potential chemical reactions that are likely to affect the physical properties of the mortars. Additionally, petrographic analyzes of thin sections show that mixtures containing GPW at up to 20% replacement produce consistent, high-quality cementitious material. Petrography also reveals microstructural changes associated with increasing the replacement of cement with GPW. A decrease in adhesion between the cementitious matrix and the sand particles in the interstitial zone is observed. Furthermore, the percentages of the cementitious matrix and voids increase with increasing substitution level.

Finally, the use of GPW in mortar mixes offers an opportunity for waste reuse, thus reducing cement use and providing an alternative disposal method.

For future research on GPW as a cementitious material, it is advisable to develop tests for pozzolanic activity and durability to assess the long-term performance of materials incorporating GPW.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial or personal interests that could have appeared to influence the work reported in this paper.

AUTHORSHIP CONTRIBUTION

Andrés Felipe Múnera Yepes: Conceptualization, Methodology, Experimentation, Writing, Formal Analysis.

Andres Felipe Conejo López: Conceptualization, Methodology, Experimentation, Writing, Formal Analysis

Carlos Fernando Herrera Corrales: Conceptualization, Methodology, Experimentation, Writing– Review and Editing, Formal Analysis, Supervision.

Alba Gallego Hernández: Conceptualization, Methodology, Experimentation, Writing– Review and Editing, Formal Analysis, Supervision.