Advanced and Sustainable Technologies
ASET
E-ISSN 2976-2294

Volume 5, No 2, September 2026 [240-255]

Thermoplastic Consolidation of Emerald Mining Waste Into Cement-Free Mineral–Polymer Composite Bricks

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Received 10 June 2026, Revised 15 July 2026, Accepted 30 July 2026

ABSTRACT

This study investigates the feasibility of manufacturing sustainable cement-free composite bricks from emerald mining waste using recycled polyester fabric scraps and post-consumer PET powder as thermoplastic binding agents. The manufacturing process comprised raw material characterization, material proportioning, homogenization, compaction, thermal treatment, and demolding. The physical and mechanical performance of the composites was evaluated through water absorption and compressive strength tests. The best-performing formulation achieved a characteristic compressive strength of 3.53 MPa and a characteristic water absorption of 7.62%, meeting the performance requirements specified in ASTM C129 for masonry units. The results demonstrate that emerald mining waste can be successfully transformed into value-added construction materials through a cement-free consolidation process employing recycled polymeric binders. This approach simultaneously promotes the valorization of mining, textile, and plastic wastes while reducing the consumption of virgin raw materials and eliminating the use of Portland cement. Overall, the developed composite shows considerable potential as a sustainable construction material by contributing to circular economy strategies and supporting the United Nations Sustainable Development Goals related to responsible consumption and production and sustainable cities and communities.

Keywords: Composite, Free-cement brick, Emerald, Recycling, Thermoplastic.

1. INTRODUCTION

Mining plays a fundamental role in modern society by supplying the raw materials required for infrastructure, manufacturing, and technological development. However, mineral extraction and processing also generate enormous quantities of waste that are frequently stockpiled or disposed of without adequate environmental management. These residues occupy extensive land areas, alter natural landscapes, contaminate soil and water resources, and constitute long-term environmental liabilities for surrounding communities [1].

Brazil is among the world's leading mineral-producing countries, extracting more than seventy different mineral commodities, including metallic minerals, industrial minerals, gemstones, and energy resources. Although mining plays a fundamental role in the national economy, it is also associated with significant environmental and socioeconomic impacts resulting from mineral extraction, ore processing, and waste disposal [2]. In many regions, inadequate waste management practices have contributed to environmental degradation, reinforcing the need for sustainable strategies capable of recovering and valorizing these residues [3].

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Among Brazil's mineral resources, emeralds occupy a prominent position because of their high commercial value and international demand. Emerald is a transparent green variety of beryl whose characteristic color originates primarily from chromium and vanadium impurities. Owing to its rarity and economic importance, emerald is often referred to as "green gold" [4]. One of the country's principal emerald deposits is located in the municipality of Campos Verdes, Goiás State, where mining activities expanded rapidly following the discovery of economically viable deposits in the early 1980s [5, 6].

The extraction and processing of emerald-bearing rocks generate substantial quantities of coarse and fine mineral waste. Historically, these residues have been stockpiled in open areas surrounding mining sites or discharged into nearby watercourses without adequate environmental control, creating significant environmental liabilities. Despite their abundance and potential value, the reuse of emerald mining waste has received considerably less attention than that of other mining residues, particularly iron ore tailings.

In recent years, the construction industry has increasingly sought alternatives to reduce the environmental impacts associated with conventional building materials. The incorporation of mining waste into construction products has emerged as a promising strategy for simultaneously promoting waste valorization, conserving natural resources, and reducing the environmental footprint of the construction sector. Likewise, recycled polymeric materials have attracted considerable attention as alternative binding agents due to their favorable mechanical properties, low water permeability, and excellent adhesion.

In addition to mining waste, polyester textile waste, and post-consumer PET have become important environmental concerns owing to the increasing quantities generated worldwide and the limited recycling rates achieved in many regions. Their incorporation into construction materials represents an attractive strategy for extending their service life while simultaneously reducing the demand for virgin raw materials.

Despite the growing interest in the reuse of mining and polymeric wastes, the application of emerald mining waste in cement-free composite masonry units remains largely unexplored. This knowledge gap highlights the need to evaluate its technical feasibility and engineering performance as a sustainable construction material.

Unlike Portland cement, whose binding capacity results from hydration reactions and the formation of cementitious products, thermoplastic polymers develop their binding effect through a fundamentally different consolidation mechanism. When subjected to thermal processing above the softening and melting range of the thermoplastic phase, the polymer becomes sufficiently fluid to flow around the mineral particles and penetrate the interparticle voids. Upon cooling, it solidifies to form a continuous matrix that mechanically interlocks and binds the particles together. This thermoplastic matrix promotes efficient load transfer throughout the composite while reducing interconnected porosity and limiting water ingress. Consequently, the mechanical performance and durability of the resulting composite are achieved through physical consolidation rather than through chemical reactions analogous to those that harden Portland cement. This physical consolidation mechanism provides the scientific rationale for investigating recycled thermoplastic waste as a sustainable alternative to hydraulic cement binders in mineral-based composites.

Therefore, the objective of this study was to evaluate the technical feasibility of manufacturing cement-free composite bricks using emerald mining waste as the granular phase and recycled polyester textile waste or post-consumer PET bottle powder as thermoplastic binding agents. The manufacturing process was evaluated at both pilot and full scales, and the physical and mechanical performance of the bricks produced was assessed using water absorption and compressive strength tests conducted in accordance with the relevant Brazilian standards.

2. LITERATURE REVIEW

Although emerald mining generates substantial quantities of solid waste, relatively few studies have investigated the valorization of these residues. Most of the available research has focused on ceramic applications. Emerald mining waste has been successfully incorporated into ceramic coatings, producing materials with mechanical and aesthetic properties comparable to those of conventional porcelain and stoneware products [7]. In addition, its high refractoriness has enabled the production of refractory ceramic bodies containing up to 45 wt.% mining waste while satisfying the corresponding technical requirements [3]. Emerald mining waste has also been evaluated as a partial replacement for feldspar in ceramic coatings at replacement levels of up to 20 wt.% without significant losses in engineering performance [8].

The potential applications of emerald mining waste extend beyond the construction sector. Owing to its mineralogical composition, this material has also been investigated for agricultural applications, particularly as an alternative source of mineral nutrients for soil conditioning. Previous studies have demonstrated that these residues contain significant amounts of potassium, magnesium, and other elements of agronomic interest, supporting their potential use as mineral fertilizers and soil amendments [9–12].

More recently, the incorporation of mining waste into masonry products has attracted considerable attention as a strategy for simultaneously reducing the environmental impacts associated with mining activities and conventional construction materials. Several investigations have demonstrated the feasibility of incorporating different types of mining residues into fired and unfired bricks while maintaining satisfactory physical and mechanical performance [13–23]. These studies include iron ore tailings, uranium mill tailings, gold tailings, lead-zinc tailings, vanadium-bearing tailings, and other mineral residues used to manufacture sustainable masonry units. Collectively, these studies demonstrate that mining waste can successfully replace conventional raw materials while promoting waste valorization, conserving natural resources, and reducing the environmental footprint of construction materials.

In parallel, recycled polymeric materials have emerged as promising alternatives to conventional cementitious binders. Previous investigations have demonstrated that recycled polymers can improve the mechanical performance, durability, and water resistance of composite construction materials [24–27]. In particular, recycled PET-based polymers and epoxy systems have shown considerable potential for producing polymer concrete and other cement-free composites owing to their excellent adhesion characteristics, rapid hardening, and low water permeability.

Despite these advances, no previous study has investigated the combined use of emerald mining waste, recycled polyester textile waste, and post-consumer PET powder for the manufacture of cement-free composite masonry units. Furthermore, the influence of these two recycled thermoplastic binding agents on the engineering performance of such composites has not been comparatively evaluated. This knowledge gap provides the scientific rationale for the present investigation.

Accordingly, this study investigates the development of sustainable cement-free composite bricks manufactured from emerald mining waste using recycled polyester textile waste and post-consumer PET powder as thermoplastic binding agents. The proposed approach simultaneously addresses three important environmental challenges by promoting the valorization of mining, textile, and plastic wastes while reducing the consumption of virgin raw materials and eliminating the use of Portland cement.

3. EXPERIMENTAL METHODS

3.1 Sampling

Samples of emerald mining waste were collected from a disposal area belonging to a small-scale processing facility located in the municipality of Campos Verdes, Goiás State, Brazil. The sampling site is located at 14°16′05.1″ S, 49°39′25.8″ W, at an elevation of approximately 164 m above sea level. Figure 1 shows the emerald-bearing rock supplied to local processing facilities for manual beneficiation.

Figure 1: Emerald-bearing rock supplied for manual processing. (Source: the author himself).

After extraction, the material is mechanically crushed to reduce particle size. The crushed material is subsequently transferred to a manual separation table, where the operation locally known as *hand picking* is performed. During this operation, emerald gemstones are manually recovered from the coarser mineral fraction, while the washing and sieving processes generate a fine sandy residue. This stage of the beneficiation process is illustrated in Figure 2.

Figure 2: Manual recovery of emerald gemstones during the beneficiation process (A), and nearby silted watercourse (B). (Source: the author himself).

The beneficiation process generates two principal waste streams. The first consists of a coarse fraction with particle sizes typically ranging from 1 to 4 mm, locally referred to as *bagasse*. The second corresponds to a much finer residue, with particle sizes generally smaller than 1.0 mm. At the processing facility investigated in this study, the wash water carrying the fine mineral particles is discharged into a nearby watercourse. Field observations revealed that this watercourse has become heavily silted by the continuous deposition of fine mining residue. In contrast, the coarse fraction (*bagasse*) is deposited on adjacent land, where local residents manually recover small emerald fragments from the discarded material that still have limited commercial value.

Approximately 200 L of each waste fraction were collected for the experimental program. The fine residue was collected directly from the banks of the affected watercourse together with a small amount of water, whereas the coarse residue was collected under essentially dry conditions.

3.2 Physicochemical characterization of emerald mining waste

Both waste fractions were transported to the laboratory, where they were air-dried, successively quartered, and prepared for particle-size distribution analysis, apparent dry density determination, X-ray diffraction (XRD), scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), and mineralogical characterization.

Particle-size distribution was determined in accordance with Brazilian Standard ABNT NBR NM 248 (2003) [28]. The fine waste exhibited a broad particle-size distribution, with a predominance of particles smaller than 0.60 mm and a significant proportion of particles finer than 0.15 mm, indicating a predominantly fine granular material. The apparent dry density of the fine fraction, determined according to ABNT NBR NM 45 (2006) [29], was 1.57 g/cm^3.

The coarse waste also exhibited a relatively broad particle-size distribution, ranging from 4.75 mm to less than 0.15 mm, with approximately 60% of the particles concentrated around 1.18 mm. The apparent dry density of this fraction, determined according to ABNT NBR NM 45 (2006) [29], was 1.61 g/cm^3.

Scanning electron microscopy combined with energy-dispersive spectroscopy revealed the presence of aluminum, calcium, potassium, magnesium, and other mineral constituents, confirming the heterogeneous mineralogical nature of the waste. Figure 3 shows a representative SEM image of the fine emerald mining waste, illustrating its morphology and characteristic particle size.

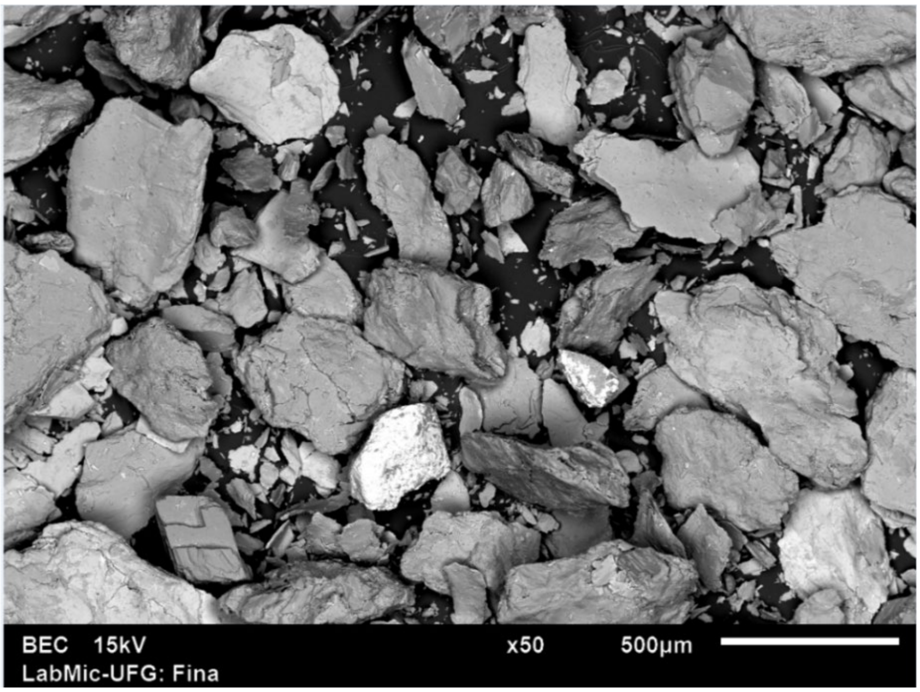

Figure 3: Enlarged image of emerald mining waste grains (fine phase).

A representative sample of the fine waste was submitted to thermogravimetric analysis (TGA) at the Analytical Center of the Institute of Chemistry, Federal University of Goiás. The thermogravimetric curve showed negligible mass loss between 350 °C and 570 °C, whereas a pronounced mass loss occurred between 600 °C and 665 °C. Since the specimens were processed in a muffle furnace at 300 °C, while the measured temperature inside the metallic molds remained approximately 265 °C, no significant thermal degradation of the mineral phase is expected during the manufacturing process.

3.3 Characterization of polyester textile waste

The polyester textile waste used as the thermoplastic binding agent was obtained from clothing manufacturing facilities as cutting scraps. Approximately 500 kg of textile waste were collected and mechanically ground to obtain a fine granular material. Particle-size analysis indicated that 65.38% of the material was retained on the Tyler Mesh 16 sieve, corresponding to particle sizes smaller than 1.0 mm. Thermogravimetric analysis, shown in Figure 4, demonstrated negligible mass loss between 37 °C and 378 °C. Above this temperature, rapid thermal degradation occurred up to approximately 451 °C. Considering that the processing temperature adopted in the present study was 300 °C, while the temperature measured inside the metallic molds remained close to 265 °C, no significant thermal degradation of the polyester binding phase is expected during specimen production.

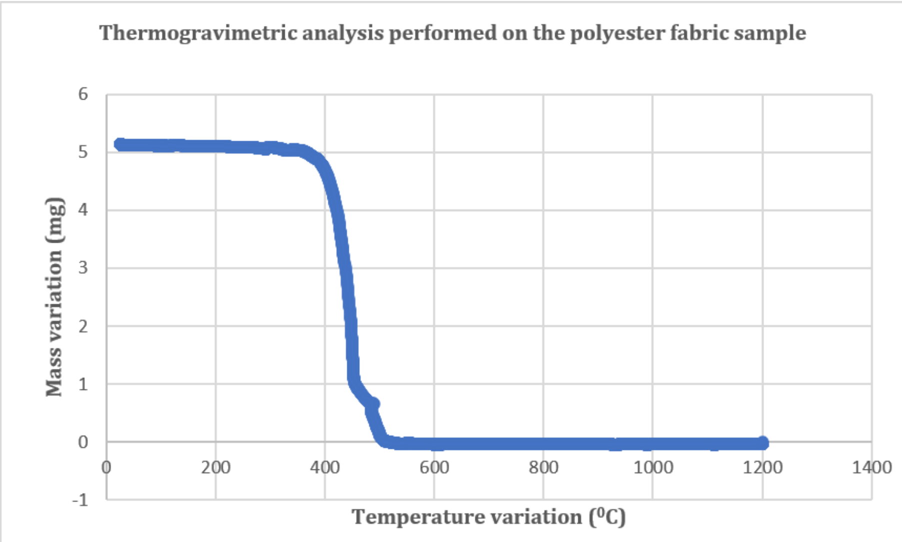

Figure 4: Thermogravimetric analysis on the polyester fabric sample.

3.4 Characterization of PET bottle powder

Approximately 50 kg of post-consumer PET bottle powder were obtained from a PET recycling company. After homogenization and quartering, a representative sample of approximately 500 g was subjected to particle-size analysis in accordance with Brazilian Standard ABNT NBR NM 248 (2003) [28]. The results indicated that approximately 50% of the particles had particle sizes between 1.18 mm and 2.36 mm. Thermogravimetric analysis, shown in Figure 5, indicated that thermal degradation began at approximately 285 °C. Considering that the specimens were processed at 300 °C, while the temperature inside the metallic molds remained close to 265 °C, no significant thermal degradation of the PET binding phase is expected during specimen production.

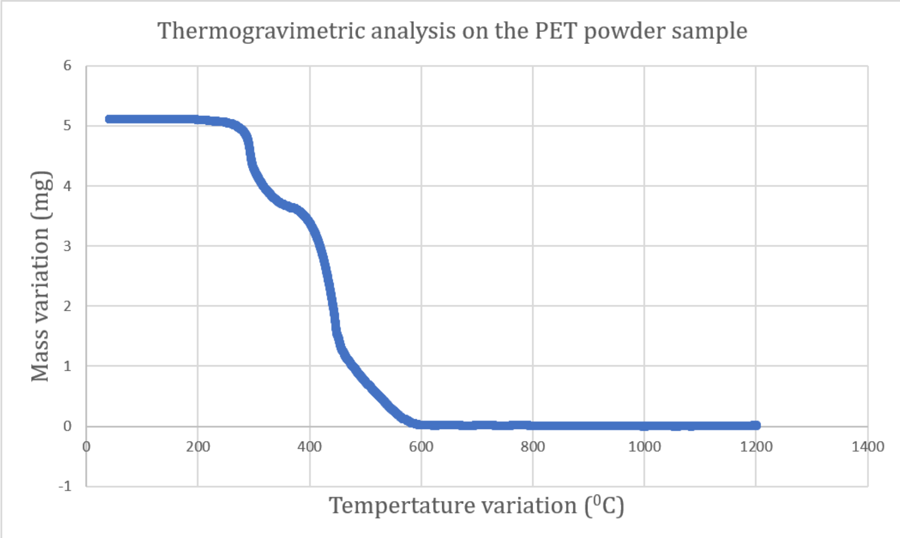

Figure 5: Thermogravimetric analysis on the PET powder sample.

4. RESULTS

To evaluate the feasibility of manufacturing cement-free composite bricks from emerald mining waste using the manufacturing approach previously developed for iron mining waste and recycled polymers [30], a pilot-scale experimental program was conducted. Two thermoplastic binding agents were investigated: recycled polyester textile waste and post-consumer PET powder.

Small-scale specimens were produced using carbon steel molds with dimensions proportional to those specified for conventional soil-cement bricks in the Brazilian Standard ABNT NBR 8491 (2012) [31]. The molds measured 12 cm × 6 cm × 3.5 cm and were equipped with a compaction system that enabled material mixing, hydraulic pressing, and subsequent thermal processing in a muffle furnace at 300 °C. Figure 6 shows the experimental apparatus and representative specimens.

Figure 6: Compression device (left) and the finished test specimens (right). Source (the author himself).

Two experimental series were performed using either recycled polyester textile waste or post-consumer PET powder as the thermoplastic binding agent. For each binder, three aggregate compositions were investigated:

- 100% coarse emerald mining waste;
- 50% coarse waste + 50% fine waste;
- 100% fine waste.

The experimental variables included the binder-to-mineral mass ratio, compaction force, and processing temperature. A binder-to-mineral mass ratio of 1:20 was adopted throughout the pilot study. The mixtures were homogenized, placed into the metallic molds, compacted under a force of 1.5 tons (corresponding to a compaction stress of 2.083 MPa), and heated at 300 °C for 60 min, following the manufacturing procedure proposed by Ref. [30].

Water absorption and compressive strength were determined in accordance with Brazilian Standard ABNT NBR 8492 (2012) [32]. The results obtained for specimens produced from polyester textile waste are summarized in Table 1, with 1 specimen per formulation.

Table 1: Water absorption and compressive strength of the small-scale specimens using polyester fabric waste as the thermoplastic binding.

	Water absorption (%)	**Compressive strength (MPa)**
100% fine material	16.40	1.73
50% fine material + 50% coarse material	13.28	2.63
100% coarse material	12.76	2.62

An identical experimental procedure was subsequently performed using post-consumer PET bottle powder as the thermoplastic binding agent. Three additional specimens were produced using the same binder-to-mineral ratio (1:20), compaction stress (2.083 MPa), and thermal cycle (300 °C for 60 min), while varying only the proportions of fine and coarse mining waste. The corresponding water absorption and compressive strength results are presented in Table 2, with one specimen for each formulation.

Table 2:Water absorption and compressive strength of the small-scale specimens using PET powder waste as binding material.

	Water absorption (%)	**Compressive strength (MPa)**
100% fine material	11.54	2.954
50% fine material + 50% coarse material	7.03	3.589
100% coarse material	6.80	3.769

Based on the exploratory pilot-scale results, the mixture containing 50% fine waste and 50% coarse waste was selected for full-scale manufacturing because it provided the best balance between the utilization of both waste streams and engineering performance. Full-scale specimens were then produced using metallic molds with the dimensions specified in Brazilian Standard ABNT NBR 8491 (2012) [31] (24 cm × 12 cm × 7 cm). Figure 7 shows the metallic mold and a representative composite brick manufactured using polyester textile waste.

The first full-scale specimens were manufactured using a binder-to-mineral mass ratio of 1:20, a compaction force of 9.0 tons (3.125 MPa), and a heating period of 3 h at 300 °C. Two specimens were produced, one using polyester textile waste and the other using post-consumer PET bottle powder as the thermoplastic binding agent. The corresponding water absorption and compressive strength results are presented in Table 3, with 1 specimen for each formulation.

Figure 7: Metallic mold (left) and representative cement-free composite brick manufactured with polyester fabric waste (right). (source: the author himself).

Table 3: Water absorptions and compressive strengths of full-scale samples using polyester textile waste and PET powder waste as binding agents.

Samples	Water absorption (%)	Compressive strength (MPa)
Polyester textile waste	13.89	2.073
PET powder waste	6.07	3.229

Following these preliminary full-scale results, the experimental program was expanded to investigate the influence of compaction pressure. Additional full-scale specimens were produced using the same binder-to-mineral ratio (1:20), heating temperature (300 °C), and heating time (3 h), while adopting compaction forces of 9.0 tons (3.125 MPa) and 25.0 tons (8.680 MPa). The two thermoplastic binding agents, polyester textile waste and PET powder, were evaluated using the mixture containing equal proportions of fine and coarse emerald mining waste.

Five specimens were produced for each experimental condition. Water absorption and compressive strength were determined in accordance with Brazilian Standard ABNT NBR 8492 (2012) [32]. The results are summarized in Table 4.

Table 4: Summary of results from the production of full-scale specimens.

Binding agent	Testing format	Compaction force (ton)	Average compressive strength (MPa)	Standard deviation (MPa)	Characteristic compressive strength (MPa)	Average water absorption (%)	Standard deviation (%)	Characteristic water absorption (%)
Polyester fabric waste	Cut	9.0	1.311	0.142	1.078	14.89	1.08	16.65
Polyester fabric waste	Whole	9.0	1.955	0.086	1.812	13.55	0.54	14.44
PET powder waste	Cut	9.0	1.728	0.554	0.813	6.31	2.68	10.75
PET powder waste	Whole	9.0	2.910	0.359	2.318	7.24	0.72	8.42
Polyester fabric waste	Cut	25.0	2.520	0.522	1.960	8.82	0.43	9.53
PET powder waste	Cut	25.0	4.008	0.288	3.532	6.74	0.43	7.62

The characteristic compressive strength values reported in Table 4 were calculated in accordance with Brazilian Standard ABNT NBR 12655 (2022) [33] using the following expression (eqs. 1 and 2):

$$Fk = \text{mean value} - 1.65 \times \text{standard deviation} \quad (1)$$

The characteristic water absorption values were calculated as:

$$Absk = \text{mean value} + 1.65 \times \text{standard deviation} \quad (2)$$

These characteristic values were subsequently adopted as the basis for the comparative analysis presented in the Discussion section.

5. DISCUSSIONS

5.1 Water absorption and compressive strength of the small-scale specimens using polyester textile waste as the binding agent

The small-scale experimental program previously conducted with iron mining waste under identical processing conditions resulted in a water absorption of 17.76% and a compressive strength of 1.996 MPa [30]. Compared with these reference values, all three formulations investigated in the present study exhibited lower water absorption (Table 1), indicating reduced susceptibility to moisture ingress and a denser composite structure.

Regarding compressive strength, the specimen produced with 100% fine emerald mining waste exhibited a slightly lower value than that obtained with iron mining waste. In contrast, the formulations containing 50% fine waste and 50% coarse waste, as well as those produced with 100% coarse waste, achieved higher compressive strengths than the reference material.

The improved performance observed for the formulations containing the coarser emerald mining waste fraction can be attributed to the combined effects of particle-size distribution and thermoplastic consolidation. A broader particle-size distribution promotes more efficient particle packing by allowing the finer particles to occupy the voids between the coarser ones, thereby reducing the initial porosity of the compacted granular skeleton. During thermal processing, the softened thermoplastic phase is more uniformly distributed throughout the mineral framework, promoting the formation of a continuous polymer matrix that mechanically interlocks the particles and enhances load transfer within the composite. This interpretation is consistent with the consolidation mechanism proposed in the Introduction and explains the simultaneous improvement in compressive strength and resistance to water penetration observed in these formulations.

5.2 Water absorption and compressive strength of the small-scale specimens using PET powder as the binding agent

The reference experimental program conducted with iron mining waste under identical processing conditions resulted in a water absorption of 17.76% and a compressive strength of 1.996 MPa [30]. As shown in Table 2, all formulations produced with emerald mining waste and PET powder exhibited substantially lower water absorption and higher compressive strength than the corresponding reference specimens, indicating that the substitution of iron mining waste with emerald mining waste significantly improved the engineering performance of the cement-free composite.

Regardless of the proportions of fine and coarse waste, all specimens exhibited water absorption values below 20%, thereby satisfying the maximum limit established for the intended application. In addition, all formulations achieved compressive strengths exceeding the reference value, demonstrating that PET powder effectively promoted thermoplastic consolidation of the emerald mining waste under the adopted processing conditions.

Although the specimens produced with 100% coarse waste exhibited the highest compressive strength, the formulation containing equal proportions of fine and coarse waste achieved essentially the same mechanical performance. This behavior suggests that optimizing the particle-size distribution can compensate for the slight reduction in coarse aggregate content by improving particle packing and promoting a more homogeneous distribution of the thermoplastic binding phase throughout the mineral skeleton. Because this formulation simultaneously maximizes the utilization of both waste fractions while maintaining essentially the same engineering performance, it was selected for the subsequent stages of the experimental program.

5.3 Water absorption and compressive strength of full-scale specimens using polyester textile waste and PET powder as binding agents

The full-scale experimental program previously conducted with iron mining waste using whole specimens resulted in a characteristic water absorption of 17.29% and a characteristic compressive strength of 1.093 MPa [30]. Compared with these reference values, the full-scale composite bricks produced with emerald mining waste exhibited substantially improved performance in both evaluated parameters (Table 3). Water absorption was considerably reduced, whereas compressive strength increased significantly, demonstrating that emerald mining waste provides a more suitable mineral framework for the proposed cement-free manufacturing process than the iron mining waste investigated in the reference study.

The improved performance can be attributed to the combined effects of the particle-size characteristics of the emerald mining waste and the efficiency of the thermoplastic consolidation mechanism. The enhanced particle packing promoted a denser granular skeleton, allowing the softened thermoplastic phase to form a more continuous binding matrix during thermal processing. After cooling, this continuous polymer network mechanically interlocked the mineral particles, resulting in improved load transfer, lower permeability, and higher compressive strength.

These findings further demonstrate that the manufacturing procedure originally developed for iron mining waste can be successfully extended to emerald mining waste without compromising engineering performance. On the contrary, the superior results obtained in the present investigation indicate that emerald mining waste is an even more suitable raw material for producing cement-free thermoplastic composite bricks via the proposed manufacturing route.

5.4 Results of the production of full-scale specimens

Particular attention should be given to the last two experimental conditions presented in Table 4, corresponding to the specimens produced under a compaction force of 25.0 tons. Both formulations, using polyester textile waste and PET powder as thermoplastic binding agents, exhibited water absorption values well below the maximum limit of 20% established by Brazilian Standard ABNT NBR 8491 (2012) [31]. Regarding compressive strength, the specimens produced with polyester textile waste achieved values only slightly below the minimum requirement of 2.0 MPa established by the same standard, indicating that only minor adjustments in mixture composition or processing conditions may be sufficient to achieve full compliance.

The superior performance of the specimens produced with PET powder can be interpreted in light of the thermoplastic consolidation mechanism proposed in the Introduction. During thermal processing, the thermoplastic phase softens and becomes sufficiently fluid to penetrate the interparticle voids and surround the mineral particles. Upon cooling, it solidifies to form a continuous polymer matrix that mechanically interlocks the particles and promotes efficient load transfer throughout the composite. Consequently, the final engineering performance depends not only on the intrinsic properties of the polymer but also on its ability to redistribute within the compacted granular skeleton and establish an effective continuous binding network.

Although both recycled materials are chemically based on polyethylene terephthalate (PET), they differ in polymerization degree, crystallinity, particle morphology, and the presence of additives associated with textile manufacturing. These differences directly influence their rheological behavior during thermal processing. According to the technical data provided by the suppliers, PET powder exhibits a melt viscosity of approximately 0.70 to 1.00 Pa·s, whereas the ground polyester textile waste shows a melt viscosity of 0.60 to 0.70 Pa·s under comparable processing conditions. These rheological differences appear to influence the formation and continuity of the thermoplastic matrix and, consequently, the efficiency of the physical consolidation mechanism.

The experimental evidence is consistent with this interpretation. Under identical processing conditions adopted in the previous investigation using iron mining waste [30], replacing polyester textile waste with PET powder increased the characteristic compressive strength from 0.594 MPa to 1.359 MPa, whereas the characteristic water absorption remained nearly unchanged (17.73% and 17.34%, respectively). These findings indicate that PET powder primarily improves the efficiency of the thermoplastic binder by strengthening interparticle bonding rather than by significantly reducing the intrinsic porosity of the composite.

In the present investigation, the same tendency was observed, although with substantially higher performance levels. The best-performing specimens achieved a characteristic compressive strength of 3.532 MPa together with a characteristic water absorption of only 7.62%. Since the heating temperature and heating time remained unchanged in both studies, this additional improvement can reasonably be attributed to the combined influence of the higher compaction pressure (25.0 tons), which promoted a denser granular skeleton, and the broader particle-size distribution of the emerald mining waste, which enhanced particle packing and favored the formation of a more effective continuous thermoplastic matrix. Acting synergistically, these factors improved mechanical interlocking, stress transfer, and resistance to water penetration throughout the composite.

Another important finding is the beneficial effect of combining the fine and coarse fractions of emerald mining waste. The mixture containing equal proportions of both fractions consistently exhibited better overall performance than mixtures prepared using only one particle-size fraction. This behavior can be explained by improved particle packing, whereby the finer particles fill the voids between the coarser ones, increasing the density of the compacted composite and reducing its initial porosity. As a consequence, the thermoplastic binding phase can be distributed more uniformly throughout the mineral framework, contributing to both higher compressive strength and lower water absorption.

Considering the requirements established by ABNT NBR 8491 (2012) [31], the bricks produced with polyester textile waste exhibited compressive strengths very close to the minimum specified value while fully satisfying the water absorption criterion. In contrast, the specimens produced with PET powder satisfied both performance requirements, demonstrating the technical feasibility of this formulation for the proposed application.

It is also noteworthy that ASTM C129 [34] specifies a minimum characteristic compressive strength of 3.45 MPa, with no individual specimen presenting a value lower than 2.76 MPa, together with a maximum water absorption of 15%. The bricks produced with emerald mining waste and PET powder also satisfied these requirements, demonstrating that the proposed material complies not only with the Brazilian specifications but also with the corresponding American performance requirements.

Overall, the results demonstrate that emerald mining waste can be successfully consolidated through a thermoplastic binding mechanism using recycled polyester textile waste or post-consumer PET powder, producing cement-free composite bricks with satisfactory engineering performance. Beyond demonstrating the technical feasibility of this manufacturing route, the study shows that the combined effects of optimized particle packing, thermoplastic matrix formation, and increased compaction pressure play a decisive role in improving mechanical strength and reducing water absorption. These findings contribute to the development of sustainable mineral–polymer composites while simultaneously promoting the beneficial reuse of three significant waste streams.

6. CONCLUSIONS

This study evaluated the technical feasibility of manufacturing cement-free composite bricks from emerald mining waste, using recycled polyester textile waste and post-consumer PET powder as thermoplastic binders. The experimental results demonstrated that emerald mining waste can be successfully consolidated into structural composite materials through a thermoplastic binding mechanism, completely eliminating the need for Portland cement. The proposed manufacturing process proved technically feasible at both pilot and full scales, confirming that the methodology previously developed for iron mining waste can be successfully extended to emerald mining waste.

Among the investigated formulations, specimens produced with post-consumer PET powder consistently exhibited superior engineering performance compared with those manufactured using polyester textile waste. The best overall results were obtained by combining PET powder, a higher compaction pressure, and a mineral mixture containing equal proportions of fine and coarse emerald mining waste. Under these conditions, the composite achieved a characteristic compressive strength of 3.532 MPa and a characteristic water absorption of 7.62%, meeting the performance requirements established by ASTM C129 and the corresponding Brazilian standards for masonry units.

The results further demonstrate that the engineering performance of the composite is governed not only by the properties of the recycled thermoplastic binder but also by the interaction between particle-size distribution, compaction pressure, and the formation of a continuous thermoplastic matrix capable of mechanically interlocking the mineral particles. This physical consolidation mechanism offers an effective alternative to conventional hydraulic cement binders for producing mineral–polymer composites.

Beyond its engineering performance, the proposed material offers an environmentally sustainable solution for the simultaneous valorization of emerald mining waste, polyester textile waste, and post-consumer PET, contributing to waste minimization, conservation of natural resources, and reduction of greenhouse gas emissions associated with Portland cement production. Therefore, the proposed manufacturing route represents a promising strategy for advancing cement-free construction materials within the circular economy and sustainable construction frameworks.

7. LIMITATIONS AND FUTURE WORK

Since this study represents the initial development of a novel cement-free composite material, the experimental investigation was intentionally focused on establishing its fundamental physical and mechanical performance. Consequently, additional studies are required before the proposed material can be considered for large-scale practical applications or future standardization.

Future research should investigate the long-term durability of the proposed composite, including weathering resistance, ultraviolet (UV) degradation of the polymeric phase, water permeability, dimensional stability, thermal and acoustic performance, creep behavior, freeze–thaw resistance, chemical durability, and fire performance. Such investigations will provide a more comprehensive understanding of the material's behavior under a wide range of service conditions.

From a sustainability perspective, future studies should also include life cycle assessment (LCA), carbon footprint analysis, and techno-economic assessment to quantify the environmental and economic benefits of the proposed manufacturing process and evaluate its potential for industrial-scale implementation.

ACKNOWLEDGEMENTS

The authors acknowledge the Federal University of Goiás (UFG) and the Laboratory of Extraction and Separation Methods of the Institute of Chemistry, where this study was carried out. The authors also acknowledge the Graduate Program in Environmental Sciences (CIAMB) at the Federal University of Goiás for its institutional support.

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Conflict of interest statement: The authors declare no conflict of interest.

Author contributions statement: Methodology: H.E. Silva; Laboratory investigation: H.E. Silva; Formal analysis: N.R. Antoniosi Filho; Writing – original draft: H.E. Silva; Writing – review & editing: H.E. Silva and N.R. Antoniosi Filho; Supervision: N.R. Antoniosi Filho.

Data Availability Statement: The main data used in this work are currently available through doi.org.10.1002/rem.70012 (reference number 30) and also through the thesis and dissertation library of the Federal University of Goiás, accessible at the website www.ufg.br. (Namely: Produção de tijolos de interesse ambiental utilizando resíduos de mineração de ferro e esmeraldas consorciados com resíduos têxteis de poliéster e de garrafas PET (**doctoral thesis**)).