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Characterization and Classification of Mortars for Underlayment with PCR-PET Artificial Aggregate in Partial Replacement of Natural Sand Aggregate in the Mix

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GC Revista Nacional de Gerenciamento de Cidades
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SUMMARY
This study investigated the feasibility of using Post-Consumer Recycled Polyethylene Terephthalate (PCR-PET) as an alternative aggregate in mortar for civil construction, aiming to evaluate its properties and impact on the sector's sustainability. Compressive strength, substrate adhesion, workability, and water retention tests were conducted on mortars with PCR-PET addition, and the results were compared with conventional mortars and the requirements of the ABNT NBR 13281 standard. The results showed that adding PCR-PET to mortars led to a slight reduction in compressive strength and substrate adhesion; however, the values remained within the limits set by the standard. Workability and water retention of mortars with PCR-PET were similar to conventional mortars. This study contributes to the field of civil construction by presenting PCR-PET as a viable and sustainable alternative for the use of plastic waste in civil construction, contributing to the reduction of demand for natural resources and waste generation. However, further studies are needed to assess the mechanical behavior and durability of mortars with PCR-PET in the long term, as well as their complete environmental impact.

KEYWORDS: PCR-PET. Mortar, Sustainability. Civil Construction. ABNT NBR 13281 Standard.

1 INTRODUCTION

Civil construction is a crucial sector for urban development, driving economic growth and providing housing, infrastructure, and workspaces for the population. However, this activity also generates significant environmental impacts, consuming natural resources indiscriminately and producing enormous volumes of waste (MASUERO, 2021). The magnitude of these impacts requires urgent actions to minimize the negative effects of traditional construction on the environment.

In light of this concerning scenario, sustainable civil construction emerges as a viable and urgent alternative to minimize the negative effects of traditional construction on the environment. This innovative approach prioritizes the use of environmentally friendly practices and materials, aiming to reduce the consumption of natural resources, waste generation, and the emission of polluting gases throughout the entire life cycle of a building (VAZQUES *et al.*, 2019).

In the pursuit of a greener future for cities, the recycling of waste in civil construction stands out as a sustainable and promising alternative, combating the environmental impacts generated by the sector (POON *et al.*, 2009). Among the recycled materials, Post-Consumer Recycled Polyethylene Terephthalate (PCR-PET) stands out as a protagonist of sustainability, boasting versatility and potential for application in various fields, including civil construction.

Mortars, indispensable components in civil construction, are composed of a mixture of binders, aggregates, and water. Their versatility makes them key elements in various stages of construction, from laying bricks and blocks to coating walls and floors (Falcao Bauer, 2013). The quality and performance of mortars are crucial for the durability, strength, and aesthetics of buildings, fundamental pillars for the safety and well-being of occupants.

PCR-PET, derived from the recycling of PET bottles, possesses physical and mechanical characteristics that qualify it as a potential substitute for natural aggregates in mortars (TZANNIS *et al.*, 2009). The incorporation of PCR-PET as an artificial aggregate in mortars has the potential to reduce the demand for natural resources and contribute to the reduction of waste generation, promoting a circular economy (SILVA *et al.*, 2016).

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 85, 2024

In a context where sustainability in civil construction is becoming increasingly crucial, this work is dedicated to characterizing screed mortars with artificial aggregate PCR-PET as a partial substitute for natural sand in the mixture. This study represents an important step in the search for innovative and sustainable solutions for civil construction, using recycled materials and optimizing resources, in line with the guidelines of ABNT NBR 13281 and market needs.

The results of this research aim to contribute significantly to the development of more sustainable and efficient mortars, promoting the adoption of eco-efficient practices in civil construction. It is believed that this study will bring numerous benefits, representing an important step in the journey towards a more sustainable and efficient civil construction.

By sharing the research results with the scientific community, construction industry professionals, governments, and companies, it is hoped to inspire actions and decisions that promote a greener and more sustainable future for the construction industry.

2 LITERATURE REVIEW

2.1 History and evolution of mortars in civil construction

Mortars have a long history in civil construction, having been used since ancient civilizations, such as the Egyptians, Romans, and Greeks. In these cultures, mortars were primarily composed of a mixture of lime, sand, and water. These ingredients were skillfully combined to create a versatile and durable substance. Over the centuries, their ability to bond and provide stability to structures allowed these civilizations to erect buildings that have stood the test of time (FALCAO BAUER, 2013).

With the passage of time and technological advancements, mortar manufacturing techniques have been improved, and new materials have been introduced. In the 20th century, with the emergence of the chemical industry, additives and binders were developed that enabled the enhancement of mortar properties, such as strength, adhesion, and curing time (MEHTA; MONTEIRO, 2014).

Moreover, the pursuit of sustainability and efficiency in civil construction has encouraged the research and development of mortars with special characteristics, such as high durability, resistance to aggressive agents, and reduced environmental impact. In this context, the recycling of waste and the use of alternative materials, such as PCR-PET, have gained prominence as promising alternatives for the production of more sustainable mortars (SILVA *et al.*, 2016).

Currently, mortars are widely used in various applications in civil construction, from laying bricks and blocks, coating walls and floors, to waterproofing and structural rehabilitation. The continuous evolution of mortars reflects the ongoing development and innovation in the construction sector, always striving to meet the demands for durability, performance, and sustainability in modern buildings.

2.2 Waste recycling in civil construction

ISSN 2318-8472, v. 12, n. 85, 2024

Waste recycling in civil construction emerges as a promising and sustainable alternative to mitigate the environmental impacts caused by this sector. The increasing use of recycled materials in concrete and ceramics is gaining prominence as an essential practice to promote sustainability in construction (FERRARIS, 2017; SILVA *et al.*, 2016).

Materials such as concrete, ceramics, bricks, and mortars can be recycled and reused in new constructions or other applications, reducing the need for natural resource extraction and minimizing waste generation. Additionally, waste recycling in civil construction contributes to the circular economy (KARA; TOPCU, 2010).

In Brazil, waste recycling in civil construction still faces challenges related to selective collection, waste segregation, and the lack of adequate infrastructure for processing and reusing materials (ABRELPE, 2021). However, government and private initiatives have been encouraging the adoption of sustainable practices and the implementation of solid waste management policies in civil construction (BRAZIL, 2010).

2.3 Characteristics and applications of PCR-PET

Post-Consumer Recycled Polyethylene Terephthalate (PCR-PET) is a material derived from the recycling of PET bottles, which possesses particular physical and mechanical characteristics, making it suitable for various applications in civil construction (SILVA *et al.,* 2016). PCR-PET is known for its properties such as lightness, tensile strength, flexibility, and resistance to degradation, which make it a versatile material that is easy to handle in civil works (TZANNIS *et al.,* 2009). Additionally, its light coloration can facilitate pigmentation, allowing for greater aesthetic diversity in the final products.

In civil construction, PCR-PET has been widely used as an aggregate in mortars and concretes, partially replacing natural aggregates such as sand and crushed stone. Studies have shown that the partial replacement of natural aggregates with PCR-PET can improve the mechanical properties of mortars, such as compressive strength, modulus of elasticity, and adhesion, in addition to contributing to a reduction in material density (SILVA *et al.,* 2016).

Beyond mortars, PCR-PETR can also be used in other construction products, such as concrete blocks, permeable pavements, thermal and acoustic insulators, and even decorative elements. The use of PCR-PET in civil construction not only promotes environmental sustainability by reducing the demand for natural resources and waste generation but also offers economic benefits, such as reduced costs for material acquisition and waste management (KARA; TOPCU, 2010).

However, it is important to emphasize that the use of PCR-PET in civil construction requires special care regarding its preparation, storage, and application to ensure the quality and durability of the produced materials. Therefore, continuous research and the development of recycling technologies and applications of PCR-PET in civil construction are essential to expanding its use in a sustainable and efficient manner.

2.4 Standards and guidelines for mortars

ISSN 2318-8472, v. 12, n. 85, 2024

ABNT (Brazilian Association of Technical Standards) is responsible for establishing standards that regulate various aspects of civil construction in Brazil, including specifications for mortars. The ABNT NBR 13281 standard is a technical document that defines the minimum requirements for laying and coating mortars, aiming to ensure their quality, performance, and durability (ABNT, 2018).

ABNT NBR 13281 establishes parameters for physical characteristics such as consistency, water retention, and workability, as well as mechanical characteristics such as compressive strength and adhesion. Additionally, the standard also defines chemical requirements, such as the content of organic compounds and alkalinity, that mortars must meet to be considered suitable for use in civil construction.

To ensure compliance with ABNT NBR 13281, mortar manufacturers must conduct laboratory tests in accordance with the test methods specified in the standard. These tests are crucial for evaluating the performance of mortars and confirming whether they meet the acceptance criteria established by the standard.

It is essential to emphasize that compliance with ABNT NBR 13281 not only ensures the quality of mortars but also establishes a standard of quality and safety for the materials used in civil construction. Adherence to this standard plays a fundamental role in preventing construction failures, ensuring the durability and efficiency of built structures, as well as promoting user confidence and the value of the project.

To guarantee the quality and safety of projects, it is essential that civil construction professionals are familiar with the applicable technical standards and ensure their correct application in daily construction activities. The constant updating of standards and guidelines is crucial for professionals to keep up with technological innovations and adopt the best practices in the industry.

3 MATERIALS AND METHODS

3.1 Description of the anhydrous materials used

Portland cement (binder) CP-II E 32, in a 50 kg bag, was purchased from a commercial store in the city of Cachoeiro de Itapemirim, ES. The material belongs to a single batch, which was sufficient to conduct all the tests, ensuring homogeneity in the composition of the mortars developed in the study.

Natural sand (natural aggregate) washed from a quartz river, extracted in Cachoeiro de Itapemirim, ES. The material was purchased from a construction material store in a quantity exceeding the needs of the tests, allowing the compositions developed in the research to be adequately maintained.

PET-PCR (artificial aggregate) recycled material from PET bottles. The composite material was obtained from two sources: the first, micronized PCR-PET, from the pilot recycling unit at UFES in Vitória, ES, and the second, PCR-PET sand, from an industry in the region of Campos dos Goytacazes, RJ. These materials were pre-mixed to ensure homogeneity in the tests.

ISSN 2318-8472, v. 12, n. 85, 2024

Potable water used in the preparation of the mortars is supplied by the utility company of the city of Campos dos Goytacazes, RJ.

3.2 Experimental procedures

3.2.1 Preparation of materials

The materials were prepared, separated, and stored according to the manufacturers' recommendations in a suitable laboratory, with controlled temperature and humidity, in accordance with ABNT (2016). The NBR 16541 (2016) standard specifies the "method for preparing the mortar mix in the laboratory, to be used in the necessary tests for material characterization."

3.2.2 Mortar dosage

Preliminary tests were conducted to determine the ideal proportions of each material in the mortar composition. A conventional mortar mix was established, with a volume ratio of approximately 1:6 (binder/aggregate) according to NBR-13753 (1996) and a water/cement ratio of 0.5 to achieve a “crumbly” consistency in the mixture.

Table 1 shows the volume proportions of the different mortars. AREF refers to the reference mortar without the addition of PCR-PET. AP10 indicates the mixture with a 10% replacement of sand with PCR-PET, AP20 with 20% replacement, AP30 with 30% replacement, and AP40 with 40% PET-PCR replacement of sand.

Table 1 – Volume proportion of the anhydrous components of the mortars.

Composite	Sand (%)	Cement (%)	PET (%)	Total (%)
AREF	85,7	14,3	-	100,00
AP10	77,1	14,3	8,6	100,00
AP20	68,6	14,3	17,1	100,00
AP30	60,0	14,3	25,7	100,00
AP40	51,4	14,3	34,3	100,00

Source: AUTHORS, 2024.

3.2.3 Preparation of the mortars:

The mortars were prepared in a mechanical mixer, following the established proportions and maintaining standardized control of humidity and temperature. The mixing was carried out until a homogeneous consistency was achieved, according to the procedures recommended by NBR 16541 (2016).

3.3 Tests conducted

3.3.1 Aggregate characterization tests:

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 85, 2024

Tests were conducted to characterize the physical properties, such as particle size distribution (NBR 7211, 2022) and morphology, of natural sand and PCR-PET.

3.3.2 Mortar classification tests:

Tests were conducted to classify the mortars based on at least six requirements specified in NBR 13281 (2005). These are: P - Compressive strength (MPa) NBR 13279 (2005); M - Apparent density of hardened mortar (kg/m³) NBR 13280 (2005); R - Flexural tensile strength (MPa) NBR 13279 (2005); C - Capillarity coefficient (g/dm².min1/2) NBR 15259 (2005); D - Density of fresh mortar (kg/m³) NBR 13278 (2005); U - Water retention (%) NBR 13277 (2005).

3.4 Analysis methodology

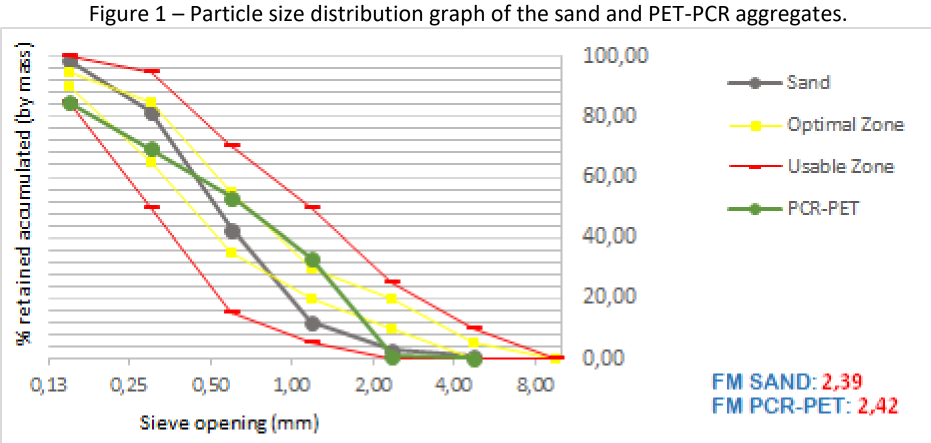
Results analysis: The test results were statistically analyzed to evaluate the influence of PCR-PET as an artificial aggregate on the properties of the mortars in relation to the proportion of sand, the natural aggregate, replaced. The statistical analysis of the samples was carried out according to the procedures established by NBR 13281 (2005).

4 RESULTS AND DISCUSSION

4.1 Results obtained from the particle size characterization tests of the mortars

Figure 1 illustrates the values of the average distribution results for the typical elements from the particle size distribution test of the natural (sand) and artificial (PCR-PET) aggregates.

Figure 1 – Particle size distribution graph of the sand and PET-PCR aggregates.



Source: AUTHORS, 2024.

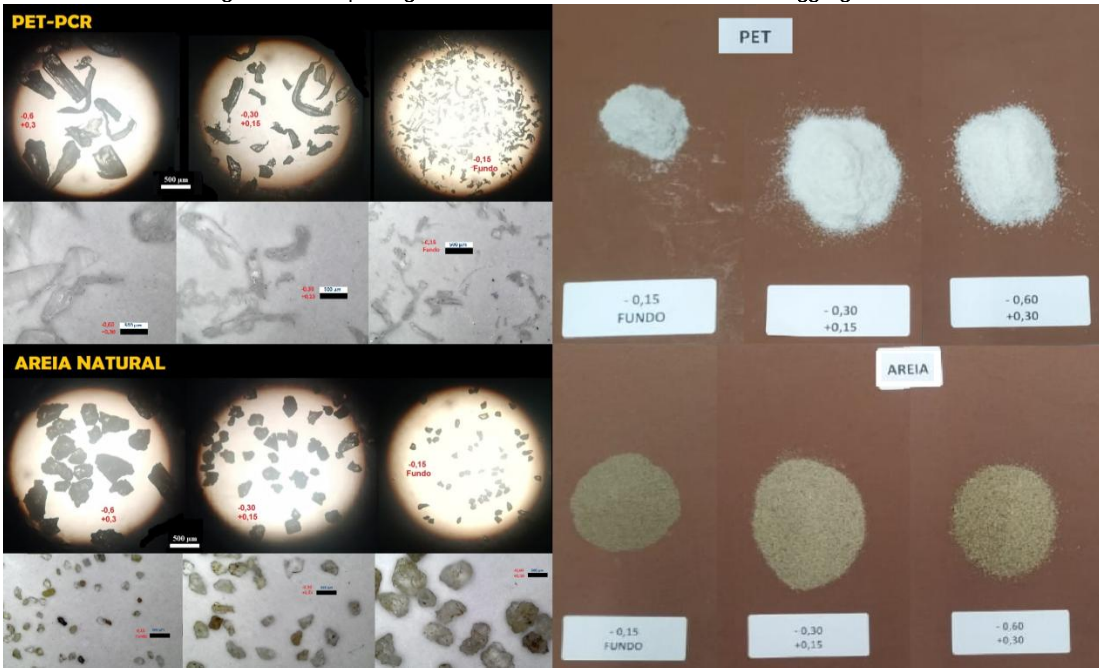
4.2 Results obtained from the tests for morphological characterization of mortars

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 85, 2024

Figure 2 presents a microscopic visualization of the typical particle samples in decreasing granulometric ranges of the natural (sand) and artificial (PCR-PET) aggregates used in the granulometry tests. These images were obtained using optical and digital microscopes.

Figure 2 – Morphological visualization of sand and PCR-PET aggregates.



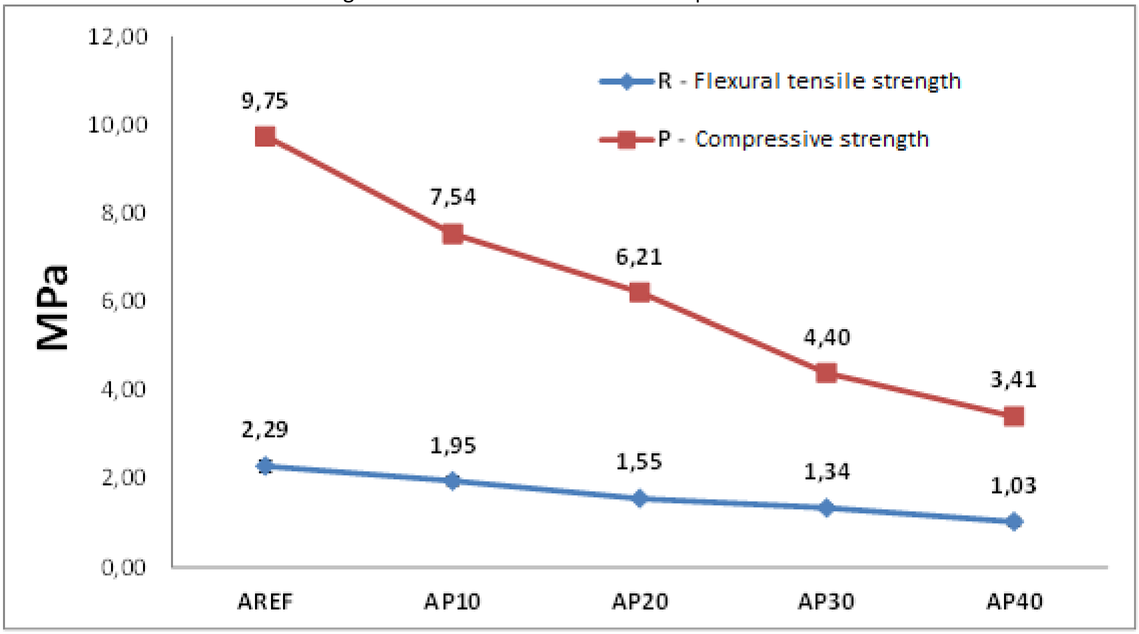
Source: AUTHORS, 2024.

4.3 Results obtained from the tests for mortar classification according to NBR 13281

Figure 3 illustrates graphs showing the average values and trend curves of the test results for the P (compressive strength) and R (flexural tensile strength) parameters in the mortars.

ISSN 2318-8472, v. 12, n. 85, 2024

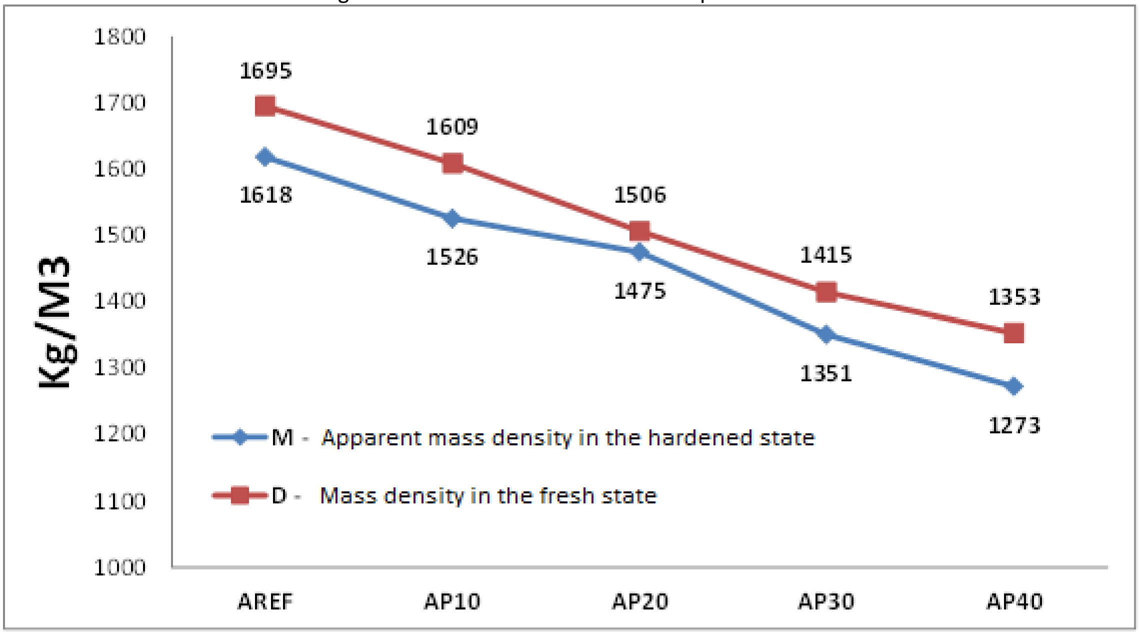
Figure 3 – Test results for the P and R parameters.



Source: AUTHORS, 2024.

Figure 4 illustrates graphs showing the average values and trend curves of the test results for the M (apparent mass density in the hardened state) and D (mass density in the fresh state) parameters in the mortars.

Figure 4 – Test results for the M and D parameters.



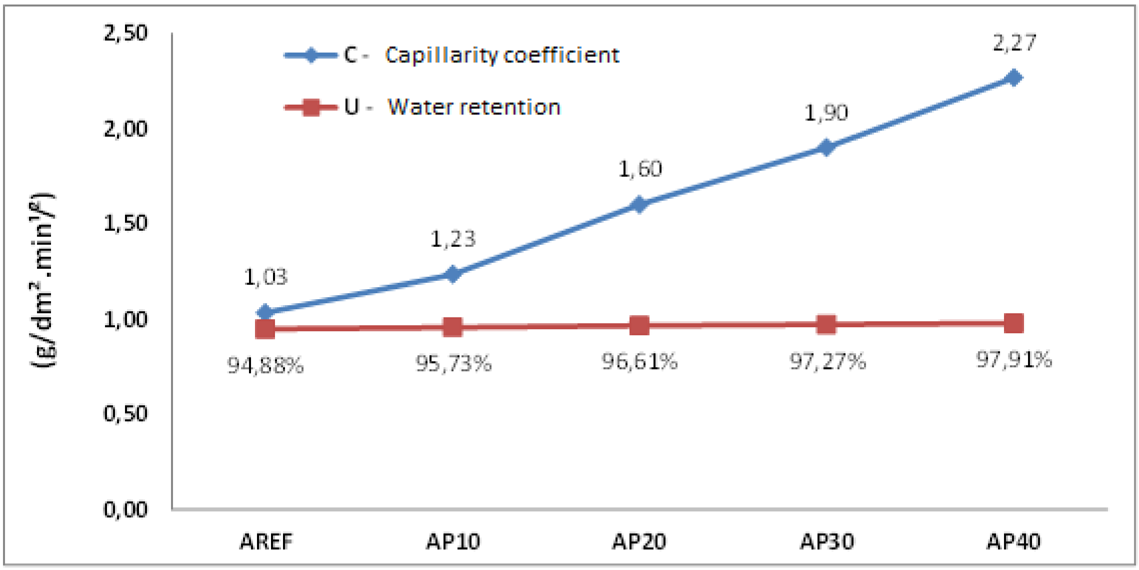
Source: AUTHORS, 2024.

Figure 5 illustrates graphs showing the average values and trend curves of the test results for the C (capillarity coefficient) and U (water retention) parameters in the mortars.

Figure 5 – Test results for the C and U parameters.

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 12, n. 85, 2024



Source: AUTHORS, 2024.

4.4 Data analysis and interpretation

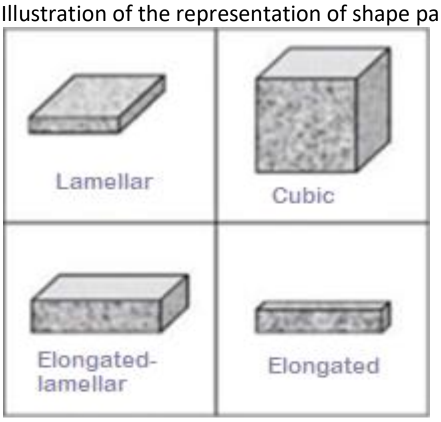
4.4.1 Granulometric characterization of mortars

The results presented in Figure 1 of the average distribution of aggregates indicate that the typical particle size (Fineness Modulus - FM) of the aggregates is within the optimal zone range (2.2 to 2.9) for applications according to the parameters defined by ABNT NBR 7211 (2022).

4.4.2 Morphological characterization of mortars

In Figure 6 by Farias; Palmeira (2010), an illustration of the representation of the parameters for defining the morphology of the aggregates is presented.

Figure 6 – Illustration of the representation of shape parameters.



Source: Adapted FARIAS; PALMEIRA, 2010.

By contrasting this illustration in Figure 6 with the elements observed in Figure 2, it is noted that the typical grains of the natural aggregate (sand) have a characteristic volumetric

ISSN 2318-8472, v. 12, n. 85, 2024

specific area with predominantly cubic shapes. On the other hand, the elements of the artificial aggregate (PET-PCR) exhibit an elongated-lamellar morphology.

4.4.3 Classification of mortars according to the requirements of NBR 13281

The results of the tests for mortar classification indicate an almost linear trend in values as the proportion of PET-PCR in the mixture increases. This trend is easily observed in all six parameters analyzed. Frame 1 presents the parameter values for mortar classification requirements according to NBR 13281 (2005).

Frame 1 – Parameters for mortar classification requirements.

Class	P	M	R	C	D	U
1	≤ 2,0	≤ 1200	≤ 1,5	≤ 1,5	≤ 1400	≤ 78
2	1,5 a 3,0	1000 a 1400	1,0 a 2,0	1,0 a 2,05	1200 a 1600	72 a 85
3	2,5 a 4,5	1200 a 1600	1,5 a 2,7	2,0 a 4,0	1400 a 1800	80 a 90
4	4,0 a 6,5	1400 a 1800	2,0 a 3,5	3,0 a 7,0	1600 a 2000	86 a 94
5	5,5 a 9,0	1600 a 2000	2,7 a 4,5	5,0 a 12	1800 a 2200	91 a 97
6	> 8,0	> 1800	> 3,5	> 10	> 2000	95 a 100

Source: Adapted ABNT NBR 13281, 2005.

After analyzing the data in Figures 3, 4, and 5 according to the parameters in Frame 1, it is possible to visualize in Frame 2 the classification information for the compositions of the studied mortars.

Frame 2 – Classification of mortars according to NBR 13281.

CLASS	P	M	C	R	D	U
AREF	6	5	1	4	4	5
AP10	5	4	1	3	4	5
AP20	5	4	2	3	3	5
AP30	4	3	2	2	3	6
AP40	3	3	3	2	2	6

Source: AUTHORS, 2024.

4.5 Discussion on the implications of the characterization and classification results

4.5.1 Implications of granulometry

In Figure 1, the data shows the graphical distribution of the granulometry of the aggregates. It is observed that the range explored in this study indicates that the aggregates are predominantly centered within the optimal zone, corresponding to a granulometric distribution typically recognized in the literature as medium sand size for both natural and artificial aggregates.

This distribution is considered suitable for the work, as it reflects a substitution with similar packing, favoring proper maintenance in the compaction of the composite mixture.

4.5.2 Implications of morphology

ISSN 2318-8472, v. 12, n. 85, 2024

According to Mehta; Monteiro (2014), grains with lamellar and elongated morphology, due to their larger specific volumetric area compared to spherical particles, result in irregular filling of the mortar. On the other hand, due to their shape and surface texture, these grains exhibit greater adhesion to the mortar, resulting in stronger elements when the mix ratio is maintained, compared to other shapes.

Analyzing the work of Falcão Bauer (2013), it is noted that increasing the percentage of elongated and lamellar elements results in a relative loss of workability, while maintaining the mix ratio. Conversely, mortars produced with rounded aggregates exhibit greater workability.

Another aspect described by Mehta; Monteiro (2014) is that elongated and lamellar particles should constitute a maximum of 15% by mass of the concrete. Therefore, higher proportions of these aggregates should be avoided relative to the total aggregate for artificial sands.

4.5.3 Implications of the classification requirements of NBR 13281

When comparing the mortar results for the control parameter P (compressive strength), it was found that all comply with the ABNT NBR 13281 standard. However, a reduction in compressive strength class is observed as the proportion of artificial aggregate in the mix increases. The reference mortar is classified as class 6, while the mortar with 40% PCR-PET replacement is in class 3, representing a variation of three classes in this parameter.

Regarding the results for the control parameter R (flexural tensile strength), all results also comply with the ABNT NBR 13281 standard. A reduction in strength class is observed as the proportion of artificial aggregate increases. The reference mortar is classified as class 4, while the mortar with 40% PCR-PET replacement is in class 2, showing a variation of two classes in this parameter.

For the control parameter M (apparent mass density in the hardened state), a reduction of two classes was observed. The reference mortar (AREF) is classified as class 5, while the mortar with the highest proportion of PET-PCR in the composition (AP40) is classified as class 3.

Regarding the control parameter M (apparent mass density in the hardened state), a reduction of two classes was also observed. The reference mortar (AREF) is classified as the highest class (5), while the mortar with the highest proportion of PCR-PET in the composition (AP40) is classified as the lowest class (3).

In the control parameter C (capillarity coefficient), an inversion in classification was observed compared to the previous requirements, with a tendency for an increase of two classes. In this scenario, the reference mortar (AREF) is classified in the lowest class (1), while the mortar with the highest proportion of PCR-PET in the composition (AP40) reaches the highest class (3).

Finally, for the last control parameter analyzed in this study, U (water retention), the classification remained constant for mortars AREF, AP10, and AP20, while there was an increase in classification for the AP30 and AP40 compositions. This variation resulted in an increase of only one class, as AP30 and AP40 reached the maximum class.

It is important to note that for all mortar compositions in this study, none deviated from the classification criteria for application according to the ABNT NBR 13281 standard.

ISSN 2318-8472, v. 12, n. 85, 2024

5 CONCLUSIONS

5.1 Main conclusions of the study

The reduction in compressive strength and flexural tensile strength of mortars with the incorporation of PCR-PET can be attributed to the lower stiffness of PCR-PET compared to natural aggregates.

On the other hand, the reduction in apparent mass densities in both the hardened and fresh states indicates a significant improvement. It is possible to identify a trend toward the development of increasingly lighter mortars, which provides benefits to the structures of built environments, making them less heavy.

In the analysis of the capillarity coefficient, the results show a significant increase in this parameter, suggesting that the reduction in the strength and density of mortars with higher incorporation of PCR-PET is due to the increase in the number of pores. Regarding water retention, there was a slight reduction, influenced by the water-repellent characteristic of PCR-PET.

It is noted that the use of PCR-PET as an alternative aggregate in mortars brings environmental benefits, contributing to the reduction of demand for natural resources and minimizing waste generation. Thus, even with variations in the mechanical properties of mortars with the addition of PCR-PET, its incorporation can be seen as a viable and sustainable alternative in civil construction.

Since the compositions meet normative requirements, their use becomes desirable, considering cost assessment as a deciding factor.

5.2 Contributions to the built environment and sustainability

This study is of great importance to the field of built environments and sustainability for several reasons. Firstly, it stands out by evaluating the potential application of PCR-PET as an aggregate in mortars. This approach represents a significant innovation, providing a sustainable and effective alternative for the use of plastic waste in construction, thereby contributing to the reduction of the environmental impact generated by these materials.

The study goes further by demonstrating that it is possible to maintain the essential properties of mortars by incorporating PCR-PET, keeping compressive and flexural tensile strengths within established normative standards. These parameters are crucial for ensuring the quality and durability of built structures. This finding not only validates the technical feasibility of using PCR-PET in mortars but also represents a significant advancement by paving the way for the adoption of more sustainable and responsible practices in construction.

Another relevant point is that the incorporation of PCR-PET can not only benefit the environment but also bring economic advantages, considering the potential reduction in costs related to the acquisition of traditional materials. This may further encourage the construction industry to adopt this alternative, promoting a gradual transition to more ecological and conscious construction methods.

ISSN 2318-8472, v. 12, n. 85, 2024

Finally, by emphasizing the importance of sustainability in construction and providing concrete data and analyses on the performance of mortars with PCR-PET, this study contributes significantly to the dissemination of knowledge and the awareness of professionals about the importance of adopting sustainable practices in the sector.

5.3 Study limitations and suggestions for future research

Some limitations were identified during the study, such as: the lack of more in-depth studies on the long-term durability behavior of mortars with PCR-PET; the need for further investigation into the complete environmental impact of the production and disposal of PCR-PET in mortars; the production costs of PCR-PET.

Based on the identified limitations, the following are suggested for future research: conduct durability studies of mortars with PCR-PET under different environmental conditions and over time; evaluate the complete life cycle of mortars with PCR-PET, from production to final disposal, to determine their environmental impact; investigate new technologies and processing methods for PCR-PET that may optimize its properties and applicability in mortars; conduct a cost feasibility assessment.

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