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Sustainable and Smart Construction: Analysis of Mortars with PCR-PET Incorporation through Impact Acoustic Spectroscopy

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Sustainable and Smart Construction: Analysis of Mortars with PCR-PET Incorporation through Impact Acoustic Spectroscopy

ABSTRACT

Objective – To evaluate the performance of mortars with partial replacement of natural aggregate by post-consumer recycled polyethylene terephthalate (PET-PCR), using the Impact Acoustic Spectroscopy (IAS) technique, focusing on sustainability and technological innovation in the construction sector.

Methodology – Mortar samples were prepared with different proportions of PET-PCR (10%, 20%, 30%, and 40%) replacing the natural aggregate. The samples underwent mechanical characterization (compressive and tensile strength) and acoustic analysis using the Impact Acoustic Spectroscopy (IAS) technique to assess behavior under impact.

Originality/Relevance – The study addresses a gap in the literature by investigating the use of recycled PET in mortars through an innovative acoustic evaluation approach. It stands out for combining sustainability with technical performance, proposing the use of plastic waste as a viable alternative to conventional construction materials.

Results – The results showed that increasing the PET-PCR content led to a reduction in mechanical strengths but significantly improved the acoustic performance of the mortars, particularly in impact sound insulation, indicating their potential for use in acoustic insulation applications.

Theoretical/Methodological Contributions – The research demonstrates the effectiveness of Impact Acoustic Spectroscopy (IAS) as an innovative tool to evaluate the properties of cementitious materials with recycled additives. It also provides an original integration of mechanical and acoustic analyses in a single study.

Social and Environmental Contributions – Replacing natural aggregates with PET-PCR helps reduce plastic waste and lessens the extraction of natural resources. The study offers a more sustainable alternative for the construction sector, with positive impacts on promoting circular economy practices and enhancing urban resilience.

KEYWORDS: Acoustic. PCR-PET. IAS.

Construção Sustentável e Inteligente: Análise de Argamassas com Incorporação de PET-PCR por Espectroscopia Acústica de Impacto

RESUMO

Objetivo - Avaliar o desempenho de argamassas com substituição parcial do agregado natural por polietileno tereftalato pós-consumo reciclado (PET-PCR), por meio da técnica de Espectroscopia Acústica de Impacto (EAI), com foco na sustentabilidade e inovação tecnológica na construção civil.

Metodologia - Foram preparadas amostras de argamassas com diferentes proporções de PET-PCR (10%, 20%, 30% e 40%) em substituição ao agregado natural. As amostras foram submetidas à caracterização mecânica (resistência à compressão e tração) e acústica, utilizando a técnica de Espectroscopia Acústica de Impacto (EAI) para análise do comportamento sob impacto.

Originalidade/relevância - O estudo preenche uma lacuna na literatura ao investigar o uso de PET reciclado em argamassas por meio de uma abordagem inovadora de avaliação acústica. A pesquisa se destaca por unir sustentabilidade e desempenho técnico, propondo o uso de resíduos plásticos como alternativa viável para materiais convencionais na construção civil.

Resultados - Os resultados mostraram que o aumento da proporção de PET-PCR reduziu as resistências mecânicas das argamassas, mas proporcionou melhoria significativa no desempenho acústico, especialmente na absorção de impacto, indicando seu potencial para aplicações em isolamento acústico.

Contribuições teóricas/metodológicas - A pesquisa demonstra a eficácia da Espectroscopia Acústica de Impacto (EAI) como ferramenta inovadora para avaliar propriedades de materiais cimentícios com adição de resíduos reciclados, além de integrar de forma inédita as análises mecânicas e acústicas em um mesmo estudo.

Contribuições sociais e ambientais - A substituição de agregados naturais por PET-PCR contribui para a redução de resíduos plásticos e minimiza a extração de recursos naturais. A proposta apresenta uma alternativa mais

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

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sustentável para a construção civil, com potencial impacto positivo na promoção da economia circular e na resiliência urbana.

PALAVRAS-CHAVE: Acústica. PET-PCR. EAI.

Construcción Sostenible e Inteligente: Análisis de Morteros con Incorporación de PET-RPC mediante Espectroscopía Acústica de Impacto

RESUMEN

Objetivo – Evaluar el desempeño de morteros con sustitución parcial del agregado natural por polietileno tereftalato reciclado pos-consumo (PET-RPC), mediante la técnica de Espectroscopía Acústica de Impacto (EAI), con enfoque en sostenibilidad e innovación tecnológica en la construcción.

Metodología – Se prepararon muestras de morteros con diferentes proporciones de PET-RPC (10%, 20%, 30% y 40%) en sustitución del agregado natural. Las muestras fueron sometidas a caracterización mecánica (resistencia a compresión y tracción) y acústica, utilizando la técnica EAI para analizar su comportamiento bajo impacto.

Originalidad/relevancia – El estudio aborda un vacío en la literatura al investigar el uso de PET reciclado en morteros mediante una innovadora evaluación acústica. Destaca por integrar sostenibilidad y desempeño técnico, proponiendo residuos plásticos como alternativa viable a materiales convencionales en construcción.

Resultados – Los resultados mostraron que: El aumento de PET-RPC redujo las resistencias mecánicas, pero mejoró significativamente el desempeño acústico (especialmente en absorción de impactos), evidenciando su potencial para aplicaciones de aislamiento acústico.

Contribuciones teóricas/metodológicas – Demuestra la eficacia de la EAI como herramienta innovadora para evaluar propiedades de materiales cementicios con residuos reciclados. Integra por primera vez análisis mecánicos y acústicos en un mismo estudio.

Contribuciones socioambientales – Reduce residuos plásticos y disminuye la extracción de recursos naturales. Ofrece una alternativa sostenible para la construcción, promoviendo economía circular y resiliencia urbana.

PALABRAS CLAVE: Acústica, PET-RPC, EAI.

GRAFIC ABSTRACT

ISSN 2318-8472, v. 13, n. 89, 2025

1 INTRODUCTION

The construction industry is one of the main consumers of natural resources and one of the largest generators of solid waste. The search for sustainable alternatives to mitigate the environmental impact of this sector has intensified in recent decades, as highlighted by Wahrlich *et al.* (2020) and Caldas *et al.* (2020).

Among these alternatives, the use of plastic waste as a partial substitute for natural aggregates in construction materials, such as mortars and concretes, stands out (Silva *et al.*, 2014). The environmental issues associated with the improper disposal of plastic waste, such as polyethylene terephthalate (PET), and the growing demand for sustainable solutions in civil construction are highly relevant topics for new research.

PET polymers have been widely studied due to their abundance as urban solid waste and their physical properties, which are suitable for incorporation into cementitious materials (Frigione, 2010). The use of post-consumer recycled PET (PCR-PET) as a partial aggregate in mortars can not only reduce the amount of plastic waste in landfills but also minimize the extraction of natural aggregates, promoting sustainability in construction (Erdem and Arıoğlu, 2017).

Impact-based acoustic testing has proven to be an effective tool for assessing the mechanical and structural properties of cementitious materials. This type of non-destructive technique enables a detailed analysis of the material's acoustic characteristics, providing valuable data on its integrity and performance (Rehman *et al.,* 2016).

In this context, the present study aims to analyze the performance of mortars with partial replacement of natural aggregate by PCR-PET using the Impact Acoustic Spectroscopy technique. In line with Brandão *et al.* (2024), this study seeks to understand the effects of this replacement on the mechanical and acoustic properties of mortars, contributing to the sustainable use of plastic waste in civil construction.

2 LITERATURE REVIEW

2.1 Use of Plastic Waste in Construction Materials

The growing environmental issue caused by the improper disposal of plastic waste has motivated research on its reuse in civil construction. Among these wastes, polyethylene terephthalate (PET) stands out due to its abundance and favorable physical properties.

Frigione (2010) investigated the recycling of PET bottles as fine aggregate in concrete, noting that the incorporation of recycled PET can enhance certain mechanical properties of the material while contributing to environmental sustainability. Studies such as Silva *et al.* (2014) explored the use of recycled aggregates from construction and demolition waste in composite materials, including the replacement of natural aggregates with recycled plastics. In Matos *et al.* (2018), a study was conducted on the production of concrete with partial replacement of fine aggregate by PET waste as an alternative to the improper disposal of residues generated by PET resin.

The reviewed studies demonstrate that the incorporation of PET can meet durability

ISSN 2318-8472, v. 13, n. 89, 2025

and strength requirements of concrete, presenting itself as a viable and sustainable alternative to conventional aggregates.

2.2 Properties of Mortars with PCR-PET

Mortars are widely used materials in civil construction, making it essential to assess how the partial replacement of natural aggregates with PCR-PET affects their properties. The partial substitution of natural aggregates with PET in mortars can result in materials with lower density and, in some cases, improved impact resistance and energy absorption.

Studies conducted by Erdem and Arıoğlu (2017) analyzed the environmental performance of gypsum reinforced with recycled PET fibers, finding that the use of plastic waste can reduce the carbon footprint of the final material. These findings suggest that incorporating PCR-PET into mortars can not only offer mechanical benefits but also contribute to the sustainability of the construction sector.

2.3 Impact Acoustic Spectroscopy Technique

Impact Acoustic Spectroscopy (IAS) is a non-destructive technique widely used to evaluate the internal properties of cementitious materials. Binda *et al.* (2001) highlighted the effectiveness of such testing in detecting flaws and analyzing the acoustic characteristics of masonry structures. The application of this technique to mortars containing PCR-PET can provide valuable insights into the structural integrity and mechanical behavior of the material.

Furthermore, similar research by Dimitrius *et al.* (2009) demonstrated that Acoustic Emission (AE) techniques are widely used for real-time damage detection in concrete. AE can be employed to monitor the progression of damage and the degradation of cementitious materials over time, allowing for a more accurate assessment of the durability and service life of structures built with alternative materials such as mortars with PCR-PET.

3 METHODOLOGY

The methodology of this study was designed to evaluate the performance of mortars with partial replacement of natural aggregates by post-consumer recycled PET, with an emphasis on the analysis of acoustic and mechanical properties. The methodological framework includes the materials used and the stages of sample preparation, molding, curing, and analysis. The Impact Acoustic Spectroscopy technique was employed as the approach to characterize the acoustic properties analyzed in the study.

3.1 Materials

The materials used for the preparation of the mortars were:

Portland cement (binder) type CP-II E 32, in 50 kg bags, was purchased from a commercial store in the city of Cachoeiro de Itapemirim, ES, Brazil. The material came from a

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

ISSN 2318-8472, v. 13, n. 89, 2025

single batch, which was sufficient for all tests, ensuring the homogeneity of the mortars developed in the study.

Natural medium-grain sand (natural aggregate), washed, dried, and sieved according to NBR 7211. This quartz-based material was sourced from a river and extracted in Cachoeiro de Itapemirim, ES. The amount acquired exceeded the required quantity for the tests, allowing for the consistent maintenance of the mortar compositions throughout the research.

PCR-PET (artificial aggregate) is a recycled material from PET bottles of different morphologies and colors, obtained from two sources: the first, referred to as micronized PCR-PET, was produced by the pilot recycling plant at UFES, in Vitória, ES; the second, called PCR-PET sand, came from an industrial facility located in the region of Campos dos Goytacazes, RJ. These materials were pre-mixed and sieved to ensure homogeneity in testing and to maintain medium particle size distribution for the replacement of the natural aggregate.

Potable and impurity-free water used in the preparation of the mortars was supplied by the water utility company Águas do Paraíba in the city of Campos dos Goytacazes, RJ.

3.2 Methods

Two series of mortar samples were prepared, each with three prismatic specimens and a curing age of 28 days (ABNT, 2005).

Control/Reference Series (CS): Mortars with 100% of the aggregate portion composed of natural material.

Experimental Series (ES): Mortars with varying mix compositions, specifically: 10%, 20%, 30%, and 40% partial volume replacement of the natural aggregate with artificial PCR-PET aggregate.

Table 1: Volumetric proportion of the anhydrous components of the mortars.

Samples	Cement (%)	Sand (%)	PCR-PET (%)
Control (CS)	14,3	85,7	0,0
10% PCR-PET (ES1)	14,3	77,1	8,6
20% PCR-PET (ES2)	14,3	68,6	17,1
30% PCR-PET (ES3)	14,3	60,0	25,7
40% PCR-PET (ES4)	14,3	51,4	34,3

Source: Autors (2024).

The proportions of cement, aggregates, and water: The mix ratios were kept constant for all samples, following a volumetric proportion of 1:6 (binder:aggregates). Mortar preparation followed these steps:

Mixing of materials (cement, sand, PCR-PET, and water): A mechanical mixer was used, following the established proportions and maintaining standardized control of humidity and temperature in the laboratory. The mixture was performed with the gradual addition of water and continuous mixing until a homogeneous consistency was achieved, in accordance with the procedures described in NBR 16541 (ABNT, 2016).

Molding and curing of samples: Prismatic molds measuring 4×4×16 cm were used, as recommended by NBR 13279 (ABNT, 2005), with three samples produced for each mixture

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

ISSN 2318-8472, v. 13, n. 89, 2025

developed in the study. After molding, the specimens were subjected to a curing process in a controlled laboratory environment at an air temperature of (23 ± 2)ºC and relative humidity of (60 ± 5)% for a period of 28 days, as specified in NBR 13279 (ABNT, 2005).

Impact Acoustic Spectroscopy (IAS) tests: The tests were performed on specimens at 28 days of age (±8 hours tolerance). The samples were subjected to IAS to evaluate their mechanical and structural properties. The testing procedure included:

Sample preparation: The sample surfaces were cleaned with an absorbent cloth to remove potential impurities and surface moisture.

Equipment setup: The IAS equipment was calibrated, and the impact and acoustic reception sensors were attached to the samples according to the technical specifications required for the tests.

Testing procedure: A steel sphere attached to a pendulum, released from a standardized height, was used to generate impact on the samples. The resulting acoustic signals were captured by piezoelectric sensors and analyzed using the specialized software provided with the equipment.

Analysis of IAS data was used to determine the following mortar properties: Sound wave propagation velocity, weighted peak sound intensity and characteristic resonance frequency (fundamental longitudinal mode).

Comparison with Control Samples: The results from mortars containing PCR-PET were compared with those of the control samples (100% natural aggregate) to assess the impact of aggregate substitution on the mechanical and acoustic properties of the mortars. Statistical analysis, including significance tests (ANOVA), was conducted to determine the relevance of the observed differences.

In addition to the non-destructive acoustic and density tests, the samples were later subjected to final destructive testing to determine compressive and tensile strength. These complementary tests made it possible to establish correlations with the acoustic analysis data, providing a broader understanding of the materials' behavior.

Figure 1 shows the execution of the acoustic and mechanical tests conducted in the study, highlighting the samples being subjected to the appropriate equipment for the tests.

Figure 1: Specimens subjected to acoustic and mechanical tests.

Source: Autors (2024).

4 RESULTS AND DISCUSSION

ISSN 2318-8472, v. 13, n. 89, 2025

4.1 Results

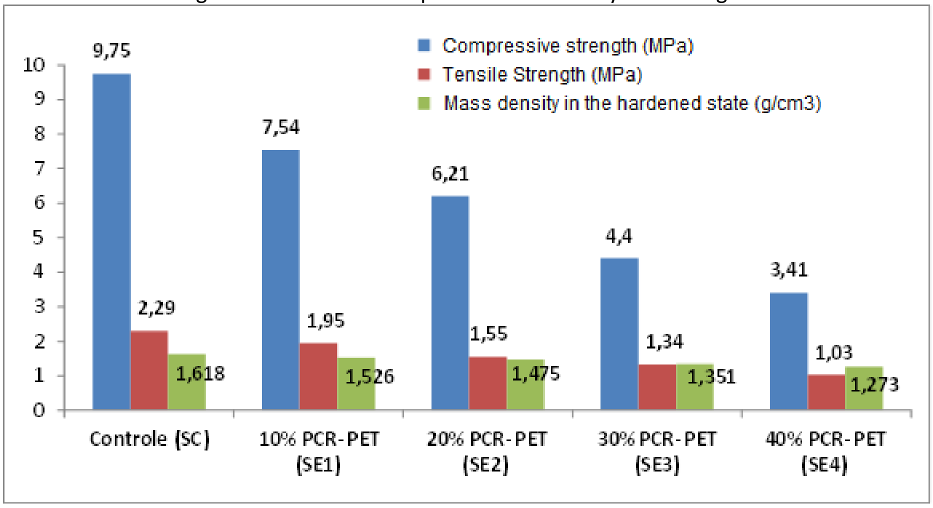
This section presents the results observed in the research for the mechanical and acoustic tests.

4.1.1 Mechanical Properties Tests

The measurements of density and the compressive strength tests conducted on the mortar samples with different percentages of PCR-PET revealed significant variations in mechanical properties compared to the control samples (SC).

Figure 2 shows the average values of apparent density in the hardened state, compressive strength, and tensile strength of the samples after 28 days of curing for the different mortar compositions.

Figure 2: Mechanical Properties: Bulk density and strengths



Source: Autors (2024).

The results indicate that compressive strength, tensile strength, and bulk density decrease as the percentage of PCR-PET in the composition increases. This behavior can be attributed to the lower density and stiffness of PET compared to natural aggregates.

4.1.2 Acoustic Properties Tests

The Impact Acoustic Spectroscopy (IAS) technique was used to evaluate the acoustic properties of the mortars developed in the research. The acoustic analysis of materials used in building environments is increasingly relevant to the construction industry. Non-destructive testing is a promising tool in the dynamic nature of construction projects, as it allows for the acquisition of integrated and comprehensive information about the structure and the elements that compose the built environment.

When it comes to stiffness and damping, it is necessary to repeat and compare tests over time in order to obtain responses related to durability and relevant structural conditions. Thus, acoustic analysis is an innovative non-destructive testing methodology aimed at determining several characteristics of cementitious materials. These parameters, when correlated with the mechanical strength properties of mortars, serve as a guideline for the design of important construction elements.

ISSN 2318-8472, v. 13, n. 89, 2025

Table 2 presents the average values obtained in the tests for the properties of sound wave propagation velocity, weighted peak sound intensity, and characteristic resonance frequency (longitudinal fundamental) for the different mortar compositions studied.

Table 2: Acoustic Properties: Wave propagation velocity, peak intensity, and characteristic frequency

Sample	Wave propagation velocity (m/s)	Peak intensity (dB)	Characteristic frequency (Hz)
Controle (CS)	2532	87,17	7914
10% PCR-PET (ES1)	2460	86,49	7688
20% PCR-PET (ES2)	2181	85,43	6816
30% PCR-PET (ES3)	1793	85,16	5604
40% PCR-PET (ES4)	1556	84,38	4864

Source: Autors (2024).

The results indicate that the velocity of acoustic wave propagation decreases with the increase in PCR-PET content, which is indicative of a reduction in the material's stiffness due to increased porosity. Additionally, the recorded weighted peak sound intensity also showed a decrease, suggesting a greater energy absorption capacity of the PCR-PET mortars when subjected to impact.

The characteristic resonance frequency, which is related to the structural integrity of the material, also decreased with the increased replacement of natural aggregate by the artificial PCR-PET aggregate. This parameter tends to indicate the presence of internal heterogeneities in the interconnection morphology between the materials.

These findings are consistent with the existing literature. Since Binda *et al.* (2001), who highlighted the effectiveness of detecting internal flaws and analyzing the acoustic characteristics of cementitious materials to be repaired, to Zhu *et al.* (2016), who confirmed that Impact Acoustic Spectroscopy (IAS) is a reliable technique for monitoring the evolution of damage and degradation of materials over time. Furthermore, in Houcine *et al.* (2023), it is evident that ultrasonic velocities decrease with the increase in the percentage of natural sand replaced by PET in concrete.

Together with these studies, there is substantial evidence that the higher the PET content in the mixture, the slower the propagation of sound waves, the greater the energy absorption, and the lower the resonance frequency when subjected to impact energy.

4.2 Discussion

This study investigated the performance of mortars with partial replacement of natural aggregate by PCR-PET, using the traditional technique for evaluating mechanical properties and Impact Acoustic Spectroscopy (IAS) to assess their acoustic properties. A summary of the main findings and research implications is highlighted below.

4.2.1 Mechanical Properties

The three parameters studied showed reduced values as the percentage of PCR-PET in the mix increased.

As the bulk density in the hardened state decreased, a downward trend was observed in relation to the increase in PCR-PET content compared to sand. This reduction in density leads to lighter mortars, which can contribute to reduced structural weight in built

ISSN 2318-8472, v. 13, n. 89, 2025

environments, offering benefits such as load minimization. The results showed density reductions of 6%, 9%, 17%, and 21% for the samples with 10%, 20%, 30%, and 40% replacement, respectively.

For the compressive strength parameter, the samples with 10%, 20%, 30%, and 40% replacement exhibited reductions of 22%, 36%, 54%, and 65%, respectively, when compared to the control sample (SC).

Regarding the tensile strength of the mortars, reductions were also observed, with 10%, 20%, 30%, and 40% replacement levels resulting in strength losses of 15%, 33%, 42%, and 55%, respectively, in comparison to the control sample.

These reductions in strength properties can be attributed to the lower density and stiffness of PET compared to natural aggregates, as well as the irregular and non-uniform morphology of the interconnection between the mixture components, which negatively affects the stress distribution and internal cohesion of the material.

4.2.2 Acoustic Properties

The three acoustic properties studied in the research showed similar behavior, with reductions in their values as the amount of artificial PCR-PET aggregate increased in replacement of natural sand. It was observed that the speed of acoustic wave propagation, the weighted sound intensity, and the characteristic resonance frequency all decreased as the PCR-PET content increased in the mortar compositions.

The acoustic wave propagation speeds ranged from 2532 m/s for the reference mortar to 1556 m/s for the composition with the highest PET content, indicating a reduction of 36%. The weighted sound intensity peak also decreased, from 87.17 dB to 84.38 dB. The characteristic resonance frequency dropped from 7914 Hz to 4864 Hz.

In all cases, this reduction occurred when comparing the reference composition with those containing higher proportions of PET, as shown in Table 2. These decreasing values indicate a reduction in material stiffness and the presence of internal heterogeneities in the bonding morphology. These findings suggest that such compositions have a greater capacity to absorb energy when subjected to impact.

4.2.3 Specific Applications

Despite the reduction in compressive strength, mortars with PCR-PET proved to be suitable for applications that do not require high mechanical strength but can benefit from improved acoustic properties, such as acoustic control in built environments.

From an environmental sustainability perspective, it is worth highlighting that the incorporation of PCR-PET into mortars represents an effective strategy to reduce the environmental impact of the construction sector, promoting the reuse of plastic waste and reducing the need for extraction of natural resources. This approach contributes to the circular economy and helps mitigate the issue of improper plastic disposal.

5 CONCLUSIONS AND FUTURE RESEARCH

5.1 Conclusions

The partial replacement of natural aggregates with PCR-PET in mortars presents both

ISSN 2318-8472, v. 13, n. 89, 2025

advantages and disadvantages. The reduction in compressive strength with increasing amounts of PCR-PET can be seen as a limitation, especially for applications requiring high mechanical strength.

However, the lower density observed in the compositions with partial replacement of natural aggregate (sand) by artificial aggregate (PCR-PET) improves the energy dissipation capacity of the mortars, which may be advantageous for specific applications, such as reducing the weight of structures and use in structural materials, infill, and architectural elements for acoustic treatment and environmental noise control.

Additionally, incorporating PCR-PET into mortars contributes to environmental sustainability by reducing the amount of plastic waste sent to landfills and decreasing the extraction of raw materials from natural resources. Erdem and Arıoğlu (2017) notably highlight the importance of such approaches for reducing the carbon footprint and promoting the circular economy in the construction industry.

Therefore, the results of this study suggest that although the partial replacement of natural aggregates with PCR-PET may compromise some mechanical properties—as seen in the mechanical strength of the mortars—it offers significant environmental benefits and may be advantageous for specific applications with considerable acoustic advantages for controlling built environments.

The Impact Acoustic Spectroscopy technique proved effective in evaluating acoustic properties, providing a valuable tool for analyzing advanced cementitious materials that incorporate recycled elements into their mixture compositions.

These findings complement previous studies, such as those by Frigione (2010) and Silva *et al.* (2014), who also observed a reduction in mechanical strength with the incorporation of PET in cementitious materials.

Furthermore, Houcine *et al.* (2023), when evaluating the acoustic properties of concrete based on the percentage of incorporated PET, detected a decrease in both densities and average compressive strength as the PET replacement relative to natural aggregates increased.

There is evidence in the literature that materials with higher porosity in their structure show improvements in sound absorption, especially concerning impact noise. In this study, the increase in PCR-PET content in the mortar compositions once again demonstrated this trend, corroborating similar findings such as those by Führ *et al.* (2021).

These results highlight improvements in the acoustic performance of mortar systems subjected to impacts, reinforcing the positive contribution of PCR-PET to sound absorption in porous materials.

5.2 Future research

This study contributes to advancing knowledge on the use of plastic waste in civil construction by providing a detailed analysis of the properties of mortars with partial replacement of natural aggregates by PCR-PET.

The results highlight both the challenges and opportunities associated with this approach, offering a foundation for future research and practical applications aimed at

ISSN 2318-8472, v. 13, n. 89, 2025

sustainability and innovation in the construction sector.

Variations in PCR-PET Proportion: Investigate other replacement ratios of natural aggregates with PCR-PET to find an optimal balance between mechanical performance, acoustic behavior, and environmental benefits.

Long-Term Evaluation: Conduct long-term durability studies to assess the behavior of mortars with PCR-PET under varied environmental conditions.

Analysis of Other Plastic Wastes: Explore the use of other types of recycled plastic waste in mortars and concretes, comparing their properties with those of PCR-PET.

Development of New Evaluation Techniques: Continue developing and applying non-destructive techniques, such as Impact Acoustic Spectroscopy (IAS), to enhance the analysis and characterization of recycled cementitious materials.

In addition to the points mentioned above, it can be concluded that a good practice to mitigate the environmental impacts caused by PCR-PET waste is the recycling of this material, incorporating it into mortars and other cement-based products in construction. This leads to the development of new composites with improved properties, highlighting the importance of ongoing efforts in materials development research.

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Nós, **Raul de Souza Brandão, Gustavo dos Santos de Oliveira, Ramon Fernandes de Abreu, José Augusto Pedro Lima, Jonas Alexandre**, declaramos que o manuscrito intitulado "**Construção Sustentável e Inteligente: Análise de Argamassas com Incorporação de PET-PCR por Espectroscopia Acústica de Impacto** ":

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