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Analysis of acoustic attenuation in impact noise and compression resistance of mortars for screed with partial replacement of natural aggregate by PCR-PET

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SUMMARY
This study aims to analyze the effects of partial replacement of natural aggregate with Post-Consumer Recycled Polyethylene Terephthalate (PCR-PET) in screed mortars, emphasizing both acoustic performance and compressive strength. The research adopts a methodological approach that encompasses material characterization to performance evaluation in terms of strength and acoustic attenuation. The originality of the work lies in the comprehensive analysis of the physical and mechanical properties of mortars, focusing on the effectiveness of replacing natural aggregate with PCR-PET. The results indicate that as the proportion of PCR-PET in the mix increases, the apparent density decreases, directly impacting compressive strength. Additionally, there is an improvement in sound absorption in mortars with higher substitution of sand by PCR-PET, highlighting positive implications for the acoustic performance of these materials. Theoretical and methodological contributions include a deeper understanding of mortar properties, while social and environmental implications reside in promoting sustainable practices in construction, emphasizing the potential use of recycled materials.

KEYWORDS: Acoustic attenuation. Impact noise. Compression resistance. Mortars for subfloor.

1 INTRODUCTION

The exponential growth of urban areas and the expansion of residential zones have intensified the demand for constructive solutions that not only provide thermal and structural comfort but also effectively address the mitigation of noise impacts in residential environments. Impact noise from everyday activities, such as footsteps, falling objects, and furniture movement, represents a significant source of acoustic discomfort in conventional residential environments (MÉNDEZ, 1994).

In this context, this study is dedicated to a thorough analysis of acoustic attenuation in impact noise, including an investigation of some physical and mechanical characteristics of the developed materials. The main focus is on screed mortars, investigating the possibility of partially replacing natural aggregate with Post-Consumer Recycled Polyethylene Terephthalate (PCR-PET).

In highlighted studies, we note works such as those by Johnson *et al.* (2018) and Lee; White (2021), which exemplify research focused on more environmentally efficient practices in the use of resources in construction and acoustic improvements in built environments (HOUCINE *et al.,* 2023).

Due to the growing search for sustainable solutions in civil construction, which has instigated research such as Green; Brown (2020) on innovative materials and eco-efficient practices, they highlighted the importance of sustainability in construction. The promising strategy of partially replacing conventional aggregates with recycled materials, such as PCR-PET, not only contributes to reducing the environmental impact but also aims to optimize specific properties of the material, highlighting acoustic attenuation. This approach offers additional benefits, raising the quality of life for occupants of conventionally constructed environments.

Although previous studies such as Führ *et al.* (2021) have examined the influence of various mortar compositions on acoustic attenuation, there is a significant gap in understanding the specific characteristics associated with the partial replacement of natural

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aggregate with PCR-PET in this context. This lack of knowledge on this subject highlights the urgency and importance of the current research.

A thorough understanding of the physical and mechanical properties of these mortars plays a crucial role in assessing their practical viability. Previous research has highlighted the importance of investigating not only acoustic attenuation effectiveness but also strength and other mechanical properties that directly influence the performance and longevity of constructed structures. In this context, Mehta; Monteiro (1994) have long emphasized that the compressive strength property plays a critical role in evaluating the performance, durability, and safety of cementitious materials used in civil construction, and its consideration is crucial.

This article proposes to fill a gap, offering a comprehensive analysis of the physical and mechanical properties of screed mortars, with a special focus on the effectiveness of partially replacing natural aggregate with PCR-PET in terms of impact noise acoustic performance and compressive strength in this application.

The integrated approach to these properties aims not only to provide relevant information for the practical application of these materials but also to contribute to the advancement of knowledge at the intersection of sustainability, acoustic performance, and physical-mechanical properties in civil construction.

In Monteiro; Veras (2017), it is highlighted that sustainable constructions should consider ecological principles, aiming at the efficient use of the resources used in their construction. This implies reducing consumption, maximizing and reusing natural resources, and using materials from recyclables, with the aim of protecting the environment. With the main objective of providing fundamental information for the technical feasibility in eco-efficient applications, the research seeks to contribute significantly to advances in sustainability in the context of civil construction of modern building environments.

2 METHODOLOGY

The methodology proposed in this research document aims to comprehensively address the procedures necessary to investigate the influence of partial replacement of natural aggregate with PCR-PET on the properties of screed mortars. This process encompasses everything from material characterization to performance evaluation in terms of strength, density, and acoustic attenuation.

2.1 Materials

The materials used in the research involved the separation, storage, and utilization of components for the production of five formulations of mortar for screed. Following a standard reference, this composition includes natural sand, cement CP II E 32, and water. In the new formulations, PCR-PET was introduced as a partial replacement for the natural aggregate. Four compositions were developed with partial sand replacement by PCR-PET, exploring different proportions to investigate the effects of this practice on the mortars.

All anhydrous materials were obtained from the same manufacturing/distribution batch, ensuring uniformity in the tests and experiments conducted. The water used in all

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samples comes from the same supplier source. This approach aims to ensure the consistency and comparability of the results, as the base materials are sourced from identical sources and batches, providing a solid foundation for the research.

Reference Composition:

Natural Sand: Used as the reference standard.
Cement CP II E 32: Standard component for the mortar base.
Water: Essential element for the mixture.

Compositions with PCR-PET Substitution:

Four distinct compositions were developed, each partially replacing the volume proportion of natural sand with PCR-PET.
Variable substitution proportions of 10%, 20%, 30%, 40% were applied to investigate different levels of influence.

2.2 Mortar Formulations

Five mortar formulations were developed, each designed to evaluate different levels of partial substitution of natural sand with PCR-PET. The reference mortar, also known as standard mortar, will be formulated without any substitution. The subsequent four formulations will have partial substitution of natural sand by 10%, 20%, 30%, and 40% of PCR-PET by volume.

It is noted in NBR 15116 (2021) that when recycled aggregates are used in Portland cement mortars for non-structural uses, precast artifacts without structural function, and mortars for masonry, rendering, and screed, it is allowed to use substitution levels of up to 100% of the mass of natural aggregates.

Each formulation was meticulously mixed to ensure homogeneity and adequate consistency. The selection of these proportions aims to cover a representative range of partial substitutions, enabling a comprehensive assessment of the impact of PCR-PET presence on the properties of screed mortars.

2.3 Aggregate Particle Size Distribution

The materials used were acquired and stored in quantities exceeding those necessary for the entire extent of the research. The preferred choice of these materials was for a composition with a medium particle size for aggregates, thus expected to present a fineness modulus measured in the range of 2.2 to 2.9. The sand was acquired in June 2023 from the Paraíba do Sul River, located in the city of Campos dos Goytacazes, RJ. The PCR-PET used in this research was acquired in March 2023 and originates from the state of Espírito Santo, voluntarily provided by the Chemistry department of UFES, which has a pilot recycling plant at the university.

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In order to analyze the particle size distribution of sand and PCR-PET, the procedures outlined by standard NBR 17054 (2022) were strictly followed. The materials, sand, and PCR-PET, underwent a controlled drying process, followed by precise weighing.

Using sieves in accordance with the guidelines of the standard, the dried materials were sieved. Different mesh openings were employed, including a 6.3 mm sieve, thus establishing the maximum size of the sample. This careful procedure ensures the consistency and reliability of the results, fully meeting the requirements of the technical standard. Figure 1 illustrates the infrastructure used for the particle size separation procedure. The infrastructure apparatus consists of standardized sieves, an oven for drying, and a balance for mass verification.

Figure 1 - Sieves, oven, and balance for aggregate separation

Source: AUTHORS, 2023.

2.4 Aggregate Morphology

In order to deepen the understanding of the morphology of PCR-PET material and natural sand used in the research, microscopic analyses were conducted on specific particle size ranges. This characterization aims to demonstrate if there are significant variations in the way the material presents itself in relation to its size.

To perform this analysis, samples of PCR-PET and natural sand were prepared in distinct particle size ranges, and optical microscopy was used as a tool for image generation.

The goal is to present, on an enlarged scale, the observed shape and size of typical particles of these materials. This approach allows for a more detailed and precise visualization of morphology, contributing to a deeper understanding of the physical characteristics of these components.

2.5 Density of Mortars

The determination of the density of screed mortars followed appropriate methods according to the guidelines of NBR 13280 (2005). Six prismatic test specimens measuring 4x4x16 were molded to evaluate the influence of PCR-PET substitution on the property of bulk density in the hardened state of each of the mixes with PET substitution, compared to the reference mix (without substitution). This procedure allowed for a robust and comparative assessment of the resulting densities, providing significant insights into the impact of partial substitution of natural aggregate by PCR-PET.

2.6 Compression Strength of Mortars

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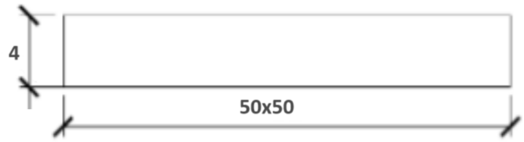
The tests were conducted following the evaluation of the test specimens used in determining the bulk density in the hardened state. Subsequently, compression strength tests were performed for each composition according to specific technical standards defined in NBR 13279 (2005). In this process, the maximum force supported by the samples was evaluated, providing a precise analysis of the load-bearing capacity of the developed mortars. The results are analyzed to express the comparison between the evaluated elements, without establishing absolute assessments of the materials, but rather a performance relationship among the samples of the studied formulations.

2.7 Acoustic Performance for Impact Noise

To conduct the tests, the Universal Acoustic Testing Chamber (UATC) and the Tapping Machine (TM) were used. The UATC provides a controlled anechoic environment for acoustic testing, while the TM is employed as a standardized noise source for application on screed samples measuring 50x50x4 cm, as depicted in Figure 2.

This procedure involves the use of appropriate equipment to ensure the accuracy and consistency of the results.

Figure 2 - Dimensional details of the screed samples



Source: AUTHORS, 2023.

During the tests, impact noises are applied in a controlled manner to the samples, followed by the measurement of acoustic attenuation rates. This process allows for a detailed evaluation of the acoustic performance of the mortars, providing essential information about their effectiveness in reducing impact noise under simulated conditions.

2.8 Statistics and Interpretation

Statistical analysis of the results was conducted, covering means, standard deviations, and analysis of variance. This process aimed to identify significant differences among the various developed compositions.

A thorough comparison of the obtained data with relevant standards and norms in the construction industry will be performed.

The analysis of the influence of partial substitution of natural aggregate by PCR-PET on the physical, mechanical, and acoustic performance properties of the mortars constitutes an essential phase of the research.

In addition to statistical analysis, this stage of the research includes the evaluation of trends or patterns identified in the statistical data. Additionally, a discussion on possible improvements or adjustments based on the obtained results is conducted.

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This part of the research goes beyond the mere presentation of numerical data, seeking to contextualize the results within the regulatory framework of the construction industry.

Engaging in an in-depth discussion provides a more comprehensive understanding of the effects of partial substitution of natural aggregate by PCR-PET on the characteristics of mortars.

This approach not only enriches the interpretation of the results but also offers a substantial contribution to advancing knowledge in this specific area.

By integrating technical analysis with normative considerations, this research aims not only to inform but also to positively influence practices and standards in the construction industry, promoting eco-efficient and sustainable solutions.

3 RESULTS

This section of the document aims to provide a comprehensive and clear analysis of the procedures adopted for the obtained results. This includes connecting the data with the research objectives, contributing to a comprehensive understanding of the effects of partial substitution of natural aggregate with PCR-PET on mortar properties.

3.1 Granulometric Characterization of Aggregates

For material characterization, representative samples of natural sand and PCR-PET are initially collected. Subsequently, granulometric analysis is conducted according to the guidelines established by the technical standard NBR 17054 (2022). This procedure aims to assess the distribution of particle sizes characteristic of each aggregate present in the mixtures.

The collection of granulometric data is crucial for understanding the granular composition of the materials, playing a fundamental role in the precise definition of proportions in mortar mixtures to understand their effects in the fresh and hardened states (CINCOTTO *et al.,* 2018). Strict adherence to the technical standard ensures standardization and reliability of results, establishing a consistent basis for the characterization of materials used in the research.

Table 1 displays the granulometric distribution data of the materials used in the research, namely PCR-PET and sand. It is possible to observe that the fineness moduli found in the distributions are in accordance with the desired specifications, i.e., corresponding to a classification of aggregates in the typical sand size range.

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Table 1 – Granulometric distribution spreadsheets of PCR-PET and sand

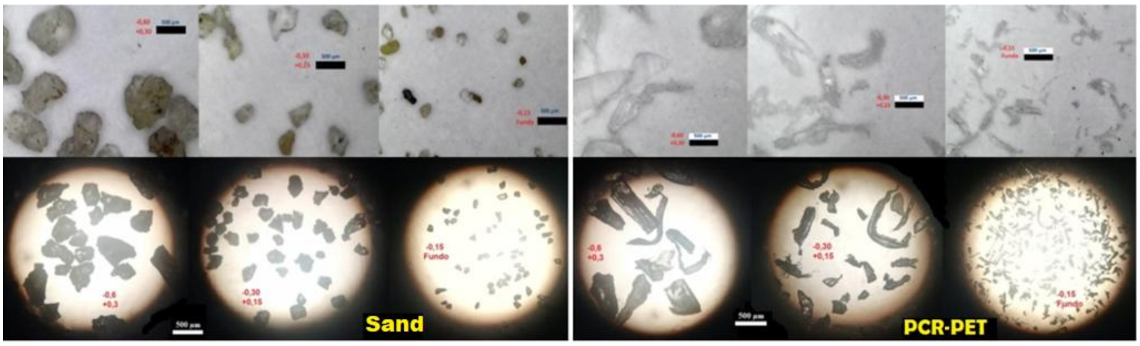
Material:	PCR-PET					**Initial Mass M1 (g):**	506,5	
Date:	12/05/2023					**Initial Mass M2 (g):**	288,6	
Sieves (mm)	**Retained mass (g)**		**Retained mass (%)**		**Variation (4%)**	**Mean (%)**	**Cumulative (%)**	**Past (%)**
	m1	**m2**	**m1**	**m2**				
4,75	2,8	0	0,55	0,00	0,55	0,28	0,28	99,72
2,36	6,5	0	1,28	0,00	1,28	0,64	0,92	99,08
1,18	329,2	0	65,00	0,00	65,00	32,50	33,42	66,58
0,60	121,3	45,4	23,95	15,73	8,22	19,84	53,26	46,74
0,30	37,4	72,5	7,38	25,12	-17,74	16,25	69,51	30,49
0,15	7,9	82,8	1,56	28,69	-27,13	15,12	84,63	15,37
Fundo	1,4	87,9	0,28	30,46	-30,18	15,37	100,00	0,00
Maximum Diameter:	**2,4 mm**							
Fineness Modulus (FM):	**2,42**							
Material:	Sand					**Initial Mass M1 (g):**	654,1	
Date:	01/08/2023					**Initial Mass M2 (g):**	351,6	
Sieves (mm)	**Retained mass (g)**		**Retained mass (%)**		**Variation (4%)**	**Mean (%)**	**Cumulative (%)**	**Past (%)**
	m1	**m2**	**m1**	**m2**				
4,75	4,4	2,5	0,67	0,71	-0,04	0,69	0,69	99,31
2,36	16,5	7,3	2,52	2,08	0,45	2,30	2,99	97,01
1,18	78,8	22,1	12,05	6,29	5,76	9,17	12,16	87,84
0,60	214,1	100,1	32,73	28,47	4,26	30,60	42,76	57,24
0,30	231,7	150,5	35,42	42,80	-7,38	39,11	81,87	18,13
0,15	100,4	64,4	15,35	18,32	-2,97	16,83	98,70	1,30
Fundo	8,2	4,7	1,25	1,34	-0,08	1,30	100,00	0,00
Maximum Diameter:	**6,3**							
Fineness Modulus (FM):	**2,39**							

Source: AUTHORS, 2023.

3.2 Morphological Characterization of Aggregates

In Figure 3, it is possible to visually observe a microscopic sample of the typical elements found in sand and PCR-PET aggregates. These elements were separated into distinct particle size ranges and subjected to digital and optical microscopy for image generation.

Figure 3 - Visualization of the morphology of typical elements of natural sand and PCR-PET.



Source: AUTHORS, 2023.

Mehta; Monteiro (1994) observe that grains with lamellar and elongated morphology, such as those found in PCR-PET elements shown in Figure 3, have a higher volumetric specific area than spherical particles, which are characteristics observed in sand particles, also exposed

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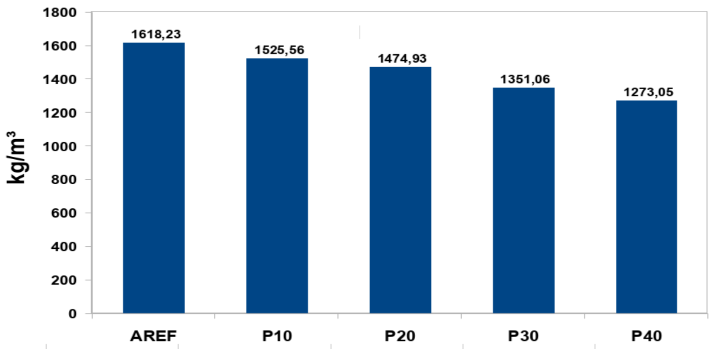
in the same figure. As a result, this leads to irregular filling of the mortar, increasing the material's porosity (MELO, 2004).

3.3 Bulk Density

In assessing the influence of PET substitution on mortar density, tests were conducted to determine the bulk density in the hardened state, following the guidelines of NBR 13280 (2005). For this analysis, 6 specimens were made for each mix, including the reference mix, in which PCR-PET substitution occurred.

Figure 4 presents the results obtained in the tests after 28 days of curing, where the prisms used were subsequently subjected to compression tests. These tests essentially consist of measuring the values of height (h), width (w), and length (l), performed with a caliper in centimeters. Additionally, the respective masses (Mcp) were measured in grams using a balance. To determine the bulk density in the hardened state (D), in kg/m³, the simple average relationship between the mass and the volume of the specimens is established.

Figure 4 - Graph of Bulk Density in the Hardened State.



Source: AUTHORS, 2023.

In the proper comparative interpretation of the data from Figure 4, a clear trend of reduction in bulk density is observed as the proportion of PCR-PET in the mixture increases, in comparison to the reference mortar.

3.4 Compression Strength Tests of Mortars

Axial compression strength tests were conducted using the EMIC DL2000 press apparatus, utilizing specimens from 6 distinct samples for each mixture, derived from density measurements. The experimental procedure followed the recommendations established in NBR 13279 (2005).

Figure 5 visually presents the results obtained from the compression strength tests conducted in the research. It can be observed from this figure that the compression strength decreases in mortars with sand replaced by PCR-PET compared to the reference mortar. This decrease is more pronounced as the proportion of PCR-PET in the mixture composition increases.

In summary, it can be observed that the higher the quantity of PCR-PET introduced into the formulation, the lower the strength obtained.

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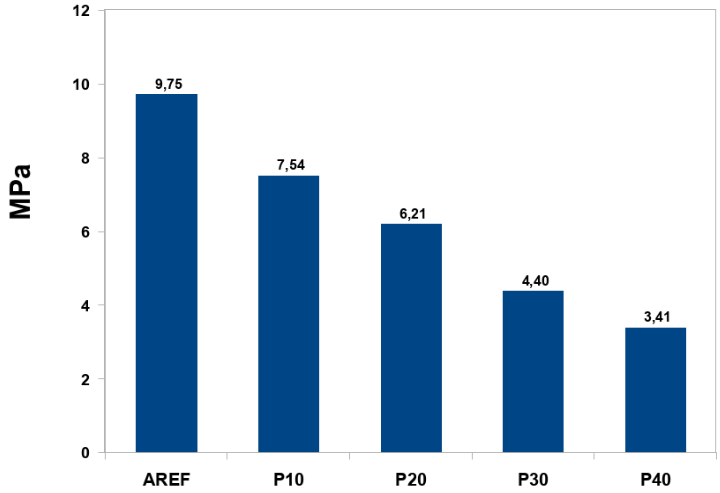
Figure 5 - Graph of compression strength in mortars



Source: AUTHORS, 2023.

3.5 Acoustic Impact Noise Tests

The results of the tests conducted to determine the sound reduction indexes by frequency bands, as well as the weighted value for each of the samples concerning impact noise in the mortar compositions intended for screed and investigated in this research, can be visually identified by collecting data from the microphone of the universal chamber of acoustic testing.

These data are acquired through the Realtime Analyzing software, integrated into the device, and after capture, the average is taken over a stabilized measurement interval. The results are meticulously presented in Table 2.

The data presented in Table 2 are expressed in terms of transmission, showing that lower values correspond to greater attenuation (absorption) of the measured noise in relation to the isolation of the source.

Table 2 - Data comparison between differences in sound pressure levels to impact noise

Frequencies	Impact Noise Transmitted with Tapping Machine				
	REF	P10	P20	P30	AP40
125 Hz	53,97	54,34	54,97	54,63	53,89
250 Hz	53,26	53,95	52,35	52,86	54,98
500 Hz	43,64	43,56	43,20	43,32	44,00
1 K Hz	45,09	45,57	45,43	47,25	40,72
2 K Hz	37,65	36,91	36,47	38,48	35,42
4 K Hz	36,64	36,20	35,69	35,75	32,27
8 K Hz	28,28	26,69	26,96	27,25	26,41
16 K Hz	28,72	26,33	26,14	26,25	24,87
Weighted	**89,08**	**87,76**	**86,89**	**86,65**	**85,46**

Source: AUTHORS, 2024.

When analyzing the frequencies captured in the research, with an octave range from 125Hz to 16kHz, established as fundamental and within the audible spectrum, we can classify the frequencies of the studied waves as low (corresponding to frequencies from 125Hz to 500Hz), mid-range (from 1kHz to 4kHz), and high-pitched (from 8kHz to 16kHz) within the

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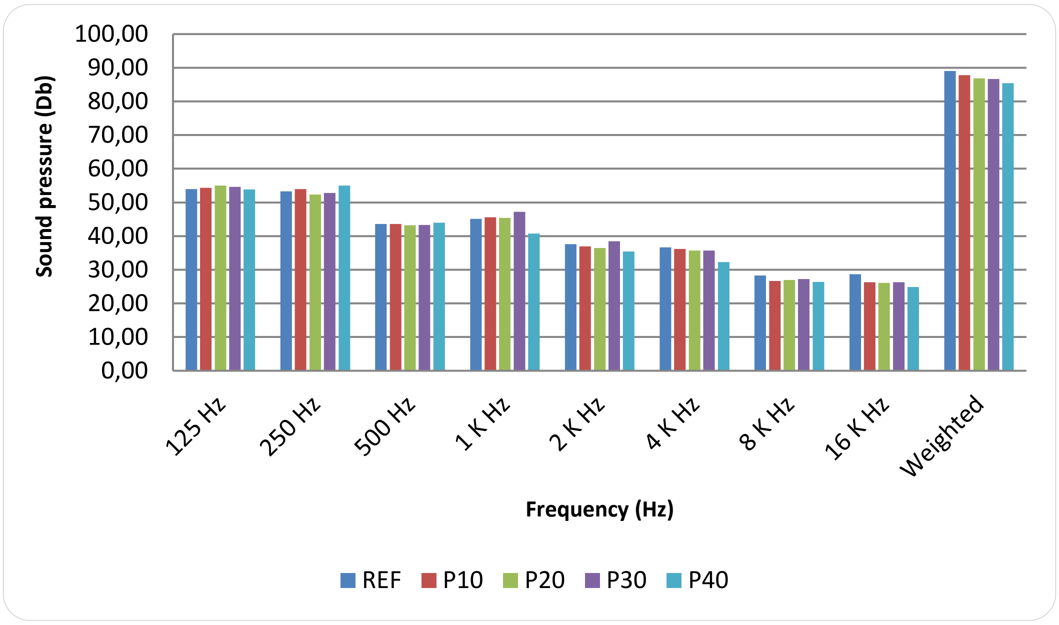
octaves used in the study. These definitions are established by taking the reference mix as a standard, as depicted in Figure 6.

Figure 6 - Graph of data comparison between differences in sound pressure levels to impact noise



Source: AUTHORS, 2024.

It is noteworthy that, in most frequency bands, the most promising results were achieved in mortars with a higher proportion of sand replaced by PCR-PET. This highlights a significant improvement in sound absorption concerning impact noise in materials containing a larger amount of PCR-PET, corroborating findings in similar research (FÜHR *et al.,* 2021).

In the weighted method, the performance results were as follows: mortar P40 showed attenuation greater than 3 dB compared to the reference, while P30 and P20 showed attenuation slightly greater than 2 dB, and P10 had attenuation greater than 1 dB. In the frequency performance analysis, a similarity in the results obtained is observed, with minor deviations.

4 CONCLUSIONS

The data from the particle size distribution, presented in Table 1, offer a clear and detailed visualization of the characteristics of the materials used in the research. This analysis is crucial for understanding the granular composition of the materials, playing a fundamental role in defining precise proportions in the mixtures (CINCOTTO *et al.,* 2018). The care taken in conducting these procedures significantly contributed to the validity and reliability of the data obtained.

The morphological analysis of the aggregates plays a crucial role in understanding the physical characteristics of these materials (MEHTA; MONTEIRO, 1994). In Figure 3, a revealing microscopic visualization of the typical elements found in both natural sand and PCR-PET was presented after the separation process into distinct particle size ranges.

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This analysis identified PCR-PET elements with lamellar and elongated characteristics, resulting from the crushing process. As previously known and expected, for the sand used as natural aggregate, morphological characteristics similar to those described in various research studies were observed, namely particles predominantly spherical.

Microscopic observation offers valuable insights into the shape and structure of particles present in aggregates. The morphology of natural sand and PCR-PET is essential to understand how these materials will behave in mortar mixtures. The diversity in particle shape, as highlighted in Figure 4, directly influences properties such as compaction, adhesion, and strength of the resulting mortars (MELO, 2004).

The evaluation of the apparent density in the hardened state, considering the partial replacement of sand by PCR-PET in the mortars, reveals significant trends that directly influence the physical properties of the materials. The tests, conducted according to the strict guidelines of NBR 13280 (2005), provided clear and elucidative data, as represented in Figure 4.

The analysis of the results indicates an evident reduction in the apparent density as the proportion of PCR-PET in the mixture increases compared to the reference mortar. This decrease is consistent with expectations since PCR-PET has a lower density compared to natural sand. The porous nature and lightweight of PCR-PET contribute to an overall decrease in mortar density.

The results demonstrate similarities with other studies, which investigated properties of materials with the addition of recycled materials and identified a potential impact on increasing porosity as seen in Smith *et al.* (2019).

This reduction in apparent density not only reflects the introduction of a lighter material in the composition but also suggests changes in compaction characteristics and particle distribution within the mixtures. Understanding these variations in density is crucial for evaluating the suitability of mortars for different applications in civil construction.

The analysis of the results of axial compressive strength tests provides a clear understanding of the impact of sand replacement by PCR-PET on the mechanical properties of the mortars. The tests, rigorously conducted according to the guidelines established by NBR 13279 (2005), generated data represented in Figure 5.

The results show a consistent trend of reduction in compressive strength as the proportion of PCR-PET in the mixture increases compared to the reference mortar. This decrease in strength is more pronounced as the amount of PCR-PET increases, indicating a direct relationship between the presence of this material and the decrease in the ability to withstand compressive loads.

The decrease in compressive strength can be attributed to the intrinsic characteristics of PCR-PET as suggested by Canellas (2005), which, while offering environmental benefits through recycling, may compromise the mechanical integrity of the mortar. The lighter and more porous nature of PCR-PET may result in less efficient distribution of compressive forces, leading to reduced load capacity.

It is essential to highlight that, despite this reduction in compressive strength, the mortars still meet the minimum requirements established by applicable technical standards.

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This suggests that even with the substitution of up to a certain proportion of sand by PCR-PET, the mortars maintain acceptable suitability for various applications in civil construction.

This understanding of changes in compressive strength provides crucial information for evaluating the mechanical performance of mortars, informing about limitations and possible specific applications in construction projects (MENDONÇA *et al*., 2021).

In the assessment of the ability to absorb impact noise in mortars intended for screed, significant results were revealed that may influence choices in architectural projects. The tests, conducted based on a wide frequency range (125Hz to 16kHz), provided detailed data expressed in Table 2.

Upon analyzing the results, a clear trend of improvement in impact noise attenuation is observed as the proportion of sand replaced by PCR-PET increases. The best performances were recorded in mortars with a higher amount of PCR-PET, indicating promising potential of this material in reducing noise transmission.

It is noteworthy that, in the weighted method, mortar P40 showed a remarkable attenuation of over 3 dB compared to the reference mortar. Mixtures P30, P20, and P10 also demonstrated considerable improvements, with attenuations proportional to the added PCR-PET proportions.

The individual frequency analysis corroborated these results, indicating consistency in mortar performance across different frequency ranges. Specifically, medium and high frequencies showed improvements proportional to the amount of PCR-PET added, consolidating the effectiveness of this material in noise absorption across various sound ranges with typical porous material behavior as described by Brandão (2016).

These findings suggest that the introduction of PCR-PET in mortars not only contributes to environmental sustainability (LAMBA *et al.,* 2021) but also offers acoustic benefits, enhancing efficiency in reducing impact noise in built environments. This may have positive implications for the quality of acoustic comfort in buildings, providing quieter and more pleasant environments, as the use of suitable materials should ensure the necessary requirements for user comfort in construction systems (MAEKAWA *et al.,* 2011).

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