Periódico Eletrônico Fórum Ambiental da Alta Paulista
Electronic Journal Environmental Forum of Alta Paulista
ISSN 2966-2931 Suporte Online / *Online Support* - ISSN 1980-0827 Suporte CD-ROM / *CD-ROM Support*
Edição em Português e Inglês / *Edition in Portuguese and English* - v. 20, n. 4, 2024

Feasibility of Using Stone Dust in Mortars as a Substitute for Natural Sand

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Received: June 19, 2024
Accepted: September 13, 2024
Online Published: November 16, 2024

DOI: 10.17271/1980082720420245235
https://doi.org/10.17271/1980082720420245235

Viabilidade do Uso de Pó de Pedra em Argamassas como Substituto de Areia Natural

RESUMO
Este artigo demonstra a viabilidade técnica da substituição da areia natural por pó de pedra na dosagem de argamassas. Ensaios laboratoriais foram conduzidos para caracterizar amostras de areia e pó de pedra, um resíduo industrial proveniente de jazidas e pedreiras. Utilizando a proporção de 1:8 e relação água/cimento de 0,5, conforme a Associação Brasileira de Normas Técnicas ABNT NBR 13.276, os materiais foram utilizados na dosagem de argamassas para assentamento e revestimento. Corpos de prova foram moldados e armazenados em câmara úmida por diferentes períodos de cura (7, 14 e 28 dias). Ensaios de compressão e verificação dos módulos de elasticidade foram conduzidos de acordo com as recomendações da ABNT NBR 7.215. Além disso, painéis experimentais foram construídos e revestidos com argamassas dosadas com areia e pó de pedra. Nesses, foram realizados ensaios de resistência à tração do revestimento. Os resultados indicaram que o pó de pedra pode substituir a areia natural na dosagem de argamassas para assentamento e revestimento de alvenarias. Em todos os períodos de cura estudados, os corpos de prova com pó de pedra apresentaram desempenho equivalente aos dosados com areia natural. Os módulos de elasticidade também mostraram valores estatisticamente semelhantes em ambas as dosagens. Portanto, a utilização de pó de pedra em substituição à areia natural oferece à construção civil uma alternativa sustentável, reduzindo o impacto ambiental ao utilizar resíduos da extração de rochas em vez de materiais naturais não renováveis.

Palavras-chave: Argamassa. Pó de Pedra. Resíduos Sólidos. Construção Civil

Feasibility of Using Stone Dust in Mortars as a Substitute for Natural Sand

ABSTRACT
This article demonstrates the technical feasibility of replacing natural sand with stone dust in mortar mixtures. Laboratory tests were conducted to characterize sand and stone dust samples, an industrial by-product originating from quarries. Using a 1:8 ratio and a water/cement ratio of 0.5, according to ABNT NBR 13.276, the materials were used for mortar mixtures for bricklaying and coating. Cylindrical specimens were molded and stored in a humid chamber for different curing periods (7, 14, and 28 days). Compression tests and verification of the elastic modulus were conducted following ABNT NBR 7.215 recommendations. Additionally, experimental panels were built and coated with mortar mixtures dosed with sand and stone dust. Tensile strength tests on the coating were conducted on these panels. The results indicated that stone dust can replace natural sand in mortar mixtures for bricklaying and coating. In all curing periods studied, the specimens with stone dust showed performance equivalent to those dosed with natural sand. The elastic modulus also showed statistically similar values in both mixtures. Therefore, using stone dust to replace natural sand offers the construction industry a sustainable alternative, reducing environmental impact by utilizing quarry by-products instead of non-renewable natural materials.

KEYWORDS: Mortar. Stone Dust. Solid Waste. Civil Construction.

Viabilidad del Uso de Polvo de Piedra en Morteros como Sustituto de Arena Natural

RESUMEN
Este artículo demuestra la viabilidad técnica de la sustitución de la arena natural por polvo de piedra en la dosificación de morteros. Se realizaron ensayos de laboratorio para caracterizar muestras de arena y polvo de piedra, un residuo industrial proveniente de yacimientos y canteras. Utilizando una proporción de 1:8 y una relación agua/cemento de 0,5, de acuerdo con la Asociación Brasileña de Normas Técnicas ABNT NBR 13.276, los materiales fueron empleados en la dosificación de morteros para mampostería y revestimiento. Se moldearon probetas y se almacenaron en cámara húmeda durante diferentes períodos de curado (7, 14 y 28 días). Los ensayos de compresión y verificación de los módulos de elasticidad se llevaron a cabo según las recomendaciones de la ABNT NBR 7.215. Además, se construyeron paneles experimentales y se revistieron con morteros dosificados con arena y polvo de piedra. En estos, se realizaron ensayos de resistencia a la tracción del revestimiento. Los resultados indicaron que el polvo de piedra puede sustituir la arena natural en la dosificación de morteros para mampostería y revestimiento. En todos los períodos de curado estudiados, las probetas con polvo de piedra mostraron un desempeño equivalente a las dosificadas con arena natural. Los módulos de elasticidad también presentaron valores estadísticamente similares en ambas dosificaciones. Por lo tanto, el uso de polvo de piedra en sustitución de arena natural ofrece a la construcción

civil una alternativa sostenible, reduciendo el impacto ambiental al utilizar residuos de la extracción de rocas en lugar de materiales naturales no renovables.

Palabras clave: Mortero. Polvo de Piedra. Residuos Sólidos. Construcción Civil.

1 INTRODUCTION

The construction industry consumes the most natural resources and intensively uses energy, resulting in significant environmental impacts (Castanheira et al., 2016). The United Nations (U.N.) Sustainable Development Goals (S.D.G.s) set a global agenda for public policies through 2030. Goal nine highlights the importance of Industry, Innovation, and Infrastructure, emphasizing that sustainable buildings must be designed to be resilient and adaptable to climate change.

Another relevant point is goal eleven, which deals with Sustainable Cities and Communities. According to the U.N. (2022), 55% of the world's population currently lives in urban areas, and this number is expected to increase to 70% by 2050. Therefore, ensuring the long-term sustainability of communities and buildings is crucial.

In addition, goal twelve promotes the circular economy, focusing on responsible consumption and production, energy efficiency, sustainable infrastructure, and access to essential services. This goal is directly related to the construction industry, which plays a vital role in reducing, recycling, and reusing waste, aligning with the circular economy principles.

Sustainability in the construction industry is essential, as the sector is responsible for a large part of the exploitation of natural resources and the generation of waste. The construction of buildings consumes large quantities of materials such as cement, lime, sand, and other aggregates, whose extraction and production processes cause environmental degradation, greenhouse gas emissions, and significant impacts on biodiversity. Moreover, the intensive use of energy in transporting and processing these materials contributes to the sector's carbon footprint. To mitigate these impacts, it is essential to adopt more sustainable practices, such as reducing the consumption of non-renewable resources, using recyclable and renewable materials, and implementing technologies that increase energy efficiency throughout the lifecycle of buildings.

In this context, sustainable construction approaches, such as the circular economy and alternative materials, are urgently necessary. Practices such as recycling construction and demolition waste, reusing water, and using renewable energy sources are fundamental to reducing environmental impacts. Using alternative aggregates, such as stone dust, is a concrete example of how the construction industry can minimize the exploitation of natural resources, reducing the extraction of sand, a finite resource often removed from sensitive ecosystems. Thus, integrating these sustainable materials into the construction process contributes to environmental preservation and the creation of a more resilient and efficient sector, in line with the Sustainable Development Goals.

Mortar, composed of sand, lime, and cement, is one of the most widely used materials in construction and is essential for building performance. However, its use causes environmental impacts due to the production and extraction of its non-renewable components. With increasing urbanization, the consumption of materials such as mortar tends to rise, making it indispensable to implement strategies to minimize the environmental impacts of its production and make it more sustainable (Caldas et al., 2019).

Damasceno (2016) states, "Sustainability in construction can be achieved by exploring natural resources in a way that minimizes harm to the environment and communities."

Improving the management of building material production is crucial to increasing sustainability in the sector and reducing the consumption of natural resources and the impacts associated with their manufacture, which can also reduce costs (Passuelo et al., 2014; Carvalho et al., 2018).

One way to promote sustainability in the construction industry is to encourage the conscious use of materials. In this context, alternative aggregates like stone dust stand out. Several authors state that evaluating the environmental impacts of building materials must consider their lifecycle (Menossi, 2004; Mota et al., 2011; Huang et al., 2020; Hossain; Thomas, 2019). Efforts to reduce environmental impacts are urgent, requiring collective actions by companies, governments, and individuals to rethink consumption and production, establish policies, and alter traditional construction practices (Barbieri et al., 2010).

This article focuses on construction practices, addressing the conceptualization and analysis of stone dust as an alternative aggregate to replace natural sand in mortar mixtures. The hypothesis is that using mortars with stone dust instead of natural sand can be an environmentally efficient alternative, considering both economic and technical aspects.

2 LITERATURE REVIEW

2.1 Use of Alternative Materials in Civil Construction

Most natural resources are non-renewable, so the technical field is committed to finding alternatives to replace them (or mitigate their use) without compromising civil works' quality, safety, and economy (Cortese et al., 2017). In this context, the development of alternative materials has gained prominence over the past twenty years. The search for solutions aligned with sustainable growth concepts has been a challenge, as the sustainability of economic activities is an urgent need (Mansur et al., 2005; Carvalho et al., 2018).

Several studies have focused on analyzing the components and behavior of alternative materials, including chemical composition, size, shape, mechanical strength, and interfaces (Diógenes, 2016). The development of reuse and recycling techniques is based on understanding waste's physical and chemical characteristics, allowing the determination of its properties and, subsequently, its incorporation into different materials (Antunes, 2020).

The interaction between new construction methodologies and nature is a crucial topic that should be addressed not only by civil engineering professionals but by all of society, which benefits from construction products (Bitsiou; Giarma, 2020). Sustainability and Sustainable Development are concepts that, with a positive impact, are becoming progressively more common in evaluating processes and new executive methods (Passuelo et al., 2019; Oliveira; Souza, 2021).

2.2 Mortars

Mortar is a construction material composed of a homogeneous mixture of binders (cement or lime), fine aggregate (sand), and water. Additives or special admixtures can be added to improve or impart specific properties to the material.

The performance of mortar depends on its characteristics in both the plastic and hardened states. In the plastic state, it must have good workability to facilitate the laying of blocks and an adequate water retention capacity to ensure cement hydration. In the hardened state, desired characteristics include adequate compressive strength and good adhesion or shear strength.

Mortar must retain the mixing water, which lubricates the dry materials and ensures cement hydration. The properties of the plastic state are closely linked to those of the hardened state. The compressive strength of mortar must be at least 1.5 MPa (Passuelo et al., 2019). Chart 1 summarizes the expected characteristics of mortars according to the relevant technical standards.

Chart 1- Summary of requirements for mortar production.

Characteristics	Requirement	Standard
Workability	A standard consistency of 255±10 mm	ABNT NBR 13276
Compressive strength	It must be specified in the design.	ABNT NBR 13279
Adhesion strength	It must be specified in the design.	ASTM E518
Water retention	80% < normal < 90%	ABNT NBR 13277
	90% < high	
Workability	Group a < 8%	ABNT NBR 13278
	8% < Group b < 18%	
	18% < Group c	

Source: Adapted from Antunes (2020) and Tokarski (2017).

2.3 Mortar obtained through dosing with stone dust

Stone dust is generated from the crushing of rocks, where specific fractions detach irregularly, acquiring a finer granulometry than usual. Due to its environmental advantages and economic benefits, the use of this by-product as a fine aggregate in mortar, whether for economic reasons or durability, has gained visibility. This has enabled quarries to commercialize a previously valueless by-product, which previously caused storage issues and environmental impact, transforming it into a product more accessible than conventional aggregates (Menossi, 2004).

Due to its fine granulometry, stone dust can be used in sidewalks and asphalt, manufacturing precast elements, and mortar preparation for bricklaying. It also serves as a soil stabilizer in the construction of subfloors. When properly controlled, it can be used in concrete mixtures to enhance their strength. Its granulometry consists of particles with diameters ranging from 0.5 mm to 5 mm (Menossi, 2004).

2.4 Research conducted with alternative mortars

The use of recycled aggregates in civil construction has increased to reduce costs and mitigate the environmental impacts resulting from the use of natural materials (Passuelo, 2019; Habert et al., 2020). Santos et al. (2014) discuss coating and bricklaying mortars dosed with artificial sand instead of material extracted from quarries. The authors concluded that the type of aggregate significantly influences the properties of mortars and that a dosing methodology that considers these principles is necessary to obtain mixed mortars of quality and with technical characteristics appropriate to the relevant standards.

Antunes (2020) analyzed the partial (50%) and total (100%) replacement of natural sand with granite sand in the dosing of coating mortar with a ratio of 1:1:6 (cement, lime, and sand).

The results showed that mortars with granite sand exhibited higher capillary absorption and mechanical strength than mortar with natural sand, indicating that the angular shape of the granite grain influenced the properties analyzed.

Tokarski (2017) studied the material obtained from the crushing of limestone in the dosing of coating mortar. Five mixture compositions were tested: the first with 100% natural sand (reference), the second with 80% natural sand and 20% of crushing residue, the third with 60% natural sand and 40% of crushing residue, the fourth with 40% natural sand and 60% of crushing residue, and the fifth with 20% natural sand and 80% of crushing residue. The mixture of cement, sand, water, and additives was tested in fresh and hardened states. The mixtures with limestone crushing residue performed better than the reference mixture with natural sand. The mixture with 60% natural sand and 40% crushing residue demonstrated the best performance in 70% of the tests, with a particle size curve within regulatory requirements (Tokarski, 2017).

Diógenes (2016) evaluated the technical feasibility of replacing riverbed sand with crushing residue (stone dust) in the preparation of coating mortars, as well as the influence of the fine material content and water on the properties of the mortars in fresh and hardened states. Using three types of stone dust from quarries in the Metropolitan Region of Fortaleza, the research found that it is possible to use this material as a replacement for natural sand at a ratio of 25%, resulting in better workability, lower water consumption, and increased mechanical strength.

Caldas et al. (2019) conducted a Life Cycle Assessment to compare the environmental impacts of three mortar alternatives with red ceramic waste (RCW) as a substitute for Portland cement, with particles of 30 µm, 10 µm, and 1 µm, in proportions of 10% and 20%. Conventional mortar with Portland cement and sand was used for comparison. The results showed that the mixture with 20% cement substitution by RCW of 10 µm presented satisfactory compressive strength and durability and lower environmental impacts.

Therefore, considering the importance of the issue presented and the interest of the technical and scientific community in the study of alternative materials for mortar dosing, the next section presents the methodological procedures used in this research.

3 METHODOLOGY

For the conduction of the tests, 20 kg of natural sand, 20 kg of stone dust, and 50 kg of Portland cement CPII F-32 were used. The samples were air-dried in the shade, then quartered and homogenized. The characterization tests of the samples were conducted at the Civil Construction Laboratory of the State University of Campinas (UNICAMP), following the procedures established for each material according to the standards of the Brazilian Association of Technical Standards (ABNT).

The stone dust was sourced from a quarry in Santa Isabel, in the Morro Grande neighborhood. The same preparation and characterization procedures were followed as it is an aggregate candidate to replace natural sand.

The medium natural sand was previously oven-dried to avoid interference in the water/cement ratio in the mortar dosage. The specific mass of the fine aggregate was determined according to ABNT NBR NM 52 procedures. At the same time, its granulometry, fineness modulus, and maximum characteristic dimension were defined according to ABNT 13.276, and the bulk density according to ABNT NBR NM 45.

ABNT NBR NM 248 was used to determine the granulometric composition of the samples, obtaining the average percentage retained on each sieve, the accumulated percentage, the characteristic dimension, and the fineness modulus. The specific mass of the fine aggregates was calculated using the Chapman flask, following the equation:

$$Y= \frac{500}{L-200} \quad (1)$$

Where:
Y — The specific mass of the fine aggregate;
L — Reading of the flask (volume occupied by the water-fine aggregate mixture).

The apparent natural specific mass of the fine aggregates was also determined according to ABNT NBR NM 45. It is known that the specific mass is the ratio between the dry aggregate's mass and its volume, excluding the permeable pores. The specific mass of the cement was determined using the Le Chatelier flask method. The specific mass of the cement was calculated using equation (2):

$$Y= \frac{\mathrm{m}}{V2-\mathrm{V}1} \quad (2)$$

Where:
Y — Specific mass of the cement;
V2 — Reading of the flask (volume occupied by the alcohol-cement mixture);
V1 — Initial reading of the flask.

The mortar was prepared in accordance with ABNT NBR 13.276, using a ratio of 1:8 and a water/cement (w/c) ratio of 0.5. Forty-eight cylindrical specimens, with a height of 10 cm and a diameter of 5 cm (L=2D), were molded using both conventional mortar (with sand) and mortar dosed with stone dust, following the recommendations of ABNT NBR 7215.

All the specimens were initially stored in a chamber with a minimum relative humidity of 95% for initial curing. Then, they were demolded and immersed in water until the test ages (7, 14, and 28 days). Before being subjected to the compression tests, an ultrasound was performed on the specimens to check for internal microcracks or discontinuities that could influence the results, as recommended by ABNT NBR 8802. Table 1 presents the number of specimens molded for this research.

Table 1 - Number of specimens vs. age at rupture

Material	**7 days**	**14 days**	**28 days**
Sand	5	5	5
Stone dust	5	5	5
Saturated sand	3	3	3
Saturated stone dust	3	3	3
Total	**16**	**16**	**16**

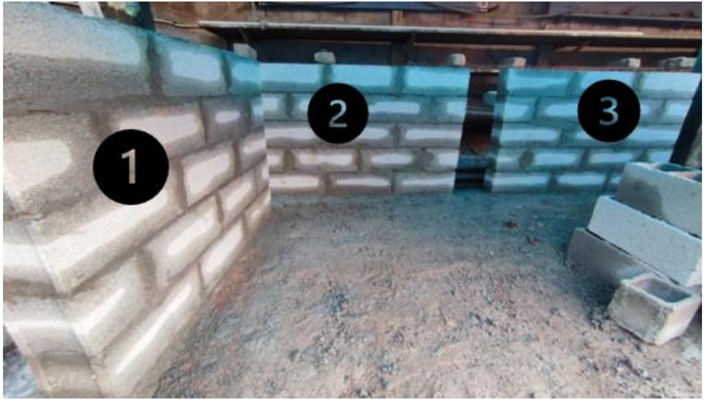
Source: Research data

After verifying the integrity of the specimens, compression tests were conducted using an axial press, type EMIC — GR48, installed in the construction materials testing laboratory of the Faculty of Agricultural Engineering at the State University of Campinas. The procedures followed the recommendations of ABNT NBR 7215. In addition to simple compressive strength, the elastic moduli of some specimens were also determined. For this, sensors were attached to measure horizontal and vertical deformations during loading.

Experimental panels were built to determine the tensile strength of the mortars dosed with sand and stone dust. The panels measured 1.0 m in height by 1.20 m in length. They were composed of concrete blocks laid with experimental mortar mixed with stone dust and sand. The mortar dosage followed the ratio of 1 part cement to 8 parts aggregate (stone dust or sand), according to regulatory requirements.

Panels 1 and 2 were built with concrete blocks laid with mortar mixed with natural sand, while panel 3 was built using mortar mixed with stone dust. Figure 1 shows the constructed panels. The panels were coated, as shown in Table 2. The dosages (cement) used for each coating layer were: a) roughcast – 1:3; b) render – 1:8. The water/cement ratio used was 0.5. Figures 2 and 3 show the panels after coating. After this stage, the experimental panels were maintained for 28 days for the mortar curing process.

Figure 1 - Panels built to determine tensile strength.



Source: Research data

Table 2 - Coating characteristics of the experimental panels. Source: Research data.

Panel	Coating
1	Scratch coat (t=5mm)
2	Scratch coat (t=5mm) + 1 layer of plaster (t=15mm)
3	Scratch coat (t=5mm) + 2 layers of plaster (t1=15mm, t2=5mm)

Figure 2 - Panels coated with a scratch coat layer.

Source: Research data

Figure 3 - Panels 2 and 3 coated with plaster layers

Source: Research data

At the end of the curing period, tensile strength tests were carried out according to the requirements of ABNT NBR 13528-2/2019. Three tests were performed for each face of the panel, for a total of nine tests. As a result, the tensile strength values of the mortar were calculated according to Equation 3. Table 3 presents the minimum tensile strength values of the mortar according to its use; these values are reported by ABNT NBR 13749/2013.

$$Pa = \frac{P}{A} \qquad (3)$$

Where:
Pa = tensile strength (MPa)
P = maximum load (N)
A = sample area (mm²)

Table 3 - Minimum tensile strength of mortars for internal and external use.

Area	Coating	Qa (MPa)
Internal	Plaster base	≥ 0.20
	Scratch coat base	≥ 0.20
External	Plaster base	≥ 0.30
	Scratch coat base	≥ 0.30

Source: Adapted from ABNT: NBR 13749.

4 OBTAINED RESULTS

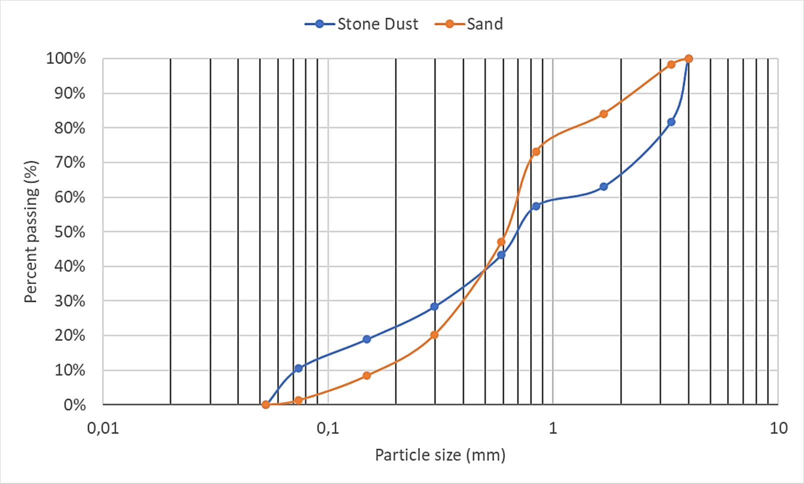
Table 4 presents the specific weights determined for the samples of stone dust and natural sand, while Figure 4 shows the granulometric distribution.

Table 4 - Granulometric characteristics of the tested samples

Characteristic	Stone dust	Sand	Cement
Natural specific weight (kN/m³)	26.9	26	---
Apparent specific weight (kN/m³)	17.1	15.1	29.3

Source: Research data

Figure 4 - Comparison between granulometric curves: stone dust and sand.



Source: Research data

Thus, based on the determined curves, the characteristics of the tested samples shown in Table 5 can be identified.

Table 5 - Granulometric characteristics of the tested samples. Source: Research data

Sand		Stone dust	
D_{10}	0.15 mm	D_{10}	0.15 mm
D_{30}	0.30 mm	D_{30}	0.30 mm
D_{60}	0.70 mm	D_{60}	1.0 mm
Cc	0.85	Cc	0.60
Grading	**Well graded**	**Classification**	**Well graded**
Granulometry	**Fine to coarse**	**Grading**	**Fine to coarse**

They were subjected to ultrasound tests to confirm that the specimens did not have internal cracks that could influence compressive strength. The results are shown in Table 6.

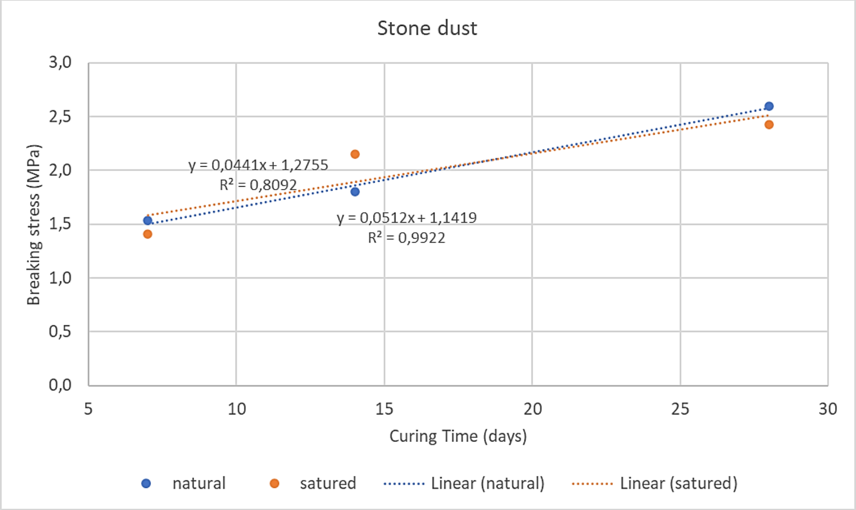
Table 6 - Ultrasonic pulse velocities (U.P.V.) for specimens molded with sand and stone dust.

Sand			
Characteristic	**7 days**	**14 days**	**28 days**
Unsaturated	3539.6 m/s	3655.56 m/s	3782.16 m/s
Saturated	33423.6 m/s	4032.32 m/s	4342.6m/s
Stone dust			
Characteristic	**7 days**	**14 days**	**28 days**
Unsaturated	2992,4 m/s	3279,02 m/s	3387,08 m/s
Saturated	3552.86 m/s	4422.46 m/s	4447.46 m/s

Source: Research data

According to the results presented in Table 6, it can be observed that the measured velocities remained above 3.000 m/s, a value expected to confirm the excellent quality of the curing of the specimens and the absence of internal microcracks that could compromise compressive strength. It is also noted that, for both dosages, the U.P.V. values increased with the curing time of the specimens. After sample characterization, molding, curing, and U.P.V. tests, compressive strength values were obtained for 7, 14, and 28 days. The average results are presented in Figures 5 and 6.

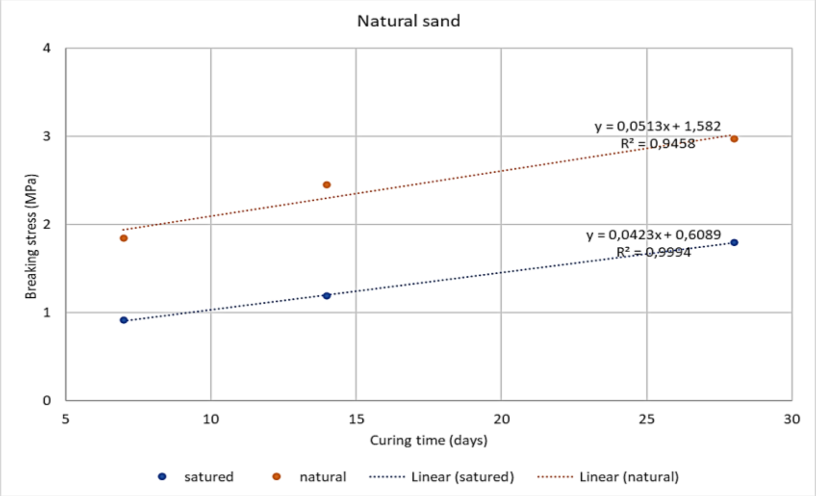
Figure 5 - Compressive strength of specimens molded with stone dust.



Source: Research data

Figure 5 shows that the specimens exhibited increasing compressive strengths with curing time, which is represented by well-fitted linear relationships (R^2=0.80 and R^2=0.99). The compressive strength values, both in the saturated and dry states, were similar. The following presents the compressive strength values determined for the specimens dosed with natural sand.

Figure 6 - Compressive strength of specimens molded with sand.



Source: Research data

Similarly to what was observed for the specimens dosed with stone dust, the compressive strengths shown in Figure 6 increased with curing time. The dry and saturated states showed a well-fitted linear relationship with time, according to the correlation coefficient values obtained (R^2 = 0.94 and R^2 = 0.99). However, the specimens presented different compressive strength results when comparing the dry and saturated states, unlike the tests conducted on the specimens dosed with crushed stone.

Nevertheless, it is noted that for both dosages studied, the compressive strengths (at any curing age) were above the minimum established by ABNT NBR 13.749, which is 1.5 MPa. Table 7 presents the correlation between U.P.V. and the maximum compressive strength obtained for both dosages after 28 days of curing.

Table 7 - Correlations obtained between U.P.V. and compressive strength (28 days)

Analysis	R (Pearson)	Obs
U.P.V. x Rcsand	+0.857	Strong positive correlation
V.P.V. x Rcstone	+0.700	Strong positive correlation

Source: Research data

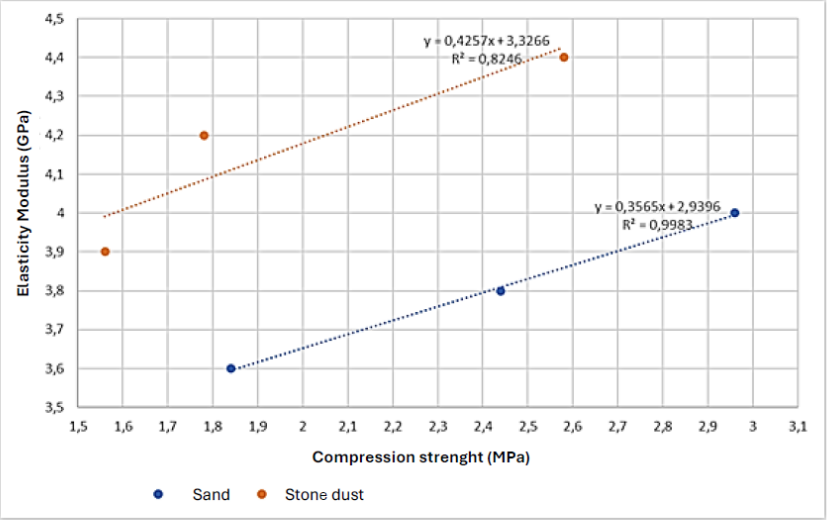
According to Table 7, there is a strong positive correlation between V.P.U. and compressive strength at 28 days for both dosages. This means that high V.P.U. values tend to correspond to higher compressive strengths. The average elastic moduli for each curing period are presented in Table 8, while Figure 7 compares the correlations between compressive strengths and elastic modulus.

Table 8 – Modulus of elasticity determined for different curing times: stone dust and sand

Mortar mixed with sand					
Characteristic	**7 days**	**14 days**	**28 days**	**regression**	**R^2**
Modulus of elasticity (GPa)	3.6	3.8	4.0	y=0.217x+3.355	0.99
Mortar mixed with stone dust					
Characteristic	**7 days**	**14 days**	**28 days**	**regression**	**R^2**
Modulus of elasticity (GPa)	3.9	4.2	4.4	y=0.2576x+3.6231	0.96

Source: Research data

Figure 7 - Correlation between modulus of elasticity and compressive strength.



Source: Research data

Table 8 shows that the elastic moduli ranged between 3.9 and 4.4 GPa, increasing over the curing time. Figure 7 presents well-fitted linear relationships between the elastic moduli and compressive strengths, considering all curing ages. The elastic moduli values and their linear correlations with compressive strengths are within the parameters established by Miranda (2000) and Mohamad et al. (2009), considering different studied mixtures. Table 9 presents the Poisson's ratios obtained for the tested mortars.

Table 9 - Poisson's ratios obtained for the tested samples

Specimen	v	Standard Deviation	Cv (%)	v Maximum range	v Minimum range	v Maximum	v Maximum
Mortar mixed with sand	0.21	0.05	23.8	0,.5	0.17	0.28	0.12
Mortar mixed with stone dust	0.24	0.10	41.6	0.31	0.16	0.40	0.14

Source: Research data

Poisson's ratio is the relationship between transverse and longitudinal deformation. In the rupture tests conducted after 28 days of curing, the Poisson's ratios obtained for the specimens dosed with sand and stone dust were 0.21 and 0.24, respectively. These values are consistent with those reported by Tokarski (2017), who indicates that the typical Poisson's ratio for mortars ranges between 0.15 and 0.25. The tables below present the average tensile strength values found for each panel.

Table 10 - Tensile strength obtained for panel 1 (1 layer of scratch coat)

Specimen	Dosage	Qr Average (MPa)	Qr (MPa) Maximum range	Qr (MPa) Minimum range	Qr (MPa) Maximum #	Qr (MPa) Minimum &
Mortar mixed with sand	Sand	0.30	0.35	0.25	0.38	0.22
Mortar mixed with stone dust	Stone dust	0.35	0.38	0.20	0.40	0.20

Where: Qr = tensile strength of the scratch coat layer; * average range obtained for a 95% confidence level; # = maximum value obtained; & = minimum value obtained. Source: Research data.

Table 11 - Tensile strength obtained for panel 2 (1 layer of scratch coat + 1 layer of plaster)

Specimen	Dosage	Qr Average (MPa)	Qr (MPa) Maximum range	Qr (MPa) Minimum range	Qr (MPa) Maximum #	Qr (MPa) Minimum &
Mortar mixed with sand	Sand	0.59	0.74	0.44	0.65	0.53
Mortar mixed with stone dust	Stone dust	0.62	0.66	0.60	0.64	0.61

Where: Qr = tensile strength of the scratch coat layer; * average range obtained for a 95% confidence level; # = maximum value obtained; & = minimum value obtained. Source: Research data.

Table 12 - Tensile strength obtained for panel 3 (1 layer of scratch coat + 2 layers of plaster)

Specimen	Dosage	Qr Average (MPa)	Qr (MPa) Maximum range	Qr (MPa) Minimum range	Qr (MPa) Maximum #	Qr (MPa) Minimum &
Mortar mixed with sand	Sand	0.65	0.80	0.50	0.69	0.58
Mortar mixed with stone dust	Stone dust	0.65	0.77	0.54	0.71	0.63

Where: Qr = tensile strength of the scratch coat layer; * average range obtained for a 95% confidence level; # = maximum value obtained; & = minimum value obtained. Source: Research data.

As shown in Tables 10 to 12, the tensile strength of the three panels was so similar that there was no significant difference between using stone dust or sand for wall coating. Therefore, the average tensile strength values of the mortars with sand and stone dust exceed the minimum values presented in Table 3. In other words, both dosages provide sufficient tensile strength according to the requirements of the Brazilian Technical Standard.

5 ANALYSIS OF THE RESULTS

To analyze the results and establish comparisons between the average parameters obtained, considering the mortars dosed with sand and stone powder, statistical analyses were conducted using the Paired T-Test, which was based on the following hypotheses:

- Null hypothesis (H0) = the differences between the variables are 0 ($p>0.05$);
- Alternative hypothesis (H1) = there is a difference between the variables ($p<0.05$).

The analyses are presented below.

Table 13 - Comparison between the average compressive strengths obtained (unsaturated samples)

Analysis	p	Obs.
RCsand7days x RCstoned7days	0.031 (<0.05)	The averages differ from each other
RCsand14daysx RCstoned14days	0.119 (>0.05)	There is no difference between the obtained averages.
RCsand28days x RCstoned28days	0.128 (>0.05)	There is no difference between the obtained averages.

Source: Research data.

Table 13 shows that only the average compressive strengths at 7 days of curing, obtained for the specimens dosed with sand and crushed stone powder, showed statistical differences. At 14 and 28 days of curing, the average strengths did not show significant statistical differences. Table 14 presents the comparison between the average elasticity modulus, specifically for the 28-day curing period. Table 15 shows the comparison between Poisson's ratios.

Table 14 - Comparison between modulus of elasticity at 28 days (unsaturated samples)

Analysis	p	Obs.
Estoned28days x Esand28days	0.49 (>0.05)	There is no difference between the obtained averages.

Source: Research data.

Table 15 - Comparison between Poisson's ratios (unsaturated samples)

Analysis	p	Obs.
vstoned28days x vsand28days	0.43 (>0,05)	There is no difference between the obtained averages.

Source: Research data.

The tables presented indicate that the values of the elasticity moduli and Poisson's ratios did not show significant statistical differences for both dosages studied. These results suggest that crushed stone powder can replace natural sand without compromising the essential mechanical properties of the mortars. Studies such as those by Antunes (2020) and Menossi (2004) had already suggested the feasibility of using alternative aggregates in civil construction, and the results of the present study reinforce this hypothesis. Additionally, a T-Test was conducted to verify whether the differences found in the pull-out strengths of the panels were statistically significant. The results are presented in Table 16.

Table 16 - Statistical comparison of the tensile strength found for each panel.

Analysis	p	Obs.
Qr stone dust x Qr sand	0.056 (>0.05)	There is no statistical difference between the averages
Qrp stone dust x Qrp sand	0.47 (>0.05)	There is no statistical difference between the averages
Qrpp stone dust x Qrpp sand	0.86 (>0.05)	There is no statistical difference between the averages

Source: Research data.

Comparing the tensile strengths (presented in Table 16) of the panels constructed with mortars dosed with crushed stone powder and sand, it is found that there are no statistically significant differences in the tensile strengths of the mortars, regardless of the type of aggregate used. This suggests that sand and crushed stone powder provide equivalent tensile strength performance.

Therefore, the tensile strength tests performed on the experimental panels demonstrated that mortars with crushed stone powder and natural sand exhibited similar performance. Previous studies, such as those by Santos et al. (2014), also reported that partial replacement of natural sand with alternative aggregates does not compromise the tensile strength of mortars. The study's results on replacing natural sand with crushed stone powder in mortars indicate significant technical and environmental implications for civil construction. Replacing natural sand with crushed stone powder reduces environmental pressure on sensitive ecosystems, such as riverbeds, by avoiding extracting natural sand. This supports adopting practices aligned with the circular economy, promoting the reuse of industrial waste.

Technically, mortars with crushed stone powder showed equivalent compressive and tensile strength, in compliance with current technical standards. This equivalence ensures that the use of crushed stone powder does not compromise durability or structural safety, maintaining adequate mechanical performance for masonry and coating applications. Thus, crushed stone powder is established as a viable and sustainable alternative.

6 CONCLUSIONS

This study has proven the technical feasibility of entirely replacing natural sand with crushed stone powder in producing mortars for masonry and coatings, offering a sustainable and effective alternative for civil construction. The characterization of materials and the tests conducted demonstrated that crushed stone powder possesses the necessary physical properties for use as fine aggregate, particularly its appropriate gradation and mechanical behavior comparable to that of natural sand. The results indicated that the specimens molded with crushed stone powder at any curing time studied showed equivalent or superior performance to those dosed with natural sand. Regarding compressive strength, the specimens with crushed stone powder achieved values similar to those molded with natural sand, remaining within the required regulatory parameters. Compressive strength, tested at 7, 14, and 28 days, was consistently high, with values exceeding the minimum established by ABNT NBR 13.749 of 1.5 MPa. Specifically, at 28 days, the crushed stone powder specimens exhibited compressive strength comparable to those with natural sand, demonstrating the robustness and technical viability of the material. Additionally, the elastic modulus of crushed stone powder mortars, ranging between 39 and 44 GPa, indicates that the material can meet the deformability requirements essential for the structural performance of buildings.

The tensile strength tests, conducted on experimental modules coated with mortars dosed with crushed stone powder and natural sand, provided concrete evidence of the technical feasibility of crushed stone powder as a complete substitute. The results demonstrated that the tensile strength of mortars with crushed stone powder exceeds the minimum values established by ABNT NBR 13.749, validating its use in masonry coatings and other structural components. The statistical analysis, using the Paired T-Test, did not show significant differences between the tensile strength values of mortars with crushed stone powder and those with natural sand, suggesting that both compositions provide equivalent performance from a mechanical point of view. This reinforces that the use of crushed stone powder does not compromise the structural integrity or durability of the mortars, maintaining the adhesion and strength required for practical applications.

Beyond the technical aspects, the use of crushed stone powder is closely aligned with the United Nations Sustainable Development Goals (S.D.G.s), particularly goals 9 (Industry, Innovation, and Infrastructure), 11 (Sustainable Cities and Communities), and 12 (Responsible Consumption and Production). Introducing industrial waste into the production cycle of civil construction, such as crushed stone powder, promotes the circular economy by reusing materials that would otherwise be discarded. Goal 9 highlights the importance of resilient infrastructures and innovative processes, and the use of crushed stone powder meets this need by offering a technical alternative that reduces the environmental impact of natural resource extraction. Goal 11 is addressed by considering that sustainable construction contributes to the longevity and reduction of city impacts. Finally, Goal 12 is directly approached by promoting recycling practices and reducing consumption of non-renewable resources, such as natural sand, which is efficiently replaced by crushed stone powder.

Therefore, using crushed stone powder as a substitute for natural sand in mortars meets the technical requirements of civil construction and presents considerable environmental advantages. For the industry, the adoption of crushed stone powder as an alternative aggregate is recommended, as the results indicate its equivalent performance in strength and elasticity tests. Furthermore, the creation of specific technical standards is encouraged to ensure quality control in its application, as well as the technical training of professionals involved in the construction process.

However, the study has some limitations. Although the laboratory results are promising, large-scale evaluations under different exposure conditions are necessary to confirm the viability of crushed stone powder in various construction scenarios. Additionally, the long-term durability of mortars with crushed stone powder under different environmental conditions still requires further investigation. Future research should focus on performance analyses in adverse climatic exposure conditions, behavior in response to carbonation, and the exploration of other waste materials as potential aggregates to further reduce civil construction's environmental and economic impacts. Conducting a comprehensive life cycle assessment (L.C.A.) would also be essential to quantify the environmental benefits of using crushed stone powder as a substitute for natural sand.

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