Experimental evaluation of mechanical properties of concrete with partial and total replacement of natural sand by manufactured sand

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Abstract
Despite the significant advances achieved over the years, concrete remains the subject of extensive research aimed at improving its properties while reducing production costs and minimizing environmental impacts. River sand, commonly referred to as natural sand, is extracted from riverbeds, and its exploitation is associated with considerable environmental degradation. Increasing environmental regulations have progressively restricted the use of materials from natural sources, encouraging the search for alternative aggregates. In this context, manufactured sand, obtained from rock crushing, emerges as a promising and economically viable alternative. This study evaluates the partial and complete replacement of natural fine aggregate with crushed sand in concrete production, using replacement levels of 0%, 30%, 50%, and 100%. The mechanical performance of the concretes was assessed through compressive strength tests conducted at curing ages of 14 and 28 days, using conventional concrete as a reference. The mix design was carried out according to the ABCP/ACI method, based on the granulometric characterization of the constituent materials. The results indicated that the concrete with 50% replacement of natural sand by manufactured sand presented the highest compressive strength, demonstrating the technical feasibility of this replacement level and its potential as a sustainable alternative to the exclusive use of natural sand.
Keywords: compressive strength; concrete; manufactured sand; modulus of elasticity; sustainable construction materials; tension strength by diametrical compression.

Avaliação experimental das propriedades mecânicas do concreto com substituição parcial e total da areia natural por areia britada

Resumo
Apesar dos avanços significativos observados ao longo dos anos, o concreto continua sendo objeto de extensas pesquisas voltadas à melhoria de suas propriedades, conciliando a redução dos custos de produção com a minimização dos impactos ambientais. A areia de seixo rolado, comumente denominada areia natural, é extraída dos leitos de rios, sendo sua exploração associada a significativa degradação ambiental. O aumento das regulamentações ambientais tem restringido progressivamente o uso de materiais de origem natural, incentivando a busca por agregados alternativos. Nesse contexto, a areia britada, obtida a partir da britagem de rochas, surge como uma alternativa promissora e economicamente viável. Este estudo avalia a substituição parcial e total do agregado miúdo natural por areia britada na produção de concreto, nos percentuais de 0%, 30%, 50% e 100%. O desempenho mecânico dos concretos foi analisado por meio de ensaios de resistência à compressão, realizados aos 14 e aos 28 dias de cura, adotando-se um concreto convencional como referência. A dosagem foi conduzida conforme o método ABCP/ACI, com base na caracterização granulométrica dos materiais constituintes. Os resultados indicaram que o concreto com 50% de

substituição da areia natural por areia britada apresentou a maior resistência à compressão, evidenciando a viabilidade técnica desse nível de substituição e seu potencial como alternativa sustentável ao uso exclusivo de areia natural.
Palavras-chave: *areia britada; concreto; materiais de construção sustentáveis; módulo de elasticidade; resistência à compressão por compressão diametral; resistência à tração por compressão diametral.*

1 Introduction

Concrete remains the most widely used material in civil engineering, being extensively applied in projects of different scales due to its versatility, durability, and satisfactory mechanical performance. With moderate replacement levels (≈20%–60%) and appropriate adjustments in mix design and admixtures, it is possible to achieve strengths comparable to conventional concrete, including in structural and pavement applications (Agrawal *et al*., 2024).

Its conventional composition—comprising Portland cement, water, and coarse and fine aggregates—results in a composite material with high structural efficiency and economic feasibility (Marques; Simões; Braga Junior, 2024). However, the continuous growth in global concrete demand has intensified concerns regarding the sustainability of its constituent materials, particularly the extensive use of natural aggregates extracted from the environment (Aparecido *et al*., 2025).

Among these constituents, natural sand—predominantly sourced from riverbeds—is one of the most commonly used fine aggregates. Its extraction has been associated with significant environmental impacts, including river siltation, ecosystem degradation, and alterations in fluvial dynamics (Rentier; Cammeraat, 2022; Poonia; Kansara; Choudhary, 2024). Furthermore, increasingly stringent environmental regulations have constrained the availability of this resource, fostering the search for alternative materials that combine adequate technical performance with reduced environmental impact.

In this context, manufactured sand, produced through rock crushing processes, has emerged as a promising alternative due to its wide availability, lower cost, and more environmentally controlled production. Previous studies have demonstrated that its use can maintain or even enhance concrete mechanical properties, particularly compressive strength, depending on parameters such as particle size distribution, morphology, and surface texture (Gurumoorthy; Madeshwaren; Pakkiri, 2025). Manufactured sand is more angular, elongated, and rough, which increases strength and elastic modulus due to improved interparticle interlocking (Wu *et al*., 2022).

Segundo Rifa *et al*. (2023), manufactured sand, industrial by-products, and recycled fine aggregates can replace natural sand while maintaining good durability and performance when properly proportioned. Several studies show equal or higher compressive strength when natural sand is partially or totally replaced by crushed sand, while maintaining the same water-to-cement ratio (Chiew *et al*., 2026).

Despite these advances, important challenges remain regarding the use of manufactured sand as a replacement for natural sand. Intrinsic differences—such as increased angularity, rough surface texture, and higher fines content may adversely affect the rheological behavior and workability of fresh concrete (Sousa *et al*., 2025). According to Aboagye, Gosselin and Wilson (2026), particle shape and surface texture reduce workability, requiring more water or superplasticizer.

Moreover, while some studies report improvements in mechanical performance, findings are not yet fully consistent, particularly for total replacement scenarios. Consequently, the technical feasibility and performance implications of partially and fully replacing natural sand with manufactured sand require further systematic investigation (Antunes; Gonçalves, 2021).

In light of these considerations, this study aims to evaluate the effects of partial and total replacement of natural fine aggregate (river sand) with manufactured fine aggregate on the properties of concrete, with particular emphasis on compressive strength.

A standardized mix design method is adopted, and the results are compared with those of a conventional reference concrete.

This research is justified by the need to develop sustainable alternatives that reduce the exploitation of natural resources while maintaining technical performance.

Additionally, it contributes to the advancement of scientific and technological knowledge on alternative aggregates, supporting the adoption of more sustainable construction practices aligned with current environmental requirements.

The remainder of this article is organized into three sections. Section 2 describes the experimental procedure, including the materials used, the characterization of the aggregates, the concrete mix design, the replacement levels of natural sand by manufactured sand, specimen preparation, curing, and the mechanical tests performed. Section 3 presents and discusses the results obtained for specific gravity, particle size distribution, workability, compressive strength, splitting tensile strength, and modulus of elasticity at 14 and 28 days. Finally, Section 4 summarizes the main conclusions of the study, highlighting the effects of the replacement levels and identifying the most favorable condition observed in the experimental program, as well as recommendations for future research.

2 Experimental procedure

The composite Portland cement type CP II-E-32, from the same production batch, was used to ensure uniformity of material properties. The selection of CP II-E-32 cement for this study is justified by its widespread use in conventional concretes and its suitability for the development of mechanical properties at intermediate and later curing ages.

This type of cement contains blast furnace slag as a supplementary material, which contributes to increased durability, reduced heat of hydration, and improved performance in potentially aggressive environments, in addition to presenting a lower environmental impact compared to purely clinker-based cements.

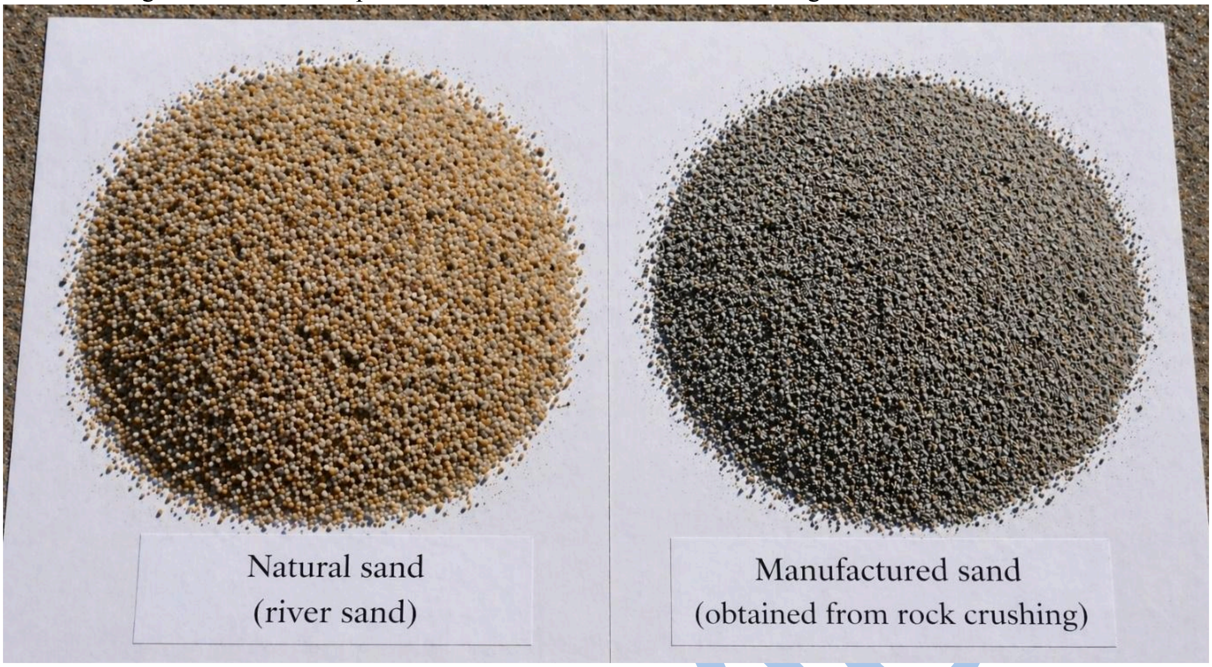
The CP II-E-32 cement is classified as a Portland composite cement with the addition of blast furnace slag, in accordance with the Brazilian standard ABNT NBR 16697 (ABNT, 2018b). Its physicochemical characteristics result directly from its composition and manufacturing process, influencing its performance in both fresh and hardened states.

From a chemical perspective, this cement consists of a mixture of Portland clinker, granulated blast furnace slag, and a small amount of gypsum. The clinker is mainly composed of calcium silicates (C_3S and C_2S), which are responsible for the development of mechanical strength, as well as aluminates (C_3A) and ferrite phases (C_4AF). The presence of slag contributes to reducing the heat of hydration and improving durability, as it promotes secondary pozzolanic reactions, forming additional C-S-H (calcium silicate hydrate) compounds. Chemically, a lower content of free calcium hydroxide is observed compared to ordinary cements, which enhances resistance to aggressive environments.

From a physical standpoint, CP II-E-32 presents controlled fineness (generally evaluated by Blaine specific surface area), which directly influences the hydration rate and strength development. Its typical specific gravity ranges from 3.0 g/cm³ to 3.2 g/cm³. The setting time is moderate, suitable for general construction applications, providing good workability. The characteristic compressive strength at 28 days is at least 32 MPa, according to the “32” classification, with progressive strength gain commonly observed due to the presence of slag.

The natural sand employed was extracted and commercialized in the local region. The manufactured sand, also referred to as crushed stone dust, was obtained from crushed rock and commercialized in the same region. The material was oven-dried at approximately 100 °C and subsequently sieved to remove particles passing through the 0.150 mm sieve. Figure 1 presents a visual comparison between natural sand of fluvial origin and manufactured sand obtained from rock crushing.

Figure 1 – Visual comparison between natural sand of fluvial origin and manufactured sand



Source: authors' archive.

After sieving, the material was properly stored in bags. The coarse aggregate used was crushed stone with nominal size 1, widely available in the region.

The particle size distribution of the natural fine aggregate (fluvial-origin sand), manufactured fine aggregate, and coarse aggregate was determined in accordance with the procedures established in ABNT NBR 17054 (ABNT, 2022b).

The specific gravity tests conducted following the procedures specified in ABNT NBR 16605 (ABNT, 2017) involve the determination of the specific gravity of Portland cement and other materials using the Le Chatelier volumetric flask.

The ABCP/ACI method was used to design the concrete mixtures with different replacement levels. A conventional mixture containing only natural sand was produced as the reference, serving as a basis for comparison with concretes incorporating partial and total replacement of natural sand by manufactured sand.

Replacement levels of 30%, 50%, and 100% were evaluated. In studies involving mixtures of natural sand and crushing waste (manufactured sand), the mix with 40% crushing waste and 60% natural sand showed the best performance in approximately 70% of the tests, including mechanical properties (Paschoalin Filho; Costa; Versolatto, 2024). Optimum levels frequently lie around 40%–70% replacement for normal-strength mixes (Shaheen *et al.*, 2023). Some studies report maximum strength at 60% replacement (Mane; Kulkarni; Prakash, 2021) or good performance at 100% in certain mixes and grades (Chiew *et al.*, 2026).

The use of stone dust and mining sands reduces the extraction of natural sand and promotes the utilization of by-products, with performance gains and potential reduction in cement consumption in some mix designs (Barbosa; Menezes, 2025).

Table 1 presents a summary of the material proportions adopted for each mixture, expressed in kg/m³, allowing a clear comparison of the constituent contents used in the different formulations.

Table 1 – Concrete mix proportions by mass with different replacement levels of natural sand by manufactured sand in kg/m³

Mix type	Cement (kg/m³)	Natural sand (kg/m³)	Manufactured sand (kg/m³)	Coarse aggregate (kg/m³)	Water (kg/m³)	Water/cement
Reference (0%)	355	789.17	–	1,036.75	213	0.60
30% replacement	355	552.42	203.31	1,036.75	213	0.60
50% replacement	355	394.59	338.85	1,036.75	213	0.60
100% replacement	355	–	677.70	1,036.75	213	0.60

Source: research data.

After all determinations were completed and the mixtures defined, concrete was mechanically mixed using a concrete mixer. Consistency was determined in accordance with ABNT NBR 16889 (ABNT, 2020): Concrete — Determination of consistency by the slump test (truncated cone method).

Specimen molding followed the procedures established in ABNT NBR 5738 (ABNT, 2015). Cylindrical molds measuring 10 cm in diameter and 20 cm in height were used. Considering testing ages of 14 and 28 days, six specimens were prepared for each mix for the evaluation of compressive strength, tension strength by diametrical compression of cylindrical test specimens and modulus of elasticity.

After molding, the specimens were kept in a protected environment for 24 hours. They were then demolded and cured by immersion in a lime-saturated water tank, as recommended by ABNT NBR 5738 (ABNT, 2015), until the scheduled testing dates. Water temperature was maintained at 23 ± 2 °C until the testing ages of 14 and 28 days.

Compressive strength tests were performed using a hydraulic testing machine, in accordance with ABNT NBR 5739 (ABNT, 2018a).

The tension strength by diametral compression of cylindrical test specimens was determined in accordance with the procedures specified in ABNT NBR 5739 (ABNT, 2018a), ABNT NBR 7215 (ABNT, 2019) and ABNT NBR 7222 (ABNT, 2011). It is emphasized that the accuracy range of the force transducers used to collect the splitting tension strength data was duly considered in the analysis of the results.

The static modulus of elasticity of concrete was determined following the procedures established in ABNT NBR 8522-1 (ABNT, 2021) which specifies the test method for obtaining the stress–strain relationship under axial compression. Figure 2 presents a schematic diagram illustrating the complete preparation process of the experimental procedure.

Figure 2 – Schematic diagram illustrating the complete preparation process of the experimental procedure

Source: elaborated by the authors.

3 Results and discussion

Table 2 presents the specific gravity of the materials used in the concrete mixtures. These parameters were considered in the mix design and are essential for ensuring proper proportioning and accurate evaluation of the concrete properties

Table 2 – Specific gravity of concrete constituent materials

Material	Specific gravity (g/cm³)
Cement (CP II-E-32)	3.04
Natural sand (river sand)	2.84
Coarse aggregate (gravel 1)	2.78
Manufactured sand (M-Sand)	2.43

Source: research data.

Table 2 presents the specific gravity of the materials used in the concrete mixtures. The cement (CP II-E-32) exhibited a specific gravity of 3.04 g/cm³, while the natural sand (river sand) showed a value of 2.84 g/cm³. The coarse aggregate (gravel 1) presented a specific gravity of 2.78 g/cm³, and the manufactured sand showed the lowest value, equal to 2.43 g/cm³.

The specific gravity value of 3.047 g/cm³ reported by Mendonça *et al*. (2022) is also within the typical range for CP II-E cements (3.0 g/cm³–3.15 g/cm³).

In Table 2, the river sand presented a specific gravity of 2.84 g/cm³. Although this value is slightly higher than the range generally observed for river sand, between 2.50 g/cm³ and 2.65 g/cm³, it may be associated with a denser sand (Yehia; Farrag, 2023).

Gravel commonly has a specific gravity between 2.59 g/cm³ and 2.76 g/cm³; your value of 2.78 g/cm³ is at the upper end, indicating a dense aggregate suitable for structural concrete (Yehia; Farrag, 2023).

Manufactured or recycled sands often have lower specific gravities due to higher porosity or residual mortar; values can range from about 2.20 g/cm³ to just over 2.60 g/cm³, so your value of 2.43 g/cm³ is consistent with these findings (Budiman; Patanduk, 2023).

These parameters were considered in the mix design and are essential for ensuring proper proportioning and accurate evaluation of the concrete properties.

Table 3 presents the results obtained from the particle size distribution analysis of river sand and manufactured sand, performed by sieve analysis. The test aimed to determine the percentage distribution of particles composing the fine aggregate, allowing the evaluation of the material's suitability according to current standards.

Table 3 – Particle size distribution of river sand and manufactured sand (M-Sand)

Sieve size (mm) ≠	Mass (g) – Manufactured	Retained (%) – Manufactured	Cum. Retained (%) – Manufactured	Mass (g) – River Sand	Retained (%) – River Sand	Cum. Retained (%) – River Sand
4.8	0.30	0.09	0.09	1.02	0	0
2.4	72.81	20.65	20.73	3.74	1	1
1.2	81.62	23.14	43.88	21.34	6	7
0.6	69.95	19.84	63.71	111.64	32	39
0.3	52.31	14.83	78.55	132.78	38	77
0.15	44.02	12.48	91.03	68.58	19	96
Pan	31.64	8.97	100.00	13.89	4	100
		100				

Manufactured Sand:
Fineness Modulus (FM): 2.98
Maximum Size: 4.8 mm
River Sand:
Fineness Modulus (FM): 2.20

Source: research data.

For the river sand, the results indicate that most of the material is concentrated in the 0.60 mm and 0.30 mm sieves, corresponding to 32% and 38% of the total retained, respectively. This distribution demonstrates a predominance of medium to coarse grains, which is a typical characteristic of fluvial sands composed of more rounded particles.

It is also observed that the finest fractions (smaller than 0.15 mm) represent approximately 4% of the material, indicating a low fines content. The sum of the cumulative retained percentages reaches 100%, confirming the completeness of the analyzed sample and the proper execution of the sieve analysis.

Based on the cumulative retained percentages, the fineness modulus (FM) was calculated by summing the cumulative retained percentages on standardized sieves and dividing by 100. The obtained value was approximately 2.20, which, according to ABNT NBR 7211 (ABNT, 2022a), classifies the material as medium sand, since $2.12 < FM < 2.71$.

This classification is fundamental for the technological control of fine aggregates, as the fineness modulus directly influences workability, water demand, concrete density, and, consequently, the mechanical performance of the hardened material.

Furthermore, the correct identification of particle size distribution allows for more accurate adjustment of material proportions in the mix design, ensuring better particle packing, void reduction, and optimization of cement consumption. In the specific case of the FM value of 2.20, the material presents a balanced granulometric distribution, without an excess of very fine or very coarse particles, contributing to good cohesion and adequate consistency of the concrete in the fresh state.

Therefore, the classification of the material as medium sand is met, since the fineness moduli obtained were $2.12 \leq FM \leq 2.71$, values that must be analyzed according to the requirements established by ABNT NBR 7211 (ABNT, 2022a).

Based on the obtained particle size distribution, it was verified that the first sieve in which the cumulative retained percentage exceeds 5% is the ≠ 1.2 mm sieve, with 7% retained. According to ABNT NBR 17054 (ABNT, 2022b) the maximum characteristic size of the fine aggregate corresponds to the opening of the sieve immediately above this one. Thus, the maximum aggregate size is ≠ 2.4 mm. This result indicates that the analyzed material fits the classification of a typical fine aggregate, with predominance of fine to medium particles. Such a characteristic favors workability and adequate accommodation of grains within the cementitious matrix, being compatible with the use in conventional concretes and mortars, as established by ABNT NBR 7211 (ABNT, 2022a).

For the manufactured sand, the accumulation of 63.71% of the material retained up to the 0.6

mm sieve demonstrates that manufactured sand presents a course granulometry compared to natural sand, which is characteristic of aggregates produced by rock crushing. This characteristic tends to influence the workability and particle packing of concrete, possibly requiring adjustments in the water–cement ratio or the use of plasticizing admixtures to maintain adequate mixture consistency.

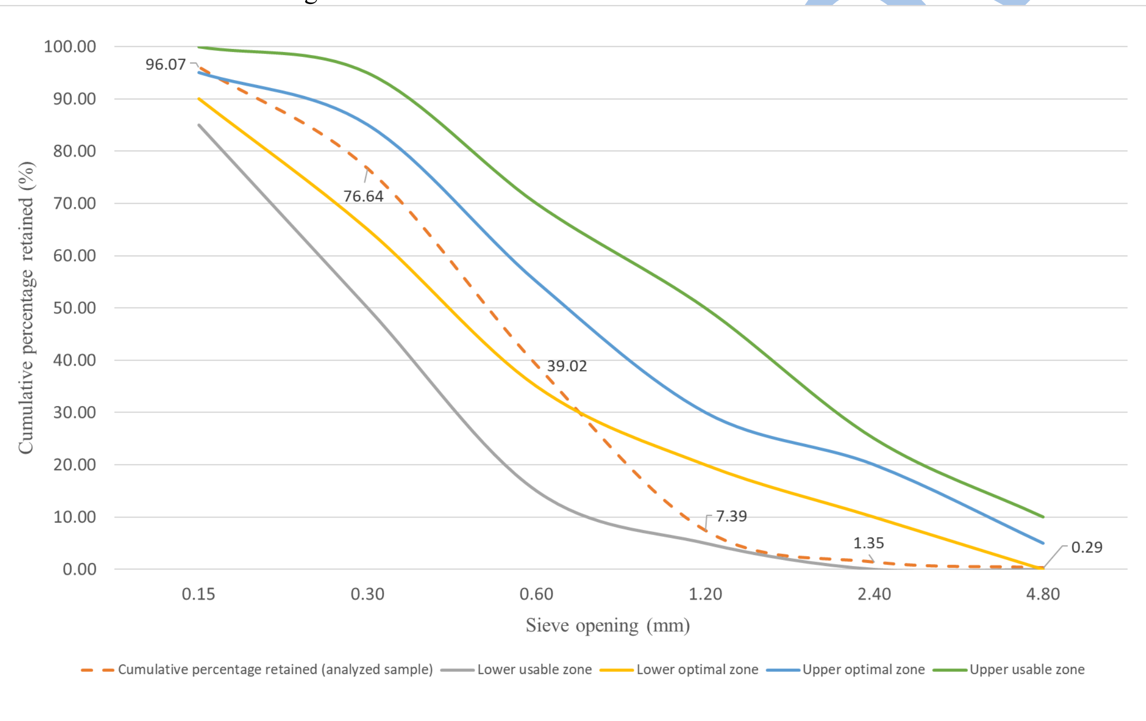
Based on the results presented in Table 3, the fineness modulus (FM) of the manufactured sand was determined as 2.98. This value indicates that the material presents a relatively coarse granulometry, according to the criteria established by ABNT NBR 7211 (ABNT, 2022a), since FM > 2.71.

The predominance of particles retained on the 2.4 mm (20.65%) and 1.2 mm (23.14%) sieves confirms the significant presence of medium and coarse grains, a typical feature of sands produced through rock crushing processes.

The nominal maximum size of the sample was identified as ≠ 4.8 mm. Although the retained percentage on this sieve was very low, its presence indicates that part of the material consists of larger grains, justifying the adoption of ≠ 4.8 mm as the nominal maximum size according to ABNT NBR 17054 (ABNT, 2022b).

Figure 3 presents the particle size distribution curve obtained for the river sand sample.

Figure 3 – Particle size distribution curve of river sand



Source: research data.

The analyzed curve generally lies within the usable limits, indicating that the material meets the recommended graduation requirements for application as fine aggregate in concrete.

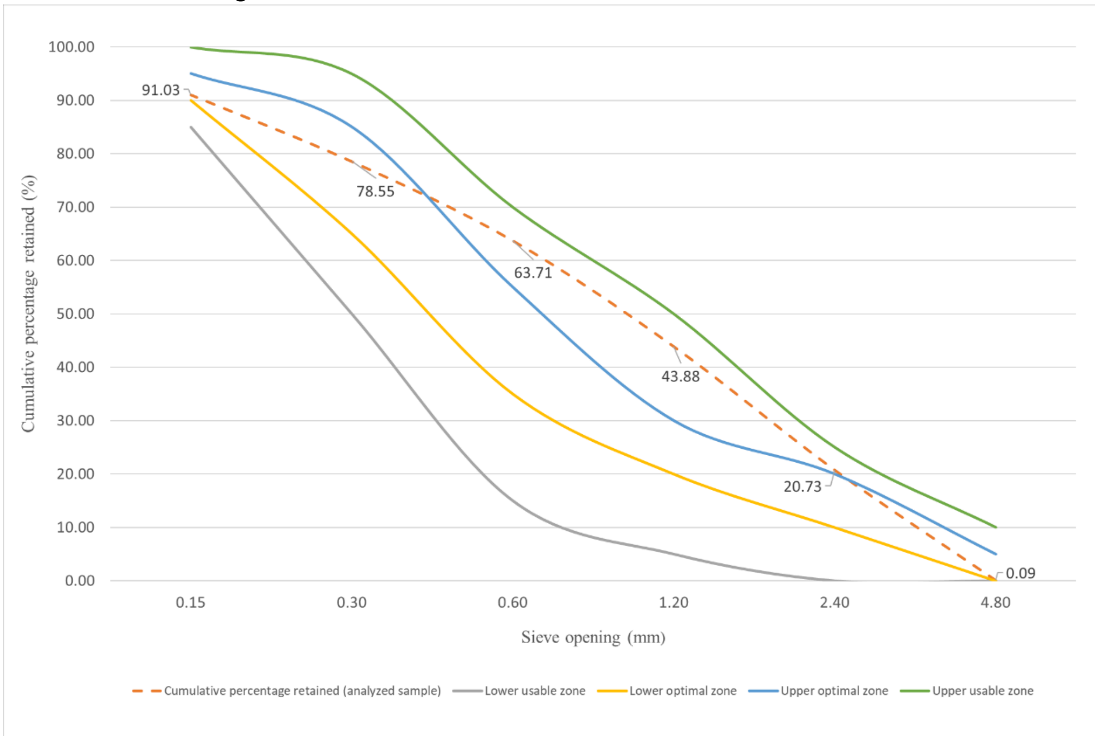
At the smallest sieve opening (≠ 0.15 mm), the cumulative retained percentage is approximately 96.07%, positioning the curve close to the upper usable limit and indicating a relatively high content of fine particles. At 0.30 mm, the retained percentage decreases to about 76.64%, still remaining within the recommended envelope. This behavior suggests a significant presence of fine fractions, which may increase the specific surface area and influence the water demand of the mixture.

For intermediate sieve sizes, particularly at ≠ 0.60 mm, the retained percentage is approximately 39.02%, placing the curve between the lower and upper optimal zones. This indicates a relatively continuous particle size distribution, which is desirable because it promotes better particle packing and reduces void content. However, at the ≠ 1.20 mm sieve, the retained percentage drops to about 7.39%, approaching the lower usable limit. This reduction suggests a lower proportion of medium-sized particles, which may slightly affect the balance of the gradation.

At larger sieve openings (≠ 2.40 mm and ≠ 4.80 mm), the cumulative retained percentages are approximately 1.35% and 0.29%, respectively, indicating a minimal presence of coarser particles. Despite this, the curve remains within the usable limits, demonstrating that the material does not present significant deviations from the recommended gradation envelope.

Figure 4 shows the slump values obtained for the reference concrete and for the mixtures with partial and total replacement of natural sand by manufactured sand.

Figure 4 – Particle size distribution curve of manufactured sand



Source: research data.

It can be observed that the curve of the analyzed sample generally remains within the range defined by the usable limits, indicating that the material exhibits a particle size distribution compatible with the standard requirements for fine aggregates intended for concrete production.

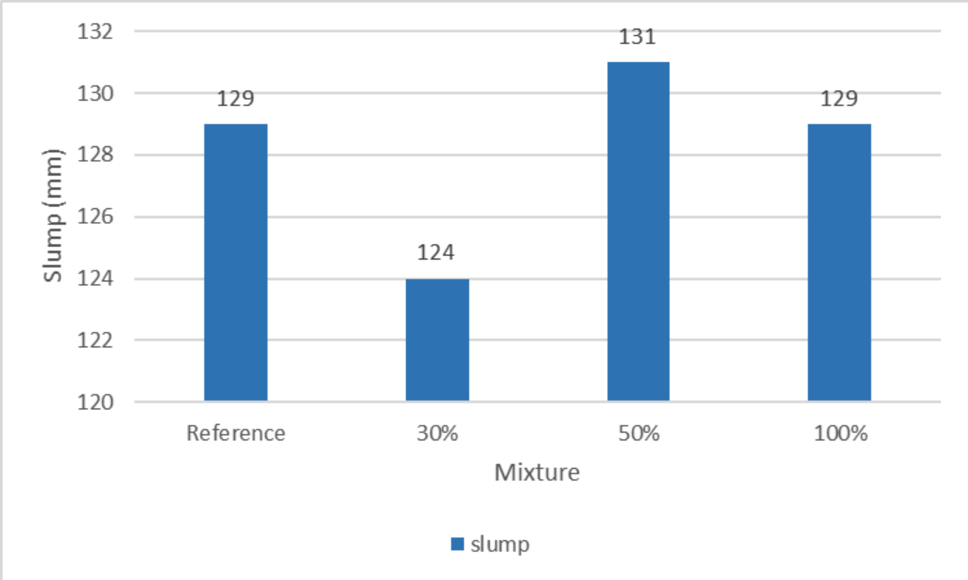
At the smallest sieve openings (≠ 0.15 mm and ≠ 0.30 mm), the cumulative percentage retained for the sample shows values close to the upper limits, indicating a relatively higher content of fine particles. This behavior may contribute to an increase in the specific surface area of the aggregate, influencing the water demand of the mixture and, consequently, the workability of the concrete (Zurauskiene; Kičaitė; Moceikis, 2026). Nevertheless, the curve remains within the recommended zone, indicating that the fines content is not excessive.

For the intermediate sieves (≠ 0.60 mm and ≠ 1.20 mm), the sample curve follows a trend approximately parallel to the reference curves, positioning itself between the lower and upper optimal zones. This behavior demonstrates a continuous particle size distribution, which is desirable as it promotes better particle packing, reduces voids, and contributes to the mechanical performance of concrete (Fonseca Junior *et al.*, 2025).

At larger sieve openings (≠ 2.40 mm and ≠ 4.80 mm), a gradual reduction in the retained percentage is observed, indicating a lower presence of coarser particles. Even so, the curve remains within the usable limits, showing that the material does not present a significant deficiency in this granulometric range.

Figure 5 presents the slump test results for the concrete mixtures with partial and total replacement of natural fine aggregate with manufactured sand at replacement levels of 0%, 30%, 50%, and 100%.

Figure 5 – Slump test results of concrete mixtures



Source: research data.

Figure 5 presents the slump test results, showing the variation in concrete workability at the different replacement levels evaluated. The slump values obtained were 129 mm for the reference concrete, 124 mm for the 30% replacement level, 131 mm for the 50% replacement level, and 129 mm for the 100% replacement level. It is observed that the mixture with 30% showed the lowest consistency, with a reduction in slump compared to the reference. This behavior indicates a decrease in workability, possibly associated with an increase in the specific surface area of the particles or higher water absorption, which reduces the mixture fluidity (Aziz *et al.*, 2024; Razzazan; Mashaan; Paraskeva, 2025).

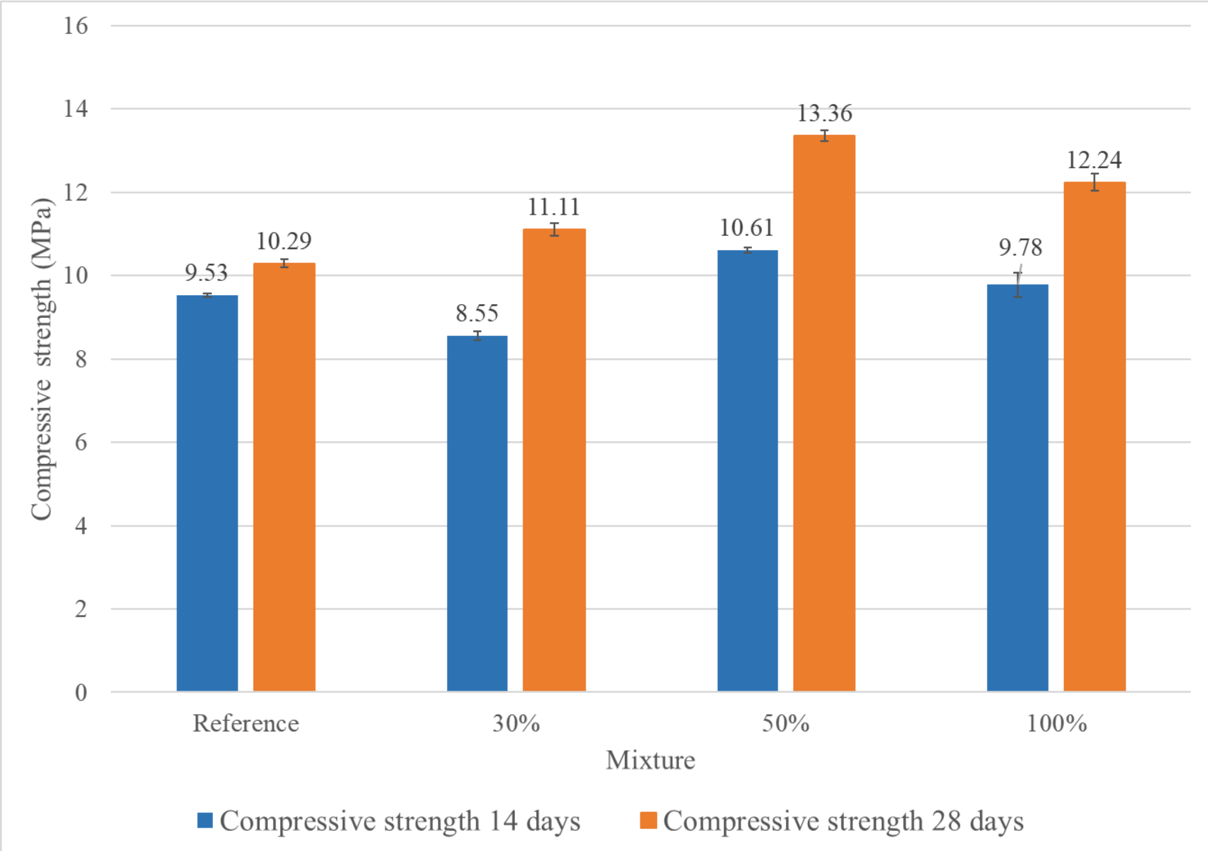
On the other hand, the composition with 50% showed the highest slump value (131 mm), indicating an increase in workability compared to the reference mixture. This result suggests better particle packing and a possible filler effect, reducing internal friction and improving the mobility of the fresh mixture (S; K, 2026).

The sample with 100% presented a slump equal to the reference (129 mm), indicating that total replacement did not significantly change the concrete consistency. This behavior demonstrates that, despite the material modification, the water demand and fluidity remained practically constant.

Overall, the results show that the 50% replacement promoted the highest workability, while 30% reduced consistency. However, all mixtures remained within a close range (124 mm–131 mm), indicating that the modification did not significantly compromise concrete workability, maintaining adequate conditions for application. In several studies, the slump decreases but remains within ranges considered acceptable by standards, allowing practical use without critical loss of workability (Gedefaw *et al.*, 2022; Oseke; Dangiwa, 2025).

Figure 6 presents the compressive strength results of the concrete mixtures at 14 and 28 days of curing.

Figure 6 – Compressive strength at 14 and 28 days



Source: research data.

At 14 days, the reference mixture reached a compressive strength of 9.53 MPa, serving as a comparative baseline for the other mixes. The 30% replacement resulted in a reduction to 8.55 MPa, indicating inferior early-age performance. This behavior may be associated with a dilution effect caused by reduced cement hydration efficiency and possible lower initial matrix compaction.

In contrast, the 50% replacement mixture presented the best performance among all evaluated conditions, reaching 10.61 MPa.

The mixture with 100% replacement achieved a compressive strength of 9.78 MPa, higher than that of the reference mixture. This indicates that complete replacement does not significantly impair early-age mechanical performance. Overall, the results indicate the existence of an optimal replacement level at 50%, which provided the best balance between microstructural development and compressive strength at 14 days.

The compressive strength results of the concrete mixtures at 28 days of curing indicate a clear influence of the replacement levels on mechanical performance. The reference mixture, produced exclusively with river sand, presented the lowest compressive strength, reaching 10.29 MPa. This behavior can be attributed to the more rounded shape of natural sand particles, which reduces internal friction and particle interlocking, negatively affecting strength development (Wu *et al.*, 2022).

With 30% replacement of natural sand by manufactured sand, the compressive strength increased to 11.11 MPa.

This improvement suggests that the incorporation of more angular particles enhanced particle packing and interlocking, although the gain was moderate (Sathvik *et al.*, 2025; Arulmoly; Konthesingha, 2022).

The highest strength was observed for the mixture with 50% replacement, which reached 13.36 MPa, representing the greatest increase among all compositions. This result indicates a more balanced granulometric distribution, combining rounded and angular particles, which contributes to void reduction and improved mechanical performance. Mixing rounded and angular particles, or combining different sizes, can improve packing, reduce voids, and enhance strength (Khan *et al*., 2025).

This is seen in composites and concretes where optimized gradation or polydisperse particles increase stiffness and strength by minimizing porosity (Semeykina *et al*., 2025).

For the total replacement (100%), the compressive strength obtained was 12.24 MPa, higher than the reference mixture but slightly lower than the 50% replacement. This small reduction may be associated with the higher angularity and surface roughness of manufactured sand, which tend to increase water demand and may hinder compaction when workability is not strictly controlled. Even so, the performance remained superior to that of conventional concrete (Guimarães; Bastos, 2022)

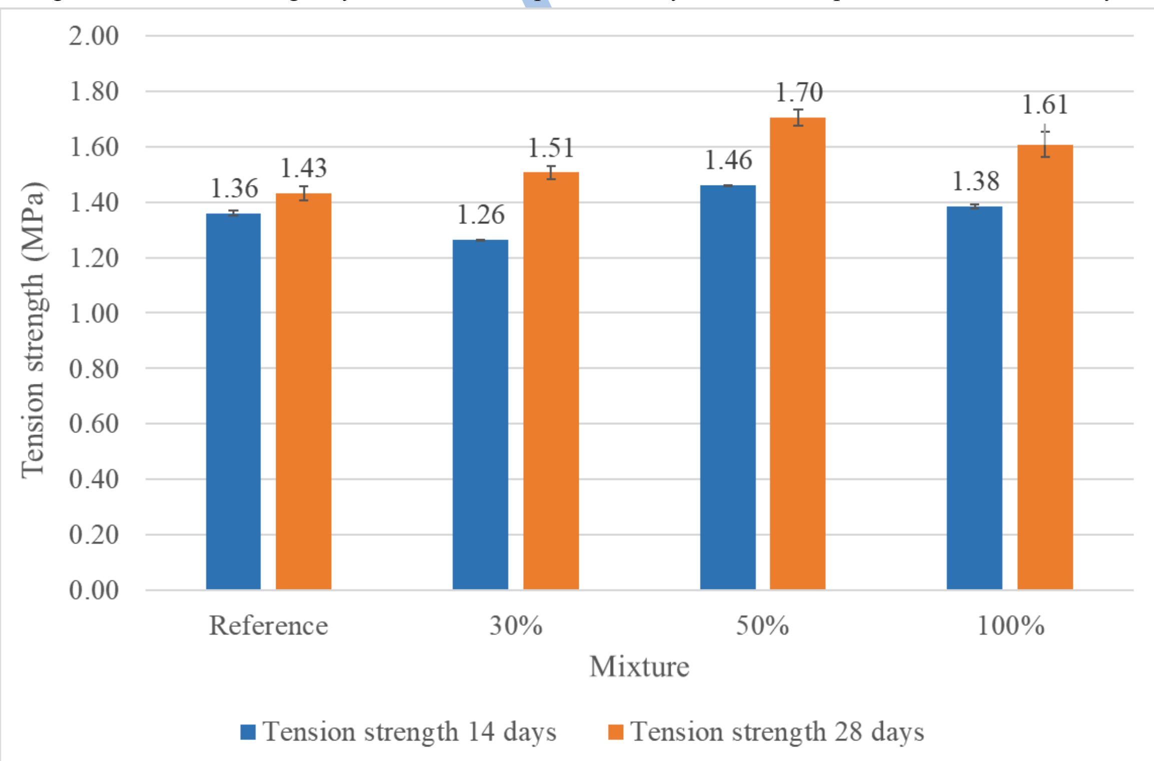
Overall, the results demonstrate that the partial replacement of natural sand with manufactured sand promotes consistent gains in compressive strength at 28 days, with the 50% replacement level showing the best mechanical performance in this study.

The relatively low compressive strength values observed, even with a water-to-cement ratio of 0.60, can be attributed to several factors related to the mixture composition and experimental conditions. First, a water/cement ratio of 0.60 is relatively high, which increases capillary porosity in the hardened matrix and, consequently, reduces compressive strength (Ding; She; Yao, 2023). Although this ratio improves workability, it usually results in lower mechanical performance.

Another important factor is the particle size distribution and packing density of the aggregates. Although the partial replacement improved particle interlocking, the overall granulometric composition may still have resulted in a higher void content, reducing the effective load-bearing area. In addition, the angularity of manufactured sand can increase water demand; when this additional demand is not compensated with admixtures, internal porosity increases. Studies show an inversely proportional relationship between the water-to-cement ratio and strength: as the w/c ratio increases, capillary porosity rises and strength decreases (Zheng *et al*., 2021; Zhao *et al*., 2024).

Figure 7 presents the tension strength by diametrical compression of cylindrical test specimens results of the concrete mixtures at 14 and 28 days of curing.

Figure 7 – Tension strength by diametrical compression of cylindrical test specimens at 14 and 28 days



Source: research data.

The reference mixture achieved a tension strength of 1.36 MPa. At 30% replacement, the tension strength decreased to 1.26 MPa, indicating that this proportion was not favorable for strength development at this age. This reduction may be associated with lower initial cohesion between the cement paste and the crushed aggregate (Gebremariam; Taye; Tarekegn, 2024).

The mixture with 50% replacement exhibited the best performance, reaching 1.46 MPa and surpassing both the reference and the other replacement levels. This behavior suggests that the combined effect of improved granulometric distribution, the angularity of manufactured sand, and enhanced particle packing contributed to a more resistant microstructure under tension stresses (Jin *et al.*, 2026).

For the 100% replacement, a tension strength of 1.38 MPa was obtained, slightly higher than the reference but lower than the 50% mixture. This result indicates that full replacement may adversely affect workability and the initial formation of the microstructure. High or full replacements commonly reduce workability, due to higher water absorption, rougher surfaces, or finer particles (Peixoto *et al.*, 2025). Moderate recycled content can refine pores and densify interfacial transition zone (ITZ), enhancing strength and durability; excessive content leads to larger porosity, weaker interfacial transition zone (ITZ), and reduced strength, even if values remain close to or slightly above the reference in some cases (Li *et al.*, 2025). Overall, at 14 days, the 50% replacement level provided the most favorable tension strength performance.

At 28 days, the reference concrete presented an average tension strength of 1.43 MPa, serving as a baseline. With 30% replacement, the strength increased slightly to 1.51 MPa, suggesting that the partial incorporation of manufactured sand improved the interfacial bonding between the cement paste and aggregates, likely due to the higher angularity of the crushed material (Sathvik *et al.*, 2025).

Rough M-sand surfaces create stronger mechanical interlocking forces between particles, contributing to higher compressive and, by extension, tension capacity (Sathvik *et al.*, 2025; Jin *et al.*, 2026).

The 50% replacement again showed the best performance, achieving 1.70 MPa. This superior result can be attributed to an optimal balance between natural and manufactured sand, promoting better particle packing and increased resistance to tension stresses.

The mixture with 100% replacement reached 1.61 MPa, also exceeding the reference. However, it remained below the 50% mixture, indicating that the exclusive use of manufactured sand may increase water demand or reduce workability, thereby limiting strength development. Studies show that partial replacement of river sand with manufactured sand (up to 50%) can improve workability and strength, but higher replacement levels often decrease these properties due to increased fine particles and water demand (He *et al.*, 2025)

Figure 8 shows the modulus of elasticity at 14 and 28 days, illustrating the mechanical behavior of concretes produced with different levels of replacement of natural sand by manufactured sand.

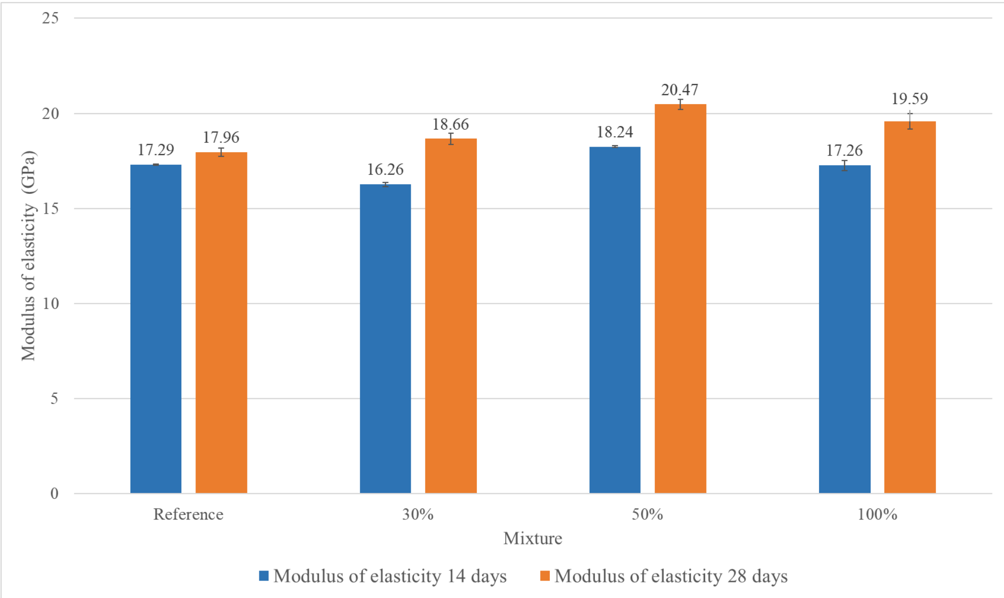


Figure 8 – Modulus of elasticity at 14 and 28 days

Source: research data.

The reference mixture exhibited an average modulus of elasticity of 17.29 GPa at 14 days, serving as a benchmark for comparison with the other compositions. This value is consistent with low-strength concretes, indicating a level of stiffness compatible with the expected behavior of the cementitious matrix at this stage of curing.

At the 30% replacement level, a reduction in the modulus of elasticity was observed, with a value of 16.26 GPa—the lowest among all mixtures analyzed. This result suggests that this proportion was not favorable for optimal particle packing, possibly leading to increased void content or weaker interaction between the cement paste and aggregates.

As a consequence, the concrete exhibited reduced stiffness and greater susceptibility to deformation under loading (Santos *et al*., 2022).

In contrast, the mixture with 50% replacement showed the highest modulus of elasticity, reaching 18.24 GPa. This improvement can be attributed to the enhanced angularity of the manufactured sand combined with a more balanced granulometric distribution, which likely promoted better paste–aggregate bonding and the development of a denser microstructure. Several studies link improved stiffness or strength to denser microstructure and better interfacial transition zones (ITZ) from optimized particle packing or supplementary fines (Xu *et al*., 2024). Thus, this replacement level appears to be the most effective for improving concrete stiffness at 14 days.

The mixture with 100% replacement presented a modulus of 17.26 GPa, very close to that of the reference mixture. This indicates that, although manufactured sand may exhibit higher intrinsic stiffness, its exclusive use does not significantly enhance the overall stiffness of the concrete.

At 28 days, all mixtures showed an increase in the modulus of elasticity compared to the values obtained at 14 days, which is expected due to the continued hydration of cement and the consequent densification of the microstructure (Jia *et al*., 2023).

The reference mixture reached a modulus of 17.96 GPa, characteristic of concretes with low to moderate stiffness. This value serves as a baseline and reflects the typical behavior of concrete without sand replacement. In comparison, the incorporation of manufactured sand positively influenced stiffness at this curing age.

With 30% replacement, the modulus increased to 18.66 GPa, indicating improved performance relative to the reference. Unlike the behavior at 14 days, this proportion resulted in a more stable and stiffer structure at 28 days. This improvement may be associated with the densification of the interfacial transition zone between paste and aggregates, enhanced by the angularity of the manufactured sand particles (Xu *et al*., 2024; Bahmani *et al*., 2024).

The 50% replacement mixture again demonstrated superior performance, achieving the highest modulus of elasticity at 20.47 GPa. This result confirms that this proportion provides optimal particle packing and structural efficiency, leading to significantly increased stiffness. The balanced combination of natural and manufactured sand likely contributed to a more efficient granulometric distribution and reduced deformability under load.

Finally, the mixture with 100% replacement reached a modulus of 19.59 GPa. Although this value is higher than those of the reference and the 30% mixture, it remains below the 50% replacement level.

4 Conclusions

The conclusions of the present study are directly aligned with the objective of evaluating the effects of the partial and total replacement of natural sand with manufactured sand on concrete properties. Based on the adopted experimental methodology, which involved mix design according to the ABCP/ACI method and the execution of standardized mechanical tests (compressive strength, tension strength and modulus of elasticity) at 14 and 28 days, it was possible to establish a consistent analysis of the performance of the evaluated mixtures.

The obtained results demonstrated that the replacement level significantly influences the mechanical behavior of concrete, confirming the initial research hypothesis. Among the evaluated replacement ratios (0%, 30%, 50% and 100%), the mixture with 50% replacement exhibited the best overall performance at both early age (14 days) and 28 days of curing, showing improvements in compressive strength, splitting tensile strength, and modulus of elasticity. This behavior is directly associated with improved particle size distribution and the packing effect resulting from the combination of natural and manufactured sand particles.

From the standpoint of workability, the slump test results indicated that the replacement did not significantly compromise the consistency of the mixtures, maintaining values within a range for practical application. However, higher contents of manufactured sand may require stricter control of the water-to-cement ratio due to the greater angularity and rough surface texture of the particles.

Furthermore, the results confirm that total replacement (100%) of natural sand does not significantly impair mechanical performance, although it did not surpass the results obtained for the 50% replacement level.

This finding indicates that, while technically feasible, full replacement may require additional adjustments in mix design to optimize performance. Therefore, it can be concluded that the objectives of the study were successfully achieved, as it was possible to identify an optimal replacement level and to understand the influence of manufactured sand on concrete properties. The adopted methodology proved to be appropriate and reliable for the proposed analysis, enabling the generation of consistent and comparable results.

To further advance the understanding of the effects of replacing natural sand with manufactured sand on concrete performance, future studies are recommended to investigate the influence of chemical admixtures, such as superplasticizers and viscosity-modifying agents, which may significantly improve concrete workability when higher contents of manufactured sand are used. Another important direction for future research involves durability assessment through tests such as absorption, permeability, carbonation, and resistance to aggressive agents, since service life analysis is essential to validate the use of this material in structures with higher performance demands. Additionally, microstructural analyses, such as scanning electron microscopy and porosimetry, are recommended to better understand the internal bonding mechanisms between the cement paste and manufactured aggregate, thereby elucidating the mechanical behaviors observed in this study.

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Conflict of interest

The authors declare no conflict of interest.

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Contributions to the article

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