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Influence of Fine Aggregates and Specimen Geometry on Mortar Compressive Strength

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ABSTRACT

The characterisation and comparison of mortars prepared with different standardised sands are essential to ensure the equivalence of results obtained under distinct national and international testing standards. The performance of mortars is heavily dependent on the physical and mechanical properties of the sand used as fine aggregates, such as particle size distribution, grain geometry, and water absorption. This study compared the standardised sand from Brazil (IPT), European sand (EN), and local sand from Porto União (Brazil), aiming to assess differences in their physical and chemical properties, their effects on mortar consistency and compressive strength, and the influence of specimen geometry (prismatic and cylindrical) on strength outcomes. The fine aggregates were characterised using Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), and other tests for organic matter content, humidity, and water absorption. Results showed no significant differences in aggregate morphology, except for minor variations in sphericity. Chemical composition was comparable across samples, though absorption rates were higher for European sands. Mortar consistency was also affected, with European mortars showing significant differences compared to others, and statistical distinctions between the mortars using Porto União sand and IPT sand. Specimen geometry had no significant influence on compressive strength. This research underscores the importance of understanding fine aggregate characteristics in optimising mortar performance.

1 Introduction

Historically, natural sand, characterised by its regular geometry, was widely used as the primary fine aggregate. However, due to the rapid development of infrastructure, the availability of natural sand has become scarce in several regions [1]. In

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response to this scarcity, alternatives, such as other types of sand, have been explored as fine aggregates in mortar production [2].

Fine aggregate is one of the main components of mortars and concrete, accounting for approximately 35% of the total volume of mixtures and influencing the properties of these systems [3]. Natural sands exhibit a diverse range of particle size distributions, requiring standardisation through regulatory guidelines — a process facilitated by production and distribution by the Institute for Technological Research (IPT). Additionally, CEN sands (Comité Européen de Normalisation: European Committee for Standardisation) can be used for applications involving cementitious materials [4].

Some studies highlight the influence of sand on the consistency and workability of mixtures, depending on the type of material produced and its application. Therefore, the quality of aggregates, such as particle strength and geometry, are critical parameters for evaluating the performance of materials produced with fine aggregates [5, 6].

However, [7] stated that the morphology of fine aggregate can be analysed on three independent scales: sphericity, roundness, and dimension. These factors influence the packing density, specific surface area, and equivalent diameter of the fine aggregate [7]. Analyses conducted by [8, 9] indicate that the particle size of sand has a significant impact on various parameters, including the coefficient of consolidation, coefficient of volume fluctuation, time to reach 90% consolidation, and compaction.

In addition to the differences in sand standardisation between the Brazilian and European specifications, there are also variations in the geometry of the test specimens. According to [10], the use of different specimen shapes results in variations in the measured strength values, since, as the authors emphasise, the compressive strength of concrete is markedly affected by the size and aspect ratio of specimens due to aggregates, altered frictions between concrete surfaces and loading platen, and differences in crack propagation and localised failure zones. Therefore, the shape and aspect ratio of the specimens influence the stress state during testing, affecting the measured compressive strength and, consequently, the correlation between the different types of specimens established in international standards.

The present study aims to comparatively evaluate the influence of the physical and chemical properties of different types of sand (EN, IPT, PU) on the workability and mechanical behaviour of mortars prepared under controlled mixing and curing conditions. Specifically, it seeks to identify how variations in particle morphology affect consistency and compressive strength at 7 and 28 days. Additionally, the study intends to assess whether specimen geometry (cylindrical versus prismatic) has a measurable influence on strength results, considering that different international standards adopt different formats, presupposing equivalence of behaviour.

2 Research significance

The standardisation of sands intended for mortar and cement testing, as recommended by international standards such as ASTM C109 [11], EN 196-1 [12], and NBR 7214 [13], presupposes functional equivalence between materials of different geological origins and preparation processes, in order that results obtained in distinct regions of the world can be comparable. This standardisation is implemented through regulations on particle size distribution, water–cement ratio, and specimen geometry, as shown in Table 1.

Table 1 - Differences in mortar standards.

Location	Standard	Water-cement ratio	Particle size (mm)	Specimen geometry
America	ASTM 109 [11]	0.485	4.75, 2.36, 1.18, 0.6, 0.3, 0.15, 0.075	cube (50×50 mm)
Brazil	ABNT NBR 7215 [14]	0.48	2.0, 1.6, 1.0, 0.5, 0.16	cylindrical (50×100 mm)
Europe	EN 196-1 [12]	0.5	2.4, 1.2, 0.6, 0.3, 0.15	prismatic (40×40×160 mm)

Brazilian standards, mirroring their international counterparts, serve as benchmarks for referencing technical regulations but do not override the laws, decrees, or regulations of individual nations [14]. Regarding mortars, these standards establish a framework for fabricating test specimens, acknowledging that the morphology and surface characteristics of aggregate particles influence the properties of cementitious materials [15, 16].

In this context, the equivalence among standardised mortars appears largely normative, as the sands differ in mineralogical composition, morphology, particle size distribution, and moisture content, directly affecting particle dispersion and mechanical behaviour. Minor variations in the physicochemical properties of the EN, IPT, and PU sands resulted in measurable differences in consistency and water absorption. Furthermore, specimen geometry introduced additional variability, influencing material confinement and stress distribution. These results highlight the remaining uncertainties regarding the physical–mechanical comparability of standardised sands and the influence of sand–geometry interactions on the mechanical response of mortars.

3 Materials and experimental program

3.1 Raw materials

Sands used in this research study included European sand standardized by CEN UNE-EN 196-1 [4], regular Brazilian sand (IPT) according to NBR 7214 [13], and sand collected in the municipality of Porto União (PU) in Santa Catarina state, southern Brazil. All these materials are commercially available as fine aggregates for mortar.

EN sand is commercially available in packages containing all mixed fractions, weighing 1,350 g, in accordance with EN 196-1 [4]. In contrast, IPT sand is supplied in packages with the fractions separated, following the specifications of NBR 7214 [13].

Brazilian sand underwent standardisation through sieving and washing, adhering to the fractions recommended by NBR 7214 [13] (Figure 1). These sands exhibit specific masses (g/cm^3) of 2.57 (EN), 2.53 (IPT), and 2.58 (PU), and bulk densities (g/cm^3) of 1.62 (EN), 1.55 (IPT), and 1.61 (PU). Portland CPV-ARI cement was used for mortar preparation, with Table 2 presenting the characterisation of physicochemical properties provided by the manufacturer.

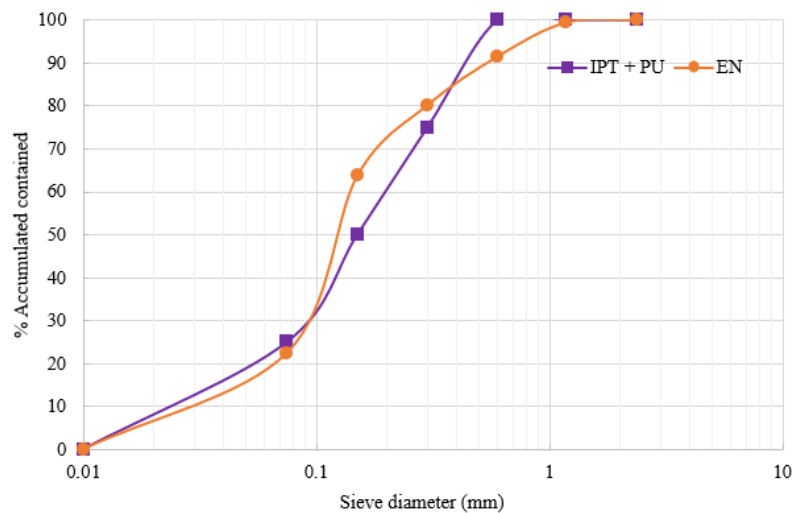


Fig. 1 – Granulometry of sands.

Table 2 - Physicochemical properties of CPV-ARI.

Specific mass (g/cm^3)	Fineness - 75 μm (%)	Fineness - 45 μm (%)	Chemical composition (%)
3.05	0.13	1.77	CaO – 61.56
			SiO ₂ – 21.7
			Al ₂ O ₃ – 5.69
			Fe ₂ O ₃ – 3.10
			MgO – 1.46
			SO ₃ – 3.99
			Na ₂ O – 0.07
			K ₂ O – 0.85
			Others – 1.58

3.2 Preparation of mortars

Mortars were prepared with each type of sand for cylindrical specimens (with EN, IPT, and PU) and prismatic specimens (with PU) (Table 3), following the preparation guidelines of NBR 7215 [14] for cement compressive strength tests. Mixing ratio was 1:3 (cement: fine aggregate), and the water-cement ratio was fixed at 0.48 for all mixtures.

Table 3 - Physicochemical properties of CPV-ARI.

Specimen	Cement (g)	Sand (g)					Water (g)
		Cumulative (%) retained					
		1.6 mm	1.0 mm	0.5 mm	0.16 mm	0.08 mm	
EN	624 ± 0.4	7 ± 5	33 ± 5	67 ± 5	87 ± 5	99 ± 5	300 ± 0.2
		1.2 mm	0.6 mm	0.3 mm	0.15 mm		
IPT	624 ± 0.4	468 ± 0.3	468 ± 0.3	468 ± 0.3	468 ± 0.3	468 ± 0.3	300 ± 0.2
PU	624 ± 0.4	468 ± 0.3	468 ± 0.3	468 ± 0.3	468 ± 0.3	468 ± 0.3	300 ± 0.2

Mortars were moulded into cylindrical specimens measuring 50 mm x 100 mm. A total of 36 specimens were moulded for each type of sand. After moulding for 24 hours, the mould was removed and then immersed in a tank for a 28-day wet curing period.

3.3 Experimental tests

Initially, sands were characterised based on their shape factor, water absorption (ABNT, 2000), and physicochemical requirements of NBR 7214 [13] for normal sands, including silica content $\geq 95\%$ (by mass), humidity content $\leq 0.2\%$ (by mass), and organic matter content ≤ 110 ppm. In addition, SEM/EDS analyses were performed. The mortars were tested for compressive strength in accordance with NBR 7215 [14] and for consistency in accordance with NBR 13276 [18]. Analysis of variance (ANOVA) and Tukey's test for multiple mean comparisons were applied to statistically analyse the results at a 5% significance level.

3.4 Analysis of Grain Morphology

A binocular magnifier, digital camera, and ImageJ software have been documented as methods for evaluating grain morphology [19, 20]. To study shape and texture, images must be captured using a photographic camera for larger fractions and a digital camera attached to a magnifier for smaller fractions [21], among other techniques. Shape factor and sphericity were evaluated using images from scanning electron microscopy, with grain measurements conducted using ImageJ software.

The investigation involved drying each type of sand in an oven at 110°C for 24 hours. For comparative purposes, 30 particles from each sample were selected in accordance with the recommendations of [19]. Following image acquisition, ImageJ software version 1.8 from the National Institute of Mental Health was utilized for image processing and analysis, allowing extraction of the shape factor parameter. This form factor was defined by Equation 1, and sphericity was determined by Equation 2.

$$\text{Form Factor} = \frac{\text{Perimeter of the Equivalent Circle}}{\text{Particle Perimeter}} \quad (1)$$

$$\text{Sphericity} = \frac{\text{Length of the Longest Axis of the Grain}}{\text{Length of the Shortest Axis of the Grain}} \quad (2)$$

Grains with shapes resembling spheres are represented by sphericity values close to one. Image processing in ImageJ included adjustments to brightness, contrast, and shadows. Particle edges were defined, noise was removed, and the image was converted into binary format. Subsequently, the software automatically calculated predetermined shape parameters (Figure 2). Particles were manually analysed, excluding those with incomplete edges or overlapping with others.

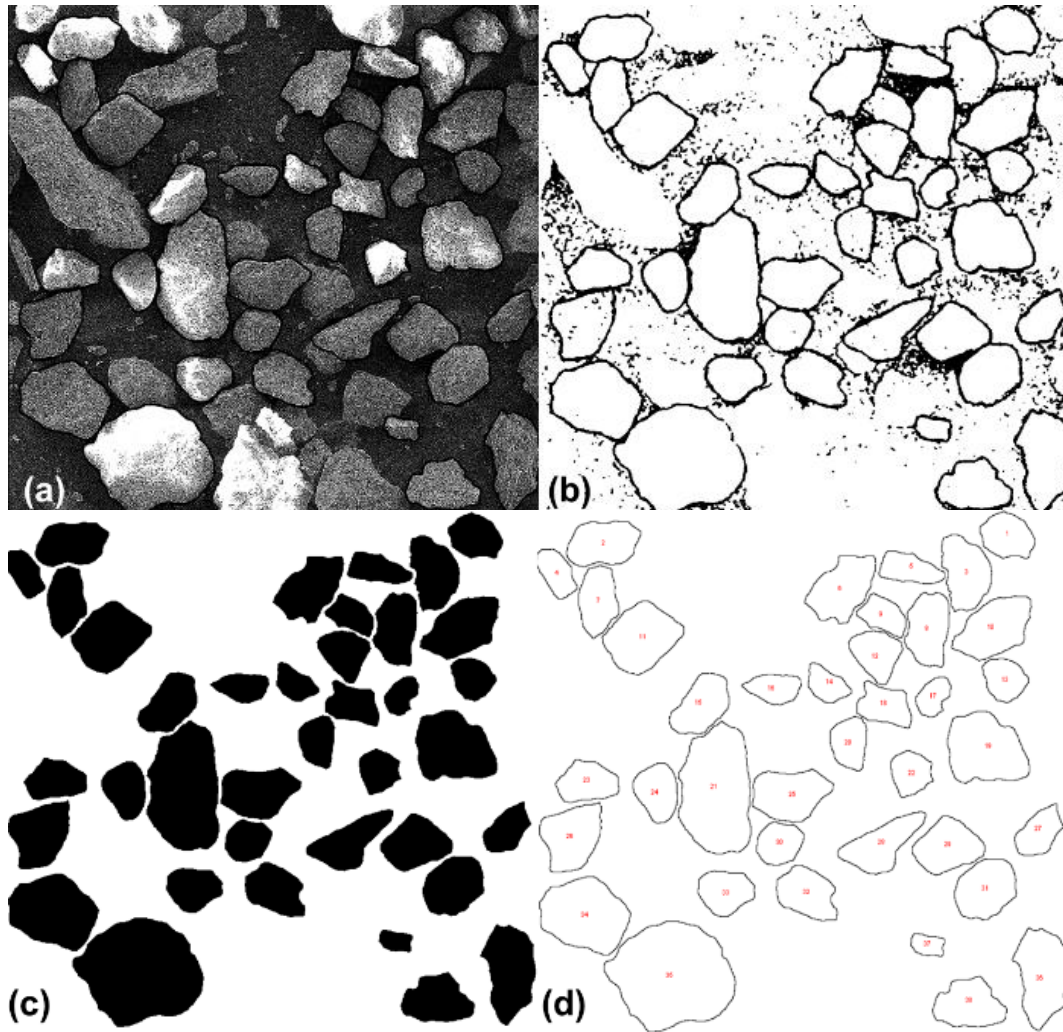


Fig. 2 - Procedure for correcting images in software – PU: a) image correction; b) particle edge delimitation; c) binary transformation; d) shape parameter determination.

4 Results and discussions

4.1 Morphology

Based on SEM images (Figure 3), particle form analysis was conducted for the three fine aggregates (EN, IPT, and PU). Using the adjusted images (Figure 4), the shape factor and sphericity of the aggregates were determined (Figure 5).

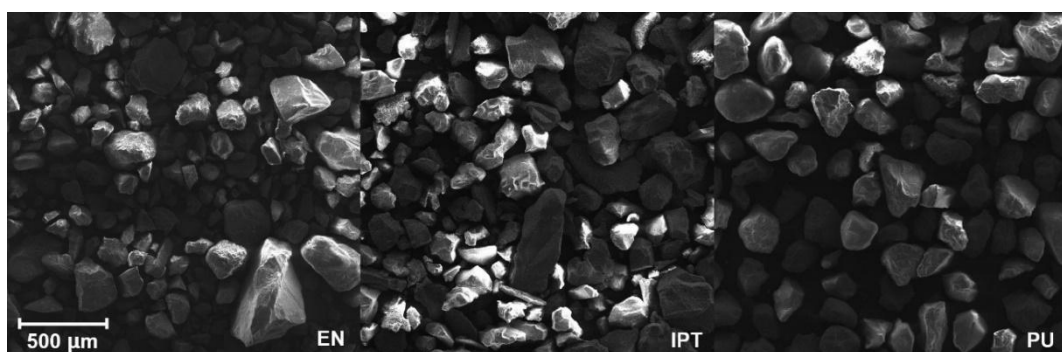


Figure 3 - SEM of aggregates: a) 100x magnification; b) 500x magnification.

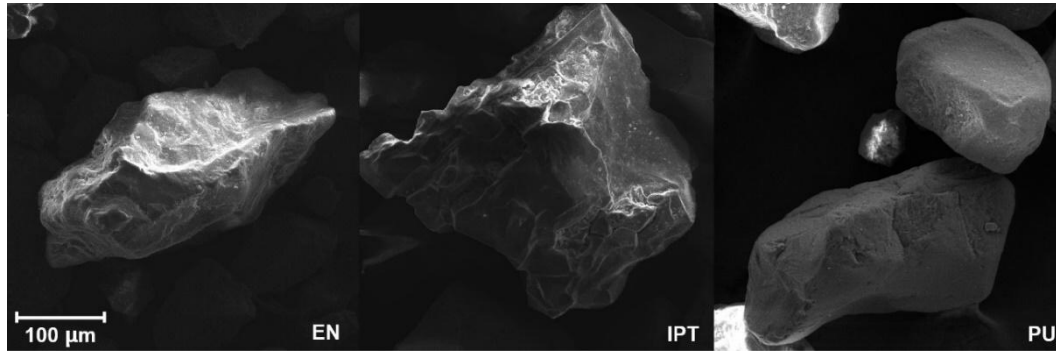


Figure 4 - Adjusted images to determine morphology.

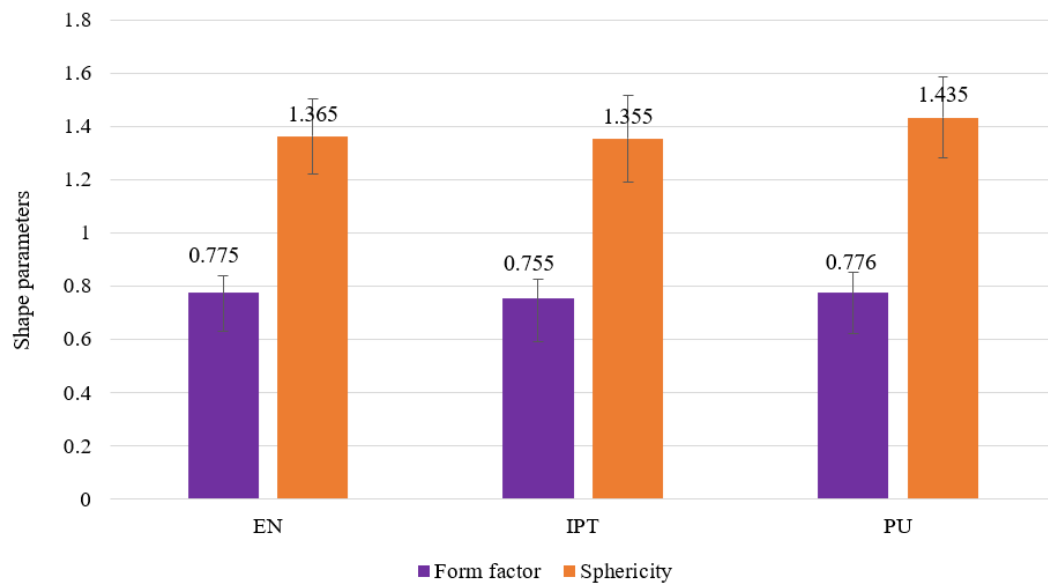


Figure 5 – Aggregate shape parameters.

The closely matched shape factors of the three samples indicate that both their shape and sphericity were similar, a finding that was statistically confirmed. The results showed no statistically significant differences in sphericity (p -value = 0.0916) or shape factor (p -value = 0.4475) among the aggregates (PU, EN, and IPT). This similarity is also evident in the SEM images (Figure 3b), which display particles with a mixture of angular and rounded shapes.

Other authors have reported shape factors of 0.643 for river sand and 0.6035 for fine aggregate recycled from excavated soil, suggesting that the 6.55% higher sphericity of river sand, along with its more uniform granulometric distribution, contributes to its greater fluidity in mortar production [22].

Analysing characteristics such as shape, angularity, and texture is essential when comparing the morphology of two materials. Research by [23, 24] corroborates this, categorising aggregate morphology into form, angularity, and texture. The mechanical properties of a material are influenced by its morphology, which also affects how a material is constructed and how load is transmitted [25, 26].

Furthermore, aggregate morphology significantly influences the strength and other properties of cementitious materials. Particles that are more spherical and rounded, with sphericity values close to 1.00, are more effective at packing grains compared to those with lower sphericity [6]. Aggregate geometry can positively affect the compressive strength of cementitious mixtures. Beyond the intrinsic strength of the aggregate, the mechanical strength of the mixture also depends on the interaction between the aggregate and the gel, as well as the internal friction between aggregates. Aggregate geometry is particularly crucial for ensuring adequate internal friction between grains, which, in turn, can enhance the compressive strength of cementitious materials [27].

4.2 Energy Dispersive Spectroscopy (EDS)

Analysis of oxides present in aggregates was conducted using EDS/SEM (Table 4). Results revealed higher silica content for all samples. Aluminium, iron, and potassium oxides were also quantified. Other chemical compounds were found in smaller amounts, such as magnesium and calcium in EN and sodium in PU. IPT aggregate did not show additional components beyond those listed in (Table 4).

Table 4 - Oxide content (%).

Element	EN	IPT	PU
Si	92.68	95.75	81.42
Al	4.91	3.25	5.99
Fe	0.89	0.6	0.54
K	0.64	0.4	11.06
Other	0.89	0.0	0.99

Analyses showed p-values ranging from 0.6245 to 0.1572, indicating no statistically significant difference for any oxide. Thus, it can be inferred that the oxide content in each aggregate is similar.

NBR 7214 [13] specifies certain physicochemical requirements for standardised Brazilian sand (IPT), including a minimum silica content of 95% by weight. This parameter was compared with the results obtained in the EDS analysis of aggregates in the present study (Table 4). It was observed that only the standard sand aggregate from IPT met or exceeded the specified standard.

According to [28], sands generally exhibit high concentrations of silicon dioxide (SiO_2) due to the presence of quartz. Furthermore, river sands, such as PU, have a lower amount of SiO_2 compared to other sands because they contain quantities of other oxides, such as aluminium oxide (Al_2O_3), potassium oxide (K_2O), and sodium oxide (Na_2O).

4.3 Organic Materials

When determining the organic matter content in fine aggregate, as standardised by NM 49 [29], all sands studied exhibited values ≤ 100 ppm, as recommended by NBR 7214 [13].

4.4 Humidity and Absorption

Humidity results and water absorption for the aggregates are presented in Table 5.

Table 5 - Aggregate humidity and water absorption.

Properties	EN	IPT	PU
Humidity (%)	0.45 ± 0.0003	0.44 ± 0.0010	0.34 ± 0.0003
Water absorption (%)	4.06 ± 0.11	2.12 ± 0.11	2.29 ± 0.05

According to the requirements of NBR 7214 [13], the maximum humidity content that aggregates should have when stored is 0.2% by mass. All aggregates studied, including IPT, which is standardised by the same norm, exhibited humidity levels exceeding this requirement. It is believed that this could be related to the relative humidity of the air in the city where tests were conducted, which was above 80% [30].

Although the PU aggregate underwent sieving, washing, and drying in an oven to achieve a constant mass, it was stored in sealed plastic bags. However, ambient humidity was not controlled. EN and IPT aggregates were stored in their original packaging upon receipt in the laboratory. Considering the similarity in humidity values for all particle sizes, it is understood that relative humidity of the air may influence the results. ANOVA statistical analysis revealed no significant difference between the humidity results for the three aggregates ($p = 0.1221$).

Regarding water absorption of the aggregates, statistical analysis showed a significant difference among aggregate types (p -value = 0.0004). Tukey's test was conducted to separate the aggregates into groups. The test resulted in a decision boundary of 0.3928, and it was observed that only the EN aggregate showed a significant difference from the others.

It is important to highlight that the particle size distribution of EN differs from IPT and PU. Different sand granulometries can result in varying levels of porosity in the final materials, affecting their relative density. The proper sand-cement ratio plays a crucial role in the composition of cement-based materials, directly influencing their physical and mechanical properties [7]. Moreover, the difference in water absorption among aggregates can influence workability, mechanical strength, and final porosity of the mixture. Consequently, some studies advocate for the addition of extra water to the cementitious mixture, considering the water absorption characteristics of the aggregates [31, 32]. In this study, the water content was not adjusted to account for absorption; the same amount of water was weighed and used for all mixtures.

4.5 Mortar

The consistency results obtained from the flow spread tests, following the preparation of the mixtures (Table 6), showed statistically significant differences among the mortars, as indicated by the analysis of variance (ANOVA) (p -value = 2.47×10^{-13}).

Table 6 – Consistency (cm).

EN	IPT	PU
18.17 ± 0.26	14.19 ± 0.35	15.60 ± 0.37

When compared to other mortars (Tukey's test), all mortars with EN displayed statistical differences. A distinction existed between mortars with PU and those with IPT. Particle size distribution of aggregates and the water combination used in mortars are responsible for the observed discrepancy in consistency. Mechanical characteristics of mortars are directly linked to variations in distribution of aggregate particle sizes. Beneficial behaviour of sand with respect to particle size distribution, homogeneity coefficient, and apparent density is responsible for the mechanical performance of mortars. These elements help produce an aggregate fraction with smaller voids, leading to mortars that are less porous, require less water, have greater densities, and higher mechanical strengths.

The consistency results showed distinct behaviour among the mortars, despite the identical water-to-cement ratio. The mortar prepared with European sand (EN) exhibited the highest flow spread, indicating greater fluidity, while mixtures with Brazilian sands (IPT and PU) showed lower consistency. This difference is attributed to the morphological characteristics of the aggregates: the more spherical and homogeneous EN particles reduce internal friction and promote better packing, compensating for their higher water absorption. In contrast, the more angular and irregular grains of the Brazilian sands increase surface area and interparticle friction, requiring more water for adequate coating and resulting in lower workability when the water content is kept constant.

After mixing in a fresh state, cylindrical specimens (EN, IPT, PUc) and prismatic specimens (PUp) were molded, then cured underwater saturated with limestone until 28 days of age. Before the mechanical test, the upper and lower surfaces of samples were ground. Subsequently, the axial compressive strength of each specimen was determined (Figure 6).

The compressive strength of mortars with EN and PU aggregates (p -value = 0.0420 and decision boundary of 2.6906) showed a statistically significant difference. Based on the results obtained, significant differences were found between the strengths of EN mortars and IPT mortars, and between IPT and PU mortars. This behaviour is related to the type of aggregate used, which influences particle packing and the interaction within the mortar matrix, ultimately affecting compressive strength. Mortars containing EN sand achieved higher strength values, while those with IPT and PU sands presented lower results. Although EN sand has higher water absorption, its more spherical shape and uniform particle size distribution promoted denser packing and stronger paste–aggregate bonding, leading to improved mechanical performance. Conversely, the Brazilian sands, characterized by more angular particles and less uniform grading, required additional water for proper lubrication and compaction. With a fixed water-to-cement ratio, this led to incomplete coating of particles and higher internal voids, reducing the overall compressive strength.

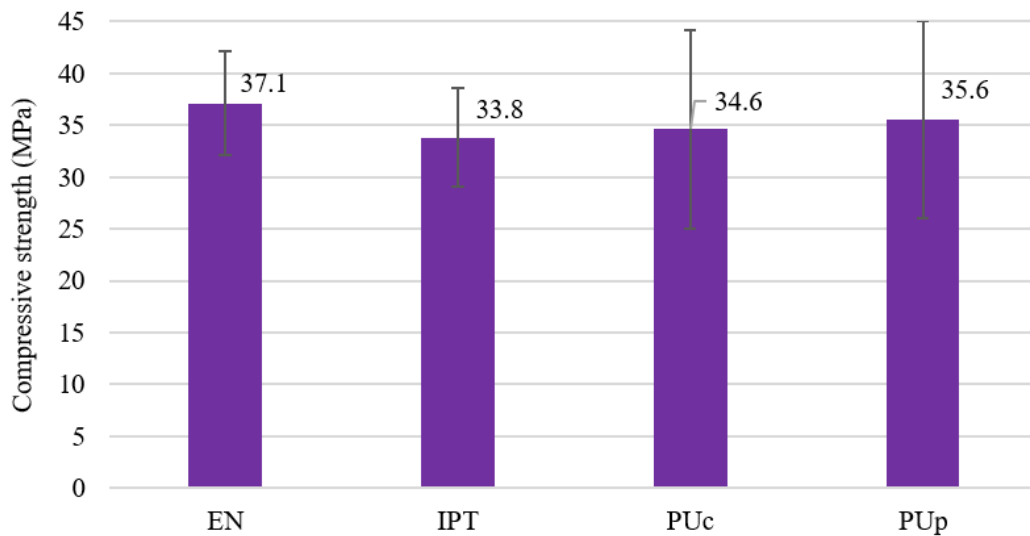


Figure 6 - Compressive strength.

Compressive strength results for PUc and PUp did not show a significant difference (p-value 0.979), indicating that specimen geometry did not interfere with mechanical performance of mortars. Although previous studies have shown that specimen geometry can influence compressive strength results, as demonstrated by [10], who reported differences between cylindrical and prismatic concrete specimens due to confinement and stress redistribution, no significant difference was observed between the cylindrical (PUc) and prismatic (PUp) specimens in this study. This result can be attributed to the homogeneous nature of the mortar, the smaller specimen size, and the strict control of moulding, compaction, and curing conditions. These factors minimize end friction and lateral confinement effects, which are typically responsible for strength variations in more heterogeneous materials such as concrete. Therefore, for the fine and uniform mortar evaluated, the geometric difference between prismatic and cylindrical specimens was not sufficient to produce a statistically significant variation in compressive strength.

5 Conclusions

The analysis of the influence of different sand types in cement mortars and across distinct specimen geometries revealed the following:

- The sands exhibited similar particle shapes, with minor variations in sphericity, which may have influenced mortar workability. This aspect is directly related to the consistency differences observed.
- All samples contained the same oxide types, with only slight quantitative variations, indicating that chemical composition was not a determining factor in performance differences.
- Water absorption values exceeded the maximum limit recommended by Brazilian standards; however, no correction for absorption was applied, and the same weighed amount of mixing water was used for all mixtures, which may have affected workability and compressive strength.
- Tests revealed significant differences among mortars: sands EN and PU provided higher workability, whereas IPT resulted in lower consistency, likely associated with particle shape and sphericity.
- Compressive strength results were generally similar across samples, except for EN and PU, with EN achieving the highest strength and PU the lowest, a difference of approximately 7.28%. Specimen geometry did not significantly affect compressive strength, as mix proportions and the water–cement ratio were maintained.

Future perspectives: Further studies should include sands from other regions with distinct physical and chemical characteristics and extend the analysis to durability-related aspects, such as long-term water absorption, to provide a broader understanding of material performance.

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