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# Rheology of Cement Mortars with Crushed Fine Aggregates of Different Lithological Types

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**Abstract:** Crushed fine aggregates are widely used for full or partial replacement of natural sands in concretes. The crushed sands present different characteristics from the natural sand, especially if taking into account the content of microfine particle, the distribution of particle sizes, the shape features, besides the different lithological origin. From the rheological point of view, the crushed sands frequently provide mixtures with high yield stress, high viscosity, high cohesion and internal friction, which hinders its use in concrete. This study is focused on the evaluation of the rheological behavior of concrete mortar phase when using different lithological types of crushed sand in total replacement of natural sand. The lithological types surveyed were granite, calcitic limestone, dolomite limestone and mica schist. Each of these sand types was studied in two ways: in natura and with adjusted grading curve. The results show the best performance of calcitic limestone providing lower viscosities and lower yield stress in mortars.

**Key words:** Crushed fine aggregate, rheology, mortar, lithology, particle shape, particle size distribution.

## 1. Introduction

The sand from the crushing of rocks is a byproduct of the classification and processing of gravel. The generation of waste from mining and quarrying of gravel is a major economic and environmental problem of the sector. The high demand for sand in the construction industry along with environmental constraints to its exploitation encourage the replacement of natural sand for crushed sand in concrete and mortars.

In relation to the properties in the hardened state, there does not seem to have problems with the replacement of natural sands by crushed sands, since, in most cases, the mechanical properties of concretes produced with crushed sand seem to be similar to those concrete made with natural sand. The properties of concrete with fresh crushing sand become differentiated in relation to the concrete with natural sand, specifically in relation to the rheology of the mixtures. The yield stress and plastic viscosity are the basic parameters for determining the rheological behavior of mortars [1-3]. The yield stress describes the shear stress required to initiate flow of the mortars, while the plastic viscosity describes how easily the mortars flow [4].

The mortars with crushed fine aggregates generally exhibit higher yield stress and plastic viscosity than the reference mortar with natural fine aggregates. This behavior is the result of both the high amount of fines and the more irregular shape of the grains in the crushed aggregates. The crushed sand particles are usually angular in shape and, depending on the lithological type, may be more or less laminated and with variable roughness. The natural sands usually are rounded and present low roughness and medium to low angularity, these characteristics are one of the main reasons for the differences in rheological behavior of mixtures. Scientific studies that deal with the full replacement of natural sand for crushed sand usually do so considering only one specific

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lithological type [5-8]. The optimization of particle size distribution of fine aggregates, which lead to a better packing density of the particles, plays an important role in workability, pumpability and segregation of cementitious materials [9].

This study concentrates in the rheological behavior of mortars with four distinct lithological types (granite, mica schist, calcitic and dolomitic limestones), taking as reference a natural river sand. Each of these sands was studied in two ways: in natura and with adjusted grading curve. For the analysis, we carried out detailed characterizations of the petrography, morphoscopy and physical aspects of particles. The rheological study is performed on the mortar phase of concrete, proceeding the evaluations of plastic viscosity and yield stress, as well as assessments of cone penetration and flow table test.

## 2. Materials and Experimental Program

### *2.1 Materials*

The experimental program developed in the present study was based on the evaluation of the concrete mortar phase behavior, using crushed sands. For that, starting from a study of concrete mix proportion, using the Faury method [10], it was obtained from a proportion (mass) of mortars study, shown as: 1:2.21:0.62 (cement:sand:water/cement). All mortars were mixed respecting this proportion.

The aggregates surveyed were from Brasilia region (Brazil) and Goiânia region (Brazil), basically:

(1) Crushed sands of lithological types

- Granite—Aparecida de Goiânia/GO, Brazil;
- Calcitic limestone—Padre Bernardo/GO, Brazil;
- Dolomite limestone (with rounded grains-crushed by VSI (vertical shaft impact) method)—Brasília/DF, Brazil;
- Mica schists—Aparecida de Goiânia /GO, Brazil.

(2) Natural river sand—Corumbá River/GO, Brazil

The crushed sands were used in two conditions:

(a) in natural, i.e., without performing any sort of classification treatment, sorting or washing;

(b) benefited by obtaining an adjusted grading curve, as explained as follows.

In most crushing plants, the crushed sands are obtained by a composition of grains that are retained in sieves with mesh opening of 0.6 mm and the grains that pass through this sieve. The idea then is to vary the particle size composition of the sands used in this study in a similar way to the one used in practice, that is, varying the proportions of the grains that are retained in the 0.6 mm sieve and the others that pass through it, controlling only the content of fine material used. This proceeding is similar to the one adopted by Prudencio, Coelho and Gustein[11]. The mixtures with variation in the granulometric composition compounded with 70% of material retained on the opening of the 0.6 mm mesh and 30% of material which passed through the opening of the mesh presented particularly interesting results in the rheological behavior and it was presented in this study.

The sands used in the study were characterized according to the petrographical aspects in relation to the ABNT (Brazilian Association of Technical Standards) NBR 7389/1992 standard [12], as well as according to their physical characterization by AMN (Asociación Mercosur de Normalización) NBR 248/2003 [13] (granulometric composition of aggregates) and NBR NM 30/2001 standards [14] (water absorption). The morphoscopic classification for sphericity and angularity was performed by image analysis of the sands studied, with the aid of a magnifying glass with the methodology adopted by Suguio [15]. The superficial texture is the aspect or feature of the grains surface, and was determined according to ABNT NBR 7389/1992 [12].

From the petrography analysis, it is noticed that two artificial sands (dolomitic limestone and calcitic limestone) have a calcite predominance in their composition and two artificial sands (mica schist and granite) presented the quartz as a main component. It is also noticed that there is a presence of micaceous minerals in all materials, which can be a negative aspect that may impair the mechanical resistances due to the cleavage plans oriented in the material. The natural sand showed the most heterogenic mineralogical composition of the analysis, but yet the most common mineral was the quartz.

The morphoscopic classification is presented in Table 1. It is noted that the materials with higher sphericity were the dolomitic limestone and the granite, and the mica schist was the one with lower sphericity. Regarding the angularity, the granite, the calcitic limestone and the mica schist presented more than 50% of its grains classified as very angled and angled. The natural sand had the highest percentage with rounded corners and edges, followed by the dolomitic limestone (very likely due to the use of a crusher, which favors higher sphericities). As for the roughness (texture), the granite presented the higher roughness, followed by the mica schist and the calcite. The natural sand presented the highest percentage of smooth and low roughness grains.

Regarding the physical parameters, Table 2 presents the obtained results. In terms of comparison, it is noted that for the calcitic limestone, the dolomite limestone, the granite and the natural sand, the great majority of the grains are located below the 2.40 mm sieve. The mica schist stands out of this rule, presenting a little thicker grading distribution, particularly in sieves of 2.40 mm and 4.80 mm. The natural sand had a higher content of particles smaller than 0.3 mm, classified as fine particles. In relation to the microfine content (passing 0.075 mm sieve), it is important to observe, mainly, the granite, the mica schist and the calcitic limestone, which presented the highest levels. The mica schist was the sand that had the highest percentage of water absorption. All sands studied were used with surface moisture of 0%. The calcitic limestone is obtained with the composition similar to the adjusted granulometry, with 70% of material retained in 0.6 mm sieve and 30% of the passing

**Table 1 Morphoscopic classification of sands (percentual incidence of the each evaluation).**

| Sands | Sphericity (%) | | Angularity (%) | | | | | | Superficial texture (%) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | High | Low | VA | AN | SA | SR | RD | SR | HR | RO | LR | SM |
| Granite | 56.7 | 43.3 | 40.0 | 36.7 | 20.0 | 3.3 | ** | ** | 50.0 | 40.0 | 6.7 | 3.3 |
| Calcitic | 33.0 | 67.0 | 13.3 | 53.3 | 23.3 | 10.0 | ** | ** | 3.3 | 68.3 | 25.0 | 3.3 |
| Dolomitic | 85.0 | 15.0 | ** | 35.0 | 35.0 | 25.0 | 5.0 | ** | ** | 57.5 | 40.0 | 2.5 |
| Mica schist | 20.0 | 80.0 | 23.1 | 38.5 | 30.8 | 7.7 | ** | ** | 3.3 | 76.7 | 20.0 | ** |
| Natural sand | 37.0 | 63.0 | ** | 6.7 | 43.3 | 33.3 | 16.7 | ** | 1.7 | 15.0 | 51.7 | 31.7 |

VA—very angled; HR—high rough; AN—angled; RO—rough; SA—sub angled; LR—low rough; SR—sub rounded; SM—smooth; RD—rounded; SR—very rounded.
** means that no percentage of grains were recorded in this category.

**Table 2 Physical parameters of the studied sands.**

| Sieves (mm) | Cumulative percentage retained | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Calc (%) | Mica (%) | Mica A (%) | Dolom (%) | Dolom A (%) | Gran (%) | Gran A (%) | Natural sand (%) |
| 6.3 | 0.1 | 2.0 | 2.2 | 0.5 | 0.5 | 0.0 | 0.03 | 0.3 |
| 4.8 | 0.1 | 2.8 | 3.1 | 0.8 | 0.7 | 0.0 | 0.04 | 1.2 |
| 2.4 | 0.6 | 20.6 | 22.5 | 2.8 | 2.6 | 7.0 | 10.4 | 6.2 |
| 1.2 | 35.2 | 53.3 | 58.3 | 51.0 | 46.9 | 34.3 | 50.8 | 30.2 |
| 0.6 | 67.8 | 64.1 | 70.0 | 76.1 | 70.0 | 47.2 | 70.0 | 44.1 |
| 0.30 | 90.7 | 75.1 | 79.2 | 94.9 | 93.6 | 63.2 | 79.0 | 58.6 |
| 0.15 | 91.3 | 84.0 | 86.7 | 98.6 | 98.2 | 76.4 | 86.5 | 78.5 |
| 0.075 | 94.3 | 93.2 | 94.3 | 99.5 | 99.4 | 87.0 | 92.6 | 94.8 |
| Total | 99.9 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Microfines (%) | 5.59 | 6.78 | 5.66 | 0.47 | 0.59 | 12.96 | 7.37 | 5.2 |
| Absorption (%) | 0.4 | 1.7 | 1.7 | 0.0 | 0.0 | 0.7 | 0.7 | 0.3 |

material in 0.6 mm sieve. In other materials, it was noted a change on the grading composition with the formation of the adjusted composition. The granite A and the mica schist A presented an increase of the thick particles in their particle size composition, and the dolomitic limestone A presented increase in percentage of fine particles.

The cement used was the Brazilian CP II Z—32 (equivalent to the American cement Type I PM, ASTM C595).

### *2.2 Methods*

The materials were previously weighed, respecting the mortar basic trace already defined, with the following amounts:

- cement—783 g;
- sand—1,730 g;
- water—485 g.

The mixture was made in a mechanical mortar mixer, on medium speed, with total mixing time of 90 s. After the mix, the mortar was kept in specific containers for plastic viscosity, yield stress, cone penetration and consistency table.

For the cone penetration test, a Solo Test device was used in accordance with ASTM C 780 [16]. The procedure for the test consists in the penetration by action of the own weight of a cone-shaped device, with standard mass and dimensions. For the validation of this test, three determinations were made.

The yield stress was determinated by using the vane test essay, according to what was described in Ref. [2]. The equipment used in this test is a bench vane tester Wykeham Farrance, equipped with a torsion spring with a $2.32 \times 10^{-3}$ N·m/° constant. A 50 mm high and 25 mm length cross-shaped vane was used.

The plastic viscosity of the mortars was determined by using a programmable rheometer, Brooksfield brand, DV-III Ultra model. The spindle used in the measurement of the plastic viscosity is a plain disk with 27.0 mm of diameter. The speed of 200 RPM (revolutions per minute), and the torque varied from 20% to 50% was applied. The plastic viscosity measurement was made after 120 s of the spindle activation.

The flow table test was made according to the item 5.3 of the ASTM NBR 13276 [17].

Aiming to evaluate the mechanical properties of mortars in the hardened state which were studied in this research, it will also be carried out the determinations of the compressive strength (NBR NM 101/1996 [18]) and of the tensile strength by diametrical compression (NBR 13279/2005 [19]) of the mortars obtained with the sands used in the research in 28 days.

## 3. Results and Discussions

The results observed in the tests with mortars, with regard to rheological parameters, can be analyzed in Table 3.

### *3.1 Relationship among Rheological Test Results*

Fig. 1 shows the behavior observed in Table 3 regarding the plastic viscosity and yield stress. A very similar behavior is noted between plastic viscosity and the mortars yield stress, i.e., when there is an increase of one of these parameters, the other one also increases.

Fig. 2 shows the behaviors presented related to the yield stress and cone penetration. The cone penetration test has a behavior inversely proportional to the one presented by the plastic viscosity and yield stress tests, which means that mortars with higher values for plastic viscosity and yield stress presented lower values for cone penetration.

This tendency is equal to the one observed by Ferraris [20] and Sousa [21], who pointed a relation between the cone penetration and the yield stress. The exception is made for the cases of natural sand and dolomitic limestone A, which, despite presenting lower values of yield stress, also presented a decrease on the flow table test.

**Table 3 Results of tests in rheological evaluation.**

| Mortars | Viscosity (Pa·s) | Yield stress (Pa) | Cone penetration (mm) | Flow table (mm) |
|---|---|---|---|---|
| Granite | 2.416 | 2,880 | 37 | 252 |
| Granite A | 1.988 | 1,350 | 58 | 297 |
| Calcitic | 1.216 | 420 | * | * |
| Dolomitic | 1.448 | 830 | 76 | 398 |
| Dolomitic A | 1.272 | 540 | 75 | 337 |
| Mica schis | 1.648 | 1,050 | 66 | 335 |
| Mica schist A | 1.712 | 1,050 | 76 | 348 |
| Natural sand | 1.280 | 410 | 85 | 317 |

* exceeded the limit of the test for excess of fluidity.

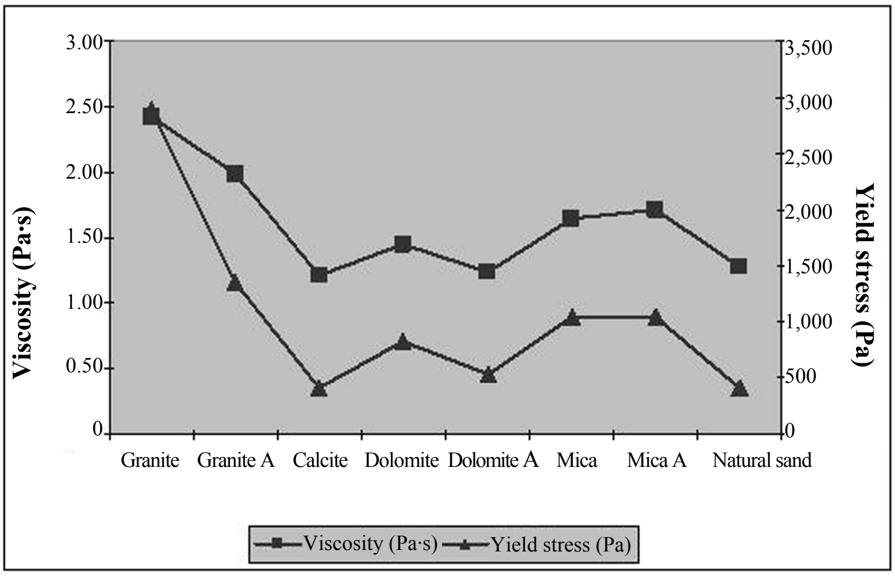


**Fig. 1 Yield stress and plastic viscosity of mortars studied.**

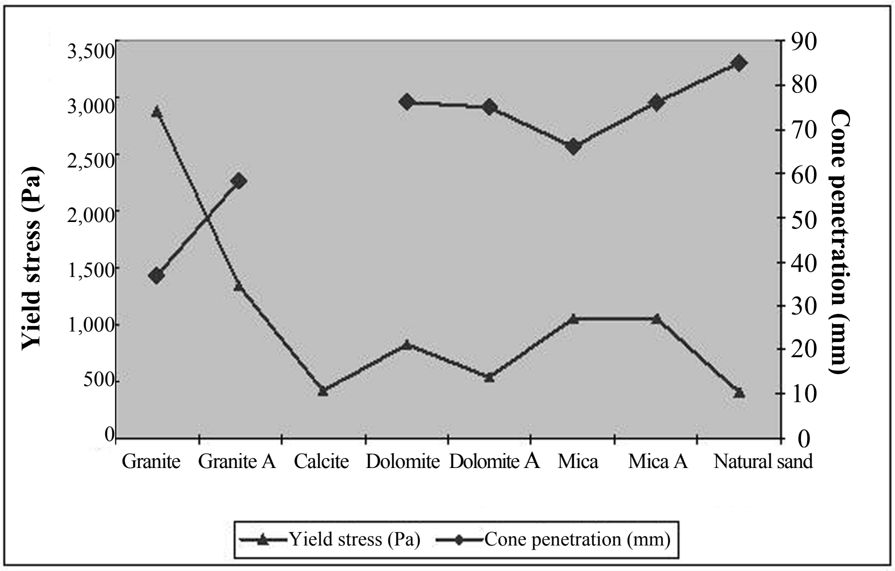


**Fig. 2 Yield stress and cone penetration of mortars studied.**

*3.2 Influence of the Lithological Type*

The correlation between the percentage of particles with low sphericity and the yield stress achieved by mortars with the sands without processing is presented in Fig. 3. The natural sand used in this study has low sphericity, low angularity and roughness surface, and the mortar made with this sand presented results related to the rheological parameters that are reference for the suitability of crushed sands used as a fine aggregate in concretes.

It is clear that granite presents the highest values of plastic viscosity and yield stress (Table 3). The lowest values for cone penetration and flow table were also noted for granite. Although the content of particles with high sphericity is significant for granite, it seems that this characteristic does not have a decisive influence on the decrease of the plastic viscosity and yield stress. From the morphoscopic analysis point of view, it is noted that the roughness and the angularity of the granite particles are higher compared with other sand types.

The mica schist presented the second higher values of plastic viscosity and yield stress among all analyzed sands. The plastic viscosity values were around 70% of the observed in natura granite value, and the yield stress values were around 35%. By the morphoscopic analysis, it was observed low sphericity and significant roughness and angularity for the mica schist. From the studied materials, the mica schist is one with the highest particles dimensions (the grading composition is thicker). It is also important to observe that, according to the petrography analysis, the mica schist tends to plaque formation, which means an important lamellarity of the particles. According to Ref. [10], the parameters related to surface texture (roughness and angularity) have little influence on the rheological behavior of the mixtures, which means that the acquisition of the most suitable properties is linked to the grain sphericity/equidimension. Angled particles, lamellarity and thick particles make the flux difficult, which may explain the significantly high values of plastic viscosity and yield stress, when compared to natural sand. The cone penetrations and flow table values were higher than granite's, which means that the fluidity was higher, supporting the behaviors discussed.

It was observed in mortars with sand originated from the crushing of dolomite limestone in natural, that the plastic viscosity values are slightly lower than it is in mortars with the mica schist in natura, but the yield stress is significantly lower. In relation to the

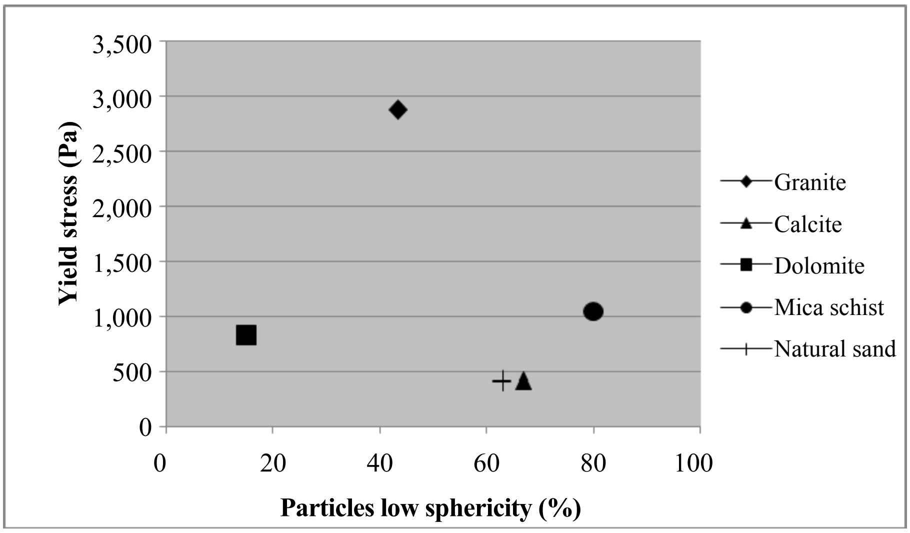


**Fig. 3 Correlation between the percentages of particles with low sphericity and yield stress achieved for mortars analyzed with the sands without processing.**

granite, the values are much lower. The dolomitic limestone sphericity is high and the angularity is low, due to the crushing treatment (rounding). This treatment possibly may have reduced the lamellarity tendency associated with muscovite (placoid). The roughness is medium, the minor of all crushed materials studied. These characteristics affect the yield stress of mortars, as the assumed low friction between the particles becomes the start of the flow easier (lower yield stress). The cone penetration and the flow table test show the trend of increased fluidity of this mortar compared to mica schist and granite.

The calcitic limestone presented plastic viscosity and yield stress similar to the natural sand, and lower than all crushed materials. This behavior was also observed in Ref. [22]. It was observed that the calcitic limestone has a low sphericity, high angularity and significant roughness. According to Ref. [23], the roughness of the particles has little influence on yield stress and plastic viscosity. However, besides the low values of plastic viscosity and yield stress, the mortar was so fluid that it was not possible to proceed with the cone penetration and flow table tests. This behavior is due to a bigger influence of the petrographic nature of calcitic limestone in relation to the morphoscopic parameters, which caused dispersion effects of the mixture particles in flow [10].

It is very evident the influence of petrographic characteristics of materials with calcite predominance, such as calcitic limestone and dolomitic limestone. This finding becomes important since the materials with calcite predominance promote the achievement of more fluid mortars and concretes, which require a lower amount of water and additives for a certain consistency [24, 25]. The calcite may influence the results possibly due to the epitaxy links that provides a greater intimacy to this mineral and the compound of the cement, or even due to the fact that the hardness of calcite is lower than in other minerals as quartz [10, 26].

### *3.3 Influence of Particle Size Distribution*

The correlations between the percentage of particles smaller than 0.3 mm and plastic viscosity for mortars achieved by the studied sands are presented in Fig. 4. The calcitic limestone and the dolomite limestone were the crushed sands with smaller amounts of particles classified as fine (smaller than 0.3 mm). The mortars produced with these crushed sands were also those that resulted in lower yield stress and plastic viscosity.

According to Refs. [4, 27, 28], with low contents of fines, there are not enough fine particles to fill the gaps between larger aggregates, which results in a

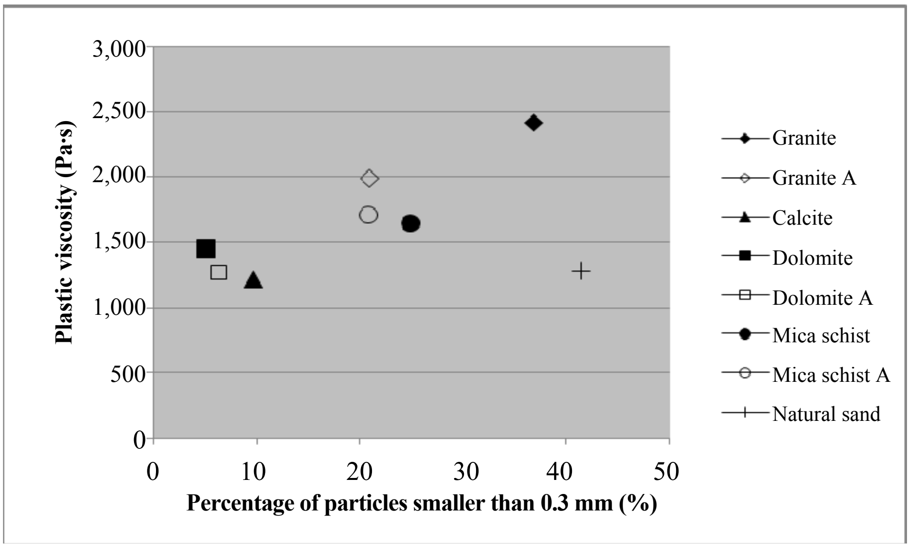


**Fig. 4 Correlations between the percentage of particles smaller than 0.3 mm and plastic viscosity for mortars studied.**

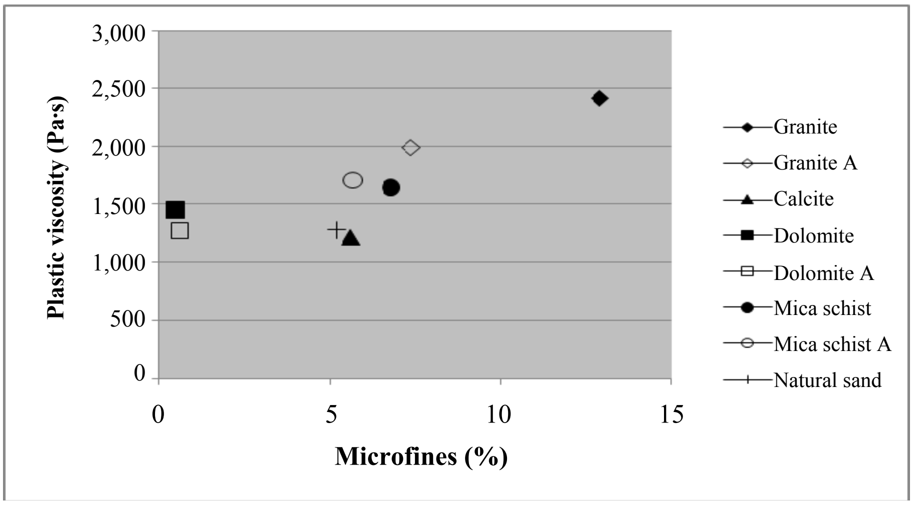


**Fig. 5 Correlations between the percentage of microfine particles and plastic viscosity for mortars studied.**

high internal friction and, thus, in high plastic viscosity. With the increase of fines content, the friction between the particles of larger aggregates decreases, and so the plastic viscosity is reduced. The increase in the content of paste, to some extent, improves the rheological parameters of mortars [29]. When the fines content further increases, the plastic viscosity can be increased due to the increase of the total surface area of the aggregates. The magnitude of this increase depends on the shape of fine particles. High contents of fine particles lead to an increase in the mortar's yield stress due to the increase of the specific surface of the crushed fine aggregates.

The correlations between the percentage of microfine particles and plastic viscosity for mortars achieved by the sands studied are presented in Fig. 5. The content of microfine particles should be considered, which in the case of the granite in natura is 12.9%. Even though these microfine particles act decreasing the friction between the largest grains, it should be assumed that such high content should be of significant influence in the rheological behavior. A decrease of the plastic viscosity and the yield stress for the granite mixture A, which has bigger particles sizes when compared to granite in natura, was observed. This tendency seems to be characteristic to the material, also in accordance to the results of cone penetration and flow table (the decrease of microfine content must have contributed to this improvement). Even with the lower levels of microfine material compared to the in natura sample, the granite A presented high values of microfine material when compared to other artificial sands. By increasing the specific area of the aggregates (increase of percentage of microfine particles), the mixture has less water to promote flow, resulting in higher plastic viscosity and yield stress.

The mica schist A presented a small reduction in particle size in relation to the mica schist in natura. A small reduction of the microfine content in the mica schist A, compared to the mica schist in natura, was also observed. Thus, it presented a rheological behavior similar in both materials, with a small increase of plastic viscosity. Due to the fact that this sand is the less spherical among the surveyed materials, there is a need for finer material to mitigate the unfavorable shape for, probably, the thicker grains are the responsible for the inner friction. The decrease of microfine content (mica schist in natura to mica schist A) makes difficult the flow, increasing the inner friction and the plastic viscosity of mortar.

A decrease in the yield stress and the plastic viscosity for dolomite limestone A, which has a finer particle size distribution when compared to dolomite limestone in natura, occurred. This refinement of grain size probably leads to a better distribution of particle

**Table 4 Results of compressive strength (NBR NM 101/1996) and the tensile strength by diametrical compression (NBR 13279/2005) of the mortars in 28 days.**

| Mortars | Compressive strength (MPa) | Tensile strength by diametral compression (MPa) |
|---|---|---|
| Granite | 18.30 | 2.26 |
| Granite A | 21.10 | 2.81 |
| Calcitic | 19.60 | 2.43 |
| Dolomitic | 21.10 | 2.70 |
| Dolomitic A | 24.30 | 3.66 |
| Mica schist | 15.20 | 1.88 |
| Mica schist A | 14.90 | 1.83 |
| Natural sand | 23.00 | 3.03 |

sizes, which reduced the inner friction from thicker particles.

### *3.4 Mechanical Properties of Mortars*

The results concerning the mechanical properties of mortars are shown in Table 4. Among the analyzed mortars, the mortars with mica shist crushed sand, both in natura and with grading curve adjusted, presented a decrease of about 35% of the values related to mechanical properties, when compared to mortars with natural sand. This behavior can be explained by the placoid shape of its grains, that tend to accumulate water on its surface, increasing the relation water/cement in the region and creating oriented cleavage planes. In the case of mortars with granite in natura, a reduction of about 20% of the mechanical properties, in relation to the natural sand is observed. By changing the particle size with the formation of granite A occurred an increase in the mechanical strength of the mortar. In the case of the mortar with calcitic limestone crushed sand, there was also a reduction in the mechanical behavior around 15%, when compared to natural sand. In the mortar with dolomite limestone sand in natura, there is also a reduction of about 10% of the mechanical strength when compared to natural sand. By changing the particle size with the formation of the dolomite limestone A, there was an increase of the mechanical behavior of the mortar in relation to the mortar with natural sand, confirming the effect of adjusting the particles size distribution of crushed sands in mechanical behavior. This behavior was also observed in Refs. [27, 28, 30, 31].

## 4. Conclusions

From this study, it is possible to enumerate the following conclusions:

- Good relations were presented among the tests results for evaluating the plastic viscosity (rheometer), yield stress (vane test), cone penetration and flow table for the mortars analyzed in this article;
- From the mortars studied, the calcitic limestone presented the lowest values for plastic viscosity and yield stress (similar to natural sand), what leads to favorable behaviors in the use of that material as a fine aggregate of concrete. This performance can be attributed to petrographic properties and particle size distribution of calcitic limestone, much more than the morphoscopic characteristics. The morphoscopical parameters are important in the study of the rheology of the studied mortars, especially in materials with the predominance of quartz such as granite, mica schist and natural sand, but it may not be analyzed isolatedly. The petrographical profile and the physical characteristics of the materials are also important;
- Although the microfine particles reduce the friction between larger particles, the excess of it, in the case of the granite, may have influenced the increase of plastic viscosity and the yield stress observed. The adjustment of the particle size composition leads to an improvement in the rheological behavior of mortars with crushed sands;

- The mechanical behavior of mortars with crushed sands was generally lower than that of mortars with natural sand. This behavior is probably due to the presence of placoid shaped particles, which tend to form cleavage areas in the mortar. Also there is an improvement in the mechanical behavior with the adjusting of the particle size distribution of crushed sand.

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