Article

Rheological and mechanical properties of self-compacting mortars with granitic rock powder and manufactured sand

Propriedades reológicas e mecânicas de argamassas autocompactantes com pó de rocha granítica e areia manufaturada

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Abstract

The study assessed the use of granitic rock powder (GRP) and manufactured sand (MS) in self-compacting mortars (SCM) to achieve desired rheological properties. Different water/cement ratios of 0.42, 0.46, and 0.63 were used with partial replacement of cement volume by GRP at levels of 17%, 20%, and 40%. Additionally, a volumetric replacement of 50% natural sand with MS was studied. The performance of SCMs was evaluated using mini V-Funnel and mini Slump Tests, as well as physical-mechanical characterization. It was found that GRP content significantly influenced superplasticizer consumption and flow time without requiring additional viscosity modifiers while incorporating MS decreased flow time parameter. Furthermore, simultaneous incorporation of GRP and MS increased mixture density by up to 14% improved compressive strength by up to 29%, and flexural tensile strength by up to19%.

Keywords: Self-compacting mortars. Granitic rock powder. Manufactured sand.

Resumo

O presente estudo avaliou a incorporação de finos de rocha granítica (GRP) e areia artificial (MS) em argamassas auto-adensáveis (SCM), visando adequação das características reológicas. Foram analisadas SCMs com relações água/cimento de 0,42, 0,46 e 0,63, teores de GRP de 17%, 20% e 40%, respetivamente, e substituição volumétrica de 50% da areia natural por MS. Para avaliar o desempenho das SCMs, foram realizados ensaios de mini V-Funnel e mini Slump, além da caraterização físico-mecânica. A distância de separação interpartículas e a espessura máxima da pasta também foram analisadas e concluiu-se que o teor de GRP é o parâmetro de maior influência no consumo de superplastificante e no tempo de escoamento das misturas. Com a incorporação de GRP, a viscosidade da argamassa foi ajustada sem a necessidade de adição de agentes modificadores de viscosidade, aumentando o tempo de escoamento, enquanto a substituição parcial de NS por MS resultou numa diminuição deste parâmetro. Além disso, a incorporação simultânea de GRP e MS aumentou a densidade das misturas, promovendo aumento da resistência à compressão em até 29% e da resistência à tração na flexão em até 19%, apesar da redução de cerca de 40% do volume de cimento.

Palavras-chave: *Argamassas auto-adensáveis. Finos de rocha granítica. Areia artificial.*

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Introduction

Self-compacting mortar (SCM) is the type of mortar that composes the self-compacting concrete, being the main responsible for its behavior in the fresh state. This material ensures workability, passing ability, and the capacity to self-compact without the application of external energy. To ensure the self-compacting mortar high fluidity and segregation resistance, properties for an adequate behavior in the fresh state, it's necessary to incorporate a high content of superplasticizer and/or viscosity modifying agents, in addition to the incorporation of fine materials.

Due to the incorporation of these materials, SCM tends to present higher cost than traditional mortars, and this is one of the obstacles to the dissemination of this technology in most constructions. On the other hand, despite the usually higher cost, the use of self-compacting mixtures presents several advantages, such as high speed of execution, greater architectural freedom due to the ease of spreading, and better surface finishing (Benli; Karataş; Bakir, 2017; Donza; Cabrera; Irassar, 2002; Şahmaran; Christianto; Yaman, 2006).

The granitic rock powder (GRP) and the manufactured sand (MS), residues from the gravel production process, appear as supplementary materials that can reduce the admixtures consumption, by adjusting the rheological properties of the self-compacting mortars, besides providing an appropriate final destination for two materials that are usually inadequately disposed in Brazil and that end up impacting the environment (Rodrigues; Mantovani; Lopes, 2004).

The incorporation of different types of rock powder affects the rheology of the cementitious matrices, with a tendency to increase the consumption of superplasticizer admixture to achieve the desired fluidity due, mainly, to its high surface area. However, the incorporation of fine materials seems to increase the matrix viscosity, improving its segregation resistance and resulting in more homogeneous matrices. Additionally, the incorporation of rock powder can improve the mechanical performance and reduce the water absorption of mortars due to their ability to fill the pores and densify the matrix (Abd Elmoaty, 2013; Elyamany; Abd Elmoaty; Mohamed, 2014; Felekoglu, 2007; Ho *et al*., 2002; Li *et al*., 2019; Sadek; El-Attar; Ali, 2016; Siqueira *et al*., 2020).

The use of natural sand (NS) in the production of concrete and mortar presents a problem because the process of its extraction has a high cost and causes several negative environmental impacts. The extraction sites, are responsible for the deforestation of riparian forests, which are essential for the balance of ecosystems (Sadek; El-Attar; Ali, 2016; Yamei; Lihua, 2017).

The partial replacement of natural sand by manufactured sand can also reduce the final cost of SCMs due to the greater proximity of the quarries to the large consumer centers of mortar, compared to the extraction sites of natural sand. Thus, the partial or total replacement of NS with MS results in a reduction in the final cost of the material, in the energy used to transport it, and in a considerable decrease in carbon dioxide emissions (Beixing; Guoju; Mingkai, 2011). Also, when properly designed, the simultaneous use of NS and MS tends to reduce mortar porosity and can minimize the consumption of superplasticizer by facilitating the mixture flow.

Studies that evaluate the influence of the simultaneous incorporation of granitic rock powder and manufactured sand from the crushed stone manufacturing process, in self-compacting mortars are rare. Most studies focus on the incorporation of one or the other waste. The purpose of this study is to evaluate the feasibility of the joint use of these wastes in SCMs to adjust the viscosity, aiming to eliminate the viscosity modifying admixtures incorporation. Additionally reducing the consumption of NS and cement. For this, the wastes were characterized, and the mortars were studied using mini V-Funnel and mini Slump Test as well as physical and mechanical characterization in the hardened state.

Methodology

The methodology of the present study was divided into five stages:

(a) characterization of the raw materials;

(b) mortar mix design;

(c) analysis of the performance of mortars in their fresh state;

(d) analysis of the performance of mortars in their hardened state; and

(e) cost analysis of the formulations.

Materials

To prepare the mortars, Portland cement of high initial strength (CP V ARI in the Brazilian classification), granitic rock powder and manufactured sand generated in a quarry located in the metropolitan region of the city of Salvador, in the state of Bahia, in Brazil, were used. The natural sand used in this research came from quarries in the region of Camaçari, also in the State of Bahia. A polycarboxylate-based superplasticizer, Hyperkem 80 from Novakem, was utilized, which presented pH of 4.0 ± 1.0, specific mass equal to (1.06 ± 0.02) g/cm³ and solid content of (21.9 ± 0.03) %. The fraction of GRP passing the sieve with mesh opening equal to 75 µm, corresponding to 74% of the mass of the material, was used in this study.

These materials had their physical properties and chemical compositions evaluated. The true density of cement and GRP were determined by helium gas pycnometry (AccuPyc 1330 V2.01 Micrometrics) and those of the sands were determined by water pycnometry, following the procedures of NBR NM 53 (ABNT, 2009). The specific surface areas of cement and GRP were determined by using a Blaine permeabilimeter (Acmel automatic, model BSA1) and a BET surface area analyzer (Gemini VII Micromeritics).

The chemical analysis of the materials used was assessed by means of the X-ray fluorescence (XRF) technique, using the S2 Ranger Brucker equipment.

The particle size distributions of the cement and the GRP were determined by laser diffraction in a Microtrac particle size analyser, model S3500, and the particle sizes of the sands were determined by sieving, according to the procedure described in NBR NM 248 (ABNT, 2003).

The morphology of the GRP was also analyzed using a scanning electron microscope (SEM Veja 3 LMU-TESCAN Phenom). The images were obtained with the assistance of a BSE (Backscattering Electron) detector with a voltage of 15 kV.

Mortar’s design and fresh state properties

In this study, an adaptation of the method proposed by Repette-Melo (Melo, 2005) was used for the design of self-compacting concretes. This method was chosen among the others due to its practical features, since it does not require the execution of several complex mathematical calculations, making it more applicable to the Brazilian and other developing countries construction scenarios.

This method indicates that, initially, the water/binder ratio to be used should be defined, according to the required compressive strength. Then, the fines should be added, replacing the cement in volume, at 5% increments until the exudation is eliminated. Finally, the superplasticizer content required for the mortars to present the adequate spread must be adjusted during the mini slump test (Melo, 2005)

In addition to the reference mortar, i.e., without the incorporation of GRP and MS, three mortars were designed for each water/cement ratio studied. This way, the following mortars were analyzed:

(a) reference mortars (REF);

(b) mortars only with the addition of GRP (GRP);

(c) mortars replacing 50% of the volume of NS by MS (MS); and

(d) mortars with the addition of GRP and partial replacement of NS by MS, simultaneously (GRP+MS).

For the mortars mixed with water/cement ratios of 0.63, 0.46 and 0.42, a volume of 9.2, 4.6 and 4.1% of GRP was incorporated, respectively. The increase in incorporated powder content is directly influenced by the amount of water available in the mix, according to the dosing method used. Table 1 shows the materials consumption, by volume, for the production of one cubic meter of each of the self-compacting mortars.

It was not possible to reach the self-compactness of the mortar GRP with a w/c ratio of 0.63GRP. This occurred because the NS used in this study is a sand classified as very fine. So, its individual use in a mixture that has a high content of fines expressively increased the demand for water or superplasticizer. Thus, this formulation was excluded from the study for not reaching the self-compactability criteria established.

The addition content of GRP and the water/cement ratios used were also defined in a preliminary study performed to produce mortars with average compressive strength of 30, 40, and 45 MPa, being fixed at 0.63, 0.46, and 0.42, respectively. The GRP content was determined according to the specifications of the adopted designing method to eliminate exudation for each water/cement ratio chosen. Powder contents of 40%, 20% and 17%, by volume of cemet, were added to mixtures with water/cement ratios equal to 0.63, 0.46 and 0.42, respectively.

Table1 – **Material consumption (m^3) for the production of 1 m^3 of mortar**

w/c	Mortar	Cement	GRP	NS	MS	Water	SP*.	GRP (%)	MS (%)
0.63	REF	0.17	0.00	0.50	0.00	0.33	0.00	0	0
	GRP	The self-compactness of this mortar was not achieved						40	0
	MS	0.17	0.00	0.25	0.25	0.33	0.00	0	50
	GRP+MS	0.14	0.09	0.25	0.25	0.27	0.00	40	50
0.46	REF	0.21	0.00	0.50	0.00	0.29	0.00	0	0
	GRP	0.19	0.05	0.50	0.00	0.27	0.00	20	0
	MS	0.21	0.00	0.25	0.25	0.29	0.00	0	50
	GRP+MS	0.19	0.05	0.25	0.25	0.27	0.00	20	50
0.42	REF	0.21	0.00	0.50	0.00	0.28	0.00	0	0
	GRP	0.20	0.04	0.50	0.00	0.26	0.00	17	0
	MS	0.22	0.00	0.25	0.25	0.28	0.00	0	50
	GRP+MS	0.20	0.04	0.25	0.25	0.26	0.00	17	50

Note: *SP. = Superplasticizer consumption.

The sand volume was set at 50% of the total volume of the mortar and it was defined according to a previous study to optimize the particle distribution of the mixtures and increase the maximum paste thickness (MPT) of the mortars studied. This content is within the range considered ideal for self-compacting mortars, which varies between 40% and 50% (Domone, 2006; Gomes; Gettu; Agulló, 2003; Jin, 2002; Melo, 2005; Okamura; Ouchi, 2003; Rizwan; Bier, 2009). This volume was kept constant to only evaluate the influence of the powder addition and the partial replacement of natural sand by manufactured sand on the mortar properties.

The superplasticizer content was adjusted to ensure that all mortars had an average mini slump spread between 240 and 260 mm, considered ideal by EFNARC (2002) and by the authors of the adopted designing method (Melo, 2005). The flow times assessed by mini V-funnel test were stratified as ideal (between 5 and 10 s), acceptable (between 3.5 and 5 s), and inadequate (between 0 and 3.5 s).

After defining the admixture content for each mortar studied, the flow time of the different formulations was analyzed through the mini V-funnel test, indirectly evaluating the influence of the incorporation of GRP and MS on the viscosity of the mortars under study. The mini-slump and mini V-Funnel tests followed the guidelines of the European Recommended Practices Manual of EFNARC (2002).

Hardened state properties

For the tests in the hardened state, three prismatic specimens (40 mm x 40 mm x 160 mm) were molded for each formulation. The axial compressive strength and flexural tensile strength at 28 days were analyzed, according to NBR 13279 (ABNT, 2005), using a hydraulic press with a load capacity of 1200 kN. Three-point bending test was performed with a span of 100 mm and a loading rate of 50 N/s. For the compression tests, four cubic specimens (40 mm x 40 mm x 40 mm) and a loading rate equal to 500 N/s were used. Additionally, the capillary water absorption test was performed with three specimens (40 mm x 40 mm x 160 mm), following the NBR 9779 (ABNT, 2012).

The water absorption by capillarity was determined following the standard procedure of NBR 9779 (ABNT, 2012). The test was performed on three specimens per series with 28 days of age, calculating the capillary absorption coefficient. The specimens were dried in an oven at 100 °C until mass constancy. After drying, the specimens were cooled to room temperature and their respective dry masses were measured. Throughout the test, the saturated mass of the specimens was determined at specific time intervals, determined by NBR 9779 (ABNT, 2012) until mass consistency.

All results comparing the performance of the mortars in the fresh and hardened states were statistically analyzed using Analysis of Variance (ANOVA) with a significance value (α) equal to 0.01.

IPS and MPT

The analysis of interparticle separation distance (IPS) and maximum paste thickness (MPT) were also performed. In this analysis, the volumetric fraction of solids in the mixture and its volumetric surface area are considered (Equations 1 and 2) (De Larrard, 1999; Funk; Dinger, 1994; Oliveira *et al*., 2000).

$$IPS = \frac{2}{VSA} \cdot \left[\frac{1}{V_s} - \frac{1}{1-P_{of}}\right] \quad \text{Eq. 1}$$

$$MPT = \frac{2}{VSA_g} \cdot \left[\frac{1}{V_{sg}} - \frac{1}{1-P_{ofg}}\right] \qquad \text{Eq. 2}$$

Where:

VSA is the volumetric surface area of the fine materials (cement and GRP) and VSA_g is the volumetric surface area of the aggregates (m²/cm³), calculated from the product between the specific mass (g/cm³) and the specific surface area (m²/g) of the material;

V_s is the volumetric fraction of solids in the mixture;

P_{of} is the pore fraction from the mixture of fine materials; and

P_{ofg} is the pore fraction from the mixture of fine aggregates.

The IPS analysis was performed on the paste constituting the mortars with and without incorporation of GRP, while the influence of the partial substitution of natural sand by manufactured sand on the aggregate separation distance in the self-compacting mortar was analyzed through the MPT values.

The pore fraction analysis of the paste was done using the compactness test, by water demand, with a compaction index (K) equal to 6.7 (Silva, 2004) by the compressible packing method and modified Aïtcin-Faury method. This index represents the compaction energy associated with the densification protocol applied. This test was performed to determine the amount of water needed to fill all the voids in the mixture.

In the first part of the experiment, the particles were in a dry and random state, with a high void content. With the initial insertion of water in the system, the particles pass to the pendulum state, i.e, the added water condenses between the grains, forming liquid bridges between the particles. With the gradual incorporation of water into the mixture, the amount of liquid bridges increases to the point that the surfaces of all particles are completely wet. This state, called the funicular state, has as a remarkable characteristic the presence of air bubbles inside the mixture (Silva, 2004).

Finally, there is the capillary phase, which begins when all the voids in the funicular phase are filled with water. From this point on, any amount of water added to the mixture causes the particles to move apart, increasing the fluidity of the mixture. The characteristic point of water demand is defined as the beginning of the capillary phase (Silva, 2004).

The adapted procedure consisted in placing a sample with approximately 350 grams of the completely dry material (cement or cement + GRP) in the mortar mixer along with 50% of the water expected to reach the water demand and mixing at low speed for one minute. At one-minute intervals, small amounts of water were added until the formation of agglomerates was visualized. After agglomerates were formed, the mixture was left to rest for 30 seconds for subsequent mixing at high speed for one minute. The test was finished when a homogeneous and compacted paste was found at the bottom of the container.

After determining the amount of water corresponding to the state in which all voids were filled by the liquid, the actual compactness could be calculated according to Equation 3 when only cement is used, and according to Equation 4 when cement is used in addition to GRP.

$$C = \frac{1}{1+me_1 \cdot \frac{M_{H2O}}{M_1}} \qquad \text{Eq. 3}$$

$$C = \frac{1}{1+\frac{me_1 \cdot me_2}{\left[me_2 \cdot \frac{M_1}{M_T}+me_1 \cdot \frac{M_2}{M_T}\right]} \cdot \left(\frac{M_{H2O}}{M_T}\right)} \qquad \text{Eq. 4}$$

Where:

m_{e1} is the specific mass of material 1 (g/cm³);

m_{e2} is the specific mass of material 2 (g/cm³);

M_1 is the mass of material 1 (g);

M_2 is the mass of material 2 (g);

M_{H2O} is the mass of water on reaching the demand state (g); and

$M_T = M_1+M_2$ is the total mass of the dry materials (g).

In order to analyze the compactness of the proportions of NS and MS adopted in the mortars, a method that employs the vibration and compaction procedure was used, with K equal to 9 (De Larrard, 1999; Silva, 2004). This test consists of inserting a standard amount of material (NS or NS+MS) inside a cylindrical apparatus with known diameter and height and applying on the sample a pressure of 10 kPa, combined with a vibration effect for a standardized time (Silva, 2004). After the vibration, the final height of the sample is measured and the compactness of the material is calculated according to Equation 5.

$$C = \frac{4 \cdot M_S}{\pi \cdot D_C^2 \cdot h \cdot \rho_S} \qquad \text{Eq. 5}$$

Where:

M_s is the dry material mass (g);

ρ_s is the material's bulk density (g/cm³);

D_c is the internal diameter of the cylinder (cm); and

h is the final height of the material layer after compaction (cm).

Once the compactness calculation is completed, the porosity of the mixture is obtained by means of Equation 6.

$$P_{of} = 1 - C \qquad \text{Eq. 6}$$

Cost assessment

For the cost investigation of the mortars produced, values based on quotations in Brazil for industrial-scale production and the necessary quantity of each of the materials to produce one cubic meter of mortar were analyzed. The cost was analyzed taking into account the average compressive strength of each of the mixtures (R$/MPa).

Results and discussions

Materials characterization

The physical properties and particle size distributions of the materials used in this research are presented in Table 2 and Figure 1, respectively. It can be seen that the GRP presents a smaller surface area than that of cement and NS presents an average diameter smaller than that of MS. This range in the particle size distribution of the materials can contribute to obtaining a better final packing of the mortars.

The chemical compositions of cement and GRP are presented in Table 3. From the results found, it is observed that the GRP is mostly composed of silica, alumina, and iron oxide.

Figure 2 presents electron micrographs of the GRP. It can be observed that the particles of the GRP have an irregular format that can be attributed to the process of forced reduction that occurs inside the crushers to generate gravel from large blocks of rock.

Fresh mortar properties

The results of IPS and MPT of the tested mortars are presented in Table 4. The results show that the combined use of cement and powders resulted in an improved particle packing, thus reducing paste porosity (P_{of}) for all water/cement ratios under analysis. On the other hand, the incorporation of powders in the pastes increases the volumetric fraction of solids in the suspension (V_s), which ultimately reduces the IPS, according to Equation 1.

When analyzing the MPT results, it is observed that the porosity of the aggregate particle size distribution of the mortars (P_{ofg}) designed only with NS is higher than those in which NS and MS were used simultaneously. This can be explained by the tendency that the particles of the natural sand used presented to fill the empty spaces left by the grains of manufactured sand, since this type of sand presented a higher average particle diameter.

The reduction of P_{of} and P_{ofg} increased the density of mortars (Table 4) that present isolated or simultaneous incorporation of GRP and MS. That is, the incorporation of GRP results in better packing of fine materials and tends to decrease porosity due to the filler effect (Sadek; El-Attar; Ali, 2016; Uysal; Yilmaz, 2011), while the incorporation of MS optimizes the particle distribution of aggregates, improving the final packing of mortars.

Table2 – **Result of physical characterization of the materials**

Properties	Cement	GRP	NS	MS
Specificgravity (g/cm³)	3.12	2.86	2.65	2.77
Superficial Area - Blaine (m²/g)	0.409	0.204	-	-
Superficial Area - BET (m²/g)	1.641	1.272	-	-
Equivalentmeandiameter, D_{50}	19 µm	44 µm	0.36 mm	1.88 mm
Maximum Nominal Size (mm)	-	-	1.18	4.75
Modulusoffineness	-	-	1.75	3.68
Loose unitary mass (kg/m³)	-	-	1470	1550
Pulverulent material (%)	-	-	1.5 ± 0.50	5.28 ± 0.24

Figure 1 - **Particle size distribution of the materials**

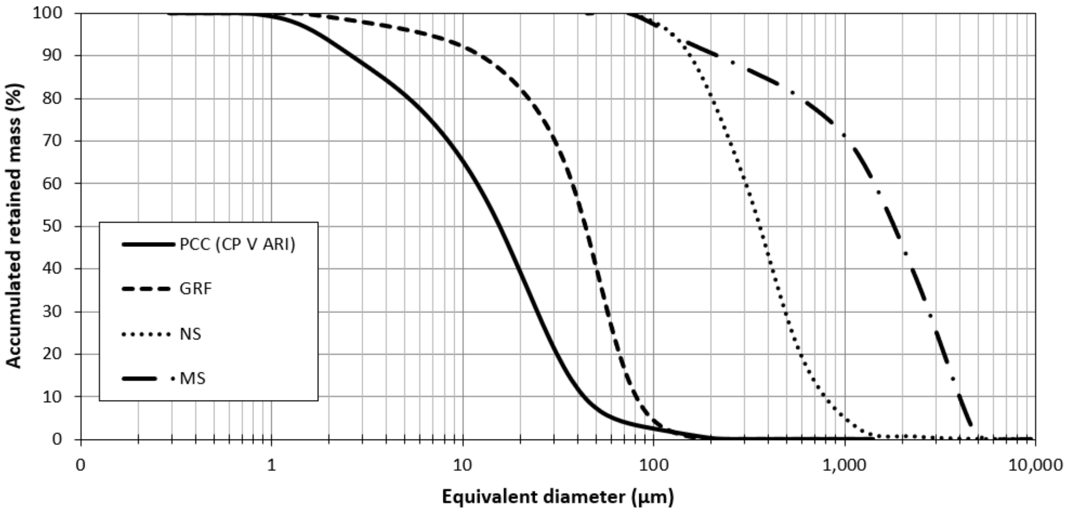


Table3 – **Chemical compositions of the cement and GRP (% by weight) determined by XRF (oxides)**

Materials	CaO	SiO_2	SO_3	MgO	Al_2O_3	Fe_2O_3	K_2O	Na_2O	Others	LOI*
PCC Type III	59.12	15.70	5.16	3.79	3.57	2.96	1.73	-	0.38	7.48
GRP	6.21	53.34	0.32	4.83	15.28	10.50	2.96	3.16	2.00	1.40

Note: *LOI = Loss on ignition at 1000 °C.

Figure 2 - **Scanning electron micrography (SEM) of GRP**

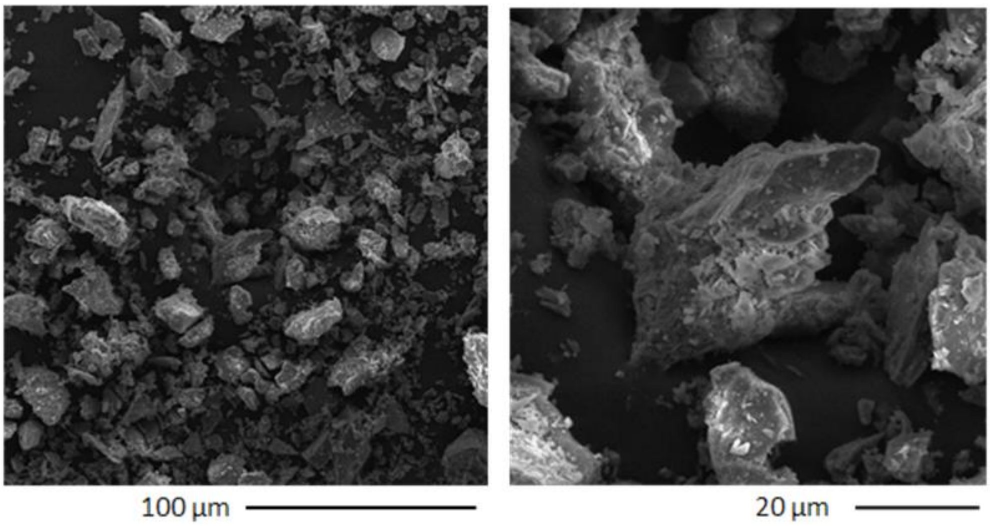


Table 4 – **Properties of mortars mixtures in the fresh and hardened states**

w/c	Mor-tar	GRP (%)	w/p*	P_{of}[1] (%)	IPS[2] (μm)	P_{ofg}[1] (%)	MPT[3] (μm)	SP (%)[3]	Slumpflow (mm)	Flow time[3] (s)	Density[4] (%)	Capillarity absorption coefficient[4] (kg/m²/min$^{1/2}$)
0.63	REF	0.00	0.63	47.73	0.412	27.91	40.79	0.28	253.29	1.75 ± 0.29	2.03 ± 0.01	0.24 ± 0.01
	GRP	-	-	-	-	-	-	-	-	-	-	-
	MS	0.00	0.63	47.73	0.412	23.28	64.74	0.21	253.53	1.23 ± 0.17	2.06 ± 0.01	0.33 ± 0.01
	GRP +MS	40.00	0.39	45.42	0.153	23.28	64.74	0.78	230.80	5.15 ± 0.10	1.99 ± 0.02	0.37 ± 0.03
0.46	REF	0.00	0.46	47.73	0.203	27.91	40.79	0.40	260.27	2.87 ± 0.38	2.04 ± 0.01	0.13 ± 0.01
	GRP	20.00	0.37	46.79	0.111	27.91	40.79	0.65	260.13	5.15 ± 0.13	2.06 ± 0.03	0.12 ± 0.01
	MS	0.00	0.46	47.73	0.203	23.28	64.74	0.36	249.50	2.15 ± 0.13	2.07 ± 0.01	0.14 ± 0.02
	GRP +MS	20.00	0.37	46.79	0.111	23.28	64.74	0.60	254.95	5.05 ± 0.10	1.92 ± 0.02	0.17 ± 0.01
0.42	REF	0.00	0.42	47.73	0.155	27.91	40.79	0.37	251.08	3.38 ± 0.15	2.12 ± 0.01	0.12 ± 0.01
	GRP	17.00	0.35	46.05	0.096	27.91	40.79	0.58	256.80	6.33 ± 0.47	2.00 ± 0.01	0.13 ± 0.01
	MS	0.00	0.42	47.73	0.155	23.28	64.74	0.35	257.98	2.13 ± 0.15	2.13 ± 0.02	0.14 ± 0.02
	GRP +MS	17.00	0.35	46.05	0.096	23.28	64.74	0.48	257.70	5.08 ± 0.15	1.86 ± 0.01	0.16 ± 0.01

Note: w/p = water/power ratio ;[1] Particle analysis; [2] Paste analysis; [3] Mortar in the fresh state analysis; [4] Mortar in the hardened state analysis.

In addition, the high content of pulverulent material present in the manufactured sand can contribute to the densification of the matrix (Beixing; Guoju; Mingkai, 2011; Shen *et al.*, 2018; Silva; Buest; Campiteli, 2005), i.e, the composition of a final particle size distribution with a greater variety of particle sizes increased the density of the mortars.

To quantify the influence of the various parameters on the consumption of superplasticizer admixture and on the flow time of the mixtures, a linear regression analysis was performed using the Minitab Software with 95% confidence level. From the Pareto charts analysis of the standardized effects, the equations were adjusted, taking into account only the properties that significantly influence the response variable. With this analysis Equations 7 and 8 were found. Equation 7 presented R^2 and adjusted R^2 values equal to 96.75% and 95.36%, respectively, while Equation 8 presented R^2 and adjusted R^2 values equal to 90.65% and 86.64%, respectively.

$$\%\,SP = 0.5529 - 0.4320 \cdot IPS - 0.0022 \cdot MPT + 0.0106 \cdot \%GRP \qquad \text{Eq. 7}$$

$$Flow\ time(s) = 6.3130 - 7.4003 \cdot IPS - 0.0379 \cdot MPT + 0.0783 \cdot \%GRP \qquad \text{Eq. 8}$$

It can be verified that the lower the IPS and MPT, the higher the admixture content (%SP) and the flow time of mortars. That is, by reducing the distance between particles of the fines the flow of the pastes is obstructed, reducing the fluidity of the mixtures. This reduction in IPS in mixtures incorporating GRP can be explained by the increase in the amount of powder when compared to the reference mortars, which leads to a reduction in the mobility of the fines. This loss of particle mobility increases the consumption of superplasticizer admixture to achieve the slump (Figure 3), in addition to increasing the flow time of the mixtures, due to the increased friction between the particles, when compared to the reference mortars (Benabed *et al.*, 2016).

As can be seen from Equation 8, the MPT does not have a very significant effect on the superplasticizer consumption, since the admixture has a stronger effect on the powder. In addition, as can be seen in Table 1, the mixtures with GRP have a lower volume of water added, which leads to a consequent loss of workability and a greater need for the addition of a super plasticizing admixture to maintain the desired fresh state behavior.

Moreover, because of the lower porosity resulting from the particle size distribution of the fine aggregates used, by keeping the paste volume of the mixtures constant, the mortars with incorporation of MS have a higher MPT, resulting in a greater amount of paste available to cover the grains of fine aggregate, making the flow of the mixture easier. This improved flow tends to reduce the consumption of superplasticizer and the flow time of the formulations (Benabed *et al.*, 2016; Kumar; Radhakrishna, 2016; Lohani *et al.*, 2012).

Replacing sand with a high surface area (NS) with a coarser sand (MS) tends to reduce the amount of water adsorbed on the surface of the particles, increasing the amount of free water present in the mixture and, consequently, reducing the existing friction between the particles (Kumar; Radhakrishna, 2016).

Thus, mixtures that provide simultaneous reduction of IPS and increase of MPT (GRP+MS) presented an intermediate value of superplasticizer content and flow time when compared to mortars with isolated incorporation of the materials. It is important to highlight, however, that the influence of the incorporation or not of MS is significantly lower than the influence of the reduction of IPS, as can be seen by the coefficients of Equations 7 and 8 and in Figures 3 and 4.

In contrast, increasing the content of incorporated GRP (%GRP) reduces the mobility of the mixtures since the incorporation of a material with a high surface area and that presents a rough and irregular surface in the mortars may provide a greater retention of free water on the surface of the mineral addition. This occurrence can culminate in a reduction in the amount of water available for lubrication of the particles, slowing down their flow (Benabed *et al.*, 2016; Felekoglu, 2007; Gesoğlu *et al.*, 2012; Gesoğlu; Güneyisi; Özbay, 2009).

It can be noticed that even with the increased consumption of superplasticizer admixture from the incorporation of GRP in the mortars, when compared to the reference mortars, there is an increase in the flow time of the mixtures. This result is an indicator of the ability of powders to increment the viscosity of the mortars even when there is a higher admixture consumption, thus reducing or eliminating the need for incorporation of viscosity modifying admixtures to adjust the flow time of the mixtures.

Analysis of the properties of mortars in the hardened state

Figure 4 shows the results of water absorption by capillarity of the mortars studied. The reference mortars and those with the incorporation of only manufactured sand (MS) have the highest capillarity absorption coefficients.

By analyzing Equation 9, which presents R^2 of 90.7% and adjusted R^2 of 88.4%, it can be seen that the parameters that most influence water absorption are the water/cement ratio and the MPT of the mixtures. That is, the higher the water/cement ratio the greater tends to be the porosity of the mixtures and, consequently, the greater the water absorption. For mortars with the same w/c ratio, the increase in MPT results in a greater thickness of paste around the aggregates that forms a preferential path for the entrance of water, increasing their absorption.

$$Abs = -0.3438 + 0.8470 * a/c + 0.0021 * MPT \quad \text{Eq. 9}$$

Besides, even if less expressively, the incorporation of GRP tends to reduce the absorption mainly due to the reduction of the porosity of the mixtures caused by its filler effect, justifying the reduction of water absorption by the mixtures with the incorporation of the residue (Benabed *et al.*, 2016; Sadek; El-Attar; Ali, 2016; Topçu; Bilir; Uygunoglu, 2009).

Figure 3 – **Correlation between superplasticizer consumption and mortar IPS**

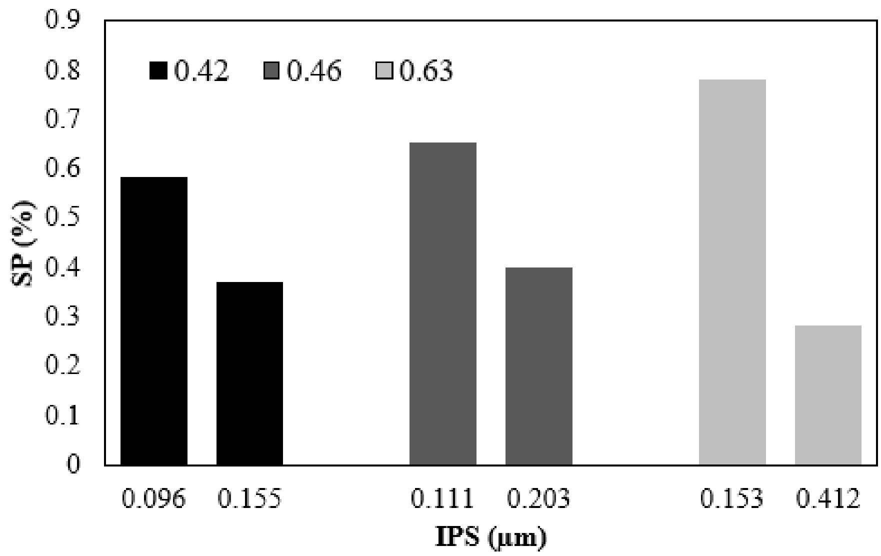
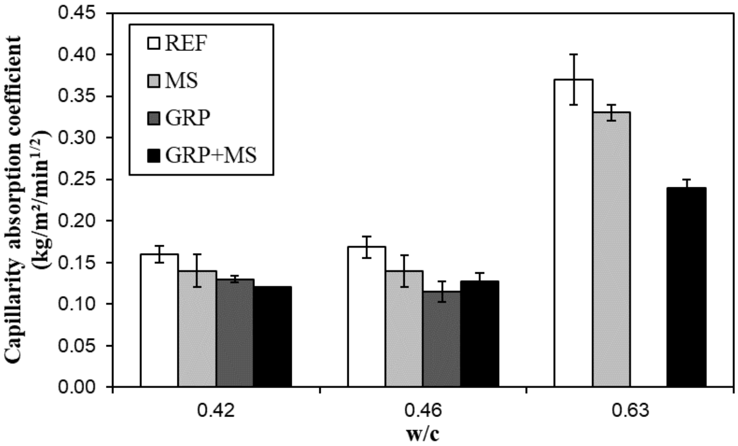


Figure 4 – **Capillarity absorption of self-compacting mortars with w/c ratios equal to 0.63, 0.46, and 0.42**



Figures 5 and 6 present, respectively, the results of flexural tensile strength and axial compression of the mortars at 28 days. It is possible to notice a tendency to increase the mechanical strength as a consequence of the incorporation of MS and GRP, individually or simultaneously, due to the reduction of P_{of} and P_{ofg} and consequent increase in the density of the mixtures (Table 4).

Increasing the amount of GRP added to mortars improves the efficiency of the hydration of cement particles as it acts as nucleation points (Vasconcellos *et al.*, 2023), as does the incorporation of superplasticizer admixture (El-Gamal; Al-Nowaiser; Al-Baity, 2012). This can explain why the reference mortars tend to show an increase in the mechanical properties when the w/c ratio is reduced.

Also, the partial replacement of NS by MS can improve the strength of the interfacial transition zone between the paste and the fine aggregates particles due to the increased mechanical interlocking with the cement paste, attributed to the irregular surface of the manufactured sand. This increased adhesion between particles can improve the internal stress distribution in mortars in the hardened state, significantly enhancing their mechanical performance (Beixing; Guoju; Mingkai, 2011; Donza; Cabrera; Irassar, 2002; Kumar; Radhakrishna, 2016; Yamei; Lihua, 2017).

The fine aggregate particles from granite rock crushing can also present higher resistance than natural sand particles, which, together with the improved adhesion of the ITZ zone compared to NS, improves, even more, the mechanical performance of the cementitious matrices (Donza; Cabrera; Irassar, 2002).

The results obtained for the three water/cement ratios studied show that the mortars with simultaneous incorporation of GRP and MS obtained equivalent or superior performance to the reference mortars, produced only with cement, natural sand, and water. These results indicate the technical feasibility of the combined incorporation of these two materials even when there is significant suppression of cement, as for the mortars designed with a w/c ratio of 0.63 in which there was a 40% reduction in cement volume, equivalent to a reduction of approximately 93 kg of cement for each m³ of mortar.

The results of the relative cost per m³ divided by the mean compressive strength of each formulation studied are presented in Figure 7. It can be observed that the mixtures designed with the isolated or simultaneous incorporation of the wastes tend to present a lower cost and a better mechanical performance than that presented by the reference mortars. The parameters that most contributed to this result were the reduction in cement and admixture consumption, highlighting the economic feasibility of using these materials, which can positively influence the wider dissemination of the use of this type of mortar.

Figure 5 - **Flexural strength of self-compacting mortars, at 28 days, with w/c ratios equal to 0.63, 0.46, and 0.42**

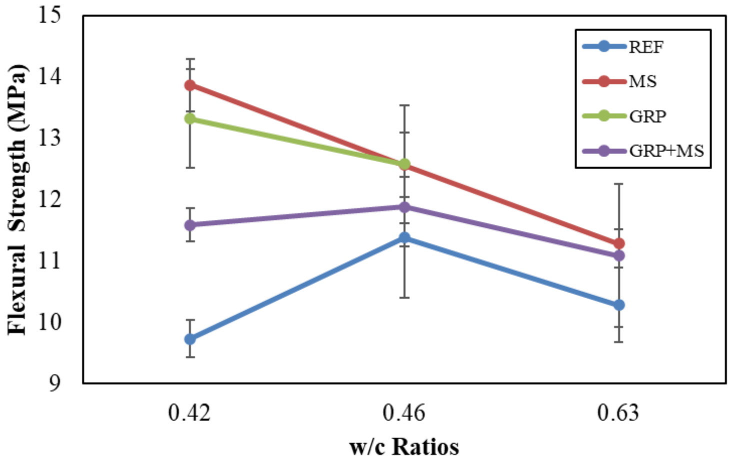


Figure 6 - **Compressive strength of self-compacting mortars, at 28 days, with w/c ratios equal to 0.63, 0.46, and 0.42**

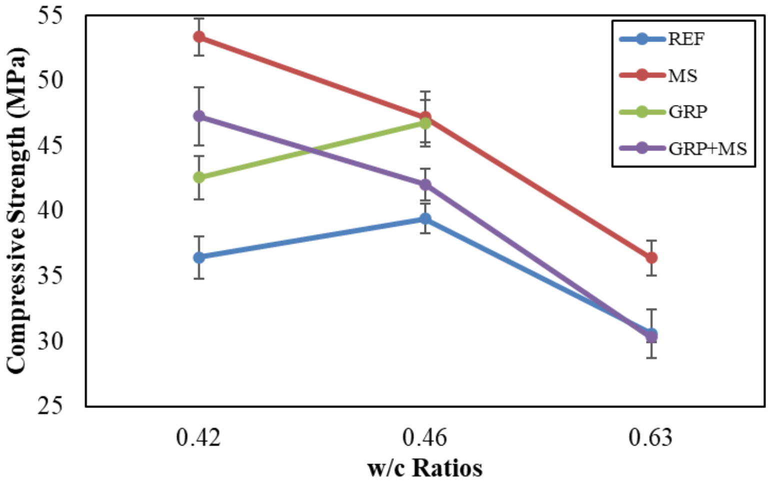
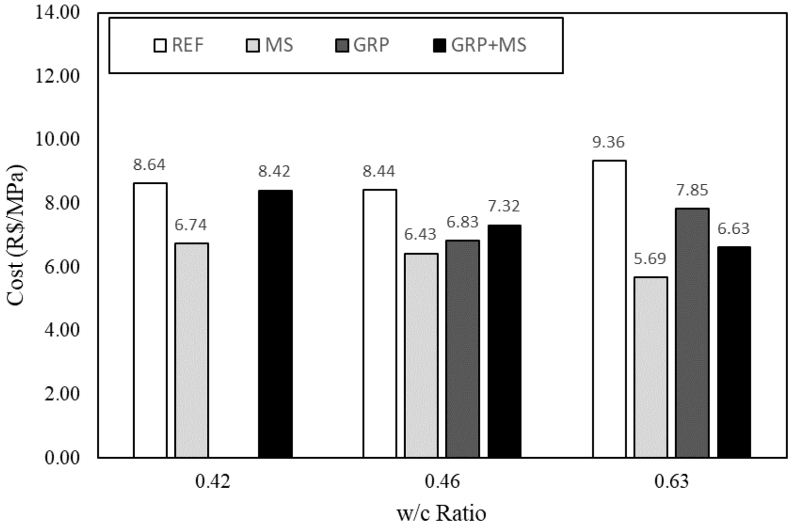


Figure 7 - **Cost per m³ per compressive strength of self-compacting mortars with w/c ratios equal to 0.42, 0.46, and 0.63**



Conclusions

From the analysis of the data obtained it can be concluded that:

(a) the addition of granitic rock powder significantly increases the density of the mixtures by reducing the water consumption. With that, there is a reduction in the capillary water absorption and, by keeping the water/cement ratio constant, this incorporation reduces the Interparticle Separation Distance (IPS);

(b) the IPS and the water consumption reduction increase the superplasticizer consumption and the flow time of the mixtures. On the other hand, the partial replacement of NS by MS increases the MPT of mortars, improving the flow of the matrices and, consequently, reducing the admixture content and the flow time of the formulations;

(c) the increase in the amount of GRP incorporated in the mortars is the factor that most significantly increases the consumption of superplasticizer admixture and the flow time of the matrices. This indicates that despite requiring a higher admixture incorporation to maintain the workability of the matrices, the GRP tends to increase the viscosity of the formulations studied, and can be used to adjust the final viscosity of self-compacting mortars without the incorporation of viscosity modifying admixtures;

(d) the incorporation of GRP and MS, individually or simultaneously, improved the performance of the formulations, despite the suppression of up to 40% of the cement volume, as a consequence of the higher mixture density; and

(e) The isolated or simultaneous incorporation of GRP and MS results in lower-cost and stronger self-compacting mortars, evidencing the economic feasibility of using these materials to produce more competitive self-compacting mortars in the market.

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