Technical viability of self-compacting concretes with by-products from crushed coarse aggregate production

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Abstract

The main objective of this work is to present the technical viability of Self Compacting Concretes (SCC) containing by-products from crushed coarse aggregate production. For this purpose, a vast characterization of these by-products was made; six mixtures of SCC were produced using two different aggregates: granite and mica schist. The binder/dry aggregate (b/agg) ratio by mass was 1:3. The following properties were analyzed: compressive strength, direct tensile strength, flexural tensile strength and splitting tensile strength. Granite presented the best mechanical performance. The replacement of natural sand by granite sand generated concretes with the same level of compressive strength and caused an increase in tensile strength values. The incorporation of silica fume into concrete with granite produced an increase of 17% in compressive strength. So, the use of these by-product materials can provide a technically feasible solution that is also consistent with the aims of sustainable development and preservation of the environment.

Keywords: self-compacting concrete, by-products, environmental preservation.

1. Introduction

Brazil is one of the most important emerging countries in the world and as a result of its rapid economic development, a lot of waste is generated. In the civil construction sector, a variety of by-product materials are produced that have potential applications (BACARJI, MARQUES and TOLEDO FILHO, 2012). According to these authors, in 2010 more than 5 million tons of quarry dust was generated from the production of coarse aggregate. If the current rate of growth continues, more than 20 million tons of quarry dust is expected to be produced in 2020, with over 290 million additional tons of artificial sand being generated in the same year as the by-product of rock crushing. If a technically feasible application for these materials is not found, the civil construction industry in Brazil will have serious environmental problems in the near future. Furthermore, these by-products do not have additional expenditure with extraction and transportation like natural river sand, implying in a reduction material cost. In the metropolitan region of Goiania city, Brazil, the cost of natural river sand, artificial sand and quarry dust is $15,00/ton, $12.5/ton and $5.75/ton, respectively; which is in line with Madurwar *et al* (2013). According to these researchers, the use of by-products can contribute to minimize the pollution problem, the problem of land-filling and the high cost of building materials. Donza *et al* (2002) investigated the use of different types of sands in High Performance Concrete (HPC). The concrete with granitic sand had higher compressive strength than the concrete with river sand at all ages. This fact was attributed to a stronger paste-aggregate interface and a greater intrinsic strength of the granitic sand. This greater interface strength was attributed to the rougher surface of granitic sand, which improves the interlocking of the aggregate with the paste, which also increased tensile strength. Kou and Poon (2009) studied the effect of the replacement of river sand by recycled concrete aggregate in SCC for various ratios of water/binder (w/b). For the ratio w/b of 0.53 to 100% replacement, there were decreases in both the compressive strength and the splitting tensile strength compared to the reference concrete without substitution; for the ratio w/b 0.44, 100% replacement and addition of approximately 20% fly ash mass relative to the cement, there was no change in the values of compressive strength and an increase in splitting tensile strength of about 20% compared to the reference concrete, after 28 days. In this case, the probable strengthening of the paste-aggregate interface was only noticeable in the property of tensile strength. Druta *et al* (2014) studied the properties of the paste-aggregate interface and the mechanical properties in CC and SCC with the aid of images obtained by scanning electron microscopy. To obtain SCC, additional minerals were used: blast furnace slag, fly ash and silica fume. The ratios w/b varied between 0.3 and 0.6. For all of the ratios, there was an increase in strength of SCC compared to CC. These results were attributed to the strengthening of the paste-aggregate interface, which in turn is explained by the reduced thickness of the micro-cracks in the paste-aggregate matrix, and thus reducing the volume of voids in the SCC in relation to CC.

The objective of the present work was to evaluate the technical viability of Self Compacting Concretes (SCC) containing quarry dust and artificial sand, by-products from the production of crushed coarse aggregate. All mixtures had similar properties in the fresh state as shown in Bacarji and Toledo Filho (2012). The performance of SCC with aggregates and quarry dust from granitic rocks and micaschist was evaluated in comparison to two types of concretes produced with natural river sand; one with quarry dust and coarse aggregates of granite and the other with quarry dust and coarse aggregates of micaschist. Evaluated also was the effect of replacing 5% of the cement by silica fume in the concretes with artificial sand. The only parameter set for grain structure was the ratio of b/agg, which in this case was 1:3.

The scope of the present research is limited to some mechanical properties. Other properties like those related to durability and long-term properties will be analyzed in a future work.

2. Materials and methods

2.1 Characterization of the materials

2.1.1 Granulometric characterization

The cement used was CP-V-ARI. This is a high early strength cement, whose use is widespread in the precast industry in Brazil. Table 1 presents the principal characteristics of binders and quarry dust.

Fine materials	Diameters(μm)			Blaine fineness (m^2/kg)	Density (kg/m^3)	Average compressive strength (MPa) for [1]w/c= 0.48		
	d_{10}	d_{50}	d_{90}			1 day	7 days	28 days
S. Fume	0.28	0.42	3.15	-	2.280	-	-	-
Cement	1.92	11.66	38.04	515.7	3.110	24.5	36.8	43.6
Micash.	9.88	51.29	133.28	-	2.840	-	-	-
Granite	13.06	80.92	291.09	-	2.735	-	-	-

[1] w/c= water/cement ratio

Table 1
Physical properties of binders and fine materials.

Table 2 presents the density, Fineness Modulus (FM) and Maximum Diameter (D_{max}) of fine and coarse aggregates and the percentages of the finest materials (sieve 0.15), those passing through a sieve of 0.15 mm of sands. Figure 1 presents the granulometric distribution curves of fine and coarse aggregates.

Properties	Sands			Coarse aggregates	
	River	Micash.	Granite	Micash.	Granite
Density (kg/m^3)	2.620	2.750	2.650	2.750	2.630
FM	1.94	2.88	3.16	6.17	5.63
D_{max} (mm)	2.36	6.3	4.75	12.5	12.5
sieve 0.15 (%)	7.2	17.1	9.0	-	-

Table 2
Physical properties of aggregates.

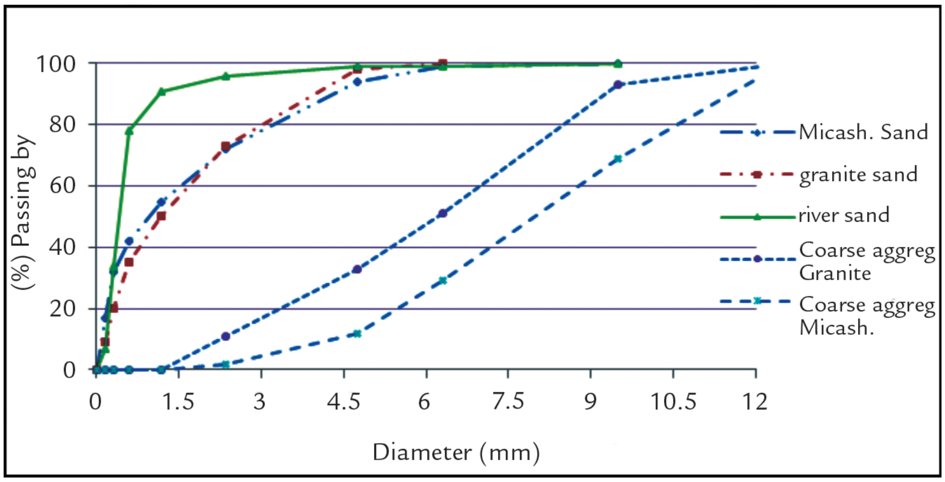


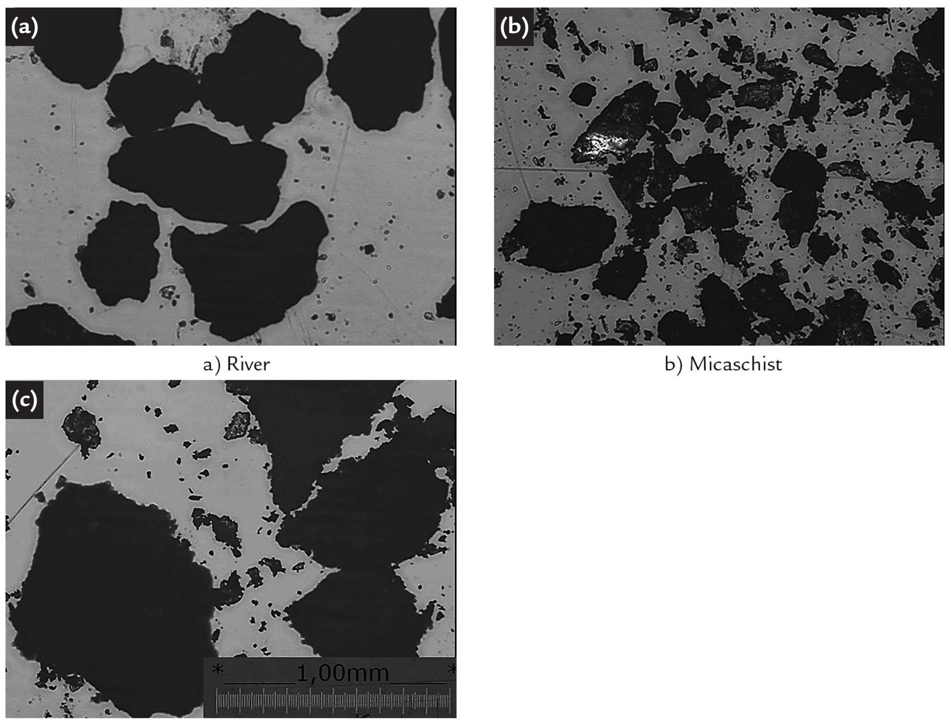
Figure 1
Granulometric distribution curves of aggregates.

2.1.2 Optical microscopy of sand

Assays by optical microscopy were performed for the three types of sand (river, micaschist, and granite) and are shown in Figure 2. Each sample was taken randomly from the batch after the process of quartering.

2.1.3 Analysis of aggregate form

Aggregate form was characterized using digital image analysis following several previous studies (Mora *et al* (1998), Kwan et al (1999), Gonçalves *et al* (2007), Fabro *et al* (2011)), and analyzed the parameters of aspect ratio, sphericity, shape factor and flakiness ratio.



a) River
b) Micaschist
c) Granite

Figure 2
Optical microscopy of sands (Optical microscope LECA – DMRM).

a) Aspect Ratio (AR)

This parameter expresses the relationship between the length of the longest axis ($Comp_1$) and the length of the shortest axis ($Comp_3$) of grit according to Equation 1.

$$AR = \frac{Comp_1}{Comp_2} \quad (1)$$

b) Sphericity (Sp)

This parameter is obtained by Equation 2:

$$Sp = \frac{p^2}{4\pi A} \quad (2)$$

Where p is the perimeter of the projected cross-sectional area of grit and A is the area, obtained through image analysis. Values of AR and Sp near 1.0 indicate a good aspect ratio and good sphericity, respectively.

c) Shape factor ($S_{f,aggreg}$)

Weidmann (2008) developed a method for determining the shape factor of aggregates and defined it as the "weighted average of the shape factor of the fraction of each aggregate contained in the composition to the fraction retained in the 0.15 mesh" and is obtained using Equation 3:

$$S_{f,\,aggreg} = \frac{\Sigma S_{f,\,fraction} \, X \, (\%ret_{fraction})}{\Sigma \, \%ret} \tag{3}$$

Where $\%ret_{fraction}$ is the percent retained fraction; The shape factor of the fraction, $S_{f,fraction}$, is given by equation 4:

$$S_{f,\,fraction} = \frac{\dfrac{m_{fraction}}{\rho_{fraction}}}{\pi/6 \, \Sigma \, comp_1} \tag{4}$$

Where: $m_{fraction}$ is the mass of the analyzed fraction; $p_{fraction}$ is the specific mass of the analyzed fraction; $comp_1$ = is the length of each grain analyzed in the image.

Weidmann(2008) obtained the following values for the shape coefficients of sands: River sand: 0.278; Rounded artificial sand "in nature": 0.170 and Flak artificial sand "in nature": 0.127.

These results were obtained using the minimum diameter retained in the 0.3 mm sieve.

The methodology developed in Weidmann (2008) was based on the French standard XP P18-540 (1997) that defines the shape factor as a volumetric ratio; that is, it establishes a relationship between the amount of grit and the volume of a sphere that circumscribes the grit. Thus, the closer the shape coefficient is to 1.0, the more spherical is the shape of the aggregate.

In the present study, the minimum diameter analyzed for the sands was that retained in the 0.6 mm sieve.

d) Flakiness indicator (λ)

According to Fabro *et al* (2011), the flakiness indicator can be calculated from the width and the area of a two-dimensional projection of a particle obtained by the digital image analysis of aggregate particles using Equation 5:

$$\lambda = \frac{M}{\rho \Sigma_{i=1}^{n} \, comp_2 A} \tag{5}$$

Where: M is the mass of the aggregate sample that was used for the measurement of dimensions using image processing; ρ is the density of the aggregate sample; $comp_2$ is the smallest dimension of a rectangle circumscribing the projection of an aggregate particle in the digital image; A is the projected area of an aggregate particle in a digital image. The flakiness indicator, λ, is always less than or equal to 1.0; the lower the ratio, the more flaky is the aggregate.

Table 3 shows the values of the parameters for the present study; for each sample were analyzed 200 grits taken randomly from the batch after the process of quartering. Shape factors of the aggregates were calculated by means of weight mean, where the weight attributed to each fraction corresponds to the percentage of material retained in the respective fraction (Equation 3). Other parameters were obtained by arithmetic means.

Aggregates	AR	Sp	$S_{f,aggreg}$	λ
River Sand	1.370	1.460	0.416	0.566
Granite Sand	1.540	1.500	0.216	0.466
Mica Schist Sand	1.570	1.780	0.206	0.398
Granite coarse aggregate	1.510	1.790	0.158	0.291
Mica Schist coarse aggregate	1.530	1.560	0.175	0.322

Table 3
Shape parameters for the aggregates.

2.2 Quantification of concrete

The SCC used in the present study was acquired following the methodology of Tutikian (2004), which in turn starts with Conventional Concrete (CC), obtained following the methodology of Helene (1992). Other details regarding the mixture of concrete used herein can be obtained from Bacarji and Toledo Filho (2012).

To obtain the SCC, a slump flow diameter in the range of 660 mm to 700mm was adopted. The data regarding the features of the SCC produced are given in Table 4. In order to obtain the required conditions of SCC in the fresh state for MX concrete, it was not possible to use 100% micaschist sand, so instead 20% of the mica schist was replaced with river sand, according to Bacarji and Toledo Filho (2012).

Table 4
Features of the SCC.

Concrete	Quarry Dust (q)	Fine Aggreg. (fa)	Coarse Aggreg. (ca)	Proportions (b:q:fa:ca)	$^{2}t_{sub}$(%)	SPP (%)	w/b	S. fume (%)
REF1	Micash.	R. Sand	Micash.	1:0.38:0.78:1.84	33	1.50	0.36	-
MX	Micash.	Micash.	Micash.	1:0.74:0.50:1.76	60	1.50	0.50	-
MX5	Micash.	Micash.	Micash.	1:0.54:0.70:1.76	44	1.80	0.50	5
REF2	Granite	R. Sand	Granite	1:0.34:0.66:2.00	34	1.50	0.38	-
GRN	Granite	Granite	Granite	1:0.53:0.55:1.92	49	1.50	0.45	-
GRN5	Granite	Granite	Granite	1:0.51:0.57:1.92	47	1.80	0.45	5

$^{2}t_{sub}$= Content of Fine aggregate substituted for quarry dust=(q/(q+fa))x100.

A polyacrylate type dispersant with a solid content of 31.2%, a density of 1,073 kg/m³ and a pH of 6.2 was used.

3. Results and discussion

3.1 Compressive strength

This property was measured at seven, 28, and 90 days and the average values are given in Table 5. Standard deviations are displayed in brackets.

Table 5
Compressive and Tensile strength of SCC.

Concrete	f_c (MPa)			f_{td} (MPa)	f_{tf} (MPa)	f_{ts} (MPa)
	7	28	90			
REF1	35.6 (0.54)	40.4 (2.93)	41.9 (0.86)	2.23	7.16	3.88
MX	27.0 (0.71)	31.7 (1.81)	33.7 (0.56)	1.47	5.48	3.45
MX5	27.6 (1.47)	33.0 (2.06)	34.7 (0.66)	2.00	6.13	3.47
REF2	48.0 (3.78)	51.0 (2.01)	60.4 (1.82)	2.28	6.67	3.49
GRN	40.6 (1.34)	47.4 (1.35)	52.7 (0.51)	2.40	7.20	3.88
GRN5	42.4 (0.61)	55.5 (2.05)	63.6 (1.36)	2.99	8.56	4.40

Concrete reference REF1 had the best results at all ages among the concrete with coarse aggregates of micaschist. This performance can be attributed to the lower water demand, the lowest level of substitution of fine material in this concrete (Table 4) and having river sand with the best properties of shape and texture (Table 3 and Figure 2). The replacement of river sand with micaschist sand caused a reduction of approximately 22% in strength at 28 days. The effect of silica fume on concrete MX5, although beneficial, was insufficient to surpass, or even equal, the results for concrete REF1 through 90 days. In this case the benefit was in allowing the full replacement of river sand for micaschist sand, which was not possible in concrete MX. The MX5 concrete strength gain in relationship with concrete MX was approximately 4% at 28 days. The worst performance of any concrete was MX. One of the main reasons to this can be attributed to the shape characteristics of its sand. Optical microscopy showed that this sand had the greatest angularity (Figure 2). The characterization of the shape of the fine aggregates (Table 3) shows that the worst properties were for micaschist sands. Considering the Aspect Ratio, Sphericity, Shape factor and Flakiness indicator, the ratios between the properties of granite sand and micaschist sand are 0.98, 0.84, 1.05 and 1.17, respectively. So, the more pronounced differences between the artificial sands are Sphericity (0.84) and Flakiness indicator (1.17). This influenced others parameters like w/b ratio and proportions of materials (Table 4) that contribute to decrease compressive strength. Another aspect that can influence these results, but that was not considered in this work, is the intrinsic resistance of the original rock. The concrete with coarse granite aggregates showed the best performance with the reference concrete REF2 having the best results at the age of seven days and concrete GRN5 and REF2 having approximately the same results at the ages of 28 and 90 days considering the standard deviations. In the case of GRN5, the effect of silica fume was more pronounced than MX5, probably because of the better packing of the particles in addition to a pozzolanic effect. The better performance of concrete REF2 in relation to the concrete GRN can be explained as in the case of REF1, that is, the lower water demand, shape properties of aggregates, and the lesser need for fine materials.

Another important result was the apparent influence of coarse aggregates that can be observed when comparing the REF1 and REF2 concrete. The latter showed increases of 35%, 26% and 44% at seven, 28, and 90 days, respectively, relative to the former. One factor of these increases can be related to the smaller particle size of coarse aggregate granite; although both coarse aggregates had the same maximum diameter of 12.5mm, granite aggregate had a lower Fineness Modulus. The reduction of the aggregate diameters strengthens the paste-aggregate transition zone, since it reduces the thickness of the micro cracks therein, as shown by Akçaoglu *et al* (2005) and Khaleel *et al* (2011). It is important to note that in the case of the coarse aggregates, the micaschist had better shape properties than granite (Table 3). Considering the Aspect Ratio, Sphericity, Shape factor and Flakiness indicator, the ratios between the properties of coarse aggregates of granite and micaschist are 0.99, 1.15, 0.90 and 0.90, respectively.

3.2 Tensile strength

Concrete tensile strength was tested using direct, flexural and diametrical compression tests at 28 days of age and obtained f_{td}, f_{tf}, f_{ts}, respectively. The results are shown in Table 5.

Overall, it appears that the tensile behavior of concrete changes in a way similar to that of compressive behavior; concrete with granite aggregates had better results. Among the concrete types with coarse micaschist aggregates, the REF1 concrete performed best. The replacement of river sand by micaschist sand caused a reduction in tensile strength of approximately 34%, 23% and 11% in the direct, flexural, and diametrical compression tests, respectively. The effect of silica fume on concrete MX5, although beneficial, was insufficient to surpass, or even equal, the results for concrete REF1. The strength gains by the MX5 concrete compared to MX concrete were approximately 36% and 12% in the direct and flexural tests, respectively. As for concrete with coarse granite aggregates, GRN5 concrete showed the best results, followed by concrete GRN. The strength gains for GRN5 concrete compared to REF2 were approximately 31%, 28% and 26% in the direct, flexural, and diametrical compression tests, respectively. The best performance of GRN and GRN5 concretes regarding to REF2 concrete can be attributed to the properties of the granitic sand shape, which improves the interlocking of the aggregate with the paste, whose increased tensile strength was similar to that observed in Kou and Poon (2002) and Druta *et al* (2014).

As intended in the scope of this work, the technical viability of the use of quarry dust and artificial sand was demonstrated. Mixtures REF1 and REF2 were obtained by substituting 33% and 34% of natural sand by quarry dust, respectively (Table 3). The mixtures MX5, GRN and GRN5 were obtained by substituting 100% of natural sand by quarry dust and artificial sand.

4. Conclusions

This study evaluated the technical viability of SCC with artificial sand and quarry dust, by-products obtained from the production of crushed coarse aggregates and considering only the mechanical properties. Two types of rocks were analyzed: Granite and Micashist. The obtained results demonstrated that these by-products offered a technically feasible solution which is consistent with the aims of sustainable development and preservation of the environment.

Considering similar properties in the fresh state of all concretes, as showed in Bacarji and Toledo Filho (2012), the following major conclusions can be related:

- The substitution of natural river sand by artificial sand of micashist decreased both the compressive and tensile strengths;
- The substitution of natural river sand by artificial sand of granite generated concretes with the same level of compressive strength and improved the properties of the tensile strength;
- The effect of silica fume was more pronounced in the concrete with granite artificial sand than with micashist sand.

So, it was possible to use fine minerals (quarry dust) and artificial sand, the by-products of the production of coarse aggregates, in the production of

SCC and to achieve good mechanical properties, with compression strengths ranging between 32MPa and 55MPa at 28 days. These materials provide interesting alternatives, since they offer a technically feasible solution that is also consistent with the aims of sustainable development and preservation of the environment.

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