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Influence of crusher type in the shape of fine crushed aggregate grains

Influência do tipo de britador na forma dos grãos de agregados miúdos de britagem

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Abstract

Quarries have invested in equipment to increase production and improve the quality of their products, such as vertical shaft impact crushers (VSI). This type of crusher works with autogenous comminution of the material to improve the shape of the coarse aggregates. However, there are few studies about the influence of crushers in the shape of fine aggregate grains. In this context, gneiss and granite fine crushed aggregates, produced in cone crushers and VSI were studied. Parameters such as coefficient of volumetric shape, aspect ratio, and circularity were used to compare these aggregates with the river sand. The results showed that there is a difference between the shape of the sand river and the fine crushed aggregates. Among the crushed aggregates, those from the VSI showed improvements in grain shape, compared to aggregates from cone crushers. However, this improvement decreases with the reduction of grain size. Mortars produced with the studied aggregates were also evaluated. It was verified their influence on the consistency, the air content and compressive strength at 28 days. For the study in the mortar, the crushed aggregates were separated in fractions by sieving and composed to obtain the same granulometric distribution for all the aggregates. The mortars made with the crushing aggregates from the VSI showed higher fluidity, lower air content and higher compressive strength when compared to the crushed aggregates produced in the cone crusher.

Keywords: crushed aggregates, grain shape, crushers.

Resumo

As pedreiras têm investido na aquisição de equipamentos para aumentar a produção e melhorar a qualidade dos seus produtos, como os britadores de eixo vertical – VSI (*Vertical Shaft Impact*). Esse tipo de britador realiza a cominuição autógena do material melhorando o formato dos grãos dos agregados graúdos. Contudo, existem poucos estudos sobre a influência dos britadores na forma dos grãos para os agregados miúdos. Nesse contexto, foram estudados agregados miúdos de britagem de gnaisse e de granito, produzidos em britadores cônicos e VSI. Foram avaliados parâmetros de forma como coeficiente de forma volumétrico, relação de aspecto e arredondamento em comparação com as mesmas propriedades obtidas para uma areia de rio. Os resultados mostraram que existe diferença entre a forma dos grãos da areia de rio e a dos agregados de britagem. Entre os agregados de britagem, os provenientes do VSI apresentaram melhorias na forma dos grãos, frente aos agregados provenientes dos britadores cônicos. Entretanto, essa melhora diminui com a redução do tamanho dos grãos. Avaliou-se, também, argamassas produzidas com os agregados estudados, verificando sua influência sobre a consistência, o teor de ar incorporado e a resistência à compressão aos 28 dias. Para o estudo em argamassa os agregados miúdos de britagem foram separados em frações por peneiramento para posterior composição da mesma curva granulométrica para todos os agregados. As argamassas confeccionadas com os agregados de britagem provenientes do VSI apresentaram uma maior fluidez, menor teor de ar incorporado e maior resistência à compressão, se comparado com os agregados de britagem produzidos no britador cônico.

Palavras-chave: agregado de britagem, forma dos grãos, britadores.

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1. Introduction

Course and fine aggregates represent 60 to 80% of the volumetric composition of a Portland cement concrete, 30% being occupied by fine aggregate. Within this universe, the employment of crushed fine aggregates by concrete dosing central centers has been growing. According to Weidmann [1], who focused his study in the State of Santa Catarina, factors such as constancy within the granulometric properties, low level of impurity and smaller environmental impact, when compared to fine aggregates coming from rivers and excavations, have been contributing to this growth. However, despite the advantages mentioned, crushed aggregates present disadvantages related to the shape of the grains.

With the objective of improving this deficiency and increasing the consumer's market, the companies that produce crushed aggregates (quarries) have invested in technology and new equipment. The main highlight has been the use of more modern and efficient crushers, trying to correct the shape of the grains, the granulometric composition and even the quality of the fine aggregates. Within this context, there is the increasing use of the vertical shaft impact crushers (VSI) [1]. These crushers were developed at the end of the 1960's in New Zealand, gaining space within the concrete industry [2]. The principle of comminution of the VSI type crushers is based on the acceleration of the particles through a central rotor that rotates in high velocity. The grains enter the central part of the rotor and are thrown by the centrifugal force to the sides of the equipment, at velocities that may go up to 90 m/sec (approximately 320 km/hr), possibly colliding with the bed formed by the accumulated aggregates in the carcass of the crusher, or in the aggregates that fall in the form of a lateral cascade (Figure 1). The reduction of the particles occurs due to the collision of the rock against rock [3], generating a greater quantity of fine particles and an aggregate with a more cubic shape when compares to the aggregates obtained in the conic crushers [5]. Normally the VSI crushers are employed in quarries as tertiary crushers, for the exclusive production of crushed fine aggregate or for the reduction of the dimension of a material that eventually presents small commercial value. Another kind of equipment commonly found in quarries as secondary and tertiary crushers is the conic crusher. It has an oscillating central piston, which, in circular movements, at one moment moves away and at another moves closer to the lateral carcass of the crusher (Figure 2). The actual crushing occurs by the compression of the rock between the coatings of the piston (mantle) and of the carcass, or between the actually pressed particles [6, 7, 8]. However, the fracture of the particles in this type of crushers obeys, in many cases, the preferential plans of the rocks, due to their mineralogical constitutions, being able to generate aggregates with not so favorable shapes for the production of concretes [9], as shown in Figure 3. The technical scientific environment already knows of the benefits of the VSI crushers in the improvement of the shape of the grains of coarse crushed aggregates (Figure 3) [9, 10]. Many concrete plants of the South of the country choose the coarse aggregate suppliers considering, besides the price and the type of rock, the type of crusher, once it can improve the shape of the material and present significant reductions of costs of the cement mixtures and consumption [9].

Related to fine aggregates, Bengtsson & Evertsson [11] evaluated the influence of a conic crusher and a VSI crusher, with different speeds of the piston, in the shape of fine aggregates of tonalite rock. The referred authors demonstrated that the aspect ratio (ratio between the smaller and greater dimension of Feret) of the fine aggregates from the conic crusher are smaller than the ones obtained with the VSI crusher. However, when the speed of the piston

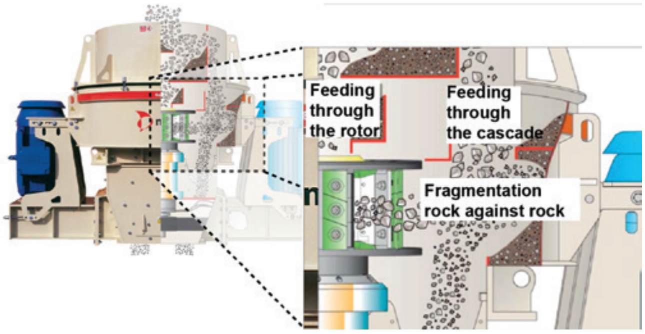

Figure 1
Detail of functioning of the VSI crusher (adapted from Metsominerals [4])

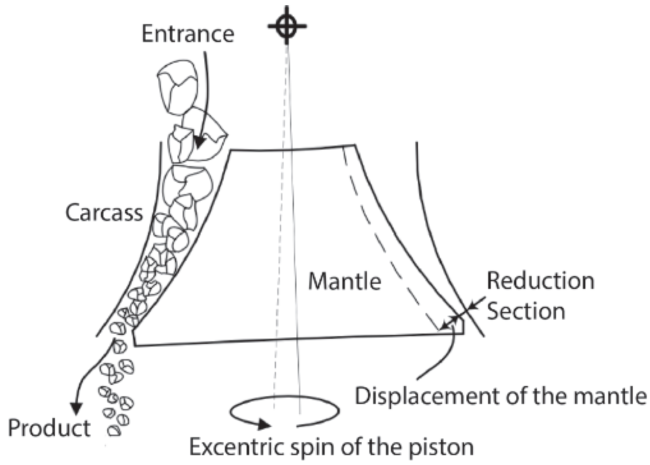

Figure 2
Details of the functioning of the conic crusher (adapted from Itävuo *et al.* [8])

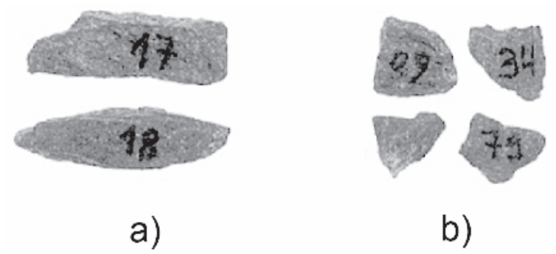

Figure 3
The shape of aggregates of basaltic origin (a) from conic type crushers (b) from VSI crushers (adapted from Wedmann[9])

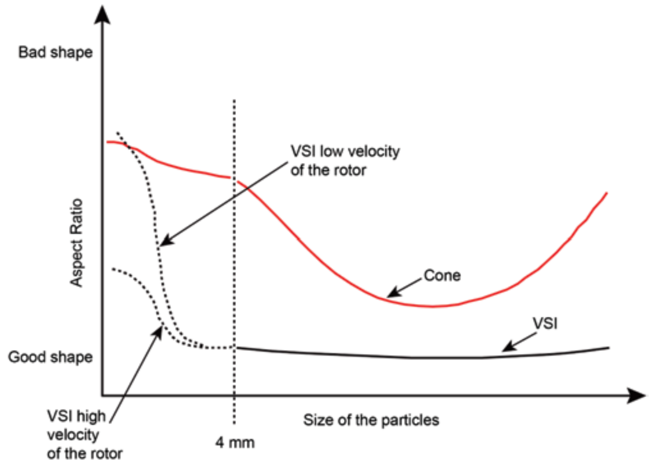

Figure 4
Aspect ratio form crushed aggregates from VSI crushers (high and low velocities of the rotor) and conic crushers
(adapted from Bengtsson *et al.*[14])

of the VSI is low, the aspect ratio of the resulting material is close to the relation of the aspect of the aggregate produced with the use of the conic crusher (Figure 4).
Weidmann [9] compared the shape of fine crushed aggregates of basaltic origin from VSI and gyrospheric crushers. The referred author employed the method proposed by Prudêncio *et al.* [12] which is based on the French norm AFNOR NF EN 933-4 [13] for the determination of the volumetric form coefficient of the fractions, using digital images to obtain the greater dimensions of the grains. Weidmann [9] demonstrated the thicker fractions of the fine crushed aggregates (fractions between the sieves of 4,8 mm and 1,2 mm) suffer significant improvements in the shape of the grains due to the type of the crusher (Table 1).
Fabro *et al.* [15] evaluated the shape of the grains of the fine aggregates of basaltic origin (fractions between the sieves of 4.8 mm to 0.3 mm) from different crushers (conic, hammer and VSI) and compared the results with the shape of a natural aggregate from a river. The results demonstrated that the shape of the crushed aggregates depends on the type of crusher and that the aggregates

Table 1
Volumetric[1] shape coefficient of the fine aggregate of basaltic origin in function of the type of crusher (Weidmann [9])

Sieve (mm)	Volumetric shape coefficient[1]	
	VSI crusher	Conic crusher
4.8	0.66	0.116
2.4	0.177	0.124
1.2	0.173	0.127
0.6	0.186	0.32
0.3	0.153	0.42
0.15	0,.63	0.153

[1] Volumetric shape coefficient determined according to AFNOR NF EN 933-4 [11] and the procedures prescribed by Prudêncio *et al.* [12]

from the VSI presented shape coefficients closer to the natural fine aggregate. Besides this, the referred authors concluded that the volumetric form coefficient [12] and the indicator of lamellarity proposed by Kwan *et al.* [16] were the parameters that allowed a greater evaluation of the shape of the aggregates.
Within this context, the objective of the present study was to evaluate the influence of the type of crusher (cone and VSI) in the shape of fine crushed aggregates of granite and gneiss compared to a natural river aggregate, besides evaluating the possible influence of the differences of shape of grains in the properties of the mortars produced with these materials. It is worth pointing out that the few studies found in the country were performed with rocks of basaltic origin.

2. Materials and the experimental program

2.1 Materials

Crushed aggregates were collected in two quarries for the conduction of this study. The first quarry, situated in the region of the greater area of Florianópolis, produces fine crushed aggregates of granite origin, and the second, situated in the area of the Itajaí Valley, produces fine crushed aggregates of gneiss. As mentioned earlier, a natural river sand was also used, from the same region as the second quarry (Itajaí Valley), more precisely, close to the city of Blumenau (Figure 5). The two quarries mentioned had, in their line of production, the two kinds of crushers – the conic crusher and the VSI as secondary and tertiary crushers, respectively, what made it possible to collect aggregates of the same origin produced by the two crushers mentioned. Both companies work with the VSI crusher without the cascade effect (only with material passing through the piston and colliding with the bed of rock of the carcass) for the production of fine crushed aggregates. The crushed sands were collected in the exit running machine of the crushers, during a day of normal production regime. The running machine was stopped

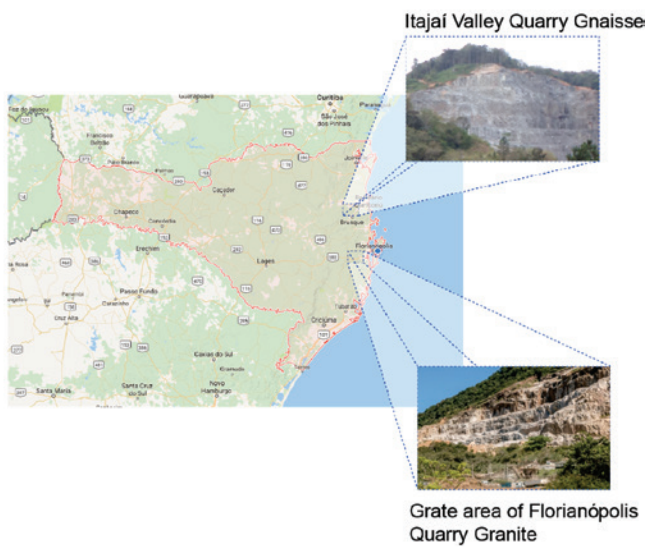

Figure 5
Location of the quarries where the materials employed in the present study were collected

for a determined period of time and the material, contained in a section with approximately 1.5 to 2.0 m of length was removed and placed in plastic containers. This procedure was performed two to three times, in intervals of approximately 1 hour, producing sufficient quantities of material for the studies in the laboratory (about 100 to 150 kg of material). The materials were sent to the laboratory of technology of materials of construction of IFSC/Florianópolis, where they were placed in a drying oven for a posterior preliminary sieving, using a 4.8 mm sieve, with the objective of eliminating the portion of the coarse aggregate present.

After the preliminary sieving, the material that passed through the sieve of 4.8 mm of each sample of crushed sand, as well as the natural fine aggregate, was characterized according to the prescriptions of ABNT NM-248 [17], ABNT NM-46 [18], ABNT NM-52 [19], for the determination of granulometric composition, the rate of powder material and specific apparent mass, respectively. Besides this, the passing material in the sieve of 0.075 mm opening was characterized as to the granulometric distribution by employing an analyzer of dynamic image of the particles with the capacity of analysis of the grains with dimensions of 800 to 1 μm.

2.2 Determination of the parameters of the shape of the grains

A sample of approximately 1.5 kg of each material was previously treated, for the determination of the parameters of shape. These samples were repeatedly washed in the laboratory through a 0.075 mm sieve until all of the powder material was removed. All of the water used in the process of the withdrawing of the powder was stored in metallic containers and submitted to drying in an oven, with the objective of collecting the passing material in the 0.075 mm sieve for posterior analysis. It is worth pointing out that the material above the 0.075 mm sieve was also taken to the oven for drying and posterior sieving.

After the process of washing and drying, the material above the 0.075 mm sieve was sieved, adopting the following series of sieves: 2.4 mm, 1.2 mm, 0.6 mm, 0.3 mm, 0.15 mm and 0.075 mm, for the removal of the eventual fraction of powder that might be, by chance, present.

The material removed with water and passing in the 0.075 mm sieve, after the drying in the oven was passed through a sieve of 0.038 mm opening, with the passing material in the referred sieve being stored in the bottom. Each fraction of material retained in the sieves mentioned above, and the material of the bottom was placed in plastic bags, closed and properly identified for posterior determination of the parameters of shape.

In this study the following items were determined:

1 – The volumetric shape coefficient, according to the recommendations of Prudêncio *et al.* [12] and employing the Equation (1). This coefficient was determined for the fractions comprehended between the 2.4 mm and 0.3 mm sieves;

2 – The aspect ratio, based on the Equation (2), for the material comprehended between the 2.4 mm sieve and the bottom;

3 – The circularity [20], given by Equation (3), also, for the material comprehended between the 2.4 mm sieve and the bottom.

$$Cf_{fraction} = \frac{m_{fraction}/d_{fraction}}{\pi/6 \cdot \sum L^3} \quad (1)$$

Where: $Cf_{fraction}$ is the volumetric shape coefficient, based on AFNOR NF EN 933-4 [13] and on the recommendations of Prudêncio *et al.* [12].

$m_{fraction}$ = mass of the grains analyzed in the digital images.

$d_{fraction}$ = apparent specific mass of the fraction analyzed.

L = Greater dimension of each grain determined according to the analysis of the digital images.

$$Ra = \frac{L_{Feret}}{C_{Feret}} \quad (2)$$

Where:

Ra = Aspect ratio.

C_{Feret} = Length of Feret, which consists in the greatest possible dimension between two parallel lines that tangential the grain in the image (Figure 6a).

L_{Feret} = Width of Feret, which consists in the smallest dimension possible between two parallel lines that tangetial the grain in the image (Figure 6b).

$$Ro = \frac{4 \cdot A_{grain}}{\pi \cdot d_{circ}^2} \quad (3)$$

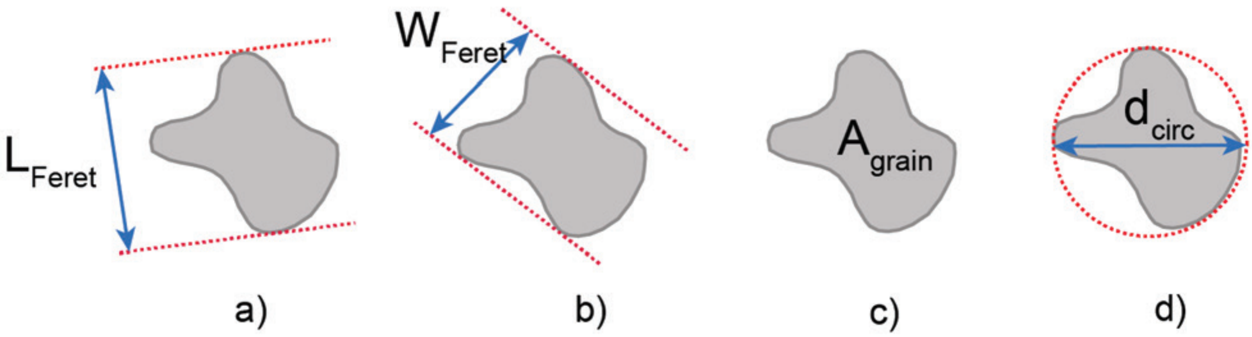

Figure 6
Details of the measurements for the determination of the aspect ratio (Ar) and of the circularity (Rr): a) Length of Feret; b) Width of Feret; c) Area of the grain in-plane projection; d) Diameter of the circle that circumscribes the grain

Where:
Ci = Circularity of the grain.
A_{grain} = Area of the grain on a plane projection (Figure 6c).
d_{circ} = Diameter of the circumference that surrounds the grain (Figure 6d).
A ZEIZZ, model Stemi 2000-C stereoscopic magnifying glass was used for the obtainment of the digital images, with direct capitation of the image through an AxioCam Erc-5s camera. The illumination system and the definition of the brightness were adjusted for the obtainment of the greatest contrast of the grains for a posterior analysis of the images with FIJI free software FIJI (Schindelin *et al.* [21]). It is worth pointing out that the equipment (stereoscopic magnifying glass) made possible the inclusion of a graphic scale of reference, due to the level of increase employed (zoom) to facilitate the calibration of the image in the FIJI software and the obtainment of the desired measurements with greater precision. For the fractions below the 0.075 mm sieve, the use of a Bamboo™ Pad tablet for the manual definition of the contour of the grains was necessary. This happened due to their small dimension, the formation of lumps and overlapping of particles, together with the fact that a great number of translucent grains, were incapable of being automatically and precisely analyzed, just through the adjustment of the histogram of frequencies (threshold) (Figure 7). It is worth pointing out that this phase of manual definition of the contour of the grains was done amplifying the images and taking the grains with the well-defined contour sand without the presence of accumulations and overlapping of grains (Figure 7).
The fractions to be analyzed were, firstly, homogenized and quartered successively up to the reduction of the size of the sample in such a way that the number of grains was a minimum of 240. This number was obtained in pilot studies, based on the standard deviation obtained and adopting a level of reliability of 95% and a margin of error of 10%. Despite Presson [22], Araújo [23] and Tristão [24] recommend that one should work with about 400 grains, the option was to reduce the number of grains by a fraction, to lower the time of image acquisition and analysis. This reduction was done based on the analysis of Goldoni *et al.* [20], who evaluated, among other things, the influence of the number of grains in the shape coefficient of the particles, of fine aggregates, demonstrating that one sample, previously sieved and composed of about 90 grains tends to result in of values of shape coefficients close to the populational average.

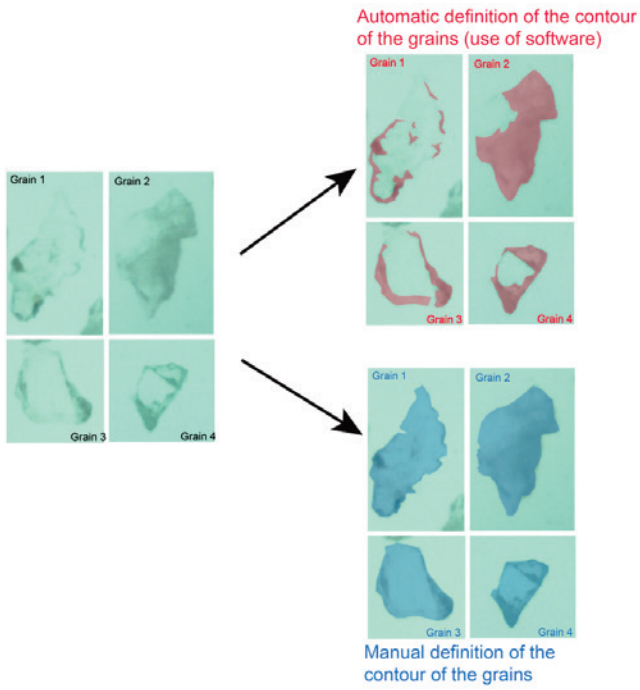

Figure 7
Detail of the automatic and manual obtainment of the contour of the grains (passing material in the 0.075 sieve)

The acquisitions of the images of the fractions retained in the sieves of 2.40 mm and 0.30 mm openings were obtained placing a sample of the grains over a glass plate in a random fashion, posteriorly making small adjustments of position in some grains to avoid their overlapping of one another. After the acquisition of the images, the grains of the fraction that was being analyzed were weighed in a scale with a resolution of a thousandth of a gram, for the determination of the real volume of the grains analyzed, posteriorly being calculated the volumetric shape coefficient of the fraction ($Cf_{fraction}$). Due to the low resolution of the scale, it was not possible to determine the volumetric shape coefficients of the fractions inferior to the 0.30 mm sieve.
For the fractions retained in the 0.15 to 0.038 mm opening sieves and in the bottom (passing the 0.038 mm sieve), the acquisition of the image was conducted with the help of an adhesive tape. Firstly, the samples of the grains were deposited over the glass plates in a random fashion. Due to the difficulty of movement of the plates and the lack of movement of the grains, that were very small and light, an adhesive tape was placed over the plates, for the grains to be fixed on them. This tape was removed with the grains adhered on its adhesive surface and placed directly on the magnifying glass (with the part of the tape without glue facing downwards). After this procedure, the images were captured from nine regions of the tape, three in the west portion, three in the central portion and three in the east portion, guaranteeing a minimum number of grains mentioned earlier and seeking for regions without overlapping of the grains. The posterior treatment of these fractions in the FIJI software was all done with the help of the *Bamboo*™ *Pad* tablet, once the automatic definition of the contour of the grains was impaired by their constant overlapping and by the elevated quantity of translucent grains in these fractions. For these fractions (0.15 mm until the bottom) the determination of the weight of the grains was not possible due to the lack of precision of the scale, and, the consequent need of many grains, besides the problems of measurement of overlapped grains and the difficulty of their adjustment; making it impossible to determine the volumetric shape coefficient for the referred material.
Besides the stereoscopic magnifying glass, an analyzer of dynamic image of particles was employed, for the analysis of the material retained in the sieves of 0.075 mm, 0.038 mm openings and of the bottom. The equipment employed in the present study was the Micromeritics® - Particle Insight dynamic image analyzer, an

equipment that functions with a humid passage and captures the images of the particles in real time, with the help of a CCD camera (Figure 8), and conducts their processing directly in the software of treatment of the image. Ulusoy & Yekler [25] used the same equipment to evaluate the influence of different mills and proposed to use the models for the evaluation of shape, based on the circles (Figure 6a), ellipses and rectangles that circumscribe the particles, and on the dimensions of Feret for very irregular particles (length and width Figure 6a and 6b, respectively), determined directly by the equipment's software. However, as mentioned before, the aspect ratio and the circularity were evaluated, employing Equations (2) and (3), respectively, with these parameters of the shape being determined directly by the software of the analyzer of dynamic images. It is worth pointing out that 15000 particles for each one of the situations were evaluated.

2.3 Evaluation of the properties of the mortars produced with the crushed fine aggregates from the VSI and conic crushers

A study was conducted on mortars with the objective of investigating if the differences found in the parameters of the shape of the aggregates exert influence in mixtures of concrete and mortars. A granulometric curve was standardized for all of the crushed aggregates, performing a previous sieving and separation of the diverse fractions for a posterior composition and adequacy to the standardized curve. It is worth pointing out that, due to the great difference between the granulometric curve of the natural fine aggregate and the curves of the crushed aggregates from the two crushers and of the small quantity of natural aggregate available, the natural fine aggregate was not employed in this phase of the study.

A mix proportion of 1:3 (cement: fine crushed aggregate) fixing the relation water/cement in 0.71. The mortars were produced in a mechanic mixer (mortar mixer), obeying the following mixing procedure:

(a) 1 min in velocity 1 (slow velocity), mixing all of the material in a dry form;
(b) 30 s in velocity 1 (slow velocity), adding water, and
(c) 1 min in velocity 1 (slow velocity), for the complete mixture of the materials.

At the end of the mixing process, the consistency of the mortars was evaluated employing the consistency table (*Flow-table*), as well as the mass density in the fresh state to detect, indirectly, the air entrainment of the mixtures, according to the prescriptions of ABNT NBR 13278[26].

In the test of the consistency table, the diameters of spreading (D) were determined, after the application of 5, 10, 15, 20 e 30 blows. This variation of blows on the test of the Flow-Table, prescribed by ABNT NBR 7215 [27], was proposed by MARTINS [28], for the evaluation of the consistency of the mortars with relations c/w close to the one employed in the present study.

Three cylindrical test bodies 5x10cm were molded, employing the prescriptions of ABNT NBR 7215 [27], for the evaluation of the resistance to compression at 28 days of age for each mixture produced. The test bodies were unmolded with 24 hours and placed in a tank of water saturated with lime, at a controlled temperature of 23 ± 2° C, until the test date. Before proceeding to the rupture, the test bodies were covered (top and bottom) with sulfur, in order to avoid concentration of tensions at the moment of the test.

3. Results and discussion

Firstly, it is valid to point that there was no control in the parameters of the equipment and of the process of production of the aggregates used in them, such as, velocity of the piston, inlet flow of the material, size of the particles in entrance (supply of the crushers), among others. Each quarry worked with the regulations and particularities of their productive processes, once many of the analysis and conclusions made in the present study may be restricted to these quarries with their respective materials. The concern at the moment of data collection was to obtain all of the resulting material of both types of equipment, without the occurrence of any mixture or contamination with other materials. Because of this, analysis and conclusions of the influence of the mineralogical origin (granite and gneiss) will not be made, in the parameters of shape. Once the different processes of production of each quarry may have exerted influence in the shape of the material this variable could not be controlled.

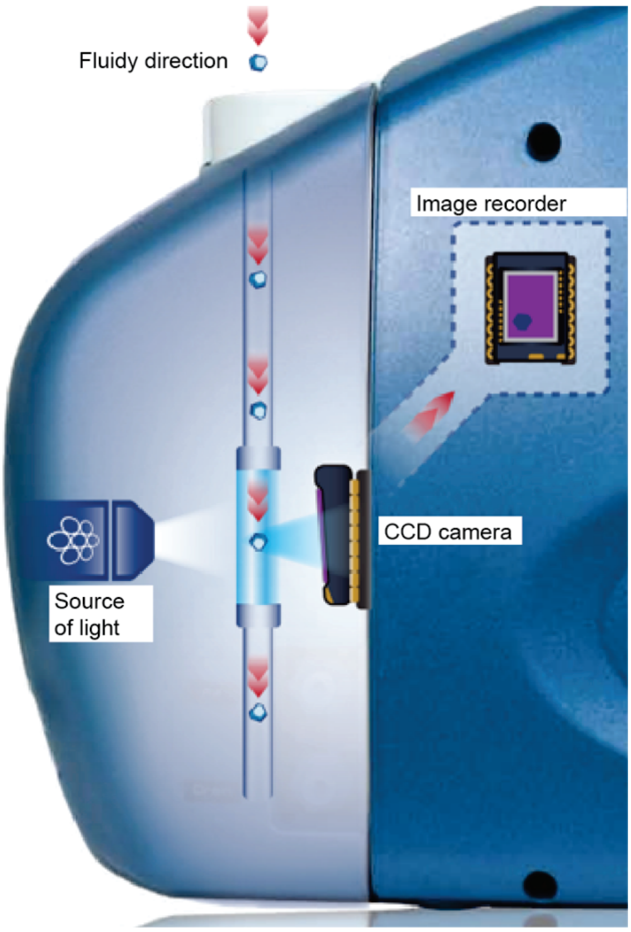

Figure 8
Detail of functioning of the analyzer of dynamic images of particles (adapted from Ulusoy&Yekler[25])

Table 2
Properties of the crushed and natural fine aggregates employed in the present study

Properties	Accumulated retained percentage				
	Granite		Gneiss		Natural fine aggregate
	Conic	VSI	Conic	VSI	
# 4.8 mm	1	0	0	1	0
# 2.4 mm	25	17	10	22	0
# 1.2 mm	46	36	38	46	1
# 0.6 mm	64	56	55	61	11
# 0.3 mm	77	71	68	70	40
# 0.15 mm	87	83	78	80	82
Bottom	100	100	100	100	100
Module of fineness	3,.1	2.63	2.49	2.80	1.34
Powder material	6.14%	9.90%	15.26%	14.94%	1.40 %
Specific mass	2.68 kg/dm³		2.0 kg/dm³		2.65 kg/dm³

3.1 Physical characteristics of the natural and crushed fine aggregates

In Table 2 the physical properties of the natural and crushed fine aggregates of the present study are presented. In Figure 9 the granulometric distributions of the passing material in the sieve of 0.075 mm opening (powder material), evaluated by the analyzer of dynamic images of particles are presented. Analyzing the results presented in Table 2, it cannot be affirmed that the type of crusher (conic or VSI) tends to generate finer or coarser crushed fine aggregate. In the process of crushing with granite rock, the conic crusher generated a thicker material, while in the process of crushing with gneiss, the passing material through the VSI crusher resulted in a coarser crushed aggregate; this can be verified through the values of the module of fineness found (Table 2).
Based on the materials analyzed in the present study, the process of production of gneiss, presented a greater content of powder material, if compared to the material from the process of production of granite, regardless of the type of crusher.
The natural fine aggregate used is an aggregate from a river, finer than the crushed aggregates and that has been being used by a company of Itajaí Valley for the production of stabilized mortars, due to its continuous granulometric distribution and in the shape of grains, which contribute to the improvement of the workability of the mortar. Because of this, this material was chosen as a reference, for the parameter of the shape of the grains that will be presented in item 3.2.
Related to the distribution of the size of the grains for the passing material in the 0.075 mm sieve, it can be verified, through Figure 9, that the type of crusher and the process of production with its respective rocks seems to not exert influence in the distribution of the size of the grains, once the variations are small. However, the natural fine aggregate has a low quantity of passing material in the 0.075 mm sieve, once this powder material is thicker than the powder materials from the crushed aggregates (Figure 9).

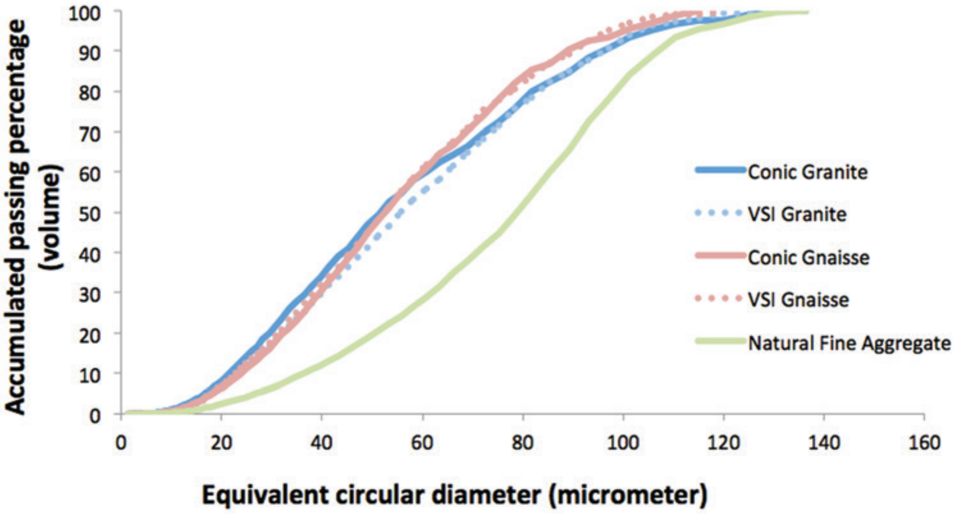

Figure 9
Granulometric distribution of the passing particles in the sieve of 0.15 mm opening

Table 3
Volumetric shape coefficients of the crushed and natural fine aggregates

Sieve (mm)	Granite						Gneiss						Natural fine aggregate		
	Conic			VSI			Conic			VSI					
	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n
2.4	0.137	24.8	300	0.254	19.8	306	0.149	21.1	587	0.217	20.8	271	–	–	–
1.2	0.149	27.7	284	0.215	23.3	308	0.097	27.7	375	0.203	25.5	602	0.297	20.7	156
0.6	0.114	25.1	310	0.175	22.2	313	0.106	28.5	247	0.174	24.4	263	0.279	20.6	177
0.3	0.094	26.6	311	0.210	24.2	314	0.112	27.4	501	0.156	27.7	315	0.309	34.8	278
0.15	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
0.075	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
0.038	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Bottom	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

[1] Coefficient of variation = standard deviation divided by the mean, expressed in percentage; n = number of particles of the sample.

3.2 Parameters of the shape of the aggregates

3.2.1 Analysis made with the stereoscopic magnifying glass

3.2.1.1 Volumetric shape coefficient

In Table 3 and Figure 10 the volumetric shape coefficients for the granite, gneiss and natural crushed fine aggregates, with its respective coefficients of variation and number of grains that composed each sample are presented.
Based on the data presented in Table 3, an analysis of variance (ANOVA) was conducted, for a factorial experiment of three factors (the process of crushing with its respective type of rock, type of crusher and the different fractions). A summary of this analysis of variance is found in Table 4.
The results obtained in the statistical analysis demonstrated that all of the factors (process of crushing with its respective types of rock, type of crusher and the fractions) influenced significantly in the results of the volumetric shape coefficients, with a level of reliability of 95% ($F > F_{tabulated}$). The interaction between these two factors also exert significant influence; with the exception of the interaction between the process of crushing and the type of crusher, demonstrating to not have a significant difference in this case.
The results demonstrated that the volumetric form coefficient of the natural fine aggregate is superior to the crushed fine aggregates'.
By analyzing the influence of the crusher in the shape of the grains, it can be perceived, considering the volumetric shape coefficient, that the VSI crusher improves the shape of the grains for both the processes of crushing and their respective mineralogical origins. It is perceived also that the fractions influence significantly in the results of the volumetric shape coefficient, with the reduction of the size of the grains.
The crushing process of the aggregates and their respective mineralogical origins exert significant influence in the volumetric shape

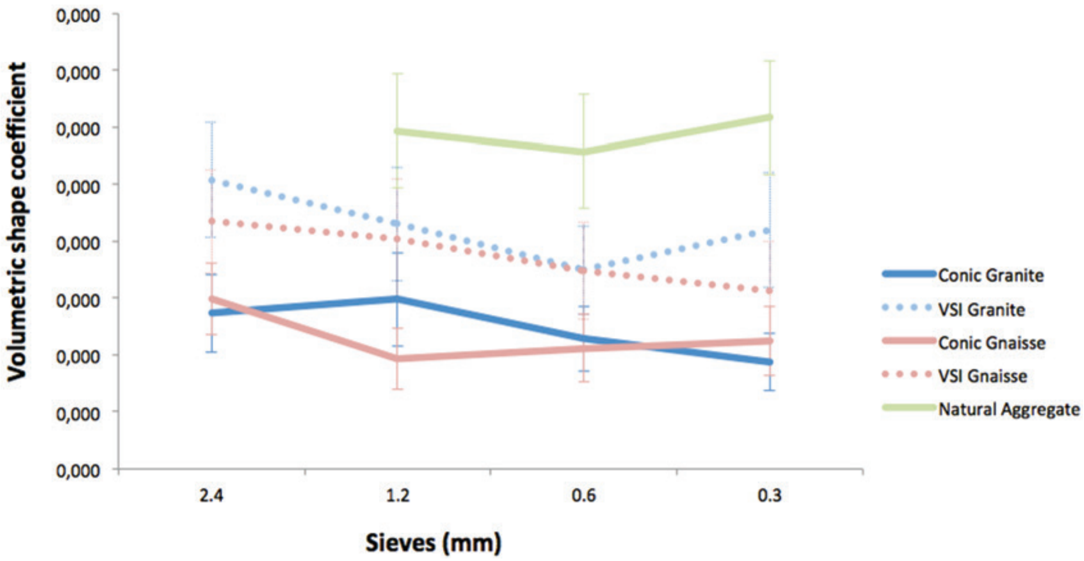

Figure 10
Volumetric shape coefficient obtained with the help of a stereoscopic magnifying glass for the crushed and natural fine aggregates

coefficient. However, when the process of crushing is evaluated together with the kinds of crushers are evaluated, the results obtained in the statistical analysis did not demonstrate any influence. In other words, the conic and VSI crushers presented very similar coefficient values, regardless of the crushing process. This can be seen in the graphics of Figure 10.

3.2.1.2 *Aspect ratio*

In Table 5 the results of the aspect ratio for the crushed fine aggregates of granite and gneiss and for the natural fine aggregate are presented, with their respective coefficients of variation and number of particles employed.

Based on the data presented in Table 5, an analysis of variance was conducted (ANOVA) for a factorial experiment of three factors (the process of crushing with its respective types of rocks, type of crusher and the different fractions). A summary of this analysis of variance is presented in Table 6.

The results obtained in the statistical analysis demonstrated that all of the factors (the process of crushing with its respective types of rocks, type of crusher and the fractions) influence significantly in the results of the aspect ratio, with a level of reliability of 95% ($F > F_{tabulated}$). The interaction between these two factors also exerts significant influence.

Regarding the aspect ratio, the natural fine aggregate presented significantly superior results, in face of the of the crushed fine aggregates, once the difference between the results of the natural sand from the VSI decreased for the coarser fractions (material

Table 4
Summary of the ANOVA – Volumetric shape coefficient of the crushed and natural fine aggregates

Source	QS[1]	Degrees of freedom	QM[2]	F	$F_{tabulated}$
Process	0.36	1	0.36	228.55	3.84
Crusher	8.81	1	8.81	5557.93	3.84
Fraction	1.77	3	0.59	372.40	2.60
Process+crusher	0.00	1	0.00	0.84	3.84
Process+fraction	0.23	3	0.08	48.22	2.60
Crusher+fraction	0.38	3	0.13	79.90	2.60
Process+crusher+ fraction	1.24	3	0.41	260.65	2.60
Residues	8.86	5591	0.0016	–	–
Total	2.,65	5606	–	–	–

[1] Quadratic sum of the deviations; [2] Quadratic mean of the deviations.

Table 5
Aspect ratio of the crushed and natural fine aggregates

Sieve (mm)	Granite						Gneiss						Natural fine aggregate		
	Conic			VSI			Conic			VSI					
	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n
2.4	0.659	19.5	299	0.734	13.	306	0.681	17.2	587	0.713	15.0	271	-	-	-
1.2	0.661	21.5	299	0.720	14.1	308	0.672	18.4	978	0.702	15.7	603	0.726	14.0	156
0.6	0.660	19.3	309	0.694	16.0	303	0.647	20.4	787	0.711	15.9	263	0.723	15.4	177
0.3	0.623	21.0	310	0.686	16.0	315	0.664	19.6	501	0.684	16.7	315	0.724	14.7	238
0.15	0.599	21.7	186	0.629	22.8	262	0.639	23.1	467	0.658	20.2	561	0.719	14.9	235
0.075	0.626	22.8	361	0.595	25.8	372	0.642	21.4	464	0.654	19.4	296	0.704	15.6	248
0.038	0.633	23.0	267	0.626	22.2	355	0.618	22.5	580	0.639	21.9	417	0.671	17.2	250
Bottom	0.662	17,8	267	0.622	19.6	322	0.628	19.2	341	0.634	19.8	274	0.653	17,6	407

[1] Coefficient of variation = standard deviation divided by the mean, expressed in percentage; n = number of particles of the sample.

Table 6
Summary of ANOVA – Aspect ratio of the crushed and natural fine aggregates

Source	QS[1]	Levels of freedom	QM[2]	F	$F_{tabulated}$
Process	0.22	1	0.22	13.28	3.84
Crusher	1.17	1	1.17	71.17	3.84
Fraction	7.62	7	1.09	66.32	2.01
Process+crusher	0.17	1	0.17	10.17	3.84
Process+crusher	0.85	7	0.12	7.3	2.01
Crusher+fraction	2.32	7	0.33	20.23	2.01
Process+crusher+ fraction	4.02	7	0.57	34.96	2.01
Residues	205.42	12514	0.02	–	–
Total	221.79	12545	–	–	–

[1] Quadratic sum of the deviations; [2] Quadratic mean of the deviations.

Table 7
Circularity of the crushed and natural fine aggregates

Sieve (mm)	Granite						Gneiss						Natural fine aggregate		
	Conic			VSI			Conic			VSI					
	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n
2.4	0.584	20.1	299	0.658	13,5	306	0.542	30.9	587	0.627	18.6	271	–	–	–
1,2	0.579	18.6	284	0.643	15,2	308	0.574	20.3	375	0.596	25.5	603	0,.64	14.8	142
0.6	0.574	20.4	309	0.614	16,8	313	0.543	21.6	274	0.605	25.4	263	0,.41	20.7	177
0.3	0.546	21.4	310	0.605	16,7	314	0.568	20.0	303	0.594	21.4	315	0,.59	15.8	238
0,.5	0.529	22.0	186	0.539	27,4	262	0.553	24.1	467	0.573	23.0	561	0,36	20.0	235
0,.75	0.552	23.1	361	0.529	26,2	372	0.565	21.8	464	0.579	20.6	296	0.638	16.4	248
0.38	0.540	24.2	267	0.532	23,0	355	0.545	24.3	580	0.571	23.0	417	0.601	18.6	250
Bottom	0.500	23.1	267	0.542	21,0	322	0.564	19.5	341	0.561	20.5	274	0.582	18.3	407

[1] Coefficient of variation = standard deviation divided by the mean, expressed in percentage; n = number of particles of the sample.

with dimension superior to 1.2mm) and also for the finer fractions (retained in the 0.038 mm sieve and in the bottom).
As for the crusher, the VSI presented more elevated values of aspect ratio if compared to the conic crusher, for both processes of crushing. However, this difference in the aspect ratio seems to decrease for the fractions below the 0.15 mm sieve, reaching, in some cases, an inversion (aspect ratio of the conic crusher was better than the VSI crusher).
Unfortunately, it was not possible to obtain the information related to the regulation of the referred equipment, and, as verified by Bengtsson *et al.* [14] and presented in Figure 4, the aggregates produced in the VSI can be obtained with the piston in lower velocities, reducing this way the quality of the material in what is related to the shape.
Regarding the process of crushing and its respective mineralogical origins, the values obtained for the aspect ratio with the VSI crusher indicate an improvement in the shape of the grains of the fine aggregate in the process with the granite aggregate, for the fractions retained in the 2.4 and 1.2 mm sieves. Between the 0.6 and 0.3 sieves, the aspect ratio remained practically the same. There was an inversion in the improvement of the shape of the grains for the passing material in the 0.3 mm sieve. For the conic crusher and in the fractions between the sieves of 2.4 and 0.6 mm and below the 0.15 mm sieve the process of crushing with the aggregate of gneiss presented a better aspect ratio. There was an inversion in these results in the material retained in the 0.3 and 0.15 mm sieves.

3.2.1.3 Circularity

In Table 7 the results of circularity for the crushed fine aggregates of granite, gneiss and the natural fine aggregate are presented. Based on the data presented in the referred table, an analysis of variance (ANOVA) for a factorial experiment of three factors was conducted (crushing process with its respective types of rock, type of crusher and the different fractions). A summary of this analysis of variance is found in Table 8.
The results obtained in the statistical analysis for the circularity of the aggregates demonstrated that, except for the crushing process, all of the other factor and their interactions influence significantly in the results of the circularity, with a level of reliability of 95% ($F > F_{tabulated}$).
The natural fine aggregate presented a circularity significantly superior to the crushed fine aggregates.
Again, the material from the VSI crusher presented parameters of shape superior to the material from the conic crusher. However, below the 0.15 mm sieve this improvement was not very pronounced – in the case of the process of production with material of granite origin and for the fractions retained in the 0.075 mm and 0.038 sieves there was an inversion in the results (material form the conic crusher presented a better circularity than the material from the VSI crusher).
The results for the circularity obtained with the VSI for the process of crushing with the gneiss aggregate were always superior to the aggregate produced with the conic crusher, except for the material retained in the bottom, where the circularity was equal for the fractions over 0.15 mm, once the fractions inferior to the referred opening of the sieve seemed not to have influence on the circularity of the grains due to the type of crusher.

Table 8
Summary of the ANOVA – Circularity of the crushed and natural fine aggregates

Source	QS[1]	Levels of freedom	QM[2]	F	$F_{tabulated}$
Process	0.02	1	0.2	1.12	3.84
Crusher	2.53	1	2.3	158.24	3.84
Fraction	4.36	7	0.62	38.98	2.01
Process+crusher	0.04	1	0.04	2.39	3.84
Process+fraction	2.56	7	0.37	22.90	2.01
Crusher+fraction	2.15	7	0.31	19.21	2.01
Process+crusher+ fraction	5.01	7	0.72	44.81	2.60
Residue	178.70	11194	0.02	–	–
Total	195.35	11225	–	–	–

[1] Quadratic sum of the deviations; [2] Quadratic mean of the deviations.

3.2.2 Evaluation of the shape with the dynamic analyzer of particles for the material below the 0.15 mm sieve

In Table 9 and 10 the results of the aspect ratio and circularity, together with the size of the samples and coefficients of variation for the passing materials in the 0.15mm sieve are presented, analyzed by employing the analyzer of dynamic image of particles.

By doing an analysis of variance (ANOVA) of 4 factors (crushing process, crusher, fraction and type of test), employing the results obtained with the analyzer of dynamic image and with the stereoscopic magnifying lens (type of test) for the determination of the aspect ratio and circularity, it is possible to perceive that all of the factors exert significant influence on the parameters of shape with a reliability of 95%, except for the fraction where $F < F_{tabulated}$ (Table 11).

Similar to the results presented previously, the natural aggregate presented a better relation of the aspect and circularity if compared to the crushed aggregates. However, when the type of crusher was analyzed, the results for the conic crusher were superior to the results of the VSI in some situations.

The results of circularity demonstrated that, for the material retained in the bottom, there is a tendency of convergence of results, including for the natural aggregate, It is believed that this happened due to the size of the particles retained in the bottom and the precision of the analysis; where many times the size of the grain evaluated with the analyzer of the dynamic image is resumed to a few pixels.

It is worth pointing out that the variabilities (coefficients of variation) are much greater when the analyzes of the dynamic image are

Table 9
Aspect ratio of the crushed and natural fine aggregates employing the analyzer of dynamic images of particles

Sieve (mm)	Granite						Gneiss						Natural fine aggregate		
	Conic			VSI			Conic			VSI					
	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n
0.075	0.641	36.0	15097	0.620	38.3	15036	0.649	39.9	15025	0.690	36	15084	0.690	29.3	15002
0.038	0.635	37.0	15180	0.608	40.1	15068	0.616	36.4	15257	0.622	36	15144	0.712	28.5	15037
Bottom	0.641	32,0	15135	0.628	34.0	15080	0.651	30.9	15143	0.641	31.1	15071	0.688	28.8	15040

Table 10
Circularity of the crushed and natural fine aggregates employing the analyzer of dynamic images of particles

Sieve (mm)	Granite						Gneiss						Natural fine aggregate		
	Conic			VSI			Conic			VSI					
	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n	Mean	cv[1] (%)	n
0.075	0.558	30.5	6544	0.499	31.5	5873	0.541	32.9	4002	0.521	31.3	2163	0.615	24.9	10862
0.038	0.516	30.8	8344	0.496	32.9	8646	0.526	31.6	8720	0.533	31.7	8440	0.563	25.9	9497
Bottom	0.581	28.2	10868	0.570	28.8	10941	0.595	27.4	10867	0.587	27.4	10898	0.590	24.7	11176

Table 11
Summary of the ANOVA – Relaçtion of aspect and circularity of the grains – comparison between the analyzer of the dynamic image and stereoscopic magnifying glass

Test	Source	QS[1]	Levels of freedom	QM[2]	F	$F_{tabulated}$
Aspect ratio	Process	11,39	1	11.39	222.50	3.84
	Crusher	0,.5	1	0.75	14.58	3.84
	Fraction	0.8	1	0.18	3.60	3.84
	Test	27.44	2	13.72	268.13	3.00
	Residue	9498.94	185614	0.05	–	–
Circularity	Process	8.88	1	8.88	335.34	3.84
	Crusher	4.73	1	4.73	178.75	3.84
	Fraction	0.0018	1	0.0018	0.07	3.84
	Test	86.20	2	43.10	1627.51	3.00
	Residue	2664.16	100600	0.03	–	–

[1] Quadratic sum of the deviations; [2] Quadratic mean of the deviations.

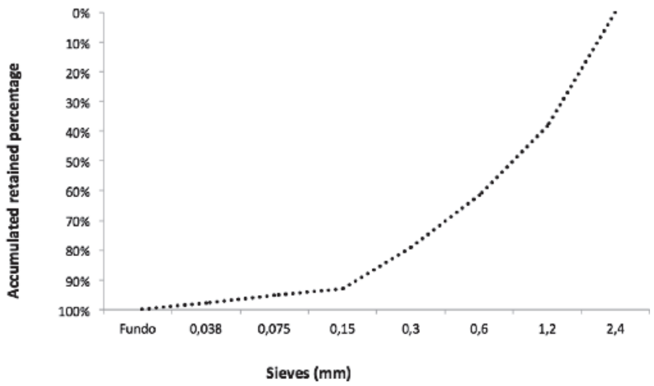

Figure 11
Granulometric distribution used to mortar production with different crushed aggregates

employed, once a grain can pass several times through the front of the reading sensor in different positions, causing a greater variation in the dimensions and parameters obtained with the equipment.

3.3 *Evaluation of the influence of the different crushed aggregates in the properties of the mortars*

As mentioned before, after the due sieving of the aggregates, the quantities were adjusted for the granulometric compositions to remain according to the curve presented in Figure 11.

Taking into consideration the results of the aspect ratio and circularity, determined with the help of the stereoscopic magnifying glass (Tables 5 and 7) and the percentages retained of the standardized granulometric curve, the weighted mean of the aspect ratio was determined, multiplying the referred parameter by the percentage retained in the respective sieve. By adding up these products, the mean weighed parameters of the shape of each material were obtained, which are presented in Table 12. In the same table, the results of the index of consistency (Flow-table) for 5, 10, 15, 20 and 30 blows and the rates of air entrainment are also presented. It is worth pointing out that for the determination of the index of consistency and of the rate of air entrainment two repetitions were performed. The results of resistance to compression at 28 days of age are presented in Table 13.

By analyzing the results of the aspect ratio and circularity, obtained for the crushed fine aggregates with the standardized granulometric curve, it is possible to perceive that the values obtained for the material from the VSI are significantly superior to the values of materials from the conic crusher, both for the granite aggregate as well as the gneiss aggregate (Table 12).

Regarding the crushing process, both the relations of aspect as well as circularity obtained for the crushed aggregates with the standardized granulometric curve did not suffer significant influences.

Based on the data presented in Table 12 and the results of the index of consistency, the graphic of Figure 12 was built, where the number of blows and the respective value of the index of consistency for the crushed aggregates employed in the present study was registered. Analyzing the referred graphic, it is possible to

Table 12
Result obtained in the mortar tests with the crushed and natural fine aggregates from conic and VSI crushers

Properties		Granite		Gneiss	
		Conic	VSI	Conic	VSI
Aspect ratio		0.643	0.685	0.657	0.691
Circularity		0.561	0.604	0.562	0.593
Index of consistency (cm)	5 blows	18.5	24.0	18.	26.0
	10 blows	22.5	29.8	23.8	29.8
	15 blows	25.5	31.8	27.3	32.5
	20 blows	28.3	33,2	29.8	34.4
	30 blows	31.3	35.0	32.8	36.5
Rate of air entrainment (%)		1.81	0.25	2.22	0.38

Table 13
Results of the resistance to compression at 28 days of age

Properties		Granite		Gneiss	
		Conic	VSI	Conic	VSI
F_c (MPa)	CP1	18.63	19.82	18.58	23.01
	CP2	17.64	21.23	17,29	18.06
	CP3	20.27	21,38	18.47	20.55
Medium resistance (MPa)		18.85	20.81	18.11	20.54
Standard deviation (MPa)		1.328	0.860	0.715	2.475
Coefficient of variation (%)		7.05	4.13	3.95	12.05

F^c = resisteance to compression

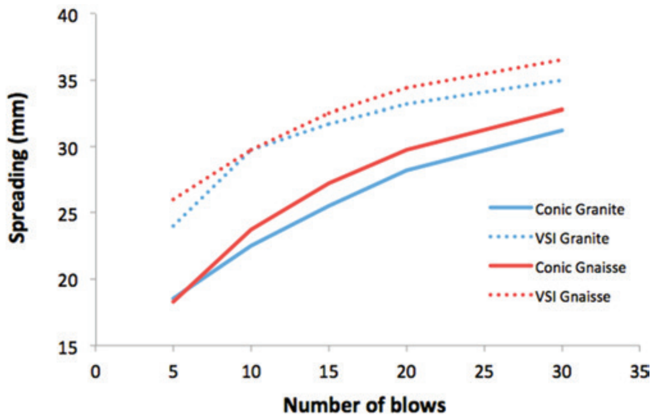

Figure 12
Results of spreading by the number of blows applied for the crushed fine aggregates employed in the present study

verify that the values of the index of consistency for the aggregates from the VSI are superior to the results obtained for the material from the conic crusher.

Regarding the crushing process, the gneiss aggregate presented slightly superior indices of consistency related to the granite aggregate, for both crushers. However, this difference was not significant. As to the rate of air entrainment of the mixtures, the material from the conic crusher presented significantly superior values than the material from the VSI. This fact may be caused by the difference in the parameters of shape, and, consequently, the difference in the indices of consistency, causing the mortars produced with VSI material (better shape) to present a greater easiness for the elimination of the air entrained. This difference in the rates of air entrainment may be the factor responsible for the differences obtained in the results of resistance to the compression. The mortars produced with the VSI material presented values of resistance to compression significantly superior to the ones obtained for the mortars produced and presented with the material of the conic crusher (Table 14). Taking as a base the data obtained and presented in Table 12, it seems that the process of crushing (granite and gneiss), did not exert influence over the rate of air entrainment in the mixtures or over the resistance to the compression of the mortars.

4. Conclusions

Based on the results obtained and presented in the present study, it is possible to conclude that:

1 – In general, the parameters of shape studied (volumetric shape coefficient, aspect ratio and circularity) presented a tendency similar of characterization of behavior in the aggregates.

2 – Except for the volumetric shape coefficient, the other parameters of shape evaluated indicate a tendency of convergence of the shape of the grains when there is a reduction of the shape of the particles, regardless of the crushing processes with their respective types of rocks or the nature of the aggregate (crushed or river).

3 – The type of crusher exerts influence in the volumetric shape coefficient, in the aspect ratio and in the circularity of the particles, once the VSI crusher presented the best results in the referred parameters if compared to the results obtained for the conic crusher. However, this improvement seems to decrease with the reduction of the size of the particles.

4 – This tendency to converge of the parameters of shape for the finer particles from the VSI and the conic crusher may have occurred due to the fact of the velocity of the piston of the VSI crushers be low, as demonstrated by Bengtsson & Evertsson [11]. Unfortunately, these data were not made available by the producers (quarries), once they view this information as secrets, particularities of the regulations of the producing plants that cannot be made available to competitors.

5 – Because the volumetric coefficient determined according to the prescriptions of Prudêncio *et al.* [12], taking into consideration the tridimensional aspects of the grains, the referred parameter seems to be the most indicated for the characterization of the shape of the particles, obtaining, including, greater differences between the materials of distinct origins. However, there are limitations in the determination of the coefficients of volumetric shape for the fractions inferior to 0.3mm.

6 – Taking as a base the mean weighed parameters of shape, determined for the standardized granulometric curve, it is verified that the material form the VSI presented better relations of mean and weighed aspect and circularity, if compared to the material form the conic crusher, regardless of the type of rock.

7 – The mixtures composed of the materials from the VSI crushers (with better mean weighed relations of aspect and circularity) present greater values of the index of consistency and lower rates of air entrainment.

8 – It is believed that the improvement in the results of resistance to compression obtained for the mixtures composed of the materials form the VSI crusher occurred due to their lower rate of entrained air. It is worth pointing out that the processes of obtainment of the crushed aggregates with their respective

Table 14
Summary of the ANOVA – The compressive strength of the specimens of mortars at 28 days of age

Source	SQ[1]	Levels of freedom	MQ[2]	F	Ftabulated
Process	0.76	1	0.76	0.33	5.32
Crusher	14.45	1	14.45	6.32	5.32
Process+crusher	15.37	1	15.37	6.72	5.32
Residue	18.28	8	2.29	–	–
Total	48.86	11	–	–	–

[1] Quadratic sum of the deviations; [2] Quadratic mean of the deviations.

rocks of different mineralogical origin seem to exert influence over the results of resistance to the compression of the mortars.

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