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Influence of fine aggregates particle shape in the concrete properties

Influência da forma dos agregados miúdos nas propriedades do concreto

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Abstract

Natural and manufactured fine aggregates are the most usual aggregates used in mortar and concrete. The most important difference between these aggregates is the particle shape. This property was analyzed using different parameters and was verified its influence in mortar and concrete performance. The digital imagem processing was used to measure the aggregate dimension and the following shape parameters were obtained: aspect ratio, sphericity, flakiness ratio and shape factor. The flakiness ratio and shape factor, which analyses the particle shape property in third dimenson showed the best results. It was observed that the crushing equipment influences the particle shape. Aggregates produced by vertical impact crushing are more rounded, with particle similar to the natural sand. In the experiments the particle shape has influenced the mortar and concrete consistence. However, it did not significantly influence the compressive strenght.

Keywords: fine aggregate, concrete, mortar, particule shape.

Resumo

Os agregados miúdos utilizados na produção de concretos são basicamente as areias naturais provenientes dos leitos dos rios e os agregados artificiais oriundos da britagem de rocha. A principal diferença entre estes dois agregados está no formato de seus grãos. O objetivo principal deste trabalho é avaliar o formato dos grãos de agregados miúdos por meio de diferentes parâmetros, analisando as diferenças entre as formas dos agregados, e suas conseqüências nas propriedades das argamassas e concretos confeccionadas com estes materiais. Para medição dos grãos dos agregados empregou-se a análise digital de imagens e foram calculados os seguintes parâmetros: relação de aspecto, esfericidade, indicador de lamelaridade e coeficiente de forma, sendo que os dois últimos foram os que melhor avaliaram a forma dos agregados. Observou-se que o formato dos grãos dos agregados artificiais depende do tipo de britador empregado pelas pedreiras no processo de britagem das rochas. Os agregados oriundos do britador do tipo vertical de impacto possuem grãos mais arredondados, semelhantes aos grãos da areia natural. Verificou-se que o formato dos grãos dos agregados tem influência direta sobre a consistência das argamassas e concretos, porém não apresentou influência nos resultados de resistência à compressão.

Palavras-chave: agregado miúdo, concreto, argamassa, forma de partículas.

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1. Introduction

Due to the exhaustion of the natural aggregates quarries near the consuming centers, the increase of this raw material transport cost and the laws for environment protection that have forbidden the extraction of natural sand in certain river beds, the use of crushed sand has been intensified as fine aggregate for the concrete production [1]. However, there are some characteristics which are different between the two fine aggregates: the natural sand formed by friction, a process that leads to the loss of the sharp points, has more rounded particles, while the crushed sand particles are generally more sharpened [2]. It is known that the aggregates characteristics have a significant influence on the properties of fresh and hardened concrete. The porosity, the density mass, the granulometry composition, the shape and the superficial texture of the aggregates mainly determine the properties of the fresh concrete and consequently influence the consumption of the concrete paste. It is noted that the more elongated, more angular and coarser the particles are, the higher the cement mixture consumption will be [1, 2, 3, 4]. From the point of view of the concrete strength, the angular particles are preferable, because they lead to a better mixture of the individual particles, thus contributing for the strength of the concrete. On the other hand, angular particles have a greater superficial area and require a higher water quantity for the same concrete consistency, which may lead to reduction in the compressive strength [3, 5].
According to De Larrard [6] the ratio between the fine particles and the total amount of particles (fine + thick) in the concrete mixture determines its reological performance. In the first moment, the volume of voids reduces with the increase of the percentage of fines aggregates in the mixture. However, when reaching a certain level, the fines start to interfere in the accommodation of the thicker particles and the effect of distancing among the particles becomes prevailing, thus increasing the voids index. The higher the volume of voids in the granulometry composition is the lower the mixing of the grits. The granular mixing connected to the interactions of the solid and liquid particles contributes for the increase of the concrete shearing.
Thus, treating the granulometry composition between the coarse and fine aggregate, the mixing grade shall be considered, which depends on the particles shape, the percentage of each particles size and the prevailing fraction of particle size [7].
Considering that the properties of the fresh concrete depend on the content and the composition of the cement paste, when there is a reduction of the quantity of paste, there is also reduction of the particles dispersion grade, increasing the interference among the grits and reducing the fluidity. On the other hand, there is a limit point for the paste quantity in order to avoid the bleeding and the segregation of the concrete (excess of water) or its cohesion (excess of fine material) [6, 8].
The format of the crushed aggregates grits, as well as their granulometry, powder material content and superficial texture depend on the mineralogical origin of the main rock and on the type of equipment used for the rock crushing. When crushers of the type cone, hammer or roller are used for obtaining the aggregates, it is noted that the grits of the aggregates are more angular than the one coming from crushing in equipment of the type vertical impact circulation, also known as VSI [9, 10].
The influence of the shape of the fine aggregates, natural and coming from different crushing processes, on the properties of concrete mortar and concrete produced of these materials has been analyzed in this work. The digital analysis of images has been used as a tool for the characterization of the aggregates, determining their aspect ratio, sphericity, flakiness indicator and shape coefficient.

1.1 Evaluation of the fine aggregate shape

There are different methodologies worldwide to evaluate the coarse aggregates shape and most of them depend on manual measuring of the aggregates dimensions. Mora et al. [11] presented the first work using an image digital analysis to evaluate the size distribution of the coarse aggregates, however Kwan et al. [12] noted that the size distribution of an aggregate is not enough for the evaluation of the grit shape of this aggregate.
D'Agostino [13] used digitalized images to obtain the parameters that would characterize the fine aggregates grits shape and calculated the rounding parameters and the aspect ratio, obtained in the equations 1 and 2, respectively.

$$Rounding = \frac{Perimeter \times Perimeter}{4 \times \pi \times Area} \tag{1}$$

Results with values equal to one for a rounding parameter represent a good rounding, similar to the shape of perfect circle, values higher than one, represent grits with low rounding, i.e. with bad rounding.

$$\text{Aspect ratio:} = \frac{length\ of\ the\ biggest\ grit\ axis}{length\ of\ the\ smallest\ grit\ axis} \tag{2}$$

Gonçalvez et al. [10], Cortes et al. [4] and Westerholm et al. [14] also used the aspect ratio parameter defined by Equation 2 and calculated the parameter nominated as sphericity, which corresponds to the reverse of the rounding parameter (reverse of equation 1) to evaluate the grit shape of the fine aggregates. It is noted that these parameters are based on the dimensions obtained from the projection of the aggregate particles, i.e. in a bi-dimensional analysis of the particle shape.
In 1999, worried with this limitation of the bi-dimensional analysis, Kwan et al. [12] proposed a new index for the evaluation of the aggregates grits shape, nominated as flakiness indicator. The definition of this indicator is based on the consideration that the aggregates particles of the same sample have more or less the same shape characteristics. Using this criterion, Kwan et al. [12] defined that the thickness of the aggregate particle can be estimated using the information obtained from the bi-dimensional image, as in equation 3:

$$average\ thickness\ of\ the\ particle = \lambda \times width\ of\ the\ particle \tag{3}$$

Where:
I = parameter that depends on the particle flakiness, flakiness indicator.
Obtaining the width and the bi-dimensional projection area of the particle from the digital analysis of the aggregate particles image and knowing the mass and the density of the analyzed aggregate sample, it is possible to calculate the flakiness indicator by the equation 4.

$$\lambda = \frac{M}{\rho \times \sum_{i=1}^{n} (width \times area)} \tag{4}$$

Where:
I = flakiness indicator
M = aggregate sample mass that was used for measuring the dimensions by means of analysis of the images processing
ρ = density mass of the aggregate sample
width = corresponds to the smallest dimension of the rectangle that surrounds the aggregate particle projection in the digital image
area = corresponds to the projected area of the aggregate particle in the digital image.
Mora and Kwan [15] and Kwan and Mora [16] verified that there is a good correlation between the values of the flakiness indicator and the mixing density of the aggregate, while the bi-dimensional parameters as elongation and aspect ratio do not correlate well with the mixing density.
Due to the difficulty for evaluation of the fine aggregates shape, Weidmann [17] used the images digital processing to measure the biggest dimension of each grit of the aggregate and calculate its shape coefficient. With the result of the images analysis, the biggest dimension of the grit is obtained, which, based on the French standard AFNOR XP P18-540 (1997) apud (Weidmann, [17]), the shape coefficient for each fraction can be calculated with, according to equation 5.

$$Cf_{fraction} = \frac{\dfrac{m_{fraction}}{d_{fraction}}}{\pi/6 \times \sum L^3} \tag{5}$$

Where: $m_{fraction}$ = mass of all grits contained in the image;
$d_{fraction}$ = density mass of the analyzed fraction;
L= biggest dimension of each grit determined with the help of the images analysis program.
Having the coefficient of each fraction it is possible to calculate the shape coefficient of the aggregate, defined by the equation 6.

$$Cf_{aggregate} = \frac{\sum_{i=1}^{n} Cf\ of\ each\ fraction \times respective\ \%retained\ in\ each\ sieve}{\sum \%retained\ in\ each\ sieve} \tag{6}$$

Weidmann [17] used the parameter shape coefficient to evaluate the shape of the fine aggregates, natural and coming from the rock crushing, and verified that the natural aggregates present higher shape coefficients (close to 0,2) than the crushed aggregates.
In this procedure, the French standard presents a volumetric shape coefficient, i.e., establishes a relation between the grits volume and the volume of a sphere that surrounds these grits. It is noted that the flakiness indicator (I) proposed by Kwan et al. [12] is also a volumetric parameter, which relates the grits volume to the volume of a parallelepiped that surrounds this grit. Although the parameters flakiness indicator and shape coefficient have been proposed more than 11 and 5 years ago, respectively, no reference has been found in the literature that analysis comparatively these parameters together with the others for the evaluation of the fine aggregates grits shape.

2. Material and experimental program

2.1 Material

The cement used was Cement Portland Compound with addition of Pozzolana – CP II Z-32, which presented a density mass of 2,99 g/cm^3, superficial area Blaine of 3568 cm^2/g and average compressive strength at 28 days - 35,3 MPa.
The natural fine aggregate used was river sand coming from Guairá (PR).
The artificial fine aggregates consisted in waste products from the basalt rock crushing process for the obtaining of coarse aggregates, which have not been exposed to any beneficiary process and thus presented a high quantity of fine material, referred to hereunder as stone powder. The stone powders came from three different quarries (nominated Quarries A, B and C) which explore basalt rock and use different types of gravels for the rock crushing. Five types of stone powder have been obtained from these three quarries, differentiating them by type of crusher, namely: Cone type crusher, Hammer type crusher and Vertical Impact crusher (VSI). In addition to these stone powders, a sixth type of artificial fine aggregate has been studied, which constituted on a waste material from crushing of basalt rock coming from the type VSI crusher and that passed through processes of washing and sieving at the proper quarry, referred to as artificial sand.
The coarse aggregate constituted of gravel coming from a basalt rock, classified as 9,5/25 by ABNT NBR 7211 [18].
The characteristics of the fine aggregates and the coarse aggregate are presented in Table 1.
A multifunctional admixture has been used as a chemical lignosulfonate base, hazel color, with density mass of 1,18 g/cm³ with the purpose to produce concrete with slumps higher than 9 cm.

2.2 Evaluation of the fine aggregates shape

The fine aggregates grits shape was evaluated by means of the following parameters: aspect ratio, sphericity, flakiness indicator and shape coefficient.
For the calculation of these parameters, it was necessary to obtain the following grits dimensions: highest and lowest dimension, projection area and perimeter. These dimensions have been obtained by means of images digital analysis; the images were obtained by a scanner (HP PSC 1210) and the measurements were made by means of the image analysis program Image Tool, according to the Method Gtec-UFSC presented by Weidmann [17].

Table 1 – Characteristics of the fine aggregates and coarse aggregate

Parameter	Fine aggregates							Coarse Aggregate
	Natural sand	Artificial sand	Stone powder Cone A	Stone powder VSI-A	Stone powder Hammer B	Stone powder Cone C	Stone powder VSI-C	Gravel 1
Maximum characteristic dimension (mm)	2.36	4.75	4.75	4.75	4.75	4.75	4.75	19.00
Minimum characteristic dimension (mm)	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	< 0.15	6.30
Thinness Module	1.71	3.05	3.22	2.93	3.10	2.88	2.69	6.91
Powder Material (%)	0.60	4.54	14.72	16.24	13.40	15.99	17.16	0.81
Density mass (g/cm³)	2.65	2.99	2.97	2.95	2.95	2.95	2.95	2.88
Unit mass (g/cm³)	1.57	-	1.72	1.85	1.66	-	-	1.49
Absorption (%)	1.00	-	0.70	1.14	0.90	-	-	2.00

Images were obtained for each fine aggregate sample analyzed according to the procedures related below:

1. The fine aggregates have been washed in the 0,075 mm sieve to remove the passing fine material;
2. The washed aggregate has been sieved, separating the retained material on each sieve, consequently, separating it in fractions per diameter: 4,75 mm; 2,36 mm; 1,18 mm; 0,6 mm and 0,3 mm;
3. A sample with 100 or 200 grits has been separated of each fraction, depending on the grits size and its mass has been determined. These grits were placed on the scanner lens in order for digitalization;
4. During the digitalization the scanner was wrapped with a dark box with lamps inside that the light on the scanner lens was provided in a homogenous way in order to avoid shadows on the digitalized image. Furthermore, together with the ag-

Figure 1 – Examples of images obtained for the determination of the aggregates shape parameters: (a) fraction 1.18 mm stone powder CONE-C; (b) fraction 4.75 mm stone powder CONE-A; (a) fraction 4.75 mm stone powder VSI-A

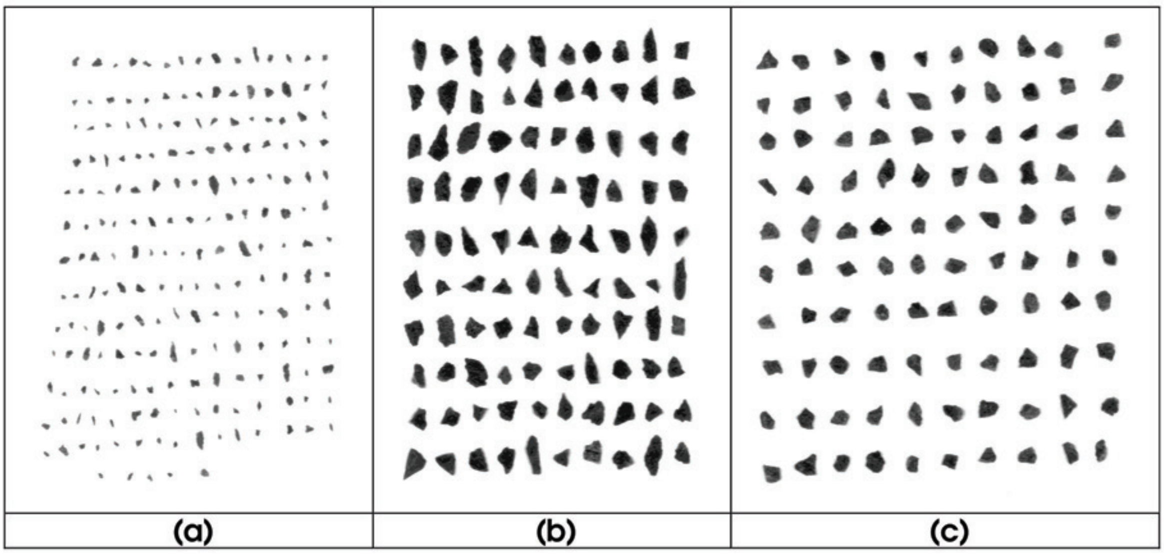
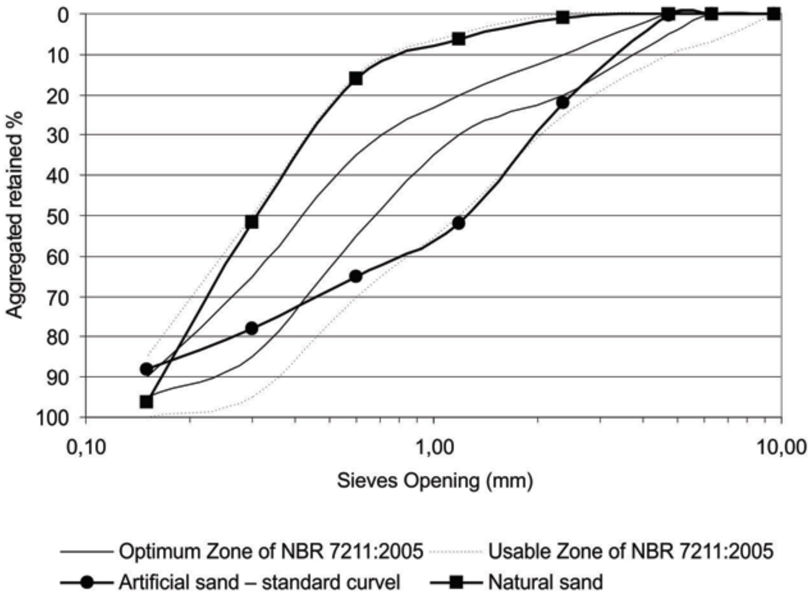


Figure 2 – Size distribution curve of the natural sand and the artificial sand (standard curve)



gregate grits a metric ruler has been digitalized so that during the image analysis process it was possible to determine the dimension of each pixel on the image and consequently the dimensions of the grit. Examples of the obtained images are shown on Figure 1.

5. Five images have been obtained from each fine aggregate, corresponding to the material retained in each sieve: 4,75 mm; 2,36 mm; 1,18 mm; 0,6 mm and 0,3 mm;
6. Then the images have been analyzed in images analysis program Image Tool, and the dimensions of each grit of each fine aggregate fraction have been obtained automatically. With this procedure, it was possible to obtain the shape parameters for each aggregate fraction.
7. The shape parameters of the aggregate were calculated by means of weight mean, where the weight attributed for each fraction corresponds to the percentage of material retained in the respective fraction, similar to the procedure recommended by Weidmann [17] for the calculation of the shape coefficient of the aggregate (equation 6).
8. A second sample of the clean fine aggregate fraction was used for the determination of the dry apparent density mass, because this property is necessary for the calculation of the shape coefficient and the flakiness indicator of the aggregate.

2.3 Mortar production

Once there is a relation between the results for mortar and concrete, a part of the work was developed for mortar with composition that is similar to one of the concrete mortar. This stage had the objective to analyze the influence of the aggregates shape on the properties of the concrete mortar.

In order to make the shape parameter the only analyzed variable, a standard size distribution curve was defined for all stone powders, thus eliminating the influence of the size distribution and the powder material content on the mortar properties, as also suggested by Weidmann [17]. The size distribution curve of the artificial sand was defined as a standard size distribution curve.

For the composition of the new standard size distribution curve all stone powders have been washed, sieved and separated in fractions according to ABNT NBR 248 [19], as well as for future weighing of equal masses of each fraction of the different aggregates, for the composition of size distribution curves equal to the size distribution curve of the artificial sand. During the washing of the stone powder, the material passing through the 0,075mm sieve (powder material) has been collected so that this material is used for the composition of the standard size distribution curve, keeping the same quantity of powder material presented by the artificial sand in all stone powder samples. Thus the new samples of each stone powder presented the same size distribution curve and the same content of powder material presented by the artificial sand.

The natural sand has been used with its original size distribution composition, once it was not possible to compose, from its original size distribution curve, a mixture with the characteristics of the size distribution curve of the artificial sand, because it was necessary to use a natural sand with thicker size distribution. In the same way that it was not possible to use the size distribution curve of the natural sand as a standard curve, due to the difficulty for composition with the aggregates coming from crushing available in a mixture within the size distribution curve of the natural sand.

The size distribution curves of the natural sand and the artificial sand (standard curve) were presented on Figure 2.

Due to the utilization of the standard size distribution curve for all aggregates coming from crushing, the calculation of these aggregates shape coefficient has been done based on the percentage retained accumulated in each fraction of the standard size distribution curve and not of the original size distribution curve of each stone powder.

Table 2 – Consumption of material per cubic meter of fabricated concrete

Concrete	Cement (kg)	Sand (kg)	Stone powder (kg)	Gravel (kg)	Water (l)	Admixture (l)
100% natural sand	324	842.40	--	994.68	184.68	2.50
30% Cone-A and 70% natural sand	345	627.90	300.15	1059.15	196.65	2.66
70% Cone-A and 30% natural sand	346	269.88	702.38	1062.22	197.22	4.15
30% VSI-A and 70% natural sand	348	633.36	302.76	1068.36	198.36	2.68
70% VSI-A and 30% natural sand	347	270.66	704.41	1065.29	197.79	2.67

For the composition of the mortar the trace 1:2,6:0,57 (cement:fine aggregate:water) and the quantity of the fine aggregate was variable, because the aggregate volume of the mixture remained constant and their density mass is different. The proportion of the mortar has been defined from the concrete proportion.
The following properties of the mortar have been evaluated: consistency (a trial carried out according to ABNT NBR 13276 [20]) and compressive strength after 7 and 28 days.

2.4 Concrete production

For the analysis of the influence of the aggregates shape on the properties of the concrete two stone powders have been chosen from the same quarry, however from different crushers which leads to production of stone powder with grits with different formats, stone powder Cone-A and VSI-A have been used. These stone powders presented the lowest and the highest shape coefficient among the studied ones. In this stage the stone powder was used without any previous treatment, i.e., presenting the original size distribution curve.
The concrete dosage was prepared using the IPT/EPUSP dosage method. From a concrete with proportion 1:5,67, the adjustment of the mortar, ideal to obtain concrete with adequate for the application consistency and cohesion has been made. This adjustment of the concrete mortar content was made on concrete with 100% natural sand, and the ideal value of mortar founded was 54%, obtaining a final proportion of 1:2,6:3,07:0,57 (cement: natural sand: gravel 1) with 0,077% of superplasticizer admixture. In the other concretes, the mortar content of 54% has been kept and the substitution of the natural sand by the stone powder was calculated keeping the volume of the fine aggregate constant in all concretes produced.
Five mixtures of concrete have been produced, in which the type of the fine aggregate used was varied: 100% natural sand; 30% Cone-A stone powder and 70% natural sand; 30% VSI-A stone powder and 70% natural sand; 70% Cone-A stone powder and 30% de natural sand and 70% VSI-A stone powder and 30% natural sand. The consumption of material per cubic meter of concrete for each concrete produced are presented in Table 2.
The following trials have been carried out with the concrete mixtures: consistency (*slump test*) according to ABNT NBR NM 67 [21] and compressive strength at 7 and 28 days. The compressive strength has been evaluated in cylindrical specimen with 10 cm diameter per 20 cm height, molded according to ABNT NBR

Table 3 – Parameters of the shape of the fine aggregates

Aggregate	Ratio of the aspect	Sphericity	Shape coefficient	Flakiness indicator
Cone-A Stone powder	1.58	0.48	0.1103	0.2053
VSI-A Stone powder	1.56	0.50	0.2070	0.3610
Hammer-B Stone powder	1.59	0.58	0.1393	0.2674
Cone-C Stone powder	1.66	0.60	0.1432	0.2861
VSI-C Stone powder	1.55	0.52	0.1470	0.2624
Artificial sand	1.50	0.62	0.2551	0.3964
Artificial sand	2.00	0.61	0.1869	0.4058

5738 [22] and tested according to ABNT NBR 5739 [23]. The consistency has been evaluated 10 minutes after the adding the superplasticizer in the concrete, because in the first two minutes a considerable loss of fluidity has been noted.

3. Results and discussions

3.1 Evaluation of the fine aggregates shape

The analyzed characteristics of the fine aggregates shape are presented in Table 3. In the case of the stone powder, the shape parameters have been calculated considering the accumulated percentage retained of the standard size distribution curve.

Analyzing the data presented in Table 3, some differences have been noted among the results of the analyzed shape parameters. For the VSI –A stone powder the values of the shape coefficient (0,2070) and the flakiness index (0,3610) were high which shows that this aggregate has rounded format grits, however, the sphericity parameter was low (0,50) which contradicts the previous analysis. It was noted that the aspect ratio values found for the aggregates VSI-A stone powder and VSI-C stone powder are very close and if this parameter was used to classify the shape of these aggregates, it could be concluded that they are aggregates with similar grit format. However, the values of the shape coefficients and the flakiness indicator are quite different, showing that the VSI-A stone powder has more rounded grits than the VSI-C stone powder. In the case of the stone powder VSI-C and Cone-C it was noted that the values of the shape coefficients and flakiness indicator are similar, however the values of the sphericity and the aspect ratio are different. These differences confirm that the aspect ratio e sphericity parameters, due to the fact that they use information from only two dimensions of the aggregates grits, can, in some cases, evaluate incorrectly the shape of an aggregate. On the other hand, the shape coefficient and flakiness indicator parameters, due to the fact that both consider the analyzed sample mass and its respective density mass, i.e., due to the fact that they provide estimation about a third dimension of the aggregate, tend to evaluate better the shape of their grits. Considering this, in the continuity of this work only these two last parameters will be used to evaluate the aggregates shape.

In the analysis of the shape coefficient and flakiness indicator values of the fine aggregates it is possible to see that in addition to the natural sand, the aggregates originated from crushing processes which use the type VSI crusher present higher shape coefficients, namely the artificial sand and the VSI-A stone powder. Taking in mind these results, it can be considered that these aggregates present more rounded grits. On the contrary to what was expected, the shape coefficient 0,1470 found for the VSI-C stone powder aggregate, was not similar to the other aggregates that are also processed by VSI type crushers. This contradictory result is probably due to the fact that the collection of this aggregate has been done immediately after the activation of the crusher and the first grits crushed by the equipment have been collected. It shall be reminded that the more rounded format of the grits of the aggregates obtained by the passage through the crusher of the type VSI is guaranteed by the impact of the rock fragments that enter the crusher with the fragments of the same rock that are forming a layer on the internal sides of the equipment. Thus, at the beginning of the crushing process, the fragment layer may not yet be formed and the crushing may occur by impact of the rock fragments that

Figure 3 – Consistency of the mortar and shape coefficients of the respective aggregates used in the mixtures

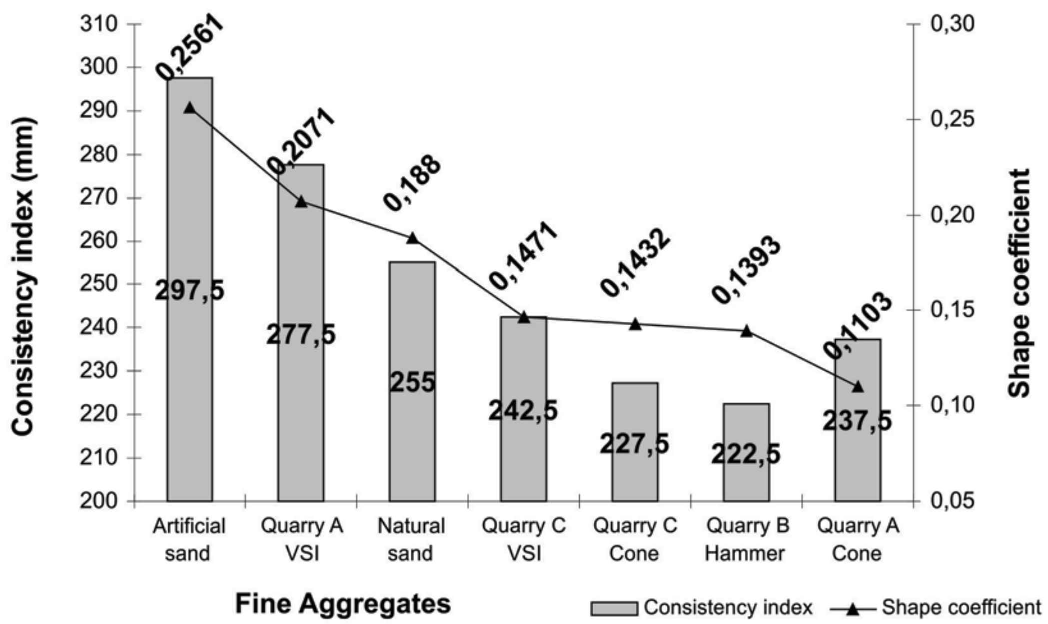
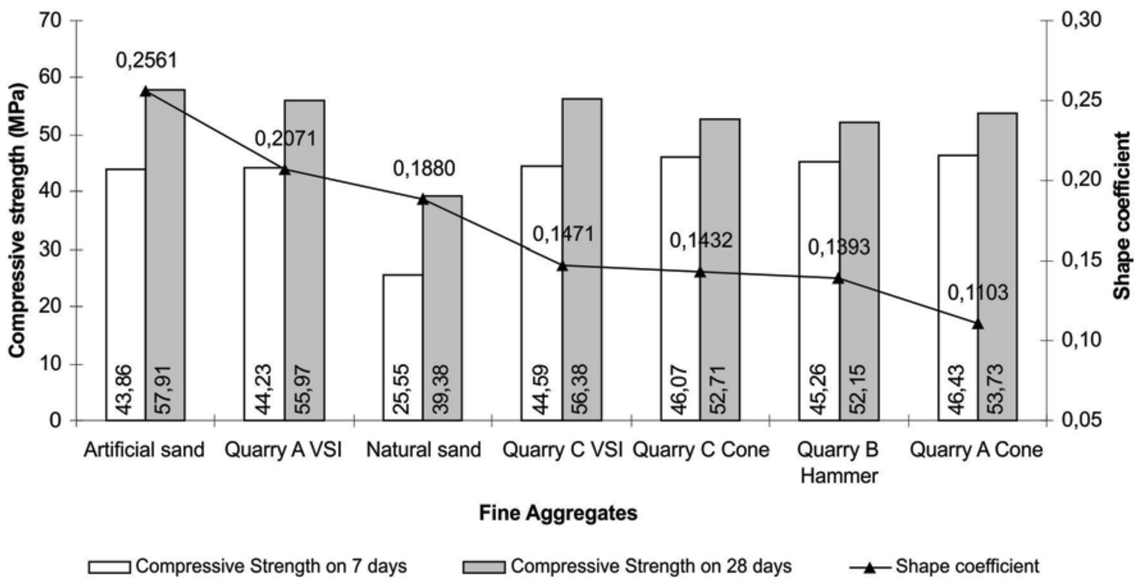


Figure 4 – Compressive strength of the mortar composed by the standard size distribution curve and the shape coefficients dos aggregates



contact the metal wall of the crusher, which provokes the formation of grits with more flaky characteristics.

The results show that the aggregates processed by crushers of the type Cone or Hammer are really more flaky than the aggregates crushed by crushers of the VSI, because they presented the lowest shape coefficients and flakiness indicators.

Although higher values have been expected for the shape coefficient and the flakiness indicator of the natural sand, because its format is defined by the friction among the grits that wear each other's surface, making them more rounded; it also presented a shape coefficient equal to 0,1869, lower than of some aggregates crushed as the ones coming from VSI type equipment, as the VSI-A stone powder and the artificial sand. This result shows that the rocks wearing process provoked by the VSI type crusher is really efficient, making the grits passing through it obtain a more rounded shape.

Within the analyzed aggregates, the aggregate that presented a highest shape coefficient and flakiness indicator, thus the more rounded aggregate, was the artificial sand and the flakiest aggregate with lowest shape coefficient e flakiness indicator was the Cone-A stone powder.

3.2 Results for mortar

The results of the consistency of the mortar produced with the fine aggregates composed in the standard size distribution curve and the respective shape coefficients of the aggregates, presented on Figure 3, show that the higher the shape coefficient of the aggregate, the higher the index of mortar consistency.

Weidmann [17] had verified a similar performance of mortar produced of crushed fine aggregates with granite origin. With these results it is possible to conclude that the aggregates with more rounded grits (higher shape coefficients) guarantee a higher fluidity mortar com. These aggregates are, in decreasing order of higher shape coefficient and higher consistency index: the sand artificial, followed by the VSI-A stone powder and the natural sand. It is also noted that the other mortar mixtures composed of aggregates coming from crushing processes which do not use a VSI type crusher present drier consistency as they are composed of flaky format grits, presenting an average value of consistency index of 233 mm, while the mortar with VSI-A stone powder present a consistency index higher than 277 mm.

The compressive strength results of the mortar at 7 and 28 days and the respective shape coefficients, presented on Figure 4, show that it was not possible to verify the existence of a direct influence of the particles format on the compressive strength results of the mortar.

All mortar mixtures produced of aggregates coming from crushing present high values of compressive strength, which were similar and not varying according to the shape coefficient of the different aggregates. The mortar that presented the lowest resistance was the mortar composed of natural sand.

3.3 Results for concrete

For the production of concrete, the fine aggregates were used in their original size distribution curve, and a standard size distribution curve was not used, that 's why the calculation of the shape coefficient of these aggregates is necessary in their original size distribution curves. The values of the shape coefficients

are presented on Figure 5 together with the slump values of the produced concrete.
On Figure 5 it is noted that the concrete, which contains VSI-A stone powder that substitutes the part of the natural sand presented a slump higher than the slump of concrete with 100% natural sand. This can be justified by the aggregates particles shapes, because the VSI-A stone powder presents a shape coefficient higher than the shape coefficient of the natural sand, indicating that the stone powder grits are more rounded than the natural sand grits and consequently contributing to the increase of the concrete fluidity. The slump of the concrete with Cone-A stone powder substituting 30% of the natural sand volume was higher than the slump of the concrete with 100% natural sand. However, when the volume of substitution of the natural sand by Cone-A stone powder was 70%, the concrete with this material presented null consistency, even though the content of superplasticizer admixture has been increased. These results are also justified by the fine aggregates particles shape, because the Cone-A stone powder is the one that presents a lower shape coefficient, indicating that its particles have a flaky format. In this way, when the quantity of stone powder in the concrete increases, the quantity of material with flakier shape particles increases as well which influences negatively the concrete consistency. It shall be pointed out that the powder material content of the VSI –A and Cone-A stone powder were very similar (16% and 15%, respectively) and higher than the content in the natural sand (0,60%), considering this it can be concluded that the content of the powder material is not responsible for the slump alteration of the concrete, and the slump is more influenced by the aggregates particles shape.
The concrete mixtures produced with VSI-A stone powder present cohesion and texture similar to the concrete produced with 100% natural sand, while the concrete with Cone-A stone powder presents lack of cohesion and coarse texture which makes the workability of the concrete difficult. Thus it is noted that the aggregates particles shape influences not only the consistency of the concrete, but also the cohesion and the texture, more rounded aggregates (with higher shape coefficients) guarantee higher fluidity concrete, better cohesion and superficial texture.
The results of the compressive strength tests at 7 and 28 days for the produced concrete show that all concrete mixtures, in which there was a substitution of the natural sand by stone powder presented higher compressive strength than the concrete with 100% natural sand (Figure 6).
Comparing the concrete mixtures produced with stone powder coming from different crushers it is noted that there are no significant differences in the compressive strengths for both substitution contents. It is noted the aggregates particles shape does not influence the concrete compressive strength, as there was not any relation between the shape coefficients and the compressive strength. The higher compressive strength of the concrete with stone powder can be attributed to the better closure of the concrete pores due to the higher quantity of powder material present in the stone powder.

4. Conclusions

Based on the results of this work it was possible to conclude that:
- the flakiness indicator and the shape coefficient parameters evaluate the aggregates shape more precisely as they provide a tri-dimensional analysis, while the aspect ratio and the sphe-

Figure 5 – Slump of the produced concrete and the shape coefficients of the fine aggregates

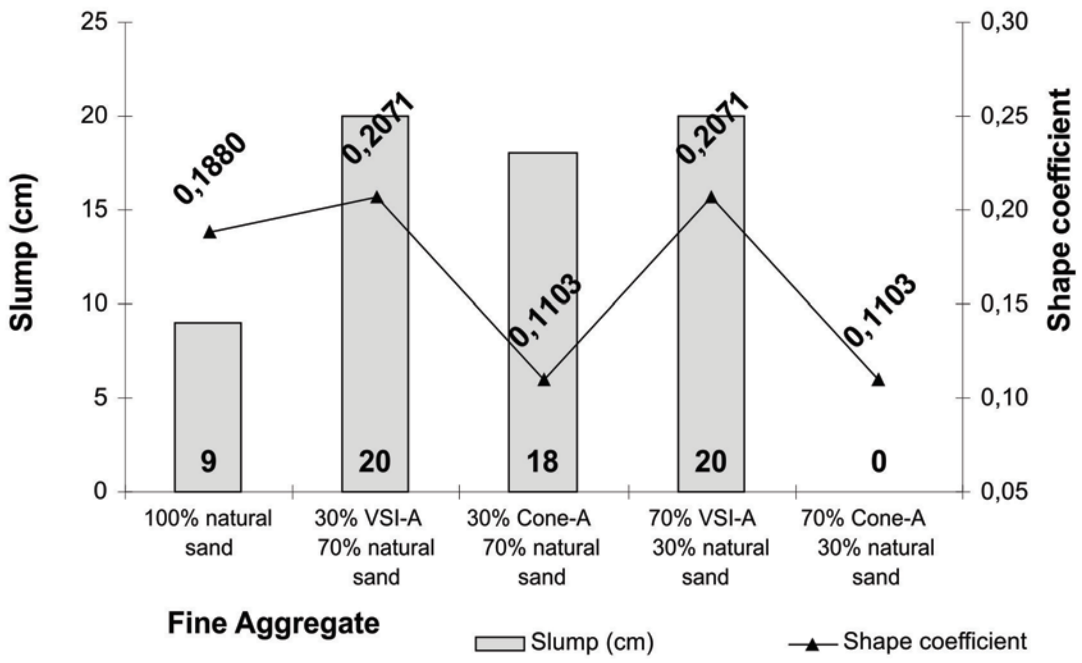
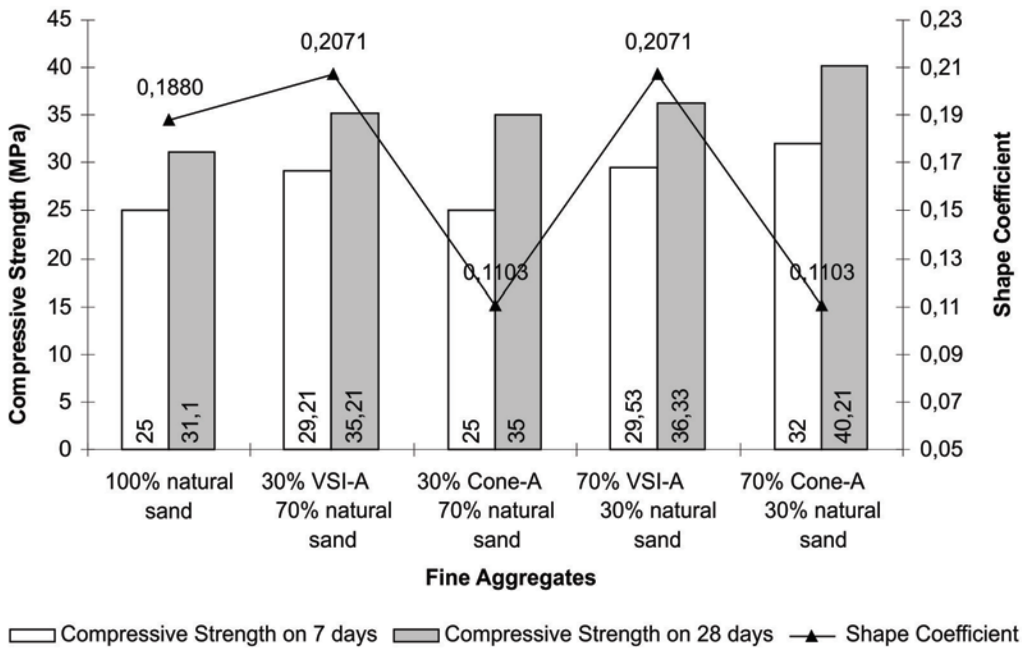


Figure 6 – Concrete compressive strength and coefficients of the aggregates shape



ricity parameters do not evaluate aggregates particles shape correctly;

- the aggregates particles shape depends on the extraction method and the type of equipment used for crushing, the artificial aggregates originated from an impact vertical crusher present more rounded particles than the natural sand and these, on their hand, present more rounded particles than the aggregates originated from the hammer and cone crushers;
- the aggregates particles shape strongly influences the fluidity of the mortar, and the higher the aggregate shape coefficient, the higher the mortar fluidity. Sands constituted of sphere and rounded particles have a friction angle considerably lower that the sands constituted of flaky particles and that is why they benefit the fluidity;
- the aggregates particles shape influenced the slump of the concrete, the higher the shape coefficient the higher the slump of the concrete. The particles treatment provided by the VSI crusher, i.e., the more rounded particles, leads to higher fluidity concrete.
- the influence of the aggregates particles shape on the slump of the concrete was more significant than the influence of the powder material content of the aggregates, once concrete with fine aggregates with higher powder material content and higher shape coefficients present higher slumps to the concrete with natural sand which showed very low powder material content.
- there is very low influence of the aggregates shape on the mortar and concrete strength, however all mortar and concrete mixtures produced with artificial aggregates presented slightly higher strength than the mortar and concrete with natural sand. The higher strength of the concrete with stone powder can be attributed to the higher closure of the pores, provided by the powder material in the stone powder.

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