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The effect of blending granular aggregates of different origin on the strength of concrete

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ABSTRACT

This work correlates the resistance of concrete cores with the physical properties of the granular material forming it. A basic physical characterization is conducted, taking into account the origin of the grains involved in the concrete mixture; that is, if they come from natural degradation (natural granular aggregates) or from a grinding process (crushed granular aggregates). Apparent and real densities, shape factors, packing densities, and specific surface areas of the grains are measured. The results are discussed as a function of size and origin of the grains. Several mixtures are prepared following a standard protocol and using different ratios of natural and crushed aggregates. For each ratio, six cores are prepared and uniaxial compression tests are performed. A non-monotonic relation between the resistance of concrete and the percentage of crushed aggregate present in it is obtained, with an optimum ratio depending on the physical properties of the grains.

1. Introduction

The interest in studying the physical properties of grains making up a granular packing is a consequence of the significant impact they have on the final properties of that packing [1,2].

In the case of structural concrete, the strength in compression has been accepted as its most important mechanical property. Consequently, a lot of experimental work has been performed to find and study the relationship between concrete composition and compressive strength [3–5]. The factors affecting the compressive response of concrete include the type and size distribution of the granular aggregate, the amount and type of cement, water mass/cement mass ratio, chemical additives, and curing conditions, among others.

The material filling the gaps between the grains (called the mortar), the grains themselves (coarse aggregate), and the interface between them have been demonstrated to be crucial in determining the strength of a concrete [3]. This means that, for the same quality mortar, different types of coarse aggregate with different shapes, textures, mineralogy, and strength may result in different concrete strength.

On the other hand, the aggregate plays a more important role when water/cement limitations are present each time a high-strength and high-performance concrete is pursued. In this case, it is possible to make use of the full potential of the coarse aggregate particles [6,7].

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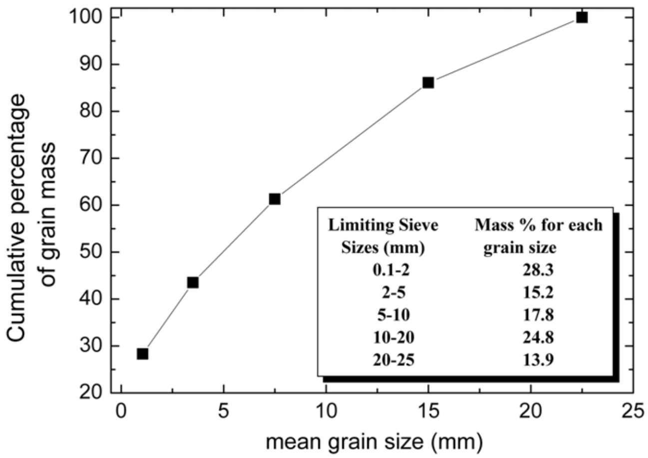

Fig. 1. Cumulative percentage of grain mass as a function of the grain size. The inset shows the size distribution of the grain mass by indicating the size of the sieves used to classify the material.

Among the most important physical aspects of aggregates affecting the strength of concrete are the specific surface areas of the grains, their hardness or resistance to abrasion, their shape factors, such as elongation or flatness ratios, and their grading curve [5].

The measurement of the aggregate surface area per unit mass (specific surface area) will depend on the shape and the origin of grains, i.e., if the size of the grains was the result of natural degradation or was obtained by crushing [4]. We can calculate the specific surface area by direct measurement or by means of theoretical calculations. The first method involves image analysis and requires special measuring devices [8,9]. The second involves the experimental measurement of shape factors and the theoretical calculation of the grain surface areas based on the grading curve [4].

In spite of all the mentioned studies, interest in characterizing the granular material involved in the manufacture of concrete has not decreased [10–12]. For this reason, the main goal of this paper is to relate certain physical parameters of the grains with the mechanical behavior of the structure of concrete under simple compression.

2. Experimental study

In this section, we present the results from the physical characterization of the granular material used as coarse and fine aggregates in the mixture of concrete. The methodology and results are presented in each subsection along with a brief discussion of each item.

2.1. Classifying the grains according to their origin

The size distribution of the grains used as aggregates in the preparation of concrete obeys standard criteria, and is presented in Fig. 1. The curve in that figure shows the cumulative percentage of the grain mass as a function of the grain size. The first column of the inset shows the range of the grain size by indicating the size of the sieves used to classify the material. The second column indicates the mass percentage for each grain size, that is, the size distribution of the grain mass.

It is expected that grains from different quarries have different mineralogical and physical properties. For this reason, we employed material from two different quarries, Q1 and Q2. The physical characterization of the grains and the compression tests for concrete cores were performed separately on grains from Q1 and Q2.

On the other hand, it is also expected that crushed grains have different physical properties than natural ones. Therefore, within each set of grains Q*i*, we distinguish two types of grain: those resulting from grinding, CA (crushed aggregates), and those coming from river rocks, NA (natural aggregates). It is important to note that the grains used in the range from 0.1 to 2.0 mm were always taken from natural river sand, because our intention was to set aside the effect of crushed dust studied by other authors [13].

We were also interested in varying the ratio between the mass of CA and NA present in the grain size distribution in order to study its effect on concrete strength. The percentages used were 0%, 25%, 50%, 75%, and 100%, given in terms of the presence of the crushed grain mass, i.e., 0% (100%) corresponds to a sample where pure natural grains (crushed grains) are present. According to this, we define a parameter f as follows:

$$f(\%) = \frac{m_{CA}}{m_{CA} + m_{NA}} 100, \quad (1)$$

where m_{CA} (m_{NA}) represents the mass of crushed (natural) aggregates present in the grading curve.

Table 1
Bulk and apparent densities (g/cm^3) for different size ranges and for natural and crushed grains from quarries Q1 and Q2. Absolute errors are of the order of 10^{-2} g/cm^3 in all cases. The packing densities, c, corresponding to Fig. 2, are also shown for each case. Errors are of the order of 10^{-2}.

Size (mm)	Natural						Crushed					
	Q1			Q2			Q1			Q2		
	δ	δ_a	c	δ	δ_a	c	δ	δ_a	c	δ	δ_a	c
2–5	2.67	1.50	0.56	2.65	1.43	0.54	2.73	1.28	0.47	2.71	1.25	0.46
5–10	2.67	1.53	0.57	2.66	1.51	0.57	2.72	1.34	0.49	2.71	1.30	0.48
10–20	2.69	1.57	0.58	2.7	1.51	0.56	2.73	1.41	0.52	2.72	1.39	0.51
20–25	2.9	1.57	0.54	2.68	1.52	0.57	2.71	1.45	0.53	2.73	1.40	0.51

Table 2
Apparent density for the five values of f (Eq. (1)) used in the mixture of aggregates to be added in each concrete preparation. The values for grains from the two quarries are shown in each column. Absolute errors are of the order of 10^{-2} g/cm^3 in all cases.

f (%)	δ_a (Q1) (g/cm^3)	δ_a (Q2) (g/cm^3)
0	1.88	1.80
25	1.85	1.77
50	1.80	1.73
75	1.77	1.71
100	1.67	1.70

2.2. Physical characterization

The physical characterization of the grains was performed taking into account their origin and size range. For the determination of the actual solid density, δ, we employed the standard method that makes use of the Archimedes Principle. We used an analytical balance with an accuracy of 10^{-3} g. We used an average of ten equivalent measurements.

The apparent density δ_a was determined with the help of a container with well-known volume into which the material was poured from a short constant height and with a constant flow rate. The container with the material was weighed using an electronic balance and the apparent density was determined as the ratio between the mass and the volume. The procedure was repeated 15 times to obtain average results. Table 1 presents the results for δ and δ_a for each grain size range and for natural and crushed grains from quarries Q1 and Q2. We also determined δ_a for the five different f percentages used in the mixture of grains, for each quarry. These results are shown in Table 2.

Using these results, we calculated the packing density or compactness of the grains, c, as the ratio between the volume of grains and the total volume occupied by them, which can be approximated by [14]

$$c = \frac{\delta_a}{\delta}. \tag{2}$$

The measurement of c gives an idea of how the grains are arranged in a packing as a function of their size. This parameter will be important to describe the compressive strength of the material in a mixture for concrete.

In Fig. 2, the results for c as a function of the mean size of the grains are shown for quarries Q1 and Q2 and for natural and crushed stone. In general, the packing density tends to increase with the size of the grains, especially for crushed aggregates. The behavior for natural aggregates is less evident, since the variation is small. As expected, c for natural aggregates is greater than that for crushed ones.

Fig. 3 shows the packing density for the mixtures of all the grain sizes (from 0.1 to 25 mm, as shown in Fig. 1) with different values of f and for both quarries. Each polydispersed sample has a different ratio of CA and NA (given by f). As observed, the values of the packing density are higher than those obtained for each granular size separately, as shown in Fig. 2. It is well known that polydispersion enhances the packing density of a granular sample [15]. The lines in the figure indicate the two linear fits performed on the two sets of data. For both quarries, as the percentage of crushed stone increases, the packing density of the whole mixture decreases. For Q1, the decrease in c is somewhat more pronounced than for Q2, and the packing ability for both cases is rather similar. The behavior of c as a function of f is related to the results for uniaxial compression, as discussed below.

2.3. Shape factors

Two commonly used shape factors are the flatness and elongation ratios α and β, which are defined, respectively, as

$$\alpha = \frac{T}{W}; \qquad \beta = \frac{W}{L}, \tag{3}$$

where T, W, and L are the characteristic thickness, width, and length of the grains, respectively. If the two shape factors result in being equal to 1, a perfectly cubic (or spherical) shape is assumed for the grain. The smaller the values of these factors, the further from cubic (or spherical) geometry are the grains.

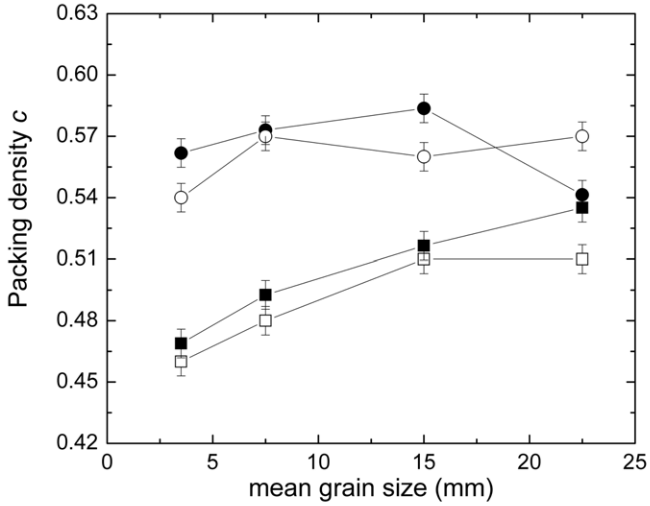

Fig. 2. Packing density as a function of the mean grain size for natural (circles) and crushed (squares) aggregates. Solid symbols correspond to Q1 and open symbols to Q2. Error bars are indicated.

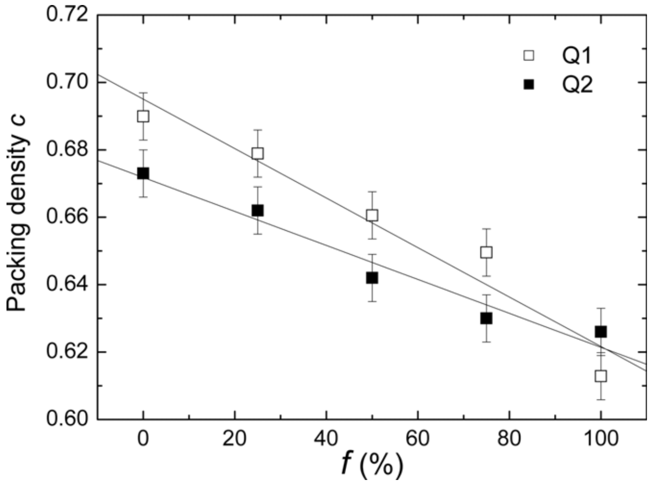

Fig. 3. Packing density as a function of the percentage of crushed grains, f, for the mixtures to be used in the preparation of concrete cores, for quarries Q1 and Q2. The grain size range of the mixtures is from 0.1 to 25 mm. The lines are the corresponding linear fits: $c = 0.70 - 7.34 \times 10^{-4} f$ for Q1 and $c = 0.67 - 5.04 \times 10^{-4} f$ for Q2. Error bars are indicated.

These factors were determined by measuring the three characteristic dimensions, T, W, and L, of a representative number of grains taken from each size range. The measurement was performed using digital calipers. The results corresponding to natural and crushed grains for both Qi are shown in Fig. 4. The upper parts of the figure correspond to natural and crushed grains from quarry Q1 and the lower parts to those from Q2.

In most cases, β is greater than α and, besides, natural aggregates present a smoother variation than crushed ones. Comparing Q1 and Q2, the shape factors for natural grains present quite a similar behavior while those for crushed stones are quite different and have a different range of variation.

2.4. Calculation of the specific surface area

In the context of our present interest, a more useful quantity to measure is the specific surface area, SSA, which can be calculated from the grain characteristics T, L, and W.

As explained above, the SSA can also be measured directly by image analysis, but here we use a theoretical method developed by Hunger [4]. The explanation of the method is given in detail in that reference, and we present below only the basic information to carry out the calculation of the SSA.

The total surface area of a monosized sample (assuming that all particles are ideal spheres) is expressed as

$$a = \frac{6m_{sample}}{d\delta}, \tag{4}$$

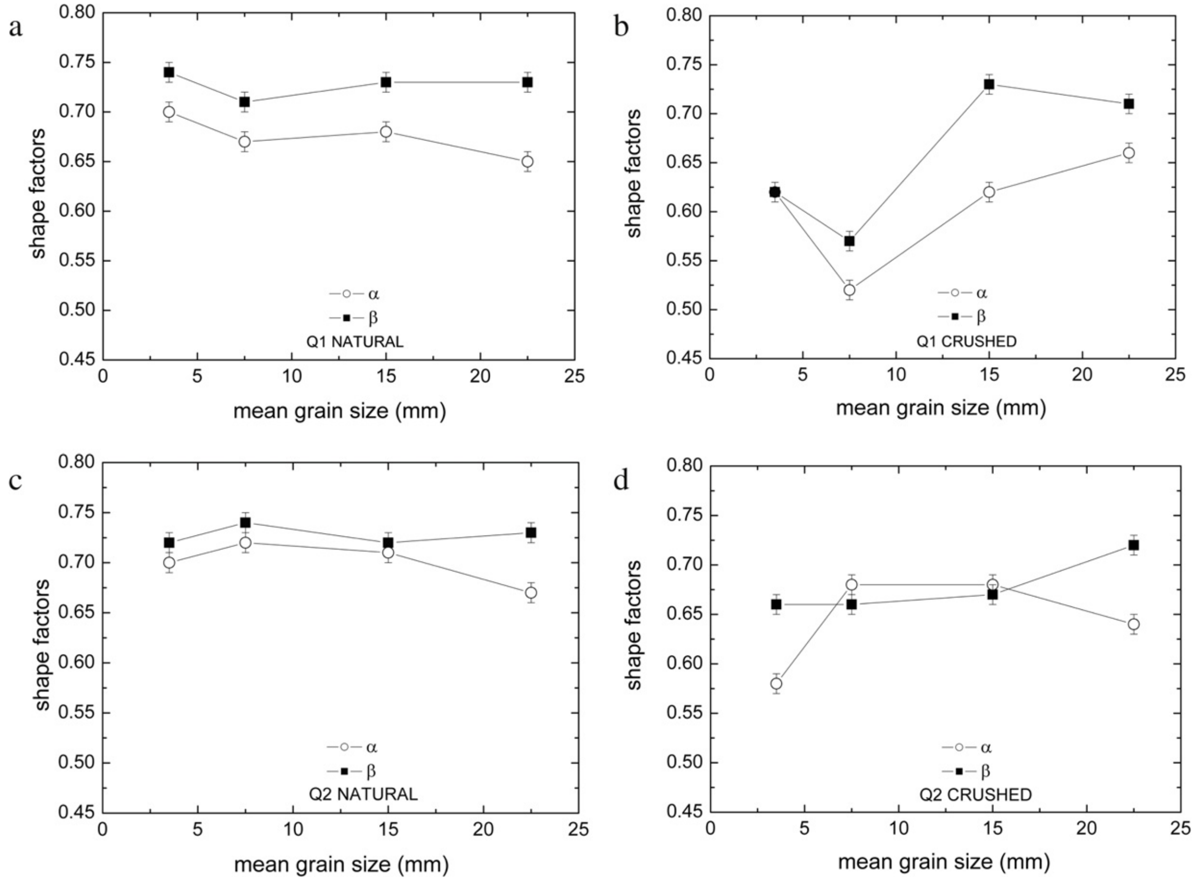

Fig. 4. Shape factors, α and β, as a function of the mean grain size for natural and crushed grains and both quarries, as indicated in parts (a)–(d). Error bars are indicated.

where m_{sample} is the total mass of the sample, and d and δ are the diameter and the density of the particles, respectively. Thus, the total surface area, S, of a granular material with known particle size distribution can now be computed as

$$S = 6 \sum_i \frac{\omega_i m_{sample} \xi_i}{\bar{d}_i \delta} \tag{5}$$

where ω_i is the mass fraction of the grain fraction i, i.e., the mass percentage of the grains between size diameters d_i and d_{i+1}, and $\bar{d}_i$ is the arithmetic mean diameter of fraction ω_i. The factor ξ_i is a shape factor that has to be included in order to correct for the non-spherical shape of particles. According to Hunger et al., the shape factor for each grain size range is defined as [4]

$$\xi_i = \frac{s_i}{\varepsilon_i}, \tag{6}$$

where s refers to the surface area of a typical grain belonging to the grain fraction i, and ε to the surface area for an equivalent volume made with a sphere in the same range of grains as the one defined for s. Assuming a parallelepiped shape for the grain size, we compute s_i from the results obtained for T, W, and L for each set i.

On the other hand, considering a sphere with the same volume as that for the aggregate grain, we calculate its corresponding diameter and used it to compute ε_i. The total surface area S is then calculated from Eq. (5). Finally, the calculation of the SSA is completed dividing S by the total volume of the sample.

Results for the SSA are shown in Fig. 5 for both quarries. As is clearly seen, there is a linearly increasing trend of SSA as the ratio f increases in both cases. This feature is related to the fact that the shape factor ξ increases for crushed stones. As the ratio of crushed stone in the mixture increases, the specific surface area SSA is enhanced. As discussed later, this behavior contrasts with that found earlier for c, offering an advantage for the uniaxial compressive response of concrete cores.

Another point to note is that the slope for Q1 is greater than that for Q2, as shown by the linear fits on the corresponding data. This could be related to the greater fluctuations in the shape factors for grains from Q1 (see Fig. 4). This different behavior has a clear effect on the strength response of the cores.

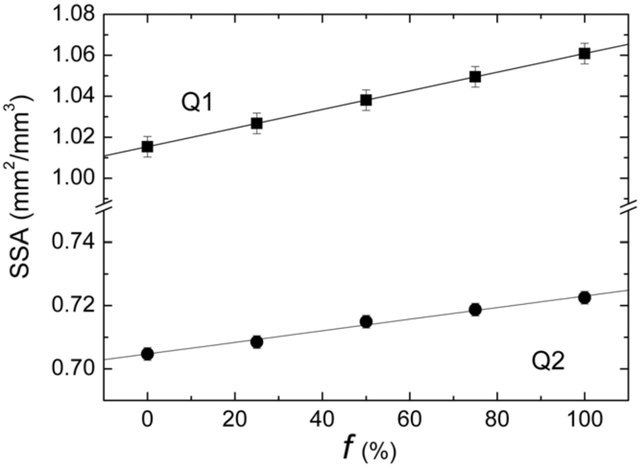

Fig. 5. Specific surface area of the grains, SSA, as a function of f, for Q1 and Q2. The lines are the corresponding linear fits: $c = 1.02 + 4.55 \times 10^{-4} f$ for Q1 and $c = 0.70 + 1.83 \times 10^{-4} f$ for Q2. Error bars are indicated.

2.5. Results for uniaxial compression tests

As explained above, we sought to correlate the resistance of concrete cores prepared with the different mixtures – from Q1 and Q2 – with the physical properties of the granular material forming it. Hence, we prepared a standard concrete called "H21 type", i.e., a solid that would have, theoretically, 21 N/mm^2 resistance to uniaxial compression. Evidently, this resistance will depend on the type of grains used in the mixture.

We used coarse and fine grains according to the size distribution in Fig. 1 and from one of the quarries at a time. A fixed water mass/cement mass ratio equal to 0.65 was used in all experiments. We used a standard Portland cement with a calcareous (limestone) filler. It is important to remember that the sand added in all experiments (size 0.1–2 mm) was always from the same natural origin, i.e., it never came from crushed stone sources. We prepared six identical specimens for each of the f percentages and for each quarry. The cylindrical specimens were prepared in cores with 5 cm diameter and 30 cm height; a total of 30 cores per quarry were produced to be tested under uniaxial compression. All the cores were made using the same concrete mixer and following exactly the same procedure. In all the cases, we followed standard preparation protocols for concrete manufacturing. We mixed the concrete paste for a period of time sufficient to get a good homogeneization but not too long, to avoid segregation. To prevent the presence of weak planes, the cylinder ends were smooth and perpendicular to the axis. The cores were cured for 28 days in water at constant ambient temperature, as required by standard protocols for testing concrete cores.

The compressive strength until failure, F_c, as a function of f is plotted in Fig. 6. As explained before, each point on the figure is the average over six equivalent cores. As clearly illustrated by the figure, the compressive strength presents a maximum for a given value of f that depends on the origin of the grains. In the figure, a parabolic fitting performed on the data as well as its corresponding equation are shown, demonstrating that the strength depends on the square of the fraction f.

According to the experimental results and to the predictions of the fitting curves, the specimens in the range $f \in (10\%, 80\%)$ for Q1 and $f \in (10\%, 100\%)$ for Q2, show a good performance against the comparison level of 21 N/mm^2 (see the dashed line in the figure). On the other hand, for pure natural stone in both quarries ($f = 0$) and for pure crushed grains in Q1 ($f = 100$), the aggregates are below that comparison level.

The presence of a maximum in the behavior of F_c is an important feature resulting from the competing effect of two variables, as will be explained in the next section.

3. Discussion

The results shown so far demonstrate that the packing density of different mixtures of natural and crushed grains from two different quarries diminishes as the proportion of CA content increases. This result is in agreement with the expected idea that rounded particles form a denser packing than irregular ones.

On the other hand, the calculated surface area, SSA, increases as a function of the shape factor ξ. This shape factor is greater for particles further from the spherical shape. This results in an increase of SSA as the fraction f of CA increases.

Because both the water/cement ratio and the size distribution of the grains are kept constant all over the experiments, the main factors influencing the behavior of concrete under uniaxial compression are the packing density and the specific surface area. On the one hand, the decrease of c in the mixtures of grains with a greater amount of crushed stone (greater f) does not favor the compressive strength of the core [15]. On the other hand, the increase in SSA for mixtures with greater

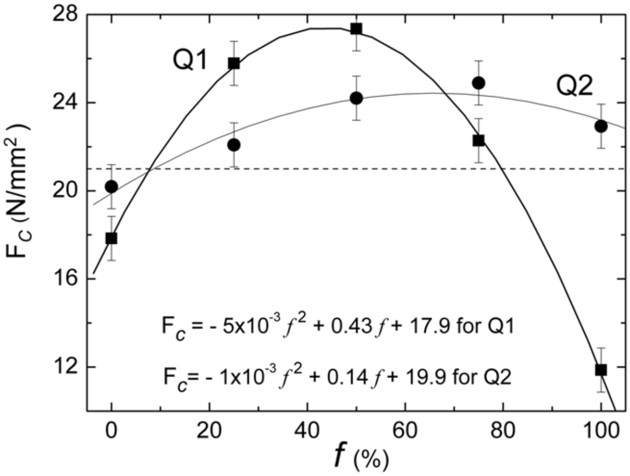

Fig. 6. Compressive strength until failure, F_c, as a function of f, for Q1 and Q2. The curves correspond to the fitting over the experimental points. The corresponding fitting equation parameters are displayed at the bottom. The statistical dispersion of the data is indicated by the error bars. The dashed line indicates the H21 reference resistance.

f causes an increment in water requirements. Indeed, it is known that grains with a higher specific surface area require more water to wet the particle surfaces adequately and to maintain a specific workability [13]. Because the water/cement ratio is kept constant in all the experiments, the availability of water to wet the grains is always the same. For that reason, those mixtures with a higher percentage of crushed stones (greater SSA) will use more water to wet the grain surface. Consequently, the amount of water that is involved in the concrete paste is reduced, thus increasing the strength of the cores [5,16]. The compression strength has been shown to be very sensitive to both the water content and the specific surface area [4,5]; consequently, it increases with f. It is worth mentioning here that we are interested in showing the effect of the surface area of the different grains used without changing the water/cement ratio because it is precisely this effect that will have important practical applications since it is common practice to keep the water/cement ratio constant.

In Fig. 6, the dominant effect in the left branch of the parabola is that of the specific surface area, while in the right branch the packing density of the mixture prevails.

Comparing the behavior found for each quarry, the variation in both SSA and c is more pronounced in the case of Q1 compared with Q2. This feature may explain the shape of the corresponding parabolas for F_c, i.e., the curve for Q2 is smoother than that for Q1. On the other hand, the maximum value expected for the strength is achieved at a higher f in the case of Q2. Looking at the fitting parameters in Figs. 3 and 5, we can compare the slope for c with that corresponding to SSA for each quarry. In the case of Q1, the ratio between the two slopes is 1.61 while in the case of Q2 the ratio is 2.75. This means that the packing density decrease compared to the increase of SSA is greater for Q2 than for Q1. For that reason, the mixtures for Q2 have to have a higher percentage of crushed grains to have their maximum strength performance.

4. Conclusions

The results obtained for uniaxial compression tests show a maximum for the strength response of concrete at an optimum value of f that depends on the physical properties of the grains involved in the mixture. This result could be explained in terms of two competing effects. On the one hand, the decrease of the packing density with f does not favor the compressive strength of the core and, on the other hand, the increase in the specific surface area with f provokes an increment in the water requirement that enhances the response.

The behavior of c and SSA depends on the quarry where the grains come from. The variation for both SSA and c is more pronounced in the case of Q1 and, besides, the decrease of the packing density compared to the increase of SSA is greater for Q2 than for Q1. These features give as a result that the parabola in the plot of F_c versus f is more open in Q2 than in Q1 and that the maximum value expected for the strength in Q2 is achieved at a higher f than in Q1. In most cases, the addition of crushed grains improves the resistance of concrete obtained from a pure natural aggregate.

In conclusion, the characterization of the behavior of the packing density and the surface area in different aggregate mixtures can be used to predict the subsequent concrete performance under compression. This result contributes to a better use of aggregates and to improving the basic knowledge for the optimization of the grain mixtures used in concrete preparation.

Future efforts will be focused on obtaining a theoretical model to quantify the above-discussed competing effects between c and SSA in order to predict the optimal value of f for the maximum strength response.

Acknowledgments

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