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Physical Characterization of Granular Aggregates and the Incidence on Concrete Strength

María E. Médici, Martín Dolcemáscolo, Rodolfo O. Uñac, Ana M. Vidales

Abstract— **The resistance of concrete cores to uniaxial compression has been proved to be sensitive to the physical properties of the granular materials used in their production. In the present work, we demonstrate that a simple and easy protocol for measuring some physical properties like shape factors, apparent density and specific surface of the granular aggregates before being added to the concrete, can predict, at least qualitatively, the future behavior of a core made of that concrete and subjected to uniaxial compression. But, unlike in previous works, we find an important physical factor that has a crucial role: the presence of cleavage planes in the aggregates. This assessment is contrasted here with experimental evidence using granular materials resulting from huge waste deposits of flagstone and granite coming from the mining production. These discards provoke a significant environmental pollution, in addition to economic losses. Besides the correlation between the physical parameters of grains and the resistance response of concrete cores, we also prove that granular discards may be used as part of the aggregates in the concrete mixture if proper proportions are chosen. This last issue is promising when environmental recovery is on course.**

Index Terms— **Aggregates, Compactness, Concrete resistance, Surface area.**

I. INTRODUCTION

Interest in the study and characterization of granular matter has always been present in scientific work and especially when this characterization can be correlated with the behavior of the system under manipulation. In particular, the application to specific industrial problems (segregation, mixing, compaction, etc.) where these materials are used as raw materials in production processes with high added value, requires the correct description of the grains participating in them. For example, particle size distribution and particle shape of the materials involved in a granular mixture, are very important in determining the packing fraction of that mixture. This, together with the specific surface area, has great influence on the microscopic and macroscopic properties of the concrete mix [1]. Despite decades of research, there are still many questions and, besides, it is often not possible, or even not convenient, to develop a high cost characterization in a low cost production. This is where a simple characterization methodology is welcome to ensure at least an estimate of the expected behavior.

In the case of concrete production, much scientific work has been done in the last fifty years to produce materials for numerous industrial and consumer applications. A surprising number of production methods is found in the literature, always linked to the geographical region of interest and target applications. However, from the viewpoint of basic physics, many of these methods base their success on the correct prediction of the behavior of concrete from the determination of a set of key physical parameters of the particles involved in the mixture.

Alongside the need for improving the quality of concrete according to its applications, we also find the environmental problems. Recycled aggregate concrete and the use of discards from different sources (rice husk ashes, rocks, plastics, organic matter, etc.) have been proposed for lowering production costs and/or cooperating with a sustainable development [1]-[6].

It has been demonstrated [7]-[9] that mixing of aggregates from two different origins (from natural degradation or from a grinding process) can improve the concrete response to compression if an appropriate proportion of the different aggregates is provided. A non-monotonic relationship is obtained between the resistance of concrete and the percentage of crushed aggregate present in it, with the presence of a maximum at an optimum ratio, depending on the physical properties of the grains [9]. Nevertheless, the methodology proposed there, has never been applied using discards of application rocks like granite or flagstone, which offer an important source of raw materials that, in many cases, is a source for contamination of large areas. The non-monotonic behavior for the resistance as a function of the rate of different nature aggregates has also been found by other authors [2], [10].

Although surface area and surface roughness are strongly related to the interfacial bond strength between the aggregates and the concrete paste, it has been demonstrated that these quantities alone are not enough to characterize the final response of concrete under uniaxial tension [11]. Rocks with different mineralogy can present different behaviors when subjected to tension. In particular, the presence of cleavage planes in rocks can be the reason for a low bond and tensile strength on these planes. Cleavage describes how a rock breaks when subjected to stress on a particular plane. If part of the rock breaks due to stress and the broken piece presents a smooth plane, the rock has cleavage [11].

We present our work in the scenario described above and base our study on a set of granular aggregates belonging to discarded materials produced by mining in our region. These discards will be used as part of the aggregates added to the concrete mixture along with the use of crushed standard arids. We propose a simple physical characterization method for granular aggregates by measuring a set of parameters such as shape factors, particle size, specific surface area, packing fraction and resistance to abrasion of the grains. Once the characterization is ready, it is possible to relate those physical parameters with the mechanical behavior of the structure of concrete under simple compression and, thus, to predict qualitatively the expected behavior that concrete cores will have when subjected to uniaxial compression.

One of the main parameters that will vary in this study is the ratio between the aggregates coming from discard and the standard aggregates added to the mixture. As a result of our tests, we are able to ensure that the type of discarded rocks employed can be used for the production of concrete in structural and non-structural applications, depending on the chosen ratio.

It is worth saying that, although the discards used here belong to our geographical region, they are just an example of the many sources of recyclable rock material that can be found elsewhere in the world, thus extending the conclusions of this work to other kind of scenarios.

II. Physical Characterization of Aggregates

In this section, we develop the procedures involved in the physical characterization of the granular material used as coarse and fine aggregates in the mixture of concrete, along with the presentation of the results and comments. We split the section in two subsections: one related to the direct measurement of the shape factors and densities, and the other related to the theoretical calculation of the specific surface area based on the data obtained earlier.

Before proceeding with the characterization methodology, let us describe the origin and classification of the granular material. Basically, the production of concrete involves adding coarse and fine rock aggregates, along with sand, cement and water. As supply sources for the aggregates three quarries are chosen. One quarry provides crushed standard aggregates, typically used in the concrete production. The second and third sources are the discards coming from two huge stone quarries, one of flagstone and the other of granite, both representing the many quarries that exist in the region. In this way, and to produce our samples, we use a mixture with different ratios of flagstone and standard aggregates, or, of granite and standard aggregates, respectively. We do not mix here flagstone and granite together in any case.

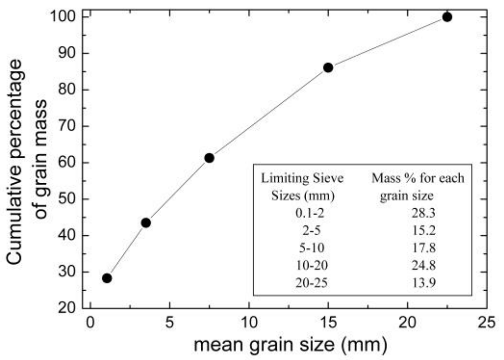

Fig. 1 Cumulative percentage of grain mass vs. mean grain size.

Material from discards is subjected to grinding to obtain the desired particle size distribution. Once we have the three kinds of bulk material, we proceed to classify by sieving. The size distribution of the grains used obeys standard criteria, and is presented in Fig. 1 [12],[13]. 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 important to clarify that we use always the same grain size distribution in all the experiments. This means that a given mixture, with a given proportion of the two kind of grains (for instance, flagstone and standard aggregates), follows, as a whole, the size distribution indicated in Fig.1.

In order to quantify the composition of the aggregate mixtures used in the generation of our cores, we define a parameter f as follows

$$f(\%) = \frac{m_{DR}}{m_{DR} + m_{SA}} 100 \qquad (1)$$

where m_{DR} represents the mass of the discarded rocks (flagstone or granite) and m_{SA} refers to the mass of standard aggregates added to the mixture. For each kind of discarded rocks, the percentages used were 0%, 25%, 50%, 75%, and 100%, given in terms of the presence of the discarded grain mass used. For example, in the case of the mixture with flagstone, 0% (100%) corresponds to a sample where only pure standard aggregates (pure flagstones) are present.

Once a given value for f is chosen, that percentage is kept constant inside each grain size. It is important to note that the grains used in the range from 0.1 to 2.0mm are always taken from natural river sand, because our intention is to set aside the effect of the dust coming from crushed discards, already studied by other authors [14], [15].

A. *Definition and direct measurement of physical parameters*

In order to characterize the shape of the grains we chose two simple indexes as the flatness and elongation ratios, α and β, respectively, which are defined as

$$\alpha = \frac{T}{W}\ ;\ \beta = \frac{W}{L} \qquad (2)$$

where T, W, and L are the characteristic thickness, width, and length of the grains, respectively. As most shape factors, the ones defined here try to give an idea about the departure that a grain has from a regular shape like a cube or a sphere. A value of 1 means to be close to a perfectly cubic (or spherical) shape for the grain. The smaller the values of α and β, the further from cubic (or spherical) geometry are the grains. The characteristic dimensions are measured using a digital caliper and are averaged over a representative number of grains taken from each size range.

Fig. 2 shows the results for α and β as a function of the size of the grains. The behavior for the standard crushed aggregates and granite are very similar (see Fig. 2(a) and (c)). The indexes are quite large, indicating grains of a fairly regular shape. In most cases the flatness of the grains is slightly more evident than the elongation. The shape of the grains remains quite similar as the grain size changes. On the other hand, Fig. 2(b) shows the behavior of the shape factors for flagstone, and the results are different compared to the previous cases. Flagstone grains present lower α and β values, especially for the flatness index. These results are in agreement with the formation and morphology of flagstone which presents a slab shape that is preserved even after crushing. The results presented for α and β make us presume that the ability of granite and standard aggregates to pack will be better than the one expected for flagstone.

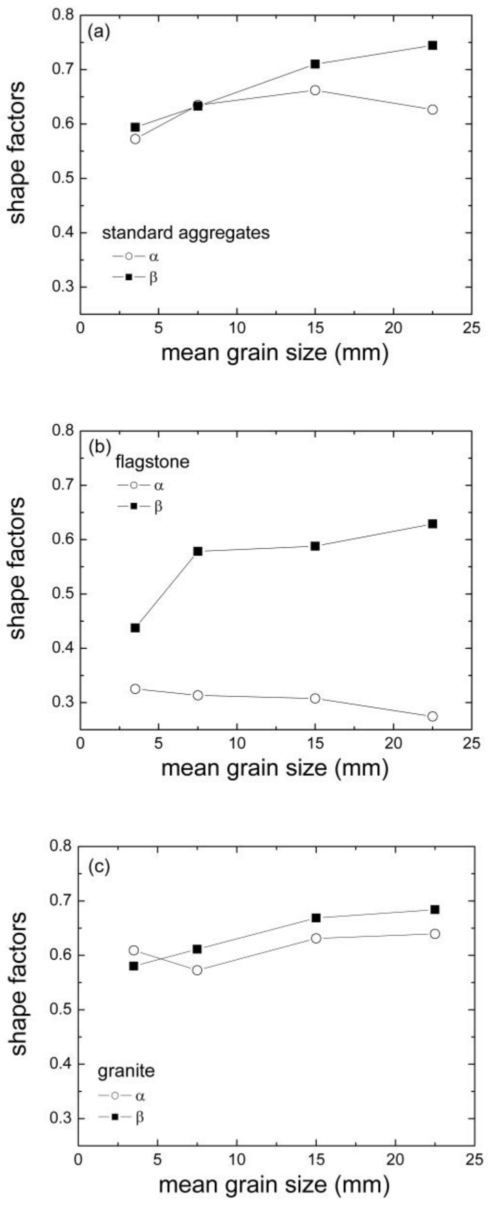

Fig. 2 Shape factors vs. The grain mean size. The standard errors are of the order of the symbols size.

Let us analyze compactness for the different grains as follows. One of the main parameters involved in the behavior of the resistance of a core is the packing capability of the grains constituting its structure. The packing density or compactness of the grains, c, can be defined as the ratio between the volume of grains and the total volume occupied by them, which can be approximated by [16]

$$c = \frac{\delta_a}{\delta} \tag{3}$$

where δ_a is the apparent density of the grains and δ is their actual solid density. The quantity c gives an idea on how the grains are arranged in a packing.

For the determination of δ, we employ the standard method that makes use of the Archimedes Principle. We use an analytical balance with an accuracy of 10^{-3} g, and we average over ten equivalent measurements. The values obtained for the three kind of materials are: (2.72±0.01) g/cm^3 for standard aggregates, (2.81±0.01) g/cm^3 for flagstones and (2.64±0.01) g/cm^3 for granite.

The apparent density δ_a is determined with the help of a container with well-known volume into which the material is poured from a short constant height and with a constant flow rate. The container with the material is weighed using an electronic balance, and the apparent density is determined as the ratio between the mass and the volume. The procedure is repeated 15 times to average results. The apparent density is measured for the different values of f cited earlier. Table 1 presents the results for δ_a for both type of mixtures, standard aggregates plus flagstones, and standard aggregates plus granite. Absolute errors are of the order of 10^{-2} g/cm^3. Using data in Table 1 and the corresponding solid densities, we are able to calculate the respective packing densities for the mixtures through (3).

Table 1. Apparent density for the five values of f

f (%)	δ_a (flagstone) (g/cm^3)	δ_a (granite) (g/cm^3)
0	1.72	1.72
25	1.67	1.71
50	1.66	1.66
75	1.63	1.64
100	1.57	1.64

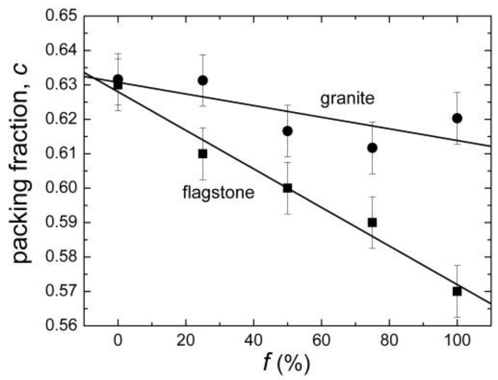

Fig. 3 Packing density vs. f for both types of mixtures, granite (circles) and flagstone (squares). Error bars are indicated.

Fig. 3 shows the results for c as a function of the mixture fraction f for flagstone and granite. According to the increment in m_{DR}, the packing fraction of the mixture decreases. In both cases the behavior can be roughly represented by a linear fit, as indicated in the figure by the straight lines. The decrease is more evident in the case of flagstones (10% decrease vs. 3% for granite), and this is explained by the flattened geometry of the grains which difficults their packing, as we have already said above. On the other hand, the packing capability of granite is better than that of flagstone. This property is related to the shape of the grains which is more close to a cubic form in the case of granite than in the case of flagstone. Based on these results, one would expect that, in general and for the two mixtures, the resistance of concrete will diminish as m_{DR} increases, and cores made using granite will be stronger than those using flagstone. In this sense, it is important to highlight the decrease in compactness undergone by the flagstone mixture, with a value close to 0.57 for f = 100%. This value is low compared with the typical compaction capability found for standard aggregates [9] and granite. It is expected that this feature will have an important incidence in the behavior of concrete resistance for the case of the flagstone mixtures.

B. *Calculation of the specific surface area*

The specific surface area, *SSA*, of the aggregates participating in the concrete production has proved to be an important factor in concrete resistance. Indeed, an increase in *SSA* causes an increment in water requirements. [9] 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 [14]. In the present experiments we keep constant the water/cement ratio, thus, the availability of water to wet the grains is always the same.

In this paper, we calculate *SSA* with the help of a theoretical development due to Hunger *et al.* [8]. This is a very useful procedure to measure specific area when direct image analysis through special measuring devices can not be carried out [17], [18]. *SSA* can be calculated from the grain characteristic parameters *T*, *L* and *W*. The explanation of the method is developed in great detail in [8], but here we present the main details necessary to perform the calculations [9].

Assuming to have an ideal monosized sample of spherical particles, the total surface area can be expressed as

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

where m_{sample} is the total mass of the sample, δ and d are the density and the diameter of the particles, respectively. In a polydisperse sample, like the ones used here, one can separate the grains in families, according to their size, and consider each family like a monosized set of grains. Thus, the total surface area, S, of a granular material with known particle size distribution, can be computed extending (4) as

$$S = 6\sum_j \frac{\omega_j\, m_{sample}\, \xi_j}{\delta\, \bar{d}_j} \tag{5}$$

where ω_j is the mass fraction of the grain family j, *i.e.*, of the grains with diameters ranging from d_j and d_{j+1}, and $\bar{d}_j$ is the arithmetic mean diameter for the grain family j. We perform the family classification taking into account the size ranges that are shown in the inset of Fig. 1. The factor ξ_j is a shape factor that has to be included due to the non-sphericity of the particles. This factor is defined as [8]

$$\xi_j = \frac{s_j}{\varepsilon_j} \tag{6}$$

where s_j refers to the surface area of a typical grain belonging to the grain fraction j, and ε_j corresponds to the surface area for a spherical grain with a volume equal to that of the typical grain belonging to family j. Assuming a parallelepiped shape for the grain, we compute s_j from the results obtained for T, W, and L for each set j. Moreover, if we consider a sphere with the same volume as that of the parallelepipedic grain, we can calculate its corresponding diameter and then use this value to compute ε_j. After the calculation above, the total surface area S is computed from (5) and, finally, *SSA* is obtained dividing S by the total volume of the sample.

As we want to measure the incidence of the fraction f of discarded rocks in the amount of surface area present in the mixture of grains and responsible of the interactions with the paste inside the concrete core, we calculate *SSA* for all the mixtures used to produce the cores in our experiments.

In Fig. 4, we show the results for both types of mixtures. The specific surface area increases linearly as the fraction f of discarded rocks is incremented. As one could expect, in the case of the mixtures with flagstone, *SSA* rapidly increases as the addition of discarded rock is larger. The specific surface area for the aggregates grows more than 60% when f changes from 0% to 100%. On the other hand, *SSA* for granite mixtures is lower for all f values when compared to flagstone mixtures. In addition, the increment in surface area with the addition of discarded rocks is more modest, reaching around 11% for the pure case (f = 100%).

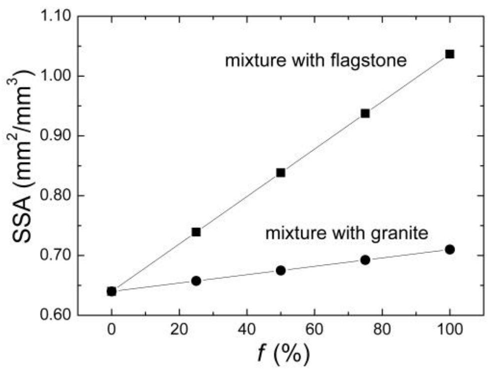

Fig. 4 Specific surface area of the grains, *SSA*, as a function of f for both types of mixtures, as indicated. Errors are of the order of the symbol size.

The mixtures with a higher *SSA* will use more water to wet the grain surface. Consequently, the amount of water that is involved in the concrete paste is reduced [3], [19]. The compression strength has been shown to be very sensitive to both the water content and the specific surface area [8], [19] and, thus, it is expected to increase 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.

From the *SSA* point of view, one could expect that flagstone mixtures would contribute to enhance concrete resistance because of their high specific surface area. For the case of granite mixtures, although the increment of *SSA* with m_{DR} is lower, we expect that the addition of granite will also enhance the resistance.

III. Uniaxial compression tests

In this section we explain the experimental procedure employed to produce the concrete cores with the mixtures of flagstone and standard aggregates, and granite and standard aggregates, respectively. Then, we correlate the resistance of those cores with the physical properties of the grains participating in the mix and we corroborate the expectation about this behavior.

A standard concrete called "H21 type" is prepared, where the proportions of the different granular components and the water are such that the concrete structure resists, in theory, 21 N/mm^2 to uniaxial compression. If the type of grains used in the mixture or the net of contacts are not strong enough, the core resistance will be lower that the theoretical one [19].

A standard experimental procedure is used as in previous works, [9] following typical preparation protocols for concrete manufacturing. Both coarse and fine grains used in the mixture correspond to the size distribution in Fig. 1. We recall that we do not mix the flagstone grains with the granite grains in any preparation. A fixed water/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 the experiments (size 0.1–2 mm) is always coming from the same natural origin (river sand), *i.e.*, it never comes from crushed stone sources.

Once a given *f* value and a discarded rock type are chosen, six identical samples are prepared. The specimens are prepared in cores with 15 cm diameter and 30 cm height. Thus, if we chose 5 different values for *f*, a total of 30 cores have to be produced for each type of discarded rock in order to be tested under uniaxial compression.

To prepare the paste, we employ the same concrete mixer and follow exactly the same procedure. First, the water is added to the mixer, then, the grains are incorporated, beginning by the coarse ones and following by the fines. Finally, the cement is added and a given time (around 3 minutes) is waited until the mixer is turned off, thus obtaining a homogeneous paste, without segregation. Once the concrete is distributed in the six cores and to prevent the presence of weak planes, the cylinder ends are smoothed and are made 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.

After the time of curing, the cores are left out of the water during one day, in order to dry. Then, they are subjected to uniaxial compression. The pressure exerted over a core until failure is called F_c. For each value of *f* tested, an average of F_c is obtained from the six equivalent cores.

Fig. 5 shows and compares the results for the resistance strengths of the cores for the mixtures with flagstone and with granite. There, he dashed lines indicate the H21 and H17 reference resistances. The results for the two rocks are quite different. First, the response of the cores made with granite presents an increment of the strength respect to the pure case (0% granite) up to *f* around 50-60%. For greater values of *f*, F_c diminishes. The general behavior is similar to the one found in previous works for mixtures of other type of grains [2], [9]: the presence of a maximum between the pure cases, showing an optimal mixing percentage for the resistance to uniaxial compression. Furthermore, regardless the case for f = 100%, all the mixtures are appropriate for structural applications (upper dashed line). The behavior can be approximately fitted by a parabola, like the one shown in the figure. We will discuss this behavior in a greater detail in the next section.

Secondly, the behavior for the mixtures with flagstone is monotonous decreasing with *f*, in contrast with previous results, and can be roughly fitted by a straight line, as indicated in the figure. The strength is always lower than that for f = 0%, nevertheless, for f < 50%, F_c is still suitable for non-structural applications (lower dashed line).

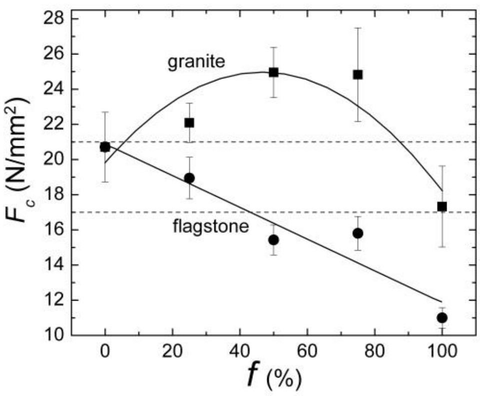

Fig. 5 Compressive strength until failure, F_c, as a function of *f* for both types of mixtures. The statistical dispersion of the data is indicated by the error bars.

According to the above results and trends, one should say that the cores made with granite which are in the range $f \in$ (10%, 90%) present a good and appropriate performance when compared to the standard 21 N/mm^2. On the other hand, for flagstone mixtures, all the values, except, of course, the first one corresponding to f = 0%, are below the H21 level, and they are not suitable for structural applications. However, they may be employed for non-structural works in the range of 17 N/mm^2 < F_c < 21 N/mm^2, for f < 40%.

The presence of a non-monotonic behavior for F_c is an interesting and fruitful feature resulting from the competitive effect of two variables such as *SSA* and compactness. On the other hand, although this competitive effect may also be present in flagstone mixtures, another factor is influencing the behavior found, as we will discuss in the next section.

IV. Discussion

The discarded rocks selected for the mixtures present different behaviors when shape factors are measured. Granite grains present flatness and elongation factors which are similar to the typical values obtained for standard rocks and they are close to a cubic form (Fig. 2 (a) and (c)). Flagstone grains have lower α and β values, especially the flatness index, in coincidence with the fact that these rocks present cleavage planes that are conserved all over the size range studied. This particular feature makes the mixtures using flagstone grains to show a considerably decrease in the packing density, *c*, as the percentage *f* increases (Fig. 3), while the granite mixtures decrease only slightly and have values just a little lower that those which are typical for standard aggregates [9].

The description above is in agreement with the fact that less-cubic-like grains form looser packings than regular shaped grains. The fact that flagstone grains have a poorer ability for packing than granite, and the existence of cleavage planes where the grains may easily fail, make it to expect that the response to uniaxial compression will be quite lower for mixtures with flagstone than with granite.

On the other hand, *SSA* is favored in both type of mixtures as m_{DR} is increased. The increment in the surface area is more evident for the case of flagstone grains and this is expected to compensate, in some sense, the drawbacks of their low packing capability.

As in previous studies [9] the water/cement ratio and the size distribution of the grains are kept constant in all our present experiments, thus, the factors to be considered as crucial ones, when analyzing the expected response of concrete cores under uniaxial compression, are *c*, *SSA* and the presence of cleavage planes. Based on the first two factors, one would expect a non-monotonic behavior for both types of mixtures, with the presence of a maximum response at a given optimum value for *f*.

Indeed, the decrease of the packing fraction in the mixtures of grains when *f* increases does not favor the compressive strength of the core [20], and, on the contrary, the increase in *SSA* for mixtures with greater *f* causes an increment in water requirements. Thus, as already pointed out in Section 2.2, if the water/cement ratio is constant, it is expected that the availability of water for the paste will be less for those cores where *SSA* is higher and, consequently, the compression strength will increase with *f*.

These two competitive effects for increasing *f*, explain the expected maximum, and this prediction has been tested in reference [9]. Nevertheless, it is important to remember that in [9] the cleavage properties of the aggregates are practically the same, independently of the quarry and the origin (natural or crushed) of those aggregates.

In the present scenario, the cleavage properties of flagstone and granite are quite different. In fact, a Los Angeles abrasion test performed on the aggregates, gives similar values for granites and standard aggregate grains, while it gives a quite lower value for flagstone grains.

We recall that a Los Angeles (LA) abrasion test is a measure of the degradation degree of mineral aggregates of standard gradings resulting from a combination of actions including abrasion or attrition, impact, and grinding in a rotating steel drum containing a specified number of steel spheres. The measured index is the percentage loss coming from the ratio of two quantities. The difference between the retained mass in a Nº 12 sieve (larger particles) and the original sample mass is placed in the numerator, and the total original sample mass is placed in the denominator. Thus, a larger index means a lower resistance to abrasion.

The resulting values for the three different kinds of grains are: 34% for standard aggregates, 33.8% for granite and 19.4% for flagstone. These indices correspond to a type A LA test. The results are calculated by dividing the mass of grains passing a Nº 12 sieve, *i.e.*, with a size less than 1.70 mm, by the total initial mass of grains that are put into the rotating drum (5.000 g). The size range of the initial mass of grains is from 25mm to 9.5mm.

Although the LA test is not always directly related to the field performance of aggregates, it gives a good idea about the degradation of the grains. From this point of view and looking at the obtained values, one would conclude that flagstone grains are more resistant to abrasion than granite ones and that, eventually, they will be more appropriate for concrete. But, indeed, what is demonstrated from the LA test is that the flagstone grains break following their cleavage planes, in such a way that they adopt a slab geometry that makes them to be retained in the Nº 12 sieve. They do not crush in the same way in all directions and are more fragile in the direction of the cleavage planes. For flagstones, this effect works in the same direction as the one due to *c*, and explains the monotonous behavior found for the resistance of the flagstone mixtures vs. the percentage *f* in Fig. 5. On the other hand, the absence of cleavage planes in granite gives rise to the expected non-monotonous behavior resulting from the competing effect between the growth in *SSA* and the decrease in *c*, as *f* is increased.

From the point of view of the applications, the resistance values obtained for the different mixtures show that granite is a very good candidate to replace part of the standard aggregates used in concrete production, while, in the case of flagstone, it is limited to a non-structural use, where a resistance between 17 and 21 N/mm^2 is allowed.

V. Conclusions

The results shown here demonstrate that a simple physical analysis can be performed on discarded rocks to predict, at least qualitatively, their field performance and to determine their suitability for different applications.

We apply a simple protocol to determine some important physical parameters belonging to discarded rocks as granite and flagstone, along with those corresponding to standard aggregates used in the production of concrete.

Through analyzing the behavior of those parameters, we are able to predict the expected response to uniaxial compression of the cores of concrete made with mixtures of discarded rocks and standard aggregates.

The results for the uniaxial tests performed on the concrete cores show that the response for granite mixtures is comparable to the one for other kind of rocks tested in previous works [9], *i.e.*, they present a maximum for a given value of *f*. Conversely, the flagstone mixtures show a monotonous decrease with *f*, where the role of the cleavage planes is crucial.

We demonstrate that discarded rocks like granite and flagstone can be used as part of the aggregates in concrete production. For the case of granite, mixtures with *f* up to 90% are suitable for structural applications, while, for flagstone, mixtures with *f* up to 40% are good enough for non-structural applications. This is good news when environmental recovery is pursued.

Acknowledgment

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María E. Médici Civil Engineer. She is finishing her PhD. at Departamento de Minería and INFAP, Universidad Nacional de San Luis, San Luis, Argentina. Research interests in concrete production and characterization of building materials. She is also a professor, teaching at the mining department.

Martín Dolcemáscolo Mining Engineering student at Departamento de Minería, Universidad Nacional de San Luis, San Luis, Argentina. He is finishing his grade in march 2016.

Rodolfo O. Uñac Doctor in Physics. He is a senior researcher at the Argentinian Council of Research and Technology (C. O. N. I. C. E. T.) and is a Permanent Professor at Departamento de Física, Universidad Nacional de San Luis, San Luis, Argentina. He has published more than 50 research papers in international reviews in subjects like adsorption phenomena, granular matter and resuspension of dust particles. Present research interests in statistical mechanics and, especially, in granular matter and resuspension of particles phenomena.

Ana M. Vidales Doctor in Physics. She is a senior researcher at the Argentinian Council of Research and Technology (C. O. N. I. C. E. T.) and is a Permanent Professor at Departamento de Física, Universidad Nacional de San Luis, San Luis, Argentina. She has published more than 90 research papers in international reviews in subjects like transport in porous media, percolation problems, granular matter and resuspension of particles. Present research interests in statistical mechanics and, especially, in granular matter and resuspension of particles phenomena.