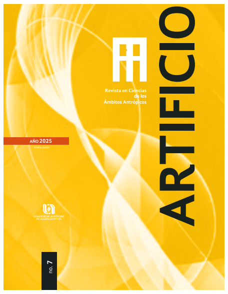

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Influence of the morphological characteristics of coarse aggregate on the mechanical properties of concrete

Influencia de las características morfológicas del agregado grueso en las propiedades mecánicas del concreto

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Centro de Ciencias del DISEÑO Y DE LA CONSTRUCCIÓN eB2

Influence of the morphological characteristics of coarse aggregate on the mechanical properties of concrete

Mario López-Rojas

Resumen

La morfología de los agregados puede tener un efecto significante en el comportamiento del concreto fresco y endurecido. En este estudio se obtuvieron las características morfológicas (redondez, elongación y dimensión fractal) del agregado grueso (grava natural y triturada) a través del procesamiento de imágenes binarias con el programa Image-PRO. Se correlacionaron las propiedades morfológicas con las propiedades del concreto fresco (revenimiento) y endurecido (resistencia a la compresión). Los resultados muestran una tendencia hacia valores bajos en los parámetros de redondez, elongación y dimensión fractal para las partículas de grava natural, lo que sugiere contornos más suavizados y menos elongados, comparados con los valores altos de los mismos parámetros para la grava triturada. Adicionalmente, la forma del agregado grueso afectó significantemente el comportamiento mecánico del concreto endurecido, dado que los cilindros elaborados con partículas de grava natural tienen una tendencia hacia valores más altos y una menor desviación estándar en la resistencia a la compresión.

Palabras clave: *Agregado grueso; propiedades mecánicas del concreto; características morfológicas; resistencia a la compresión.*

Abstract

The morphology of the aggregates can have a significant effect on the behavior of fresh and hardened concrete. In this study, the morphological characteristics (roundness, aspect, and fractal dimension) of coarse aggregated (crushed and natural gravel) were obtained through binary images processed with the Image-PRO software. The morphological properties were correlated with the mechanical behavior of hardened (compressive strength) and fresh concrete (slump). The results show a trend to lower values of roundness, aspect, and fractal dimension for natural gravel particles, suggesting smoother contours and lower elongated, compared with higher values of crushed gravel. Additionally, the shape of coarse aggregates significantly affected the mechanical behavior of hardened concrete, because the concrete cylinders elaborated with the same particles (natural gravel) have a trend to higher values and lower standard deviation of compressive strength.

Keywords: *Coarse aggregate; mechanical properties of concrete; morphological characteristics; compressive strength.*

INTRODUCTION

Aggregates constitute a substantial part of the total volume of the concrete (between 70 and 75%); therefore, making an adequate selection of aggregates will result in the improvement of the quality of the concrete, and consequently, of the structure's behavior. Aggregate characteristics significantly affect the properties and behavior of fresh and hardened concrete (Jamkar & Rao, 2004). The importance of selecting quality aggregates will influence the cost of concrete and its durability (Oluwasola et al., 2020). Other concrete properties that are also associated with the aggregate shape are workability and strength (Erdogan et al., 2006). The shape and surface texture of the coarse aggregate affects the demand for sand, cement, and mixed water, the finishabilities, and the mobility of fresh concrete. The water content of the mix affects the porosity of hardened concrete, and therefore its strength. Aggregate shape, texture, and gradation characteristics affect the workability, finishing, bleeding, and segregation of fresh concrete; and the strength, stiffness, contraction, permeability, and durability of hardened concrete (Quiroga & Fowler, 2004).

Due the cement is the most expensive component of concrete and the cement paste (cement and water) is the mix filling the voids among aggregates, is very important to analize morphological characteristics of coarse aggregate, since selecting aggregates with certain morphological features, affect the cost of concrete and structures.

The aim of this study is to analyze the effect of coarse aggregate morphological characteristics on the mechanical properties of concrete, using coarse aggregated, crushed and natural gravel (come from a local river).

EFFECT OF MORPHOLOGICAL FEATURES OF AGGREGATES IN CONCRETE

The morphology and gradation of the aggregates are properties that have a significant effect on the behavior of fresh concrete. Water absorption is perhaps the property of coarse aggregate which tends to have a greater influence on the consistency, and therefore on the workability of concrete, since the gravel particles absorb water during mixing, decreasing the workability of the mix (Cham-Yam et al., 2003). Thus, a concrete mix with aggregates with rounded shapes and smooth surfaces will require less water-cement paste compared to a mix whose aggregates are elongated, angular, and with rough surfaces (Oluwasola et al., 2020). Additionally, uniformly graded aggregates and adequate amounts of each size will result in concrete that requires less water. Consequently, there will be a more economical water-cement paste with fewer durability problems caused by the generation of heat, porosity, and contraction (Quiroga, 2003).

The shape and surface texture of the coarse aggregate affects the demand for sand. Thus, gravel grains with flat, elongated, angular shapes and rough surfaces have more voids to fill and require more sand to fill those voids from coarse aggregate and provide workable concrete, thus increasing water demand (Legg, 1998). Flat and elongated particles tend to produce concrete mixtures with rougher surfaces and affect finishabilities, in addition to reducing the mobility of the mixture and producing hollow structural elements, whose strength can be affected (Legg, 1998). Planar particles could be oriented in a way that could decrease the strength and durability of the concrete (Galloway, 1994). In hydraulic concrete pavements, the flat particles near the surface cause the separation of the bleed water of the mortar, thus causing damage to the surface (Kosmatra, 1994). The efficiency of uniform particle distribution is also affected by the aggregate's shape. Concrete mixes with elongated, flat, and rough-surfaced aggregates require more cement paste due to the high content of surface voids in the particles, so it is reasonable to expect a saving of 4 to 5% in the cement paste if the aggregate shape is cubic or spherical (Hudson, 1998).

Another aspect to highlight is that elongated particles tend to break along their longest axis (Piotrowska et al., 2014). In this way, the particle shape affects the strength of the aggregate and the life expectancy of the materials such as concrete, asphalt, and railroad ballast (Oluwasola et al., 2020). In contrast, rough-surfaced aggregates will have higher bond strength, both on concrete and asphalt (Fernlund, 2005b). The strength and stiffness of coarse aggregate have a direct influence on the behavior of hardened concrete. Although in ordinary concrete, the strength of the concrete mix is controlled by the cement paste characteristics or by the transition zone between the paste and the aggregate, in high-strength concrete, the strength depends not only on the strength of the aggregate but also on its mineralogy (Oluwasola et al, 2020). In their study, Neville and Brooks (2010) indicated that aggregates with flat shapes produce concrete with lower compressive strength. On the other hand, spherically shaped aggregates contain less surface area, reduce friction during mixing, and therefore workability of concrete is higher. Concrete slump is higher when the aggregates have elongated and flat shapes (Matias et al., 2013).

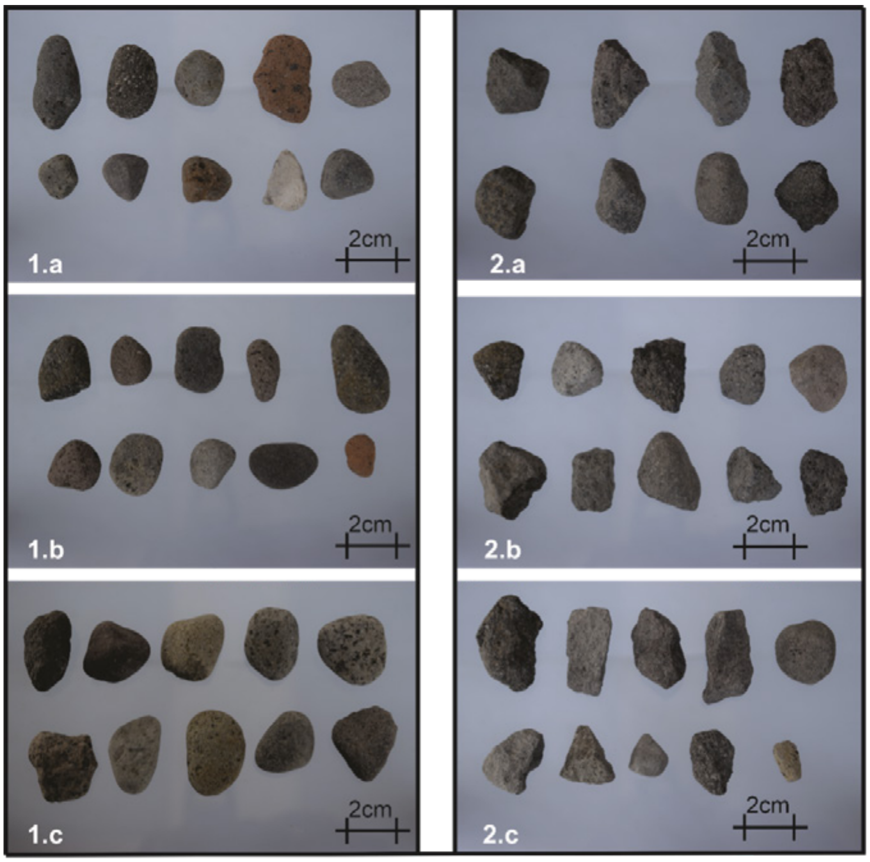


Figure 1. Images of samples of natural and crushed gravel particles. Images 1.a, 1.b and 1.c correspond to natural gravel particles and images 2.a, 2.b, and 2.c correspond to crushed gravel particles. Note that crushed gravel particles present more angular shapes compared with the forms of natural gravel particles.

MORPHOLOGICAL ANALYSIS OF AGGREGATES

The shape analysis of concrete aggregates has been carried out through parameters or shape descriptors such as roundness and elongation through qualitative methodologies (Meddah et al., 2010; Oritola et al., 2014); through quantitative techniques such as the Fourier transform (León & Ramírez, 2010) or through 3D analysis using X-ray microtomography (Erdogan, 2005; Fernlund, 2005b; Masad et al., 2005). By general definition, roundness measures the angularity degree or edges angularity of a particle (Neville & Brooks, 2010), and elongation needs no explanation.

The irregular shape of the aggregates cannot be described by Euclidean geometry, but its characterization through Fractal geometry is possible. Malderbrot (1977) introduced the concept of fractal for describing shapes formed in nature. The key parameter for fractal analysis is the fractal dimension, which is a real non-integer number, differing from the more common Euclidian or topological dimension. The fractal dimension for a line of any shape varies between one and two (as is the case for the contour of a coarse aggregate particle), and between two and three for a surface.

The fractal dimension can be viewed as a quantitative expression of the complexity of the particle contour, in this case the ruggedness of an gravel particle. In this study we applied fractal analysis to calculate the general fractal dimension values of particles of gravel grains.

METHODOLOGY

The coarse aggregate samples used in this study to determine the mechanical properties of concrete and image acquisition are of two types: natural gravel, from a local river (Figures 1.a, 1.b, and 1. c); and crushed gravel, from banks of material in the region (Figures 2.a, 2.b and 2.c). To consider representative grains of all coarse aggregate sizes, between 8 and 12 grains of gravel were selected from each of the 3/4", 3/8", and #4 grids.

Preparation of concrete mix and tests

For the development of the compression strength tests, concrete cylinders of 10 cm in diameter and 20 cm in height were manufactured. To determine the consistency of the concrete, concrete slump tests were carried out. As compression strength tests, then the concrete slump tests, the concrete was prepared considering the two types of coarse aggregate (crushed and natural gravel), considering the same dosage by weight according to the N-CMT-2-02-005 Mexican standard (Table 1).

The granulometry of the coarse aggregate was determined according to the NMX-C-077-ONNCCE-CURRENT standard, which is the current standard for the quality control of aggregates in the manufacture of concrete in Mexico. The results of the granulometric distribution of the gravel samples are shown in the annexes section. In each sample, 20 kg of gravel was used to determine the granulometry.

Material	Weight (kg)
Cement	1.968
Gravel	6.970
Sand	7.298
Water	1.855

Table 1. Dosage by weight for concrete of compression strength and slump.

Determination of aggregate morphology

To carry out the coarse aggregate morphological characterization, between 29 and 30 gravel grains with a 19 mm maximum size were selected in each sample. A total of 178 gravel grains with 19 mm size were used, of which 89 are fragments from crushed gravel, locally called "mine gravel", and 89 grains of natural gravel, known as "river gravel". Table 1 shows the amounts of coarse aggregate used.

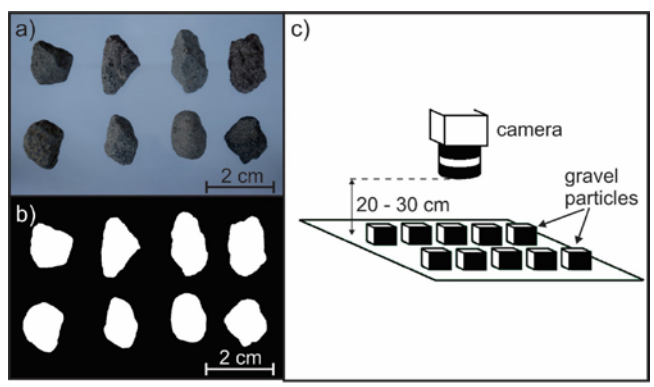


Figure 2. a) Top view of gravel particles setup for imaging. b) Binary image of the same sample of gravel particles. c) sketch of geometry of lateral view of gravel particles setup. The camera was located at a height of 30 cm above the gravel particles.

The values for the morphological parameters of the gravel grains were obtained by processing binary images. To generate the binary images, images of the gravel grains placed on white paper (Figure 2) were first obtained using a 24.2 – megapixel – Nikon digital camera. Each image was processed with Photoshop software to threshold the contours and generate binary images. The binary images were then processed using Image-PRO software.

Sample	Size (grid)	Crushed gravel (grains number)	Sample	Size (grid)	Natural gravel (grains number)
M1	3/4"	8	R1	3/4"	10
	3/8"	10		3/8"	10
	# 4	12		# 4	10
M2	3/4"	10	R2	3/4"	10
	3/8"	9		3/8"	10
	# 4	10		# 4	10
M3	3/4"	10	R3	3/4"	10
	3/8"	10		3/8"	10
	# 4	10		# 4	9
TOTAL		**89**			**89**

Table 2. Gravel fragments used in the morphological characterization of this study. Samples M1, M2 and M3 correspond to gravel from crushed rocks and samples R1, R2 and R3 are grains of natural gravel come from river. Of the same gravel grains used in the concrete for cylinders and slump test, and after to sieving the sample between 8 and 12 gravel grains were selected of each size fraction.

The parameters used to analyze the morphological features of gravel particles are roundness, aspect, and fractal dimensión and were obtained through the Image PRO Plus 6.0 program. The formulas for obtaining these parameters and used by Image PRO Plus 6.0 are shown in Figure 3.

Roundness represents the parameter that numerically compares the contour of a particle with the circumference of a circle with the same area. The range of roundness values is from 1.0 to ∞, where a roundness value of 1.0 represents a circle and the further this value is from 1.0, the more irregular or sinuous the particle's contour will be.

The aspect ratio is obtained as the ratio between the major axis and the minor axis of the equivalent ellipse. The equivalent ellipse is the ellipse whose area is equal to the particle area. Therefore the range of roundness values is from 1.0 to ∞. An aspect ratio value of 1.0 corresponds to a compact particle. The aspect ratio will increase proportionally to the increase in the elongation of the particle.

Including aspect and roundness, also fractal dimensión of gravel particles was calculated using the Image-Pro software. For this purpose this program uses the "caliper or ruler dimension method"; a method based on the application of a series of linear step lengths of various sizes to approximate the total length of the particle perimeter (Clark, 1986).

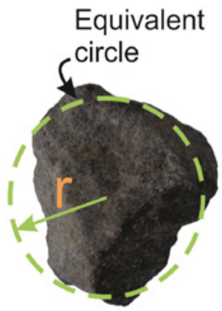
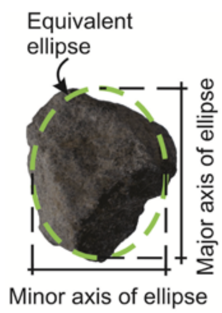
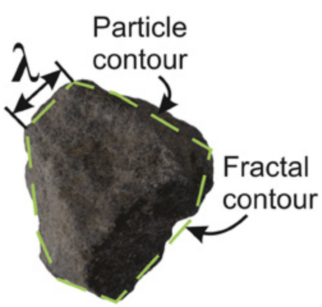
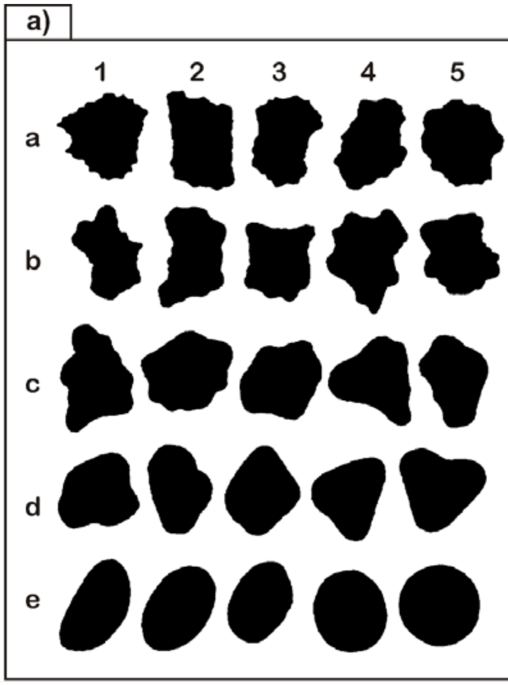
Adimensional parameter	Formula
Roundness 	$$Roundness = \frac{(particle\ perimeter)^2}{4 * \pi * (particle\ area)}$$
Aspect 	$$Aspect = \frac{Major\ axis\ of\ equivalent\ ellipse}{Major\ axis\ of\ equivalent\ ellipse}$$
Fractal dimension 	*D=1-m* *m=Slope of the linear regression line of Richardson diagram*

Figure 3. Explanation of the formulas used in this study for the determination of the dimensionless morphological parameters through Image-Pro software, as well as the geometric meaning of each one of the variables that each formula considers

As the step length (L) becomes smaller, the shape of an irregular boundary is more accurately reproduced. The relationship between the step length (L) and perimeter length (P) can be plotted as a line allowing the particle shape to be characterized. On a plot of log L versus log P (a so-called Richardson plot) (Clark et al., 1992), a straight line with a single slope represents a particle that has a self-similar, or true, fractal shape (i.e. morphological variations are the same at any scale). The fractal dimension (D) is related to the slope, S, of the log L versus log P plot by:

$D = 1 - S$ (1)

Values of D range from 1.0 to 2.0 with an increasing value corresponding to a more irregular boundary.



b)

Particle	Aspect	Fractal dimension	Roundness
a1	1.06	1.058	1.75
a2	1.54	1.034	1.64
a3	1.51	1.037	1.65
a4	1.55	1.036	1.62
a5	1.14	1.032	1.45
b1	1.63	1.042	1.88
b2	1.66	1.028	1.77
b3	1.13	1.035	1.63
b4	1.32	1.041	1.81
b5	1.21	1.037	1.61
c1	1.44	1.027	1.67
c2	1.22	1.020	1.37
c3	1.22	1.016	1.35
c4	1.11	1.016	1.54
c5	1.51	1.017	1.47
d1	1.17	1.013	1.36
d2	1.51	1.014	1.38
d3	1.24	1.012	1.37
d4	1.19	1.013	1.43
d5	1.04	1.012	1.42
e1	1.82	1.009	1.40
e2	1.52	1.009	1.30
e3	1.46	1.011	1.32
e4	1.14	1.008	1.21
e5	1.02	1.006	1.16

Figure 4. a) Comparative chart of Russel, Taylor and Pettijohn (Muller, 1967) on roundness of sedimentary particles. Row a = angular particles; row b = subangular particles; row c = subrounded particles; row d = rounded particles; row e = well-rounded particles. b) Morphological parameters used in this study and calculated for the particles of chart of Russel, Taylor and Pettijohn. In the first column appear the names of each particle, which correspond to the row (indicated with a letter) and the column (indicated with a number) of its location in the Comparative chart of Russel, Taylor and Pettijohn. The morphological parameters each synthetic particle are those that appear in each row. This way, the values of aspect, fractal dimension and roundness from the particles a1 to a5 correspond to synthetic particles of row a of Comparative chart and so on.

RESULTS AND DISCUSSION

Considering that the natural gravel particles come from the margin of a local river, which is subjected to wear and abrasion during transport, and that the crushed gravel grains come from a local mine, the morphological features present some significant differences that are manifested in the values of the morphological parameters and its mechanical behavior, reflected in the resistance to compression and the slump of the concrete, elaborated with the same coarse aggregate. The effect that morphological features of gravel grains had on the behavior of fresh concrete is explained in detail in the following sections.

Aggregates morphological characteristics

The morphological features presented by the crushed and natural gravel grains present very marked differences in the values of the roundness parameters and the fractal dimension. The values of aspect are very similar for the two types of gravel. The natural gravel particles have a range of roundness values between 1.2 and 1.26, with a standard deviation of 0.019; while the crushed gravel presents roundness values between 1.28 and 1.37, and a standard deviation of 0.035 (Figure 5c). According to the chart of Russel, Taylor, and Pettijohn (Figure 4), the roundness values of natural gravel correspond to figures e3 and e5 of the well-rounded category, and the roundness values of crushed gravel could correspond to figures between e1 and e3. (well-rounded), but also between d1 and d3 (rounded), or the figure c2 (subrounded). Crushed gravel grains had slightly higher aspect values than those corresponding to natural gravel. While the crushed gravel presents values from 1.28 to 1.55, the values of the natural gravel are between 1.21 and 1.52. In this case, the values could belong to any of the five categories of Russell, Taylor, and Pettijohn chart figures (Figure 4).

It was observed that the differences between the values of the roundness, aspect, and fractal dimension parameters can be better appreciated by obtaining the average value for each grain size. Therefore Figures 5a, 5b, and 5c were made from the average value of each of the 3 grain sizes (3/4", 3/8", and #4 grids) of gravel, and each size of gravel is considered gravel as a sub-sample. In this way, for both crushed gravel and natural gravel, 9 sub-samples were considered, which appear in figures 5a, 5b, and 5c. Since roundness and fractal dimension are parameters that measure the degree of roughness of a particle's contour, in Figures 5b and 5c one can see higher values of these two morphological parameters for crushed gravel particles. Higher values of roundness and fractal dimension of the crushed gravel grains, compared with the values of roundness and fractal dimension of natural gravel, indicate a greater roughness in the contour of the crushed gravel grains. The aspect ratio values are very similar for the two types of gravel (Figure 5a).

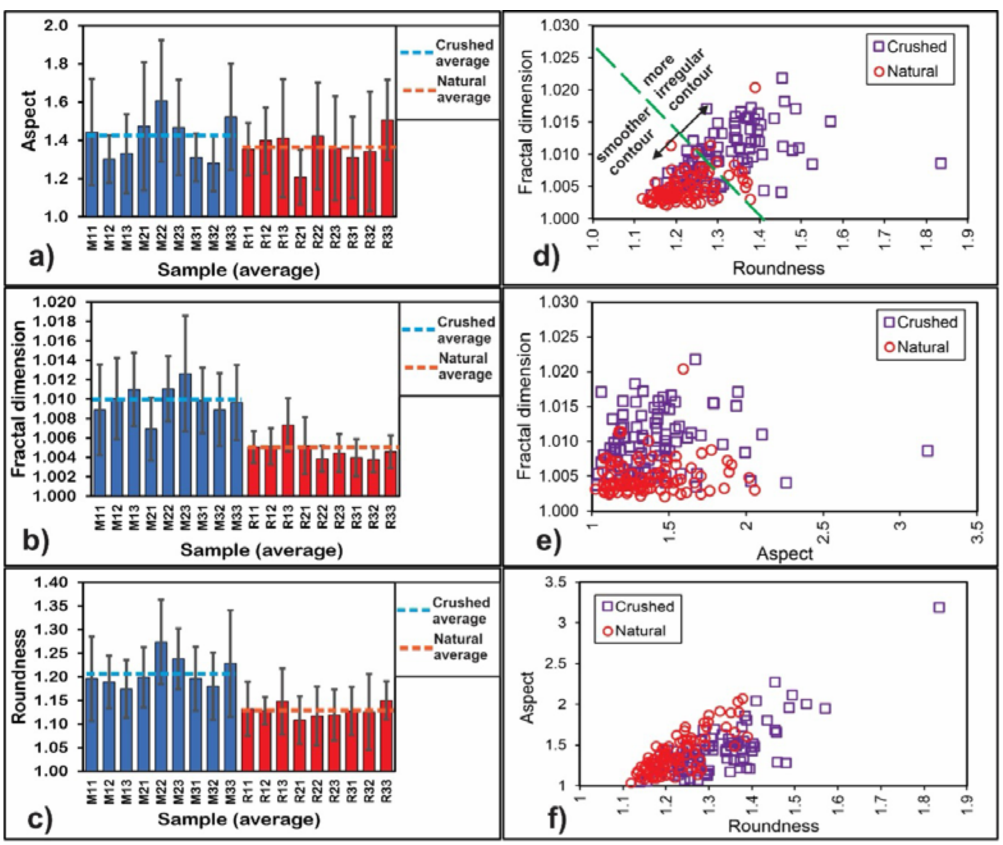


Figure 5. Figures a), b) and c) show a comparison of the behavior of roundness, aspect ratio and fractal dimension between natural and crushed gravel grains. Figures d), e) and f) show the correlation between morphological parameters for the two types of gravel (natural and crushed).

In oder to elaborate Figures 5d, 5e and 5f, individual grains were considered. Figure 5d shows a zone of crushed gravel with a tendency towards particles with more irregular contours and the zone of crushed gravel for particles with smoother contours. This corroborates a greater irregularity in the contour of the crushed gravel grains.

There is no correlation or pattern clear between the morphological parameters of the aspect and the fractal dimension, but there is a slight trend to major values of these parameters of crushed gravel (Figure 5e); something similar happens between the aspect and roundness parameters, there is a slight trend to major values of these parameters of crushed gravel (Figure 5f).

Influence of aggregates morphology on mechanical properties of concrete

To determine the compressive strength the concrete cylinders to 28 days were made with the two types of gravel (crushed and natural), two tests were carried out for each of the three samples, both crushed gravel and natural gravel [R1, R2 and R3; (Table 3)].

Natural gravel			Crushed gravel		
Sample	Test	F´c (kg/cm2)	Sample	Test	F´c (kg/cm2)
R1	1	151	M1	1	119
	2	159		2	108
R2	1	141	M2	1	135
	2	136		2	148
R3	1	139	M3	1	115
	2	126		2	111
	Average:	142		Average:	123
	Standar deviation	13		Standar deviation	15

Table 3. Results of concrete cylinders compression tests made with coarse natural aggregate (come from river) and crushed aggregate (come from mine)

The concrete elaborated with samples of natural gravel resulted in a maximum compressive strength value of 159 kg/cm², corresponding to test 2 of sample R1, and a minimum value of 126 kg/cm², corresponding to test 2 of sample R3. , an average compressive strength value of 142 kg/cm² and a standard deviation of 13 kg/cm². On the other hand, the maximum value of resistance to compression presented by the cylinders made with crushed gravel was 148 kg/cm², a minimum value of 108 kg/cm², an average of 123 kg/cm², and a standard deviation of 15 kg/cm². According to these values, the concrete made with natural gravel presents greater resistance to compression on average and less variability of values of said resistance (Table 3). Specifically, the compressive strength value of concrete made with natural gravel was 15% higher than that presented by concrete made with crushed gravel.

Figure 6a shows the average value of the morphological parameters on the horizontal axis and the corresponding average value of the two compressive strength tests (F'c) of each sample was considered on the vertical axis. Figure 6a shows that the natural gravel particles, with lower roundness values, produced concrete with higher compressive strength (diamonds), compared with higher roundness values and lower compressive strength values of the concrete made with crushed gravel (tilted cross). In addition to the above, it can be seen in Figure 6a that there is a greater tendency toward higher values of the aspect ratio and a lower compressive strength of concrete made with grains of crushed gravel (asterisks), compared with higher values of the aspect ratio.

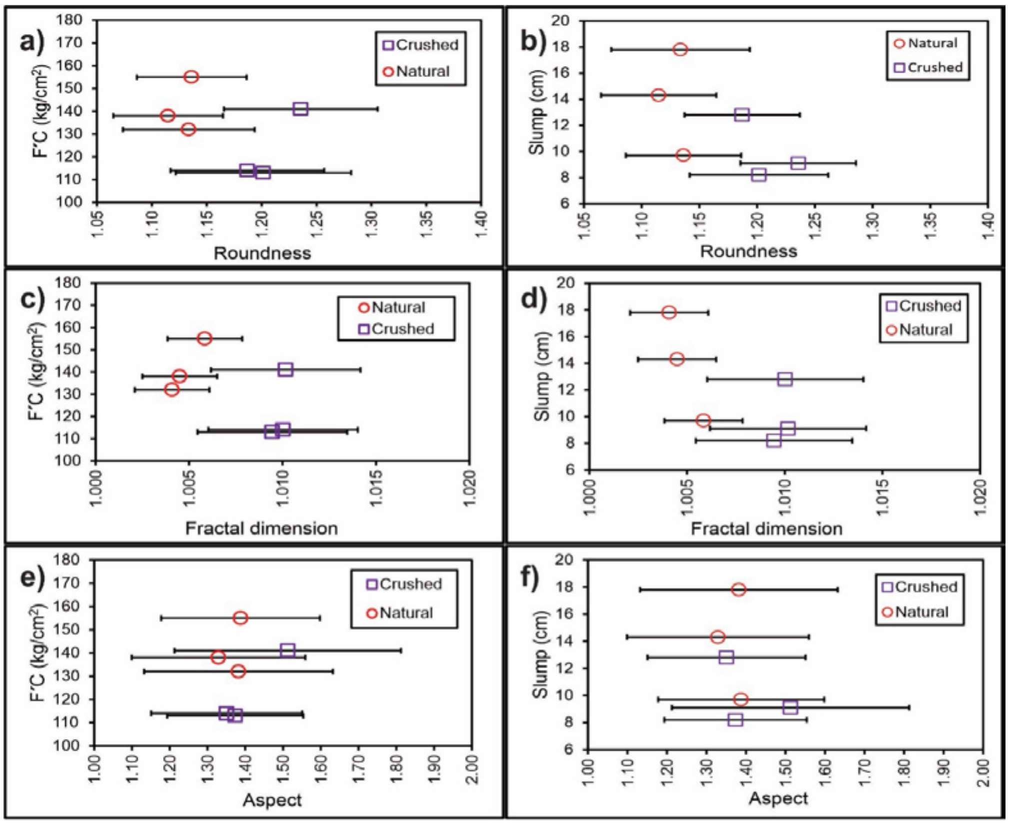


Figure 6. a) Influence of morphology on the compressive strength of concrete. b) Influence of gravel morphology on concrete slump. In both figures the same symbology was used to distinguish natural gravel grains from crushed gravel grains. Diamonds indicate roundness of natural gravel, slant cross indicates roundness of crushed gravel, triangles indicate aspect of natural gravel, asterisk indicates aspect of crushed gravel, circle indicates fractal dimension of natural gravel, and square indicates fractal dimension of crushed gravel.

Compressive strength of natural gravel grains, which present a tendency towards lower values of elongation (triangles). Due to the scale of the horizontal axis of Figure 6a, it is not possible to appreciate the differences in the values of the fractal dimension between the natural gravel (circles) and crushed, however, a tendency towards higher values of the compressive strength can be noticed in the natural gravel, comparing with the resistance values of the samples of crushed gravel (squares).

All shown in Figure 6a summarizes that natural gravel grains with lower values of roundness, aspect ratio, and fractal dimension, that is, with smoother and less elongated contours, produced concrete samples with higher compressive strength, considering that the same water-cement-sand ratio with the same granulometry was used in both cases. This could be associated with the fact that the more irregular and elongated shapes of the crushed gravel grains require more water-cement paste to achieve the same compressive strength (Oluwasola et al., 2020). Considering more elongated shapes of the crushed gravel grains, these could have been oriented in the concrete mix to achieve lower strength and possibly durability (Galloway, 1994). It is also very likely that the more elongated shapes and rougher contours of the crushed gravel grains have required more water-cement paste (Hudson, 1999). On the other hand, it is likely that the most elongated particles of crushed gravel have broken along their longest axis and thus affect their strength (Piotrowska et al., 2014).

Similarly, in Figure 6b the average values of the morphological parameters were associated with their respective average value of concrete slump for each sample. The samples of crushed gravel with higher roundness values (slant crosses), i.e., with more irregular contour, show lower values of slump. Additionally, it can notice slightly lower values of the natural gravel aspect and the corresponding higher values of slump for these particles. Although the differences between the values of the fractal dimension (for the two types of particles) cannot be noticed in Figure 5b, it is clear that natural gravel particles show higher values of slump. The above idea suggests that natural gravel particles showed higher values of slump because they are less elongated and have smoother contours (Matias et al., 2013).

CONCLUSIONS

The fractal dimension is a very useful tool to study the morphology of gravel particles due to is sensitive to contour of particle. Although roundness has the same purpose as fractal dimension, roundness can be a complement. Aspect is morphological parameter more focused in the general shape of particle.
The results of this study are consistent with the idea that gravel particles with lower values of roundness, aspect, and fractal dimension, i.e., smoother surfaces and lower elongated (natural gravel) produce higher values of concrete compressive strength and lower variability (minor standard deviation). Additionally, the concrete elaborated with these same particles (natural gravel) can require minor water-cement paste, presenting an mix more workable (more consistency) and likely a more economical water-cement with fewer durability problems, and also, better finishabilities.

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ANNEXES

Figure 7 show the particle size distribution (grading) of natural and crushed gravel used in this study and maximum and minimum limits of ASTM standard. The weight of each sample, as natural of crushed gravel were of 20 kilograms.

Figure 8 show the particle size distribution (grading) of sand used in this study and maximum and minimum limits of ASTM standard. The weight of sand sample was 701.6 grams. The same sand was used for concrete used in cylinders of the compression strength and slump tests.

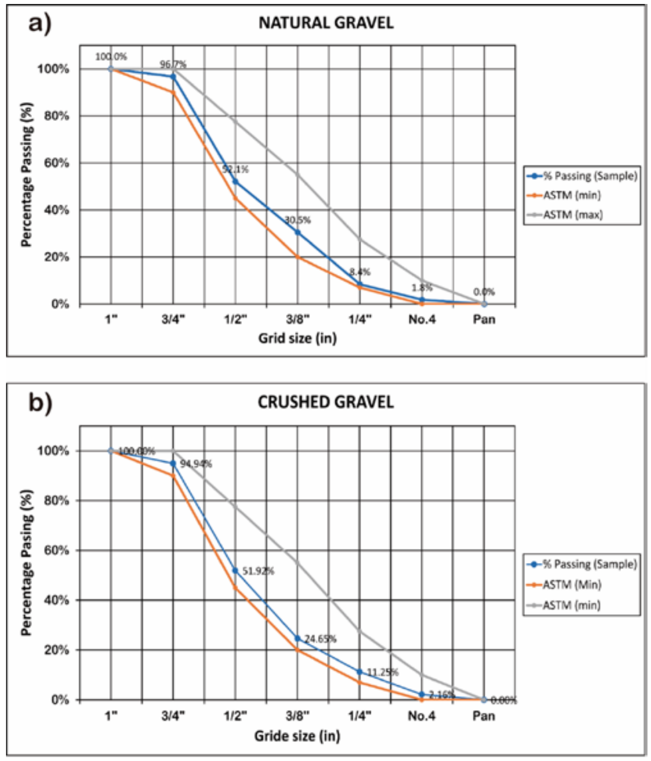

Figure 7. Gravel particle size distribution are shown and maximum and minimum values of ASTM standard of : a) natural and b) crushed gravel. Both types of particles show a optimum grading; it can be seen that particles size fall inside of ASTM standard limits. The size of grids are inches.

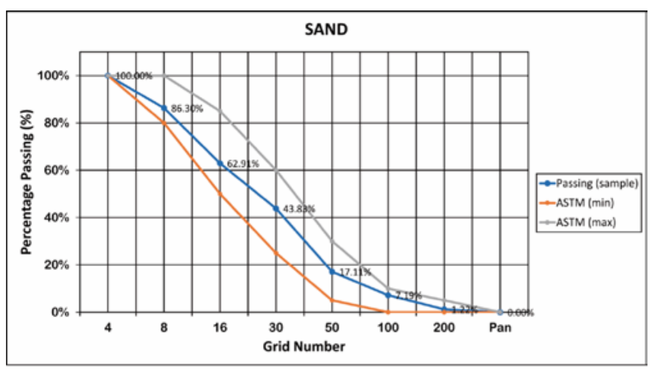

Figure 8. Sand particle size distribution are shown and maximum and minimum values of ASTM standard. Sand particles show a good grading; it can be seen that particles size fall inside of ASTM standard limits.

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