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Comparison of natural and manufactured fine aggregates in cement mortars

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Abstract

The performance of cement mortars using manufactured fine aggregates produced by cone crushing or impact crushing has been compared to that of mortars prepared from a natural sand control-sample. Samples from both crusher products have been additionally subjected to classification for partial removal of fines, being also used in preparing mortars. Particle shape analyses indicated that material produced by impact crushing presented intermediate sphericity and aspect ratio, between those found in natural fine aggregate and cone-crushed material, and that the aspect ratio of the cone-crushed material increased for finer particle sizes. The unclassified impact crusher product presented the highest packing density, and mortars produced from it had comparatively low porosity and low absorptivity and the highest unconfined compressive strength. The classified product from cone crushing presented low packing density and mortars were characterized by the highest porosities, absorptivities and lowest unconfined compressive strength, probably mostly due to its poor particle shapes. Modeling of the stress–strain response with scalar damage mechanics showed that manufactured aggregate produced from classification of the cone crusher yielded a mortar with highly inelastic deformation response, whereas mortars produced from unclassified product of impact crushing showed more elastic deformation response. Results were also analyzed in light of de Larrard's Compressible Packing Model.

Keywords: Aggregate; Mortar; Mechanical properties

1. Introduction

Aggregates have a significant influence on both rheological and mechanical properties of mortars and concrete. Their specific gravity, particle size distribution, shape and surface texture influence markedly the properties of mortars and concrete in the fresh state. On the other hand, the mineralogical composition, toughness, elastic modulus and degree of alteration of aggregates are generally found to affect the properties of mortars and concrete in the hardened state [1].

In an attempt to explain variations in mixing water requirements, Wills [2] investigated the effect of particle shape of both fine and coarse aggregates on water demand on concrete. He found that the shape of the fine aggregate has a more significant impact on water demand than the shape of the coarse aggregate. Further, within the permitted standard limits, the particle size distribution of the fine aggregate was found to have a greater influence in the properties of concrete than that of the coarse aggregate [3]. As a result, the choice of the appropriate type of fine aggregate for a given application is of primary importance as far as properties of mortars and concrete are concerned.

In Brazil, natural fine aggregates have been traditionally used in mortars and concrete. However, growing environmental restrictions to the exploitation of sand from riverbeds have resulted in a search for alternative materials to produce fine aggregates, particularly near the larger metropolitan areas. Manufactured fine aggregates (MFA) then appear as an attractive alternative to natural fine aggregates for cement mortars and concrete.

The type of process and feed material will influence directly grading, shape [4], surface texture and even integrity [5] of the

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aggregate manufactured by crushing, and thus its performance in mortars and concrete. Among the various size reduction machines used in MFA production, cone and impact crushers are the most common.

Impact crushers of various types have been employed in MFA production, in particular vertical shaft impactors [6]. Comminution in this type of crusher is the result of propelling particles with a rotor moving at high speeds, against an anvil or a curtain of falling particles. Such loading conditions leads to a higher probability of fracture of either weak or flaky particles, with fracture occurring by cleavage, with a marked contribution from surface attrition. The result is that particles with greater integrity and more isometric shapes are produced by this crushing process in comparison to other comminution machines, such as cone, jaw and roll crushers. In the case of cone crushers, particle fracture depends on loading condition [7]. Under starve–fed conditions, particles are crushed from direct contact with the crusher plates (low coordination number), resulting in their breakage by cleavage alone and in a way that is irrespective of particle shape and strength, leaving particles of highly irregular shapes and moderate integrity in the product. Under choke–fed conditions, particles are crushed predominantly by interparticle forces (high coordination number) [7], through a combination of cleavage and attrition, so that shape and integrity of particles in the product are intermediate in comparison to those produced in impact crushers and cone crushers operating under starve–fed conditions.

Besides particle shape, crushing processes also influence grading of the MFA, and the proportion of microfines (minus 75 μm material), particularly when compared to natural fine aggregates. This proportion of non-deleterious microfines, however, may be controlled not only by setting the appropriate crushing conditions, but also by using appropriate size classification processes. As a result, the application of crushing and classification processes to a given rock type potentially enables reaching grading curves and particle shapes that vary significantly, meeting almost any desired specification.

A number of studies have dealt with the influence of both grading and particle shape of the fine aggregate in mortars and concrete. At a given water/cement ratio, it has been found that concrete made with MFA (with up to 7% microfines) achieved compressive strength equal to or higher than concrete made with natural sand [8], reducing the void content of the aggregate, thereby lubricating the aggregate system without increasing the water requirement of the mixture [9]. In a comprehensive investigation of MFAs of various rock types [6] produced in vertical impact crushers, it was observed that, for a fixed flow, the greater the content in microfines, the greater the water/cement ratios required, and that increasing fineness modulus, flow and compressive strength increased. However, no studies were found that compared in great enough detail the performance in mortars of MFA produced in different crushing and size classification routes.

The present paper analyzes the performance of manufactured fine aggregates produced by different crushers and containing different amounts of microfines in mortars, comparing them to natural fine aggregates. These mortars are analyzed in both fresh and hardened states in light of de Larrard's compressible packing model [10]. Differences in load-deformation response and the appearance of strain softening in compression testing of mortars were analyzed with the aid of a model based on scalar continuum damage mechanics.

2. Experimental

The rock used in the present work to produce the manufactured fine aggregate is classified petrologically as granulite and its mineralogical composition consists of alkaline feldspars (32%), plagioclase (21%), quartz (15%), hyperstene (15%) and hornblende (12%). Biotite is present only in very small amount (3%).

All minerals are present, on average, in medium to coarse grains (>1 mm). The rock structure is classified as isotropic and free of foliations and its degree of alteration is very limited. It is, however, characterized by the presence of internal fractures that are within the scale of individual mineral grains (Fig. 1).

The specific gravity of the rock was measured as 2.77 g/cm^3, determined by pycnometry.

The rock was crushed with two alternative processes: using cone crushers in an industrial plant or by using a pilot-scale vertical shaft impactor (VSI), both operating in closed circuit with vibrating screens. The cone crushers used in multiple stages in the industrial plant are hydrocones, models H4000 and H3000, while the pilot-plant VSI is a BARMAC® 3000, all manufactured by Svedala Inc. The crushing actions of these two types of comminution equipment are very different, as discussed in the Introduction.

Additionally, the products of each of these crushing circuits were either used as produced or were subjected to size classification in a pilot-plant dynamic rotor (air) classifier, in order to partially remove the microfines.

In order to compare the behavior of the crushed fine aggregate to standard natural fine aggregate, a natural riverbed sand, composed mainly of quartz, was used in control tests throughout the investigation. The sample had been previously

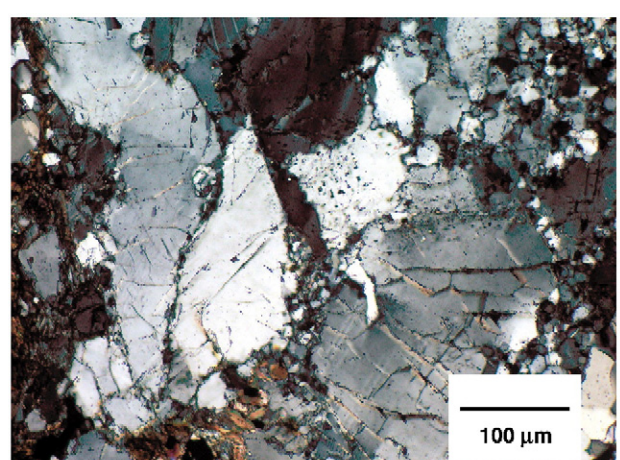

Fig. 1. Micrograph of the granulite rock, inspected under crossed nicols.

Table 1
Designation of the fine aggregate samples investigated

Type of fine aggregate	Crusher type	Classification	Designation
Natural	–	Yes	NFA
Manufactured	Impact	No	MFA-IC-U
Manufactured	Impact	Yes	MFA-IC-C
Manufactured	Cone	No	MFA-CC-U
Manufactured	Cone	Yes	MFA-CC-C

classified using wet processes in order to remove the deleterious material below about 75 μm.

A total of five samples have been used to prepare mortars and were tested both in fresh and hardened states. A summary of the identification of these samples is given in Table 1.

Samples of the fine aggregates were characterized in respect to particle size distribution (grading) with sieve analysis by washing, with a RO-TAP® shaker. Particle shape was characterized by direct inspection of narrow size particles of the various materials tested with an optical microscope, followed by image analysis. After image capture and treatment (filtering, segmentation), different characteristic dimensions of a number of particles were determined for over 150 images for each sample. Two parameters were measured from the two-dimensional images [11]: the aspect ratio describes the ratio between the length and the width of each particle, and the sphericity is given by:

$$\text{Sphericity} = \frac{4\,.\pi\,.\text{Projected area of the particle}}{\text{Perimeter}^2} \quad (1)$$

For the case of a spherical particle, both measures are equal to one, whereas for irregularly-shaped particles the sphericity is smaller than one and the aspect ratio is larger.

Measurements of the (virtual) packing density of the fine aggregate samples were carried out from the ratio of the volume of solids to the volume of a cylinder after vibration and pressing with 10 kPa. The packing density of cement grains was measured by the water demand test, which consists of determining, for a given mass of cement, the mass of water that fill the voids between the cement grains, thus creating a smooth paste [10].

A constant fine aggregate/cement ratio of 1.5:1 (in weight) was used throughout the study to prepare the cement mortars. Water/cement (W/C) ratios (in weight) were 0.4 and 0.5 and a planetary mixer was used to prepare the pastes.

Workability of the cement mortars was assessed with the aid of the flow table, by measuring the diameter of the spread material, following the Brazilian standard NBR 13276.

Stress–strain relationships for the mixtures under uniaxial compression were determined after 28 days of age, through measurements on four cylindrical specimens measuring 50 mm of diameter and 100 mm of length. Samples were tested using a universal testing machine (Shimadzu®), with displacement control, at a rate of 0.01 mm/min. Test data were continuously recorded with a microcomputer. Displacements were measured using two LVDT transducers, and an average value was used in the computations. The elastic (secant) Young modulus was estimated from the values at 40% of critical stresses, according to ASTM C469-02.

Table 2
Summary of the characteristics of the fine aggregate samples tested

Sample	Particle size distribution		Virtual packing density	Particle shape	
	%<75 μm	Fineness modulus		Sphericity [a]	Aspect ratio [a]
NFA	0.5	3.02	0.59	0.723	1.408
MFA-IC-U	14.5	2.45	0.74	0.706	1.460
MFA-IC-C	1.6	3.40	0.74	0.706	1.460
MFA-CC-U	17.7	2.57	0.61	0.664	1.534
MFA-CC-C	4.8	3.32	0.60	0.664	1.534

[a] Mean values for selected size fractions.

The total porosity of the mortar sample in the hardened state was estimated from the ratio between the weight of the test sample after curing in an oven at 105 °C until reaching constant weight, followed by saturation of the sample by immersion in water for 72 h, according to ASTM C642-97. This allowed to determine the fraction of the pore volume accessible to water in the mortar.

Capillary absorption tests were conducted following ASTM C1585-04. The test allows the assessment of the rate of water penetration by capillary suction, by monitoring the gain in weight as a function of time.

3. Results and discussion

3.1. Fine aggregates characteristics

A summary of the characteristics of the samples is given in Table 2. The proportion of fines (−75 μm) varied from 0.5% to as high as 18%. Fig. 2 compares the size distributions of the fine aggregates used in the experimental work. Table 2 shows that air classification of the crushed products results in an increase in the fineness modulus. Value of fineness modulus of the natural aggregate was found to be intermediate among the values encountered for unclassified and classified MFA samples.

In respect to particle shape, inspections on the microscope allowed to classify, qualitatively, the natural aggregate (NFA) as predominantly subrounded, the product of impact crushing (MFA-IC) as subangular, and the product of cone crushing (MFA-CC) as angular, according to Popovics [12]. A quantitative

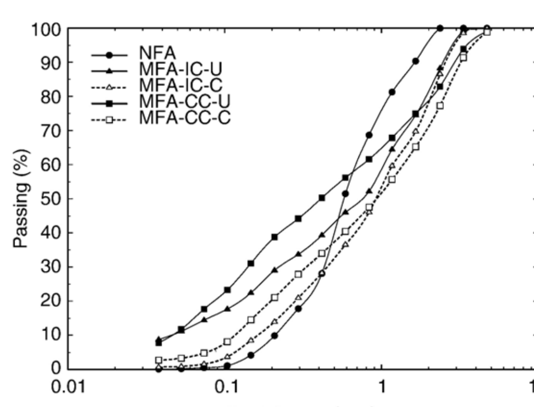

Fig. 2. Particle size distributions of fine aggregates tested.

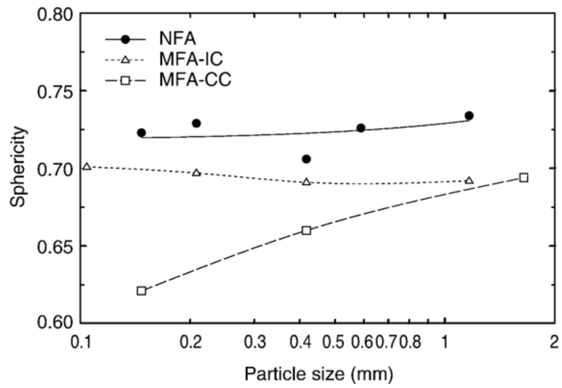

Fig. 3. Effect of particle size on sphericity of the fine aggregates tested.

assessment of particle shape is given in Table 2, which shows that the aggregate produced by cone crushing presented more irregular shapes, evident from the lower mean values of sphericity and high aspect ratios. In the case of the impact-crushed material, it was found that both sphericity and aspect ratio were intermediate between values found for natural sand and the cone-crusher product.

Particle shape of crushed materials is often found to vary with particle size. Figs. 3 and 4 show the variation of the sphericity and aspect ratio with particle size for the different fine aggregates, respectively. Fig. 3 shows that sphericity of cone-crushed material decreased with particle size, whereas sphericity of natural aggregate and impact-crushed material remained relatively constant. In the case of the aspect ratio (Fig. 4), an increase – although modest – is observed for both manufactured fine aggregates as particle size decreased.

3.2. Consistency and durability of the mortars

Data in Table 3 show that, for a W/C ratio of 0.5, all mortars present nearly the same workability (similar consistency values measured using a flow table), regardless of particle shape or grading, when the experimental error of the test (about ±10 mm) is considered. For the lower W/C ratio (0.4), mortars prepared with natural aggregate present better workability than those prepared from manufactured fine aggregates. The most significant difference is found when the consistency index of the mortar mixture prepared from the unclassified cone crusher product (MFA-CC-U) is compared to the one prepared using natural sand (NFA), corresponding to a reduction in 14%. For the mixture MFA-IC-U the consistency is reduced only by 6%, indicating the direct influence of the particle shape. The same trend was found for the manufactured aggregates that contained a greater proportion of microfines (MFA-CC-C and MFA-IC-C), although in a smaller magnitude (8% and 4%, respectively), which demonstrates the influence of content of fines as well.

Table 3
Summary of measures of consistency and durability of the mortar mixtures (mean values, with coefficient of variation in parentheses)

Mixture characteristics: Fine aggregate	Mixture characteristics: W/C	ϕ^w	Consistency index (mm)	Total porosity (%)	Absorptivity (g/cm^2 h$^{1/2}$)
NFA	0.4	0.65	255	10.1 (1.0)	0.089 (3.7)
	0.5	0.62	300	12.9 (1.8)	0.216 (2.7)
MFA-IC-U	0.4	0.67	240	9.2 (2.7)	0.064 (5.3)
	0.5	0.62	280	11.2 (1.3)	0.165 (5.8)
MFA-IC-C	0.4	0.68	245	10.6 (1.9)	0.106 (3.1)
	0.5	0.62	290	12.8 (0.9)	0.234 (4.5)
MFA-CC-U	0.4	0.60	220	10.1 (1.1)	0.080 (6.9)
	0.5	0.60	290	13.0 (1.5)	0.157 (5.9)
MFA-CC-C	0.4	0.63	235	11.0 (1.4)	0.122 (3.8)
	0.5	0.62	300	13.4 (1.2)	0.253 (2.5)

It is known that the rheology, and thus the workability of mortars, is codetermined by the amount of liquid phase and by characteristics of the solid phase, being the lubricating effect mainly associated to the liquid phase whereas the rolling effect can be linked to solid characteristics such as packing and particle shape [1]. The greater relative contribution expected from the solid phase at lower W/C ratios is consistent with the significant effect of type of crusher used to produce the fine aggregate, and thus of particle shape, that is observed in the present study (Table 3). On the other hand, the smaller relative contribution of the solid phase at higher W/C ratios probably explains the less pronounced influence of the fine aggregate characteristics on the workability of the mortar mixtures, also observed in the present study.

Absorptivity and porosity of the cement mortars have also been measured, with results presented in Figs. 5 and 6 and a

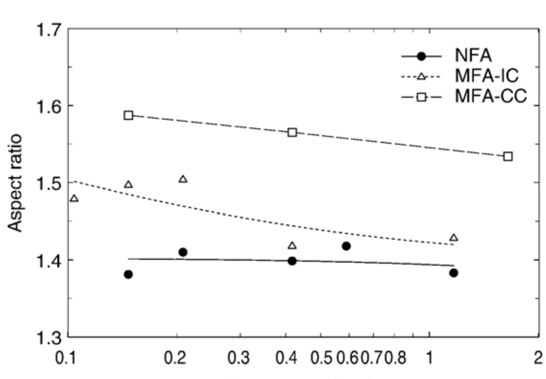

Fig. 4. Effect of particle size on aspect ratio of fine aggregates tested.

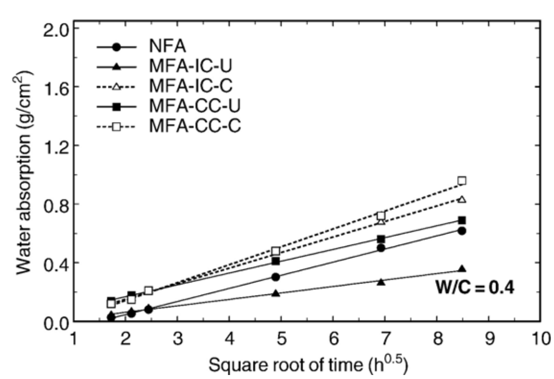

Fig. 5. Cumulative gain of water weight as a function of the square root of time for mortars tested at $W/C = 0.4$.

summary in Table 3. Absorptivity is estimated from the slope of the line that relates the gain in water weight and the square root of the exposure time.

In Fig. 7 porosity is plotted against absorptivity. As observed in the literature for several porous building materials, including concrete and mortars [13], a power–law may be used to relate absorptivity and porosity, which is demonstrated using the data in the present study as well. Indeed, whereas an increase with absorptivity with a power of 2.6 has been observed for clay bricks [13], data in the present study are well described by a power of 3.5.

Data in Table 3 show that all mortars containing unclassified manufactured fine aggregate present lower absorptivity than the one produced with natural sand, which, in turn, presents marginally lower absorptivity than the mortar mixtures where most of the microfines were removed by classification (MFA-IC-C and MFA-CC-C).

For the lower W/C ratio studied the absorptivity of mortar mixtures prepared using the unclassified product of impact crushing (MFA-IC-U) is significantly lower (by about 28%) than that measured for the natural sand mortar (NFA), whereas for the mixture MFA-CC-U the absorptivity is reduced only by 11%, indicating the influence of particle shape. Such difference in respect to the type of crusher used in preparing the aggregate (not classified) is not observed for the mixtures with W/C ratio of 0.5, in spite of the different porosities of the mixtures (see Table 3). Regarding the mortars prepared using the classified manufactured aggregates, the one produced using cone-crushed material presents slightly higher absorptivity than the one produced using material crushed by impact, in both W/C ratios investigated.

Attempts have been made to correlate porosity with particle shape and packing density of the fine aggregates, but correlations were reasonably weak. In fact, the porosity is influenced by the packing characteristics of the entire mixture that includes fine aggregate, cement and water. A model that is capable of describing very accurately the packing characteristics of mixtures is briefly reviewed as follows.

3.3. Characterization of the grain mixtures: packing density

The Compressible Packing Model — CPM [10] has been used to characterize the packing density of the grain mixtures. Within the framework of this model, a grain category i is classified by its mean diameter d_i. Its virtual packing density (β_i) is defined as the volume of grains contained in a unit volume, compacted with an ideal compaction energy that would correspond to a maximum virtual packing. It represents the intrinsic capacity of a category of grains to pack. The virtual packing density of a mixture of n categories of grains is denoted φ, and may be obtained by a model that has as input $\beta_i, i=1, n$, the volumetric fraction of the several categories, and some constants that take into account loosening effects and wall effects induced by the interaction between the particles.

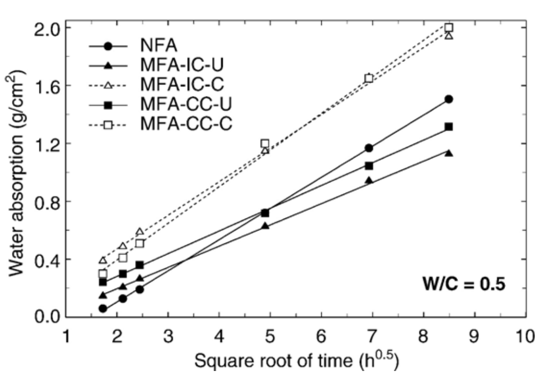

Fig. 6. Cumulative gain of water weight as a function of the square root of time for mortars tested at $W/C=0.5$.

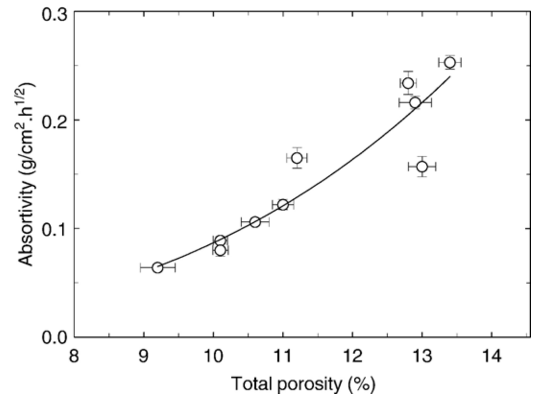

Fig. 7. Relationship between total porosity and absorptivity (error bars represent standard deviations of the measurements). Solid line indicates power–law fitting of the data.

The actual packing density (ϕ) depends on the intrinsic capacity of the grain mixture to pack (φ), and the method of processing the packing. The CPM allows making the transition from virtual packing density to the actual packing density by using a scalar K, called compaction index, that makes the link between φ and ϕ. This scalar is strictly dependent on the packing protocol, in such a way that as K tends to infinity, ϕ tends to φ. Some typical values of K are: 4.5 for the simple pouring; 6.7 for mixing with water (water demand test [14]); 9.0 for vibration plus 10 kPa compression. When water is added to the dry mix, the wet packing density (ϕ^{w}) can be calculated by Eq. (2):

$$\begin{aligned} &\text{for } W < \phi \quad \phi^{\mathrm{w}} = \phi \\ &\text{for } W \geq \phi \quad \phi^{\mathrm{w}} = 1 - W \end{aligned} \tag{2}$$

where W is the water content of the mixture.

The CPM encompasses several sub-models to determine the properties of fresh and hardening concrete. In what concerns the compressive strength, the prediction formula is based on proportionality relationship given by [10]:

$$f_{\mathrm{c}} \propto \left(\frac{v_{\mathrm{c}}}{v_{\mathrm{c}} + v_{\mathrm{w}} + v_{\mathrm{a}}}\right)\left(\frac{\mathrm{MPT}}{A}\right)^{-0.13} \tag{3}$$

where v_{c}, v_{w} and v_{a} are the volumes of cement, water and air, respectively, $A=1$ mm is a constant, and MPT stands for the maximum paste thickness, i.e., the largest gap that exists between two aggregate particles [10].

The virtual packing density (φ) of the fine aggregates and of the cement, as well as the wet packing density of the mixtures

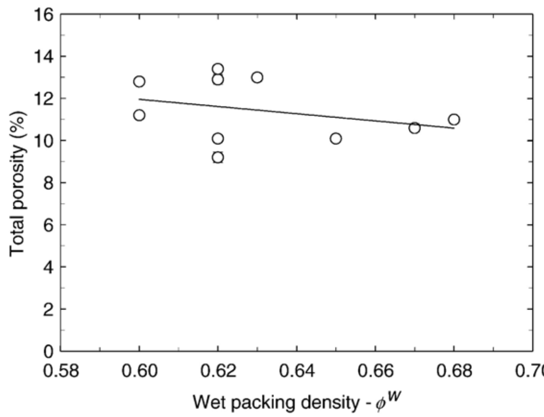

Fig. 8. Relationship between wet packing density and total porosity.

(ϕ^w), were determined within the framework of CPM, and the values are presented in Tables 2 and 3, respectively. The virtual packing density was found to be higher for MFA samples produced by the impact crusher, being also marginally higher for unclassified samples.

At first, comparisons have been made between the sphericity and aspect ratio and the virtual packing density of the fine aggregates, with no direct correlation being identified. The reason is that the virtual packing density is a parameter that encompasses the effects of both grading and particle shape, whereas the sphericity and the aspect ratio concern only the shape of the particles.

Fig. 8 shows the relationship between total porosity and the wet packing density (ϕ^w). Although a great deal of scatter exists, the trend line indicates that total porosity decreases with an increase in wet packing density. This suggests that the combination of sand grading and shape, sand/cement ratio and W/C ratio that maximizing ϕ^w, for a given required workability, will lead to minimum porosity and absorptivity, and thus maximum durability.

3.4. Stress–strain relationships

Typical stress–strain relationships for the mortar mixtures tested are presented in Figs. 9 and 10, with a summary of the results shown in Table 4.

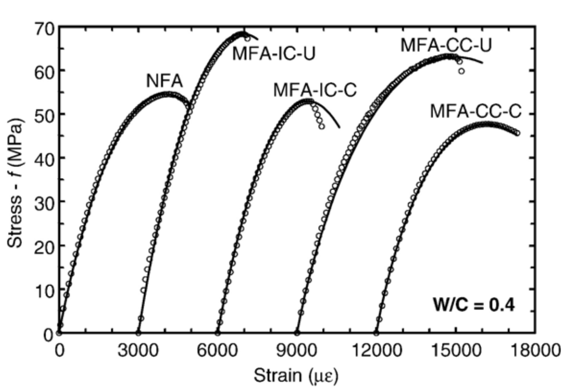

Fig. 9. Typical stress–strain relationships for mortars tested at W/C=0.4. Experimental data represented with symbols and fitted results to Eq. (5) with lines (all tests start from zero strain).

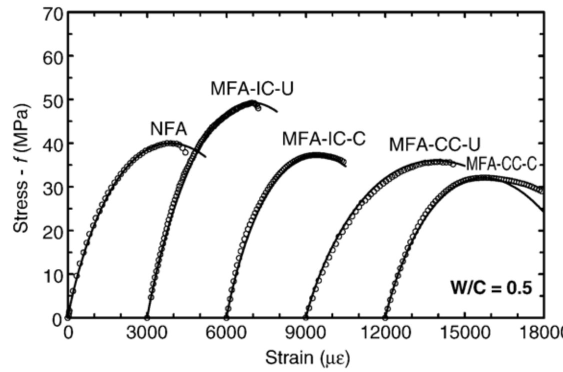

Fig. 10. Typical stress–strain relationships for mortars tested at W/C=0.5. Experimental data represented with symbols and fitted results to Eq. (5) with lines (all tests start from zero strain).

The increase in W/C ratio from 0.4 to 0.5 resulted in a reduction of the compressive strength for all mixtures investigated in the order of 30%. This reduction was lower for the case of mortar mixtures using NFA, being equal to 26%, and higher for mortar mixtures using MFA produced using cone crushers and classified (32%). The replacement of NFA by MFA was found to be beneficial only in the case of the unclassified product and, at water/cement ratio of 0.5, only for the material produced using impact crushing.

In the case of manufactured fine aggregates produced by both crushing methods (cone and impact), a significant reduction in strength was observed after partial removal of microfines by classification. This is attributed to the reduction in packing capacity of the mixtures and the increase in fineness modulus, which may have produced a larger interface zone between paste and aggregate. Of particular interest is the high strength of mortars produced from unclassified MFA produced in the impact crusher (MFA-IC-U in Table 4), which demonstrates the significance of the presence of non-deleterious microfines and appropriate particle shape in developing mortar strength.

Statistical analyses of variance confirmed the significance (at 95% confidence) of the effects of both W/C ratio and type of

Table 4
Summary of measures from strain–stress compression curves (mean values, with coefficient of variation in parentheses and given in %)

Mixture characteristics		f_c (MPa)	E (GPa)	Peak ε_c (με)	D_o (–)	D_c (–)
Fine aggregate	W/C					
NFA-C	0.4	55.1 (0.7)	26.6 (1.2)	3778 (5.2)	0.101	0.507
MFA-IC-U	0.4	67.9 (1.5)	28.0 (2.1)	4050 (6.0)	0.092	0.456
MFA-IC-C	0.4	52.0 (1.5)	26.0 (5.1)	3884 (8.0)	0.106	0.540
MFA-CC-U	0.4	58.5 (4.8)	25.0 (3.7)	4237 (9.1)	0.101	0.503
MFA-CC-C	0.4	47.5 (4.5)	24.8 (2.5)	4138 (3.1)	0.110	0.588
NFA-C	0.5	40.9 (2.4)	24.6 (1.5)	3661 (18.0)	0.129	0.604
MFA-IC-U	0.5	49.8 (3.3)	27.7 (7.1)	4028 (5.2)	0.112	0.603
MFA-IC-C	0.5	37.2 (3.8)	25.0 (4.3)	3732 (6.3)	0.128	0.652
MFA-CC-U	0.5	36.2 (1.4)	24.1 (0.3)	4152 (14.0)	0.130	0.685
MFA-CC-C	0.5	32.5 (1.7)	22.6 (5.6)	3822 (3.7)	0.134	0.674

fine aggregate used, as well as their interaction, on the uniaxial compressive strength of the mortars studied.

In Fig. 11 the values of the compressive strength are compared to the second term of Eq. (6) from the Compressive Packing Model. The linear trend line indicates that the proportionality assumed by the model is reproduced by the experimental values and is not only valid for concrete but also for mortars.

The influence of type of fine aggregate and *W*/*C* ratio on the deformation at peak stress ε_c (Table 4) was also analyzed statistically. It was found that deformation at peak stress was only influenced by the type of aggregate used and not by the water–cement ratio, and no interaction effects between type of fine aggregate and *W*/*C* ratio were evident at 95% certainty. Indeed, the relatively constant values of deformation at peak stress are due to the compensating effects of reduction of compressive strength and modulus of elasticity with the increase in water–cement ratio.

Table 4 also shows the influence of *W*/*C* ratio and type of fine aggregate on the elastic (secant) modulus. Statistically significant differences (at 95% confidence) were observed in respect to the influence of *W*/*C* ratio and type of fine aggregate used in the mortar, with no interaction between the two. This shows that the type of aggregate used has the same influence on the modulus of elasticity, independent of *W*/*C* ratio.

In general, an increase in *W*/*C* ratio results in a decrease in the elastic modulus, but such reduction was found to be very limited, particularly for mortars prepared from unclassified cone-crushed and impact-crushed material. Mortars prepared from unclassified impact-crushed (MFA-IC-U) material were found to respond more rigidly (higher elastic moduli) to the applied loads than all other mortars studied. In contrast to that, mortars prepared using classified cone-crushed (MFA-CC-C) material presented the lowest values of elastic modulus when compared to all mortars studied.

Figs. 9 and 10 show that not only the deformation response in the initial stage of loading (used to calculate the secant modulus of elasticity), but the entire stress–strain curves are influenced by the type of fine aggregate used. Indeed, they show

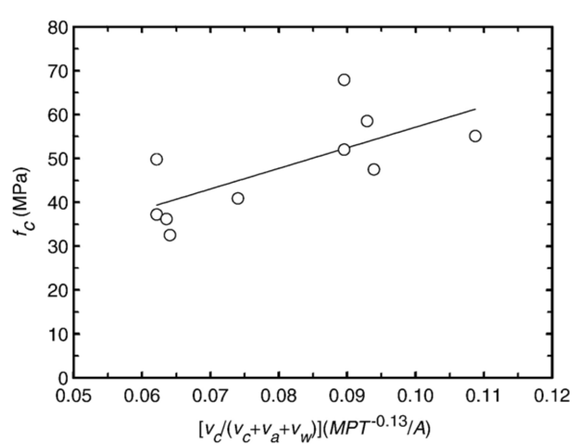

Fig. 11. Relationship between compressive strength and $(v_c/(v_c+v_a+v_w))$ $(\mathrm{MPT}^{-0.13}/A)$.

that different degrees of strain softening are found for the different cement mortars. In order to quantitatively describe that, a more detailed analysis of the experimental data may be possible by using elements from continuum damage mechanics.

Loland proposed a model, based on damage mechanics, that describes strain–stress relationships that has been applied successfully to concrete under tensile [15] and unconfined compressive stresses [16]. Damage mechanics [17] combines the strain–stress relationship from linear elasticity with the definition of an effective elastic modulus $[(1-D)E^*]$ in the constitutive equation

$$f = (1-D)E^*\varepsilon \tag{4}$$

where E^* is the modulus of elasticity of the material in a state free of voids or cracks (undamaged and intact), D is the scalar damage variable, f are stresses and ε strains. Loland [15] proposed that the damage variable may be related to strain by a power–law relationship

$$D = D_o + A_o\,\varepsilon^{\gamma} \tag{5}$$

where D_o is the initial damage at the onset of the unconfined compression test, and A_o and γ are empirical constants for the material. This initial damage has been considered by Loland [15] for the case of concrete, to be essentially due (and therefore equivalent) to initial porosity. It also may be related to the nominal modulus of elasticity (the ordinary Young's modulus E) calculated from the linear part of the actual stress–strain relationship by

$$E = E^*(1-D_o) \tag{6}$$

Replacing Eqs. (6) and (5) in Eq. (4), it gives [16]

$$f = (E - E^*A_o\varepsilon^{\gamma})\varepsilon \tag{7}$$

From the derivative of Eq. (4) equal to zero and the definitions of maximum stress f_c and the corresponding deformation at peak stress ε_c, Eq. (7) may be rewritten as

$$f = \left[1 - \left(\frac{\varepsilon}{\varepsilon_c}\right)^{\gamma}\frac{1}{1+\gamma}\right]E\,\varepsilon \tag{8}$$

The critical amount of damage D_c, which corresponds to maximum stresses, may be given by

$$D_c = 1 - \frac{f_c}{E^*\varepsilon_c} \tag{9}$$

from which the constant γ, required to calculate the stress–strain relationship Eq. (8) is given by

$$\gamma = \frac{1-D_o}{D_c-D_o} - 1 \tag{10}$$

Figs. 9 and 10 compare measured stress–strain relationships to estimates using Eq. (8) from selected experiments. It shows that the equation offers a good fit to the data up to the point of maximum compressive stress. At this point, called damage localization [17], continuum damage mechanics considers that accrual of damage no longer results from the growth of a network of cracks, but rather to their coalescence into a macrocrack, that leads to the failure of the solid [17].

If the initial porosity is considered as the initial damage (D_o) value for the mortar, then MFA-IC-U presents the lowest initial damage, with classification increasing the amount of initial damage (Table 3). MFA-CC samples presented higher initial damage values.

Table 4 shows that not only the initial damage (D_o), but also the critical damage (D_c) increases with the *W*/*C* ratio. Data in Table 4 can also be used to demonstrate that the critical damage has a very well-defined inverse relationship with the compressive strength, so that the same combination of sand type and *W*/*C* ratio responsible for increasing the compressive strengths also lead to less pronounced strain-softening. Such inverse relationship between compressive strength and nonlinear response in the strain–stress curve is also found when comparing conventional to high-performance concretes. Among the various fine aggregates tested, the unclassified impact-crushed material (MFA-IC-U) yielded mortar mixtures with the lowest critical damage, for both *W*/*C* ratios studied. In fact, the mortar prepared from this aggregate at a *W*/*C* ratio of 0.4 was the one that presented the more elastic deformation and brittle fracture response and, thus, the less pronounced strain-softening response. At the lower *W*/*C* ratio, the mortar that showed the most gradual damage accumulation – and therefore the most inelastic and strain softening response – was the classified cone crusher product.

The critical amount of damage D_c may be used to offer an indication on the integrity of the concrete or mortar just at the point of maximum stress. Therefore, given the close relationship between the internal porosity of mortars and concrete and their water absorption and permeability (and thus their susceptibility to the action of aggressive gases, liquids and ions from damaging the paste and reinforcement) the critical damage is a valuable measure that should correlate well with the expected durability of mortars and concrete under severe loading conditions. In this case, the use of unclassified impact crusher product should lead to significantly longer durability of the mortar than when all other manufactured and natural aggregates studied in the present work are used.

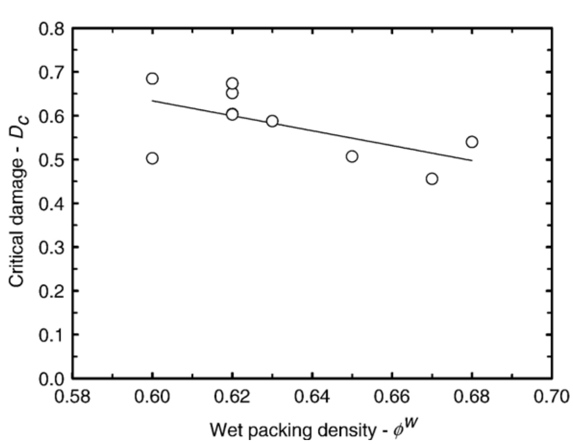

Fig. 12. Relationship between wet packing density and critical damage.

Fig. 12 compares the wet packing density to critical damage during compressive loading. The trend found is such that lower values of the critical damage variable are found with increasing packing densities.

4. Conclusions

Analyses of the fine aggregate samples allowed to conclude that particles produced by impact crushing presented intermediate values of sphericity and aspect ratio when compared to the natural fine aggregate and cone-crushed material, with the latter found to produce the flakiest material. Particle shape was also found to vary with particle size, with flakiness increasing as size decreased for cone-crushed material, to a lesser extent also to impact-crushed material, being approximately independent of size for the natural aggregate.

Analyses of cement mortars prepared from the fine aggregate samples allowed to conclude that:

- Consistency was found to be relatively independent of fine aggregate characteristics for the *W*/*C* ratio of 0.5. However, for the higher fraction of solids in the mortar mixture (*W*/*C*=0.4), the influences of both particle shape and grading (proportion of microfines) become evident.
- Porosities and absorptivities were found to be correlated by a power–law relationship and were consistently lower for fine aggregates produced by impact crushing and also for those containing large proportions of microfines (unclassified).
- The packing density, calculated from de Larrard's compressive packing model, was found to exhibit some correlation with porosity of the mortars, independently of particle shape and grading of the fine aggregate, demonstrating that it represents a primary property.
- The results indicate that characteristics of the mortars such as compressive strength and absorptivity – which can be considered secondary or dependent properties – are governed by the packing density of the mixture independently of grading and particle shape of the sand used.
- Loland's scalar continuum damage model has been capable of appropriately describing measured strain–stress relationships from unconfined compression tests up to peak stress.
- The critical damage, and thus the degree of nonlinearity in the stress–strain relationship, presented an inverse relationship with compressive strength.
- The most significant results obtained for the manufactured aggregates studied in comparison to natural fine aggregate were found by using fine aggregate produced using the impact crusher and containing 14.5% microfines. It allowed, with nearly no change in workability, to produce a cement mortar with 28% lower absorptivity and 23% higher strength, and a significantly more inelastic deformation response, than the one prepared using natural sand at the same *W*/*C* ratio of 0.4.

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