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Influence of very fine fraction of mixed recycled aggregates on the mechanical properties and durability of mortars and concretes

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Influencia de la fracción muy fina de áridos reciclados mixtos en las propiedades mecánicas y durabilidad de morteros y hormigones

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ABSTRACT: Recycled aggregates from mixed recycled wastes have a high content of particles with size under 63 µm. This material is generally considered undesirable, since it increases water demand. However, these fines could fill out gaps between cement grains and increase packing density. The present work assesses the influence of fines under 63 µm on mortar and concrete made with mixed recycled aggregates. Pozzolanic activity of the powder, measured by isothermal calorimetry proves to be very low, so the material acts basically as a filler. Mortars with 6% of this fine material have a higher water demand, and thus a reduced compressive strength. However, the fine material contributes to decrease the effective porosity and increases the density of the matrix. This effect could help improving durability of the cementitious matrix. Alkalis tests carried out on mortars having 6% of fines under 63 µm show that expansion is reduced, and the probable cause is the refinement of the pore structure through the increased packing density. Observations of polished section of concrete having 6% of fines under 63 µm made with at SEM, coupled with image processing, show a densification of the ITZ around the aggregates, possibly due to the contribution of the very fine fraction to packing density. The beneficial contribution of the very fine fraction could compensate problems with rheology and mechanical properties assessed in mortars and concrete.

RESUMEN: La producción de áridos de residuos mixtos reciclados genera un elevado contenido de partículas por debajo de 63 µm. Este material puede ocasionar un incremento de la demanda de agua, sin embargo, pueden contribuir a rellenar espacios entre los granos de cemento. El presente trabajo evalúa la influencia del material por debajo 63 µm de áridos reciclados mixtos en las propiedades de hormigones y morteros. La actividad puzolánica medida por calorimetría isotérmica fue muy baja. El uso del 6% del material en morteros incrementa la demanda de agua, ocasiona una reducción de la resistencia, pero disminuye la porosidad efectiva de la matriz e incrementa la densidad de la ITZ. Los ensayos de expansión por álcalis en morteros mostraron una reducción de la porosidad conectada de la matriz. La misma tendencia fue observada en el hormigón. La contribución beneficiosa de dicha fracción puede compensar los problemas en la reología y en las propiedades mecánicas.

1. Introduction

Construction and demolition wastes (CDW) are an environmental problem, which represents a high percent of the total wastes generated by the society [1, 2]. Every year around 850 millions ton of construction and demolition waste are generated in the European Union that represents 31% of the total generated wastes in this region [3, 4].

The studies on the use of recycled aggregates from CDW have mostly focused on their coarse fraction and ignored the fine fraction. Research on the use of the fine fraction of construction and demolition waste in mortars (unlike concrete) is still rather restricted, beyond the scope of refereed international journals. This is basically because the extreme porosity of fine recycled materials and consequently their lower density and higher water

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absorption, leads to reduction in the concrete performance [5-7].

A great quantity of very fine material under 63 μm, is generated during the manufacturing process of mixed recycled aggregates, is advisable to eliminate through washing. This fine material is mainly composed of wastes of mortar and cement pastes adhered to the grains of the recycled material. Also in some cases, it could be red powder of ceramic bricks, plaster or other materials. The mortar adhered to the grains causes low density, high absorption and increases the presence of sulphates, which has negative influence on the concrete properties [8].

The presence of fines under 63 μm brings about an increase of the water demand of the material, which is reflected in a moderate decrease of the mechanical strength. Concrete elaborated with 25% and 100% of fine recycled aggregates presents a reduction of the 15-30% of the compressive strength [9-11]. In mortars, however, there is no consensus in the literature concerning compressive and flexural strength, since some studies led to higher values in mortars with recycled aggregates and vice versa [5]. According to [6], compressive strength decreased with an increase in the replacement ratio of the fine fraction. When the replacement ratio reached 100%, the compressive strength of the mortar at 28 days was approximately 33% lower than that of the original samples and all specimens with over 60% of fine natural aggregate replacement presented a significant drop in compressive strength.

However, these small particles could fill in gaps between cement grains, and through this contributing to improve the packing density of the cementitious matrix, which indirectly could reduce the water absorption and the connected porosity in hardened state [12]. These fine grains could also contribute to increase the packing density of the recycled aggregate-paste Interfacial Transition Zone, ITZ, therefore, it could reduce locally the relationship water/cement in the ITZ, and decrease circulation of liquid by percolation [12, 13].

The contribution of the very fine particles depends on their chemical and mineralogical composition as well as of their fineness. Very fine particles, resultant of the crushing of calcined clay wastes, could have pozzolanic properties, thus, they could contribute to the mechanical strength and the refinement of the pores structure of the matrix [14, 15].Fine ceramics are among the ones on which greater emphasis has been laid essentially due to their potential pozzolanic properties. Many studies demonstrated the contribution of the fines particles on the properties of the matrix [16].

This fine material can also improve the compactness of mortars due to a filler effect and it presents advantages in terms of rheology. Being a highly capillary material, it enhances the mortar's water absorption, but its water retention may also increase its capacity to fully hydrate the cement [16]. If these particles appear in a coarser form in presence of alkalis (given by the cement), expansion processes can take place, and the durability of the cementitious matrix could be compromised [17-20].

On the other hand, it is accepted that the fine particles of recycled aggregates may contain some non-hydrated cement that gives them binding properties. The filler effect is also expected to compensate characteristics that could be jeopardized by the high water absorption of these particles [6].

In addition, it is well established that aggregates with greater porosity and surface area per volume unit absorb more water and therefore, they make the resulting mortar more consistent. Other authors observed that mortars made with recycled aggregate consumed 75% more water than that made with sand [5, 16].

Furthermore, some researchers studied the influence of recycled ceramic fines on the reduction of 30% of cement content compared with conventional mortars. They observed in their studies that the results from tests on mortars with a reduced cement content (from a volumetric ratio cement: aggregate of 1:4–1:5 and 1:6) were acceptable. Also demonstrated the potential of the filler effect of ceramic fines and the viability of replacing natural sand by fine ceramic waste, but maintaining the aggregate's size distribution [6].

In terms of water absorption by capillary action, replacing sand by recycled aggregate led to a decrease of 20% to 30% in absorption by capillary action of the mortars made with recycled aggregate. This better initial performance is explained by the combination of the slight pozzolanic effect of the fine ceramic aggregates incorporated with a filler effect [5, 16].

This paper studies the influence of the very fine fraction - under 63 μm - of recycled aggregates from mixed construction debris in the properties of mortars and concretes. The study includes evaluating the hydraulic contribution of this fraction, the influence on the rheological properties of the mixes of concretes and mortars, as well as the impact of this fraction on the pores structure of the cementitious matrix. It is also included the evaluation of the durability of mortars subjected to alkaline attack.

2. Experimentation

2.1. Raw materials

The experimental program in mortars and concrete was done using mixed recycled aggregates obtained from a recycling plant at the south of Germany. All potentially dangerous materials from organic origin were removed. The plant for the processing of the aggregates is equipped with primary and secondary crushers, and also metal remover. CDW were crushed and sieved to prepare coarse and fine aggregate. The recycled aggregate is referred as M2. Natural aggregates of calcareous origin from a plant in Germany, referred as M5-D, were used as reference for the study. A fine fraction of 0-4 mm and a coarse fraction of 4-8 mm were used for the manufacture of mortars and concrete. Before washing the fine aggregate, very fine particles having size under 63 μm were found to be 6% of the weight.

Fine and coarse aggregates were studied using the DIN German norms. The following tests were carried out: (a) particle size distribution and geometrical properties (DIN EN 933-1) [21]; (b) Particle size distribution for mortar and concrete (DIN 4226-100) [22]; (c) Presence of impurities (DIN 52099:2005) [23]; (d) Chemical properties (DIN EN 1744-1:2009+A1:2012) [24]; (e) Resistance to fragmentation, Los Angeles (EN 1097-2:2010) [25]; (f) Impact of weathering on aggregate, Frost-Thaw (DIN EN 1367-1:2007) [26].

Figure 1 presents the particle size distribution of fine aggregate. Both aggregates M2 and M5 have a similar grain size distribution, which can be helpful at the time of the comparing the results. Table 1 presents the physical and mechanical properties of natural and recycled aggregates.

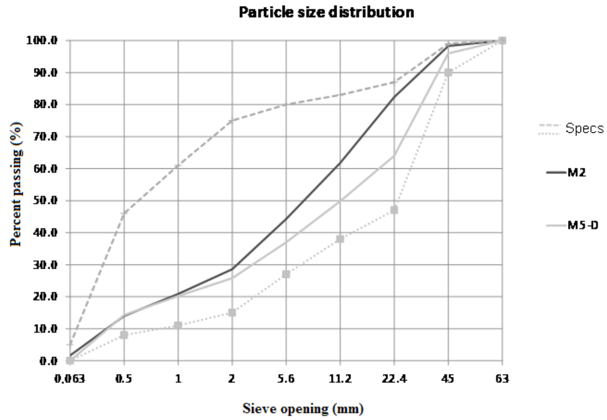

Figure 1 Particle size distribution of natural and recycled aggregate

Table 1 Physical and mechanical properties of natural and recycled aggregates

Properties	M2	M5
Current density fraction 0-4mm (g/cm^3)	2.344	2.568
Apparent density fraction 4-8mm (g/cm^3)	2.535	2.769
Water absorption (%) 0-4mm	4.75	1.02
Water absorption (%) 4-8mm	5.34	1.08
Unit Weight compacted fraction 4-8mm (kg/m^3)	1229.16	1553.40
Unit Weight compacted fraction 0-4mm (kg/m^3)	1248.50	1452.00
Organic impurities	plate 2	plate 1
Clay particles (%)	10.80	3.60
Abrasion resistance, Los Angeles (%)	28.75	23.50
Frost-Thaw resistance (%).	6.05	2.31

Mineralogical composition of both aggregates was assessed aided with X-ray diffraction tests. Table 2 presents the most common phases found in both aggregates. M5 aggregates are of calcareous origin, with calcite and dolomite as main phases, whereas M2 aggregates seem to be of mixed origin, with several phases, including anhydrate cement, which is typical of a mix recycled aggregate.

Table 2 Mineralogical composition of natural and recycled aggregate

Aggregate	Main phases found at X ray diffraction
Natural M5	Dolomite, calcite, traces of clay
Recycled aggregate M2	Quartz, mica, clay particles, unhydrated cement

The chemical composition of the powder of recycled aggregate, M2, was determined with X-rays Fluorescence technique. Samples of natural aggregates, denominated M5 for the comparison, were included. Table 3 shows the results of chemical composition that is consistent with the mineralogical composition presented.

Pozzolanic reactivity of the powder under 63 μm at the recycled aggregate M2 was assessed by measuring the heat of hydration of cement pastes with composition 70% cement/30% powder by isothermal calorimetry using a calorimeter, at a temperature of 30°C for the first 7 days. Heat of hydration was compared with a paste made with 100% plain cement and a paste with 70% cement and 30% inert filler. Pastes were prepared with a water to cement ratio of 0.42.

Portland cement CEM 42.5 R was used in all experimental trial. A commercial superplasticizer admixture was used for mortars and concrete.

Table 3 Chemical composition of the natural and recycled aggregate

Component (%)	Sample	
	M5	M2
SiO_2	20.48	45.97
Al_2O_3	6.38	6.77
Fe_2O_3	2.05	2.52
MnO	0.06	0.07
MgO	5.06	1.86
CaO	31.47	19.88
Na_2O	0.00	0.52
K_2O	1.73	1.73
TiO_2	0.26	0.32
P_2O_5	0.09	0.12
SO_3	1.428	0.386
Cr_2O_3	0.008	0.041
NiO	0.004	0.075
LOI	30.66	19.29

2.2. Experimental methods

Mortar prisms of 40 x 40 x 160 mm with a ratio cement - sand of 1:3 and water-cement ratio of 0.6-0.7 were prepared. Also the water/cement ratio was kept constant as well as the consistency, with the aim of having mortars with similar mechanical properties. Furthermore, the increase in water demand was compensated with an increased supply of superplasticizer.

After the preparation of the mixes and the casting of mortars prisms, these specimens were cured until 7 and 28 days. The mortars were subjected to the compressive strength tests following the norm UNE-EN 1015-11 [27]. In addition, water absorption of the mortars was measured using the procedure established on the German norm DIN EN 480-5:1997-02 [28].

On the other hand, the concrete was designed using a method that combines aggregates and cement with the aim of optimizing packing of the resulting mix. The procedure provides the volume of each aggregates in the mix for an optimized packing and calculates the mass of cement, SCM and water required to fill the void space and any overfill amount (for workability) that is decided. It allows adjusting the mass of aggregate and water to account for the moisture contents of the aggregate, as supplied [29].

Three concretes series were cast with the recycled aggregate identified as M2. The concrete series identified as M2c was made with a fine aggregate where powder under 63 µm was removed by washing. The concrete series M2of was made with the fine aggregate containing 6% of powder under 63 µm, and the series M2scm, where part of the cement of the mix is substituted by the amount of fines under 63 µm (6%).Moreover, a reference concrete series identified as M5 was made with calcareous aggregates. The water/cement ratio was kept constant in all concrete mixes, as well as the consistency, with the aim of having concrete with similar mechanical properties. For this reason, the increase in water demand was compensated with an increased supply of superplasticizer. Table 4 presents the mixture designs.

Consistency of the fresh material was assessed aided with the flow table following the protocol established in the norm DIN IN -12350-5:2009 [30]. Concrete was cast in 100 x 100 x 100 mm cubes, and cured by immersion in water at ages of 7, 28 and 90 days. Compressive strength was measured according to the procedure of the norm DIN IN 12390-3 [31]. Capillary absorption was measured following the requirements of the Cuban norm NC 345:2005 [32].

Slices of the concrete elements were cut off and set to stop hydration at 28 days for further microstructural observations with the petrographic and electronic microscope, which were performed at the Laboratory for Building Materials at the *Ecole Polytechnique Federal de Lausanne* in Switzerland. For SEM observation, each piece of dried sample was impregnated using epoxy-based resin, polished at 150 rpm with a machine down to 1 µm. The sample was then coated with a º30 nm carbon film and the samples were stored in desiccators. Observation in the SEM was done in high vacuum conditions using backscattered electron imaging (BSE) at 15 kV. Images were taken with 1024x768 size and magnification from 140x to 600x in 12.5 mm frame width. In this way the resolution ranges from 0.4123 µm/pixel to 1.41237 µm/pixel. These images were processed aided with image processing tools. Furthermore, it was used the segmentation of porosity to compare both the impact of the aggregate on the cement matrix surrounding it and also to assess the impact of SCMs for encapsulating recycled aggregates.

It is commonly accepted that engineering properties are related to porosity, thus it is better to characterize the pore system than the solid phases formed during cement hydration [33]. For this reason, the strategy of this paper was to assess the area percentage on the pore size distribution determined at the SEM-BSE image.

Considering these elements, the authors chose to apply a quantitative SEM-BSE images analysis for the quantitative evaluation of the pore structure. According to this proceeding, the area fractions obtained for a 2D cross section are equal to volume fractions for the 3D real structures when materials have a completely random and isotropic nature. Also, the cement microstructure is considered to meet these stereological conditions [34].

Finally, the regions of aggregate and paste in the digital images were delineated manually and them pore thresholding procedure was performed using the cumulative histogram inflection point (tangent-slope) [35,

Table 4 Summary of the mixture design used for concrete

Sample	Cement (g)	Sand (g)	Coarse aggregate (g)	w/c	Additive (%)
M5	409	694	1093	0.5	1.1
M2c	504	570	897	0.5	1.6
M2of	553	530	834	0.5	2.5
M2scm	474	571	899	0.5	2.9

36]. The asymptotes and their intercept were calculated automatically taking 0.9 of the overflow point (upper threshold).The tangent-slope method was found to be consistent, economical and reliable. Significantly few images were required to achieve a satisfactory level of statistical confidence for quantifying porosity assuring the repeatability condition and the reproducibility of the precision. According to the achieved image resolution and the irregular pore cross section outline in a 2D image, the pore size distribution classifies them according the pore area by morphological area opening in two classes: micro and meso pores with the boundary between meso and micro pores at 1 μm of diameter or 0.7854 μm2 if image resolution is 0.41231 μm/pixel (magnification 600x).

On the other hand, the impact of the very fine fraction in the durability of mortars was evaluated according to the procedures established by ASTM C33 [37], to measure the volume changes produced in mortar prisms through alkalis attack. There were carried out two tests: the quick test that establishes the norm ASTCM C1260 [38] and the test at one year according to the norm ASTM C227 [39]. Three mortar series were evaluated in each test; the first one, identified as M5, it is a standardized mortar with the fine aggregateM5; the second one, identified as M2c, it is a standardized mortar with the recycled aggregate M2, where fines have been removed by washing. The last series, identified as M2f, it is a standardized mortar made with the recycled aggregate M2, with6% of fines under 63 μm.

For the accelerated test, mortar prisms of 40x40x160 mm were prepared, with ratio cement - sand of 1:3 and water- cement relationship of 0.6-0.7; a consistency around12-14 cm at flow table was targeted. Metal inserts were placed in the ends of the prisms to carry out measurements of length accurately (see Figure 2). The specimens were cured by 24 hours in a humid booth.

An initial reading of the length of the prisms was carried out aided by a digital length comparator prior to initiating the treatment. Then the samples were laid in a recipient with a 1M NaOH solution water at temperature 80°C ±2°C. During the next 23 days, length measurements were carried out daily. The differences of longitude in relation to the initial longitude were considered as the increments of volume in the specimen.

This test was complemented with assessing volume changes up to one year, following the protocol of ASTM C227 [39]. Mortar prisms in size 40x40x160 mm, with cement-sand ratio 1:2.25 and water-cement ratio 0.6 were cast. Aggregates were prepared according to the requirements of particle size distribution established in the referred norm. A NaOH solution with a concentration 1.25% of the mass of the cement in the mortar mixture was used instead of plain water. Table 5 presents the proportions of each mortar in the expansion test.

Figure 2 Device for the measurement of expansion in mortar prisms

Table 5 Proportion of the mortar mixes in the expansion test

Prisms for ASR Test according to ASTM C1260					
M5	450	1350	0.6	0	15.00
M2	450	1350	0.6	1	15.40
M2f	450	1350	0.6	2	15.10
Prisms for ASR Test according to ASTM C227					
M5	300	675	0.6	1	11.75
M2	300	675	0.6	2	12.00
M2f	300	675	0.6	4	12.00

3. Results and discussion

3.1. Pozzolanic activity of the very fine fraction- under 63 μm

To assess the reactivity of the material under 63 μm, the increase in heat of hydration in a cement paste where 30% of cement is substituted by the fine powder was measured. A reference paste is made with inert filler instead of the powder. Figure 3 presents the calorimetric curves for the three pastes evaluated. The system with cement-filler shows an increase of the heat of hydration per gr of cement in reference to the pure cement system, due to the dilution effect, as referred in the literature, that is, the cement grains have more water available and can thus hydrate better. The system cement-powder shows only a slight increase above the cement-filler system, which is attributed to pozzolanic activity of the powder. A more reactive pozzolan should have a higher increase of the heat of hydration due to the pozzolanic reactivity [40]. This could indicate that the pozzolan evaluated –powder with size under 63 μm - does not attain a high reactivity.

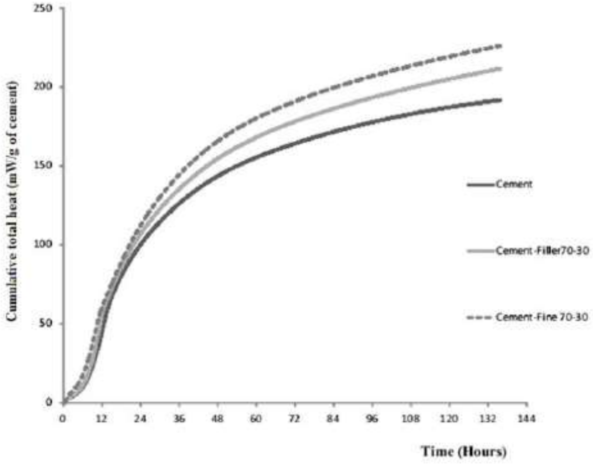

Figure 3 Accumulated heat according to calorimetry test in system: cement, cement-filler and cement-fines

3.2. Influence of the fraction under 63 μm in the properties of mortars

Table 6 presents the evaluation of the rheological properties of the studied mortars. The reference series M5 reaches a consistency of 15 cm without superplasticizer. The series made with recycled aggregates, without fines, M2, demands1% of superplasticizer to reach the desired consistency. The mortar series manufactured with the recycled aggregates with fines, M2f, demands the maximum recommended dosage of the superplasticizer, and even so it could not keep the planned w/c ratio to reach the desired consistency. This trend is coherent with the results obtained by [16] because of the high water absorption of these porous aggregates.

Figure 4 presents the results of compressive strength of the studied series at the age of 7 and 28 days. All mixes have been cast with similar W/C ratio and SP has been added until the desired consistency was reached -spread 40 cm-, so one would expect similar strength results in all series. The presence of fines and the slightly higher water/cement ratio in the mixture in M2f brings about a decrease of the strength with respect to the sample M2, where fines under 63 μm were removed. It can likely be caused by the presence of adhered mortar which favors a higher water demand, a weaker mortar matrix and therefore, a decrease of the compressive strength [15], although the high dosage of superplasticizer could have inhibited cement hydration, as strength gain from 7 to 28 days is very low.

Figure 5 presents results of water absorption for the mortars M2, M2f and the reference M5. The series M2f yielded lower water absorption than the series M2, which indicates the impact of the fines under 63 μm on the connected porosity. Mercury Intrusion Porosimetry tests, presented in Figure 6, do confirm the improvement of the pore structure apparently due to the contribution of the fines under 63 μm. The mortar series M2f presents an increase on the percentage of pores on the sizes 0.01-0.1 μm, that correspond with a refinement of the pores structure, caused probably by the presence of these fines particles that fill pores and discontinuities and block the system of pores, thus decreasing the connectivity of the pore system

Table 6 Evaluation of the impact of very fine fraction in the rheology of mortars

Series	W/C	Additive(g)	SP (weight)	Consistency (cm)
M5	0.61	0.00	0%	15.00
M2	0.61	2.10	0.5%	14.50
M2f	0.70	9.66	2%	14.20

[41]. Some authors obtained similar results, a reduction of water absorption of the mortars due to the filler effect of fines particles of recycled aggregates [5, 16].

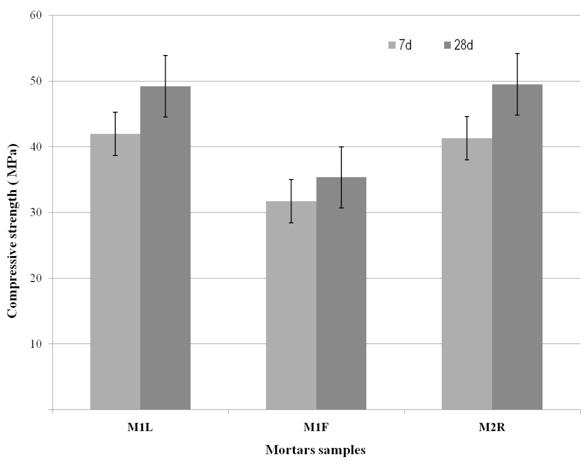

Figure 4 Compressive strength of mortars samples, 7 and 28 days

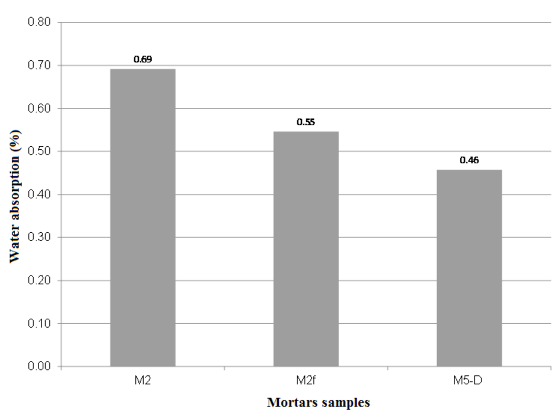

Figure 5 Water absorption, M2, M2f and M5 mortar series

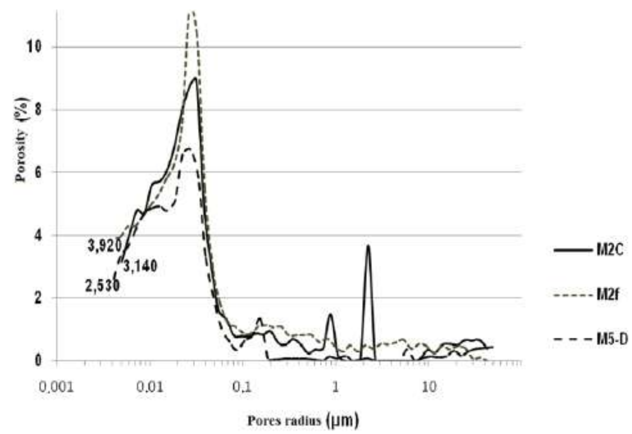

Figure 6 Relative volume of pores, samples of mortars

3.3. Influence of the fraction under 63 µm on the properties of concrete

Table 7 presents the results of the evaluation of the properties in fresh state of the concretes. In all cases, it was observed the same tendency that in the mortar mixtures, that is to say, as the presence of fines in the mixture increases, more superplasticizer needs to be supplied in order to reach the same consistency. Similar results were obtained [12]. It was necessary an increase of the superplasticizer content in order to reach the fixed consistency The series M2of having the highest fines content demanded the maximum dosage of SP to reach the consistency planned for a constant W/C ratio. The negative impact of the fine on the rheology of the mixture is thus confirmed. There are, however, not significant differences in the content of air and the volumetric weight of the evaluated mixtures.

Figure 7 presents the results of compressive strength of the studied series to the age of 7, 28 and 90 days. Considering

Table 7 Properties of concrete in fresh state

Samples	W/C	SP (%)	Cont. air (%)	Consistency (cm)	Weight Vol. (kN/m³)
M5	0.5	1.1	3	43	23
M2c	0.5	1.6	2.5	42.5	22.2
M2scm	0.5	2.5	2.3	42.5	21.8
M2of	0.5	2.9	2.5	40	21.92

that all the mixtures have similar W/C ratio, it is expected that all of them attain similar compressive strength. The differences can be related with problems of the aggregates. The series M2of and M2scm have similar compressive strength to that references M5.

The similar compressive strengths achieved in all concretes, can be attributed to the lower effective water/cement ratio of recycled concretes respect to conventional concrete, because the same content of water is used in all concretes, and the water absorption capacity of recycled aggregates (in special fine and very fine fraction) is much higher than natural sand. Consequently, part of the added water is absorbed by recycled fine aggregate [9].

The presence of fines in the series concretes M2of and M2scm produced an improvement in compressive strength, also this increase might be due to slight pozzolanic reactions and filler effect. These reactions improve the interfacial transition zone between the paste and the aggregates (in special very fine fraction) consequently improving the mechanical properties of the concretes produced with this type of fine recycled aggregates. Furthermore, this waste may contain some non-hydrated cement that completes its hydraulic reactions and sets when in contact with water, leading to greater cohesion between the particles and strength [6].

In general, the presence of adhered mortar and the high absorption of the recycled fine aggregate do not seem to have the same influence that in the case of mortars. No fall in the 90 days is reported in any of the evaluated series, thus indicating that no deleterious reaction which could affect concrete has been triggered.

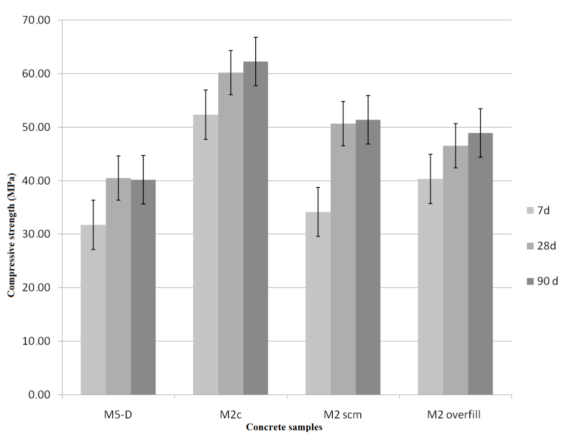

Figure 7 Compressive strength of concrete samples

Figure 8 presents the results of water absorption by capillarity. The mixture M2of, with excess of fines, attains similar results of absorption to the reference series, and much lower than the two remaining series (M2c and M2scm). This can be explained through a refinement of the pore structure likely caused by the presence of fines, which is consistent with results in mortars presented in this paper before.

Also, these results are consistent with other research. The durable behavior of recycled concretes is as good as that of conventional concrete. This fact is due to the lower effective water/cement ratio of recycled concretes respect to conventional concrete, and probably because the interface transition zone (ITZ) of the fine recycled aggregates (with very fine fraction-under 63μm incorporated) is better than that of natural sand [9].

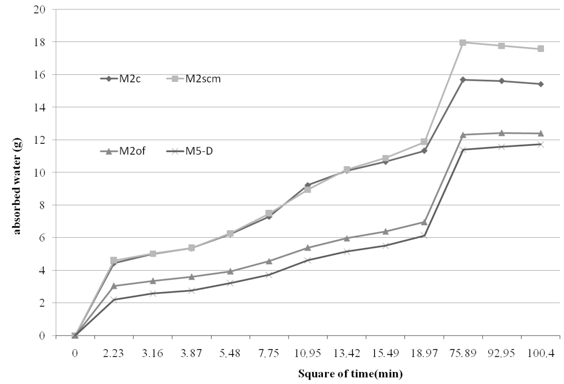

Figure 8 Water absorption of concrete mixes

A detailed study of the interface aggregate-paste, ITZ, could help clarifying the impact of the fines under 63 μm on improving the impermeability of the concrete matrix. SEM images of the concrete series M2c, M2scm and M2of were processed aided by though image processing tools as described above. The study focused on measuring porosity on the cementitious matrix surrounding the aggregate grain. Table 8 presents the results of percentage of pores located at the three different levels defined for the study. Figure 9 presents the image processing done for this study.

a. SEM-BSE images of series M2c, M2nc and M2of with image resolution of 0.41231 μm/pixel (magnification 600x).

b. Total segmented pores (denoted in red) on paste regions.

c. The pore size distribution of each region in area percentage

The highest total porosity at the cement matrix surrounding the grain appears at concrete M2c.The porosity is mainly distributed on the meso area, with only few pores on the micro area. This is consistent with the coarse porosity which is characteristic of a matrix with poor packing. M2scm has a total porosity which is 3 times smaller than M2C, and the amount of micro pores in reference to meso pores is much higher. This could indicate pore refinement caused by the fine grains under 63 μm which fill out gaps between cement grains. M2of, with more fines than M2scm, reaches the lowest porosity, 2 times smaller than that of M2scm and 7 times smaller than that of M2C. The percentage of micro pores continues to rise, and the number of meso pores is reduced. This indicates a clear pore refining effect produced by the increase of packing caused by the presence of extra

Table 8 Pore size distribution of the matrix at the ITZ surrounding the aggregate grain

Series	Total porosity (%)	Micro pores (<1μm)(%)	Meso pores (> 1μm) (%)
M2c	35.4349	1.24	98.76
M2scm	11.1086	4.78	95.22
M2of	7.9001	6.45	93.55

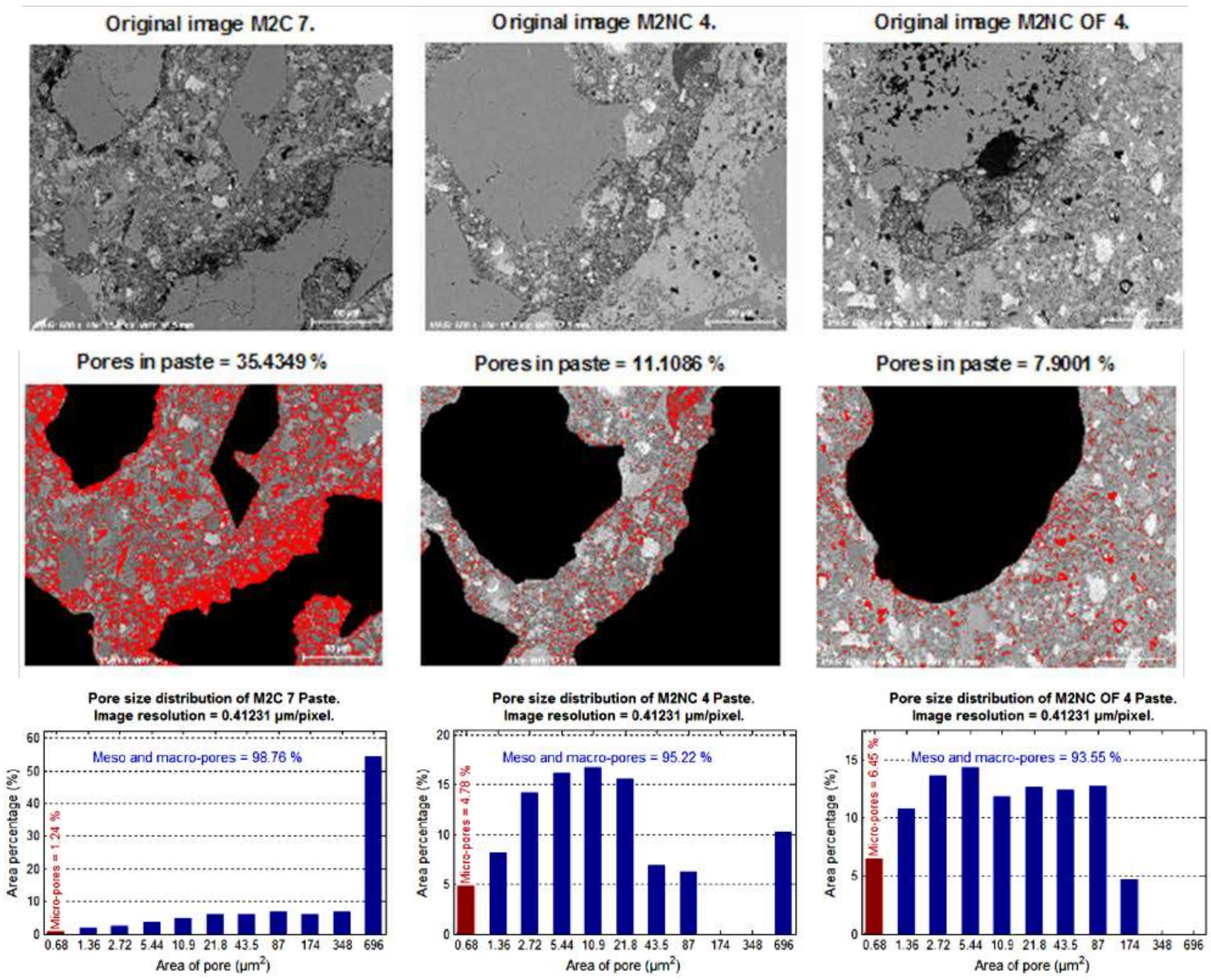

Figure 9 Assessment of impact of the fines under 63 μm through image processing of SEM pictures. a) SEM-BSE images of series M2c, M2nc and M2of with image resolution of 0.41231 μm/pixel (magnification 600x). b) Total segmented pores (denoted in red) on paste regions. c) The pore size distribution of each region in area percentage

fine particles.

3.4. Influence of the very fine fraction-fines under63 μm- on the durability of the matrix mortar

The impact of the very fine fraction on durability was studied in mortars, and considering the nature of the problems with recycled materials, the study of the volume changes by possible alkali-silica reactions (ASR) was chosen, following specifications provided by ASTM C33 and the procedures described in the norms ASTM C1260 and ASTM C227.

Figure 10 presents the results of measurement of volume changes in mortars according to the accelerated test. The norm ASTM C 33 explains that if after 16 days of application of the test, the expansion of the mortar prisms remains under 0.1%, the aggregates are considered inert; for values between 0.10% and 0.20% the aggregates can be considered either inert or reactive. The mortar series M2c reaches the highest values of expansion after 18 days, while the other series M2f and M5 remains well under the limit of expansion accepted. The reduction of expansion in mortar series M2f referred to M2c can be explained by the presence of the very fine fraction under 63 μm, which increases packing of the cement matrix and refines the pore structure, thus preventing alkalis to go deep into the matrix.

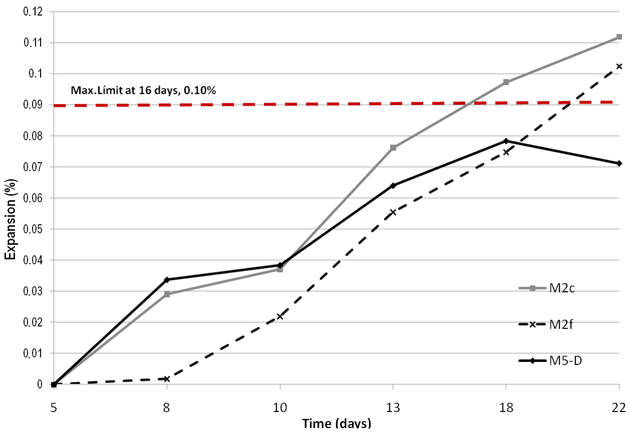

Figure 10 Expansion of mortars after 16 days according to ASTM C 1260

Figure 11 presents measurement of volume changes in mortars following the ASTM C 227 protocol. The norm ASTMC C33 refers that the aggregate is potentially reactive if expansion levels are higher than 0.05% after three months of measurement, and are higher than 0.1% after six months of measurement. If a mortar exceeds 0.05% at three months but remains below 0.1% at six months, the aggregates are yet considered inert.

Following the same trend, mortar series M2c reaches the highest expansion for both three and six months, thus the aggregates M2 is potentially reactive. The expansion can be produced by reactive aggregates present in the parent concrete used to produce the recycled aggregates. The mortar series M2f, with eventually the same problem of originally reactive aggregates, does not expand further after three months of measurement. Again, this could be the consequence of a very impermeable matrix, where gaps have been filled out by the very fine grains, which prevents alkalis from entering and reacting with the aggregates.

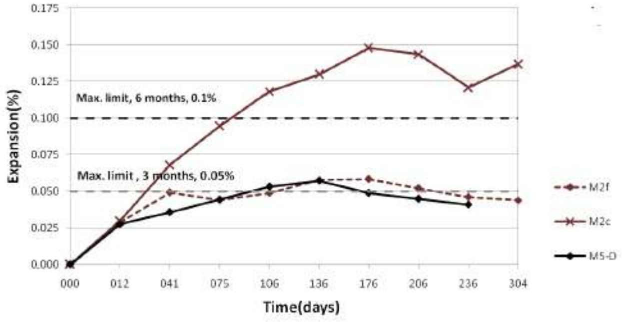

Figure 11 Expansions of mortars after 304 days according to ASTM C 227

4. Conclusions

This paper proves that the presence of fine powder having size under 63 μm in the fine fraction of recycled aggregates, despite its negative impact on rheology, could have some beneficial effects in terms of durability of cementitious materials. This could lead to avoid the practice of washing out these fines from the aggregate during processing.

The reactivity tests carried out on this very fine material -under the 63 μm- prove that their primarily function is as filler material. Their main contribution is to increase packing of the matrix by filling out the gaps between cement grains.

The presence of this material in mortars and concretes produced with aggregates from mix recycled debris increases the water demand, which brings about an increase in water demand and thus the use of more superplasticizer, and mechanical properties could be eventually affected. However, the presence of fines has proven an increase on the impermeability of the cement matrix, which reflects in lower water absorption. In concrete, the fines occupy spaces surrounding the aggregates and improve the interfacial transition zone, thus causing an overall improvement of the properties of concrete, especially durability.

Tests carried out in mortars submitted to alkalis attack prove that the presence of the very fine fraction can increase the resistance of the matrix towards the penetration of alkalis and thus hindering alkalis expansion reaction, even in the presence of reactive aggregates.

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