USE OF FINE RECYCLED AGGREGATES FORM CONSTRUCTION AND DEMOLITION WASTE, CDW, IN MASONRY MORTAR MANUFACTURING

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ABSTRACT

This research aims to study the feasibility of incorporating fine fraction of recycled aggregates coming from construction and demolition waste in masonry mortars productions, implying a new way for CDW recycling. For this reason, three samples of fine recycled aggregates have been used: one of them was obtained from concrete recycling, one from ceramic recycling and one from mixed recycling line. The volumetric cement-to-aggregate ratio used to perform the tests were 1:3 and 1:4, and the replacement percentages for three types of recycled aggregates were 50%, 75% and 100%.
Physical characterization of recycled aggregates shows a continuous size distribution curve, lower density and higher absorption, that makes the use of additive necessary to obtain workable mortars. The main crystalline phases determined are calcite, quartz and gypsum. Compression and flexural strength, bonding strength and shrinkage tests revealed poorer performance of recycled mortars compared to the mortars fabricated with natural sand. However, obtained values are within the limits established by the standards and manufactures. Therefore, this study shows the real possibility to substitute 100% of natural sand with studied recycled aggregates in mortar production.

Keywords: recycled aggregates, mortar, physical and chemical characterization, mechanical tests.

1.- Introduction.

The construction sector belongs to one of the less developed human activities. Nevertheless, during the last years the environmental problems and the urgent necessity to solve them encourage the search for alternative waste management model and sustainable construction activity.

During the last years before the financial crisis, generation of waste has been significantly increased, what, in combination with an important lack of disposal sites, imposes the necessity of efficient waste management policy.

Industrialized countries have been developed plans for the waste accumulation prevention as well as the reutilization, recycling and recovery of waste. In particular in Spain the Law 10/1998 [1] aims at establishing the responsibility and obligations of the Autonomous Communities to approve the National Waste Management Plans. Complying with this obligation, the Second Integrated National Waste Plan (PNIR) [2] has been drafted with an aim to guarantee that the waste management does not damage the environment neither endanger human health.

The Royal Decree 105/2008 [3] regulates the production and management of Construction and Demolition Waste (CDW), defining it as any residue generated in the construction process, reform, excavation or demolition. About 15% of the CDW produced in Spain is recycled, and approximately 35% is commercialized as a recycled material to be used as filler in road construction and in concrete fabrication [4]. The Code on Structural Concrete (EHE-08) [5] permits the usage of coarse fraction of recycled aggregate in concrete fabrication, recommending substitution of up to 20% of natural sand by recycled aggregate. However, the fine recycled aggregate has not been considered by most standards until now. Therefore, the incorporation of this material in masonry mortars production implies a new alternative for recycling construction and demolition waste in the building and construction sector.

Various scientific researches have studied the feasibility of incorporating fine fraction of recycled aggregate in masonry mortar production. The characteristics of this material vary depending on the production process used in Integral Waste Treatment Plants [6] and on the properties of source material [7]. The quality of recycled aggregates in terms of physical, mechanical and chemical characteristics is determined mainly by the content of adhered mortar, contaminants and impurities [6] [8].

Corinaldesi et al. [9] evaluated mechanical and rheological behaviour of cement mortar manufactured using three types of recycled aggregates: rejected prefabricated concrete material, recycled bricks waste and plant recycling rubble. In three cases, 100% of recycled aggregate has been used, determining poorer mechanical behaviour and higher mortar-brick bond strength of recycled mortars comparing to traditional mortars.

Jiménez et al. 10], concluded that the incorporation of up to 40% of ceramic waste in mortar production does not affect significantly the properties of cement mortar in the fresh and hardened state, with exception of its density and workability.

Other authors, such as Vegas et al. [11] and Dapena et al. [12] have came to the conclusion that mortar may contain up to 25% and 20% by weight of concrete recycled aggregate, respectively, without their main mechanical properties being affected.

The main aim of this work is the characterization of fine fraction recycled aggregate, and to study the feasibility of incorporating this material in the masonry mortar production, replacing natural sand with recycled aggregate in different percentages (50%, 75% and 100%). To that end, three types of recycled aggregate coming from the Tec-Rec recycling plant situated in Madrid region have been studied: concrete,

mixed and ceramic recycled aggregate. One of the established classifications of recycled aggregates is based on the composition of different material they are formed of. In this way, the ranges of the maximum and minimum percentage of all materials that form recycled aggregate are established in order to define to which type they belong [4]:
- Concrete recycled aggregate: contains minimum 90% of concrete by weight.
- Ceramic recycled aggregate: contains minimum 70% of ceramic materials.
- Mixed recycled aggregate: contains mixed ceramic and concrete material.

2.- Materials and experimental part.
There were used the following basic cement mortar manufacture materials in this study: cement, sand and water. Furthermore, the use of an additive Glenium SKY 604 was necessary to achieve the proper consistency of recycled mortars, because of higher water absorption of recycled aggregates comparing to the natural sand.

2.1.- Materials.
2.1.1.- Binder.
The binder used in the study was CEM II/B – L 32.5 N, suitable for mortar production and for masonry in general. The properties of this cement are specified by Spanish and European standard UNE-EN 197-1[13] and by the Instruction for the cement placing (RC-08) [14]. The main characteristics are shown in (Table.1).

Physical characteristics	
Density (g/cm3)	3.08
Blaine specific area (cm²/g)	4000
Initial set (min)	175
Final set (min)	275
Chemical characteristics	
Elements	Result (%)
Al_2O_3	3.25
CaO	60.10
Fe_2O_3	2.56
K_2O	0.26
MgO	1.75
SiO_2	18.13
TiO_2	0.14
MnO	0.02
P_2O_5	0.16
NaO_2	0.22
Loss on Ignition	11.85

Table1. CEM II/B-L 32.5 N characteristics

2.1.2.- Aggregates.
Different types of aggregates were used in this study. Standardized sand packed in 1350 gr. bags by the Eduardo Torroja Institute and natural river sand provided by the CEMEX company in 15 kg. bags were used for the reference mortars.
Recycled aggregates used in this study come from the Tec-Rec integral waste treatment plant situated in Madrid Region. There were used samples of three typed of recycled aggregates commercialized by this company: concrete recycled

aggregate (RA-Con), mixed recycled aggregate (RA-Mix) and ceramic recycled aggregate (RA-Cer).

2.1.3.- Additive.

For the elaboration of recycled mortars it was necessary to use the Glenium SKY 60 additive, prescribed by the BASF Company technical department to improve consistency of the mortars. The Glenium SKY 60 additive is a liquid product based on polycarboxylates free from any substances that would have negative effects on mortars. In different mixes there was used 0.8% of additive over the weight of cement. The use of plasticizer additive was necessary in recycled mortars fabrication in order to obtain plastic mortars that could be used as masonry mortars.

2.2.- Characterization.

Fine recycled aggregates size distribution was determined according to the technical requirements established by the UNE-EN-933-2[15] and the UNE-EN-933-1 [16] standards "Tests for geometrical properties of aggregates", in particular Part 1: "Determination of particle size distribution." Graphical representation of this test is shown in (Fig.1).

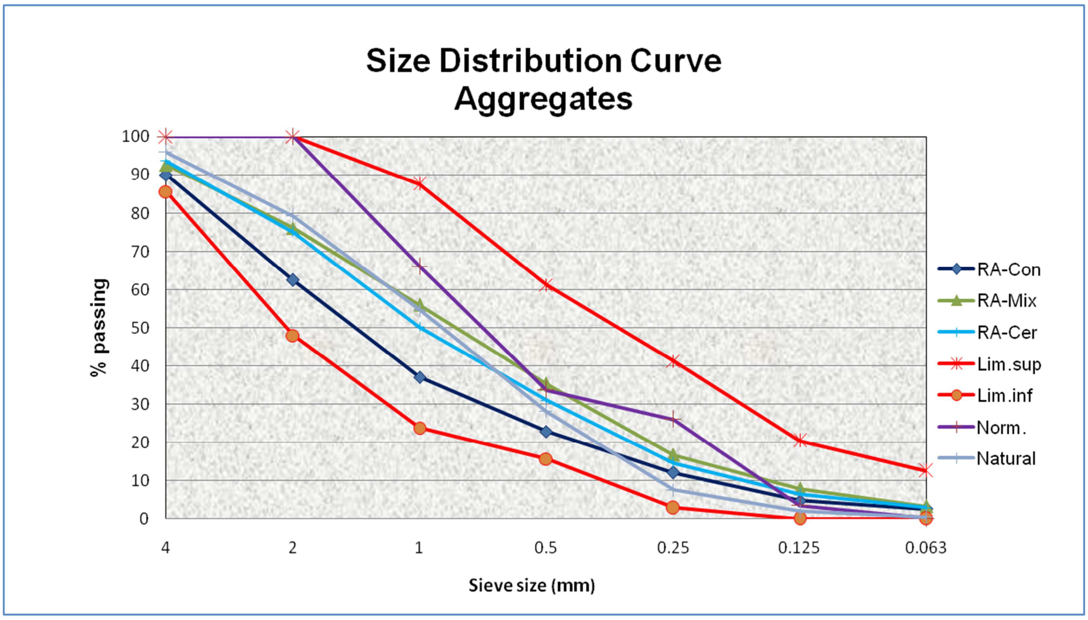

fig1. Recycled aggregate size distribution curve compared to the limits of NBE.FL 90 adapted to sieve size established by UNE-EN- 933-2.

As can be observed in (fig.1), the size distribution line is continuous for three types of recycled aggregates and does not exceed the limits established by the Basic Norm NBE-FL 90 taken as a reference. Size distribution is one of the most important properties of aggregates, as it affects mortar compactness, workability and strength [6] [7]. (Table.2) summarizes the most important characteristics of recycled aggregates used in this study.

Aggregates Characteristics						
Test	**Norm**	**RA-Con**	**RA-Mix**	**RA-Cer**	**Standardized Sand**	**Natural Sand**
Fine Content	UNE-EN 933-1	3.91%	3.96%	4.23%	0.12%	0.42%
Fineness Modulus	UNE-EN-13139	4.26%	3.88%	4.66%	3.71%	4.32%
Bulk Dens. (gr/cm^3)	UNE-EN-1097-3	1.21	1.25	1.32	1.66	1.32
Relative Dens.(gr/cm^3)	UNE-EN-1097-6	2.34	2.40	2.10	2.55	2.45
Water absorption	UNE-EN-1097-6	6.03	6.67	7.02	0.68	0.92

Table2. Aggregates Characteristics.

Recycled aggregates samples were also tested through the X-Ray fluorescence method in order to obtain their chemical composition. The X-Ray fluorescence method analyses amorphous and crystalline materials in terms of quantity and quality. Results of this test are shown in (Table.3).

Samples	**Al_2O_3**	**CaO**	**Fe_2O_3**	**K_2O**	**MgO**	**SiO_2**	**MnO**	**TiO_2**	**SO_3**	**P_2O_5**	**Na_2O**	**PF %**
RA-Cer	10.30	16.90	2.85	2.36	1.79	43.5	-	0.37	4.32	0.12	0.82	16.5
RA-Mix	7.18	13.40	1.57	2.17	0.61	64.5	0.024	0.17	-	0.08	0.35	9.5
RA-Con	6.98	10.67	1.22	2.16	0.54	68.2	0.022	0.15	-	0.10	0.22	9.4

Table3. Recycled aggregates chemical analysis

As can be observed, recycled aggregates are composed mainly of silicates, being the majority of them Calcium and Aluminium silicates. As samples of mixed and ceramic recycled aggregate contain more clay and ceramic they show higher content of Al_2O_3 comparing to concrete recycled aggregates. Obtained values of CaO and loss on ignition fall between the ranges of values found in other researches [17].
Furthermore, recycled aggregate samples were tested through the X-ray diffraction and thermogravimetric analysis. Observed phases, with the exception of quartz, do not show a high crystalline state, although they have wide diffraction peaks with low intensities. This characteristic is typical of poorly crystalline and/or amorphous phases, due to low crystallinity of compounds formed as a result of concrete hydration and materials coming from ceramics. The diffractogram and principal phases observed in the X-ray diffraction are shown in (fig.2).

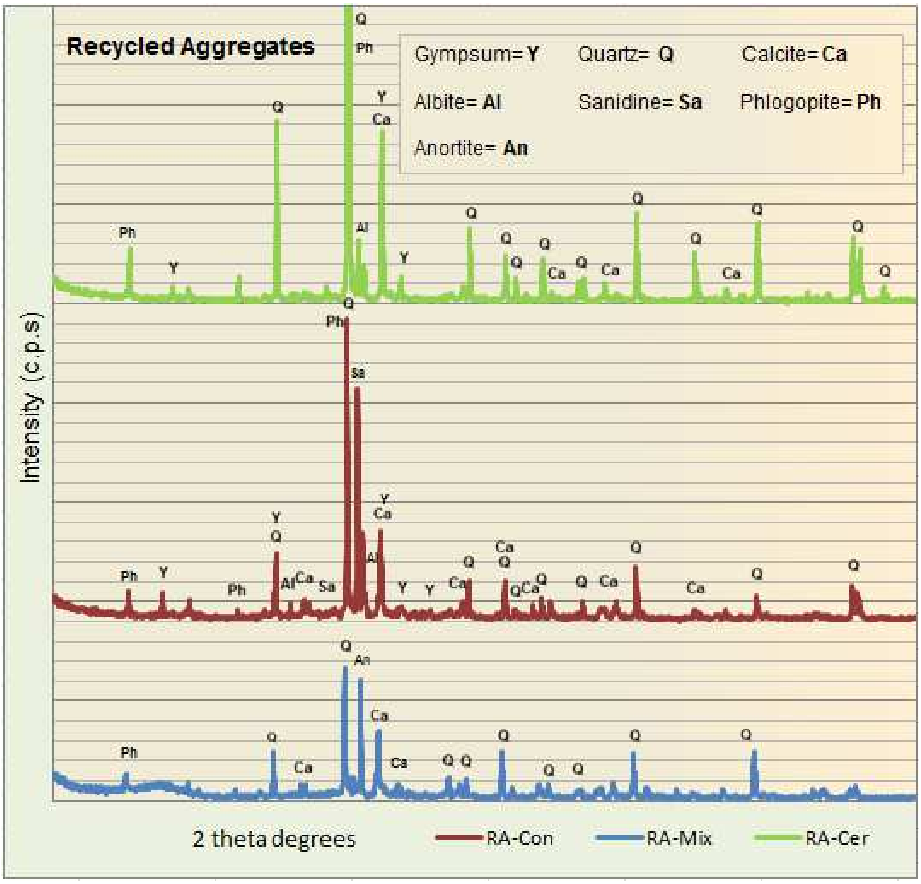

fig2. X-ray diffractogram.

During the thermogravimetric analysis the samples were initially maintained during 5 minutes at 100ºC in order to eliminate humidity. Decomposition of gypsum occurs between 160ºC-185ºC. Above 570ºC a change of phase from αSiO_2 (alpha-quartz) to βSiO_2 (beta-quartz) takes place, characterized by the endothermic peak under this temperature without mass loss. Between 650ºC and 750ºC the decarbonation of calcite is observed. An example of this test and calcite and gypsum percentage calculations can be observed in (fig.3) and in (Table.4) respectively.

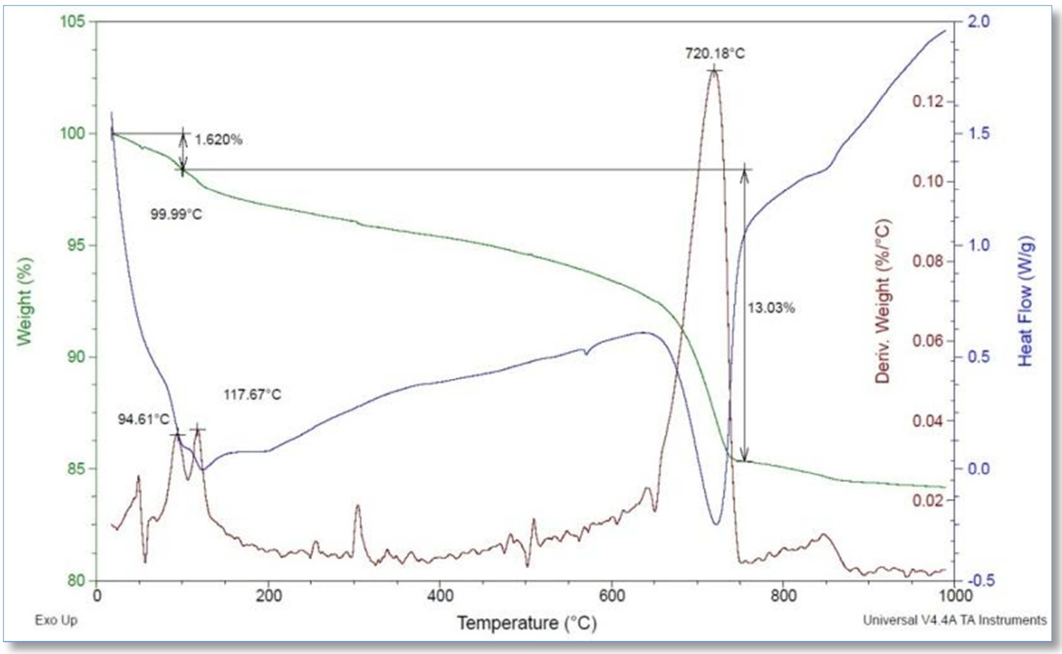

fig3. Thermogravimetric Analysis.

	RA-Cer	RA-Mix	RA-Con
% Gypsum	4.62	3.77	3.65
% Calcite	19.62	17.73	17.03

Table4. Calcite and Gypsum %

2.3. Testing Program.
With an aim to characterize recycled aggregates used in this investigation and to study the technical feasibility of their incorporation in masonry mortars fabrication, the testing program was established. The following tests were carried out for the characterization of recycled aggregates: size distribution curve, fine content, fineness modulus, bulk and relative density and water absorption. Moreover, the X-Ray fluorescence and diffraction method and thermogravimetric analysis were used for the chemical characterization of recycled aggregates. A single type of binder that was used in the study is CEM II/B-L 32,5 N, suitable for mortar production and for masonry in general. Standardized sand was replaced with three types of recycled aggregates in three substitution percentages: 50%, 75% and 100% and cement-to-aggregate by weight proportions were 1:3 and 1:4. Recycled aggregates obtained from treatment plants were sieved in the laboratory, eliminating material retained on the 4 mm sieve and material passed through 0,063mm sieve. The mixtures containing 50% and 75% of recycled aggregates were completed with standardized sand until 100% of necessary aggregate was achieved. Mixture proportions used in the study can be observed in (Table.5).

Mixture Proportions						
RA type	**Dosage 1:3 c/s**			**Dosage 1:4 c/s**		
	50%	**75%**	**100%**	**50%**	**75%**	**100%**
RA-Cer	0.57	0.64	0.68	0.75	0.86	0.89
RA-Mix	0.55	0.63	0.66	0.73	0.84	0.87
RA-Con	0.53	0.62	0.64	0.72	0.83	0.85
Note: 0.8%. Additive use percentage over the weight of cement.						

Table5. Mortar Mixture Proportions.

The following code was employed for the mixtures identification:

A-Nº-X%

Where Nº = recycled aggregates type (Cer = ceramic recycled aggregate, Mix=mixed recycled aggregate and Con = concrete recycled aggregate)
X% = Recycled aggregates substitution percentage (50%, 75% or 100%).

3.- Results and discussion.
Cement mortar attached to recycled aggregates is one of the most important factors that cause poorer properties of recycled aggregates. It is a reason of lower density of recycled aggregates comparing to natural sand, what leads us to believe that the weight of recycled mortars would be lighter than that of the reference. Water absorption of recycled aggregates is higher than that of the natural sand, what makes the use of additive necessary to achieve the adequate workability of recycled mortars. The density and absorption values obtained in the study are similar to those found in other researches [9] [11].

3.1.- Fresh mortar.
Consistency and wet density tests were carried out to study the properties of fresh recycled mortars. As it can be seen in (Table.5), incorporation of higher percentage of recycled aggregates increases water demand for two studied proportions. These proportions were proposed to obtain plastic recycled mortars, presenting consistency values between 165 mm and 185 mm according to the technical requirements of the UNE-EN 1015-3[18] standard.
(Table.6) shows that wet density values of fresh recycled aggregates with 100% substitution ratio are slightly lower than that of the reference mortars fabricated using natural sand (2,119 gr/cm^3) and standardized sand (2,102 gr/cm^3). This fact and values obtained in this study are similar to those presented by other authors [11]. Wet density of fresh mortar was determined according to the technical prescriptions established by the UNE-EN 1015-6 [19] standard.

Recycled Fresh Mortars Characteristic							
RA type	TEST	1:3			1:4		
		50%	75%	100%	50%	75%	100%
RA-Cer	Consist.(mm)	168	170	167	172	175	168
	Wet Dens.(gr/cm3)	2.163	2.131	2.094	2.062	2.081	1.979
RA-Mix	Consist.(mm)	170	169	166	172	165	166
	Wet Dens.(gr/cm3)	2.212	2.151	2.106	2.091	2.081	2.059
RA-Con	Consist.(mm)	174	171	170	173	167	168
	Wet Dens.(gr/cm3)	2.182	2.116	2.082	2.043	2.025	2.002

Table6. Consistency and wet density of fresh mortars.

3.2.- Hardened mortar.
Mortars in the hardened state were tested to measure the following properties: dry bulk density, real density, compression, flexural strength, bond strength and shrinkage.

3.2.1.- Dry bulk density and real density.
Dry bulk density of the mortars was measured according to the technical prescriptions established by the UNE-EN 1015-10 [20] standard. Real density of the mortars was determined with a stereopycnometer using high purity helium gas. The results of these tests can be observed in (Table.7).

Dry Density and Real Density							
Type RA	Test	1:3			1:4		
		50%	75%	100%	50%	75%	100%
RA-Cer	Dry density (gr/cm3)	1.74	1.68	1.74	1.87	1.79	1.71
	Real density(gr/cm3)	2.33	2.26	2.22	2.43	2.36	2.27
RA-Mix	Dry density(gr/cm3)	1.92	1.89	1.89	1.90	1.82	1.76
	Real density(gr/cm3)	2.41	2.38	2.37	2.36	2.33	2.31
RA-Con	Dry density(gr/cm3)	1.89	1.86	1.83	1.87	1.79	1.71
	Real density(gr/cm3)	2.44	2.41	2.39	2.34	2.28	2.28

Table7. Mortars density.

Density of recycled mortars is slightly lower compared to reference mortars fabricated using natural sand (2,38 gr/cm^3 for 1:3 proportion and 2,32 gr/cm^3 for 1:4

proportion). The values that were obtained are similar to those found by other authors in their studies [21].

3.2.2.- Compression and flexural strength test.

To study compression and flexural strength there were manufactured prismatic specimens (40x40x160mm), which were cast and cured in a humid chamber at 20ºC during 28 days. Flexural strength and compression were determined according to the UNE-EN 1015-11 [22] standard.

In relation to mechanical strength, increased percentage of three types of recycled aggregates used for recycled mortar fabrication produces poorer flexural strength (Table.8), being the obtained values lower than that of the reference mortars. These values are higher compared to those obtained in other investigations [11]. Other researchers obtained higher results using 100% of recycled aggregates with 110±5 mm consistency [9].

Obtained values of compression strength (Table.8) also indicate poorer properties of recycled mortars compared to mortars fabricated using natural sand. Nevertheless, the values that were obtained comply with existing standards that establish 7.5 MPa as a minimum acceptable value for compression strength. Compression values obtained in the study are higher than that found in other researches [11] [23].

Flexural and compression strenght							
Type RA	**Test**	**1:3**			**1:4**		
		50%	**75%**	**100%**	**50%**	**75%**	**100%**
RA-Cer	Flexural (MPa)	5.11	4.61	4.19	3.12	2.90	2.94
	Compression (MPa)	22.18	15.83	14.33	12.66	9.10	9.07
RA-Mix	Flexural (MPa)	6.19	4.89	4.61	3.08	2.97	3.17
	Compression (MPa)	23.42	18.43	14.23	12.11	8.91	9.76
RA-Con	Flexural (MPa)	5.66	5.31	4.74	3.35	3.24	3.12
	Compression (MPa)	24.49	18.55	20.57	12.38	10.23	9.85
Natural.S	Flexural (MPa)	-	-	5.11	-	-	4.01
	Compression (MPa)	-	-	21.94	-	-	19.54

Table8. Compression and flexural strength test.

3.2.3.- Bond strength and shrinkage tests.

The bond strength test was carried out on a ceramic support of 400x500x50 mm, with a specimen diameter of 50 mm and coating thicknesses of 10 mm, following the technical prescriptions of the UNE-EN 1015-12 [24] standard. The obtained results are shown in (Table.9)

Bond and shrinkage test							
Type RA	Test	1:3			1:4		
		50%	75%	100%	50%	75%	100%
RA-Cer	Bond strengh (N/mm^2)	0.48	0.43	0.41	0.41	0.39	0.37
	Shrinkage (mm/m)	0.056	0.081	0.084	0.069	0.076	0.121
RA-Mix	Bond strengh (N/mm^2)	0.49	0.46	0.42	0.42	0.41	0.39
	Shrinkage (mm/m)	0.043	0.064	0.089	0.072	0.075	0.108
RA-Con	Bond strengh (N/mm^2)	0.51	0.44	0.41	0.42	0.40	0.37
	Shrinkage (mm/m)	0.043	0.064	0.082	0.065	0.068	0.090
Natural.S	Bond strengh (N/mm^2)	-	-	0.51	-	-	0.49
	Shrinkage (mm/m)	-	-	0.019	-	-	0.022

Table9. Bond strength and shrinkage tests.

According to the results shown in (Table.9), bond strength of recycled mortars is lower compared to the reference mortars, and these values decrease with higher percentage of recycled aggregates. Mortars fabricated using 100% of recycled aggregates show similar results in three cases, complying with the limit of 0,30 N/mm^2 established by the UNE-EN 998-1 [25] standard. Other studies give similar bond strength values such as 0,37 N/mm^2 [23] or 0,40 N/mm^2 [26] using 50% of recycled aggregates with 1:4 cement-to-aggregate proportion.
The results of shrinkage test (Table.9) show higher values compared to reference mortars. Mortars were studied during 72 hours, taking readings every 60 minutes. The mixture that gives the highest shrinkage value of 0,121 N/mm^2 is one that corresponds to the ceramic aggregate with 1:4 proportion. This values is significantly higher than that of mortars fabricated with natural sand, however, it does not exceed the limit of 0,20 N/mm^2 established by the Technical Building Code. Similar results were obtained in other researches [21] [27].

4.- Conclusions.

The aim of the testing program of this study is to analyze mechanical behaviour and relevant properties of masonry mortars fabricated replacing natural sand with different types of recycled aggregates. The main conclusions that arise from this study are given below:

- Main characteristics of three types of recycled aggregates that were studied are high content of 4mm particles retained in sieve, as well as lower density values and higher water absorption compared to natural sand. Obtained water absorption values are between 5% and 10% that is an acceptable percentage for recycled aggregates.
- Recycled aggregate size distribution curves of three types of recycled aggregates are continuous and within the limits established by the standards.
- The X-Ray diffraction method identifies crystalline phases of a material. Main crystalline phases exhibited in three types of recycled aggregates are calcite and quartz. The results obtained through the X-ray fluorescence method show that recycled aggregates are composed mainly of silicates, being the majority of them calcium and aluminium silicates.
- Mechanical performance of recycled mortars fabricated using 100% of recycled aggregates is poorer than that of the mortars fabricated with natural sand. In case of compression strength, the results obtained comply with the standards allowing its use in construction with both 1:3 and 1:4 proportion for three types of studied recycled aggregates.

- Results of the bond strength tests show poorer vales of recycled mortars. As the percentage of incorporated recycled aggregates increases, bond strength values lower. Nevertheless, the mixtures that show the poorest values comply with the limits established by the standards and manufacturers for masonry mortars.
- Recycled mortars shrinkage values are superior to those of the reference mortars, being mixture that corresponds to ceramic recycled aggregate using 1:4 by weight proportion one that shows the highest shrinkage values. Obtained values are within the limits established by the standards.
- In view of the above, it can be concluded that cement-based mortars may be fabricated with recycled aggregates coming from ceramic, concrete and mixed recycling processes, using 1:3 and 1:4 cement-to-aggregate proportions, complying with the Spanish standards.

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