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Re-use of ceramic wastes in construction

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1. Introduction

Recent decades have seen a marked upsurge in industrial and economic growth, contributing to an improved quality of life and well-being for citizens. However, we should not lose sight of the fact that every production system creates by-products and waste products which can affect the environment. These effects may occur at any point in the product's life-cycle, whether during the initial phase of obtaining raw materials, during the transformation and production phase, during product distribution or when the end user must dispose of products which are no longer required.

As a result, recent years have witnessed rising social concern about the problem of waste management in general, and industrial waste and waste from the construction industry in particular. This problem is becoming increasingly acute due to the growing quantity of industrial, construction and demolition waste generated despite the measures which have been taken in recent years at European Community, national and regional levels aimed at controlling and regulating waste management, in accordance with sustainable development policies and the Kyoto Protocol. The need to manage these wastes has become one of the most pressing issues of our times, requiring specific actions aimed at preventing waste generation such as promotion of resource recovery systems (reuse, recycling and waste-to-energy systems) as a means of exploiting the resources contained within waste, which would otherwise be lost, thus reducing environmental impact.

In addition to helping protect the environment, use of such waste offers a series of advantages such as a reduction in the use of other raw materials, contributing to an economy of natural resources. Moreover, reuse also offers benefits in terms of energy, primarily when the waste is from kiln industries (the ceramics industry) where highly endothermic decomposition reactions have already taken place, thus recovering the energy previously incorporated during production.

Ceramic waste may come from two sources. The first source is the ceramics industry, and this waste is classified as non-hazardous industrial waste (NHIW). According to the Integrated National Plan on Waste 2008-2015, NHIW is all waste generated by industrial

activity which is not classified as hazardous in Order MAM/304/2002, of the 8th February, in accordance with the European List of Waste (ELW) and identified according to the following codes:
10 Waste from thermal processes.
10 12 Waste from the manufacture of ceramic products, bricks, roof tiles and construction materials.
10 12 08 Ceramic, brick, roof tile and construction materials waste (fired).
The second source of ceramic waste is associated with construction and demolition activity, and constitutes a significant fraction of construction and demolition waste (CDW), as will be addressed in more detail below. This kind of waste is classified by the ELW according to the following codes:
17 Construction and demolition waste
17 01 Concrete, bricks, roof tiles and ceramic materials
17 01 03 Roof tiles and ceramic materials
Globally, the ceramics industry sector is unusual in that it is primarily found in regional concentrations where the majority of agents or industries involved in the system whereby the end ceramic product attains value are located. The development of these ceramic "clusters", with companies in the same or related sectors located in geographical proximity, has enabled the sector globally to attain a state-of-the-art level of progress and technological innovation. The main ceramic "clusters" are located in Brazil, with one in Santa Catarina and two in the state of Sao Paulo; in Portugal, in the Aveiro region; in Castellón, Spain; and in the province of Emilia Romagna, Italy. The ceramics industry in China has also begun to take on greater prominence, representing 35% of global production in recent years.
The ceramics industry is comprised of the following subsectors: wall and floor tiles, sanitary ware, bricks and roof tiles, refractory materials, technical ceramics and ceramic materials for domestic and ornamental use. In both the European Union and Spain, the scale of production within these subsectors with regard to total production follows the same trends, where the production of wall and floor tiles represents the highest percentage with respect to the total, followed by bricks and roof tiles, and finally, the other subsectors, as can be seen in Figures 1 and 2.

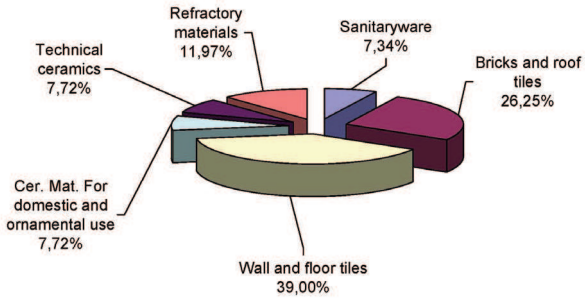


Fig. 1. Scale of production: ceramics industry subsectors in the EU

Ceramic products are produced from natural materials containing a high proportion of clay minerals. Following a process of dehydration and controlled firing at temperatures between 700ºC and 1000ºC, these minerals acquire the characteristic properties of fired clay.

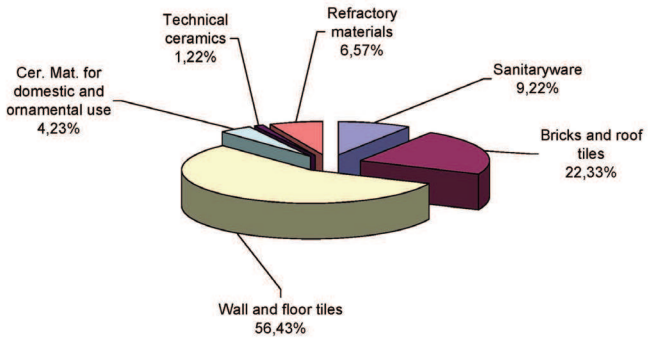


Fig. 2. Scale of production: ceramics industry subsectors in Spain

Ceramic factory waste is not sorted according to the reason for rejection, which may include: breakage or deformation and firing defects.

As regards waste generated by construction activity it is estimated that some 200 million tons of rubble is produced each year in the European Union (EU) as a result of the construction and demolition of buildings. According to data from the Spanish National Plan for Construction and Demolition Waste, 40 million tons are generated annually in Spain, the equivalent of 2 kg per inhabitant per day, which represents a higher figure than that for domestic waste. Within the EU as a whole, 28% of this waste is recycled. Pioneering European countries in this matter include the Netherlands, where 95% of construction waste is recycled, England, with 45% and Belgium with 87%, 17% of which is used in making concrete. In Spain, approximately 10% of total construction and demolition waste is recycled, and reuse mainly consists of using the waste for road subgrade and subbase.

Construction and demolition waste principally consists of two fractions: the stony fraction and the rest (see Table 1). The most important fraction is the stony fraction, comprising ceramic materials (bricks, wall tiles, sanitary ware, etc.), concrete, sand, gravel and other aggregates.

MATERIALS	COMPOSITION (%)
STONY FRACTION	**75**
Bricks, wall tiles and other ceramic materials	54
Concrete	12
Stone	5
Sand, gravel and other aggregates	4
REST	**25**
Wood	4
Glass	0,5
Plastic	1,5
Metals	2,5
Asphalt	5
Plaster	0,2
Rubbish	7
Paper	0,3
Others	4

Table 1. Composition of construction and demolition waste

As can be seen, more than half (54%) corresponds to the ceramic fraction, representing the highest percentage of all materials shown, followed by concrete waste (12%). This illustrates the importance of the treatment and recovery of this kind of waste. In many cases, the possibility of reuse or recycling will depend on the existence of previous studies into the viability of this waste fraction, such as that proposed by this present research.

2. Activated clays from industrial waste with pozzolanic properties

2.1. Introduction

Activators are defined as products which, once incorporated into Portland cement, contribute to the development of the cement's hydraulic and strength qualities. Due to their chemical-mineralogical composition, some products have hydraulic properties in their own right, setting and hardening under water. This is the case for granulated blast – furnace slag or fly ash with high lime content. In contrast, others do not have hydraulic qualities per se, but due to their composition, rich in silica and aluminium oxide compounds, and their extreme fineness, are capable of fixing calcium hydroxide at normal temperatures and in the presence of water in order to create stable compounds with hydraulic properties. These latter are known as pozzolans. The calcium hydroxide necessary for a pozzolanic reaction can come from inert lime or from a hydrating Portland cement.

The use of materials with pozzolanic properties in cement achieves:

- Economic Advantages: Reduced need for clinker production (lower energy consumption).
- Environmental Advantages: Reduced CO_2 emissions (Kyoto Protocol)
- Technical Advantages**:**
  - Long-term mechanical strength
  - Stable resistance to expansion due to the presence of free lime, sulphates and aggregate-alkali reactions.
  - Durable resistance to the action of pure and acid water.
  - Reduced hydration heat
  - Impermeability, reducing porosity and increasing compactness.

Clays are natural materials which do not present pozzolanic activity, although they can be activated thermally. Clay activation is achieved by a dehydration process beginning at around 500ºC and accompanied by the separation of amorphous, very active aluminium oxide, the maximum concentrations of which are achieved at different temperatures, depending on the type of mineral. Clay minerals such as kaolinite or montmorillonite, or a combination of both, acquire pozzolanic properties through controlled calcinations at temperatures between 540ºC and 980ºC. Illite type clays, or schist type clays containing a high proportion of vermiculite, chlorite and mica, need higher temperatures for activation. It is well-known that one of the first materials used as pozzolans were thermally treated clays (Calleja, 1970).

Activated clays may come from natural products, once these have been activated by controlled thermal processes, or from industrial waste.

This present paper presents research on wastes from the paper and ceramics industries, carried out by the Working Group on Materials Recycling at the Eduardo Torroja Institute for Construction Sciences.

2.2. CERAMICS INDUSTRY WASTE

As regards the ceramics industry in Spain, some 30 million tons of ceramic products such as bricks, roof tiles, breeze blocks, etc., were produced in 2006. Although by 2009 the recent industrial crisis had resulted in a 30% drop in production, the industry continues to generate a significant volume of material unsuitable for commercialization.

The percentage of products considered unsuitable for sale and thus rejected depends on the type of installation and the product requirements. Such waste can be considered inert, due to its low capacity for producing contamination. However, dumping constitutes a major disadvantage, producing significant visual impact and environmental degradation. Ceramic factory waste (figure 3), known as masonry rubble, is not sorted according to the reason for rejection, which may include:

- Breakage or deformation, which does not affect the intrinsic characteristics of the ceramic material.
- Firing defects, due to excessive heat (over-firing) or insufficient heat (under-firing), faults particularly associated with the use of old kilns and which may affect the physico-chemical characteristics of the product.

Fig. 3. Ceramic factory waste

Ceramic products are made from natural materials which contain a high proportion of clay minerals. These, through a process of dehydration followed by controlled firing at temperatures of between 700ºC and 1000ºC, acquire the characteristic properties of "fired clay". Thus, the manufacturing process involved in ceramic materials requires high firing temperatures which may activate the clay minerals, endowing them with pozzolanic properties and forming hydrated products similar to those obtained with other active materials.

Research carried out into the influence of firing temperatures on waste product properties has found that the chemical and mineralogical composition of ceramic masonry rubble resulting from incorrect firing temperatures (over- or under-firing) varies significantly from that of products obtained from optimal firing conditions. However, the temperature applied (around 900ºC) is sufficient to activate the clay minerals, with the result that the different rejects acquire similar pozzolanic properties. Furthermore, studies have been carried out into the viability of substituting cement by using ceramic rejects or masonry rubble as raw materials in prefabricated concrete, exploiting their pozzolanic properties

(Frías et al., 2008, Sánchez de Rojas et al., 2001; Sánchez de Rojas et al., 2003; Sánchez de Rojas et al., 2006; Sánchez de Rojas et al., 2007).

Ceramic masonry rubble must be suitably fine in order to be used as a pozzolanic additive in cement, and thus must be crushed and ground until reaching the specific surface, or Blaine value, of around 3500 cm^2/g. This material presents a chemical composition similar to other pozzolanic materials, with a strongly acid nature where silica, aluminium oxide and iron oxide predominate (75.97%), and with a CaO content of 12.41% and an alkali content of 4.22%. Loss through calcination is 3.44% and sulphate content, expressed as SO_3, is 0.79%. Mineralogical composition, determined by X-ray diffraction, mainly comprises the crystalline compounds quartz, muscovite, calcite, microcline and anorthite.

In order to assess pozzolanic activity, an accelerated method is used in which the material's reaction over time with a lime-saturated solution is studied. The percentage of lime fixed by the sample is obtained through calculating the difference between the concentration of the initial lime-saturated solution and the CaO present in the solution in contact with the material at the end of each pre-determined period. This assay is performed by comparing ceramic masonry rubble with two traditional additives described in the standard EN 197-1: 2005 (UNE-EN 197, 2005), fumed silica (FS) and siliceous fly ash (SFA), which are used as a reference.

The results, which are shown in Figure 4, demonstrate that ceramic waste presents pozzolanic activity; at one day, the percentage of fixed lime is 19% of all available lime. This level of activity is lower than that corresponding to the fumed silica considered, but greater than that of the fly ash. After longer periods, fixed lime values tend to equal out, and thus after 90 days very similar results are obtained for all three materials considered. It was also established that the firing temperatures used for producing ceramic material (around 900ºC) are sufficient to activate the clay minerals and thus obtain pozzolanic properties.

Therefore, in the light of these results, it can be stated that rejected ceramic material, or ceramic masonry rubble, presents acceptable pozzolanic properties, since the firing temperatures used in manufacture are ideal for activating the clays from which they are constituted.

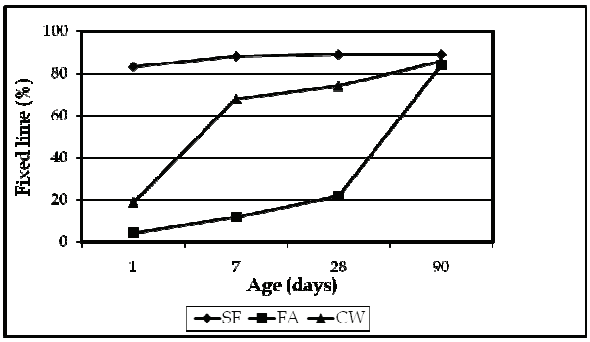


Fig. 4. Pozzolanic Activity

An important factor to be taken into account when studying construction materials is that of durability. The degradation of mortars and concretes caused by aggressive external agents is

usually due to the reaction between these agents and the cement paste. The degrading action of external chemical agents begins on the surface of mortar or concrete, gradually penetrating the interior as porosity, permeability and internal tensions increase and producing loss of mass and a reduction in strength as the degree of degradation advances. There is a long list of aggressive agents and substances; however, the most frequent include soft water, acids and some salts in solution containing soluble sulphates, ammonia and magnesium. In the present case, durability studies were conducted using the methodology reported by Koch & Steinegger (Koch & Steinneger, 1960). For durability assays, agents used included drinking water (the reference), artificial sea water (ASTM D114, 1999), sodium chloride (at a concentration of 0.5 M) and sodium sulphate (at a concentration of 0.5 M). For the cement pastes, ceramic masonry rubble was used as the pozzolanic material, substituting 20% cement. The water/cement ratio was 0.5.

Using the Koch & Steinegger corrosion index, the resistance of pastes to various aggressive agents was established. This index is obtained from the quotient between the flexural-tensile strength values of 56 day old cylinder samples maintained in a determined dilution of an aggressive agent and the values obtained for cylinder samples of the same age maintained in water. For a paste to be considered resistant to a determined aggressive agent, its Koch & Steinegger index value must be greater than 0.7 in this medium.

Results for pastes made with ceramic masonry rubble and CEM I-52.5R cement following standard EN 197-1:2005, where the cement/rubble ratio is 100/0 and 80/20, are shown in figure 5. It can be observed that all the cylinder samples except for the 100/0 samples maintained in sodium chloride, present a Koch & Steinegger index value greater than 0.7, and thus can be considered resistant to different aggressive media. Furthermore, according to the Koch & Steinegger index criteria, all pastes made by partially substituting cement with ceramic material showed better durability than pastes made with 100% cement, with higher index values except in the case of sea water, where values were slightly lower.

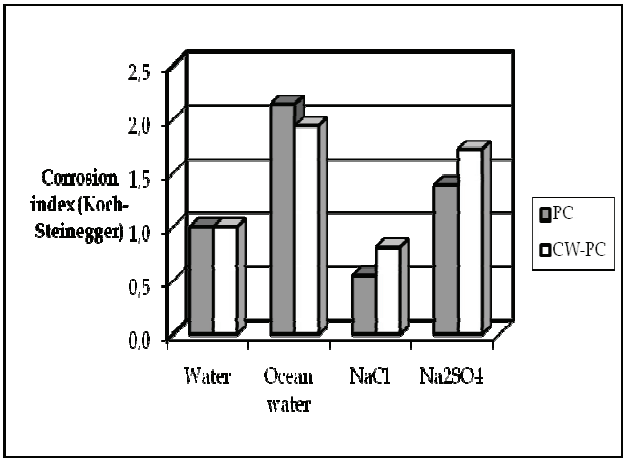
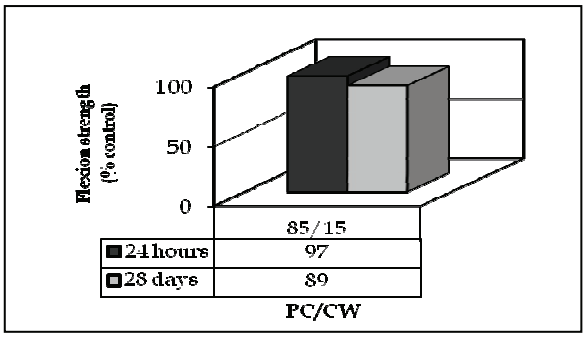


Fig. 5. Koch&Steinegger corrosion index

A study was conducted of the mechanical properties of mortars made according to the standard EN 196-1:2005: I part cement to 3 parts normalized sand, with a water/cement ratio of 0.5. 15% of the cement was substituted with ceramic material.

Results obtained for flexural and compressive strength, given as a percentage with respect to the control mortar (without masonry rubble) at 24 hours and 28 days, are shown in Figures 6 and 7, respectively.



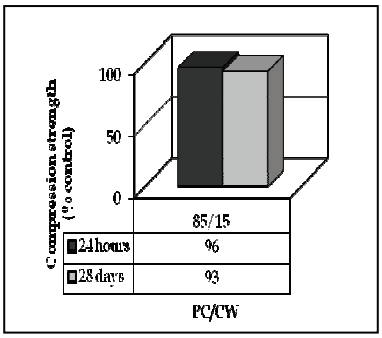


Fig. 6 and 7. Flexural-tensile and compressive strength

As can be seen, both the flexural and the compressive strength values obtained at 24 hours were very similar to those of the control mortar. However, at 28 days, values were slightly lower than those for the control mortar (without ceramic masonry rubble). Nevertheless, in all cases the reduction percentage, calculated with respect to the control, was lower than the degree of cement substitution, indicating that waste materials act as pozzolans, providing mechanical strength.

Therefore, this research confirms that ceramic masonry rubble endows cement with positive characteristics. As regards the economic advantages, these derive from energy savings in cement manufacture. Substituting a material that requires a costly thermal treatment, in this case clinkerization, with a material which is cheaper in energy terms (such as industrial waste which is normally dumped, even though it requires crushing and grinding before use), results in improved energy consumption and makes a positive contribution to environmental conservation.

3.- Ceramic waste as recycled aggregate

3.1. Introduction – Antecedents

Recycled aggregates can be defined as the result of waste treatment and management where, following a process of crushing to reduce size, sieving and laboratory analysis, the waste complies with technical specifications for use in the construction sector and civil engineering.

According to Ignacio (2007) it is not possible to carry out an exhaustive characterization of all kinds of recycled aggregates. Therefore, this topic will be discussed in more general terms by looking at concrete aggregates, asphalt agglomerate aggregates and other recycled aggregates which incorporate aggregates from clean ceramic material waste and aggregates from mixtures.

As mentioned previously, one of the objectives of the new waste reuse and recycling policies in the construction and industrial sectors is to use recycled aggregates as a substitute for conventional natural aggregates, with the aim of reducing both use of natural resources and

environmental impact caused by dumping. According to a Statistical Report by ANEFA (Asociación Nacional de Fabricantes de Áridos-Spanish Association of Aggregates Producers) (2008), consumption of aggregates in Spain in 2007 reached the figure of 479 million tons in the construction sector and 72 million tons in industrial applications (cement, glass and ceramics industries). Meanwhile, sources from the European Aggregates Association (UEPG) indicate that from the total volume of aggregates used by the construction sector in 2007, most (62.7%) was employed for manufacturing concrete, mortar and prefabricated blocks, followed by use in road construction. In the case of industrial use, most (82%) was destined for the manufacture of cement, whilst the remainder was employed for different industrial applications such as the manufacture of lime and plaster, glass and ceramics, among others.

A further important aspect for analysis, as mentioned at the beginning, is the energy factor. The processes involved in cement manufacture, in ceramics production, or in transport, endow construction materials with energy, called *embodied energy*. It has been estimated that of all the embodied energy incorporated in a building, only around 20% corresponds to the construction phase. Therefore, when a defective construction material is discarded, or a building demolished, a huge quantity of embodied energy is wasted. According to data provided by Alaejos (Anon. 2001), one of the best ways to take advantage of this waste is to include it in mortar and concrete manufacturing processes. This reuse not only recovers embodied energy but also reduces the number and size of dumps. A concrete capable of incorporating such waste would constitute an eco-efficient material.

The possibilities for using recycled aggregates in concrete production have been studied in depth, although such research has fundamentally concentrated on reuse of recycled aggregate from concrete. Thus, Sánchez and Alaejos (2003, 2005, 2006) established the possibility of using this kind of waste to substitute up to 20% of conventional coarse aggregate. This maximum substitution percentage is basically due to the high absorption coefficient of this kind of material, although they also established the possibility of reuse in combination with enhanced natural aggregates, and for structural concretes with a compressive strength equal to or less than 50 MPa. It is noteworthy that practically the same limitations are established in appendix 15 (*Recommendations for the use of recycled concrete*) of the recently published Spanish Instructions for Structural Concrete (EHE-2008**).**

Along the same lines, Huete et al. (2005) and Rolón et al. (2007) established maximum reuse limits of 20%, also highlighting the high absorption coefficient of this material and reporting a 6% reduction in strength after 28 days – aspects which could be improved, especially as regards absorption, by the use of superplastifying additives. Other studies have established maximum proportions at 50% (González and Martinez, 2005), although they also emphasized the high absorption coefficient and the need to increase the water/cement ratio by approximately 6% with respect to the reference concrete in order to achieve strength characteristics greater than 30 N/mm^2. Likewise, Domínguez et al. (2004) reported the viability of recycled aggregate reuse in concretes with strengths of 150, 200 and 250 kg/cm^2, establishing the possibility of reuse via a small increase in the quantity of cement employed (2.5%), whilst at the same time stressing the consequent environmental and economic advantages. Along the same lines, Evangelista and de Brito (2007) analysed the feasibility of reusing CDW as fine aggregate in concretes, in proportions of 30% with respect to the reference concrete without noting any relevant reduction in compressive strength. Kim y Kim (2007) demonstrated the possibility of producing recycled concrete (MSC-Modified

sulphur concrete) with better physical properties (compressive strength greater than 78 N/mm^2 and an absorption coefficient of 0.5%) than those of conventional concrete using a mixture of modified sulphur, recycled aggregates and dust obtained from concrete debris.
Other studies have focused on the reuse of CDW from the stony fraction corresponding to ceramic waste, both in the manufacture of concrete and in pastes and mortars. For example, de Brito et al. (2005) and Correia et al. (2006) reported the use of recycled aggregates of ceramic origin in non-structural concrete, which showed good abrasion resistance and tensile strength and offered the possibility of use as concrete slabs (also due to the greater durability of recycled concrete). As in previous studies, they reported higher absorption rates for recycled aggregates, which could be partially resolved by implementing pre-saturation methods. Other research has demonstrated the possibility of reusing recycled ceramic aggregates as coarse aggregate in structural concrete (Senthamarai and Devadas Manoharan, 2005), although with some reservations until further in-depth research is conducted. Koyuncu et al. (2004) analysed 3 types of ceramic waste (paste, dust and crushed floor tiles) as road subbase filler and as a substitute for natural aggregates in concrete, demonstrating the feasibility of reuse in non-structural concrete (concrete blocks) with a strength of 40-50 kg/cm^2. Likewise, Binici (2007) used crushed ceramic waste and pumice stone as a partial substitute for fine aggregates in the production of mortar and concrete, finding that the resultant product showed good compressive strength and abrasion resistance, together with less penetration by chlorides which could provide greater protection for the reinforcement used in reinforced concrete. Similarly, Puertas et al. (2006) studied the use of 6 types of ceramic waste as an alternative material in the production of unrefined cement. The research demonstrated the viability of this use, as the waste presented a suitable chemical and mineralogical composition together with a level of pozzolanic activity. Another noteworthy study was that of Portella et al. (2006) in which the possibility of incorporating ceramic waste from electrical porcelain into concrete structures was analysed. This study demonstrated the viability of reuse, although the damaging effect of certain by-products which generated an alkali-aggregate reaction made it necessary to use sulphate resistant cement. Gomes and de Brito (2009) studied the viability of incorporating coarse aggregate from concrete waste and ceramic block waste in the production of new concrete, and concluded that as regards durability, structural concrete can be made using recycled aggregates, but that the 4-32 mm fraction of natural aggregates cannot be totally substituted. Cachim (2009) crushed and used waste from different kinds of ceramic blocks as a partial substitute (15, 20 and 30%) for coarse natural aggregates, observing that with 15% substitution there was no change in concrete strength, whilst when 15-20% was substituted, alterations were noted according to the kind of ceramic block used and when 20-30% was substituted, the recycled concrete showed a reduction in strength regardless of the kind of ceramic block from which the recycled aggregate had been obtained. Silva et al. (2010) analysed the feasibility of using red ceramic waste as a partial and total substitute for natural fine aggregates, finding that at substitution percentages of 20 and 50% results which were at all times superior to those for the reference mortar. However, when natural fine aggregate was totally substituted, behaviour was poorer than that of the reference.
Finally, we should mention the most relevant research carried out to date by members of this research team, López et al. (2007), Juan et al (2007), Guerra et al. (2009), and Juan et al. (2010), in which various mechanical assays have been conducted under laboratory conditions in order to test the use of sanitary ware waste and white ceramic dust. Findings

indicate that reuse is viable, producing strength characteristics greater than for the reference concrete, established as 30 N/mm².

3.1. Using sanitary ware waste as recycled aggregate in structural concrete

Spain is the world leader in the ceramic sanitary ware market. The industry produces over 7 million items a year and generates approximately 24 tons of waste a month, which is simply dumped. The percentage of products considered unsuitable for sale, and thus rejected, depends on the kind of installation concerned and the corresponding product requirements.
The reuse of ceramic waste from the sanitary ware industry as a partial substitute for conventional coarse aggregates requires a simple treatment process comprising crushing, using a jaw-crusher, and subsequent washing and sieving.
Two fractions are obtained from crushing; the fine fraction of less than 4 mm in size, and the coarse fraction, over 4 mm in size. It is the coarse fraction (figure 8) which is used as recycled aggregate in the production of recycled concrete.

Fig. 8. Recycled ceramic aggregate

This material has a composition similar to that of other ceramic materials, with a strongly acidic character and a predominance of silica, aluminium and iron oxide (93.81%); CaO content is 0.63% and alkali content, 4.45%. Mineralogical composition, determined by X-ray diffraction, mainly comprises quartz, orthoclase, mullite, hematite and zircon.
In order to assess the suitability of this material in the production of concrete for structural purposes, the physical-mechanical characteristics indicated in table 2 were determined, and the results obtained were compared with those for natural coarse aggregates (gravel), confirming compliance with the specifications given in the Spanish Instruction for Structural Concrete (EHE-08).

Characteristic	Standard
Particle size distribution. Assessment of fine aggregates	EN 933–1
Dry sample density	EN 1097-6
Water absorption coefficient	EN 1097-6
Elongation Index	EN 933-3
"Los Angeles" coefficient	EN 1097-2

Table 2. Characterization of aggregates

The granulometric curves presented in figure 9, were obtained from a granulometric analysis of aggregates (sand, gravel and recycled ceramic aggregates). From an analysis of

these curves it can be seen that all the aggregates present continuous granulometric curves, which would have a positive influence on concrete docility. Furthermore, it should be noted that the curve for recycled ceramic aggregate is very similar to that for natural coarse aggregate.

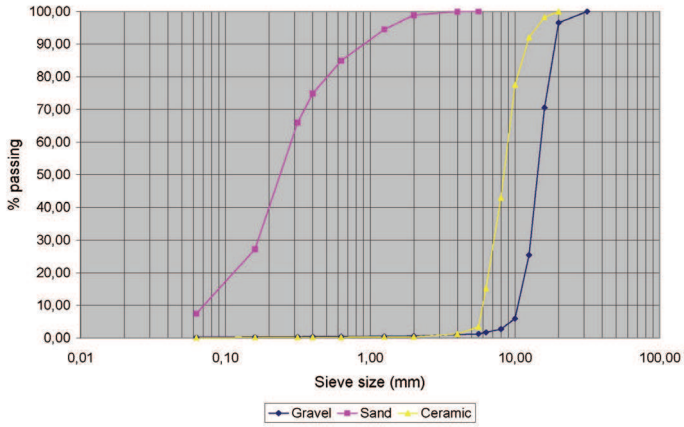


Fig. 9. Aggregate size distribution curves

The results obtained for the other physical-mechanical characteristics determined are presented in table 3.

Characteristic	Gravel	Ceramic	EHE-08
Grading modulus	6,93	6,17	-
Maximum size (mm)	20	12,5	-
Fine content (%)	0,22	0,16	< 1,5
Dry sample real density (kg/dm^3)	2,63	2,39	-
Water absorption coefficient (%)	0,23	0,55	$\leq$ 5
Elongation Index (%)	3	23	< 35
"Los Ángeles" coefficient (%)	33	20	$\leq$ 40

Table 3. Characterization results of aggregates

The results presented in table 3, show that the percentage of fine aggregate in the recycled aggregates is lower than that for gravel. Dry sample density for natural aggregates is higher than that for aggregates of a ceramic origin, enabling us to deduce that concretes made with the latter would be slightly lighter than the reference concrete. As was expected, the absorption coefficient for the recycled aggregate is higher than that of gravel, but this difference is not highly significant and would not, therefore, have much impact on the workability of concrete made with this kind of recycled aggregate. With regards to the elongation index, a substantial difference can be observed between the two aggregates, a result explained by the process used for obtaining the recycled aggregate, which produced an aggregate with irregularly shaped, sharper edges. As for the values obtained for resistance to fragmentation, these indicated that the recycled aggregate presented higher

resistance values than the natural aggregate, leading us to predict that the concretes obtained with the former would have greater compressive strength.
Consequently, in the light of these results, it can be stated that recycled aggregates from crushed ceramic sanitary ware present suitable characteristics for partial substitution of natural coarse aggregates. The natural aggregates used were of a siliceous nature; the gravel comprised pebbles and river sand was used. The cement used was Portland cement without additives (CEM I), which complies with the specifications set down in the Instructions for the Authorization of Cements (Instrucción de Recepción de Cementos (RC-08)); rapid hardening and strength class 52.5 N/mm^2
Mix design was determined following the de la Peña method, a commonly used method for calculating mix proportions for structural concrete, whereby the initial step is to establish the characteristic concrete strength desired. In this case, the aim was to produce recycled concrete for structural purposes with a characteristic strength equal to 30 N/mm^2, and the proportion of gravel to be substituted by recycled ceramic aggregate was set at 15-20 and 25%. As a result of this process, the mixes presented in table 4 were obtained. As can be seen in this Table, all mixes complied with requirements regarding minimum cement content and maximum water/cement ratio given in the EHE-08 to ensure durability.

Type concrete	**Materials (kg/dm^3)**				
	Sand	Gravel	Ceramic	Cement	Water
Concrete reference (CR)	716,51	1115,82	0,00	398,52	205,00
Concrete containing 15% recycled aggregate (CC-15)	723,48	948,45	162,32	390,36	205,00
Concrete containing 20% recycled aggregate (CC-20)	725,81	892,66	216,43	387,64	205,00
Concrete containing 25% recycled aggregate (CC-25)	728,14	836,87	270,53	384,91	205,00

Table 4. Mix proportions of concretes

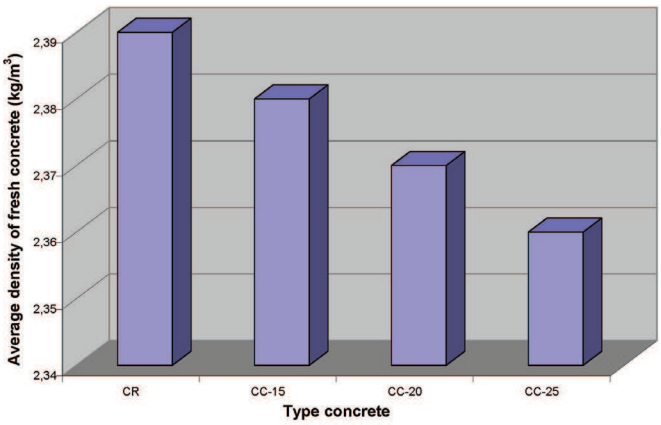


Fig. 10. Average density of fresh concrete

A study of fresh and hardened concrete properties was carried out using 15 x 30 cm cylinder samples made according to the standard EN 12390-1 and cured following standard EN 12390-2. The fresh concrete properties studied were consistency, using the Abram's cone slump test (EN 12350-2), and density (EN 12350-6). Consistency testing showed that all the concrete mixtures presented a soft consistency (6-9 cm), as recommended in EHE-08, section 31.5.

As can be seen in figure 10, results obtained for fresh concrete density studies showed that as the percentage of natural aggregates substituted rose, density of the recycled concrete fell. The results obtained for compressive and tensile splitting strength are shown in figure 11 as a percentage with respect to the reference concrete (with natural aggregates only), for 7, 28 and 90 days in the case of compressive strength, and at 28 days for tensile strength.

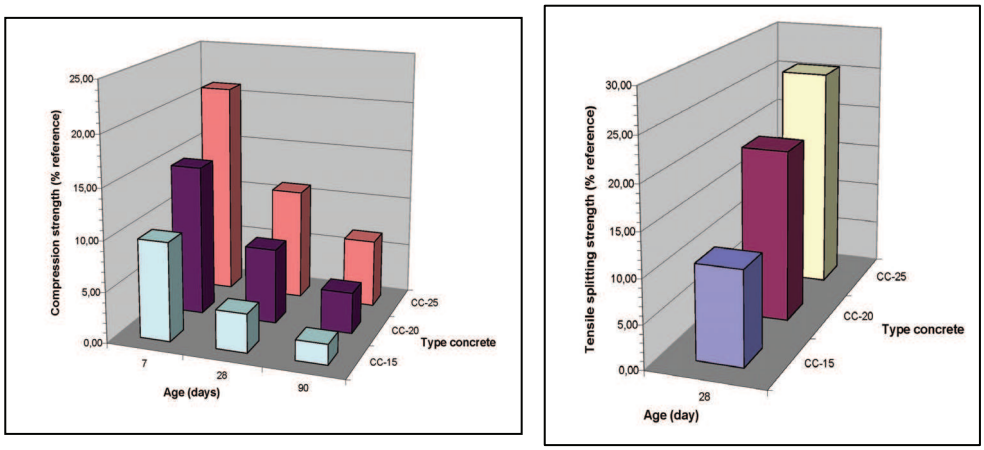


Fig. 11. Compressive and tensile splitting strength

As can be observed, both the compressive and tensile strengths obtained at different ages are higher for recycled concrete than the reference concrete. In addition, as the percentage of conventional coarse aggregate substituted by ceramic coarse aggregate rose, so too did the strength when compared with the reference concrete.

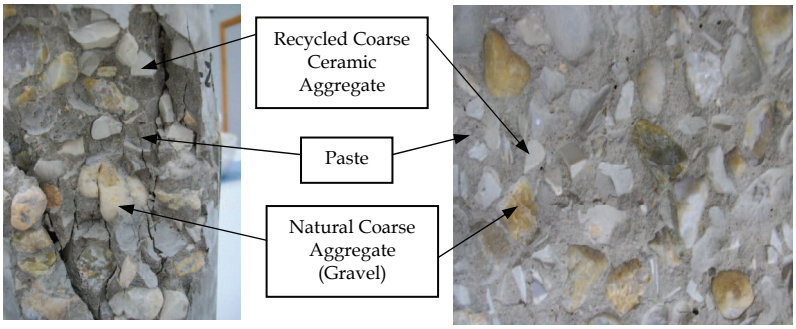


Fig. 12. Specimens showing natural and ceramic recycled coarse aggregates and cement paste

Furthermore, this improved mechanical behaviour on the part of recycled concrete is a consequence of the fact that crushed aggregate presents a greater specific surface area than pebble aggregate and thus their adherence is greater, which in turn results in a more compact aggregate-paste interfacial transition zone (ITZ) in the case of recycled aggregate than in that of natural aggregate (figure 12).
Finally, it should be noted that the different crystalline phases resulting from the hydration process during concrete setting and hardening were identified by X-ray diffraction, the results of which are presented in figure 13.

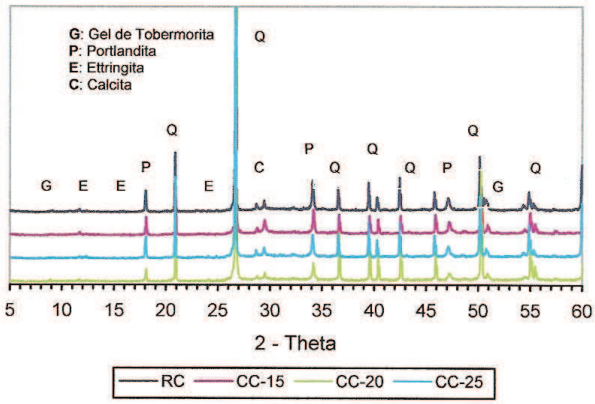


Fig. 13. X–ray diffraction of different concrete pastes

An analysis of the results demonstrates that the introduction of recycled ceramic aggregates has no negative effects on cement hydration, and can thus be considered an inert material.
In the light of the results obtained from the research conducted to date, we can confirm that following prior treatment (crushing, washing and sieving), waste from the ceramic sanitary ware industry can be used to partially substitute natural coarse aggregates, and indeed confers the recycled concrete with positive characteristics as regards mechanical behaviour. The recycled concrete obtained can be used for structural purposes, since its characteristic compressive strength exceeds 25 N/mm^2, the minimum strength requires for structural concrete.
Reuse of this kind of waste has many advantages, not least of which are the economic advantages, including job creation in companies specializing in the selection and recycling of this kind of material. It goes without saying that reuse is better than recycling; thus, there are considerable environmental benefits to using materials with such a high level of *embodied energy*, such as a reduction in the number of natural spaces employed as refuse dumps and a decrease in the quarrying necessary to extract conventional natural aggregates. Indirectly, all the above contributes to a better quality of life for citizens.
Lastly, it should be noted that the production of **concrete made with recycled aggregates** comprises part of the **correct management of CDW** – Law 10/98, EU ministerial council of the 27th June, 2006 – given that:

- it avoids the use of new raw materials
- it reduces waste generation

- and it makes maximum use of the energy already contained in the waste

Together, these factors constitute one of the basic cornerstones of sustainable development.

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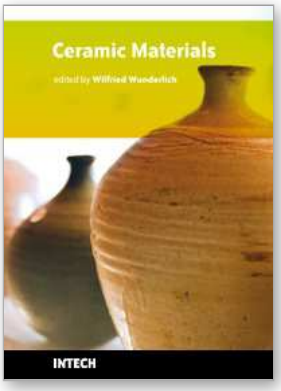

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