24

Using Ceramic Materials in Ecoefficient Concrete and Precast Concrete Products

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1. Introduction

The industrial and economic growth witnessed in recent decades has brought with it an increase in the generation of different types of waste (urban, industrial, construction, etc.) despite the waste management policies which have been adopted nationally and internationally.

The practice of dumping and/or the inadequate management of waste from the various manufacturing sectors have had a notable impact on the receiving environment, leading to water, soil, air and noise pollution, amongst other complications, and adding to existing environmental problems. At the same time, these practices represent an economic cost. However, if waste is managed correctly it can be converted into a resource which contributes to savings in raw materials, conservation of natural resources and the climate, and promotes sustainable development, all of which complies with strategies for sustainable development within the European Union and Spain.

Spain occupies an important position in the ceramics industry world market, second only to China as a producer of wall and floor tiles and, according to data from the Spanish Ministry for Industry, Tourism and Commerce (Subdirección General de Estudios y Planes de Actuación, 2009) , the world leader in the ceramic sanitary ware industry. Within the European Union, Spain is the leading manufacturer of ceramics: 26.11 % of all ceramics manufacturing facilities in the European Union are located in Spanish territory (Fraunhofer Institute for Systems and Innovation Research Öko-Institut, November 2009).

The Spanish ceramics industry includes the following sectors: ceramic flooring and wall coverings (ceramic floor and wall tiles, respectively), ceramic sanitary ware, bricks and roofing tiles, refractory materials, ceramics for technological applications (insulators, etc.), and ceramic objects for domestic and decorative purposes (tableware and ornaments).

This sector has witnessed a fall in production as a direct result of the continuing world economic crisis. Nevertheless, production figures for the main ceramics subsectors in Spain for 2008 were as follows: the brick and roofing tile subsector, 20 million tons (according to data from HISPALYT); the tiles and flooring subsector, 495.2 million m^2 (according to ASCER); and the ceramic sanitary ware subsector, 7 million items, providing an indication of the volume of waste involved. The percentage of items rejected for sale and thus discarded depends on the type of industry in question, on product requirements and on other technical considerations. In total, rejects account for 5-8 % of final production according to data provided by manufacturers.

The manufacturing process inevitably generates a percentage of products deemed unsuitable for sale and thus discarded, regardless of any improvements made to the manufacturing process. The two principal reasons for rejection are breakage and deformation, defects which do not affect the intrinsic properties of the ceramic material, or firing defects as a result of too little or too much heat, which do affect the material's physical and chemical properties.

Waste from the ceramics industry is classified as non-hazardous industrial waste (NHIW). According to the Integrated National Plan on Waste, 2008-2015 (España. Ministerio de Medio Ambiente y Medio Rural y Marino, 26/02/2009), NHIW encompasses all waste generated in the course of industrial production which is not classified as hazardous in Order MAM /304/2002 (España. Ministerio de Medio Ambiente, 19/02/2002), of the 8th of February, establishing the classification of waste in accordance with the European Waste Catalogue (EWC) using the following codes:

- 10 Waste from thermal processes
- 10 12 Waste from the manufacture of ceramic goods, bricks, roofing tiles and construction materials
- 10 12 08 Waste ceramics, bricks, roofing tiles and construction materials (after thermal processing)

Ceramic goods are produced from natural materials containing a high proportion of clay minerals. Following controlled thermal processing, these acquire the characteristic properties of fired clay.

These properties include durability, stable behaviour throughout its service life, chemical inertia, heat- and fire-resistance and good resistance to electricity. As regards chemical composition these materials present a highly acid nature, with a predominance of silica, aluminium and even iron oxide, in addition to other compounds present in lesser proportions (Commission, August 2007).

This chapter will address and focus on the extent to the use of ceramic waste and ceramic and sanitary ware rubble in the applications which have been developed (structural and precast ecoefficient concretes) comply with current standards. The scientific aspects of this research have been described elsewhere (Juan et al., 2010).

2. State of the art

Much research worldwide has been conducted on the recycling of these kinds of wastes, and many researchers are involved in the study of this subject. The reason for this interest can be located in the characteristics presented by these materials, which make them extremely versatile and provide them with great potential as regards being used as raw materials in various construction sector applications; they can be used as an active additive thanks to their pozzolanic properties, or as recycled aggregate in the manufacture of mortars and concretes.

Concerning the study of ceramic waste as an active additive, research into the feasibility of reusing roofing tiles as a partial substitute for cement is of particular note. Among the studies which have been conducted in this field, those reported by Ay and Unal (Ay and Unal, 2000, Ay and Unal, 2001), Bensted y Munn (Bensted and Munn, 2001) and Lavat et al. (Lavat et al., 2009) are especially relevant. These authors found that substitution percentages of below 30% had no negative effects on the mechanical behaviour of Portland cement, thus demonstrating the viability of reusing ceramic roofing tile waste in the production of pozzolanic cements.

In Spain, the authors of this chapter, all members of the Eduardo Torroja Institute of Construction Sciences – CSIC (Instituto de Ciencias de la Construcción Eduardo Torroja - CSIC), have conducted intensive research into the possibility of reusing ceramic rubble as an additive in the production of cement and the manufacture of concrete roofing tiles, (de Rojas et al., 2001a, de Rojas et al., 2001b, Sánchez de Rojas et al., 2003, de Rojas et al., 2006, De Rojas et al., 2007) (Marín Andrés and Sánchez de Rojas, 2004) (Frías et al., 2008) (Sánchez et al., 2008), the results of which will be described below.

In addition to this waste product, the reuse of waste from clay blocks has also been amply analysed, examining the viability of partial substitution of cement in the production of mortars. Results indicate that such substitution yields improved mechanical properties and durability. Examples of recently published research in this field would include studies by Silva et al. (Silva et al., 2008, Silva et al., 2009) and Naceri and Hamina (Naceri and Hamina, 2009).

The use of waste from the ceramics industry as aggregate in the production of concretes has received less international research attention than research into other types of construction and demolition waste (CDW). Nevertheless, the studies mentioned below are worthy of note.

Koyuncu et al. (Koyuncu et al., 2004), Topcu (Topcu and Guncan, 1995), de Brito et al. (de Brito et al., 2005, de Brito, 2010), Correia et al. (de Brito et al., 2005) and Bakri (Bakri et al., 2006) all concluded that it was possible to use recycled ceramic aggregate in the production of non-structural concretes, finding that these subsequently presented good abrasion resistance and tensile strength, and in paving slabs, since recycled concrete also presented increased durability. Portella et al. (Portella et al., 2006) analysed the viability of incorporating ceramic waste from electrical insulator porcelain in concrete structures, finding that reuse was possible but necessitated the use of sulphate-resistant cements due to the negative effects of certain by-products which generated an alkali-aggregate reaction. Gomes et al. (Gomes and de Brito, 2007, Gomes and de Brito, 2009) studied the viability of incorporating coarse aggregate from concrete waste and ceramic block waste in the production of new concretes, and found that structural concrete made using recycled aggregates presented satisfactory durability, but that the 4-32 mm fraction of natural aggregates cannot be totally substituted.

Lastly, Guerra et al. (Guerra et al., 2009), López et al. (Lopez et al., 2007) and Juan et al. (Juan et al., 2007, Valdes et al., 2010) studied the mechanical and physical properties of concretes in which conventional coarse aggregate had been partially substituted by coarse ceramic aggregate obtained by crushing ceramic sanitary ware, and natural fine aggregate had been substituted by powdered ceramic material, obtaining satisfactory results in both cases.

3. Ceramic sanitary ware waste as recycled coarse aggregate in ecoefficient concretes

3.1 Introduction

In this section, the viability of using waste from the ceramic sanitary ware industry as coarse aggregate in the production of structural ecoefficient concretes will be analysed. Firstly, the aggregate will be characterised, examining physical, chemical and mechanical properties. Secondly, the compliance of concretes incorporating this kind of waste with the specifications established in current standards will be analysed.

3.2 Experimental studies

3.2.1 Ceramic sanitary ware waste as coarse aggregate

The waste used for this study came from ceramic sanitary ware industry rejects, which were crushed and sieved to obtain the 12.5/4 mm granulometric fraction.

The chemical composition of this waste was strongly acidic in nature, with a predominance of silica (66.57 %) and aluminium (21.60 %). Lesser quantities of other oxides were also present, principally iron oxide (1.41 %), calcium oxide (2.41 %), sodium oxide (1.41 %), potassium oxide (2.79 %) and zirconium oxide (1.48 %). The waste did not contain chlorides, soluble sulphates or total sulphur compounds.

The aggregate employed in the production of concrete, whether natural or recycled, must present physical, chemical and mechanical properties which comply with the specifications established in the standards EN 12620 (AENOR, 2009c) and EHE-08 (Comisión Permanente del Hormigón, 2008), article 28, Appendix 15.

The properties determined in the ceramic aggregate, together with the methodology employed, are given in Table 1.

Tests	Standards	Specification
Particle size grading	EN 933-1 / EN 933-2	Maximiun and minimun size
Maximum fines content	EN 933-1 / EN 933-2	$\leq$ 1.5 % maximium percentage which passes through a 0.063 mm sieve
Water absorption	EN 1097-6	< 4.5 % of the total weight of the sample
Resistance to wear	EN 1097-2	$\leq$ 40 % of the total weight of the sample
Flakiness index	EN 933-3	< 35 % of the total weight of the sample
Organic material	EN 1744-1	No presence (point 28.7.3 - EHE-08)
Alkali-aggregate reactivity	EN 932-3	No potential reactivity

Table 1. Specifications for coarse aggregate employed in concrete production according to the standards EN 12620 and EHE-08

3.2.2 Incorporation of ceramic sanitary ware waste in concrete production

Once it had been confirmed that the new recycled aggregate was apt for concrete production, substitution percentages of 20 and 25 % of natural coarse aggregate volume were established.

The next step was to calculate the mix design of the various concretes, using the de la Peña method (Arredondo, 1968), to obtain the mix proportions for the different components: sand, gravel, ceramics, cement (CEM I 52.5 R) and water. To this end, a characteristic strength of 30 N/mm^2 and a soft consistency were established, in compliance with the recommendations given in Section 31.5 of the EHE-08.

The final step was to mix, prepare and cure the concrete test specimens following standard EN 12390-2 (AENOR, 2009a), before conducting assays to assess compliance with the specifications established by the EHE-08 for structural concretes (see Table 2).

Test	Standard	Specification
Minimum cement content	-	250 kg/m^3
Maximum water/cement ratio	-	0.65
Compressive strength (28 days)	EN 12390-3	>25 N/mm^2
Resistance to water penetration	EN 12390-8	See table 6
Total chloride content	UNE 83987	0.4 and 0.2 % of the cement weight for passive and active reinforcements, respectively

Table 2. Specifications for structural concretes, EHE-08

3.3 Results

3.3.1 Ceramic sanitary ware waste as coarse aggregate

It can be seen from Figure 1 that the particle size grading obtained for recycled ceramic aggregate is located within the granulometric zone established in Point 4.3.2 of the standard EN 12620, although it presents a lower percentage than that established by this zone for the 4/6 fraction. Furthermore, it can be observed that recycled coarse ceramic aggregate complies with the maximum content of fine aggregate (< 0.063 µm) acceptable in coarse aggregate.

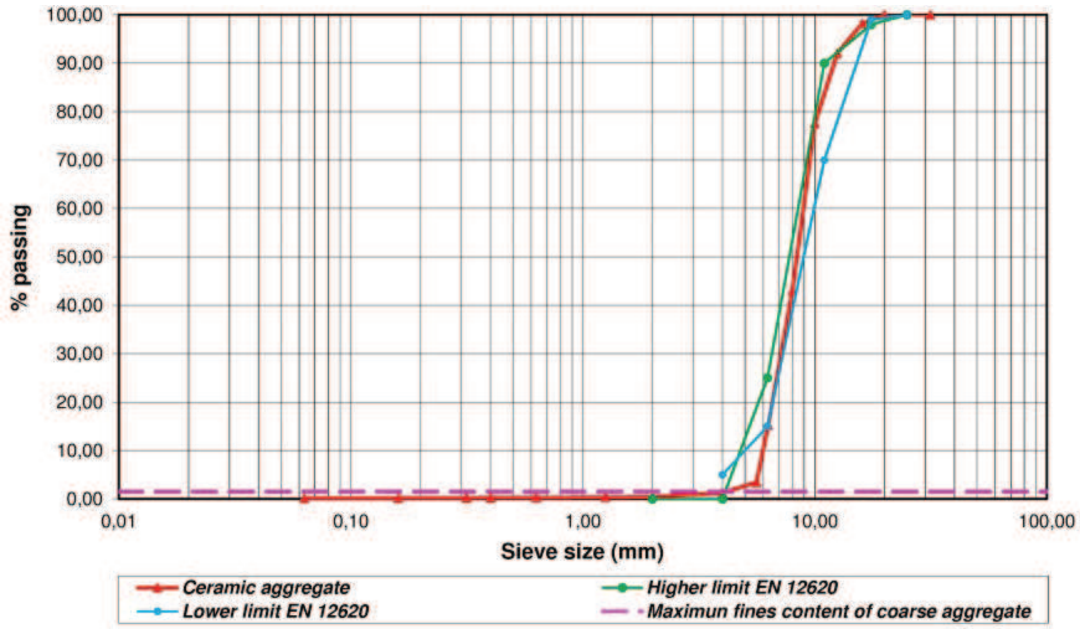


Fig. 1. Particle size grading of ceramic aggregate

The physical and mechanical properties of recycled ceramic aggregate were determined, and the results are presented in Table 3. In all cases, the properties complied with the specifications given in Table 1.

Properties	Value (of the total weight of the sample)
Water absorption	0.55
Resistance to wear	20
Flakiness index	23

Table 3. Physical and mechanical properties of ceramic aggregate

The water absorption values shown in Table 3 are lower than those found in other studies (Cachim, 2007) (Topcu and Canbaz, 2007), explained by the fact that these authors studied a different kind of ceramic waste, namely, blocks and roofing tiles, respectively.

Furthermore, it should be mentioned that this aggregate presented significant resistance to wear, with a lower value for the Los Angeles coefficient than that found for other recycled aggregates (Sánchez and Alaejos, 2006) (Martín-Morales et al., 2011), whilst also presenting a flaky morphology due both to the initial form of the waste and the subsequent crushing process.

As regards the presence of organic material which could affect time taken to harden and compressive strength, none were detected in the ceramic aggregate, which thus complied with the specifications established in the EHE-08 (see Table 1).

Lastly, with respect to the alkali-aggregate reaction, none of the minerals listed in Table 28.7.6 of the EHE-08 as being susceptible to reacting in an alkaline medium were found in the ceramic aggregate. Consequently, it can be concluded that this new recycled aggregate does not present an alkali-silica reactivity.

3.3.2 Incorporation of ceramic sanitary ware waste in concrete production

Results of concrete mix design for conventional concrete (CC) and recycled concretes incorporating 20 or 25 % of recycled aggregate (RC-20 and RC-25, respectively) are given in Table 4.

Type concrete	Material (kg/m³ concrete)					a/c
	Sand	Gravel	Ceramic	Cement	Water	
CC	548.63	1231.39	0.00	389.93	205.00	0.53
RC-20	575.65	971.64	219.96	379.10	205.00	0.54
RC-25	570.21	916.82	276.74	376.58	205.00	0.54

Table 4. Mix proportions of concretes

In the Table above, it can be seen that cement content and the water/cement ratio (w/c) comply with the specifications given in Table 1, thus ensuring satisfactory durability of the various concretes throughout their service lives and resistance to damage by chemical, physical and biological agents.

Concretes which incorporated ceramic aggregate presented greater compressive strength than conventional concrete, as shown in Figure 2. In the same figure, it can also be seen that compressive strength increased as the proportion of ceramic aggregate rose.

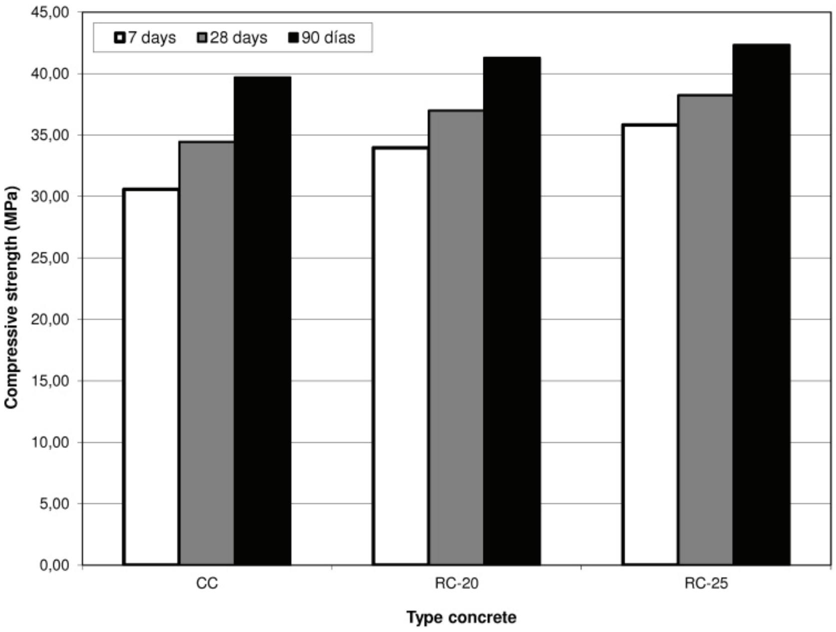


Fig. 2. Compressive strength of the concretes

The improved behaviour of the recycled concretes is primarily due to the morphology of ceramic aggregate, which provides better adhesion to the paste than natural aggregate. These results coincide with those obtained by Pacheco y Jalali (Pacheco-Torgal and Jalali, 2010) and Cachim (Cachim, 2009), who also found that recycled concretes presented improved mechanical properties.

In Figure 2 it can be seen that for all the test specimen ages assayed, the strength obtained for all concretes was better than the minimum characteristic strength required for reinforced concrete (see Table 2), as established in Point 31.4 of the EHE-08.

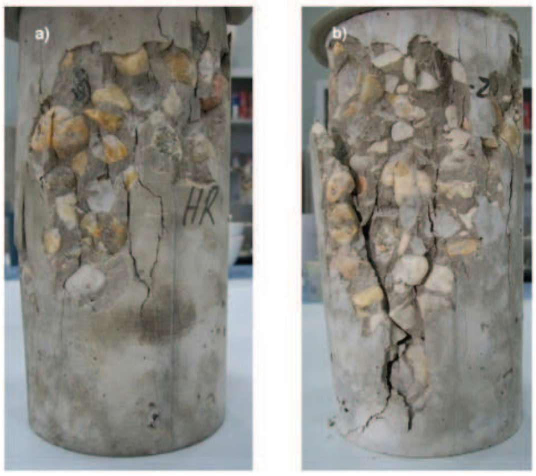


Fig. 3. Types of compressive fracture: a) Concrete CC. b) Recycled concrete RC-25

As regards the kinds of fractures observed in the various test specimens following fracture assays, these were all within the acceptable limits established in Point 8 of the standard EN 12390-3 (AENOR, 2009b). As is clearly depicted in Figure 3, the fractures present in both concretes (CC and RC-25) were similar, confirming that the incorporation of ceramic aggregate had no negative effects on the behaviour of concrete in this respect.

The results for impermeability of the recycled concretes are given in Table 5, showing maximum and average depth of water penetration under pressure. It can be seen from this table that the incorporation of ceramic aggregate did not lead to differences in maximum depth, which remained constant, whereas average depth increased slightly as the percentage of substitution rose.

Type concrete	Maximun depth (mm)	Average depth (mm)
CC	27	11
RC-20	26	12
RC-25	27	15

Table 5. Results of maximum and average depth of water penetration for concretes

Point 37.3.3 of the EHE-08 establishes that a concrete may be considered sufficiently impermeable to water if it complies with the specifications described in Table 6:

Environmental exposure class	Specification for the maximum depth (mm)	Specification for the average depth (mm)
IIIa, IIIb, IV, Qa, E, H, F, Qb (in the case of mass concrete or reinforced concrete elements)	50	30
IIIc, Qc, Qb (only in the case of pre-stressed concrete elements)	30	20

Table 6. Specifications for maximum and average depth of water penetration in concretes, as established in Point 37.3.3 of the EHE-08

From a comparative analysis of Tables 5 and 6, it can be concluded that the recycled concretes present a porous structure which renders them impermeable to water irrespective of the environment in which they are exposed, confirming their satisfactory behaviour when exposed to aggressive environmental.

Lastly, the results of the analysis to determine total chloride content in the concretes indicated the absence of chlorides at a depth of 25 mm in conventional concrete (CC), 26 mm in recycled concrete with 20% ceramic aggregate (RC-20) and 27 mm in recycled concrete with 25 % ceramic aggregate (RC-25).

According to Point 37.2.5 of the EHE-08, nominal thickness of concrete will vary depending on type of exposure, characteristic strength of the concrete, type of cement used and level of control. Consequently, assuming a service life of 100 years, the nominal thickness corresponding to the concretes produced in the present research would be 30 mm, it can be seen that the concretes incorporating ceramic aggregate comply with this durability specification.

3.4 Conclusions

Waste from the ceramic sanitary ware industry presents physical, chemical and mechanical characteristics which comply with the specifications established by current standards, confirming that they are apt for use as coarse aggregate in the production of concrete.

The recycled concretes complied with all requirements established in the EHE-08 for structural concretes, and perhaps most importantly, showed an increase in compressive strength.

The durability of the recycled concretes was similar to that of conventional concrete, confirming that they are apt for use as structural concretes in relatively aggressive environments.

To summarise, this ceramic waste can be used in the production of structural concretes, thus avoiding the use of new raw materials, reducing the generation of waste and making maximum use of the embodied energy contained in this waste, with all the consequent advantages this implies.

4. Use of ceramic rubble in the manufacture of concrete roofing tiles

4.1 Introduction

Ceramic goods 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, they acquire the characteristic properties of fired clay. Thus, the manufacture of ceramic products involves high firing temperatures and these may lead to activation of the clay minerals, which then acquire pozzolanic properties. It is well-known that one of the first materials used for their pozzolanic properties were thermally treated clays, a material which has much in common with fired clay products.

Activation of the clays is achieved firstly through a process of dehydration, which starts to occur at temperatures of around 500ºC, accompanied by the separation of amorphous aluminium. This latter is extremely active, and its maximum concentration is 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 calcination at temperatures of between 540ºC and 980ºC. On the other hand, illite type clays require higher temperatures for activation, as do the schist clays containing a high proportion of vermiculite, chlorite and mica.

This section will focus on a study of ceramic rejects, investigating their application as substitute for aggregate and cement in the production of precast concrete and in particular, concrete roofing tiles. The initial phase was conducted in the laboratory, and subsequently industrial trials of concrete roofing tiles were carried out.

4.2 Experimental studies

4.2.1 Ceramic rubble as pozzolanic material: laboratory tests

The ceramic rubble used in this study was crushed and sieved to two different grades of fineness in order to provide two different kinds of ceramic material, CC1 (5000 cm^2/g) and CC2 (3500 cm^2/g).

The chemical composition of this ceramic rubble was similar to that of other pozzolanic materials, namely, it presented a strongly acidic nature where silica, aluminium and iron oxides represented around 70% of the total content in most cases.

Assessment of pozzolanic activity was carried out using an accelerated method (40ºC), studying the reaction of the material to a lime-saturated solution over time. The percentage of lime fixed by the sample was obtained by calculating the difference between the concentration of the initial lime-saturated solution and the concentration of CaO present in the solution following contact with the sample for a determined period of time.

4.2.2 Ceramic rubble in the manufacture of concrete roofing tiles: factory tests

The industrial trials were conducted at two different concrete roofing tile factories, and consisted of incorporating ceramic rubble as a component in the manufacture of concrete roofing tiles. Each factory used a different type of cement, which is indicated in each case.

Concrete roofing tiles are generally shaped using pressure or vibration of a mortar presenting suitable granulometry, composed mainly of mineral grains, pigments, water and the later incorporation of additives.

4.2.2.1 Manufacturing process

The manufacturing process comprises the following two stages:

- *Preparation of the concrete*: The mix design of components (aggregate, cement, pigments and additives) refers to the precise weight required to produce the mixture. Water is the only component added in volume rather than weight, where volume required depends on the moisture content of the aggregate.

  Generally, high intensity mixers are employed, capable of producing a homogeneous mix and obtaining excellent dispersion of pigments, to ensure the even colour required in the finished product.

  Once the mixing process is complete and the concrete presents the required consistency, the mixture is taken via a series of mechanical transport systems to the tileworks.
- *Chaping the tiles*: The tiles are shaped by automatic roofing tile machines, which compact and press the paste on moulds. The machine comprises a continuous conveyor belt of moulds, previously oiled with a mould release agent. As these pass through the machine they receive the paste, which is shaped into a tile by a mobile roller element, compacting the paste against a sloping fixed element.

  When the moulds emerge from the machine with their tiles, they are separated by a cutting system synchronised with the speed of the conveyor belt of moulds which shapes the front and back ends of the tiles. Once separated but still in its mould, each tile receives a top coating, when appropriate; if the texture required is smooth, the top coating will consist of various coats of coloured cement (slurries); if the texture required is grainy, coloured grains will also be added.
- *Curing the tiles*: Still in their moulds the tiles are deposited in special containers which are then placed into long tunnels or chambers. Here, curing is accelerated under controlled conditions of temperature and relative humidity until the tiles have hardened enough for them to be removed from the moulds and handled.

  Once curing is complete, the tiles are separated from their moulds, which are returned to the tile making machine, and enter the final stage of manufacture.
- *Selection, packing and loading*: Once separated from the moulds, those tiles presenting manufacturing defects are rejected, whilst the satisfactory tiles are given a polymer resin coating to prevent efflorescence. When identification is used, it is at this point that the tiles are stamped. The cured tiles are then transported to the packing section.

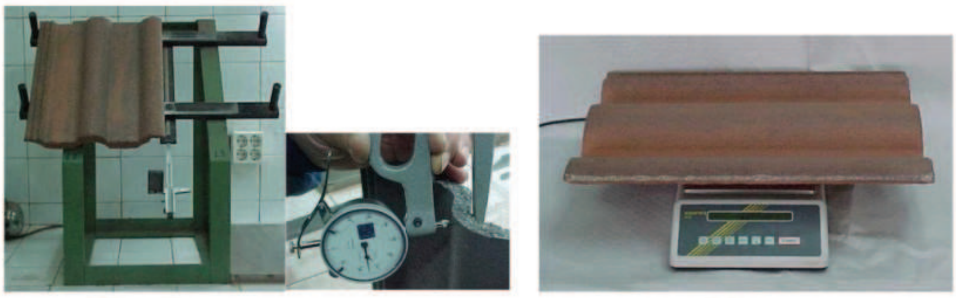
The most common packing method is to group the tiles vertically in packs of approximately 1 metre long. These packs are strapped to ensure stability.

The packs are then loaded three at a time onto wooden pallets, in a single or double layer, and they are sometimes wrapped in stretch or retractable plastic film.

Concrete roofing tiles must comply with a series of standard specifications included in standard EN 490 (AENOR, 2004a), using the assays described in standard EN 491 (AENOR, 2004b), and presented here in Table 7 and Figure 4.

Tests	**Specification**
Dimensions	± 4 mm; cover width ± 5 mm.
Mass	± 10 %
Mechanical strength	Minimum flexural strength 2.000 N
Water-tightness	Under water, no drops shall fall before 20 hours
Durability	Conformity to water-tightness and mechanical strength requirements after 25 freeze-thaw cycles +20 ºC to -20 ºC.
Nib support	1 min in vertical
Fire resistance	Class A1 for fire reaction; B_{roof} for external fire resistance

Table 7. EN 490 specifications for the concrete tiles



Dimensions **Mass**

Mechanical strength **Water-tightness**

Fig. 4. Assays according to EN 491

4.2.2.2 Incorporation of ceramic rubble

In order to conduct these tests in the factory, the ceramic materials were combined into a single product (C) for incorporation as a natural aggregate substitute. To this end, the ceramic rubble was crushed and sieved so that the mixture (natural aggregate and ceramic material) corresponded to the granulometry used in the concrete roofing tile factory (Figure 5).

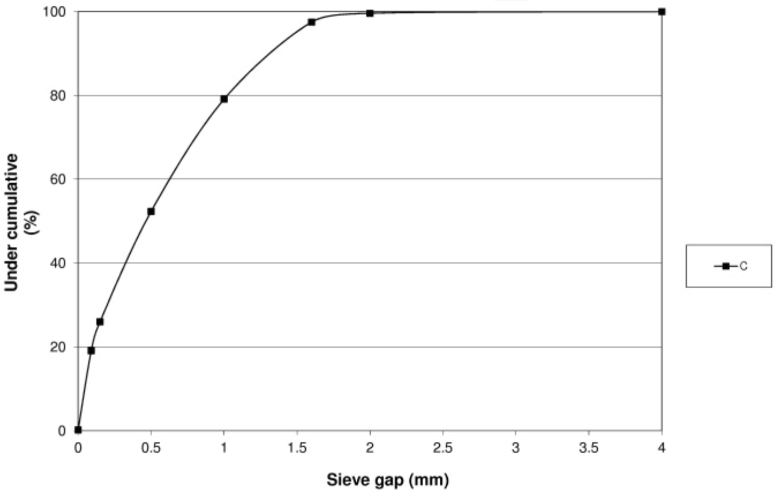


Fig. 5. Particle size grading of ceramic rubble used as aggregate

In order to be used as a pozzolanic material, it was necessary to crush the ceramic rubble until a suitable grade of fineness was achieved. For this study, the samples were crushed to two different grades of fineness, expressed as Blaine's specific surface:

- Ceramic material C1: 3500 cm^2/g
- Ceramic material C2: 3200 cm^2/g

4.3 Results

4.3.1 Ceramic rubble as pozzolanic material: laboratory tests

The results presented in Figure 6 show that the waste ceramic material presented an acceptable level of pozzolanic activity, since the percentage of lime fixed at one day in the CC1 sample was 46% of total available lime. In the case of the CC2 sample, the amount of lime fixed at one day was less (7%), due to the lower specific surface value, since grade of fineness plays a decisive role in the early stages.

At 7 days, the activity of both samples was more evenly matched, fixing over 50% of the lime. This activity was maintained until the end of the test at 90 days, by which time over 80% of the lime had been fixed. These results indicate that the firing temperature of these ceramic materials (around 900º C) is sufficient to activate the clays and for these to acquire pozzolanic properties (Murat, 1983, Sayanam et al., 1989, Johansson and Andersen, 1990, He et al., 1995, de Rojas et al., 2006).

4.3.2 Ceramic rubble in the manufacture of concrete roofing tiles: factory tests

The transverse tensile strength test established in the specifications of standard EN 490 were conducted on the concrete roofing tiles thus produced using the method described in standard EN 491. Results for median strength compared with the control tiles are given in Figure 7.

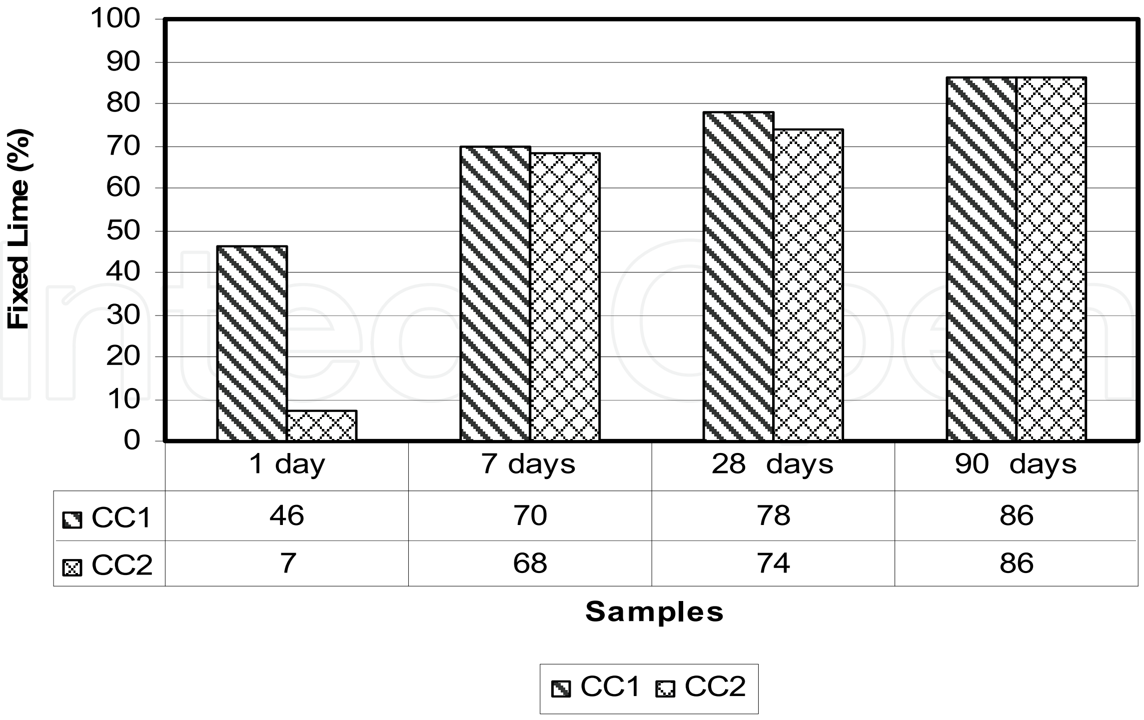


Fig. 6. Pozzolanic activity of the two types of ceramic rubble

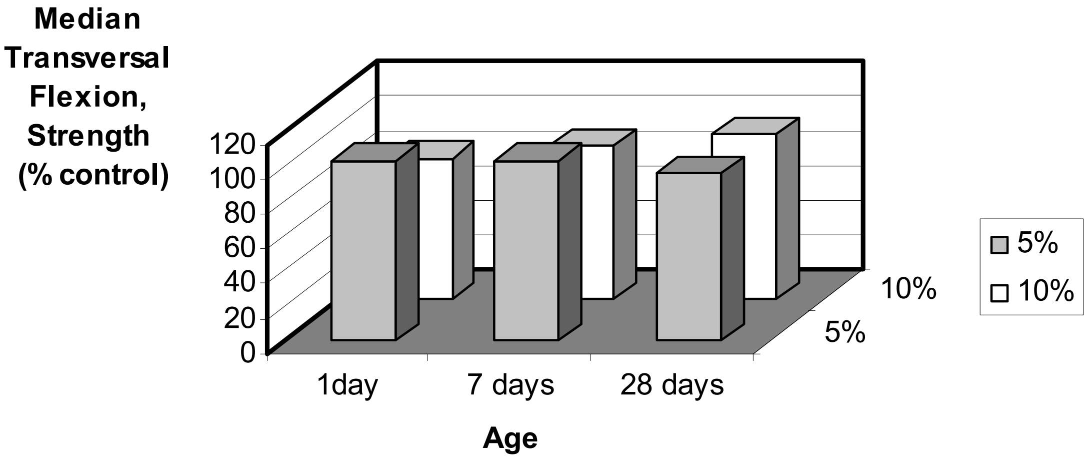


Fig. 7. Transversal flexion strength (% compared to control mortar): Ceramic rubble as aggregate

These tests of ceramic rubble as aggregate were conducted on products manufactured with a 5% and 10% substitution of natural siliceous sand by ceramic material, using the granulometries defined earlier. This factory used CEM I 42.5R cement, as established by current standards (AENOR, 2000).

The mean transverse tensile strength of the tiles manufactured with 5% of sand substituted by ceramic aggregate was very similar to that corresponding to concrete tiles without ceramic material, although at 28 days these values were slightly lower (3% lower).

When 10% of sand was substituted by ceramic material, mean transverse tensile strength was lower at 24 hours (19% lower). However, over time, the results became more equivalent to those for traditional concrete tiles (12% lower at 7 days and 5% lower at 28 days).

The tiles incorporating ceramic material performed well in the impermeability and frost resistance tests described in standard EN 490, conducted following the test methodology given in standard EN 491. However, after prolonged cycles of frost resistance tests (>400 cycles) which far exceeded the number of cycles (25) specified in the standard, it was observed that resulting strength was lower than that of the control tiles.

The factory tests of ceramic rubble as a pozzolanic material were conducted using materials with two different Blaine's specific surface values, C1 (3500 cm^2/g) and C2 (3200 cm^2/g), and three percentages of cement substitution: 5, 10 and 15%. The cement used by the factory was CEM II/A-V 42.5R.

Figure 8 presents the characteristic transverse tensile strength for tiles incorporating ceramic material at 9 hours, which is when the tiles were removed from their moulds, and at 7 and 28 days.

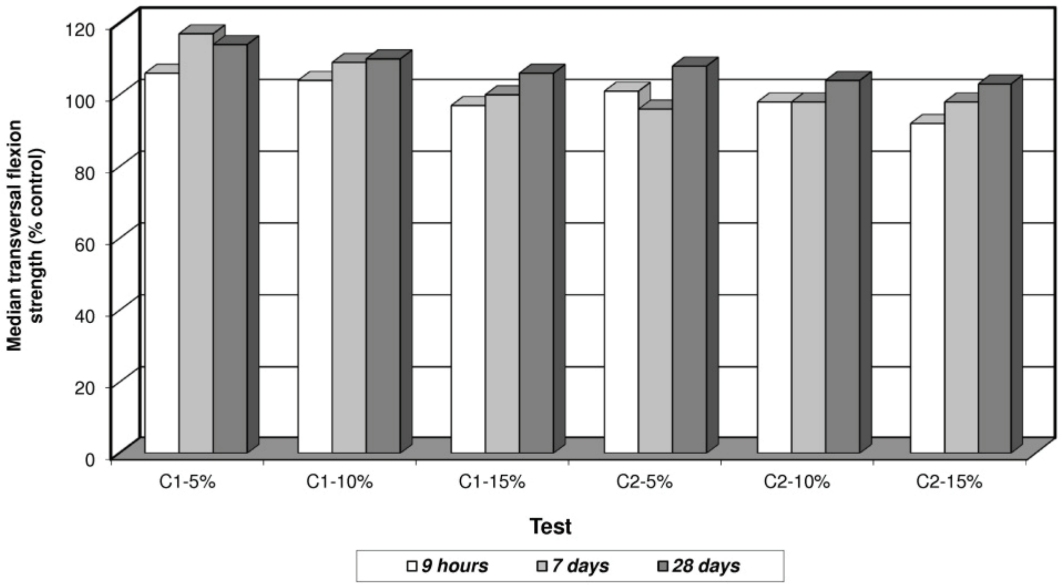


Fig. 8. Transverse tensile strength (% compared to control mortar): Ceramic rubble as pozzolanic material

As can be seen in the Figure 8, the tiles incorporating ceramic material presented transverse tensile strength values that were similar to or even higher than those for normal tiles (control tiles). The best results were obtained with cement substitution percentages of 5% and 10% using the C1 ceramic material.

These results demonstrate that the ceramic material employed acts as a pozzolanic material and, consequently, contributes to the development of mechanical strength. The use of such material thus enables the strength values required to be obtained whilst using less cement.

The results of impermeability tests conducted on roofing tiles incorporating ceramic material were satisfactory, complying with the specifications established in standards EN 490 and 491.

4.4 Conclusion

The ceramic material used (rejects, or rubble), presents acceptable pozzolanic characteristics, since the firing temperatures involved in the manufacture of these products is ideal for activating the clays contained, which thus acquire pozzolanic properties.

In the early stages, the pozzolanic activity depends more on the grade of fineness of the rubble than on the firing process it has previously undergone, as long as firing temperatures are within the normal industrial range (whether or not this is adequate for commercial ceramic products).

Ceramic rubble can be used in the production of precast concrete, whether as aggregate, in substitution of a percentage of natural aggregate, or as an active additive with pozzolanic characteristics. The latter application gave best technical results and also offers the most economic benefit. Additives endow the cements with positive characteristics, by contributing to an increase in mechanical strength in the medium and long term, and also enhance the chemical resistance of concrete to aggressive agents, which has a positive impact on the material's service life (Calleja, 1983).

As regards economic benefits, these are derived from energy savings in the production of cement. The substitution of a material which requires expensive thermal processing, such as clinkerization (Soria Santamaria, 1983), by a less expensive material in energy terms (such as an industrial reject, usually accumulated in dumps), represents a reduction in energy consumption even when it requires prior crushing, and a positive contribution to conservation of the environment.

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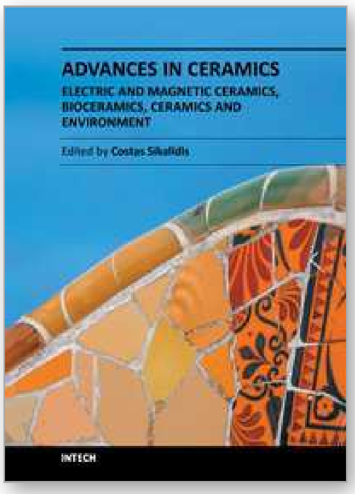

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