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# Re-use of construction and demolition residues and industrial wastes for the elaboration or recycled eco-efficient concretes

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## Abstract

Production of residues from industries and construction and demolition sectors has increased during last years. The total amount of debris produced according to different estimations reaches values close to 42 million tonnes $yr^{-1}$. Much of this waste has been thrown to landfill, without considering its potential for reuse, recycling or valuation. The aim of this research is to describe some of the physical and mechanical properties of different laboratory-mixed concretes, using various proportions of additional materials recovered from industrial waste and demolition rubble. The added materials are included either as admixtures (forestry residues, cork dust, steel fibre) or in partial substitution of natural aggregates (wire from electrical residues, tyre rubber, white ceramic, sanitary porcelain or shale). The laboratory tests have followed the standard EN protocols. Assay results were variable according to the nature of the material added to the mix: organic materials and shale, despite the steel fibre reinforcement, reduce the compression strength, but are suitable for the manufacture of lightweight concrete for agricultural pavements, with certain flexion resistance and a relatively good behaviour to impact. The substitution of natural aggregates with ceramic and porcelain wastes produces a significant increase in compression resistance, making them suitable for the manufacture of concrete with characteristic resistances above 40 MPa, which can be used both for structures or other agricultural elements: separators, feeders, slat floors. As a conclusion can be stated the possibility of reuse these wastes for the production of structural or non-structural concrete, with different applications in agricultural engineering.

**Additional key words**: incorporated energy, recycling materials, rubble.

## Resumen

**Reutilización de residuos de construcción y demolición y subproductos industriales para la elaboración de hormigones reciclados eco-eficientes**

La producción de residuos industriales y los procedentes del sector de la construcción y demolición se han incrementado en los últimos años, hasta alcanzar valores cercanos a los 42 millones de toneladas $año^{-1}$. Gran parte de estos residuos han ido a parar a vertedero, sin considerar sus posibilidades de reutilización. Los trabajos desarrollados en este artículo tienen por objeto conocer las propiedades físicas y mecánicas de varios hormigones elaborados en laboratorio, añadiéndoles diversas proporciones de residuos industriales y escombros. Estos materiales son incluidos bien como adiciones (residuos forestales, polvo de corcho, polvo de corcho+fibra de acero) o bien en sustitución parcial de los áridos naturales utilizados en la dosificación (residuo de cable eléctrico, restos de neumáticos, cerámica blanca y sanitaria o pizarra). Para la elaboración de hormigones se han seguido los protocolos de la normativa EN. Los resultados de los ensayos son variables en función del material incorporado: los materiales orgánicos y la pizarra, a pesar del refuerzo de fibra de acero reducen la resistencia a compresión, pero son adecuados para la elaboración de hormigones ligeros para pavimentos agropecuarios, ya que mantienen cierta resistencia a la flexión y un buen comportamiento al impacto. La inclusión de cerámica y residuos de porcelana produce aumentos apreciables de la resistencia a la compresión, lo que les hace adecuados para la elaboración de hormigones con resistencias superiores a los 40 MPa, que pueden ser utilizados tanto para estructuras como para otros elementos del ámbito agropecuario: separadores, comederos, suelos, enrejillados, etc.

**Palabras clave adicionales**: energía incorporada, materiales, reutilización de escombros.

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## Introduction

For many years now, the councils of large and medium-sized urban centres, not only in Spain, but in Europe have been expressing growing concern over the collection, storage and, more recently, treatment of domestic waste. At the same time, public and political awareness about the issue of environmental degradation has heightened. This has led to the elaboration of the National Plan for Residues of Construction and Demolition [*Plan Nacional de Residuos de Construcción y Demolición* (PNRCD)], which in turn forms part of the 2008-2015 Integrated National Residues Plan (BOE No. 49, 26/2/2009) [*Plan Nacional Integrado Residuos* (PNIR)]. This plan identifies two objectives: firstly, qualitative objectives aim to reduce the generation of construction and demolition residues at source, through correct management, re-evaluation and sorting in terms of recycling potential, and the closure of refuse tips and quarries. Secondly, quantitative objectives aim to achieve the controlled collection and correct management of 95% of wastes from construction and demolition from 2011 onwards, to reduce them by 15%, or reuse 15% by 2011, to recycle 40% of these types of wastes by 2011, to re-evaluate construction packaging materials by 2011, and to introduce selective collection and correct management of the same from 2008 onwards. In order to achieve these objectives, a variety of facilities will be required, such as evaluation and sorting plants, controlled refuse tips and transfer plants.

It has been estimated that some 200 million tonnes of rubble from the construction industry and building demolition is produced annually in the European Union (EU) (Aneiros Rodríguez, 2008). According to data from the National Plan for Residues of Construction and Demolition (2009), approximately 40 million tons are generated annually in Spain, the equivalent of 2 kg per inhabitant per day, a figure higher than that for domestic waste. According with Aneiros Rodríguez (2008) in the EU as a whole, 28% of these residues are recycled. The pioneering countries in this area are Holland, where 95% of construction residues are recycled, England, with 45%, and Belgium, with 87%, 17% of which is used in concrete production. In Spain, approximately 5% of total residues from construction and demolition is recycled, generally as road-fill and road sub-base or in buildings for pavements.

On the other hand the last decade has seen an alarming rise in the demand for aggregates in Spain. According to data for 2007, more than 450 million tonnes of aggregates is extracted annually in Spain, 65% of which is used in the production of concrete and asphalt. This spectacular increase in demand for aggregates, together with the obvious environmental restrictions on uncontrolled quarrying, has led to the proposal from within the sector for substituting recycled residues as an alternative to part of the aggregates used in concrete mixes.

Another significant aspect to consider is *incorporated energy.* One of the most important world-wide ecological objectives is the reduction of $CO_2$ emissions into the atmosphere (Kyoto Protocol, 1997). Indirectly, the construction industry is one of the principle sources of these emissions. Consider the enormous furnaces used in steel manufacture, or cement factories and the ceramics industry, or transport. These all include processes which invest energy in the production of construction materials, energy which can be termed *incorporated energy.* To give an idea of the magnitude of incorporated energy, it has been calculated that in order to produce one ton of steel, of bricks or of concrete, it is necessary to invest 60, 6 and 4 GJ of energy, respectively (Gordon, 2004). Furthermore, calculations suggest that of all the energy invested in the construction of a building, only 20%, approximately, corresponds to the actual construction process, whilst the remaining 80% is contained in the materials themselves (Presti, 2002). Thus, when a construction material is rejected as defective, or demolition is carried out, a large amount of incorporated energy is lost. It is necessary therefore, to develop practical methods for reusing these materials, and especially those representing most incorporated energy. According to data provided by Pilar Alaejos (Anon, 2001), one of the best means of recycling these residues is to incorporate them into mortar and concrete production. Such reuse would not only take advantage of the incorporated energy, but the number of refuse tips would be reduced. A concrete capable of incorporating these residues would be an *eco-efficient material.* In many cases, these possible uses will depend on the existence of pre-feasibility studies, as that proposed in this work. The main goal of this study is to show and demonstrate the real possibility of use construction and demolition residues or wastes from industrial sector to produce structural and non-structural concretes.

The first use of this type of eco-efficient concrete is an indirect one, but equally important as direct ones, concerning environment with a positive impact both ecological and landscape. This aspect is related directly with agricultural and forestry sector as is one of the most damaged with the presence of tips, mostly of them unlawful with lack of control. Also the possibility of reduction of quarries could positively affect the agro-forestry sector.

Whilst much research has investigated in detail the use of recycled aggregates in concrete production, such studies have basically focused on the reuse and recycling of aggregates from concrete. In our country mainly works by Sánchez and Alaejos (2003, 2005, 2006) reported the possibility of using these kinds of residues as a substitute for conventional coarse aggregates. They suggested a maximum percentage of 20%, due to the elevated absorption coefficient of this kind of material, although they also acknowledged the possibility of combining recycled aggregates with enhanced natural aggregates, and their use in structural concretes with a compression resistance equal to or less than 50 MPa. These studies suggested the possibility of use these eco-efficient concretes in the agricultural sector with a direct application in construction: structural with recycled concretes with ground white ceramic or sanitary porcelain ($f_{ck}$ greater than 25 MPa) in medium or small buildings (storehouses, animal housing, etc.) and non-structural ($f_{ck}$ less than 25 MPa) with a good traction behaviour in pavements or floors in animal housing for cows, sheep, etc. (recycled from cork dust with or without steel fibre), in forestry or garden paths, with recycled concretes from tyre rubber. In non-structural precast elements, with recycled concretes from shale or forestry residues, that give a more warm background in agricultural buildings.

Other interesting works about the possibility of reuse residues from construction and demolition are those published by Ryu (2002), Domínguez *et al.* (2004), Poon *et al.* (2004), Suárez *et al.* (2004), González and Martínez (2005), Evangelista and De Brito (2007), González *et al.* (2007), López *et al.* (2007), Rolón *et al.* (2007) and Guerra *et al.* (2008). The basic conclusion of all these studies is the real possibility of reuse recycled aggregates to produce concretes and mortars under certain conditions. Some of these studies also report a better durability behaviour of recycled concretes, this aspect is especially important for livestock o other agricultural buildings where aggressive environments are usually.

All these researches analyses the properties shown by the concretes thus mixed, where a percentage of the aggregates has been replaced by waste materials. The long-term aim of the work is to create ways of recycling different waste products, and in particular, waste materials from the construction industry and from demolition activities.

There are two objectives behind the development of this line of research: firstly, to find alternative sources of aggregates used in the construction industry, and secondly, to develop methods for recycling waste products, especially those which contain a significant amount of «incorporated energy». Given these objectives, the use of defective products produced by the ceramics industry is of great interest as these products have subjected to firing at high temperatures, endowing them with certain mechanical properties which may be profitably used in several contexts.

Another noticeable aspect is the inclusion in the recently published Spanish Standard for Structural Concrete, EHE-08 (2008) of a new annex of recycled concretes. This fact gives an idea of the importance and the real possibilities of this type of concrete.

# Material and methods

## Material

Two lines of research have been carried out to date. On the one hand, material for recycling was added directly to the concrete mix. The organic nature of these materials suggested a resultant low-resistance concrete, and therefore a concrete of characteristic resistance ($f_{ck}$) of 20 MPa was taken as the reference. The residues used in the production of these concretes included cork dust, cork dust with steel fibre, and forestry residues. On the other hand, structural concretes were produced either by substituting a percentage of the aggregates with wire from electrical and electronic residues, tyre rubber, white ceramics, or sanitary porcelain, or by substituting the total fraction of coarse aggregates with shale from slag heaps (Truchas syncline, in the western Asturias-León region). In the latter cases (structural concretes), a structural concrete mix with a characteristic resistance of 30 MPa and 25 MPa respectively, was taken as the reference.

All assays used smooth silicate aggregates (maximum size 20 mm) and density was determined previously in the laboratory. The type of cement used is shown in Table 1. Dosage was designed to produce a plastic consistency, however, it was not always possible to achieve the desired consistency in all cases.

Using previous findings, and following De la Peña's granulometric module method (Arredondo, 1968), a water-cement ratio, and a theoretical dosage of water was established for each case, which later had to be corrected due to an excess of cement, aggregates humidity, or, in the case of concretes produced with cork dust, the high water absorption rate of cork.

All residues used were previously triturated and sieved until they were of the same size as the aggregate fraction they were to substitute. Table 2 shows the different proportions in which the various materials were added, either as an additional component or as a substitute for aggregates (sand or gravel) in the overall dosage of the different concretes assayed. Quantities were determined on the basis of the dosage for the reference, or control, concrete, which also served as the basis for comparison of results.

**Table 1.** Cements used for different concretes

| Concrete aggregates | Cement type |
|---|---|
| Forestry residues | CEM I 52.5 R |
| Cork dust | CEM I 52.5 R |
| Cork dust with steel fibre | CEM I 52.5 R |
| Wire from electrical and electronic residues | CEM II / B-V 32.5 R |
| Tyre rubber | CEM II / B-V 32.5 R |
| White ceramic | CEM I 52.5 |
| Sanitary porcelain | CEM I 52.5 |
| Shale | CEM I 52.5 |

**Table 2.** Substitution/addition percentages of the different materials added to the concrete

| Material | Contribution | Percentage substitution/addition |
|---|---|---|
| Forestry residues | Addition | 2.8% of total aggregates weight = pine shavings (2.8% pine)<br>3% of total aggregates weight = pine shavings (3% pine)<br>5% of total aggregates weight = pine shavings (5% pine)<br>5.3% of total aggregates weight = shredded white heather (5.3% white heather)<br>2% of total aggregates weight = shredded white heather (2% white heather)<br>1% of total aggregates weight = shredded white heather (1% white heather) |
| Cork dust (CD) | Addition | 10% of total WG (10% WG)<br>10% of total WA (10% WA)<br>10% of total DG (10% DG)<br>10% of total DA (10% DA)<br>5% of total DA (5% DA)<br>8% of total DA (8% DA) |
| Cork dust with steel fibre | Addition | 10% of total aggregates = CD, and 20 kg $m^{-3}$ SF [10% CD + SF (20)]<br>8% of total aggregates = CD, and 20 kg $m^{-3}$ SF [8% CD + SF (20)]<br>8% of total aggregates = CD, and 30 kg $m^{-3}$ SF [8% CD + SF (30)]<br>8% of total aggregates = CD, and 40 kg $m^{-3}$ SF [8%CD + SF (40)] |
| Wire from electrical and electronic residues | Substitution | 2% of total sand (2% S)<br>4% of total sand (4% S)<br>6% of total sand (6% S) |
| Tyre rubber | Substitution | 1% of total sand (1% S)<br>3% of total sand (3% S)<br>5% of total sand (5% S) |
| White ceramic | Substitution | 10% of total sand (10% S)<br>20% of total sand (20% S)<br>30% of total sand (30% S)<br>40% of total sand (40% S)<br>50% of total sand (50% S) |
| Shale | Substitution | 100% of total gravel (100% G) |
| Sanitary porcelain | Substitution | 3% of total gravel (3% G)<br>5% of total gravel (5% G)<br>7% of total gravel (7% G)<br>9% of total gravel (9% G) |

DA: dry aggregates. DG: dry gravel. G: gravel. S: sand. SF: steel fibre. WA: wet aggregates. WG: wet gravel.

## Methods

The methodology which has been developed for the research reported here is based both on the specific guidelines for laboratory tests, detailed below, and on published research concerning concretes mixed with steel fibre (Moreno Almansa and Fernández Cánovas, 1997; Song and Hwang, 2004; Song *et al.*, 2005; Kaltakci *et al.,* 2007), ceramics (Sánchez *et al.,* 2001; Amorim *et al.,* 2003; Koyuncu *et al.,* 2004; Correia *et al.,* 2005, 2006; Senthamarai and Devadas Manhoharan, 2005; Portella *et al.,* 2006; Puertas *et al.,* 2006; Binici, 2007; López *et al.,* 2007; Guerra *et al.,* 2008), rubber (Witoszek Schultz *et al.,* 2004), sludge (Yagüe *et al.,* 2003), cork powder (González *et al.,* 2007) and shale (Suárez *et al.,* 2004).

The methodology used was that typically used in the preparation of concrete test moulds. The aggregates were crushed and then sieved following European Standard EN 933-2 for sieving, and European Standard prEN 932-2 for crushing. The equipment used to test aggregates characteristics was previously calibrated following European Standard prEN 932-5.

Sand friability coefficients were determined following Spanish Standard UNE 83115-89. Gravel fragmentation resistance was determined using the Los Angeles test (EN 1097-2:1998). In all cases sand friability and gravel fragmentation were less of 40, value recommended by Spanish Standard for Structural concrete (EHE-08, 2008). Aggregates density and water content was determined following European Standards EN 1097-6:2000 and EN 1097-6:2000/A1.

Mixing was carried out using a 250 L capacity mechanical concrete mixer. The components of the concrete mix were added to the mixer in the following order: first the water, next, part of the gravel followed by the gradual addition of cement, then the sand and the rest of the gravel. Mixing took 10 min approximately, after which a sample was taken to measure consistency using Abrams cone, according EN 12350-2.

The freshly-mixed concrete was used to fill $15 \times 30$ cm cylindrical moulds and $10 \times 10 \times 40$ cm prismatic moulds following Standards EN 12390-1:2000 and EN 12390-1/AC: 2004. For each type of concrete, at least 11 cylindrical moulds and 3 prismatic moulds were filled. Cylindrical moulds were filled in three layers using a collector. Each layer was compacted using a standard steel rod, 600 mm long and 16 mm in diameter, with which they were each given 25 uniformly distributed blows to ensure amalgamation between the layers. Finally, the external surface of the moulds was vibrated lightly using a needle vibrator.

The prismatic specimens were filled using a collector and a filling hopper whose inner edge coincided exactly with that of the mould. They were compacted on a vibration bench using 50 blows, following which any excess concrete was removed.

All the specimens were covered with a sheet of plastic, and kept at 20°C for 48 h. After this, they were removed from their moulds and cured at 20°C and 95% relative humidity, following European Standard EN 12390-2:2000.

Breakpoint tests were carried out after 7, 14 and 28 days. The cylindrical moulds were used to carry out compression tests following EN 12390-3:2001, and indirect traction tests (Brazilian test), following Standards EN 12390-6:2000 and EN 12390-6:2000/AC:2004, using a universal press. The simple compression test was carried out using previously capped moulds.

The prismatic moulds were used to carry out flexotraction tests following EN 12390-5:2000 and EN 12390-5:2000/AC: 2004, and subsequent compression tests, following EN 196-1:2005.

European Standard EN 14158:2004 was followed to carry out impact assays on some of the moulds. Two types of mould were used for this test, comprising small pyramid-shaped plates (Type S), with a $193 \times 193$ mm upper face, $170 \times 170$ mm lower face, and 44-49 mm thick, and big plates (Type B), with a $190 \times 390$ mm upper face, $180 \times 370$ mm lower face, and 40-45 mm thick.

The number of moulds used for compression tests on each type of concrete is shown in Table 3. For all other tests, see Table 4.

**Table 3.** Number of moulds used for the compression test

| Type of concrete | No. moulds |
|---|---|
| Concrete with forestry residues | 34 |
| Concrete with cork dust | 34 |
| Concrete with cork dust and steel fibre | 40 |
| Concrete with wire from electrical and electronic residues | 33 |
| Concrete with tyre rubber | 48 |
| Concrete with ground white ceramic | 30 |
| Concrete with shale | 25 |
| Concrete with sanitary porcelain | 25 |

**Table 4.** Number of moulds fractured in the various tests

| Test type | No. moulds |
|---|---|
| Indirect traction (Brazilian) | 87 |
| Flexotraction | 48 |
| Flexocompression | 141 |
| Impact | 51 |

# Results

Results obtained for each type of concrete are presented in Table 5. As can be observed, the mean resistance $f_{cm}$ of experimental concretes with white ceramic and sanitary porcelain is greater than that of the reference concrete.

However, for all other experimental concretes, a reduction in characteristic resistance can be observed, compared to the reference concrete, indicating that structural applications would not be appropriate. Table 6 gives consistency, measured using Abrams cone.

As regards the indirect traction tests (Brazilian test), flexocompression tests and flexotraction tests, the same conclusions can be drawn as those respecting the compression tests: concretes mixed with white ceramic and sanitary porcelain show good resistance behaviour, whilst the remaining mixes show bad or very bad resistance behaviour, and are not appropriate for structural applications.

As can be seen in Table 5, the impact test was only carried out on those concretes not intended for structural use, that is, concretes with cork dust or forestry residues. For all these, fracture energy was highly variable, according to the dosage employed, but capacity for absorbing impact energy was surprising, although inferior to that of the reference concrete. Nevertheless, the difference was much less than that observed for all other resistance tests. It should also be noted that the two types of concrete for which best results were obtained were those incorporating forestry residues.

# Discussion

Results obtained demonstrate the possibility of reusing different wastes from several industries, mining, forestry activities and construction and demolition as components of eco-efficient concretes.

Related with this subject there are similar works (Ryu, 2002; Sánchez and Alaejos, 2003, 2005, 2006; Domínguez *et al.,* 2004; Poon *et al.,* 2004; González and Martínez, 2005; Evangelista and De Brito, 2007; Rolón *et al.,* 2007; among others); their results show that in many cases the concrete obtained present a loss of resistance. It is possible to establish the following: the use of materials as admixtures for concrete such as: shale, triturated wire and tyre rubber as a substitute for aggregates, as well as the incorporation of cork dust, cork dust with steel fibre and forestry residues as additional components reduce characteristic resistance in the resultant concretes, making them inappropriate for structural applications. These concretes could, however, be used for non-structural applications, for example for tiles or pavements in farms or others agricultural buildings (González *et al.*, 2007).

Related with admixture of cork dust, the final concrete hardly reached a 10% of resistance compared with control concrete, but it keeps a good behaviour in the impact test: 6.1 J (5% dry aggregates) *vs.* 8.8 J of control concrete. The addition of 1% of forestry residues decrease the characteristic resistance of concrete up to values of 60%, compared with control, whilst the impact resistance is similar to the reference concrete, some concretes with these type of residues (2.8% pine) even improve these resistance.

In the same line is the concrete with electrical and electronic residues, the mean characteristic resistance (18.1 MPa) hardly reaches the requirements for mass concrete (established in 20 MPa according EHE-08). It is noticeable that the higher the proportion of wastes on the dosage, the worse the final resistance, which makes sense in these cases, where the added materials do not improve any of the properties of the material replaced.

The use of shale as coarse aggregate did not produce the expected resistance in concrete (Suárez *et al.*, 2004), the final resistance was nearly 50% of the reference concrete. The behaviour of rubber addition in the proportion of 1% was much better than expected, obtaining a compression and indirect traction resistances approximately equal to the reference concrete.

A special case is concrete produced with white ceramic and sanitary porcelain wastes. These ones reached resistance values greater than the reference concrete. With the use of 20% of white ceramic in substitution of ordinary sand, the compression resistance of concrete has been of 55 MPa, a higher value compared with 36 MPa obtained for the reference concrete. In general, this resistance is maintained with other higher proportions of recycled aggregate (Guerra *et al.*, 2008).

**Table 5.** Mean values of results obtained for each type of concrete

| Concrete type | Compression at 28 days (MPa) | Indirect traction (MPa) | Flexocompression | | Flexo traction (kN) | Impact (J) |
|---|---|---|---|---|---|---|
| | | | Flexion (MPa) | Compression (MPa) | | |
| *Forestry residues* | | | | | | |
| RC | 34.8 | 2.76 | 93.9 | 58.7 | — | 7.96 |
| 5% pine | 1.4 | 0.45 | 6.50 | 4.1 | — | 6.37 |
| 3% pine | 14.5 | 1.99 | 30.5 | 19.1 | — | 8.94 |
| 2.8% pine | 15.2 | 1.92 | 37.0 | 23.1 | — | 8.08 |
| 5.3% white heather | 0 | 0 | 3.0 | 1.8 | — | — |
| 2% white heather | 8.4 | 1.06 | 22.4 | 14.0 | — | 3.92 |
| 1% white heather | 21.9 | 2.01 | 58.1 | 36.3 | — | 7.22 |
| *Cork dust* | | | | | | |
| RC | 23.25 | 2.12 | — | — | — | 8.82 |
| 10% WG | 6.60 | 0.39 | 1.82 | 4.87 | — | 5.51 |
| 10% WA | 0 | 0 | 0.46 | 1.53 | — | 1.84 |
| 10% DG | 3.60 | 0.76 | 1.93 | 6.33 | — | 5.27 |
| 10% DA | 0.80 | 0.29 | 0.68 | 1.78 | — | 3.19 |
| 8% DA | 1.00 | 0.60 | 0.93 | 2.68 | — | 4.53 |
| 5% DA | 5.30 | 0.59 | 1.86 | 5.78 | — | 6.13 |
| *Cork with steel fibre* | | | | | | |
| RC | 32.37 | 2.98 | 7.08 | 48.62 | — | — |
| 10% CD + SF (20) | 0.90 | 0.27 | 0.68 | 2.77 | — | — |
| 8% CD + SF (20) | 2.00 | 0.32 | 1.11 | 3.90 | — | — |
| 8% CD + SF (30) | 2.90 | 0.35 | 1.44 | 4.32 | — | — |
| 8% CD + SF (40) | 2.20 | 0.56 | 1.51 | 4.23 | — | — |
| *Electrical and electronic residues* | | | | | | |
| RC | 31.45 | 3.42 | — | — | — | — |
| 2% S | 19.57 | 2.98 | — | — | — | — |
| 4% S | 18.43 | 2.84 | — | — | — | — |
| 6% S | 16.38 | 2.63 | — | — | — | — |
| *Tyre rubber* | | | | | | |
| RC | 32.60 | 3.65 | — | — | — | — |
| 1% S | 30.48 | 3.10 | — | — | — | — |
| 3% S | 29.66 | 2.80 | — | — | — | — |
| 5% S | 30.03 | 2.88 | — | — | — | — |
| *White ceramic* | | | | | | |
| RC | 36.05 | 3.90 | 6.72 | 67.85 | 25.00 | — |
| 10% S | 44.97 | 3.35 | 8.21 | 64.05 | 25.05 | — |
| 20% S | 54.89 | 4.00 | 7.82 | 75.90 | 23.95 | — |
| 30% S | 48.46 | 0 | 8.68 | 70.10 | 28.15 | — |
| 40% S | 51.95 | 0 | 7.02 | 71.40 | 28.10 | — |
| 50% S | 53.27 | 0 | 7.09 | 76.80 | 23.60 | — |
| *Sanitary porcelain* | | | | | | |
| RC | 41.40 | 3.53 | 8.13 | 63.00 | 27.90 | — |
| 3% G | 41.20 | 3.59 | 8.34 | 64.10 | 31.00 | — |
| 5% G | 43.40 | 3.25 | 8.07 | 64.50 | 33.00 | — |
| 7% G | 44.80 | 3.76 | 7.78 | 63.40 | 29.70 | — |
| 9% G | 45.20 | 3.37 | 8.01 | 65.40 | 29.30 | — |
| *Shale* | | | | | | |
| RC | 31.0 | 3.3 | — | — | — | — |
| 100% G | 15.70 | — | — | — | — | — |

CD: cork dust. DA: dry aggregates. DG: dry gravel. G: gravel. RC: reference concrete. S: sand. SF: steel fibre. WA: wet aggregates. WG: wet gravel.

**Table 6.** Concrete mould consistency (Abrams cone)

| Concrete type | Consistency |
|---|---|
| Concrete with forestry residues | Dry / soft / plastic |
| Concrete with cork dust | Soft / dry |
| Concrete with cork dust and steel fibre | Plastic / dry |
| Concrete with wire from electrical and electronic residues | Plastic |
| Concrete with tyre rubber | Plastic |
| Concrete with ground white ceramic | Plastic |
| Concrete with shale | Plastic |
| Concrete with sanitary porcelain | Plastic |

Results obtained with sanitary porcelain are in the same line. In this case, the porcelain has replaced a part of the coarse aggregate (between 3 and 9%). The results show that the resistance of the new concrete remains similar to reference concrete in all tests: compression, indirect traction and flexion.

Therefore these recycled aggregates can be used to obtain structural concrete (López *et al*., 2007; Guerra *et al*., 2008). However, this conclusion does not agree with the results obtained by Correia *et al*. (2006) in concrete produced with ceramic wastes aggregates; in these studies a loss of resistance was observed in comparison with reference concrete and therefore non-appropriate for structural use. The explanation for this discrepancy may be due to the different origin of the waste used in each case. The studies developed for Correia used a direct debris from demolition and construction, containing other residues and dirt, this is the ultimate cause of the loss of resistance observed. In the other cases the ceramics residues used in the study comes from an industry wastes, clean, free of impurities. This waste is not contaminated with other components and have an adequate quality in order to obtain a structural concrete. The immediate consequence is: for a suitable reuse of these wastes a previous process is essential. This process must include separation and clean from other materials, nowadays these processes are not implemented in treatment plants.

Finally it can be considered the high amount of acquired energy contained in the recycled concrete using wastes as ceramic or porcelain, which have a previous oven thermal process, maintaining their resistance properties. These concretes can be described as structural and eco-efficient. Therefore we can conclude that recycled concrete with ceramic is an eco-efficient material.

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# Annex

**a) Norms published by the European Committee for Standardization, Brussels, Belgium**

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