Structural recycled aggregate concrete made with precast wastes

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ABSTRACT

This paper presents the main results of the characterization of recycled aggregate concrete made with precast structural concrete wastes as a case study. The use of recycled aggregates presents two main benefits. On the one hand, there would be an economic and environmental saving because it would not need to deposit waste in landfills. On the other hand, there would be a further economic and environmental saving because it would reduce the need for natural aggregate. However, because of the need of a greater amount of cement not all degrees of substitution present advantages. The results were obtained from four degrees of substitution and different mixing proportions and methods using natural and recycled aggregates and superplasticizers. After obtaining the optimal mixing proportions, the concretes have been fully characterised performing mechanical and durability tests, the methods analysed and the results compared with the literature.

1. Introduction

Humans generate large volumes of construction and demolition waste. Although there are no exact figures, it is estimated that in Spain 325 kg/year per capita is produced, this value being similar to the European average [1].

Construction and demolition waste (CDW) can be defined as waste generated in new construction, repair, remodelling, renovation and demolition. The aim of the Spanish National Plan of Construction and Demolition Wastes [2,3], European 2020 Horizon [4] is to reduce the amount of CDW dumped in landfills through climate action and resource efficiency. The wastes generated by the precast industry, also under the name CDW, are subject to the requirements of another standard, the Spanish National Plan of Industrial Wastes [5]. At present, most of these wastes are carried to landfills, creating a great visual impact on the landscape. The percentage of wastes that come from precast plants or control laboratories is only 5% of the total production of CDW. However, these wastes are of a far superior quality [6-8]. In general, recycled aggregates derived from crushed concrete consist of 65–70% by volume of natural coarse and fine aggregates, and 30–35% by volume of old cement pastes [9]. Furthermore, with the increasing rates charged in landfills and the higher transport costs, these activities are gaining more prominence. However, in terms of CO_2 emissions, the environmental benefit may not be noteworthy if the amount of cement needed is greater than that required in a traditional concrete [10]. If the low quality of recycled aggregates requires increasing amounts of cement to maintain its strength against traditional concrete, recycled aggregates should not be used in structural concretes.

In a general context, the term recycled aggregate refers to "aggregate resulting from the processing of CDW", as defined by the standard prEN 13242 "Aggregates unbound and hydraulically bound for use in civil engineering and road construction" in its version of May 2002 and the prEN 2002 12620 "Aggregates for concrete" April 2002 [11]. These materials are generated as waste during the process of construction, demolition, precast fabrication and testing. A special case of recycled aggregate concretes is those composed of clinker Portland cement and natural aggregates, crushed, screened and processed to produce a secondary material called "recycled aggregate concrete" (RAC). Recycled concrete aggregate (RCA) is derived from a single type of primary material: concrete. Its basic composition, as is known, is a paste of cement mixed with natural aggregates, additives and/or additions.

The Spanish standard [12] recommends that the recycled aggregate, from 25 MPa concrete, can be used for both plain concrete and reinforced concrete with a compressive strength not exceeding 40 MPa, its use in prestressed concrete being excluded. Furthermore, recycled aggregates obtained from healthy structural concrete, or high strength concretes, as the one here analysed, could be suitable for the manufacture of structural recycled concrete with compressive strengths higher than 40 MPa [13]. It should be noted that this type of recycled aggregates for structural concrete comes from a high strength concrete so it should present excellent mechanical characteristics, and secondly, its properties should improve.

Therefore, most of the studies and experiments made in this regard seem to agree that the use of recycled aggregate for the manufacture of structural concrete should be limited to only those aggregates from concrete, and they recommend the use of the coarse fraction or fine fraction, pointing out that the quality deteriorates substantially in the case of recycled concrete [6,13-20]. However, the durability properties of the concrete could be improved by using nano silica particles [21], mineral additives [22] or silica fume [23]. Also, the addition of cement to concrete mixtures utilising recycled aggregates produces concrete with mechanical properties comparable to control concretes made with the same w/c ratio [24]. H. Qasrawi used steel slag aggregate to enhance the mechanical properties of recycled aggregate concrete [25]. H. Zhang used silica fume grout and polyvinyl alcohol solution as a method to improve the thickness of the interfacial transition zone (ITZ) [26] and E. Arifi et al. show the effect of fly ash on recycled concrete [27]. E. Anastasiou et al. improved the properties of recycled aggregate using fly ash and steel slag and the fine fraction of recycled aggregates [28].

Moreover, the need for the use of recycled aggregates in construction is based on environmental purposes and sustainability, as an alternative to the problem of the generation of large volumes of waste. As is known, the poor quality of recycled aggregates compared with natural concretes is due to the mortar adhered to its surface [29,29-32]. However, there are great variations in the results; especially those properties related to deformability, such as modulus of elasticity or retraction. This variability in results is largely due to the wide diversity of recycled aggregates regarding where and how they are produced [33-35]. R.V. Silva et al. proposed a performance-based classification for the use of RA in concrete construction, based on their physical properties [36] and C. J. Zega et al. analysed the influence of the type and content of RA on the transport properties of recycled concrete, finding that the durability of recycled concrete can be as good as that of concretes prepared with natural aggregates and is of a similar compressive strength [37]. M. Tuyan found similar results for self-compacting concrete [38].

This work presents the results obtained from the characterisation of recycled aggregate from a precast plant after crushing and screening self-compacting concrete. The aim is to reuse this waste as recycled aggregate in the production of new recycled concrete elements subjected to static [13,38], cyclic [20,21,39,40] and multiaxial loading [21,41].

The waste is selected exclusively from quality structural concretes, which provide high performance recycled concrete very similar to the original concrete made with natural aggregate. In order to verify these, an ambitious experimental program has been devised, described below, in which not only the complete characterisation of the recycled aggregate is contemplated but also its suitability for making structural concrete in the precast industry.

2. Materials and Methods

Four mixtures have been studied: a control concrete (CC) with natural limestone aggregate (NA) similar to the structural concrete used in the precast plant and substitutions of 20%, 50% and 100% by weight of the coarse NA by recycled aggregate (RA) have been prepared. RA were obtained from clean structural concrete of precast elements rejected in the quality control of the company Norten PH; rejects due to defects of filling and in no case due to the quality of the concrete with, at least, 25 MPa of compressive strength. The recycled aggregates have been obtained in two stages. The first one, in the precast plant where the waste is produced: the structural elements are crushed to recover the reinforcing steel. Subsequently, the waste is crushed and sieved to a maximum size of 32 mm. Under these conditions, the aggregates are sent to the laboratory where they are analysed in the 1-32 mm fraction and, in parallel, at 4-20 mm fraction. This last fraction is the most appropriate for structural applications.

CEM I 52.5 N/SR with a density of 3.11 g/cm^3 and a Blaine specific surface of 361 m^2/kg was used. Table 1 shows the chemical composition of this Portland cement. Table 2 shows the physical and mechanical properties of the coarse limestone aggregate.

The results of the tests described below will be evaluated in accordance with the recommendations contained in the Spanish standard, in order to validate the suitability of the recycled aggregate for making structural concrete.

2.1. Recycled aggregate geometrical and tribological characterisation

2.1.1. Grading

The test to determine the particle size distribution is performed in accordance with the EN 933, Parts 1 and 2: "Determination of particle size distribution. Sieving method".

Coarse recycled aggregates present large contents of particles smaller than 4 mm because of the high friability of the adhered mortar, generated during handling after making the size classification. Thus, it is important to evaluate the fines content of the sample. The method for determining the content of particles smaller than 4 mm is also specified in the EN 933-2 and is quantified by the value of the cumulative percentage of aggregate passing through the sieve of 4 mm.

2.1.2. Fine content

It is well known that RA generates fines during handling due to the material adhered to its surface [42]. Also the presence of fine particles on the surface of recycled aggregate from the cement paste of the old mortar can cause problems of adhesion between it and the new cement paste as well as causing an increase in the amount of mixing water required [6,13,43,44].

The test for determining the fines content is carried out according to the specifications of the UNE - EN 933 – 2.

2.1.3. Flakiness index

Regarding the form of the recycled aggregate, there is some disparity in the criteria depending on the test method employed, although in general it is considered that the recycled coarse aggregate has a form suitable for structural concrete. The methods for determining the form of recycled aggregates involve the use of optical techniques, electron microscopy, to estimate the shape coefficient or the flakiness index. The flakiness index is determined according to the standard EN 933-3.

2.1.4. Shape index

The determination of shape index is made according to the standard EN 933-4. At least 50 particles for 4/8 and 8/16 fractions and 20 particles for the fraction 16/31.5 have been tested. The main difficulty in performing this test is the method to determine the two dimensions. In this case, a calliper was used. The new optical analysis techniques allow this test to be performed more effectively [45].

2.2. Recycled aggregate physical properties

Recycled aggregate density is lower than that of natural aggregate, mainly due to the cement paste which is adhered to the aggregate. Furthermore, the presence of the mortar aggregates causes a rougher and more porous texture, which has a decisive influence on the water absorption.

Absorption is one of the physical properties of recycled aggregate that makes it different from natural aggregate. The absorption of recycled aggregate is greater than that of natural aggregates due to the high residual porosity of the mortar adhered to it; the natural aggregate absorption coefficient is usually between 0-4%, while for the mortar this value reaches 15 to 17%. The absorption coefficient of the recycled aggregate found in the literature for coarse aggregate is from 0.8 to 13%, with an average value of 5.6%. For these reasons, it is of great importance to control the physical properties of recycled aggregates.

The density, absorption and porosity test is performed using the methods described in the standards EN 1097-6 and EN 1936. The standard EN 1097-6 suggests using the pycnometer with fractions 0.063/4 mm and 4/31.5 mm and the hydrostatic balance only for the entire aggregate to 31.5 mm. The second method uses vacuum to ensure complete pore water saturation although the use of vacuum is suggested only for the 4/31.5. The test was performed using a pycnometer without vacuum because of the low porosity of the aggregate. However, the vacuum is used for the saturation of the test performed in the hydrostatic balance.

2.3. Recycled aggregate mechanical properties

Recycled aggregate has certain peculiarities different from natural aggregate as regards its mechanical and, by extension, tribological behaviour (wear resistance, abrasion, etc.).

Again, this behaviour is strongly conditioned by the adhered mortar, so it is necessary to conduct a specific program of characterisation for this group of properties.

2.3.1. Los Angeles wear coefficient

Recycled aggregate has a high Los Angeles (LA) coefficient, because during the test all of the mortar adhered to the aggregate comes off. The determination of this parameter is described in the EN 1097-2.

2.3.2. Soft particles content

This test is performed in accordance with the standard UNE 7134-58. In general, the presence of adhered mortar, which is less resistant than brass, will mean that a large number of the particles of the recycled aggregates must be considered as soft particles. However, there may be notable exceptions to this rule, especially in the case of recycled aggregates from high performance concrete in which the residual adhered mortar presents a very high quality and is not scratched by the action of the brass. This may also be significant in recycled aggregates from prefabricated concrete, as is this case, with the presence of particles containing adhered mortar but not necessarily soft particles.

2.3.3. Resistance to fragmentation

This test was performed following standard EN 1097-2:2010. The aggregate resistance to fragmentation is an indication of its compressive behaviour; the compressive strength exerted by a particle on its neighbour by subjecting the whole to an external loading. The compressive load is applied progressively at a rate of 40 kN/min up to 400 kN. Fig. 2

shows the aggregate before (a) and after (b) testing. This sample is then screened through the 2.5 mm sieve and the amount of sample retained is weighed (m_{nf}).

2.4. Recycled aggregate durability properties

The durability of concrete is its ability to perform satisfactorily against aggressive physical or chemical actions during its service life. In this respect, the quality of aggregates used plays a predominant role, as they make up most of the volume of the solid skeleton of concrete. Therefore, it is necessary to check the quality of recycled aggregates against aggressive actions, in order to establish their durability and their contribution to the durability of the concrete.

2.4.1. Magnesium sulphate test

This test is performed according to the specifications of EN 1367-2: 1999. In some cases, this method is not suitable for evaluating the durability of recycled aggregates because the sulphate solutions used might have a destructive chemical effect on the cement paste, and the results might be not representative. To prevent great losses in the recycled aggregates due to its high attrition wear, a special sample preparation protocol has been followed.

2.4.1. Freeze–thaw cycles

The freeze-thaw test provides information about the behaviour of the aggregate against volume variations caused by thermal variations above 0 °C. The volume or mass stability of natural aggregates is usually assessed by the loss of weight after subjecting them to ten cycles of freezing - thawing in water or a sodium chloride solution. The stability is evaluated by the loss of volume or mass using a sieve. It is expected that the recycled aggregate will be affected by the cycles because it has a high absorption coefficient. The test is performed in accordance with the standard EN 1367-1: 2007. However, the test procedure followed here is not exactly the same as the one defined in that standard regarding the cooling rates, in order to make the use of a climate chamber unnecessary.

2.5. Recycled aggregate contaminants and impurities

The recycled aggregate often incorporates impurities and contaminants that can affect the properties of the concrete made with them. Here a contaminant is considered to be any material with any origin other than the concrete and can take several forms: plastic, wood, brick, organic matter, asphalt, etc. The most important effect of these impurities is the reduction in the strength. Some of the contaminants little studied that can be found in RA from CDW are the consolidants and repellents used in the maintenance of structures [46] and polymeric materials used in the reconstruction or rehabilitation of structures [47]. However, in the case of recycled aggregates from the precast in the plant, the number of impurities is not very high.

2.5.1. Impurity content

There is no specific standard for this, so the separation of contaminants and impurities was performed by visual identification in a fraction of the recycled aggregate.

2.5.2. Determination of light particles

The purpose of this test is to determine the quantity of substances that can cause stains or blisters on the surface of the concrete. Examples of light particles are coal and wood. The test is described in EN 1744 - 1.

2.5.3. Clay lumps

The procedure for determining the clay lump content of the recycled coarse aggregate is described in the standard UNE 7133. Some clay lumps are difficult to identify visually. In this case, if the particle is dissolved in water, it is considered as a clay lump.

2.6. Recycled aggregate chemical properties

The presence of sulphates and total soluble sulphur compounds highlights the potential instability of the aggregate, indicating that its use could affect the durability of concretes.

2.6.1. Content of water-soluble chloride

The procedure of the water-soluble chloride test is described in the standard EN 1744-1. There are three alternative methods proposed in the standard. In this case the determination of chloride content was performed by the method of Mohr.

Recycled aggregates may have chlorides, depending on the origin of the concrete used as raw material. The chloride concentration may be particularly high in concrete from marine structures and the concrete of bridges exposed to de-icing salts.

The calcium aluminate of the cement of the recycled aggregate adhered may be formed by hydrated calcium aluminate chlorine, thereby reducing the content of free chloride detected with this test. However, the presence of sulphate ions, for example from marine environments, could release these chloride ions to form hydrated calcium aluminate. Other factors such as temperature, crystallography form of tricalcium aluminium and chlorine decomposition of hydrated calcium aluminate, due to carbonation, can also cause corrosion of reinforcements.

2.6.2. Content of soluble sulphates in acid

Sulphates are extracted performing a test described also in EN 1744-1.

2.6.3. Total content of sulphur compounds

This test procedure is described again in EN 1744-1. In general, recycled aggregate can have a high content of sulphates. Sulphates present in the cement paste will not cause problems, but it will be necessary to avoid the presence of impurities such as gypsum, which may cause unwanted expansion inside the concrete. This is not relevant in the present case, however, since the recycled aggregate comes exclusively from waste of a precast plant, where a limitation to the content of total sulphur compounds, rather than to the soluble sulphates in acid, is established.

2.7. Mix proportions

Control concretes (CC) of 30 MPa strength class have been studied with w/c ratio equal to 0.55, in accordance with the specifications for an exposure to a class of corrosion induced by carbonation, Class IIb (XC-Corrosion induced by carbonation). The mix designs are shown in Table 4. The effective w/c ratio has been calculated considering that, when using dry aggregates, they absorb 70% of their total absorption capacity during batching [6,30,48]. The Abrams cone for all the mix proportions were inside the interval: 16 ± 2 cm.

2.8. Specimens and curing conditions

A total of 160 cylindrical (150x300 mm) specimens, according to EN 12390-1:2001 and EN 12390-2:2009 were manufactured and cured in a standard controlled atmosphere of 20 ± 5 °C and 97 ± 2% humidity.

2.9. Recycled concrete physical properties

The densities and porosities were determined according to standard EN-12390-7:2009. The water absorption capacity of hardened concrete can be determined by evaluating the open pore volume, these open pores having been previously saturated. Another way to express the absorptive capacity of the material is in terms of porosity. The relationship between the volumes of accessible pores, calculated evaluating the difference between saturated and dry weights, provides the porosity of the material.

2.10. Recycled concrete mechanical properties

A universal servo-hydraulic press of 1500 kN maximum load was used. Load rates of 8 kN/s were applied for the tensile splitting, EN-12390-6:2010, and 10 kN/s for compressive strength tests, EN 12390-3:2009 and EN 12390-4:2001. A series of 3 tests on 7 and 28 day specimens cured in a moist room were carried out on each mixture. Also, the modulus of elasticity in compression of the concrete has been determined.

2.11. Recycled concrete durability

Three cylindrical specimens of each mixture were used for the maximum water penetration under pressure tests. In this test, a water column acts on the specimen 72 hours under 5 bars of pressure, equivalent to keeping the specimens 50 m depth under water, EN-12390-8:2009.

100 mm disks, extracted from the centre of a standard cylinder (150 mm diameter), using a diamond disk saw were used for the oxygen permeability test. The test was carried out according to the Spanish standards UNE 83966:2008.

3. Results and discussion

The results obtained are presented and discussed in the following sections.

3.1. Recycled aggregate geometrical and dimensional properties

In this section, the grading, the fine particles content and the content of particles of less than 4 mm, the flakiness index and the shape coefficient are presented.

3.1.1. Grading

A sample with a dry mass of 12980.2 g of the recycled aggregate was taken directly from the crushing. The dry mass of the same sample after washing and screening by the 0.063 mm sieve was 12944.5 g. Therefore, the dry mass of the fine particles removed by washing is 35.7 g, 0.27% by wt.

After the separation of the fine particles, the grading of the sample was performed using two different aggregate categories, according to the same standard EN 12620, d/D of 1/31.5 and 4/16. According to the standard, the aggregate category is Gc90/15. Fig. 3 shows the grading of these two fractions and the recommendation of the standards studied.

The geometrical module of the recycled aggregate of 1/31.5 is 6.25 but for the 4/16 fraction of the same aggregate it is 6.78. It can be observed that the geometrical module of the recycled aggregate depends mainly on the maximum size and grinding system used to prepare it. The values found in the literature vary in the range of values between 6.2 and 7.6, with an average value of 6.8 for maximum sizes between 20 and 25 mm.

The recycled aggregate from the higher strength concrete has a slightly higher module than those from less resistant concretes when the fabrication method is the same. Also, if the fabrication is performed by a greater number of crushing steps, the module of the recycled aggregate as the aggregate size is reduced. There are no restrictions or recommendations on the EHE – 08 [49] for this parameter, although the "Manual of

Concrete Practice" ACI [50] establishes common values for the coarse aggregate in the range of 5.5 and 8.5 for this parameter.

As shown in Fig. 3, the finer fraction of the tested 1/31.5 recycled aggregate is outside the lower limits defined by the standards. However, the situation improves when considering the maximum sizes of aggregate D<20 mm. The results show that for proper particle grading, the recycled aggregate should be mixed with another aggregate in order to obtain a combined aggregate with a grading curve between the recommended limits. Also, the EHE - 08 recommends in its Annex 15, to limit the content of recycled coarse aggregate to 20% wt. of the total content of coarse aggregate. The grading curves have also been compared with the recommendations of the American standard ASTM C 33-93, "Standard Specification for Concrete Aggregates" [51] for D <37.5 mm, which is slightly more restrictive for the particle size. In this case, it can be seen that the experimental grading curves are quite far from the ones proposed by the standard for this maximum aggregate size. However, again the situation improves when the 4/16 fraction is considered. As with the European standards, the grading of the fraction 1/31.5 is in the area between the two limits in its central region, while the curve of the fraction 4/16 is fully inside that area.

The situation is better when the grading curves are compared with the limits proposed by standards specifically designed for recycled aggregates. For example, the grading curves of the two fractions of aggregate considered are situated between the recommendation limits of the Belgian standard for recycled aggregate from concrete, fraction 4/32 [52]. The situation is significantly better than in the case of the EN and ASTM for the same fractions.

The results also fulfil the grain size limits established in the Japanese standards for recycled aggregate [53-55]. Fig. 3 shows the position of the grading of the tested recycled aggregate with respect to the maximum and minimum limits proposed by the Japanese standard corresponding to D <25 mm. Also, Fig. 3 shows the recommended limits for a maximum aggregate size D<40 mm, D<25 mm and D<20 mm. In general, considering smaller maximum sizes, the position of the grading between the limits improves. As can be seen, the 4/16 recycled aggregate fraction is placed inside the limits with a maximum size of 20 mm, both for use in construction (ed) and civil works (co).

3.1.2. Fine content

For the tested sample, the amount of fines passing through the 0.063 mm sieve, calculated by (1) is f = 0.45%. The usual values found in the literature for recycled aggregates [30,56] are in the range of 0.27% to 1.14%. Moreover, this content is smaller than the most restrictive limits set by the standard EHE – 08 [49] of 1.5% for coarse aggregate. In this sense, both the Belgian [52] and Berman DIN 4226-1 [57] standards and the recommendations of the RILEM [58,59] allow a higher content of fines 2-3% wt. The EHE - 08 states that "the content of lower declassified of recycled aggregate is usually higher than that of natural aggregates, because these can be generated after the screening, during storage and transport. Furthermore, the recycled fine fraction is characterised by a high content of mortar, which results in some poorer properties that negatively affect the quality of concrete. This is the main reason to restrict their use for structural concrete ".

3.1.3. Content of particles smaller than 4 mm

The results obtained for the content of particles smaller than 4 mm are respectively 27.77% wt. for the complete fraction (1/31.5 mm) of recycled aggregate and 1.38% for small fraction (4/16) where particles of a size of less than 4 mm were removed. This new percentage corresponds to the creation of new fines during the sieving a result of the high friability of recycled aggregates. In general, typical values for different fractions larger than 4 mm are 0.5-2% wt., as reported in the literature [30]. These percentages are attributed to residual disintegration suffering during handling.

Some standards or recommendations establish an additional limitation to the content of particles smaller than 4 mm of recycled coarse aggregate. For example, the German standard DIN 4226 - 100: 2000 [57] allows up to 7% (in volume) of particles less than 2 mm for its use in non-aggressive environments. Other standards, such as the Belgian, Dutch and Japanese ones allow between 10% and 15% smaller than 4 or 5 mm of declassified. The recommendations of the RILEM establish an additional limitation of 5% for the particle content smaller to 4 mm. If this limit is exceeded, the additional percentage of recycled sand should reduce with natural sand. The EHE - 08, indicates that the recycled aggregate minimum size must be 4 mm and a content of declassified less than or equal to 10% and the content of particles passing through the 4 mm sieve must not exceed 5%.

3.1.4. Flakiness index

Two different samples were considered (Sample 1 and Sample 2) to determine the flakiness index of recycled aggregate. Based on the results of the grading, the bar sieves used for determining the flakiness index were selected. Tables 1 and 2 show the results of the determination of the flakiness index of each considered fraction, as well as the recycled aggregate.

The results of the flakiness index found in the literature for recycled aggregates sets it between 7% and 22% [30], smaller than for natural aggregates because of the adhered mortar, which is more friable, which increases the roundness.

3.2. Recycled aggregate physical properties

In this section, the results of the real, relative, apparent and saturated densities of the recycled aggregate are presented. Also, the values of the absorption coefficient and the porosity of the coarse fraction are specified.

3.2.1. Real, apparent and relative density

Table 4 shows the results of the real, relative and apparent density for the three fractions considered: 0/1, 1/4 and d>4 mm. The results for the real density of the fine fraction, are slightly higher than those found in the literature, between 2.32 g/cm^3 and 2.57 g/cm^3 [30]. In the fine fraction, the amount of mortar or cement paste is greater than in coarse fractions [28,60-63] and its density is heavily influenced by the quality of the original concrete. In this case, the obtained value indicates that the original concrete is a good quality concrete. Also, the concretes used have an age of over 28 days since their manufacture, and thus a significant amount of the cement may continue to react and increase the density of the new material [6]. Furthermore, the results obtained for the coarse fraction of the recycled aggregate are presented in Table 4. In this case, the values of accessible porosity, bulk, relative and saturated density are provided. The obtained values are consistent with those found in the literature, which provide a range of densities between 2.07-2.65 g/cm^3, while the saturated density with dry surface varies between 2.10-2.64 g/cm^3. For the tests performed in the CEDEX [30], the saturated density varies between 2.24 and 2.42 g/cm^3 for the fraction 4/8 mm and between 2.33 and 2.47 g/cm^3, for the fraction 8/16 mm. For the fraction 4/16 mm, the saturated surface-dry density is between 2.30 and 2.45 g/cm^3. For these same samples, the real density varies between 2.01 and 2.30 g/cm^3 in the fraction 4/8 mm and between 2.14 and 2.37 g/cm^3 in the fraction 8/16 mm. For the 4/16 mm fraction, the density is slightly lower than for the coarse aggregate, and is in the range 2.10 - 2.40 g/cm^3. Other results found in the literature are in the range 2.10 - 2.54 g/cm^3 for the finest fraction 5/10 mm and 2.18 - 2.46 g/cm^3 for the fraction 10/20 mm.

Therefore, the density values of these recycled aggregate are slightly higher than those reported in the literature. For this reason, an aggregate with a density of between 2.00 g/cm^3 and 3.00 g/cm^3 can be considered to have a normal weight.

3.2.2. Water absorption coefficient

The obtained water absorption coefficient of the coarse recycled aggregate, expressed as percentage by mass, is 4.37%wt. The recycled aggregate absorption is generally greater than that of natural aggregates, due to the high absorption of adhered mortar; while the absorption of natural aggregate is usually between 0-4%, the absorption of mortar reaches values of 16-17%. The values of these coefficients found in the literature for the recycled coarse aggregate is from 0.8 to 13%, with an average value of 5.6%.

Meanwhile, the absorption coefficients obtained by CEDEX [30] are between 5.1% and 11.5% for the 4/8 mm fraction and between 4.2% and 8.8% for the 8/16 mm fraction. The combined aggregate fraction (4/16 mm) has an intermediate absorption coefficient from 4.8 to 9.6% wt. The Spanish standard EHE - 08 sets the limit for the water absorption at 5% wt. Recycled concrete containing less than 20% wt. recycled aggregate must have an absorption of no more than 7%. Additionally, the coarse natural aggregate used in the mixture should have an absorption not exceeding 4.5% wt. For recycled concrete with more than 20% wt. of recycled aggregate, the combination of coarse, natural and recycled aggregate should be in accordance with the specifications established by the standard, presenting an absorption coefficient, for the concrete, of no more than 5% wt.

3.2.3. Accessible porosity

The accessible porosity obtained for the coarse recycled aggregate, expressed as percentage by volume, is 9.76%. There are no reference values for this property and no limitation is established by EHE - 08. As a guide, it is worth pointing out that the specifications for the concrete used in the manufacture of railway sleepers set a limit for the porosity at 12% vol.

3.3. Recycled aggregate mechanical and tribological properties

In this section, the results of wear tests using the Los Angeles method, the content of soft particles and the flakiness index of recycled aggregate are presented.

3.3.1. Los Angeles coefficient

The Los Angeles coefficient obtained by the expression (14) is 31%wt. The values found in the literature for recycled aggregates vary between 12% and 43%, with an average value of 28%. CEDEX have obtained values between 35% and 42%, similar to those obtained for the natural aggregates. The EHE - 08 set the limit at the 40%wt. This standard states that it is necessary to limit the Los Angeles coefficient of the coarse aggregates for concrete because there is a correlation between it and its stiffness and strength. In addition, for high-strength concrete, it is recommended that the Los Angeles coefficient does not exceed 25%wt.

3.3.2. Soft particles coefficient

Table 7 shows the results of the determination of the soft particles coefficient for the different fractions of recycled aggregate considered. The values obtained are significantly lower than those found for recycled aggregates in the literature, between 35% and 85%, with a coefficient of variation 24%. In this case, the softening effect of the cement paste is minimised by the quality of the original concrete, from precast concrete waste. Therefore, it should be noted that the aggregate with adhered cement paste is not necessarily a soft particle.

In any case, the limit established by the EHE for the content of soft particles in coarse aggregate is 5%wt. However, this limitation receives no further consideration in the new version of the same document.

3.3.3. Flakiness index

Tables 8 shows the results obtained for the flakiness index, 10/14 mm and 10/14 mm fractions. The average value for this index is M10/14 = 30%. There are no reference values for this property and no limitation is established by the EHE - 08.

3.4. Recycled aggregate durability properties

In this section, the durability properties of recycled aggregate concrete are presented.

3.4.1. Resistance to magnesium salts

Table 10 shows the results obtained for the resistance to attack by magnesium salts on the recycled aggregate. MS=2 is the final value of the test, expressed as the average of the results obtained for each subsample, rounded to the nearest integer. According to Japanese studies, most recycled aggregates do not meet the requirements set for this property for natural aggregates. In tests carried out by the CEDEX, the weight loss of recycled aggregate subjected to five cycles is between 0.5% and 21.8%wt. Moreover, the UNE - EN 12620 provides a maximum value of mass loss of 1% when the concrete is exposed to aggressive environments, while for normal environments it withstands up to 4%. EHE - 08 sets a limit at 18%wt. for coarse aggregate when the concrete is exposed to aggressive environments and the aggregates have more than 1%wt. water absorption.

3.4.2. Resistance to freezing - thawing

The obtained loss of mass of recycled aggregate subjected to ten cycles of freezing - thawing inside water was H = 5.6%wt. The values found in the literature regarding this property are between 8.3%wt. and 14.6% wt. for oven-dried aggregates and between 1.6%wt. and 5.8%wt. for air-dried aggregates. Furthermore, in Spain there are no limitations for the value of resistance to freeze - thaw cycles.

3.5. Recycled aggregate contaminants and impurities

In this section the results of content of contaminants and impurities are presented.

3.5.1. Impurity content

Contaminants in recycled aggregates coming from construction and demolition wastes (CDW) are plastic, wood, plaster, brick, organic matter, paper, glass, asphalt, etc. Some of them may be harmful to the development of recycled concrete. In the present case, recycled aggregates are particularly clean as they come exclusively from waste precast concrete.

These impurities lead to a decrease in the strength of the concrete. In addition, depending on the type of impurity, there may be other problems as alkali-silica reactions (due to the presence of glass), sulphate attack (caused by plaster), chipped surface (caused by wood scraps or paper), high shrinkage (clay soils) or misbehaviour by freeze - thaw (caused by the presence of some ceramic waste). For these reasons, the recycled aggregate content of impurities should be controlled, with the following maximum values: ceramic ≤ 5%wt.; asphalt ≤ 1%wt.; other materials (glass, plastics, metals, etc.) ≤1.0%.

3.5.2. Determination of light particles

The lightweight nature of the particle of the recycled aggregate depends on its origin. Recycled aggregates come from a mixture of ceramic and concrete rubble wastes, and the materials found are basically cork, ceramic materials and to a lesser extent, mortar. For samples coming from concrete rubble, as is this case, the light particles are composed mainly of particles of cement paste, plastic or wood. In any case, the thicker recycled aggregate fractions generally exhibit a lower content of light particles.

Table 11 shows the results of the determination of the content of light particles for two different fractions (4/8 and 8/16) of recycled aggregate. In this case, the coarser fraction of recycled aggregate has a higher content of light particles than the smaller fraction. The usual values found in the literature are between 0.5%wt. and 5%wt. and the limit established by the EHE - 08 maximum is 1%wt.

3.5.3. Clay lumps

In the coarser analysed fraction (20/40), no clay lumps have been found, A(20/40) = 0%wt. Meanwhile, in the finest fraction, small lumps of clay were found, and some aggregates heavily contaminated by clay. The content of clay lumps in the fraction 10/20 of recycled aggregate was A (10/20) = 0.25%wt. These results are consistent with those found in the literature. In the finer fractions (4/8 mm), the content is generally higher, between 0.04%wt. and 1.0%wt., while for the coarser fractions (8/16 mm) slightly smaller results are obtained, between 0.0%wt. and 0.6 %wt., the results obtained being practically in the middle of this range. Typically, the origin of the clay particle lies in the fact that the samples are collected from the stockpiles of recycled aggregates, and during the storage period, the aggregate may suffer contamination of the surrounding soil.

With regard to the regulatory aspects, the Dutch standard provides an additional limitation to the content of clay lumps, allowing values below 0.5%wt. Other standards, such as BRE 433 and the Hong Kong standard include clay lumps within the allowable impurities (metals, plastics, asphalt, glass, clay lumps, etc.) with a maximum content less than 1%wt. EHE - 08 states that in the case of recycled concrete, containing not more than 20% of recycled aggregate content, clay lumps should not exceed 0.6%wt., and for the natural coarse aggregate 0.15%wt. However, if the quantities of recycled concrete incorporate more than 20% recycled aggregate, extreme care must be taken during production to eliminate the maximum impurities. In the case of using 100% recycled coarse aggregate, it must meet the highest specification of 0.25%wt. of clay lumps.

3.6. Recycled aggregate chemical properties

In this section, the results regarding the chemical properties of recycled aggregate are shown and compared.

3.6.1. Content of water-soluble chloride

The obtained content of water-soluble chloride of the recycled aggregate, determined by the method of Mohr, is C = 0.00159%wt. EHE – 08 sets a limit to the content of chloride ion soluble in water for coarse and fine aggregates, used in reinforced concrete, of 0.05% by mass, and 0.03%wt. for prestressed concrete. These limitations are intended to reduce the risk of corrosion of the reinforcements. In the case of mass concrete there are no limitations, although it is recommended to limit it for fine and coarse aggregate at

0.15%wt. to avoid efflorescence on the surface of concrete. Also, the total chloride ion should not exceed the following limits: 0.2% by weight of cement for prestressed concrete and 0.4% by weight of cement concrete for mass concrete.

3.6.2. Content of soluble sulphates in acid

The obtained content of soluble sulphates in acid of the recycled aggregate, expressed as a percentage by mass of SO_3, is 0.65%wt. According to studies conducted by the RILEM [58,59], the average content of soluble sulphates in acid of an aggregate from a recycling plant is approximately between 0.38%wt. and 0.62%wt. The countries with recommendations for the use of recycled concrete aggregate establish similar limits for natural aggregates. But the RILEM recommends a maximum of 1%wt for the use of recycled aggregate concrete, expressed in SO_3 and referred to the dry aggregate. EHE - 08 sets a content of soluble sulphates in acid, expressed in SO_3, for coarse and fine aggregate, at 0.8% by weight of the aggregate.

3.6.3. Total content of sulphur compounds

The value obtained for the total content of sulphur compounds, expressed as percentage by mass, is 0.28%wt. According to EHE – 08, the total sulphur compounds from the coarse and fine aggregates, determined in accordance with UNE - EN 1744-1, should not exceed 1% by weight of the total weight of the sample. In the case of the presence of oxidisable iron sulphides, as pyrrhotite, the sulphur content should be less than 0.1%wt. It is recommended not to use those aggregates whose difference between total soluble sulphur compounds, expressed as SO_3, and sulphates, also expressed in SO_3, is greater than 0.25%wt., as this is an indirect way of limiting the oxidised sulphides of the aggregates.

3.7. Recycled concrete physical properties

3.7.1. Density

Table 5 shows the apparent, relative and saturated density of the reference recycled concrete with 28 days.

The apparent, relative and saturated densities of CC and RAC, with 28 days, decreases in proportion with the percentage of substitution of the natural aggregate by the recycled aggregate, in accordance with other studies [6,13,43,44,64]. The effective w/c ratio is different in each of the concretes with different degrees of substitution. The reason is the increased absorption capability of the RA. It means that the cement paste of the RAC, thus manufactured method, is denser than the cement paste of the CC. However, the loss of density is more pronounced than in the mentioned studies because the volume of recycled aggregate, in relative terms to volume, is greater. Therefore, the influence of recycled aggregate on the density is greater too. In the present research, the loss of density is around 3,9% for the 100% of substitution.

3.7.2. Absorption coefficient

Table 4 shows the absorption coefficient of the RAC and the CC. The absorption coefficient increases with degree of RA substitution. An absorption of 100 % RAC with w/c=0.51 decreases from 5,58% to 5,42% in respect of the CC with 0.55. This increase is due to two effects. First, the incorporation of a low absorption recycled aggregate (4.2% wt.) does not increase the absorption coefficient of the aggregates, compared to the natural aggregate, as that found in research where the RA come from the demolition of lower quality concretes. Moreover, the absorption of the RA causes, as mentioned, a decrease in the w/c ratio which results in a less absorbent cement paste isolating the accessible porosity of RA, cushioning the negative effect it could have. Indeed, the w/c ratio of the 100% RAC is 0.51, value that corresponds to a quality cement paste with an absorption coefficient of 5.42 wt%. similar to the value of 5.3 obtained in [13]. The negative effect of recycled aggregate is significantly lower for low w/c. In this case, both the porosity and absorption of the RA are partially isolated for the surrounding less absorbent cement paste.

3.7.3. Open porosity

Table 5 shows the obtained values for the open porosity of the RAC and the CC.

In general, it is noted that the accessible porosity and the absorption coefficient present the same behaviour. Compared with the control concrete, this parameter increases with the degree of substitution. The RA porosity is 9.76 %Vol., notably less than that of the CC (12.46 %Vol.). The used RA comes from structural components of concrete made with the same mix proportions as the CC. As a result, the difference could be explained by the compaction used method. In the first, the precast components, were compacted in the factory being this method more energetic and efficient than the one used in the laboratory, compacted manually by steel bars. Because the cement paste is always more porous than the RA, the RA porosity do not penalize the accessible porosity of the concrete made with them. Thus, the incorporation of RA penalizes the durability of non-compact cement paste concretes [13]. The incorporation of RA leads to an increase of porosity in relation to the w/c and the degree of substitution. Similarly, the best quality of the paste, less porously, also improve the wear behaviour of precast elements made with this material [65].

3.8. Recycled concrete durability

3.8.1. Water depth penetration under pressure

Table 5 shows the water depth penetration for the different substitution degrees.

It is found [13] that water permeability increases with the w/c ratio and with the percentage of incorporated RA. The scatter of these values is significant, but the tendency of concrete with age of curing is to reduce the permeability. Also, in general, the maximum recorded depth is related to the degree of incorporation of RA. However, in this research, due to the high permeability of the cement paste, it couldn't be possible to compare results of the different concretes because all of them presented total penetration (more than 90 mm) at the 72 h under pressure. For this reason, the test was repeated but in this case with only 24 h under pressure.

The values obtained by Zega et al. [66], 24 mm for CC and all RAC can be attributed to the lower effective w/c ratio of RAC concretes compared to CC concrete, due to the incorporation of dry RA. However, as has been noted below, with a w/c under 0.45 the obtained water penetration values are very similar in all cases.

3.8.2. Oxygen permeability

Table 5 shows the oxygen permeability of the RAC with different degrees of substitution.

The results show a decrease in permeability to gases with the degree of substitution.

Olorunsogo et al. [67] find that the RAC reduces the oxygen permeability by 15%. This reduction can be attributed again to the lower effective w/c ratio of RAC concretes with respect to the CC concrete. According to Zaharieva et al. [68] the replacement of coarse natural aggregate by recycled aggregate doubles the air permeability of the concrete. Also, it is important to consider that the cement pastes with low w/c ratios isolate the RA preventing the increased of permeability due to the substitution of the natural aggregate. However, the observed effect is not itself a decrease of the permeability of the concrete with the addition of RA because the comparison is between different w/c ratio pastes and therefore different concretes. To properly compare the CC and the RAC, two variables have to be analysed simultaneously: the aggregate higher permeability and the lower permeability of the paste. In [13] both are considered.

Medina et al. [69,70] find that recycled concretes made with recycled ceramic sanitary ware aggregate have not negative effect on concrete oxygen permeability reducing slightly the w/c ratio. However, the permeability of concretes made with these recycled aggregates is less than the permeability presented by the RAC.

3.9. Recycled concrete mechanical properties

3.9.1. Compressive strength

Table 5 shows the compressive strength of the RAC and CC.

The results show that the use of 20% RA produces no significant changes with respect to the CC. Where the substitution is 100%, there is a increment of compressive strength. Applying the model of compressive strength proposed [13], for a CC with a strength of 31 MPa, a total replacement would provide a 29 MPa compressive strength recycled concrete. However, the value obtained in this research is almost 40 MPa.

As already mentioned, the replacement of natural aggregate by dry recycled coarse aggregate causes a reduction in the water/cement ratio proportional to the degree of substitution. The consequent reduction of the volume of water has caused an increase in the amount of cement per volume unit reflected in the increase of the compressive strength. Therefore, the negative effect of recycled aggregate is offset and exceeded by the increase of the amount of cement. However, increasing the amount of cement per unit volume leads to an increase in the cost of the concrete and negatively affects the environmental benefits arising from the use of recycled aggregates. In this sense, the Binder Intensity [71,72] has been calculated, taking into account the volume reduction and compressive strength, as the required mass of cement per cubic meter to obtain 1 MPa. According to the values obtained in the case of concrete with 100% substitution of recycled aggregate, 2%wt. more cement was required to obtain the same strength. Also, the Binder Intensity of another study where construction and demolition wastes were used [13] was evaluated, obtaining for the 100% recycled concrete an increment of

4.5%wt. content of cement. These results confirm that the recycled aggregate used here as a reference is one of a very high quality.

3.9.2. Tensile splitting strength

Table 5 shows the tensile splitting strength of the RAC and CC.

As with the compressive strength, there is a tendency for the tensile splitting strength of the RAC to be higher than the CC strength. In general terms, the tensile strength of RAC depends on the degree of substitution, decreasing with it but in this case, as with other properties, the decrease of the w/c ratio with the incorporation of the dry RA, increasing the cement content, causes a slightly increment of the mechanical properties.

3.9.3. Modulus of elasticity

Table 5 shows the modulus of elasticity of RAC and CC. The influence of RA on the elastic modulus is significantly higher than on the compressive strength. In this case, a loss of stiffness of the concrete of 9% is observed for a substitution of 100% of the coarse aggregate, less than the reduction of other properties. If the matrix of the recycled concrete has a greater amount of cement than the control concrete, the reduction in the stiffness due to the recycled aggregate is significantly greater than 9%. Other research, keeping constant the amount of cement and water by saturation of aggregates [13,30] has shown that the decrease in the elastic modulus is situated between 15 and 20%, showing a greater loss in concretes with a smaller amount of cement.

4. Conclusions

Different mixtures of structural concretes with different degrees of substitution of coarse aggregate by recycled aggregates coming from a precast plant have been studied; the most important conclusions can be stated as follows.

The grading curves of the different recycled aggregate considered fall outside the limits defined by same standards for the maximum size. However, this situation can be solved by mixtures with natural aggregate for a suitable particle size distribution or by adjustment at the crushing stage, choosing the appropriate comminution system.

The content of fines in these recycled aggregate is 0.45%wt. Usually a higher value than for natural aggregates, is found, due to its higher friability but the registered value is below the limit established by the EHE - 08, supporting up to a maximum of 1.5 %wt.

Although the densities for all fractions (fine, medium and coarse) are slightly higher than those usually reported in the literature, these recycled aggregates can be considered as normal density aggregates.

The value of the coefficient of water absorption of recycled aggregate, 4.37%wt., is well below the limits of the EHE Instruction – 08 (5%). Also, porosity (less than 10%) is better than the values usually found for recycled aggregates. However, the high friability of recycled aggregate, causes an increase in the Los Angeles coefficient (31%) under the limit of 40%.

The crushing value of the recycled aggregate is 30%wt. There is no limitation to the value of this parameter by the standards but it is considered here as a representative parameter of the aggregate behaviour inside the concrete. Also, the durability of the recycled concrete aggregate coming from precast components exceeds all the analysed chemical and impurity parameters.

The workability of the concrete made with different percentages of substitution of natural aggregate by recycled aggregate is not compromised, resulting in all the cases a fluid slump according to its structural application. However, the use of superplasticizers is required.

The compressive strength of concrete made with different percentages of replacement of natural aggregate by recycled aggregate are higher because of the reduction in the water/cement ratio. The compressive strength (30 MPa) required by the Company is already obtained but the need of cement is greater and for the concrete with total replacement makes it less profitable. Also, both the density and the porosity (around 11%) are suitable for the use of these recycled concretes in structural applications. The absorption coefficient is slightly higher than 5% for all cases studied.

The values of the of oxygen permeability coefficient and water penetration under pressure, obtained for concrete with different degrees of substitution, are similar to those reported for conventional concrete, and consistent with the values of porosity.

Finally, it is possible to make the following general considerations:

The concretes made with 20% of recycled aggregate have shown an excellent performance in relation to the reference concrete, according to the Annex 15 of EHE - 08 which recommends a 20% maximum degree of substitution of natural aggregate by recycled aggregate.

The results of this research have been obtained, in all cases, on laboratory scale and cannot be directly transferable to an industrial scale. For this reason, large-scale testing is recommended.

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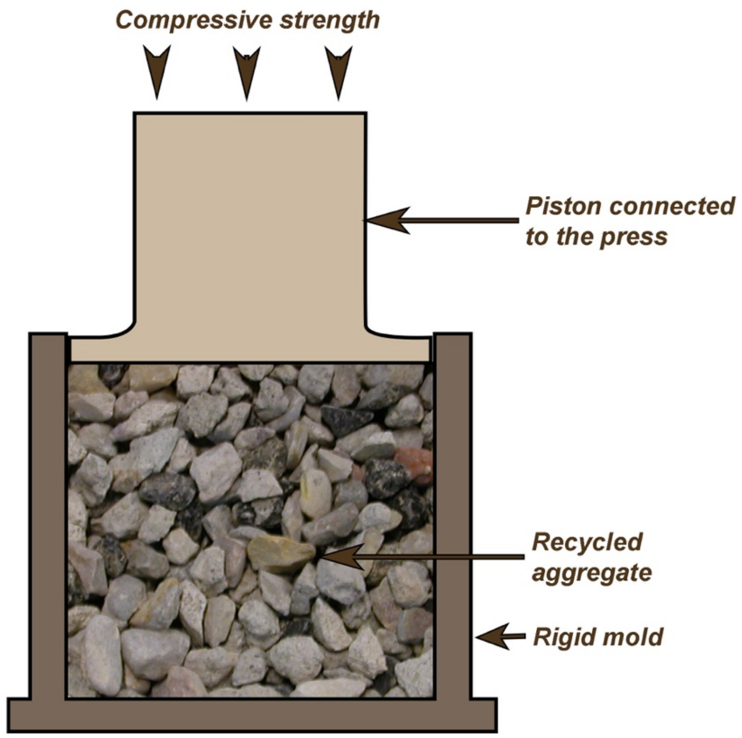

Fig. 1. *Flakiness index device.*

Fig. 2. *Aspect of the sample after the test inside (a) and outside (b) the mould.*

Fig. 3. *Aspect of the sample after the separation using the 2.5 mm sieve.*

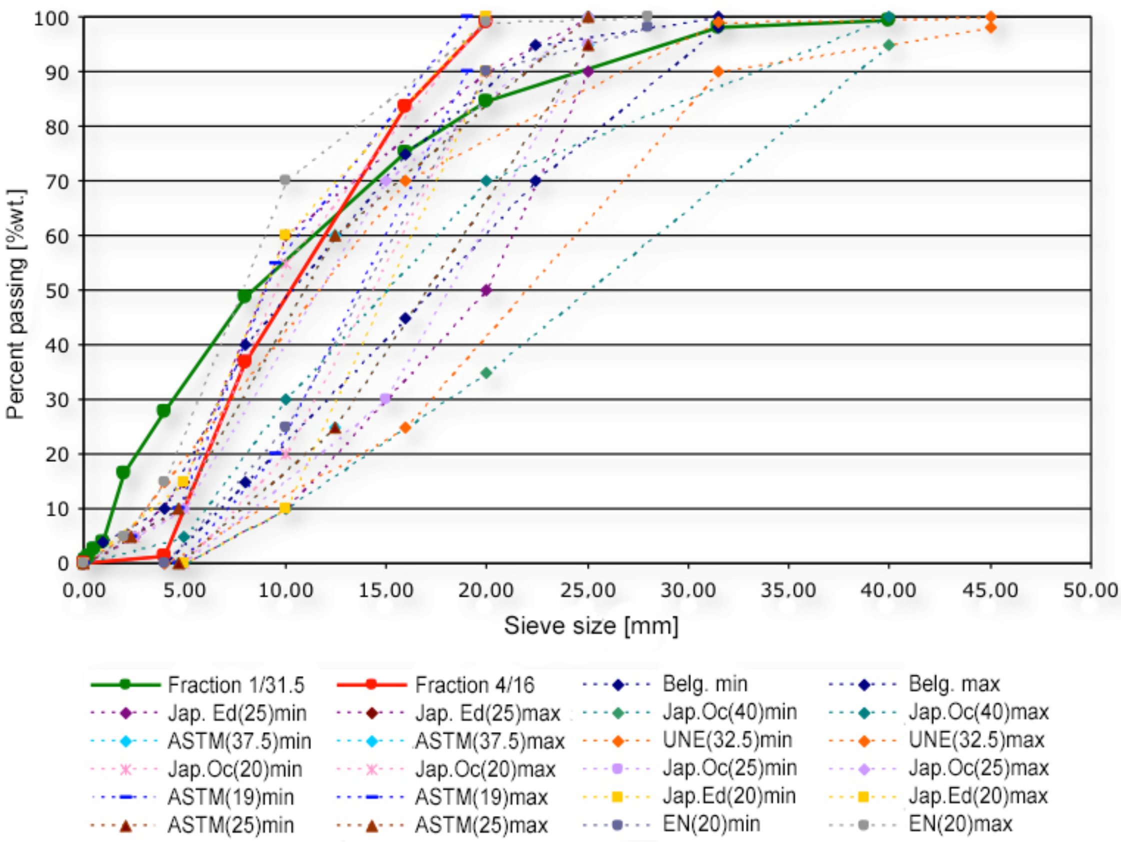

Fig. 4. *Grading of the fractions 1/31.5 and 4/16 of recycled aggregate and the recommendations of the studied standards. Grading of the fractions 1/31.5 and 4/16 of recycled aggregate and the recommendations of the studied standards. EN 12620 [11]; ASTM C 33 – 93 [51]; Belgian standard for recycled aggregate from concrete, fraction 4/32 [52]; Japan [53-55].*

Table 1. Chemical composition by XRF of the cement.

Cement	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	K_2O	MgO	TiO_2	C
CEM I 52,5 N/SR	69.6	18.6	3.1	2.66	3.22	0.54	1.17	0.17	0.47

Table 2. Properties of the natural coarse aggregate.

Aggregate	Dr [g/cm^3]	Dsss [g/cm^3]	A [% w]	P [% v]	Dc [g/cm^3]	LA [%]
NA (6/12)	2.51	2.55	1.8	4.7	1.53	31
NA (12/20)	2.54	2.59	1.6	4.0	1.53	-

Where:

Dr	Relative density of particle (g/cm^3)
Dsss	Density of particle saturated with dry surface (g/cm^3)
A	Water absorption (% weight)
P	Open porosity (% vol.)
Dc	Aggregate density (g/cm^3)
LA	Los Ángeles Index (% weight)

Table 3. Mix proportions per cubic meter.

Substitution:	**Un.**	**0%**	**20%**	**50%**	**100%**
Cement:	kg	300	300	300	300
Water:	kg	175	175	175	175
Sand:	kg	926	900	900	800
Gravel (12/20):	kg	328	0	0	0
Gravel (6/12)	kg	674	800	500	0
RA (12/20):	kg	0	280	560	1115
Additive (Sup. Plas.)	kg	1.35	1.50	1.95	2.10
Effective w/c ratio		0.58	0.55	0.45	0.38
Fresh slump	cm	18	17	18	16

Table 4. Properties of the recycled aggregate.

Property	Spanish standard EHE08	Bibliography range values	NORTEN recycled aggregate	Attending (Y/N)
Sieve modulus	-	6.2 – 7.6	(1/31.5) = 6.25; (4/16) = 6.78	-
Fines content (%wt.)	≤1.5	0.27 – 1.14	(1/31.5) = 0.45	Yes
Particles smaller than 4 mm	≤10	0.5 – 2.0	(1/31.5) = 27.77; (4/16) = 1.38	No; Yes
Flakiness index (%wt.)	≤35	7 – 22	12	Yes
Shape coefficient (%wt.)	>0.2 (<27)	0.17 – 0.47	(4/8) = 11; (8/16) = 18; (16/31.5) = 20	Yes; Yes; Yes
Density (g/cm^3)	2 – 3	2.1 – 2.4	(≤1 mm) = 2.58; (1/4 mm) = 2.46; (>4mm) = 2.48	Yes; Yes; Yes
Absorption coefficient (%wt.)	≤5	4 – 10	(4/16) = 4.19	Yes
Porosity (%vol.)	-	10 – 18	(4/16) = 9.76	-
Los Ángeles coefficient (%wt.)	≤40	25 – 42	31	Yes
Soft particles (%wt.)	≤5%	20 – 60	16.68%	No
Crushing value (%wt.)	–	–	30	-
Resistance to magnesium salts (%wt.)	≤18	0 – 2	2	Yes
Resistance to freezing – thawing (%wt.)	–	1.6 – 14. 6	5.6	-
Light particles (%wt.)	≤1	0.5 – 5.0	(4/8) = 0.0038; (8/16) = 0.023	Yes
Clay lumps (%wt.)	≤0.25	0.05 – 0.60	0.25	Yes
Water-soluble chloride (%wt.)	≤0.05	0.001 – 0.005	0.00159	Yes
Soluble sulphates in acid (%wt.)	≤0.80	0.10 – 0.62	0.65	Yes
Sulphur compounds (%wt.)	≤1	–	0.28	Yes

Table 5. Recycled concrete properties with 28 days.

Substitution:	**Un.**	**0%**	**20%**	**50%**	**100%**
Apparent density	g/cm^3	2.23	2.24	2.19	2.16
Relative density	g/cm^3	2.55	2.54	2.47	2.44
Saturated density	g/cm^3	2.35	2.36	2.30	2.27
Absorption coef.	% wt.	5.58	5.24	5.04	5.42
Open porosity	% vol.	12.46	11.77	11.07	11.71
Oxygen permeability	m^2	$3.085 \cdot 10^{-16}$	$2.197 \cdot 10^{-16}$	$4.942 \cdot 10^{-16}$	$9.054 \cdot 10^{-17}$
Water penetration (72 h)	mm	>97	>98	>98	>96
Water penetration (24 h)	mm	55	>88	25	52
Compressive strength	MPa	36.5	36.7	37.7	38.4
Tensile strength	MPa	1.40	1.65	1.86	1.94
Elastic modulus	GPa	35.2	33.9	30.5	31.8
Cement./Vol.	kg/m^3	300.3	303.0	312.5	319.5
Binder Index	$kg/m^3 \cdot MPa^{-1}$	8.23	8.26	8.29	8.32