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Title: Effect of recycled aggregate on physical-mechanical properties and durability of vibro-compaction dry-mixed concrete hollow blocks

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Abstract: This paper deals with the feasibility of using fine and coarse recycled aggregates, both from concrete and mixed sources, as technological nutrients for the production of dry-mixed vibro-compaction concrete hollow blocks traditionally used in wall construction. Five series of blocks were prepared with different combinations and a reference one to be used as a control. The results shows that the incorporation of recycled aggregates does not compromise compliance with the European standard EN- 771-3, nor further durability requirements by means of hazardous ambient such as freeze-thawing and salts crystallization studied and the manufacturer's declared values.

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December 7, 2016

Dear Sir,

Please find enclosed the paper titled "EFFECT OF RECYCLED AGGREGATE ON PHYSICAL-MECHANICAL PROPERTIES AND DURABILITY OF VIBRO-COMPACTION DRY-MIXED CONCRETE HOLLOW BLOCKS" by María Martín-Morales, Gloria María Cuenca-Moyano, Ignacio Valverde-Espinosa and Ignacio Valverde-Palacios. The authors would like this manuscript to be considered for its publication in Construction and Building Materials.

This paper has been checked by a native tongue speaker with expertise in the field. It presents an original, complete and unpublished study on the use of recycled aggregates in the production of dry-mixed concrete hollow blocks which complies with the requirements of the European standard EN-771-3. *Specifications for masonry units. Part 3: Aggregates concrete masonry units (dense and lightweight aggregates)* which in addition are capable of manifesting an adequate durability in environments of high humidity with frost and sea salts. The results obtained show the complete viability of using recycled aggregates, regardless of their type and quantity, with a low amount of cement as binder, for this low-graded application in hollow precast pieces where its incorporation is not limited by the regulation and it has not been detrimental to their functioning.

These are new findings that are of great interest to the readers of this journal, since no papers have hitherto been published on the total use of recycled aggregates as a technical nutrient in the manufacture of concrete hollow blocks, allowing the incorporation of the prefabrication sector in the field of the circular economy.

Finally, I would like to point out that it is very rewarding to continue the collaboration as reviewer with your journal.

Best regards,

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Highlights

The production of non-structural dry-mixed concrete hollow blocks with recycled aggregate is proposed.

Geometric, physical and mechanical requirements of concrete hollow blocks according to the European standards EN- 771-3.

Durability of concrete hollow blocks through freeze-thaw and salt crystallization exposure.

Recycled aggregate as technical nutrient to incorporate the industry of precast in the circular economy.

Effect of recycled aggregate on physical-mechanical properties and durability of vibro-compaction dry-mixed concrete hollow blocks

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Abstract

This paper deals with the feasibility of using fine and coarse recycled aggregates, both from concrete and mixed sources, as technological nutrients for the production of dry-mixed vibro-compaction concrete hollow blocks traditionally used in wall construction. Five series of blocks were prepared with different combinations and a reference one to be used as a control. The results shows that the incorporation of recycled aggregates does not compromise compliance with the European standard EN- 771-3, nor further durability requirements by means of hazardous ambient such as freeze-thawing and salts crystallization studied and the manufacturer's declared values.

Keywords*:* Construction and demolition waste; Recycled aggregate; Technological nutrient; Precast Units; Normative

Abbreviations

CHB, concrete hollow blocks

EU-28, 28 member states of the European Union

C&DW, construction and demolition waste

RA, recycled aggregate

NA, natural aggregate

CRA, concrete recycled aggregate

MRA, mixed recycled aggregate

1. Introduction

According to Eurostat [1], in 2010 the total generation of waste from economic activities and households in the EU-28 amounted to 2,506 million tonnes and, despite the downturn in economic activity, construction activity accounted for the largest share of generated waste with 860 million tonnes (34.32%). With respect to treatment, almost half of these 2,339 million tonnes treated was subject to disposal operations other than incineration, predominantly in landfills. Construction and demolition waste was traditionally disposed in landfills, supposing a great management problem for governments since, besides, it significantly affects the environmental degradation.

Construction and demolition waste (C&DW) mainly comes from building and infrastructure demolitions, which fundamentally include concrete, masonry mortar and ceramic materials, thus they are not dangerous since they are considered inert according to Council Decision 2003/33/EC [2]. They, however, generate environmental problems not only derived from the high volume produced, but also from its treatment and disposal in dumps [3]. Accordingly, they should be properly treated in industrial treatment plants for the production of recycled aggregate and used as conventional aggregate, helping to preserve the environment by reducing the expenses related to construction and demolition waste management, and to protect the natural resources [4].

In recent years numerous studies have been published regarding the use of recycled aggregate (RA) in structural concrete [5-7], non-structural concrete [8-9], mortars [10-12], and road construction [13-14]. Most of them affirmed that the quality of RA is lower than that of natural aggregate (NA), being the higher absorption, the adherer mortar and the impurities those that limit their use. Notwithstanding, technical regulations allow the use of RA except for fine RA [15] where such shortcomings are more sharply manifested.

Nonetheless, RA has been infrequently used in low-value-added applications as non-structural precast concrete where there are no restrictions of RA use or at least these are not so limiting. Poon and his colleagues have focused part of their investigation on this option [16-19]. They found that it is possible to produce concrete paving blocks for pedestrian areas and for traffic with different partial combinations of recycled aggregates, even using the fine fraction of RA despite the mechanical strength reduction [19].

According to Poon and Chan [18], an allowable contamination level can be increased from 1% to a maximum of 10% in the production of paving blocks. In this regard, practically all of the studies found were about solid concrete precast pieces such as blocks [3-4, 20-25], paving blocks [26-28], or pavement flags [27, 29]. These studies have demonstrated that it is feasible to incorporate up to 100% of coarse and fine RA for the production of non-structural concrete pieces; however, the disadvantage exists that cement quantities well above to conventional need to be used for this type of precast in order to maintain the mechanical requirements.

Nevertheless, only a few authors have studied the behaviour of recycled concrete hollow precast using RA. Dominguez and his colleagues [30] produced hollows bricks obtaining not too favorable results. In the experiment of López Gayarre [31], floor blocks obtained resulted not overly affected in physical properties complying with the standards, not so in its mechanical behaviour, which resulted significantly dwindled. Recently, Rodríguez [32] also experienced a lineal loss of flexural strength in hollow tiles manufactures with coarse MRA. They concluded that the essential properties of hollow tiles are retained until a 25% of MRA substitution is reached. Finally, Matar and El Dalati [4] concluded that using RA without NA in the manufacture of concrete blocks is not economical due to the necessity of a high rate of cement addition in order to obtain the required compressive strength.

Therefore, the aim of this study was focused on the production of non-structural dry-mixed concrete hollow blocks (CHB) with the incorporation of coarse and fine RA which complied with the requirements of the European standard EN- 771-3. *Specifications for masonry units. Part 3: Aggregates concrete masonry units (dense and lightweight aggregates)* [33]; and in addition which were capable of manifesting an adequate durability against certain extreme ambient conditions such as freeze-thaw and salt crystallization. In this regard, and since recycled aggregates from C&DW can be considered as technical nutrients in the circular economy, their use in the manufacture of low-graded applications becomes a guarantee of fulfilment of the objectives established in the Directive 2008/98/CE [34] about the 70% of C&DW generated which should be reused, recycled and assessed in 2020.

2. Materials and methods

2.1 Materials

CHB were fabricated according to the dosage recommendations for these commercial precast by the manufacturer. The components used to make the dry-mixed concrete precast are outlined below:

- Portland cement EN 197-1 CEM I 42.5 R [35], commonly employed in concrete precast.
- Admixture FRIOPLAST P by SIKA. It is a compound admixture water-reducing and plasticizer indicated to achieve the adequate compaction and demoulding of dry concretes made with extruder machines. This admixture was used to improve cohesion and compactness since little water is needed in this kind of pieces because workability is not as important as in conventional concretes.

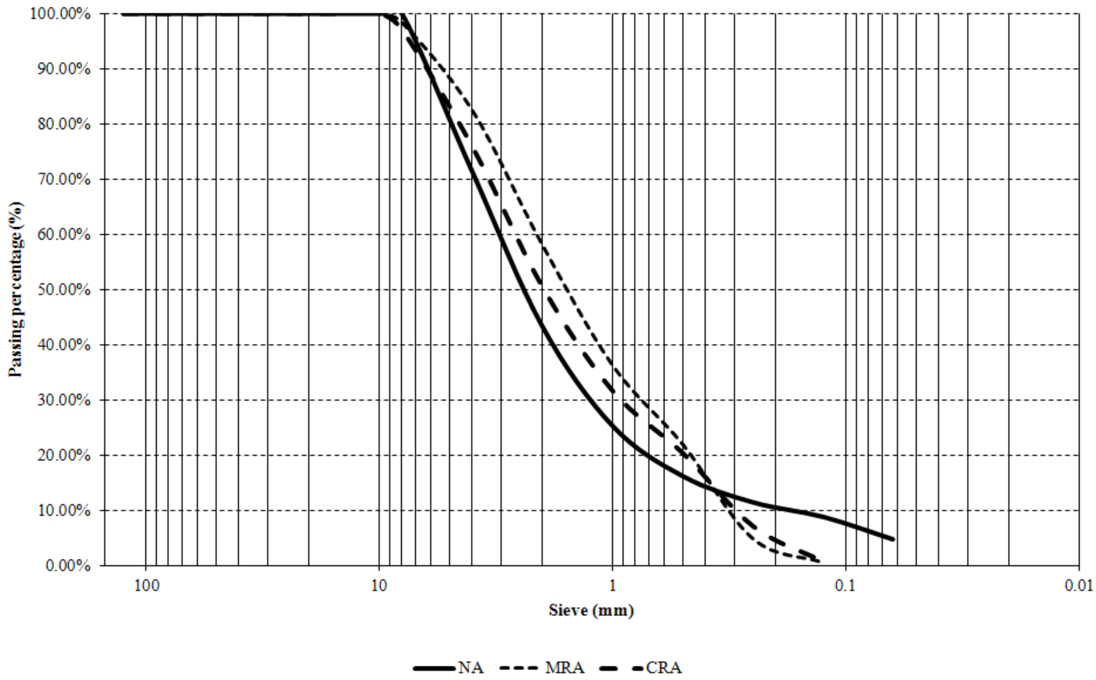

Figure 1. Particle size distribution of aggregates

- Dolomitic NA from a quarry in Padul (Granada-Spain), and concrete recycled aggregate (CRA) and mixed recycled aggregate (MRA) from a C&DW treatment and recovery plant in Granada (Spain). The aggregates in size 0/5 and 5/8mm where mixed in a proportion of 64% and 36% in weight respectively. The process at the C&DW plan consists of a simple impact crushing, and separation with vibrating screens. Metallic elements are removed by using a magnetic conveyor belt and large impurities, such as plastics, paper, glass, and gypsum are extracted by hand before the crushing process. According to the guidelines established in the European standard EN 933-11 [36] CRA fell into the category of concrete recycled aggregate due to major content in concrete and unbound aggregates i(88.34%); on the other hand, MRA was classified as mixed recycled aggregate due to the significant presence of ceramic particles (Table 1). Finally, Spanish Structural Concrete Code EHE-08 [15] and the project of European standard pN EN 12620 [37] have been considered to establish the specifications for aggregates (Table 1); according to them CRA drew continuous curves (Figure 1) and fulfilled the requirement regarding density and content in chlorides, nevertheless MRA presented a content in sulphates somewhat higher than the specified (Table 2).

Table 1. Classification of the constituents of coarse recycled aggregates according to EN 933-11 and category specified according to pN EN 12620

SAMPLE	CONSTITUENT	CONTENT (%)	CATEGORY
CRA	Rc	80.00	Rc80
	Rc+Ru	88.34	Rcu70
	Rb	11.66	Rb30-
	FL	0.00	FL0.2-
MRA	Rc	63.01	Rc50
	Rc+Ru	68.01	Rcu50
	Rb	31.85	Rb50-
	FL	0.14	FL0.2-

Rc, concrete, concrete products, mortar, concrete masonry units

Ru, unbound aggregate, natural stone, hydraulically bound aggregate

Rb, masonry units (i.e. bricks and tiles), calcium silicate masonry units, aerated non-floating concrete

FL, floating materials

2.2 Dosages

Six boards with 7.5 pieces of 400x200x200mm were elaborated with each aggregate combination, according to the manufacturer recommendation. The samples have been named according to the reference dosage and the substitution of NA by RA used, as shown in Table 3. Additionally, each series has been designated in compliance with EN 771-3 [33], indicating the number and date of publication of the European Standard, the type of piece, dimensions and manufacturing tolerances, and compressive strength. Table 4 shows the reference dosage: 7.5% of cement EN 197-1 CEM I 42.5 R, water/cement ratio of 0.61, 0.5% admixture FRIOPLAST P from SIKA, for each series.

Table 2. Specifications of aggregates according to EHE-08 and pN EN 12620

REQUIREMENT	AGGREGATE			LIMIT		
	NA	CRA	MRA	EHE-08 Article 28	EHE-08 Annex 15	EN 12620
Density oven dry (kg/dm^3)	2.675	2.546	2.498	-	-	>2.000
Density saturated dry surface (kg/dm^3)	2.679	2.690	2.658	-	-	-
Absorption (%)	0.141	5.679	6.430	< 5.00	< 7.00	-
Water-soluble sulphates (%)	0.00	0.58	0.90	-	-	-
Acid-soluble sulphates (%)	0.00	0.54	0.84	< 0.80	-	-
Total sulphates (%)	0.00	0.66	1.08	< 1.00	-	-
Water-soluble chlorides (%)	0.00	0.014	0.021	< 0.05* <0.03**	-	-
Acid-soluble chlorides (%)	0.00	0.007	0.014	-	-	-
Soft particles (%)	0.00	0.00	0.00	-	-	< 1.00

* For concrete in mass and reinforced concrete

** For prestressed concrete

Samples fabrication process has considered recommendations of numerous researches that include RA pre-soaking during 10 minutes before its use with the 80% of the water corresponding to its absorption in order to limit the absorption of the mixing water [18]. In this regard, since dry-mixed concrete was manufactured, pre-soaked water did not interfered in the increase of the water/cement ratio, inasmuch as the water absorbed by recycled aggregate only helped in the hydration of cement during the curing and hardening [23]. This requirement did not interfered with the mixing process in the precast plan since the order of pouring into the planetary mixer was as follows: (i) recycled aggregate, (ii) pre-soaked water mixed for 10 minutes, (iii) natural aggregate (if applicable), (iii) cement, and (iv) mixing water.

Finally, CHB were elaborated by means of a modular vibro-compactor POYATOS of interchangeable moulds with 3000 r.p.m. during the filling and 4000 r.p.m. of pressed and were demoulded immediately. Afterwards, CHB were cured in chamber by the water vapour given off by themselves in the first hours. This curing contributes to the final behaviour of precast.

Table 3. Designation of CHB according to EN 771-3

SERIES	AGGREGATE COMBINATION	DESIGNATION
50C + 50N	50% RCA y 50% NA	EN 771-3:2011 CONCRETE BLOCK 400x200x200 D4 R15
50M + 50N	50% MRA y 50% NA	EN 771-3:2011 CONCRETE BLOCK 400x200x200 D4 R15
100C-	100% RCA (without admixture)*	EN 771-3:2011 CONCRETE BLOCK 400x200x200 D4 R10
100C	100% CRA	EN 771-3:2011 CONCRETE BLOCK 400x200x200 D2 R15
100M	100% MRA	EN 771-3:2011 CONCRETE BLOCK 400x200x200 D4 R15
100N	100%NA	EN 771-3:2011 CONCRETE BLOCK 400x200x200 D4 R20

Compressive strength is the value immediately lower than that obtained in the corresponding tests in a multiple of 5

*Although the study of the effects of the commercial admixture on the properties in products which contain RA requires an in-depth research in the future, authors decided to make an initial proof on CHB manufactured with 100% of CRA

Table 4. Dosages of CHB in kg/Tn of dry-mixed concrete

SERIES	RA (kg)	NA (kg)	CEMENT (kg)	MIXING WATER (kg)	ADMIXTURE (kg)
50C + 50N	445.98	445.98	66.90	40.81	0.33
50M + 50N	472.21	419.74	66.90	40.81	0.34
100C-	892.26	0.00	66.90	40.81	0.00
100C	891.96	0.00	66.90	40.81	0.33
100M	891.95	0.00	66.90	40.81	0.34
100N	0.00	891.95	66.90	40.81	0.34

2.3 Laboratory procedures

Six of the manufactured pieces of each series were randomly selected for a battery of tests performed to CHB in accordance with the recommendations of the European standard EN 771-3 [33], regarding the specifications and requirements of concrete blocks made with dense and lightweight aggregates, or a combination of both, for which the main intended uses are brick masonry, exposed or for coating, both for self-supporting and non-self-supporting construction and civil engineering applications (Table 5).

Table 5. Specifications and requirements for CHB according to UNE-EN 771-3 and CTE DB SE-F

REQUIREMENT		STANDARD
GEOMETRIC		
Dimension	Dimension	EN 772-3, 1999 [41]
Dimensional tolerances	Tolerances	EN 772-16, 2011 [42] method A
	Flatness of the bearing faces	EN 772-20, 2001 [43]
	Parallelism of the bearing faces	EN 772-16, 2011 [42] method D
Configuration and appearance	Configuration	EN 1996-1-1, 2011+A1, 2013 (Eurocode 6) [44]
PHYSIC		
Density	Dry bulk density of the pieces	EN 772-13, 2001 [45]
	Absolute dry density of concrete	EN 772-13, 2001 [45]
Water absorption	Capillarity	EN 772-11, 2011 [46]
	Total immersion	
Fire resistance*	Fire resistance	EN 13501-1,2007+A1, 2010 [47]
MECHANIC		
Compressive strength		EN 772-1, 2011 [48]
DURABILITY		
Resistance freeze-thaw		EN 13198, 2004 [38] annex A
Resistance to aging in saline atmosphere chamber		EN 14147, 2004 [39]
*Fire resistance of the CHB studied can be considered as class A1, since it is set by the standard that precast concrete products cement-based made with less than 1% of organic materials, can be declared so without need for testing as class A1 of fire resistance.		

According to the standard, the pieces are suitable for all types of walls, including walls of a single sheet, the exterior walls of fireplaces, air chamber, divisions, containment and basement. Moreover, they can provide fire protection, and thermal and acoustic insulation. Furthermore, it has also been considered of high interest, due its possible applications, to determine other parameters such as absorption by total immersion until constant mass, resistance to freeze-thaw [38] and resistance to aging in saline atmosphere chamber [39], which are not included in the standard EN 771-3 [33].

These tests were done according to the recommendations proved by the Basic Document of Structural Safety Bricks Masonry of the Technical Code of Edification CTE DB SE-F [40]. With respect to the absorption, CTE establishes as a general rule the need to moisturizing the pieces by spraying or immersion for a few minutes, in order to avoid variations in the mortar consistency by suction of the mixing water. Furthermore, in regard to the Code CTE strategy for durability on bricks masonry, durability test has been done as well due to the interest to determine the behaviour of these pieces in certain extreme ambient conditions. This test would also appear to be attractive in pieces for many commercial, municipal and industrial applications [26].

3. Results and discussion

Tables 6 and 7 summarize the results of laboratory procedures regarding the requirements, including the declared by the manufacturer and the average values. The following subsections provide a discussion of the results in terms of geometrical, physical, mechanical and durability requirements.

Table 6. Dimensions, tolerances and appearance of the concrete hollow blocks according to EN 772-3, EN 772-16 and EN 772-20

GEOMETRIC REQUIEMENT	DECLARED VALUE	50C+50N	50M+50N	100C-	100C	100M	100N
Long L (mm)	400.00	398.00	399.00	398.60	398.00	399.00	400.00
Width W (mm)	200.00	199.00	199.00	199.00	198.60	199.00	199.50
Height H (mm)	200.00	199.60	200.00	200.00	198.20	200.00	199.00
Category of tolerance	D1	D1	D1	D1	D2	D1	D1
Wall thickness (mm)	n.d.	21.16	20.93	21.28	21.28	21.44	22.00
Interior wall thickness (mm)	n.d.	21.96	21.90	21.80	21.76	21.64	21.80
Parallelism (mm)	n.d.	199.67	199.79	199.80	197.13	199.92	200.00
Flatness (mm)	n.d.	445.00	445.00	445.00	445.00	445.00	445.00

3.1 Geometrical requirements

No differences in terms of homogeneity and uniformity of colour and texture were detected between samples manufactured with NA and RA, except for the variation in colour of the pieces that include MRA, which turns slightly brownish (Figure 2).

Table 7. Physical and mechanical properties and durability of concrete hollow blocks according to EN 771-3

REQUIREMENT		DECLARED VALUE	50C+50N	50M+50N	100C-	100C	100M	100 N
Density (kg/dm3)		1.900	2.045	1.891	1.856	1.887	1.816	2.175
Weight (gr)		-	14851.1	14296.6	13775.1	13873.5	13400.2	15712.0
Weight decrease (%)		-	5.50	9.01	12.33	11.70	14.71	-
Absorption by capillarity (gr/m2.s)		10.40	10.43	10.25	12.05	5.97	8.41	6.72
Absorption by total immersion (%)		n.d.	7.79	7.65	10.05	10.02	11.81	4.64
Compressive strength (N/mm2)		13.400	15.224	17.281	13.836	18.812	14.007	24.423
Category		R10	R15	R10	R10	R15	R10	R20
Freeze -thaw	Compressive strength (N/mm2)	n.d.	11.595	13.861	12.439	17.138	11.717	24.237
	Loss of strength (%)	n.d.	23.84	19.79	10.10	8.90	16.35	0.76
	Loss of weight (%)	n.d.	10.23	3.41	5.94	6.16	6.29	2.68
Class of fire resistance		A1	A1	A1	A1	A1	A1	A1
Resistance to aging	Compres.strength (N/mm2)	n.d.	13.469	13.965	12.115	15.368	10.027	21.070
	Loss of strength (%)	-	11.53	19.19	12.44	18.31	28.41	13.73
	Loss of weight (%)	-	3.17	2.62	3.02	1.87	2.71	1.10

In relation to the configuration of these precast pieces, both in measures that define its external volume, as interior and exterior walls, and the parallelism and flatness, indicate that CHB manufactured with RA do not differ in configuration compared to those elaborated with NA (Table 6). Although these requirements have not been developed in the few existing studies, similar results, but checked in entirely solid blocks, were found by Matar and El Dalati [4] and López-Gayarre [31] who asserted that for replacements equal or under 50% it is possible to obtain a good surface finishing. Likewise, in regard to the assignation of category of tolerance, according to the physical parameters relating to dimensions long (L), width (W) and height (H), it could be stated that all of the blocks reached the category of tolerance D1 (deviations between +3 and -5mm in L, W and H), except for those manufactured entirely with CRA which were categorized as D2 (deviations between +1 and -3mm in L and W, and ±2mm in H); so that dimensional variations are within the prescribed limits.

In any case, from the point of view of the geometric characteristics of the CHB studied, the incorporation of RA in every type or quantity does not compromise the pieces' appearance and configuration for further applications.

Figure 2. Precast concrete hollow blocks (CHB)

3.2 Physical requirement

3.2.1 Density

Bulk density of the recycled concrete precast studied showed lower values in relation to pattern blocks decreasing up to 16.51% in the case of total incorporation of MRA. As expected, the presence of RA in CHB in terms of quality and quantity was the determining factor of density losses, being even more pronounced in blocks which have been substituted totally with RA and in those made with MRA due to a lower density than RCA (Table 7). In addition, a considerable positive effect has been observed in terms of cohesion and compactness required by the admixture in the behaviour of CHB made with RCA with and without it. Although there are no limits in the standards for this property the results are according to the acceptance criteria stablished in the standard EN 771-3 [33] because none of them are below the 10% value declared by the manufacturer. Likewise no results from other studies were found for this king of pieces, the values obtained are in consonance with the results displayed by other authors regarding solid pieces in form of bricks and blocks [3-4, 16, 27]. Slightly higher and more homogeneous values were obtained by Poon and Chan [18] which were attributed to the higher volume of cement used, which is able to fill up the voids within the concrete mixture.

Nevertheless, these losses in density become a considerable advantage for its handling and starting. In view of the substantial high weight of these kinds of pieces, CHB manufactured with the RA studied resulted lighter and hence more comfy in their handling with respect to the weight conferred to the structure of the building than pattern pieces. Table 7 compares the weight of these products confirming the same tendency as in density, ranging the decrease with respect to the pattern pieces between 5.5%, in blocks manufactured in partial substitution of CRA, to 14.71%, in those processed entirely with MRA.

3.2.2 Water absorption

The incorporation of RA in CHB manufactured has produced several effects on water absorption by capillarity. The general trend observed for density has not been ascertained. Contrary as expected, partial substitutions provided the worst performance against this property, gains of more than 50% of capillarity absorption being verified, thus showing a relative incompatibility between natural and recycled aggregates. Besides, and although CHB fully manufactured with MRA still maintain a high rate, it has been observed that the totally incorporation of RCA has a very positive effect due to the reduction over 10% on capture of capillary water with respect to pattern blocks. In this sense, the admixture has played an important role in this property, completely changing the behaviour of CHB manufacture with RCA without admixture, where capillarity absorption reached up to 80%, with respect to those with the incorporation of the admixture, which got a lower rate than pattern blocks. In spite of this, except for the CHB manufactured without admixture, the rest fulfilled the value declared by the manufacturer.

No limitation is prescribed by the standards, therefore no study regarding this property has been found. However, it has to be considered as a fundamental requirement since, indirectly, the wetting of the pieces prior to starting is recommended in order to not vary the consistency of the mortar, both sucking the mixing water or incorporating water to the mortar [40]. So that CHB which incorporates RCA in total substitution of NA and water-reducing/plasticizer admixture considerably improve the implementation of masonry blocks where the absorption of water from mortars is required to limit.

In contrast, water absorption by total immersion is not considered in the standards but it has been studied by other authors. As expected, this parameter, with values ranging from 7.65% (50M+50N) to 11.81% (100C), is more than twice the value in recycled blocks made with total substitution with respect to pattern blocks (4.64%), having CHB which have been partially substituted a better performance than those which have been totally substituted. Practically, differences in the absorption with regard to the type of aggregate and the presence of admixture have not been found, except for CHB fabricated totally with RA, in which those made with MRA have been observed to experiment a significant grow in the absorption index. These results are lower than those obtained by other authors [18], which reached values up to 20% [27] due to the presence of clay bricks aggregate [23-24] and to the recycled aggregate itself, which is more absorbent [28-29].

In this study, the lower presence of fine particles in recycled granular materials used (see Figure 1) could justifies these phenomena related to moisture, both water absorption by capillarity and by total immersion, whereas fines provide less filling in concrete, so that ascension of water by capillarity is hindered, and on the other, the capacity to retain it by total immersion in greater.

Based on the foregoing and considering the greater responsibility of masonry blocks during its starting, it can be concluded that CHB manufactured totally with RA, previously wetted, result plenty adequate in so far as they do not sucked the mixing water of the mortar and they could progressively incorporate the retained water for it curing.

3.3 Mechanical requirements

As expected, the strength capacity resulting in recycled CHB measured by its resistance to compression was lower than blocks manufactured with NA (Table 7). Decreases ranged between 22.97% and 43.35% in blocks made with RCA, with and without additive, respectively, which indicate that additive plasticizer substantially improves the binding power of the paste. Even though all the pieces showed a compressive strength higher than the value declared by the manufacturer, the expected tendency was not achieved in the case of CHB fabricated with CRA of which those manufactured entirely with RA showed improved mechanical strength with respect to those replaced partially. These results have enabled to assign the declared category with respect to its compressive strength from R10 to R20 depending on the average value achieved by each type of piece.

This mechanical requirement is the only one required by the normative. In this sense, the Basic Document of Structural Safety Bricks Masonry of the Technical Code of Edification CTE DB SE-F [40] establishes the minimum value of compression strength in 5 N/mm^2 for masonry unit; thus, it can be stated that all the recycled pieces studied amply fulfilled this limitation.

The few studies encountered have confirmed the excellent results obtained in our study in terms of the mechanical strength presented by recycled CHB with respect to other researches [4,30]. Similar resistances were obtained in the study conducted by Leiva [3], whose CHB made with different replacements of fine aggregate (20%, 40% and 50%) and coarse aggregate (20% and 30%) using a quantity of cement of 20%, being well above the 7.5% of the pieces manufactured for this study.

Definitely, from the standpoint of the structural performance, the total incorporation of RA both from concrete and mixed CD&W, works out to be highly appropriate in the elaboration of dry-mixed CHB by means of the technique used, probably due to the use of a combination of vibration and compaction forces in the production process that could improve the packing and the quality of concrete products produced [24].

3.4 Durability

In terms of durability, and although it has not been found any limitation in the existing regulations, it has been considered advisable to determine the behaviour of CHB in certain aggressive environments as another quality degree of these recycled precast products. In this regard, the loss of weight and strength has been tested when pieces were subjected to ambient simulation of high humidity with frost and sea salts.

3.4.1 Freeze-thawing resistance

CHB subjected to 25 freeze-thaw cycles, consisting in freezing at -18ºC during 3h and thawing in total immersion in water at 20ºC, have significantly reduced their mechanical strength with respect to the concrete blocks not under test (Table 7). Whereas pattern concrete blocks only have experienced a loss of strength of 0.76%, recycled pieces have responded to this test with losses between 8.90% and 23.84%, in CHB totally and partially substituted by RCA respectively. In this respect, it should be noted that CHB made with the replacement of RCA revealed the most extreme results for this requirement, showing the poor coupling between natural and recycled concrete aggregates again. In this case, it has not been able to ascertain a large effect of the admixture in enhancing the performance of CHB against this action. Although these losses are significant, CHB which underwent such conditions of temperature and humidity still complied with the minimum of 5 N/mm^2 established in the CTE [40].

Moreover, both of the pieces manufactured with NA and RA showed losses of mass, fundamentally visible at the edges and corners, (Figure 2) which were ranged from 3.41% (50M+50N) to 10.23% (50C+50N), although they do not correspond with the strength decrease. It is worth highlighting, contradicting the expected tendency, the weight loss experienced by CHB manufactured with partially replaced with RCA, whose result was significantly higher than its counterparts made with 100% of substitution. This phenomenon, which occurs in the absorption by capillarity and the previous compressive strength measures (both in normal conditions and after exposure to freeze-thaw cycles), could be associated with a greater open porosity in the precast concrete resulting with the mixture of natural and recycled concrete aggregates [28-29, 31].

Therefore, in view of the results obtained for this requirement it can be concluded, as Jankovic [27] ensured, that it is possible to produce recycled concrete precast for cold climate according with European standards, and contrary to the assertions of some authors [28-29, 31] a low correlation between absorption and resistance to freeze-thaw has been found (R^2 = 0.5099 and R^2 = 0.476 respect to the total and capillarity absorption respectively).

3.4.2 Resistance to aging

Finally, CHB were subjected to 60 cycles of wetting-drying in a saline chamber at 35ºC, where they were sprayed water with 10% of sodium chloride for 4h and dried during 8h in order to simulate ambient of high humidity with frost and sea salts. After these conditions, the pieces experimented significant drops in strength from 11.53% (50C+50N) to 28.41% (100M), being, as expected, this effect more pronounced in blocks totally substituted by RA. In this sense, it is noteworthy the best behaviour of CHB made with 50% of RCA and with 100% of RCA without admixture that presents larger values of absorption by capillarity and total immersion, in whose porous structure salt crystallization practically do not cause damages. In any case, these variable and irregular losses of durability measured by the decrease in strength have no particular significance since CHB manufactured still remain well above the minimum value of 5 N/mm^2 established in the CTE [40].

With regard to its weight, it has been found a relatively low loss of weight, being CHB totally and partially replaced with RCA those presenting more extreme values, ranging between from 1.87% to 3.17%, respectively. The consequent loss of mechanical strength does not run parallel to the weight loss. It has been observed that the CHB manufactured with 50% of RCA and with 100% of RCA without admixture were the ones which experienced more weight losses and the lowest decrease in strength. In contrast, pieces elaborated with MRA are those which suffer greater resistance decreases but middle weight losses.

Therefore, based on the results of resistance to aging it can be say that CHB manufactured with RA, regardless of its type and quantity, can be used in environments of high humidity with frost and sea salts as marine environment, being completely guaranteed that physical and mechanical properties will not diminish.

Conclusions

The production of non-structural dry-mixed concrete hollow blocks (CHB) with incorporation of coarse and fine recycled aggregate (RA) which meet the requirements of the European standards EN- 771-3, and, in addition, were capable to manifest an adequate durability against certain extreme ambient conditions such as freeze-thaw and salt crystallization, as the primary objective of the study conducted, has been achieved.

Despite the variability of the results obtained, it can be established the complete viability of using recycled aggregates (RA), regardless of their type and quantity, for this kind of low-graded applications by using the technique of vibro-compaction, where its incorporation is not limited by the regulation and it has not been detrimental to the functioning of the precast.

In general terms, both concrete recycled aggregate (CRA) and mixed recycled aggregate (MRA) have shown a proper behavior in the CHB studied. However, precast manufactured entirely with RCA has presented the best performance, mainly in relation to its mechanical resistance, before and after exposure to extreme ambient, and to the absorption by capillarity, since the incorporation of admixture is required to achieve the desired effect. Contrary to expected, the worst results were obtained for these requirements in partial substitutions of natural and RCA due to its bad coupling.

The CHB fabricated with 100% of MRA, despite the fact that they have shown its validity for the applications described by the standard, have thrown the worst results in every requirement. Nevertheless, partial substitutions of MRA have provided the most adequate results in the performance of recycled CHB with respect to its absorption by total immersion and losses of weight after freeze-thawing exposure.

Finally, it has been found a great weight reduction in CHB studied up to 15%, offering enormous advantages for the operators handling these pieces of 15kg of average weight and to the weight conferred to the structure.

Based on the foregoing, the production of competitive non-structural dry-mixed concrete hollow blocks (CHB) by the vibro-compaction technique has proven highly appropriate with the total incorporation of concrete and mixed recycled aggregate from CD&D waste and with no increase in cement concrete, allowing the incorporation of the prefabrication sector in the field of the circular economy.

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