Secondary aggregates and seawater employment for sustainable concrete dyke blocks production: case study

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Abstract

The main objective of this research work was to validate the on site real scale production of dyke blocks employing coarse mixed recycled aggregates, steel slag aggregates and seawater. A laboratory experimental phase (Phase 1) was carried out prior to real scale concrete block production within Barcelona's port (Phase 2). According to the results, the concretes produced with a combined mixture of 50% coarse mixed aggregates and 50% of coarse steel aggregates achieved the most adequate properties for use in dyke block manufacturing. The concrete produced employing high percentages of coarse mixed recycled aggregates (without steel slag aggregates) could achieve adequate properties in its saturated state. The use of seawater instead of freshwater reduced the concrete's setting time as well as the porosity of the concretes produced, resulting in both the reduction of water penetration and the capillary water absorption capacity of the concretes. The use of seawater increased concrete's compressive strength at early age. It was also concluded that the results obtained in the laboratory studies and the technical know-how achieved can be transferred to large scale projects.

Keynotes: sustainable concrete; recycled aggregates; steel slags; sea water; concrete block; case study; cores; properties

1. INTRODUCTION

The use of recycled aggregates (obtained from the treatment of construction and demolition waste) and steel slag industrial by-products as coarse aggregate in normal concrete mixes is primordial in reducing the environmental problems created by the dumping of these materials, thus helping to maintain sustainability of the environment by reducing the opening of new quarry developments for concrete production.

Due to its diverse content, i.e. large amounts of ceramic material and other impurities besides concrete and raw aggregates, the resulting recycled aggregate sourced from the C&DW treatment plants is commonly designated as mixed recycled aggregate (MRA) [1-3].

Concretes produced with high percentages of MRA suffer a decrease of density, and mechanical and durability properties with respect to those of conventional concrete [2,4–7].

However it is well-known that concrete produced with steel slag aggregates achieve a higher density as well as higher mechanical properties than those of conventional concrete [8-10]. This is due to both their high density and rough surface which results in an effective ITZ [11, 12].

The use of steel slag aggregates together with recycled aggregates can produce better structural concrete [13]. The percentage reduction in compressive strength is greater than that of the flexural strength when recycled concrete aggregates are incorporated. However, the strength reduction in mixes containing slag aggregates is much less resulting in the production of a better structural concrete.

Additionally, the use of freshwater in concrete production causes a serious impact on those areas in which freshwater is a scarce resource. The substitution of freshwater for seawater could play a key role in the obtaining of more sustainable environments, especially with regard to those construction projects near to coastal areas, where there would be a notable reduction in transportation costs.

Seawater is, as other research work has shown, suitable for use in plain un-reinforced concrete production [14]. Several studies agree that concrete mixed with seawater increases early-age strength and reduces setting time in comparison with concretes mixed with freshwater [15-18]. The chloride-ion content produces an acceleration of the cement setting and early hardening of the concrete. According to Shi et al. [19] at a given age, the content of cement hydrates were found to be higher in seawater mixed concretes due to the hydration acceleration via $CaCl_2$. However, long-term studies revealed contradictory conclusions over the influence that seawater had on these higher percentages.

The major preoccupation concerning seawater use in concrete mixing is over the negative influences on durability properties, as the resulting concrete could suffer from a chemical attack, or reaction [20] caused by dissolving chloride, sulphate, sodium and magnesium in seawater. As part of a complex series of chemical reactions and physical changes in the concrete microstructure, magnesium and sulphates affect the durability of concrete by producing expansions whilst chlorides affects reinforcement by accelerating corrosion [21].

The main objective of this research work was to determine the properties of on site real scale dyke blocks produced using coarse mixed recycled aggregates, steel slag aggregates and seawater. Two experimental phases were carried out: Phase 1 was developed at laboratory level and Phase 2 was developed within the Port of Barcelona where concrete blocks were produced on site. The properties of the concrete dyke blocks were analyzed via means of concrete specimens as well as extracted cores from the dyke blocks themselves after being exposed to a sea environment for 1 year.

Four different types of concretes were produced in the laboratory and in the Port of Barcelona, using separately freshwater or seawater. The mixes are referred to as: CC (conventional concrete), CRA-50 (concrete produced with 50% of natural coarse aggregate and 50% of coarse recycled aggregate), CRS (concrete produced with 50% of coarse recycled aggregate and 50% of steel slag gravel) and CRA-100 (concrete produced with 100% coarse recycled aggregate). The fine aggregate employed in all concretes was 100% natural sand. The results obtained by concretes produced with recycled and slag aggregates using seawater were evaluated with respect to those obtained from the conventional concrete. The results obtained from the laboratory test samples were compared with the results of the core samples extracted from the real scale manufacture of the concrete blocks.

2. EXPERIMENTAL PHASE

2.1. Materials

2.1.1 Cement

Type I Portland cement, CEM I 42.5 N/SR, sulphate resistant cement was used in all concretes mixtures. Table 1 shows the chemical compositions of the cement.

2.1.2 Aggregates

Three types of aggregates were used; natural limestone aggregate divided into three fractions (0/5mm, 5/10 mm and 10/20 mm), two fractions of coarse steel slag aggregates (SA, 5/10mm and 10/20mm) and one fraction of coarse mixed recycled aggregate (RA, 5/20mm). Particle size distributions of all aggregates were determined as described in the UNE EN 933-1:2012 regulation (see Figure 1). The results of the density and water absorption of the aggregates were determined according to the UNE EN 1097-6:2001 regulation. The SA aggregates density was higher than those of the natural or recycled aggregate (see Table 2). All fractions of aggregates satisfy the requirements specified by the Spanish Standard of Structural Concrete EHE-08.

The composition of the recycled aggregate was carried out according to the UNE EN 933-11:2009 regulation. The composition is described as: 46.96% concrete; 21.18% bricks-tiles; 26.25% Natural aggregates; 3.36% Asphalt; 1,77% gypsum; 0.48% plastic and glass. Due to the high percentage of concrete and bricks composition, the water absorption capacity of mixed recycled aggregates was much higher than that of natural or slag aggregates. The soluble SO_3 was 1.47%. In addition, the gypsum impurity was also high, however, the use of

SR cement minimizes the sulphate attack that may be produced by gypsum within the aggregate, a fact which has been demonstrated in a previous work [22].

2.1.3 Water

Two types of water were used for concrete production, water from the city's mains supply network (W-freshwater), and seawater (SW) extracted directly from the Port of Barcelona. Table 3 shows the chemical properties of both the waters employed.

2.1.4 Admixture

An admixture with a polycarboxylates base was employed in all concrete productions in order to obtain the same slump.

2.2. Concrete manufacture

A laboratory experimental phase (Phase1) was carried out prior to real scale concrete block production within the port. The onsite production of blocks was nominated as phase 2 of the experimental work. In both phases recycled aggregates were used together with natural aggregates and steel slag for concrete production. The results obtained from the recycled concretes were compared to those obtained from the conventional concrete.

2.2.1. Laboratory experimental phase, Phase 1

Four types of concretes were produced using different kinds of coarse aggregates; CC (concrete produced employing 100% natural aggregates), CRS (concrete produced using 100% natural sand, 50% recycled aggregate, 50% steel slag gravel); CRA-50 (concrete produced using 100% natural sand, 50% natural coarse aggregate and 50% recycled aggregate); CRA-100 (concrete produced with 100% natural sand and 100% recycled aggregate). Natural limestone sand was used in all concrete mixes. Table 4 shows mix proportions of all produced concretes. Freshwater (W) and seawater (SW) were used in each mixture.

The total water-cement (w/c) ratio of 0.5 was set up for the conventional concrete. Following Neville's [20] definition of effective water in the mix (amount of water which occupies space outside the aggregate particles), the effective water-cement ratio was of 0.45 and was kept constant in all mixtures. The reason for keeping the effective water-cement ratio constant in all concretes production was in order to achieve the same conditions with respect to the hydration of the cement paste caused by the high absorption of RA (mixed recycled aggregate). RA was used with high moisture content, nearly saturated surface-dry conditions (80-90% of water absorption capacity), in order to avoid bleeding or water surface layers influencing the mechanical properties of the concrete [23]. RA moisture content was measured prior to its use and the dosages were adjusted according to the remaining effective water absorption capacity (the effective water absorption of the aggregates was determined by submerging them in water for 20 minutes) of the RA, steel slag and natural aggregates.

After 24 hours of casting, the concretes specimens were demolded and stored in the humidity room at 22°C and 90% of humidity, until they were tested at 7 days, 28 days and 1 year.

2.2.2 Phase 2. Concrete block production

Seven concrete dyke blocks of 2.8x 2.8x 2.8 m were manufactured in-situ in the Port of Barcelona (see Figure 2). Block 0 was produced on the 3rd of July; Block 1, 2, 3 and 4 were produced on the 4th of July and the Block 5, 6 and 7 were produced on the 5th. The maximum temperature at the Port for those days was 25.9ºC, 28.4ºC and 27.5ºC, respectively with approximately 70% of humidity every day.

Table 5 shows the mix proportions of all the blocks manufactured. Block 0 (W-freshwater mix) and Block 1 (SW- seawater mix) were both produced with 100% of raw aggregates. Block 2 (W-freshwater mix) and block 3 (SW-seawater mix) were produced using 50% of coarse recycled aggregates and 50% of coarse slag steel aggregates on substitution of 100% of coarse raw aggregates. Block 4 (W-freshwater mix) and block 5 (SW-seawater mix) were produced using 50% of coarse recycled aggregates on substitution of raw aggregates and Block 6 was produced using 100% of coarse recycled aggregates on substitution of natural aggregates and seawater. In order to control the strong influence of the mixed recycled aggregates on the concrete's properties [22, 24] as well as the onsite concrete manufacture by the employees, block 6 concrete with 100% of recycled aggregates was produced using 10% (by weight) more cement than any of the other concretes. Similar mentioned actions were carried out in a previous research [22].

In this experimental phase, the total w/c ratio for the conventional concrete (Block 0) was also established at 0.5 (defined in phase 1). The effective w/c ratio was also determined as 0.45. It was necessary to add extra water to the concretes produced with seawater or employing recycled aggregates in order to obtain similar workability to that of CC-W concrete. In consequence, the effective water /cement ratio of concrete mixtures was modified with respect to that of CC-W concrete (conventional concrete produced with freshwater) see Table 5. Blocks 1 and 3 were the most affected. The high temperature (28.4ºC) on the 4th of July, as well as the use of sea water had an influence on the slump value. According to several researches [25] the use of seawater would require an increase in the water amount to obtain a certain level of fluidity.

The concrete blocks' properties were determined by testing the concrete specimens which were produced when the concrete blocks were manufactured. After 24 hours of casting, the concretes specimens were demoulded and stored in the humidity room at 22°C and 90% of humidity, until they were later tested at different ages until the final test at 1 year of age. The real scale concrete blocks were demoulded after 24 hours of production and were employed in the construction of the dyke at 28 days of age (see Figure 2).

The manufactured concrete blocks were exposed to the sea environment for one year, at the end of which the six test core specimens were extracted from each type of concrete block (see figures 3). Unfortunately it was impossible to extract test core samples from block 2 CRS-W due to its extreme inaccessibility. The extracted test core samples were tested for density, water absorption, compressive strength and depth of penetration of water under pressure, and their values determined. The results of the information gained were carefully studied to ascertain the quality of the blocks.

2.3. Test procedure

2.3.1 Laboratory experimental phase. Phase 1

Setting time

The setting time of the CC-W and CC-SW concretes was determined in accordance with ASTM C 403, in order to determine the influence of seawater on the setting time. The specimens were kept in constant environment conditions of 20°C and 70% relative humidity during the testing period in order to reduce the effect of the temperature variations.

Hardened properties

Physical properties of hardened concrete were determined at 28 days of curing according to ASTM C 642-97 standard. Mechanical properties were determined according to UNE-EN 12390-3. The compressive strength was determined after 7 days, 28 days and 1 year of curing.

The splitting tensile strength and modulus of elasticity were also determined after 28 days of curing.

With respect to durability properties; capillary water absorption (sorptivity) was carried out following the Swiss Standard - SIA 162/1 standard, electrical resistivity and the depth of penetration of water under pressure (UNE EN 12390-8:2009) were also evaluated at 28 days of curing. Three specimens were employed to determine each of the values.

2.3.2. Real scale production analysis, properties of concrete blocks. Experimental Phase 2

Physical properties of concrete specimens were determined at 28 days of curing according to ASTM C 642-97 standards. The properties of cores extracted from concrete blocks after being exposed to a sea environment during 1 year were also analysed.

Mechanical properties of concrete specimens produced at experimental phase 2 were determined according to UNE-EN 12390-3 standard. The compressive strength was determined after 7 days, 28 days, 90 days, 180 days and 1 year of curing. The splitting tensile strength was also determined after 28 days of curing The compressive strength of the blocks' cores (after one year of exposure to a sea environment) were also determined and compared with the results obtained from the test specimens produced at phase 2 (block manufacture) and phase 1 (laboratory phase).

With respect to durability properties, capillary water absorption (sorptivity) was carried out following the Swiss Standard - SIA 162/1 standard, electrical resistivity and depth of penetration of water under pressure (UNE EN 12390-8:2009) were evaluated by the testing of the concrete specimens at 28 days and 1 year of curing. The value of depth of penetration of water under pressure in extracted cores was also determined. Three specimens were employed in order to determine the average values.

3 RESULTS AND DISCUSSION

3.1 Laboratory experimental phase. Phase 1

3.1.1 Setting time

Figure 4 indicates that the initial setting time of concrete produced with seawater (CC-SW) was achieved approximately 1 hour before that of concrete produced with freshwater concrete (CC-W). In addition, the final setting time of CC-SW was achieved more than 100 minutes (1 hour and 40 minutes) before that of CC-W. This fact was due to the higher presence of chloride in seawater which clearly influenced the acceleration of the cement hydration. Certain researchers [19, 25] also stated this influence of seawater on concrete setting time in their research work.

With respect to workability, the concretes with 0.75-0.83% of admixture (with respect to cement weight) achieved a slump of 10-12 cm (see table 4).

3.1.2 Hardened concrete properties

Physical properties

Table 6 illustrates that those concretes produced using seawater achieved slightly higher density to those of the corresponding concretes produced with freshwater. In addition, it was observed, as expected, that the inclusion of high density steel slag aggregate also had the effect of significantly increasing the density. Similar behaviour patterns have been described by Qasrawi [13]. The technical requirement specifications laid down by Barcelona's Port Authorities indicated that the concrete blocks must have a minimum density of 2.2-2.3 kg/dm^3. Concretes CRA-100-W and CRA-100-SW did not achieve the minimum requirements, however CRA100-SW achieved a value of density 2% lower than the minimum of 2.2 kg/dm^3 required. According to the values obtained on water absorption capacity and porosity, the concretes produced with 100% of recycled aggregates achieved the highest values. The use of seawater decreased porosity with respect to the corresponding concrete produced employing freshwater. It was also confirmed by certain researchers [25] that the average pore size of concrete employing seawater was smaller than that of concrete employing freshwater.

<u>Mechanical properties</u>

The compressive strengths of all concretes exceeded the minimum compressive strength of 30 MPa required for concrete blocks employed in dyke construction within the Port of Barcelona (see Table 7).

All the concretes produced using recycled aggregates achieved lower compressive strengths than those obtained by CC concrete. The use of steel slag aggregates did not increase the compressive strength achieved by CRA-50 concrete. It was determined that the low quality of mixed recycled aggregates limited the compressive strength of concretes, whereas, the use of higher percentages of steel slags could produce an increase of compressive strength due to the adequate behaviour of concrete produced with high percentages of steel slags on that property [11-13]. The concretes produced with 50% and 100% of RA achieved 20-22% and 30-35% lower compressive strength, respectively than that of the CC concretes at 28 days. Those reduction percentages of compressive strength were maintained after 1 year of curing. The splitting tensile strength of concrete produced with RA was also lower than that of CC concretes. The reduction was lower when the steel slag aggregates were used for concrete production as the results of their effective ITZ [12].

With respect to compressive strength values at 7 days of curing, the concretes produced employing seawater were found to achieve higher values than those obtained by the concretes produced with freshwater. However at 28 days and 1 year of age, the concretes produced with seawater achieved similar or lower strength values to those obtained by the freshwater concretes. This behaviour has also been described by other researchers [25]. The CRA-100-SW was the only concrete which maintained a higher strength value than that of the same concrete type employing freshwater (CRA-100-W) after 1 year of age. The reason for this was the higher reduction of porosity caused by the recycled aggregates' high absorption of seawater.

Concretes produced using 50% of steel slag aggregates in substitution of natural aggregates (CRS concretes) achieved a higher modulus elasticity than CC concrete. A fact which has been determined in other works [5,13] as the steel slag aggregates increase the modulus of elasticity of concretes. The modulus of elasticity of CRA-50 and CRA-100 concretes suffered a decrease of 6% and 40%, respectively, with respect to that of CC concrete. It must be noted that concretes manufactured with seawater proved to have a higher elastic modulus than those manufactured with freshwater. It is well known [20, 26, 27] that the modulus of elasticity depends on the density of concrete. The results of our research determined this value increased with the use of seawater (see Table 6)

<u>Durability properties</u>

Although all concretes achieved similar values of suction coefficient (see Table 8), the concretes manufactured with seawater showed lower suction coefficient values than those of the corresponding concrete produced with freshwater. This effect was more evident when the concrete was produced with higher percentages of recycled aggregates. Figure 5 illustrates the suction coefficient reduction of each type of concrete due to use of seawater. It was noted that there was a greater reduction of the sorptivity in concrete with a higher porosity.

It was observed that all concretes produced with recycled and slag aggregates had a lower electrical resistivity to those of CC concretes. The use of seawater and high percentages of recycled aggregates considerably reduced the electrical resistivity. According to the obtained results of the depth of penetration of water under pressure, CC concretes achieved the lowest value. This low value was expected due to the much high water absorption capacity of recycled aggregates in comparison to natural aggregates. In general, the concretes produced with seawater achieved lower water penetration than that of the corresponding concrete produced with only freshwater. Katano et al. [28] also found that the water permeability of concrete mixed with seawater was 0.5 times compared with that with freshwater. It must be noted, however, that the porosity of recycled aggregates had a stronger influence on the water penetration mentioned, irrespective of the type of water used. All the concretes except CRA-100-W achieved the requirements determined by EHE98 (Spanish standard of concrete structures).

3.2 Real scale, properties of concrete blocks. Experimental Phase 2

3.2.1 Concretes properties via testing of specimens

In this section, the results of the physical, mechanical and durability properties of concrete specimens which were produced from the same concrete mixes employed in the manufacture of each type of concrete block are described.

Physical properties

As indicated in Table 9, the CRS concretes, produced with 50% of recycled aggregates and 50% of slag aggregates achieved a higher density than those of the CC concretes, this was due to the high density of the slag aggregates. This also occurred during the tests carried out at the laboratory phase. The obtained results guaranteeing the minimum density requirement for concrete block production. The test elements of the concrete made with 100% of recycled aggregate achieved a density of 2.15 kg/dm^3. This density value was slightly lower than the minimum value requirement of 2.2-2.30 kg/dm^3 required in real scale concrete block production. The use of seawater had the effect of slightly increasing the concrete's density while reducing its porosity as other researchers have described [25]. These qualities are more evident in concretes produced with recycled aggregates. In general, the concretes produced in the laboratory and within the Port (real scale) achieved similar properties.

<u>Mechanical properties</u>

According to an analysis of the test results on compressive and splitting tensile strengths, the concretes produced with recycled and slag aggregates achieved a lower compressive strength than those of CC concrete at any of the ages of testing (see Table 10). The concretes used for block manufacturing achieved a lower compressive strength than the concretes produced in the laboratory. As mentioned previously, the concretes produced with seawater and recycled aggregates needed more water than the CC-W concrete in order to achieve the same workability (the on-site high temperature being distinct to that of the laboratory, which was much lower), which in turn had an influence on the mechanical properties of the concretes. However all the concretes, with the exception of the CRA-100-SW, obtained the minimum compressive strength of 30 MPa at 28 days. The CRA-100-SW obtained a lower compressive strength value of 29.21 MPa at 28 day, increasing to a compressive strength of 36 MPa at 1 year. The compressive strength results obtained from the concretes produced with a maximum of 50% of recycled aggregates were found to be acceptable, as the minimum requirement of compressive strength is 30 MPa. As observed in the phase 1 and described by several researchers [25], the compressive strength at 28 days of concretes produced employing seawater achieved similar or lower strength to freshwater concrete.

The splitting tensile strengths of concretes made employing steel slag with recycled aggregates improved with respect to that of concrete using 50% of RA and 50% of natural aggregates. The use of steel slag aggregates guarantee an effective ITZ [11,12].

Durability properties

Table 11 shows the results of the durability test. The use of steel slag aggregates in substitution of natural aggregates did not improve the capillary absorption capacity of CRA-50-W. This, in all probability, was due to the higher effective water-cement ratio used in the manufacturer of block 2 and 3 compared to that of block 4 and 5 (see Table 5).

The use of seawater significantly reduced the capillary absorption capacity of the concretes. The concretes manufactured with seawater showed a lower capillary suction coefficient than that of the corresponding concrete produced with freshwater. Moreover, the CRS-SW and the CRA-50-SW concretes achieved a similar or lower capillary absorption capacity at 72 hours of age compared to that determined in the CC-W concrete. This, in all probability, was due to an accumulation of salts in the pores of those concretes, see Figure 6. As mentioned previously, certain researchers [25, 28] also determined that the average pore size of concrete mixed with seawater was smaller than that of freshwater. They also concluded that the water permeability of concrete employing seawater was 0.5 times compared to that of concretes employing freshwater.

According to the results obtained on electrical resistivity, the concretes produced with seawater proved to have a reduced electrical resistance. The concretes produced with recycled aggregates obtained a lower electrical resistance due to the higher amount of accessible pores.

The concretes produced with steel slag aggregates had a lower electrical resistivity value due to the high electrical conductivity of those aggregates. According to the results of the tests on the depth of penetration of water under pressure, the concretes produced employing recycled aggregates achieved a higher water penetration than those of the CC concretes, although, all concretes obtained the minimum requirements defined by Spanish standard of concrete structures (see Table 11). In general the concretes produced with seawater at 28 days and 1 year of curing had lower permeability than the concretes produced with freshwater, probably due to the accumulation of salts within the pores.

3.2.2 Properties of the extracted cores

Table 12 shows the results of density, absorption, compressive strength and the depth of penetration of water under pressure of the concrete cored samples extracted from the real scale blocks manufactured for use in Barcelona's Port dyke. The mentioned values were taken after 1 year of exposure to a sea environment.

The blocks produced using a concrete mix incorporating 50% recycled mixed aggregates and 50% steel slag aggregates obtained an adequate value of density. These values were similar to those of conventional concrete and also very similar to those obtained at the laboratory phase (phase 1). The concretes produced with 50% of coarse recycled aggregates and 50% of natural coarse aggregates achieved a density higher than that of 2.2 kg/dm3, but lower than that of the more acceptable standard value of 2.3 kg/dm3. According to technical recommendations the blocks produced with 100% of recycled aggregates were too light for use in dyke construction. The concrete blocks produced using recycled aggregates achieved a higher absorption capacity than conventional concrete blocks due to the higher water absorption capacity of RA and steel slag in comparison to natural aggregates. As depicted in Table 12, there was no difference on the physical properties of concretes produced using seawater or freshwater. However, it can be observed that the absorption capacity of conventional concrete produced using seawater was higher than that produced using freshwater. This was probably the result of a higher water-cement ratio as well as the lower slump value (workability) of block 1 concrete, which caused greater difficulty in its compaction.

The density and absorption capacity of core elements were lower and higher, respectively, than those of test elements (phase 2), due to different surface finish of both elements.

The compressive strength values of the concretes produced with recycled aggregates and using steel slag aggregates were lower than those obtained by the conventional concrete. Both the concrete types produced with 50% of recycled aggregates or 50% of natural aggregates or steel slag achieved 26-29% lower compressive strength than that of conventional concrete. The concretes produced with 100% of coarse recycled aggregates suffered a reduction of 42% compressive strength with respect to that of conventional concrete. The requirement of 30 MPa of compressive strength was achieved for all the concretes after 1 year of age. As it was expected , the compressive strength values of the 1 year concrete core samples produced with seawater were slightly lower than those produced with freshwater. The obtained results taken from the extracted cores were very similar to the values obtained by the concrete specimens produced in the laboratory experimental Phase1.

According to the results of the tests carried out on the depth of penetration of water under pressure, all the concretes achieved the minimum requirements of the maximum and average water penetration depth of 50 mm and 30 mm respectively. The obtained values were comparable to the results obtained from the testing of the Phase 1 and Phase 2 concrete specimens.

4. CONCLUSIONS

The following conclusions can be drawn from the results of this study:

- In accordance with the use of recycled aggregates for dyke blocks manufacture:
    - It is imperative that concrete manufactured with 50% mixed recycled aggregates be mixed with 50% of steel slag aggregates as this effectively increases the density of the concrete, thus creating an adequate material for dyke block production
    - Concrete produced with 50% of mixed recycled aggregates achieved minimum compressive strength for dyke block production. Although the use of steel slag aggregates on substitution of natural aggregates did not improve that property, the use of those aggregates increased the splitting tensile strength as well as the modulus of elasticity of recycled concretes.
    - The use of high percentage of recycled aggregates (without slag aggregates) achieved adequate properties after 1 year of curing when the blocks were maintained in a saturated state.
- In accordance with seawater employment for concrete production:
    - The setting time of concrete manufactured with seawater was probed to be reduced when compared to the same mixes produced with freshwater. A fact which became more evident on site during the large scale production of dyke blocks.
    - The use of seawater slightly increases the density and decreases the porosity and absorption capacity of concrete. A consequence of this is the occurrence of the reduction of sorptivity and water penetrability of those concretes.
    - The use of seawater increases the compressive strength at an early age. However, at 28 days or 1 year of age, the concretes produced employing freshwater o

seawater achieved similar strength. The modulus of elasticity was also slightly increased when seawater was employed.

- Although seawater employment in concrete production did not appear to have significant consequences on the properties of the concrete tested up to one year of age, the durability of seawater concretes must be evaluated previous to its use when the aggregates employed in the concrete could prove to be reactive to the high alkalinity of seawater. The same evaluation is also applicable to seawater concrete which would be exposed to freezing and thawing [25]. Further investigation is required. However the use of CEM III (with ground blast furnace slag cement) could improve those durability properties as stated in certain research works [15, 25].

The tests carried out to determine the properties of the concrete core samples extracted from the dyke blocks were very similar to those of the concretes produced in the laboratory. Evidently, this verifies that the results obtained in the laboratory can undoubtedly be put into practice on real scale projects.

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List of Tables

Table 1. Chemical composition of cement

Composition	Fe_2O_3	MnO	TiO_2	CaO	K_2O	P_2O_5	SiO_2	Al_2O_3	MgO	Na_2O
CEM I 42.5 SR (%)	4.58	0.02	0.20	63.88	0.78	0.10	20.71	4.22	1.68	0.17

Table 2. Physical properties of the aggregates

	Natural			Slag aggregates		Recycled aggregates
Fraction	Sand 0/4mm	Gravel 5/10mm	Gravel 10/20mm	SA1 5/10mm	SA2 10/20mm	RA-Gravel 5/20mm
Dry density (kg/dm^3)	2.58	2.63	2.65	3.33	3.31	2.07
Absorption (%)	1.70	0.87	0.67	1.50	1.24	10.43

Table 3. Chemical compositions of freshwater and seawater.

Element	Ca	Mg	Na	K	S	Sr	B	Cl	SO_4	Br-
Freshwater (W) (%)	0.010	0.002	0.006	0.001	0.003	0.000	0.000	0.006	0.013	0.000
Seawater (SW) (%)	0.049	0.136	1.164	0.042	0.096	0.001	0.001	2.080	0.282	0.006

Table 4. Laboratory concrete's mix proportions, in units of kg per m^3 of concrete.

Materials	CC (-W/-SW)	CRS(-W/-SW)	CRA-50(-W/-SW)	CRA-100(-W/-SW)
CEM I 42.5/N SR	300	300	300	300
Sand 0/4 mm	976	976	976	976
Gravel 4/10mm	210	-	105	210
Gravel 10/20	765	-	383	765
RA 5/20 mm	-	382	382	764
SA1 5/10 mm	-	133	-	-
SA2 10/20 mm	-	479	-	-
Effective water	134	134	134	134
Total water	150	192	188	230
Effective W/C	0.45	0.45	0.45	0.45
Admixture (%)	0.80/0.77	0.83/0.79	0.75/0.74	0.80/0.78
Slump (cm)	12/11	12/10	11/10	11/11

Table 5. Concrete's dosing, in units of kg per m^3 of concrete.

	Block 0	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
Dosing according to PROMSA	**CC-W**	**CC-SW**	**CRS-W**	**CRS-SW**	**CRA-50-W**	**CRA-50-SW**	**CRA-100-SW**
CEM I 42.5/N SR	300	300	300	300	300	300	335
Sand 0/4 mm	976	976	976	976	976	976	826
Gravel 4/10mm	210	210	-	-	105	105	-
Gravel 10/20	765	765	-	-	383	383	-
Recycled aggregate 5/20 mm	-	-	385	385	385	385	889
Steel slag 5/10 mm	-	-	143	143	-	-	-
Steel slag 10/20 mm	-	-	506	506	-	-	-
Effective water	134	153	145	157	143	149	151
Total water	150	169	177	189	175	181	201
Effective W/C	0.446	0.509	0.484	0.524	0.477	0.497	0.451
Admixture (%)	1	1.11	1.16	1.21	1.16	1.26	1.26
Slump (cm)	10	7	10	7	10	10	10

Table 6. Physical properties of concretes produced in laboratory

		CC		CRS		CRA-50		CRA-100		PORT*
		-W	-SW	-W	-SW	-W	-SW	-W	-SW	
PHYSICAL PROPERTIES (28 days)										
Dry density (kg/dm^3)		2.34	2.39	2.33	2.34	2.24	2.25	2.09	2.16	2.2
Water absorption (%)		2.82	2.72	4.67	4.26	4.58	3.91	6.39	5.06	-
Porosity (%)		6.58	6.52	10.90	9.98	10.26	8.79	13.38	10.93	-

*Port requirements (a minimum density of 2.2-2.3 kg/dm^3)

Table 7. Mechanical properties of concretes produced in laboratory

		CC		CRS		CRA-50		CRA-100		PORT*
		-W	-SW	-W	-SW	-W	-SW	-W	-SW	
MECHANICAL PROPERTIES (28 days)										
Compre--ssive strength (MPa)	7 days Cubic	48.2	49.7	37.8	39.1	37.7	38.8	31.5	35.0	-
	28 days cubic spec	56.7	56.4	44.1	44.4	43.7	46.3	36.4	39.0	30
	28 days Cylind. Spec.	50.9	49.5	35.7	35.2	33.5	35.3	34.2	33.8	-
	1 year cubic spec (**)	65.0 (15%)	59.9 (6%)	49.1 (11%)	48.5 (9%)	48.5 (11%)	48.6 (5%)	40.5 (11%)	42.9 (9)	-
Splitting tensile (MPa)		3.7	3.9	3.3	3.2	2.95	2.92	2.4	2.5	-
Modulus elasticity (GPa)		40.6	42.9	42.7	44.8	38.2	40.6	23.7	24.6	-

*Port requirements (a minimum compressive strength of 30MPa)

**The data in brackets is the increase (in %) of compressive strength from 28 days to 1 year.

Table 8. Durability properties of concretes produced in laboratory

		CC		CRS		CRA-50		CRA-100		PORT* (EHE)
		-W	-SW	-W	-SW	-W	-SW	-W	-SW	
DURABILITY PROPERTIES										
Suction coefficient (mm/min$^{1/2}$)		0.043	0.036	0.047	0.038	0.064	0.045	0.073	0.046	-
Electrical resistivity (Ω*cm)		7571	6296	5311	3568	5502	3656	4949	3562	-
Water penetration maximum (mm)		29.5	19.0	44.0	26.5	44.0	34.0	53.0	47.5	50

*Spanish standard for structural concrete (EHE) maximum requirement for durable concrete

Table 9. Physical properties of the concrete specimens of each concrete block

		CC		CRS		CRA-50		CRA-100	Port*
	Test Period	-W Block0	-SW Block1	-W Block2	-SW Block3	-W Block4	-SW Block5	-SW Block6	
PHYSICAL PROPERTIES (28 days)									
Dry density (kg/dm^3)		2.34	2.36	2.40	2.43	2.24	2.25	2.15	2.2
Water absorption (%)		4.04	3.30	4.96	4.58	5.07	4.94	5.67	-
Porosity (%)		9.47	7.77	11.89	11.14	11.36	11.12	12.19	-

*Port requirements (a minimum density of 2.2-2.3 kg/dm^3)

Table 10. Mechanical properties of concrete specimens of each concrete blocks produced within the port of Barcelona

		CC		**CRS**		**CRA-50**		**CRA-100**	**Port ***
	Test Period	**-W Block 0**	**-SW Block 1**	**-W Block 2**	**-SW Block 3**	**-W Block 4**	**-SW Block 5**	**-SW Block 6**	
MECHANICAL PROPERTIES (28 days)									
Compressive strength (MPa)	7 days Cubic	38.64	37.68	35.14	31.,82	31.85	29.83	25.37	
	cubic spec 28 days	46.97	45.56	36.79	35.76	39.07	36.05	29.21	30
	cubic spec 90 days	47.97	44.52	39.22	35.89	39.27	34.37	31.65	
	cubic spec 6 months	57.4	57.6	45.4	43.3	42.7	41.9	34.4	
	cubic spec 1 year	58.9	60.2	50.3	43	42.5	42.5	36.0	
Splitting tensile (MPa)		3.92	3.29	2.83	3.09	2.47	2.50	2.39	

*Port requirements (a minimum compressive strength of 30MPa)

Table 11. Durability properties of the concrete specimens of each concrete block

		CC		**CRS**		**CRA-50**		**CRA-100**	**Port* (EHE)**
	Test Period	**-W Block0**	**-SW Block1**	**-W Block2**	**-SW Block3**	**-W Block4**	**-SW Block5**	**-SW Block6**	
DURABILITY PROPERTIES									
Suction coefficient (mm/min$^{1/2}$)		0.052	0.033	0.080	0.057	0.065	0.041	0.059	-
Electrical resistivity (Ω*cm)		5533	2957	3623	2180	4669	2301	2072	-
Water penetration maximum value (mm)	28 days	28	28	43	23	39	32	45	50
	1 year	28	24	36.5	18	35	20	30	-

*Spanish standard for structural concrete (EHE) maximum requirement for durable concrete

Table 12. Properties of cores extracted form concrete blocks.

	Dry density (kg/dm3)	Absorption (%)	Compressive strength (MPa)	Water penetration (mm)	
				Maximum	Average
CC-W Block0	2.33	4.83	53.8	25	15
CC-SW Block1	2.33	5.07	51.3	35	23
CRS-SW Block 3	2.34	6.75	36.4	27	19
CRA-50-W Block 4	2.22	6.66	38.6	32	22
CRA-50-SW Block 5	2.20	6.66	37.5	25	17
CRA-100-SW Block 6	2.08	9.13	29.9	36	28

Figure
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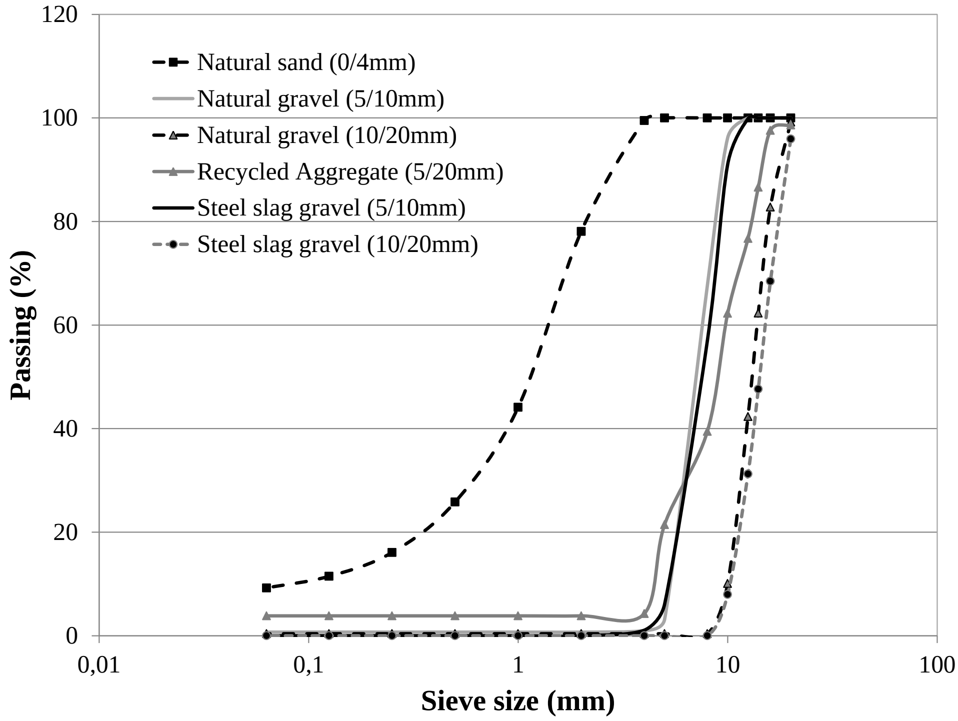

Figure 1. Particle size distribution of all aggregates according to UNE EN933-1:2012

Figure 2. Production process and placing of concrete blocks

Figure 3. Core extraction process of the blocks after 1 year of being exposed to a sea environment

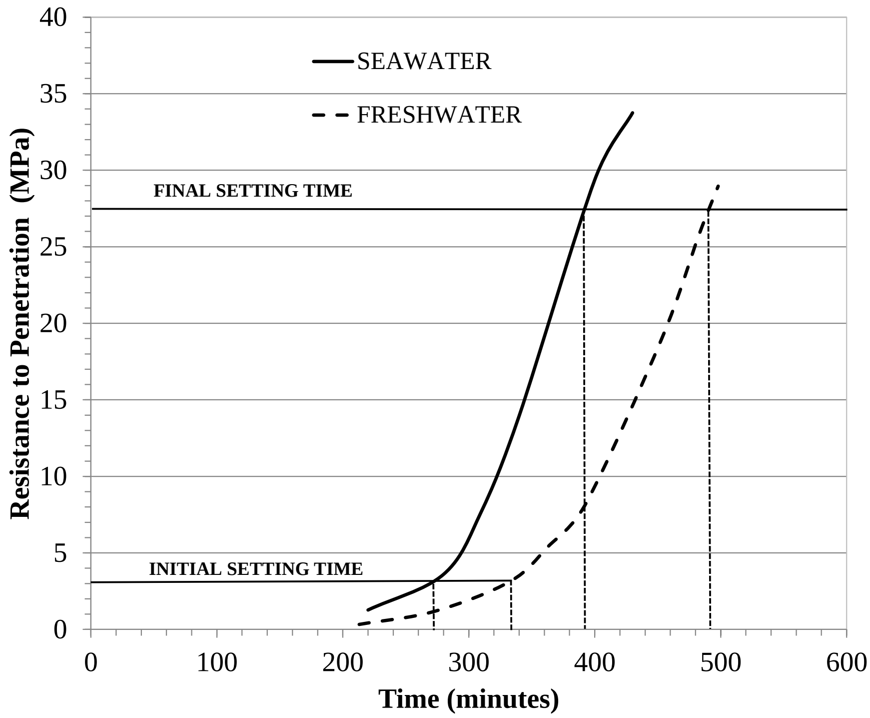

Figure 4. Initial and final Setting time of concretes made using fresh and seawater

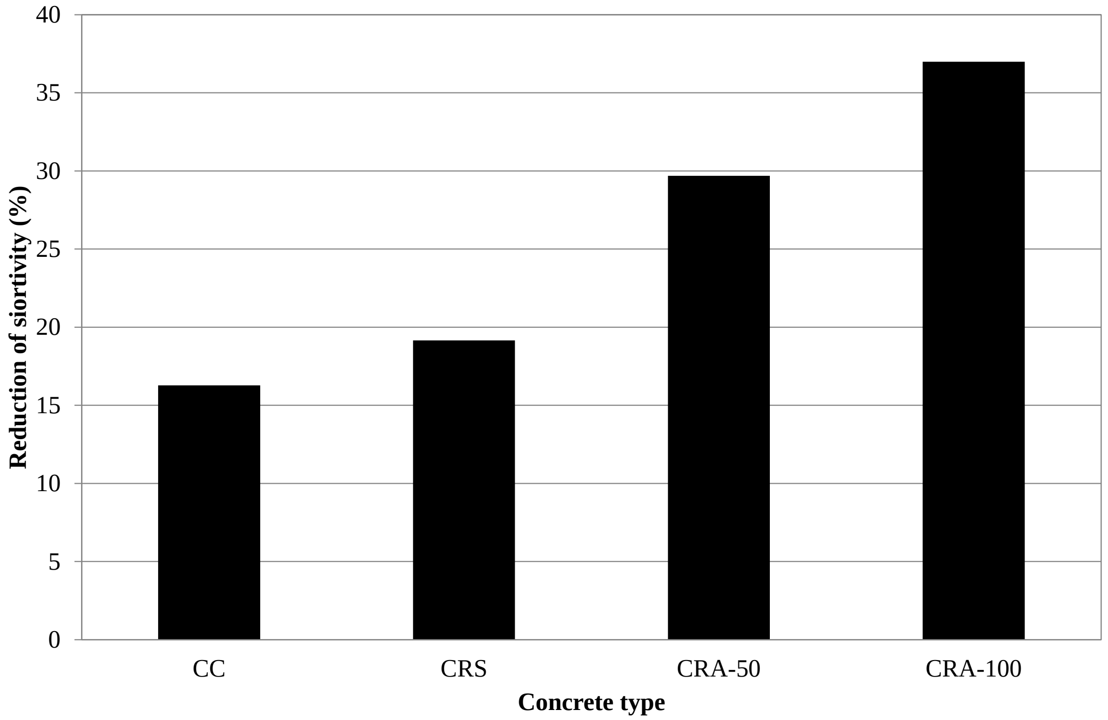

Figure 5. Reduction of sorptivity of the different types of concrete due to the use of seawater

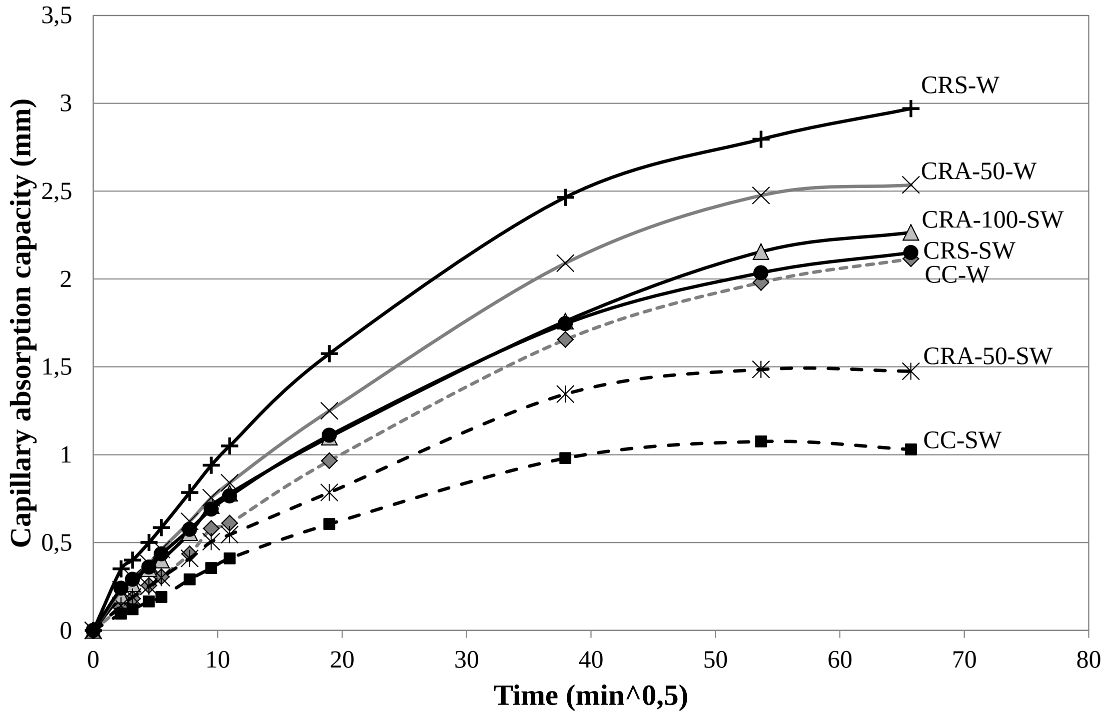

Figure 6. Capillary water absorption of concretes