Influence of seawater and blast furnace cement employment on recycled aggregate concretes' properties

Miren Etxeberria[1*], **Andreu Gonzalez-Corominas**[1], **Patricia Pardo**[1]

[1]*Dr. Eng. Associate professor, Department of Construction Engineering, Polytechnic University of Catalonia, Jordi Girona, 1-3 B1 building, Barcelona 08034, Spain, telephone: +34934011788, Fax: +34934017262, E-mail: miren.etxeberria@upc.edu

Abstract

Recycled aggregates of mixed composition (MRA) may exhibit great variability in their properties, which in turn reduces their applicability. This study intends to extend the use of MRA in a broadened scope of applications by producing recycled aggregate concretes (RAC), which were mixed using two different types of cement, ordinary Portland cement and cement incorporating blast-furnace slag, and two types of water, fresh and seawater. The testing programme included analyses of the properties of concrete in its fresh (setting time and plastic shrinkage) and hardened state (physical, mechanical and drying shrinkage). The results showed that all of the physical and several of the mechanical properties as well as drying shrinkage were negatively influenced by the use of MRA. In contrast, however, the plastic shrinkage and flexural strength were improved. The use of seawater improved the mechanical properties, reduced setting time and increased drying shrinkage, however, it was found that the cement type was more influential on most of the properties. The use of seawater and cement with blast-furnace slag improved the performances of the RAC.

Keywords: Recycled aggregate concrete; seawater; blast furnace slag cement; Properties; Plastic shrinkage; drying shrinkage

1. INTRODUCTION

The world's expanding population and the knock on effect of rapid growth in cities as well as development in infrastructures has led to a significant increase in construction and demolition waste (C&DW). In the EU member states, the high amount of C&DW generated each year and their low recycling ratios have become a major economic and environmental concern for governments, as a result of the problems created with regard to its disposal, especially with respect to the opening of new landfill sites [1]. European standards and directives, such as the European Parliament's Waste Framework Directive 2008/98/EC [2], guarantee suitable recycling levels as well as advocating the use of C&DW waste produced by the construction industry.

Building techniques, which include differing construction materials, generate what is commonly described as a mixed waste constituted of inorganic materials, such as concrete, ceramic, secondary aggregates and contaminants [3]. Consequently, after the mixed C&DW has undergone a process for its recycling in a treatment plant it is designated as mixed recycled aggregate (MRA) [4,5]. However, very few specifications establish its composition; Brazil and the United Kingdom's specifications [6,7] define MRA as less than 90% of cement-based fragments and NA, by weight, which signifies a higher presence of masonry-based materials; Germany and Portugal's specifications [8,9] define MRA as those aggregates with a minimum of 80 to 90% of ceramic plus concrete particles.

Numerous authors [3,5,10] agree that the variability of MRA's composition represents an obstacle in the path of a far greater use of this recycled material in construction works. At present, the construction industry employs MRA primarily in non-structural applications and low-grade requirement works [11]. However, besides existing studies being mostly focused on MRA in non-structural concretes [12–14] or low-grade applications [15,16], certain researchers have analysed the possibility of using MRA for higher grade applications, such as medium-strength concrete [10,17,18] and high-performance concrete [19].

The most detrimental properties of MRA when compared to those of natural aggregates are: density, water absorption capacity and content of contaminant particles, in particular gypsum which can lead to possible expanding pressures due to the internal sulphate attack [3,11,17]. A higher absorption capacity as well as the presence of certain impurities have negative influences on the fresh and hardened properties of concretes [14, 20]. A decrease in the mechanical properties takes place when the replacement level of MRA increases. Concretes ranging from 25-50MPa suffer up to 25% loss of compressive strength when the replacement level of the natural aggregates by MRA is up to 50% [3,10,11,14,17]. High MRA replacement ratios, from 50% to 100%, may produce a severe decline on durability properties of concretes. In such cases, the exposure category should be limited due to the higher permeability of concretes produced with MRA [10,17]. Nevertheless according to Medina et al. [17], the durability properties of MRA concretes were marginally affected by replacements ratios of up to 25%.

Recycled aggregate concrete (RAC), with respect to a given compressive strength, usually shows higher drying shrinkage than natural aggregate concrete [21-25]. In the specific case of MRA, Hoffmann et al. [10] found considerably higher shrinkage ratios up to 91 days, which were attributed to both the higher water content and the composition of the higher amount of adhered mortar and ceramic aggregates in MRA. Nevertheless, similar drying shrinkage values, which were affirmed to be caused by the higher porosity of the ceramic particles as well as their higher capacity for storing water, have been observed up to 7 days. MRA would counteract early-age shrinkage compensating the water consumed in hydration reactions and also evaporation by the water contained inside the recycled aggregates [10,26].

The use of freshwater in concrete production causes a serious impact on areas where it represents a scarce resource. However, researchers' opinion concerning the suitability of using seawater in concrete is still divided [27]. Although the high risk of corrosion implied in the use of seawater in the production of reinforced concrete has led to its prohibition by various international standard regulations, it has been allowed in plain concrete manufacture under the proviso that it complies with the given standards criteria of the pertinent regulation [28-30]. Certain authors agree that in comparison with concrete produced with freshwater, concrete employing seawater causes early strength gain and reduces setting time [27,30,31] . The concrete microstructure improves at an early age due to the chemical reaction of the seawater, which in turn is a result of the acceleration of the hydration process by chloride ions input [31,32]. The compressive strength differences between the use of either freshwater or seawater in the concrete mix also becomes less significant at long-term exposures [27].

The principle negative aspect concerning the use of seawater in concrete production is its influence on durability properties. Seawater, containing dissolved salts such as chloride, sulphate and magnesium, may produce chemical attacks, physical changes on microstructure and expansions [33,34]. Otsuki et al. [31] recommended the use of blast-furnace slag (BFS) cement in the mix in order to achieve lower permeability and low water-cement ratios as countermeasures against the seawater presence. Besides the negative influence of seawater on durability, Nishida [27] and Otsuki [31] affirmed, that with respect to chloride diffusion, the effect of the binder type used had a greater influence than that of the type of mixing water employed, at least during the initial stages of the concretes' life. However, over time an increase in chloride ion penetration would cause a significant decrease in the binding capacity, thus leading to the same durability issues.

This study aims to encourage the use of recycled aggregate and seawater in the manufacturing of plain concrete for port applications such as pavements and dyke blocks. According to the Port of Barcelona's Technical Specifications, the obligatory requirements for the production of concrete dyke blocks is a minimum strength of 30N/mm^2 and a minimum density of 2.300kg/m^3. In this work, four series of concretes were produced combining two different types of cement: Ordinary Portland Cement, CEM I 42.5 SR (1) and blast furnace slag cement CEM III / B 42.5 L / SR (3) and two types of mixing water: freshwater (FW) and seawater (SW). The setting time and plastic shrinkage were determined while the concrete was in its fresh state. This was carried out by the 0% and 100% replacement of natural aggregates for MRA in order to analyse the most critical cases. In the concretes' hardened state, both types of cement were mixed with each type of water and with varying replacement ratios of 0%, 20%, 50% and 100% of coarse MRA in replacement of natural aggregates. The physical properties (density, water absorption and permeable pore volume), mechanical properties (compressive strength, flexural strength and modulus of elasticity) and drying shrinkage were determined.

2. EXPERIMENTAL PHASE

2.1. Materials

2.1.1. Cement and admixture

Type I Portland cement (OPC), CEM I 42.5 SR, and type III (Ground BFS cement), CEM III/B 42.5 L/S, with Blaine fineness of 3000 cm^2/g and 4500 cm^2/g, respectively, were used. The chemical compositions are given in Table 1. These cements were chosen in compliance with the recommendations laid out in international standards and because of their positive behaviour in seawater environments as described by several authors [27,31,33-35].

The superplastizicer water-reducer based on polycarboxylate ethers admixture was used in the concrete production, the density of which was 1,056 g/cm^3.

2.1.2. Aggregates

All natural aggregates were crushed limestone aggregates, three size fractions being employed (sand 0-4mm, gravel 4-10mm and gravel 10-20mm). The MRA were sourced from Gestora de Runes de la Construcció SA, a local C&DW treatment plant situated in the Port of Barcelona. The particle size distributions of the natural and recycled aggregates, which are described in Figure 1, were determined according to BS-EN 933-1:2012. [36]

The classification of the coarse components of the MRA was carried out according to BS-EN 933-11:2009 standards [37], the results of which are given in Table 2. The main components were old natural aggregates and concrete (74.32%), which according to certain European standards would be classified as good quality. Nevertheless, due to the presence of a high amount of asphalts (12.61%) they could be classified as Type IV according to DIN 4226-100:2002, mixed recycled aggregates (MRA) [8].

The percentage of gypsum contained in the MRA was lower than that of the 1.5% recommended by Agrela et al. [3]; unfortunately, however, it had a higher sulphate content than the maximum permitted by the Spanish Structural concrete code (0.8%) [29]. Nevertheless, according to our research, the use of sulphate resistant (SR) cement in concrete production minimizes the possibility of a sulphate attack that may be produced by the gypsum within the aggregate [38].

The density and water absorption (BS-EN 1097-6:2013, [39]), abrasion resistance (BS-EN 1097-2:2010, [40]) and flakiness index (BS-EN 933-3:2012, [41]) properties were determined for each aggregate fraction (see Table 3). The MRA showed lower density and abrasion resistance, and a higher absorption capacity and flakiness index than those of the crushed limestone as a result of the ceramic and old mortar attached to the concrete particles. The MRA characteristics mentioned are in accordance with the findings of other authors [3,11].

2.1.3. Water

In this study, seawater directly sourced from the Port of Barcelona was used for concrete mixing in order to analyse its effect on RACs. RACs were also produced using freshwater from the mains supply network. Table 4 shows the chemical properties of both waters. Typically, seawater shows a higher concentration of alkali chlorides, sulphates or sodium than freshwater.

2.2 Concrete production

The four series were produced from combining two different types of cement; CEM I 42.5 SR (1) and CEM III / B 42.5 L / SR (3) with each of the both types of mixing water employed; freshwater (FW) and seawater (SW). For each concrete series, four kinds of aggregate mixtures were studied: a Natural Aggregate Concrete (NAC), used as the reference concrete, and three RACs using 20%, 50% and 100% of MRA in substitution of coarse natural aggregates. The NAC were proportioned following the Bolomey dosage method [42, 43] in order to obtain a characteristic strength of 30 MPa with a total w/c ratio of 0.50. The effective w/c ratio was maintained constant in all concretes. According to Neville [33], the effective water-cement ratio is the ratio of water occupying the space outside the aggregate particles (used in the cement hydration process and lend workability to concrete) and the cement. The recycled aggregates were used in nearly saturated surface-dry conditions, at its 90% of water absorption capacity, and their moisture content was measured prior to their use. The amount of mixing water added to each concrete mix was adjusted in accordance with the effective water absorption capacity of the aggregates at concrete production. This procedure was used in order to maintain the same effective w/c constant in all concretes and to avoid bleeding or water surface layers influencing the mechanical properties of the concrete [44] (the effective water absorption of the aggregates was determined by submerging them in water for 20 minutes). In RAC, both coarse natural aggregates (Gravel 4-10 mm and Gravel 10-20 mm) were replaced (in volume) by coarse mixed recycled aggregates. Table 5 shows the mix proportioning used and the admixture amount used to achieve fluid consistencies, between 100-150 mm in the concrete slump test (S3 class following the BS EN 206:2013 standard, [45]).

The concrete specimens were produced and cured following UNE EN 12390-2:2001 [46] regulations and were manually compacted using a steel rod. The concrete specimens were then covered with a plastic sheet and air-cured for the first 24 hours. After 24 hours of casting, the specimens were demoulded and then stored in a humidity room and kept at 21°C and 95% humidity until the test ages were reached.

2.3 Tests of concrete properties

2.3.1 Fresh state properties

The setting time and shrinkage tests conducted using 0% and 100% replacement ratios were carried out in order to analyse the most critical cases.

Setting time

The setting times of the concrete mixtures were determined in accordance with ASTM C 403 [47]. Initial and final setting times are defined as the times at which the penetration resistance reaches values of 3.5 and 27.6 MPa, respectively. The fresh concrete was sieved, immediately after concrete mixing, using a 5 mm sieve and the resulting mortar was cast in a prismatic mould of 100x100x400 mm. The test was performed by measuring the strength required for the appropriate needle to penetrate 25 mm into the testing mortar. The specimens were kept in constant environment conditions of 20°C and 70% relative humidity during the testing period in order to reduce the effects of the temperature variations.

Plastic shrinkage

The plastic shrinkage phenomenon is caused by the loss of water through evaporation or suction during the plastic state of the concrete. A volume reduction on the concrete’s surface as well as the appearance of surface cracks (in the case of restrained concrete) are caused by plastic shrinkage, which is proportional to the rate of water loss. This phenomenon basically depends on the relative temperature, humidity and wind speed of the environment [33].

The setup for the plastic shrinkage test is based on previous studies performed by Saliba et al. [48]. The mould used in this test was a square prism with an inner size of 600 x 150 x 150 mm, the internal sides being covered by Teflon. Both squared-bases of the prismatic mould were attached to the concrete specimen by embedding four 50 mm-long steel bars. While one base was fixed to the rest of the mould, the other could move without obstruction and free of friction due to the Teflon covering. An LVDT was used to measure the displacement of the mobile base, which was dragged along by the concrete specimen while shrinking. The test was conducted in a static climatic chamber with a constant temperature of 20°C and relative humidity of 50% and no-wind condition. Two specimens were tested for each concrete batch and the top surface was not covered in order to permit water evaporation.

2.3.2 Hardened state properties

Physical properties

Physical properties were measured according to ASTM C 642 “Standard Test Method [49] for Density, Absorption and Voids in Hardened Concrete” at 28 days after casting. Three cubic specimens were used in this test for each concrete mixture produced.

Mechanical properties

The compressive strength, flexural strength and modulus of elasticity were determined in all concretes. The compressive strength was measured at the ages of 7 and 28 days following BS-EN 12390-3:2009 specifications [50]. Three 100mm cubic specimens were used for each testing age. The flexural strength and modulus of elasticity were determined after 28 days of casting in accordance with BS-EN 12390-6:2010 [51] and BS-EN 12390-13:2014 [52] specifications, respectively. The flexural strength and modulus of elasticity of each concrete mixture were determined via the testing of three prismatic laboratory specimens of 100x100x400 and three cylindrical core specimens ø100 x200 mm, respectively. The testing of the concretes’ mechanical properties was carried out via the use of a compression machine with a loading capacity of 3000kN.

Drying shrinkage

It is known that autogenous shrinkage is more relevant in concretes with low water-binder ratio and with high amounts of cement such as high-performance concrete, in which self-desiccation is much greater than that found in normal strength concrete [53]. In this work, due to the use of normal mixtures and hardened concrete properties, the concretes’ drying shrinkage was determined. Drying shrinkage depends on the age of the concrete when the drying starts, specimen dimension and external parameters, such as relative humidity and temperature. Three prism specimens of 70 x 70 x 285 mm taken from each concrete were prepared for the measuring of the drying shrinkage in accordance with ASTM C 596-07 specifications [54]. The concrete specimens were cured in their moulds for 24 h, during which time they were covered in plastic sheeting to prevent water evaporation. The specimens were then demoulded and cured in lime-saturated water for 48 h. At the age of 72 h, the specimens were removed from the water, wiped dry with a damp cloth and their length immediately tested. The specimens were then placed in a climatic chamber for 25 days, where length comparison tests were taken at 4, 11, 18, and 25 days. The climatic chamber was kept at constant temperature of 20°C and 50% humidity, according to ASTM C 157-03 [55].

3 RESULTS AND DISCUSSION

3.1 Fresh state properties

3.1.1 Setting time

A setting time test was conducted on concretes with MRA replacement ratios of 0% and 100% for all the series and its results are shown in Table 6. The use of MRA produced similar initial setting times and considerably longer final setting times than those of natural aggregates for a given concrete series. The RAC with 100% of MRA produced on average a 10% longer final setting times than NAC concretes. According to Pepe et al. [56], it was found that the extra amount of water in RAC plays a significant role on the the hydration process of the cement, which could in fact influence the setting time. The water content available in the mixture modifies the hydration process with the resulting possible delay in the setting time. Consequently the higher water content in the RACs had a slight influence on increasing its setting time with respect to that of NAC concrete.

Initial and final setting times of concretes produced using seawater were reduced in averages of 21% and 16%, respectively with respect to those of concretes produced employing freshwater. Such reductions being within a lower range than those found by Ghorab et al.[57] or Kaushik and Islam [58] whose results on seawater use showed 25% and 30% lower initial and final setting times, respectively. The higher presence of chloride in seawater clearly influenced the acceleration of the cement hydration. JCI [59] estimates that such a difference in the setting time caused by the type of mixing water could be a result of the hydration acceleration effect of NaCl contained in seawater. As stated by Neville [33] the action of sodium cchloride is similar to that of calcium chloride but is of lower intensity. It is known [33, 60, 61] that the presence of CaCl2 increased the combined water content of the pastes, accelerating the hydration of the calcium silicates, mainly C3S, by formation of “innert product” calcium silicate hydrate (CSH). This reduction in the concretes’ setting time using seawater it is a fact corroborated by many other previously stated studies [27, 57, 58, 62, 63].

The use of BFS cement instead of just OPC produced significant delays of 35% in the initial, and 31% in the final setting times when freshwater was used for concrete production, however, the initial setting time of both BFS and OPC concretes was similar to that of when seawater was employed. The chloride ions of seawater had a higher influence on the calcium silicate within the BFS cement. The BFS cements had a lower volume of calcium silicate than that of the OPC cement, consequently the increase in the amounts of slag used had the effect of increasing the seawater’s influence on the setting time, as also stated by other researchers [33, 64]. The final setting time took longer in BFS concretes than in OPC. However, the use of seawater also decreased the BFS concretes' setting times.

3.1.2 Plastic shrinkage

Figure 2 shows the results from testing horizontal plastic strain due to plastic shrinkage. The plastic strain results are graphed up to seven and a half hours, which was longer than the highest final setting time. The plastic shrinkage strain increased over a period of 4-5 hours before finally stabilizing at an almost constant value until final setting time. The stabilization occurred earlier than those times recorded in other studies [48, 65] as a result of lower water-cement ratios or more severe atmospheric conditions.

Concretes produced with natural aggregates and freshwater achieved the highest plastic shrinkage strain of 405-430με. Such strains were lower than those found by other authors [48, 65, 66] and significantly lower than that proposed by Baghabra Al-Amoudi et al. [65] as a threshold strain value (1100 με) which could result in plastic shrinkage cracking. The use of recycled aggregates in concrete reduced plastic shrinkage strains and this was more evident when BFS cement was used for concrete production. MRA concretes showed 20% and 81% lower values than those obtained from the natural aggregate concretes produced with OPC and BFS cement, respectively. However, concrete produced with BFS cement and natural aggregates showed similar results to those of the concrete produced with OPC cement. The use of seawater produced lower plastic shrinkage, an influence which was even more apparent in RACs.

According to Won et al. [67] plastic shrinkage strain occurs as a result of the absence of sufficient bleed~~ing~~ water, which would act as a substitute for the evaporated water. Moreover, according to Shaeles and Hover [68], concretes containing high water amounts, while having the potential for greater volumetric shrinkage than mixtures with lower water content, actually show lower plastic shrinkage. RAC also had a high total water amount due to the MRA aggregates being used in a saturated condition. In effect, MRA represents an important internal curing agent due to its high water quantity and can act as a water supply in case of water deficit. The reduction of plastic shrinkage observed in the comparative tests carried out on the seawater concretes can be attributed to both a faster achievement of tensile strength to overcome the internal tensions [68] and the reduction of pore size distribution which allowed reductions on the capillary pore pressure [48].

3.2 Hardened state properties

Both physical and mechanical properties were determined in the concretes produced employing the four percentages of MRA on substitution of natural aggregates (0%, 25%, 50% and 100%).

3.2.1 Physical properties

The results obtained from testing dry density, water absorption and permeable porosity are shown in Table 7. Only NAC and RAC-25 concretes achieved dry-density values higher than 2.30 kg/dm^3, which is the minimum required according to the Port of Barcelona's Technical Requirements Specification for the production of concrete dyke blocks. As certain authors have previously stated [3,19, 69], the use of recycled aggregates significantly reduces the density of the hardened concrete. The concrete produced with 100% of coarse MRA achieved 9% lower density than NAC concrete, which is consistent with the results found in other studies [18–20]. In those cases, the density loss percentages were between 8-12%

when a high amount of MRA was used. The results from dry-density appearto be more sensitive to the amount of MRA employed than to the type of cement or water used.

The lowest water absorption capacity for a given ratio of aggregate replacement was achieved by the concretes produced employing seawater and BFS cement. It was observed that an increase of MRA content greatly influenced water absorption (see Table 3). The water absorption capacity of concretes produced using 100% of MRA being between 62-97% higher than those of NAC for a given series.

As stated in other researcher works [59, 63], the use of seawater reduced the water absorption and porosity in all concretes. In particular, results determined that the use of seawater in concretes produced with OPC and BFS cement reduced the water absorption on average by 13% and 8%, respectively.

The use of BFS cement produced notable water-absorption reductions. Several studies have stated that cement containing BFS as a partial replacement of ordinary Portland cement (OPC) has the effect of generating densification on the binder matrix which in turn generates reductions on the permeability and porosity of hardened concretes [35, 70, 71]. Also, certain researchers [30, 72, 73] argued that the deposition of ettringite and the ingress of chlorides can produce the solid phase Friedel's salt at a larger size that precipitates in the pores. As a consequence, the porosity as well as the permeability of the concrete is reduced. However, in our research work there was not evidence of expanded material (see Figure 3). The salt accumulation could have influence on the reduction of concrete's absorption capacity.

3.2.2 Mechanical properties

Compressive strength

Table 8 shows the compressive strength results of concretes tested at 7 and 28 days for each series. NAC concretes achieved the highest compressive strength in each series. The concretes produced with 100% of MRA suffered the highest reduction in compressive strength with respect to that of NAC concrete. Concretes produced employing seawater obtained a higher compressive strength than those produced with freshwater.

However, at 28 days of age, all concretes fulfilled the Port of Barcelona's Technical Requirements Specifications of (30 MPa) minimum compressive strength, in compliance with their use in the production of plain concrete dyke blocks.

Concretes produced with 25% MRA showed, on average for each series, 12% lower compressive strength after 7 days, than those achieved by natural aggregate concretes. The increase of MRA content to 50% and 100% produced, on average, 22% and 42% compressive strengths losses, respectively. Concretes produced with OPC, at 28 days of age, showed similar compressive strength losses to those found after 7 days. However, concretes produced using MRA with BFS cement showed lower compressive strength reductions; the compressive strength of concretes produced employing 25%, 50% and 100% of coarse MRA reduced by 6%, 15% and 33%, respectively with respect to NAC concrete after 28 days of curing. These compressive strength reductions are in a higher range than those described in other studies [14,17,19,20]. According to Silva et al. [5], the quality of the recycled aggregates containing mortar and ceramic particles is a determining parameter on compressive strength behaviour.

As can be observed in Figure 4, the compressive strength gains were higher in RACs, especially in concretes produced with BFS cement. The compressive strength gains of NAC from series 3FW (concretes produced with BFS and freshwater) and 3SW (concretes produced with BFS and seawater) ranged between 21-25% while RAC ranged between 27-30%. As stated by Kou et al. [74, 75], the compressive strength gains of recycled aggregate concrete prepared with mineral admixtures were also higher, these gains might be attributed to the nature of RA used. Generally RA are more porous than natural aggregates. When concrete containing RA are prepared with the use of mineral admixtures, two possible mechanisms may enhance the properties of the concrete produced: (1) part of the mineral admixtures would penetrate into the pores of RA, which would subsequently improve the interfacial transition zone (ITZ) bonding between the paste and the aggregates; (2) cracks originally present in the aggregates would be filled by hydration products.

As detailed in Figure 4, the water type used had no influence on the increase of compressive strength over a period of 7-28 days.

With respect to the use of seawater for concrete production, various comparative studies [30,32, 58,76] have exposed similar performance results with regard to the initial higher compressive strength of seawater concrete compared to that of freshwater. This fact according to the authors has a consequence of lower strength developments. In our case, the initial and final compressive strength of concretes produced employing seawater was higher than those produced with freshwater. This was due to its denser cement matrix [35, 70, 71]. The porosity of concretes produced employing seawater was lower than in the concretes produced with freshwater (see Table 7). However, unlike the comparative studies previously mentioned, in this case the development of the compressive strength was similar to that of concretes produced with seawater or freshwater.

Flexural strength

Table 8 shows that concretes produced with MRA had similar or even higher flexural strength than natural aggregates concretes. The reason for this higher flexural strength is that it has a higher dependence on the aggregates' properties (maximum particle size, particle shape or flakiness index) and on the quality of the interfacial transition zone (ITZ) than on the compressive strength [33]. The RAC's enhanced performance in flexural strength can be attributed to slightly lower grading size distribution and to the quality of the ITZ whose improvement via the use of recycled aggregates has been reported by various authors [77, 78].

An analysis of the flexural strength results contained in Table 8, shows that the concretes from series 3SW, produced using BFS cement and seawater, achieved the highest flexural strength for each replacement ratio. However, the cement type proved to have a higher influence on the flexural strength than the water type used in the concrete mix. Test results concluded that after 28 days the concretes produced employing BFS cement had on average between 11% and 18% higher flexural strengths than those produced with OPC using fresh and seawater, respectively. The use of seawater produced similar flexural strength results to those of concretes produced with freshwater when using OPC. However in the case of BFS cement the flexural strength values of the seawater concretes increased by 5% on average in comparison to those of the flexural strength achieved by concretes mixed with freshwater.

Modulus of elasticity

The results of the modulus of elasticity of each type of concretes are shown in Table 8. The modulus of elasticity of the concrete is proportional to the modulus of elasticity of the aggregates themselves, which in turn is dependent on the aggregates own density, as exposed by Lydon and Balendran [79]. A comparative study between NAC concrete and MRA concrete revealed that the use of MRA in concrete production resulted in a drop in the modulus of elasticity. This drop was due to the fact that the mixed recycled aggregates had a lower density than those of the natural aggregates. Test results determined that there was an average modulus of elasticity drop of 11%, 18% and 36%, respectively when replacement ratios were increased to 25%, 50% and 100%. These reductions are in accordance with those results documented in Martinez-Lage et al. [20] and Gonzalez-Corominas and Etxeberria [19] in concretes produced with high replacement ratios of MRA. The results for each replacement ratio showed that, concretes produced with BFS cement and seawater achieved the highest modulus of elasticity, this was the results of a higher development of the cement matrix hydration, a fact also observed in the density and permeable pore test.

3.2.3 Drying shrinkage

The drying shrinkage test measurements began 3 days after casting. Figure 5 shows the negative influence of the use of high percentages of MRA on the drying shrinkage of concretes. While NAC concretes showed drying shrinkage strains between 261-403με after 28 days of casting, RACs reached between 422-814με. A comparative study of the drying shrinkage results obtained between NAC and MRA concrete revealed that the concretes produced with 100% of MRA increased the values obtained on average by 65% using OPC cement and 110% using BFC cement. These results are in accordance with results obtained by other authors [10,21,24, 80-83] which emphasised that recycled aggregates increased drying shrinkage. Kou and Poon [81] also stated that the mortar adhered to the recycled aggregate contributed to an increase in the total cement mortar volume, resulting in increasing strain from drying shrinkage. Dhir et al. [21] attributed the higher drying shrinkage to the lower modulus of elasticity of recycled aggregates, which results in the production of lower movement restriction. Silva et al. [25] also defined that the modulus elasticity of concrete is a parameter that should be considered when estimating the shrinkage of concrete, especially when considering RAC.

Nevertheless, an analysis of the results obtained in this study on the drying shrinkage strains from RAC demonstrated that they were in a higher range than those found in the literature review concerning concretes produced with recycled concrete aggregates [80-82] and even MRA [10, 83,84]. Many studies [10, 24,33,63, 65, 81, 83] agree that cement/water ratio and aggregate content have an influence on the drying shrinkage. The drying shrinkage increase observed by the use of BFS cement was attributed to the lower density of BFS cement as well as the delayed strength gain which reduced movement restrictrions [85].

As can be observed from the test results exposed in Figure 5, the RAC concretes showed significantlly higher mass losses than those performed by NAC. The high porosity of MRA particles resulted in the containing of a high proportion of water susceptible to evaporation, which in turn produced the high drying shrinkage values.

The use of seawater produced slight increases with respect to drying shrinkage strains as certain researchers also stated [79, 86], however, it did not have a significant influence on the mass loss. The behaviour detected could, in all probability, be caused by the earlier and enhanced binder hydration resulting from the higher presence of chlorides.

4. CONCLUSIONS

The following conclusions can be made based on the results of this study:

According to fresh state properties of concretes:

- The concrete’s setting time was increased by using recycled aggregates, as those aggregates contained a higher amount of absorbed water than natural aggregates. The setting time was reduced by using seawater which produced a quick initial setting.
- The low initial hydration process of BFS cement, combined with seawater and recycled aggregates achieved a similar initial and final setting instant to that of conventional concrete produced with OPC cement, freshwater and natural aggregates.
- The plastic shrinkage was lower when concretes were produced employing recycled aggregates and seawater. The concretes produced with BFS cement employing recycled aggregates achieved the lowest plastic shrinkage.

According to hardened state properties of concretes:

- The use of recycled aggregates increase the absorption capacity of concretes, however this can be reduced by means of using BFS cement with seawater in concrete production.
- The compressive strength and the modulus of elasticity were notably reduced by increasing the MRA content in concrete production. However the use of MRA produced higher or similar results in flexural strength to those of conventional concrete. Seawater combined with BFS cement improved mechanical properties, the cement type being more influential than the water type used. Concrete produced with MRA and BFS cements achieved the highest compressive strength gain.

- The use of mixed recycled aggregates (MRA) as well as BFS cement increased the drying shrinkage of the concrete. The same happened when seawater was employed for concrete production.

The use of MRA in high replacement ratios had a significantly negative influence on most of the physical, mechanical and shrinkage properties, with the exception of setting time, plastic shrinkage and flexural strength.

Nevertheless, MRA use in combination with BFS cement and seawater considerably improved the concrete's properties. However, the influence of the water type was, in most cases, less significant than that of the cement type.

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Table 1. Chemical composition of cements (%)

	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 (1)	4.58	0.02	0.20	63.88	0.78	0.10	20.71	4.22	1.68	0.17
CEM III/B 42.5 L/SR (3)	1.56	0.25	0.72	49.76	0.88	0.09	28.42	8.07	6.02	0.69

Table 2. Mixed recycled aggregate composition and soluble sulphates content.

Components classification	**Concrete**	**Bricks, tiles**	**Natural aggregate**	**Asphalt**	**Gypsum**	**Plastic and glass**
MRA (%)	27.31	11.05	47.01	12.61	1.45	0.57

Table 3. Physical properties of the aggregates.

	Natural aggregates			**Mixed recycled Aggregates**
Physical properties	**0-4 mm**	**4-10 mm**	**10-20 mm**	
Density after drying (kg/dm^3)	2.60	2.64	2.59	2.19
Water Absorption (%)	2.05	1.60	2.35	7.82
Abrasion resistance (%)	-	19.80	19.80	33.60
Amount of fines (<0.063mm) (%)	5.69	0.80	0.55	6.03
Flakiness Index (%)	-	7.81	10.35	18.36

Table 4. Chemical compositions of freshwater and seawater.

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

Table 5. Concrete proportioning of each mixture (Coded as: Natural aggregate concrete (NAC) and Recycled Aggregate Concrete (RAC-X), X indicates the replacement percentage of recycled aggregates. Depending on the cement type used, CEM I (1) or CEM III (3) and the water source, freshwater (FW) or seawater (SW), the corresponding initials were added at the end of the concrete code).

Concrete reference	Natural aggregates			Mixed recycled Aggregate (kg)	Cement (kg)	Total water *(kg)	Admixture (kg)	Effective water/cement ratio
	0-4 mm (kg)	4-10 mm (kg)	10-20 mm (kg)					
NAC	976	210	765	-	300	150	1.20	0.45
RAC-20	976	168	612	163	300	162	1.50	0.45
RAC-50	976	105	382	417	300	180	1.65	0.45
RAC-100	976	-	-	815	300	211	3.00	0.45

*the water absorbed by recycled aggregates is included. The MRA were humid to 90% of its water absorption capacity

Table 6. Results from assessing the setting of concrete mixtures.

Concrete Reference	Freshwater mixtures		Concrete Reference	Seawater mixtures	
	Initial setting time (hours)	Final setting time (hours)		Initial setting time (hours)	Final setting time (hours)
NAC-1FW	3.08	4.83	**NAC-1SW**	2.51	4.07
RC100-1FW	2.67	5.17	**RC100-1SW**	2.49	4.94
NAC-3FW	4.17	6.87	**NAC-3SW**	3.09	5.30
RC100-3FW	4.31	7.24	**RC100-3SW**	2.96	5.60

Table 7. Density, water absorption and porosity of concrete mixtures.

Concrete Reference	Freshwater mixtures			Concrete Reference	Seawater mixtures		
	Dry density (kg/dm^3)	Water absorption (%)	Porosity (%)		Dry density (kg/dm^3)	Water absorption (%)	Porosity (%)
NAC-1FW	2.38	2.98	7.12	**NAC-1SW**	2.37	2.69	6.47
RAC-20-1FW	2.32	3.19	7.46	**RAC-20-1SW**	2.35	3.13	7.32
RAC-50-1FW	2.23	4.19	9.49	**RAC-50-1SW**	2.28	3.32	7.74
RAC-100-1FW	2.11	5.88	12.60	**RAC-100-1SW**	2.18	4.78	10.75
NAC-3FW	2.37	2.46	6.05	**NAC-3SW**	2.38	2.21	5.34
RAC-20-3FW	2.32	3.00	7.03	**RAC-20-3SW**	2.34	2.59	6.39
RAC-50-3FW	2.27	3.09	7.21	**RAC-50-3SW**	2.28	2.98	7.04
RAC-100-3FW	2.14	3.98	8.67	**RAC-100-3SW**	2.18	3.73	8.52

Table 8. Mechanical property results; compressive strength, flexural strength and modulus of elasticity.

Concrete Reference	**Freshwater mixtures**				**Concrete Reference**	**Seawater mixtures**			
	Compressive strength (MPa)		**Flexural strength (MPa)**	**Modulus of elasticity (GPa)**		**Compressive strength (MPa)**		**Flexural strength (MPa)**	**Modulus of elasticity (GPa)**
	7 days	**28 days**	**28 days**	**28 days**		**7 days**	**28 days**	**28 days**	**28 days**
NAC-1FW	52.39	61.46	5.89	38.27	**NAC-1SW**	52.61	61.46	5.09	40.16
RAC-20-1FW	44.10	49.49	4.27	32.64	**RAC-20-1SW**	47.11	50.41	4.40	34.56
RAC-50-1FW	39.56	48.82	6.26	31.01	**RAC-50-1SW**	42.50	50.16	6.53	31.26
RAC-100-1FW	26.48	32.82	4.90	22.09	**RAC-100-1SW**	28.88	36.69	5.10	24.54
NAC-3FW	45.35	57.51	5.70	37.21	**NAC-3SW**	48.27	64.32	6.03	42.28
RAC-20-3FW	38.55	53.55	5.13	35.95	**RAC-20-3SW**	44.25	61.26	5.45	37.56
RAC-50-3FW	35.41	49.50	6.55	33.00	**RAC-50-3SW**	37.66	53.56	6.66	34.45
RAC-100-3FW	29.35	40.53	6.01	27.00	**RAC-100-3SW**	29.53	40.46	6.42	27.38

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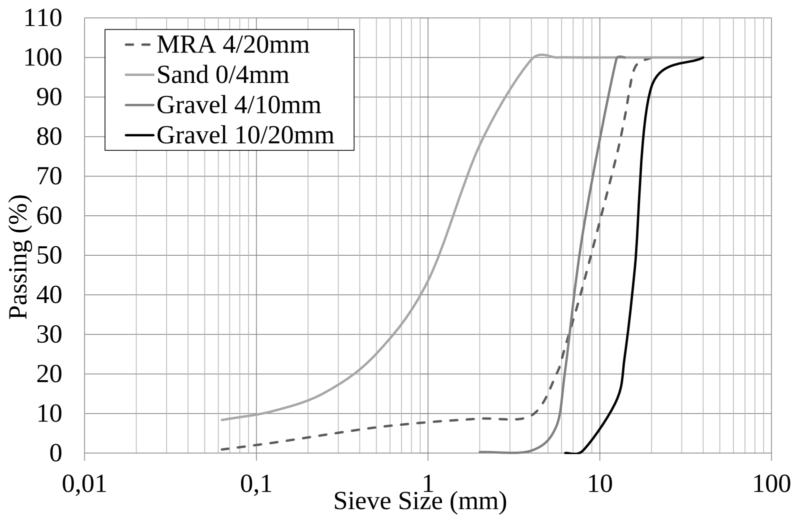

Figure 1. Particle size distributions

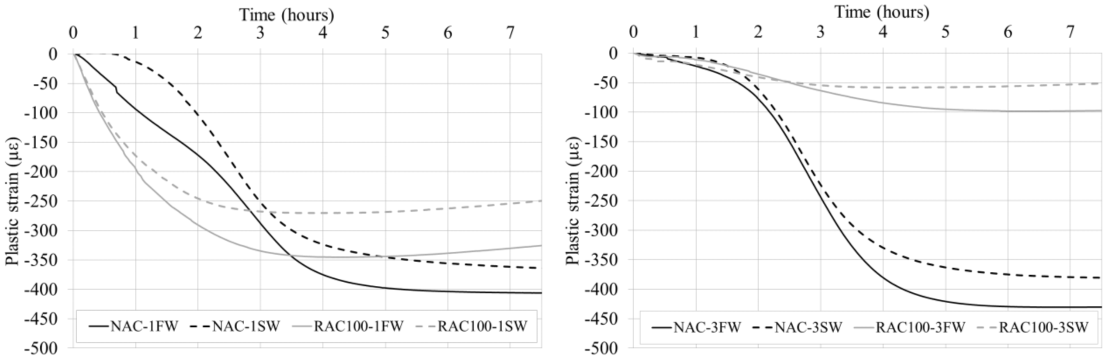

Figure 2. Plastic shrinkage of the series produced with OPC (left) and series produced with BFS cement (right)

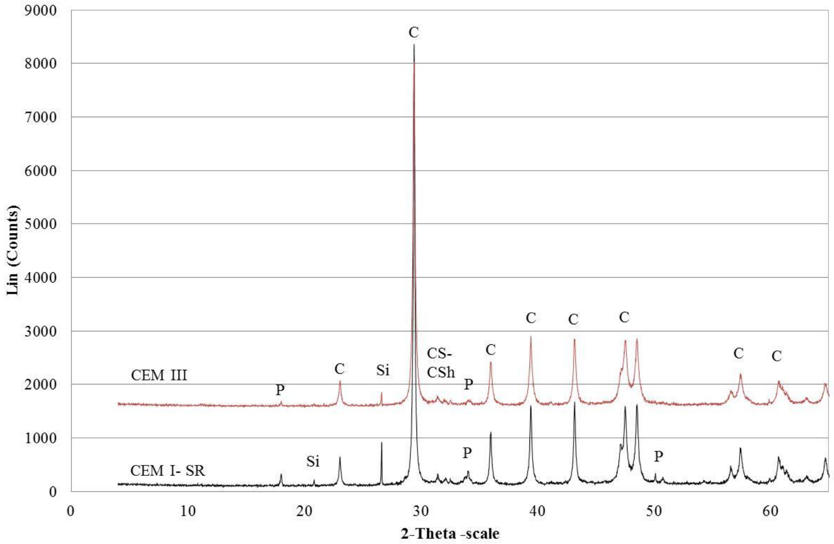

Figure 3. The XRD analysis of concretes produced employing seawater and sulphate resistant cement CEM I and GBS cement, CEM III.

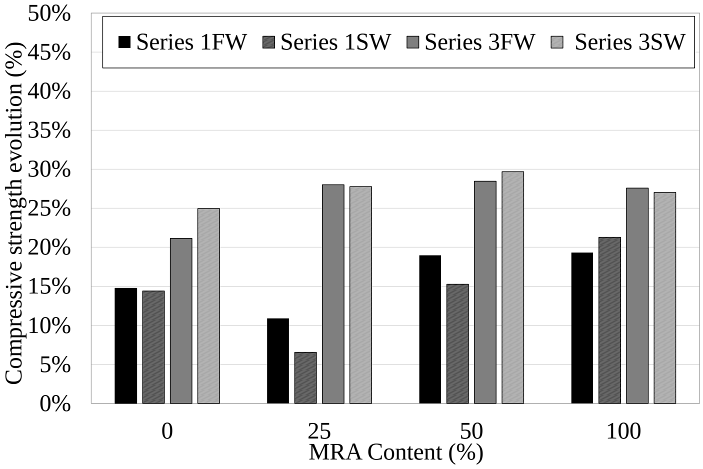

Figure 4. Compressive strength evolution from 7 to 28 days

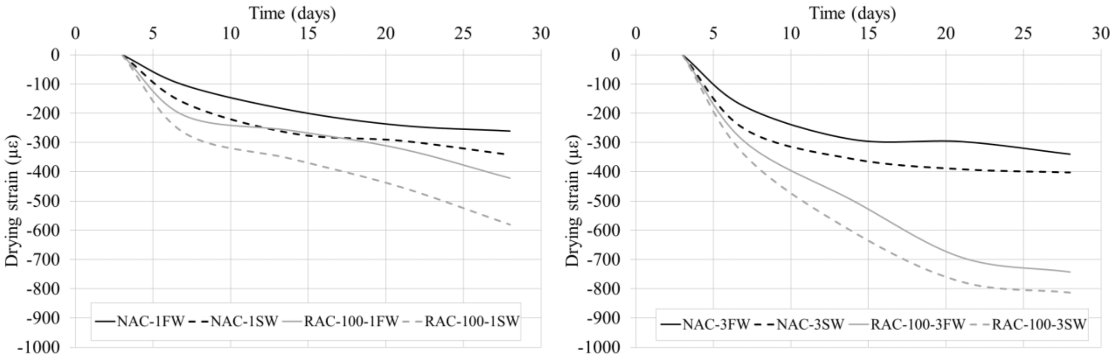

Figure 5. Drying shrinkage of series produced with OPC (left) and series produced with BFS cement (right)

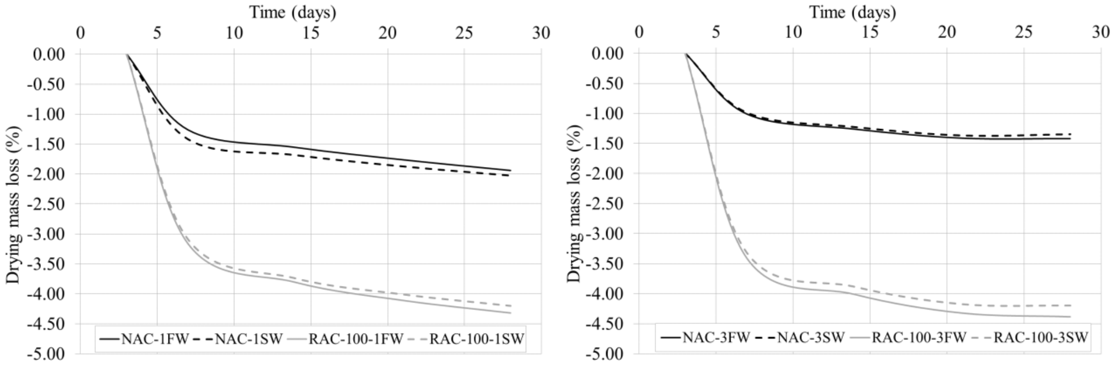

Figure 6. Drying shrinkage of series produced with OPC (left) and series produced with BFS cement (right)