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

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## HIGHLIGHTS

- The use of MRA improved the plastic shrinkage and flexural strength of concretes.
- The use of seawater improved the mechanical properties, reduced setting time and increased drying shrinkage.
- The cement type was more influential than the use of seawater on concretes' properties.
- The use of seawater and cement with blast-furnace slag improved the performances of the RAC.

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## 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.



## 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 80–90% 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

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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 to 50 MPa 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 30 $N/mm^2$ and a minimum density of 2.300 $kg/m^3$. 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 superplasticizer water-reducer based on polycarboxylate ethers admixture was used in the concrete production, the density of which was 1056 $g/cm^3$.

#### 2.1.2. Aggregates

All natural aggregates were crushed limestone aggregates, three size fractions being employed (sand 0–4 mm, gravel 4–10 mm and gravel 10–20 mm). 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 Fig. 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.