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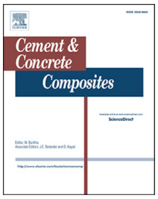

# How do recycled concrete aggregates modify the shrinkage and self-healing properties?

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ABSTRACT

This paper presents the main results of a research carried out to analyze the mechanical properties, intrinsic permeability, drying shrinkage, carbonation, and the self-healing potential of concrete incorporating recycled concrete aggregates. The recycled concrete mixtures were designed by replacing natural aggregates with 0%, 30%, and 100% of recycled concrete gravel (RG) and 30% of recycled concrete sand (RS). The water to equivalent binder ratio was kept constant and recycled concrete aggregates were initially at saturated surface dried (SSD) state. The contribution of the porosity of natural and recycled aggregates to the porosity of concrete was estimated to understand the evolution of the intrinsic permeability and the open porosity. At long term, the maximum variation of drying shrinkage magnitude due to recycled concrete gravels did not exceed 15%. The correlation between drying shrinkage and mass-loss through "drying depth" concept showed that recycled concrete aggregates are affected by drying as soon as concrete is exposed to desiccation. A good correlation between 1-day compressive strength and 18-month carbonation depth was observed. The recycled concrete aggregates presented a good potential for self-healing as the relative recovery of cracks reached up to 60%.

## 1. Introduction

Concrete mixtures for general construction are composed on average of 75–80% of coarse and fine aggregates by volume [1]. The concrete industry worldwide, which produces more than 6 billion cubic meters of concrete per year, consumes more than 10 billion tons of sand and rocks annually. This imply a depletion of natural resources and significant $CO_2$ emissions due to the aggregate manufacturing process [2]. Despite this, the use of concrete will continue to grow in the coming decades, mostly in developing countries. The challenge of the concrete industry in the next decades will be to practice "industrial ecology" in the light of sustainable development. This involves the use of "greener" building materials such as recycled concrete aggregates, obtained from concrete construction and demolition waste [3–6]. This helps reducing the environmental impacts of concrete and promotes conservation of natural raw materials by reducing the need to quarry virgin aggregates.

The study of these aggregates called recycled concrete aggregates (RCA) is not recent. During and after the Second World War, rubble from buildings destroyed by bombing was already employed in Britain and Germany for the reconstruction of buildings. As shown by Hansen [7] and Nixon [8], between 1945 and 1985, extensive research was conducted on recycled aggregates and recycled aggregates concrete. Similarly, today, many studies regarding these materials can be found in literature [9,10]. These studies show that the physical and chemical properties of RCA are significantly different from natural aggregates. The use of RCA modifies the properties of concrete, namely: strength, porosity, permeability, and shrinkage. However, shrinkage does not systematically result in cracking, and the effects of cracking on concrete permeability can be mitigated by self-healing, for instance. Does the influence of RCA on concrete properties necessarily affect the overall performance of concrete and the durability of concrete structures?

Prior to the design of recycled aggregate concrete mixtures, a good characterization of RCA is required. RCA are actually composed of original aggregates and mortar and the crushing procedure is a prime factor influencing their properties [9]. The source of the original aggregates is generally not known and it is not easy to determine the amount and quality of initial mortar bonded to original aggregates, which modifies the properties of the

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new concrete [11]. The proportion of bonded mortar in recycled aggregate has been found to be higher than 30% [7]. This mortar greatly influences the physical properties of RCA (porosity, coefficient of water absorption, absorption rate, shape, specific surface, etc.) [12] and unfavorably the quality of RCA [9,13–15]. According to most of studies, the density of RCA is lower than the density of original aggregate. The relative decrease does not exceed 10%. The water absorption of recycled aggregates is much higher than the water absorption of original aggregates. It is one of the most significant differences between RCA and natural aggregate. As it will be seen later, this considerably affects the long-term behavior of recycled aggregate concrete [7,8,14,15]. If the amount of original bonded mortar increases, the density of RCA tends to decrease whereas the absorption capacity tends to increase, regardless of the water-to-cement ratio of original concrete. All these observations can be explained by the amount of bonded mortar as well as its lower density and higher porosity than natural aggregates [7,8,14,15].

RCA show a higher water demand, which induces a lower workability of fresh concrete especially when the replacement ratio exceeds 50% [7,16,17]. Moreover, the fresh density of recycled aggregate concrete is generally 5%–15% lower than the corresponding natural aggregate concrete [16]. The entrapped air content of the recycled aggregate concrete (RAC) is generally 4–5% (for RCA replacement percentage equal to 100%) higher than the corresponding natural aggregate concrete. This is most likely due to the higher porosity of RCA and the increase in water demand. Consequently, this reduces the strength of the RAC. Some researchers propose to pre-treat the RCA in order to prevent excessive water absorption by aggregates during mixing and maintain concrete workability. Several pre-treatment methods are suggested in the literature [16,18–20].

Despite the precautions taken during the RAC production, it was often found that the compressive strength of RAC is lower compared to conventional natural aggregate concrete [7–9,14,21–23]. According to McNeil et al. [10] it can be explain by several factors such as aggregate replacement rate, aggregate preparation conditions (saturated or unsaturated), quality of the parent concrete, or water-to-cement ratio (W/C) of both concretes. However, it is necessary to keep in mind that this is not a general property of RAC. The strength of RAC can be as good as the strength of the original concrete if, for example, the W/C of the RAC is lower or the same as the original concrete, the other factors being otherwise identical [16,24,25]. Moreover, even if the natural concrete often has better compressive strength at 28 days, in the long term (one year), the recycled concrete has the best performance gain. Its strength can even exceed the standard concrete over the very long term (5 years) [26,27]. Concerning the indirect tensile strength of RAC, its value does not seem significantly different from that of conventional concrete. However, a review of the literature shows no consensus about the question [14,28]. Some authors have found an average reduction up to 10% for the tensile strength of RAC, compared to conventional concrete [29]. For others, RAC can sometimes exhibit slightly greater tensile strength [30]. According to Etxeberria et al. [9] et Katz [16], this improvement is due to the good paste-aggregate bonding developed by the RCA.

Shrinkage is also likely to affect the RAC performance. Shrinkage of recycled aggregate concretes is found to be higher than conventional concretes [29,31]. This increase depends on the percentage of substitution of RCA, the source of parent aggregate, the water-to-cement ratio, the mixing and curing procedure, the lower restricted free strain of RCA particles compared to natural aggregate, etc. [14,29–31]. According to Domingo-Cabo et al. [31], a limited substitution rate of coarse aggregate (20%) has a negligible effect on shrinkage, compared to natural aggregate concrete. However, for a period of 6 months, a 50% RCA content was found to cause an increase in shrinkage near 10% and a total replacement of coarse aggregate resulted in a 70% increase compared to natural aggregate concrete. Other results and the main factors influencing the RAC shrinkage are reported in Silva et al. [32].

Considering these properties, studies carried out on RAC showed that these concretes presented a significant sensibility to cracking [33]. Durability of concrete structures is so affected. One of the means of reducing this cracking is self-healing, a phenomenon which is well known for conventional concretes. Indeed, many studies and observations showed that, in the presence of water, not only the cracks (even the most visible) lead to close but in some cases, strength was restored as well [34–40]. However, the self-healing ability of recycled aggregate concretes has not been studied yet.

This paper presents a research on long-term behavior of concretes designed with recycled concrete aggregates produced by crushing concrete blocks from building demolition waste. This work aims particularly to:

- Study the influence of recycled concrete aggregate substitution level on drying shrinkage and durability indicators (permeability, porosity, carbonation) of RAC mixtures designed with the same effective water to equivalent binder content. RAC mixtures with 0%, 30% and 100% of coarse RCA and 30% of fine RCA have been studied.
- Investigate the effects of autogenous healing of cracks in these RAC through permeability measurements and its contribution in the durability enhancement.

## 2. Experimental program

### 2.1. Materials and mixtures

Natural aggregates (NA) were crushed dark limestone aggregates. The physical properties of aggregates are summed up in Table 1. Recycled concrete aggregates (RCA) were obtained by crushing unknown waste concrete from the recycling plant of DLB Gonnesse (Paris region, France – RECYBETON project). According to Concrete Standard NF EN 206/CN [41], they are classified as aggregates type I, RCU95 which means that they can be considered as good quality RA. The adhered mortar content of these RCA was quantified by Ref. [42]. The old paste of the two fractions 4/10 and 10/20 represent 34.5% and 66% of total mass respectively. Fig. 1 shows the particle size distribution of fine and coarse aggregates.

Four mixtures have been studied: one control concrete (0RS-0RG-100SSD) with natural aggregates (NA), three substitutions of 30% (0RS-30RG-100SSD; 30RS-0RG-100SSD) and 100% (0RS-100RG-100SSD) of recycled concrete aggregates. The concrete designation *x*RS-*y*RG-100SSD means that *x*% (in mass) of sand and *y* % (in mass) of gravel used is recycled; 100SSD means that the aggregates are at SSD state [42]. Table 2 summarizes the mixture proportions, the fresh concrete properties and the materials used. All the concrete mixtures were designed to reach C25/30. Thus, the water to equivalent binder ratio was maintained close to 0.65 ($W_{eff}/B_{eq} \approx 0.65$) for all the mixtures [41]. The equivalent binder content is determined according to European standard EN 206/CN (Eq. (1)). The same batch of Portland cement CEM II/A-L 42.5 N proceeding from the same cement plant were used. Its Blaine fineness and density are of 370 $m^2/kg$ and 3.09 $kg/m^3$ respectively. MC PowerFlow 3140 was added as superplasticizer (SP).

$$B_{eq} = Cement + k \times Limestone \tag{1}$$

where *k* is the activity coefficient of limestone filler given by NF EN