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Early age behaviour of recycled concrete aggregates under normal and severe drying conditions

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ABSTRACT

The use of recycled aggregates in concrete mixtures is a part of waste recovery strategy. The French national project RECYBETON aims at developing scientific knowledge to facilitate the use of recycled aggregates into concrete. In this experimental study, two exposure conditions were combined to analyse the behaviour of fresh and hardening concrete in standard and severe drying conditions (8 $m\,s^{-1}$ wind speed). High evaporation rate promotes the development of plastic shrinkage and cracking of fresh concrete. The influence of recycled concrete aggregates proportion and initial water saturation rate were investigated. Two series of concrete mixtures were designed to reach two strength classes. The strains and weight loss of concrete samples were monitored until the stabilization of plastic shrinkage. The increase in evaporation rate accelerated the development and increased the maximum value of plastic shrinkage but did not significantly influence the shrinkage-to-weight loss ratios. In severe conditions plastic shrinkage developed before initial setting thus reached higher magnitudes. The main mix-design parameter affecting the shrinkage-to-weight loss ratio and cracking was the total water-to-binder ratio. The total water content includes the water added and the water used to pre-saturate the aggregates. High evaporation rate triggered the release of water initially absorbed by recycled concrete aggregates.

1. Introduction

Concrete is the most widely used material in the world. The production of concrete causes the extraction of huge amount of natural resources. Aggregates are the main part as they represent 70% of concrete volume. Sand and coarse aggregates are generally extracted locally due to the relatively high transportation costs. In several countries and regions it is more and more difficult to provide concrete producers with good aggregates while complying with environmental regulations. As construction and deconstruction often occur in the same areas, recycled concrete aggregates are expected to be more and more widely used [1].

The influence of recycled concrete aggregates (RCA) on the properties of recycled concrete has already been widely studied. The variability of recycled concrete properties is influenced by RCA, since the properties of initial concrete significantly vary. Recycled concrete has been found to show lower strength and elastic modulus, and higher shrinkage [2–6]. In conventional concrete, a higher water-to-cement ratio generally implies a higher drying shrinkage magnitude [7–9]. In concretes with porous aggregates, the water contained within these aggregates also plays an important role in the development of shrinkage strain [8,10,11]. The water released by porous aggregates is likely to induce different behaviours in drying or sealed conditions. The drying shrinkage has actually been found to increase for low-quality recycled aggregates [12,13], as drying aggregates show shrinkage themselves [14]. In sealed conditions, the use of recycled concrete aggregates resulted in lower shrinkage aggregates [12,13,15]. As autogenous deformation is due to self-desiccation [16], saturated recycled aggregates could actually mitigate shrinkage by water desorption mechanism and provide an internal curing [8,15,17].

RCA actually show significantly higher porosity than natural aggregates [18,19]. The higher porosity of recycled aggregates leads to higher water absorption, especially during the concrete mixing [20,21]. The porosity of aggregates is generally expressed as the coefficient of water absorption at 24 h, defined in standards [22]. According to European standard on specification and production of concrete [23], the total water content is the added water plus water already contained in the aggregates. The effective water content (W_{eff}) is the difference

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between the total water present in the fresh concrete and the water absorbed by the aggregates. W_{eff} is the water content taken into account to define the water-to-cement ratio and recommendations for limiting values of concrete compositions. Using the effective water concept, it is theoretically possible to keep the water-to-cement constant using porous aggregates with variable initial water saturation and using appropriate quantity of added water content. However experimental studies have shown that the mechanical properties and the cracking sensitivity of concrete are significantly influenced by the initial water saturation of aggregates [11,21,24,25].

Plastic shrinkage occurs when the evaporation rate exceeds the bleeding rate [7,26]. Plastic shrinkage cracking spreads when the surface tension increases due to the development of menisci in the pores which implies the increase of the capillary pore stress [27,28]. Plastic shrinkage depends on water-to-binder (W/B) ratio and cement fineness [29]. An increase in cement fineness and a decrease in W/B ratio led to a decrease in the bleeding rate and an increase the capillary tension level [30]. Plastic shrinkage strain is reduced when the evaporated water is replaced by bleeding water, which could be provided by saturated recycled concrete aggregates [31].

Thus accelerated drying of fresh concrete is likely to increase plastic shrinkage [32,33]. Cracking of concrete generally occurs when several parameters simultaneously lead to an increase in cracking sensitivity [34]. Mix-design parameters and boundary conditions are often associated. Very few results can be found in literature about the influence of recycled concrete aggregates on plastic shrinkage and cracking.

The present experimental study aims at assessing the plastic shrinkage of recycled concrete in severe conditions, i.e. when the evaporation rate is high and when the aggregates are initially partially saturated. Two series of concretes were studied: C 25/30 and C 35/45 strength classes. Concrete mixtures were designed varying the initial water saturation of recycled aggregates, the total water-to-binder ratio (W/B), and the rate of substitution of natural aggregates by coarse recycled concrete aggregates. Plastic shrinkage measurements were associated with other experimental techniques to understand the evolution of plastic shrinkage and the influence of recycled aggregates.

Two series of concrete mixtures were designed keeping effective water or added water contents constant. Fresh concrete was exposed to standard and severe drying conditions. The properties of the concrete mixtures with different initial water saturation and proportion of recycled aggregates under standard and severe drying conditions are analysed and discussed in this paper.

2. Experimental program

2.1. Testing program

Two series of concrete mixtures have been studied: one for building applications called B and one for civil engineering applications called CE. They were designed with different total water-to-binder ratios (W/B) in order to reach C 25/30 and C 35/45 strength class [1]. Concrete mixtures were designed varying the water-to-binder ratio, the proportion of recycled concrete aggregates (RCA), and the initial water saturation of recycled concrete aggregates.

The samples were tested under normal drying conditions, “exposure 1”, or under severe drying conditions, “exposure 2”, that is to say under wind (Table 1). In exposure 1, effective water was kept constant. In exposure 2, added water was kept constant.

For example, a building concrete (B) in exposure 1 with natural sand (0% of recycled sand) and recycled coarse aggregates (100% of recycled concrete aggregates, RCA) pre-saturated at 1.2 A is named: 1-BR1.2 A. “A” is the initial water saturation of aggregates corresponding to the coefficient of water absorption measured at 24 h (NF EN 1097-6) for dried in surface aggregates state (SSD state). All studied concretes are detailed in Table 2.

Table 1
Exposure conditions.

	Exposure 1		**Exposure 2**	
	Standard drying		Severe drying	
Concrete family	B	CE	B	CE
RH (%)	50	50	45	45
Temperature (°C)	20	20	21	21
Wind (m/s)	< 0.3	< 0.3	**8**	**8**

Table 2
Testing program.

	Initial water saturation of recycled concrete aggregates	
	0.5 A	**1.2 A**
0% RCA		1-BN / 2-BN 1-CEN / 2-CEN
100% RCA	$2\text{-BR}_{0.5A}$ $2\text{-CER}_{0.5A}$	$1\text{-BR}_{1.2A}$ / $2\text{-BR}_{1.2A}$ $1\text{-CER}_{1.2A}$ / $2\text{-CER}_{1.2A}$

2.2. Water

The water absorption of aggregates is a key parameter in concrete mix design. Moreover, aggregates can be partially or totally saturated when concrete is mixed. This initial water saturation of aggregates influences the early-age as well as long-term behaviour of concrete. Thus, the use of recycled aggregates in concrete modifies the available water in time. To clarify these water exchanges into fresh concrete, some notions are required.

First, the pre-saturation water (W_{ps}) corresponds to the amount of water in the aggregates before mixing. The additional water (W_{ad}) is the complementary water introduced in the mixer. The absorption water (W_{abs}) is the water corresponding to saturated aggregates at nominal absorption (SSD state). The water remaining in cement paste is called the effective water (W_{eff}). The total water (W_{tot}) introduced in the mix is given by Eq. (1).

$$W_{tot} = W_{abs}(A) + W_{eff} = W_{ps} + W_{ad} \tag{1}$$

In this paper, the 1.2 A concretes have been made with aggregates at 120% SSD initial water saturation, which means a pre-saturation degree corresponding to the nominal absorption plus approximately 1% of dry mass of aggregates.

Two test programs have been conducted:

- The first one deals with tests under standard conditions.

The trials have been done with a constant effective water (W_{eff}); additional water varied as a function of presaturation water, balancing the theoretical aggregate absorption [35].

- The second one deals with tests under severe conditions.

It has been chosen to work with constant additional water (W_{ad}) to observe the effect of aggregates water absorption in concrete [24].

2.3. Raw materials and concrete mix-design

The recycled aggregates used in this study were provided by the French National Project RECYBETON [1]. They had a relatively high coefficient of water absorption, from 5.6% to 5.8% for 4/10 and 10/20 fractions [36].

The test results on the physical properties of natural and recycled aggregates, such as maximum size, specific gravity and water absorption are given in Table 3. Fig. 1 also shows the particle distribution of fine and coarse aggregates.