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Self-compacting concrete with recycled concrete aggregate: Study of the long-term properties

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HIGHLIGHTS

- Long-term behavior of self-compacting concrete is investigated.
- Coarse and fine recycled concrete aggregates are used in self-compacting concrete.
- Self-compacting characteristics are maintained when recycled aggregates are used.
- Recycled aggregates of good quality promote high mechanical properties.
- Creep behavior is influenced by the content and assortment of recycled aggregates.

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ABSTRACT

This paper investigates the shrinkage and creep of self-compacting concrete prepared with coarse and fine recycled concrete aggregates (up to 40% of total amount of aggregates). Physical properties and porosity measurements are studied and related to the mechanical properties.

Results highlight that self-compacting characteristics are maintained when recycled aggregates are utilized and their good quality promotes high mechanical properties. Creep behavior and pores size distributions are more influenced by the content and assortment of recycled aggregates, although their effect is more limited compared to what occurs in traditional concrete with recycled aggregates.

1. Introduction

In the last decade the study of new methods for reusing concrete waste from construction and demolition (C&DW) has turned into large attractiveness in order to decrease the environmental impact due to natural aggregates exploitation and waste disposal [1–6]. Nowadays European Standards and Eurocodes [7,8] allow the use of C&DW in the mix design of new concrete, when preparatory adequate characterizations are made. Indeed, the good quality of the aggregates is a crucial issue for new structural concrete applications [9,10]. Moreover, it is well known that the introduction of self-compacting concrete (SCC) has improved both the concrete technology and the working safety and health conditions due to the removal of mechanical compaction in the construction sites [11–15].

The present work falls within the framework of circular economy strategy, one of the main ambitions of Europe, which wants to move towards a recycling society with a high level of resource efficiency. The art. 11.2 of the Waste Framework Directive (2008/98/EC) [16] stipulates that "(EU) member States shall take the necessary measures designed to achieve that by 2020 a minimum of 70% (by weight) of non-hazardous construction and demolition waste shall be prepared for re-use, recycled or undergo other material recovery". Although the level of recycling and material recovery of C&DW varies greatly in Europe, the effort to strengthen the concept of sustainability in civil constructions needs to be pursued not only preparing recycled conglomerates suitable for low cost operations such as backfilling and embankments, but also developing innovative recycled aggregate concrete that can be exploited for structural applications.

SCC prepared with recycled concrete aggregate has not been extensively studied yet. In particular, in the last few years some researches have been made using C&DW in SCC [17–36], particularly with coarse recycled concrete aggregates [18–21,23–27,30,3

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3,35,36], thus showing a great interest toward this topic, but there are no data on the long-term behavior of SCC with C&DW. On the contrary, some studies are present on the long-term properties of structural concrete with C&DW [3,4,37–43]. The study of the time-dependent properties is a key factor that can greatly influence the real utilization of the SCC in terms of durability and needs to be deeply investigated.

Following a previous research where the long-term behavior of structural concrete containing coarse and fine and C&DW was studied [3], the aim of this work is to extend the study to the long-term properties of SCC replacing both coarse and fine natural aggregates with recycled ones. Accordingly, the effects of different formulations are studied in relation to the SCC properties at both fresh and hardened states to determine the practicability of SCC with good mechanical resistance.

Comparing this research with the most recent state of the art of the use of C&DW in SCC, the important issues highlighted in this paper are (i) the evaluation of the contemporary use of both fine and coarse concrete recycled aggregates on fresh behavior; (ii) the mechanical characterization at long-term (i.e., shrinkage and creep); (iii) the integrated approach involving microstructure-physical-mechanical parameters in explaining the strengthening mechanisms occurring in the new mixes; (iv) the comparison with traditional concrete prepared with the same C&DW.

As in the previous work [3,4,44,45], the recycled concrete aggregate hail from the destruction of a never completed concrete construction in Italy (e.g., buildings of Punta Perotti, Bari, Italy) where masonry and gypsum were totally absent, thus constituting an adequate selection for the reuse of medium-high compressive strength concrete in new structures. C&DW was suitably crushed and combined with appropriate grain size distributions to obtain structural SCC.

Three SCC mixes were designed with an amount of C&DW varying from 25 to 40% of total volume of aggregates in substitution of natural coarse and fine aggregates. With the aim of a complete characterization of the long-term properties of the SCC mixes, the time-dependent properties such as shrinkage and creep were studied and associated with the other essential properties of the SCC materials such as the characteristic at the fresh state, as well as the physical and mechanical properties and the porosity measurements (total porosity and pore size distribution). For comparison, the same characterizations were performed on a reference SCC mix, prepared with 100% natural aggregates.

2. Experimental investigation

2.1. Materials

Cement type CEM II-A/LL 42.5R, in accordance with EN 197-1 [46], and calcium carbonate with an average grain size of 7.5 µm, were used as binder and filler, respectively. An acrylic based superplasticizer and a biopolymer based viscosity modifying agent were used as admixtures in all the SCC mixes.

As natural aggregates (*N*, Fig. 1), sand (*N0-6*, 0–6 mm) and gravel (*N6-16*, 6–16 mm) (Cave Pederzoli, Bologna, Italy) were used. Following previous studies [3,4,44,45], a cumulative grain size distribution curve (called *NA16*) was prepared according to Fuller distribution, setting the aggregate maximum diameter equal to 16 mm: it was made of *N0-6* at 60 vol% and *N6-16* at 40 vol% (Fig. 1).

As recycled aggregates (*R*, Fig. 1), C&DW of good mechanical quality coming from the demolition of an Italian concrete building started in 1995 and never finished was used (2006, Bari, Italy) [3]. Concrete cores extracted form the original construction showed a compressive strength of about 36 MPa.

After demolition, a large part of the concrete waste was disposed to landfill and the University of Bologna collected a part of it for scientific purpose [3,4,44,45], after on-site crashing procedure and steel detachment. Hereinafter, further crushing procedures were made in the laboratory to produce three different fractions (Figs. 1 and 2) named as *R0-4* (0–4 mm), *R4-8* (4–8 mm) and *R8-16* (8–16 mm).

In order to obtain a cumulative grain size distribution curve of aggregate similar to that one of *NA16*, 47 vol% of *R0-4* + 21 vol% of *R4-8* + 32 vol% of *R8-16* were mixed. The resulting grain size distribution was named *RA16* (Fig. 1).

Table 1 reports the physical properties of natural and recycled aggregates, determined according to EN 1097-6 [47]: dry bulk density (ρ_{rd}), saturated surface-dried density (ρ_{ssd}) and water absorption (*WA*). *R* aggregates present dry bulk density values lower than *N* aggregates and, correspondingly higher values of water absorption, according to previous studies [3,4,44,45]. In particular, *R0-4* fraction shows the lowest values of dry bulk density (i.e., 2.1 g/cm^3) and similarly the highest values of *WA* (i.e., 10%).

2.2. Concrete samples preparation

Three new SCC mixes were studied starting from a reference mix-design (named *R0*) with 100% of natural aggregates following the cumulative grain size distribution curve named *NA16* (Fig. 1) and varying the amount of recycled aggregates between 25 and 40 vol% over the total content of aggregates (Table 2).

A concrete mix, named *R25,* was obtained substituting 25 vol% of natural aggregates (coarse and fine) with recycled aggregates. *R25* contains 45 vol% of *N0-6*, 30 vol% of *N6-16*, 12 vol% of *R0-4*, 5 vol% of *R4-8* and 8 vol% of *R8-16*.

Two different mixes were obtained substituting 40 vol% of natural aggregates. In the mix named *R40* both coarse and fine natural aggregates were partially substituted with recycled aggregates. *R40* contains 36 vol% of *N0-6*, 24 vol% of *N6-16*, 19 vol% of *R0-4*, 8 vol% of *R4-8* and 13 vol% of *R8-16*.

In the mix named *CR100* the total volume of gravel (i.e., *N6-16*) was replaced by the two fractions *R4-8* and *R8-16* of recycled aggregates. Thus, *CR100* contains 60 vol% of *N0-6*, 16 vol% of *R4-8* and 24 vol% of *R8-16*.

Table 3 shows the investigated mixes. For all the SCC formulations, cement content (350 kg/m^3), filler content (220 kg/m^3), D_{max} (16 mm) and viscosity modifying agent were kept constant. Similar water/cement (*w/c*) ratio (i.e., 0.50 ± 0.01) and superplasticizer amount (i.e., 1.1 ± 0.1%) were utilized for all the SCC formulations. The small increase in the superplasticizer amount of both *R25* and *R40*, compared to *R0*, compensates for their lower water content (i.e., 172 instead of 179 kg/m^3). For this reason, fresh state results are comparable.

All aggregates were utilized in wet condition and their total moisture content was directly established before the mixing procedure: the surface/free moisture value was obtained by subtracting from the total moisture the moisture in saturated-surface dry condition. SCC is more easily influenced by the initial humidity of aggregates than traditional concrete [48,49]. Even if the water content of the aggregates is compensated in all the mixes, different initial aggregates humidity, as well as the real amount of water compensated in every mix, can contribute to a change of the fresh state behavior of the SCC mixes. For this reason, in this study the initial humidity of the aggregates was the same for all the mixes. In particular, aggregates (both natural and recycled ones) were previously treated in order to have wet condition almost identical to their ssd condition, with the only exception of natural sand that was stoked in sealed plastic bags at an almost constant humidity of 6%. For this reason in each mix the water was adjusted by decreasing its amount.

The SCC mixes were obtained by using a laboratory concrete mixer (190 L volume) introducing gravel and sand. After 5 min of mixing, cement, water (75%), superplasticizer and viscosity modifying agent with the remaining water (25%) were introduced and mixed for further 3 min.

2.3. Concrete samples characterization

In the fresh state, the slump-flow (*SF*) and the flow rate (t_{500}) when the concrete has flowed to a diameter of 500 mm were determined according to EN 12350-8 [50]. A visual observation of the slump-flow diameters at the end of the flowing was made to verify the uniform distribution of the particles, the lack of segregation, and confirm the SCC behavior of the mixes.

The J-ring test (SF_J) was used to assess the passing ability of SCC to flow through tight opening, according to EN 12350-12 [51]. The bulk density in the fresh state was determined by mass/volume ratio (*M/V*), according to EN 12350-6 [52].

For physical and mechanical tests, 16 cylindrical concrete samples (diameter: 12 cm, height: 24 cm) as well as 2 prisms (10 × 10 × 40 cm) and 2 cubic samples (15 × 15 × 15 cm) were obtained for each formulation. Samples were cured for 28 days at 20 ± 1 °C and R.H. > 95%. Bulk density (*D*) and water absorption (w_a) at atmospheric pressure were obtained in accordance with UNI 7699 [53] on 2 cubic concrete samples.

Concrete strength tests were determined by means of a 4000 kN universal testing machine. Compressive strength (f_{cm}) was obtained in accordance with EN 12390-3 [54] on 4 concrete cylindrical samples for every mix after 5 (f_{cm}@5 d) and 28 (f_{cm}@28 d) days of curing. Secant elastic modulus (*E*) was measured in accordance with UNI 6556 [55], tensile splitting strength (f_{ct}) was determined in accordance with EN 12390-6 [56], and three-point flexural strength (f_{cf}) was determined in accordance with EN 12390-5 [57]: two concrete cylindrical samples were used per mix for every test, in accordance with previous work [3].

The pore size distribution of samples obtained from concrete cylinders after 28 days of curing (about 1 cm^3) was studied by mercury intrusion porosimeter (MIP, Carlo Erba 2000), equipped with a macropore unit (Fisons 120). Before MIP test, porosimeter samples were investigated by optical microscopy to confirm that they were characteristic of the cement mortar around coarse aggregates.