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Compressive strength and hydration processes of concrete with recycled aggregates

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ABSTRACT

This paper deals with the correlation between the time evolution of the degree of hydration and the compressive strength of Recycled Aggregate Concrete (RAC) for different water to cement ratios and initial moisture conditions of the Recycled Concrete Aggregates (RCAs). Particularly, the influence of such moisture conditions is investigated by monitoring the hydration process and determining the compressive strength development of fully dry or fully saturated recycled aggregates in four RAC mixtures. Hydration processes are monitored via temperature measurements in hardening concrete samples and the time evolution of the degree of hydration is determined through a 1D hydration and heat flow model. The effect of the initial moisture condition of RCAs employed in the considered concrete mixtures clearly emerges from this study. In fact, a novel conceptual method is proposed to predict the compressive strength of RAC-systems, from the initial mixture parameters and the hardening conditions.

1. Introduction

It is commonly known that the construction sector is characterised by a significant demand for both energy and raw materials [1]. Moreover, recent research highlighted that the concrete industries' share to green-house gas emissions is about 10% of its global production [2] and almost half of it can be directly or indirectly related to the production of cement [3]. Therefore, initiatives that aim at reducing the sectors' enormous demand for energy and raw materials [4] should be developed and implemented massively, in order to enhance the sectors' sustainability perspective. Developments such as the possibility to pre-design structures for "deconstructing" or to reuse Construction and Demolition Waste (CDW) [5] are nowadays pursued with the same objective. As a matter of fact, due to the significant volumes of concrete produced each year, developments that aim at reusing recycled constituents, such as aggregates, fibres or binders, are rapidly emerging. Particularly, partial replacement of the "natural" raw materials or substitution of regular Portland cement with lower CO_2 impact supplementary cementitious materials are gaining interest to reduce of the environmental footprint of the building industry [6].

Moving forward from these initial considerations and keeping in mind the guidelines about future recycling objectives recently issued by the European Union [7], a wide experimental activity was carried out at the Laboratory of Materials testing and Structures (LMS) of the University of Salerno (Italy) [8]. Part of this experimental activity is intended at observing the hydration process [9] that takes place during the hardening phase of four Recycled Aggregate Concrete (RAC) mixtures characterised by a different degree of saturation of the Recycled Concrete Aggregates (RCAs). In fact, it is widely recognised that one of the key issues of using recycled aggregates in concrete is basically related to the higher water absorption capacity of such aggregates with respect to the corresponding natural materials generally used for concrete production [10]. Thus, a higher amount of water possibly absorbed by RCAs during mixing is supposed to affect the actual values of water/cement ratio and, then, to have its consequences on both the cement hydration process and the final mechanical properties of RAC systems.

Beyond the mainly empirical investigations generally carried out to observe the possible influence of recycled constituents on the mechanical behaviour of concretes [11] and mortars [12], this paper proposes a more fundamental approach by investigating the evolution of the hydration processes and its potential correlation with the compressive strength for the four concrete mixtures under consideration.

To this end, the four different RAC mixtures that are tested in compression at different isothermal curing ages are described in Section 2. Moreover, one sample of each mixture was monitored during the first week of curing to measure the time evolution of temperature developing inside the concrete as a result of the exothermic cement hydration reaction. Particularly, temperatures were measured on a 15-cm-edge

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cubic sample of concrete poured in an insulating plastic box which realised semi-adiabatic conditions for the cement hydration reactions.

Section 3 reports the main experimental results in terms of both time evolution of temperatures and average compressive strength developed in cubic specimens tested at different curing ages ranging from 2 to 28 days. The temperature measurements obtained under the aforementioned semi-adiabatic conditions were intended to be employed for identifying a theoretical model, able to simulate the heat production and the time evolution of the degree of hydration in the cured concrete samples [14].

Section 4 outlines the theoretical basis of such a model and gives full attention to the theoretical assumptions on which it is based. It shows the relationship between the heat production of the hydration reactions and defines the "degree of reaction" and the "degree of hydration" [15] concepts.

It may be worth to mention that this research is finally aiming at obtaining a quantitative relationship between the evolution of the degree of hydration and the compressive strength for the concrete mixes under consideration. As a matter of fact, similar relationships were already found for ordinary concrete mixes, with ordinary natural aggregates [16,23–25]. This study aims at generalising such relationships by taking into account the influence of both water/cement ratio and the initial moisture conditions of recycled aggregates. In this regard, Section 5 describes the linear correlations emerged between the degree of hydration and the average compressive strength for the four concrete mixtures investigated. The regular variation of such correlations, which are clearly affected by the nominal water/cement ratio and the initial moisture conditions of RCAs, is the main finding of this paper and outlines the conceptual approach for predicting the compressive strength of RAC for different mix parameters and moisture conditions.

2. Materials and methods

The two following subsections describe the materials employed for producing the test specimens and the experimental methods carried out this study.

2.1. Materials

Four different concrete mixtures with a 30% recycled aggregate replacement are considered in the present study with emphasis on the relationship between the compressive strength development and the corresponding time evolution of the degree of hydration. Two key parameters, i.e. the water to cement ratio and the initial moisture condition of the recycled aggregates, are considered in this study and their impact on the final concrete quality is investigated. Particularly, their influence on both the hydration reaction and the evolution of the compressive strength of concretes made with recycled aggregates is investigated. Therefore, two mixtures are designed with a different nominal water/cement ratio, i.e. 0.45 and 0.60. Moreover, for the recycled aggregates two different initial moisture conditions were realised, according to the two following definitions:

- Dry condition (DRY): the coarse aggregates are dried for 24 h in an oven with a constant temperature of 100 °C;
- Saturated condition (SAT): the coarse aggregates are saturated for 24 h in water and, before mixing, their surface was dried with a cloth.

As a matter of fact, natural aggregates used in ordinary concretes are generally characterised by a low water absorption capacity and their corresponding portion of "absorbed water" can easily be accounted for in the concrete mix design. On the contrary, a higher water absorption capacity of RCAs clearly depends on their production process [17]. Particularly, internal damage and cracks, due to demolition and crushing, result in a non-negligible influence of RCAs water absorption capacity on the concrete mix performance, in both the fresh state (in terms of actual workability and rheological properties) and the hardened one (in terms of mechanical properties) [10,13]. The processing of the RCAs as considered in this study has led to the following ranges of the grain sizes:

- N3, nominal size 20–31.5 mm;
- N2, nominal size 10–20 mm;
- N1, nominal size 4–10 mm;
- Sand, nominal size small than 4 mm.

Table 1 describes the actual composition of the four concrete mixtures characterised by the two aforementioned values of the nominal water-to-cement ratios and the two initial moisture conditions. The amount of RCAs is kept constant to 30% of the total amount of aggregates, with a distribution over the different fractions, i.e. a total replacement of the coarse fraction, a partial replacement of the finer fraction, and no replacement of sand.

The volume of water absorbed by the saturated aggregates is not included in the calculation of the w/c ratio. The absorbed volumes are estimated by considering the amount of the various aggregate fractions and their respective water absorption capacity, which was determined on both the natural and recycled aggregates [8]. Table 1 reports the amounts of water absorbed by recycled aggregate in saturated conditions, apart from the regular mixing water.

Finally, a common Portland cement, type CEM I 42.5 R [19], was used as a binder in all concrete mixes.

2.2. Experimental methods

For all four tested concrete mixtures, the hydration process was monitored by measuring the temperature evolution in the centre of a concrete cube during the first seven days after casting. To this end, a cubic sample of each concrete mix was cured in semi-adiabatic conditions with the aim of measuring the temperature evolution and to use this data as input for the proposed simulation model to calculate the hydration process. For this purpose, such a concrete sample was cast within an insulated mould with a rib size of 150 mm (Fig. 1). Four out of the six side planes of the cubic sample bordered with a thick layer (about 100 mm) of insulation material, whereas two planes were insulated with a significantly thinner layer (of about 40 mm). Therefore, the heat produced by the hydration reaction was supposed to be mainly dissipated through the two faces bordering with the thinner layers of insulation material. Since these two faces are placed opposite from each other (namely, the top and bottom of the system depicted in Fig. 1) a

Table 1
Key parameters about concrete mixes.

Mix	CEM I [kg/m^3]	Mixing water [l/m^3]	Absorbed water [l/m^3]	w/c	Recycled concrete aggregates [kg/m^3]		Natural aggregates [kg/m^3]		
					N3	N2	N2	N1	Sand
0.45DRY	410	185	0	0.45	400	100	300	130	760
0.45SAT	410	185	21	0.45	400	100	300	130	760
0.60DRY	310	185	0	0.60	400	100	300	130	850
0.60SAT	310	185	22	0.60	400	100	300	130	850