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A novel mix design methodology for Recycled Aggregate Concrete

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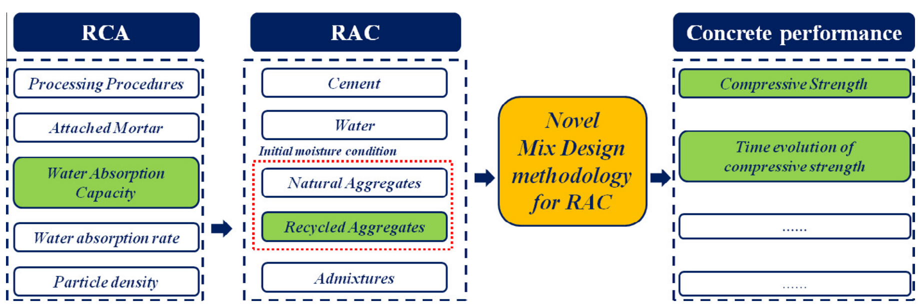
HIGHLIGHTS

- Recycled Concrete Aggregates (RCAs) are more porous because of Attached Mortar (AM).
- AM influences the key properties of RCAs, among which water absorption capacity.
- AM of RCAs influences the strength of Recycled Aggregate Concretes (RACs).
- The proposed methodology predicts the RAC strength by considering the key properties of RCAs.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper proposes a conceptual formulation for predicting and controlling the compressive strength of Recycled Aggregate Concrete (RAC) mixtures, by explicitly taking into account the specific features of Recycled Concrete Aggregates (RCAs). In fact, since RCAs are significantly more porous than Natural Aggregates (NAs), the mix design rules commonly employed for ordinary structural concrete cannot be applied as such for RACs. Therefore, the formulation proposed herein is intended at generalising the aforementioned rules with the aim to take into account the higher porosity of RCAs. Although being a mainly conceptual methodology, the proposed formulation is supported by a wide set of experimental results: they unveil the influence of several aspects and parameters (such as source and processing procedures of RCAs, aggregate replacement ratio, water-to-cement ratio, water absorption capacity and initial moisture condition of aggregates) on the resulting compressive strength of RAC. Finally, the proposed mix design methodology demonstrates that the resulting compressive strength of RACs can be predicted by taking into account only one parameter (i.e., water absorption capacity) identifying the "quality" of RCAs. Further generalisations intended at controlling other physical and mechanical parameters of RAC are among the future development of this research.

1. Introduction

The construction sector is characterised by a significant demand for both energy and raw materials [1]. Hence, the European Union has recently adopted a policy intended at promoting the use of Construction and Demolition Waste (up to 70%, by weight, for 2020) [2] with the twofold aim of reducing the demand for natural sources and minimising the environmental impact of concrete industry [3,4].

Therefore, several studies have been recently proposed for understanding the behaviour of concrete made with different types of recycled aggregates [5–9], and, among them, a clear focus was placed on using aggregates derived from the demolition of

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Notations

RCAs	Recycled Concrete Aggregates
NAs	Natural Aggregates
RACs	Recycled Aggregate Concretes
NAT	concrete made out with only natural aggregates
AM	Attached Mortar
DRY	oven-dried moisture condition for coarse aggregates
SAT	saturated surface dry moisture condition for coarse aggregates
α	degree of hydration
R_c	cubic compressive strength [MPa]
α_0	minimum value of the degree of hydration for $R_c \neq 0$
$R_{c,max}$	maximum R_c, ideally corresponding to the degree of hydration equal to 1 [MPa]
$\alpha_{0,NAT}$	α_0 for NAT mixture
$R_{c,max,NAT}$	$R_{c,max}$ for NAT mixture [MPa]
P	open porosity [%]
p_{NA}	open porosity of a natural aggregate [%]
p_{AM}	open porosity of the attached mortar[%]
D	nominal diameter of aggregate [mm]
$p_{t=0}$	open porosity for RCAs processed with autogenous cleaning time equal to 0 [%]
$p(t)$	open porosity for RCAs processed with autogenous cleaning time equal to t [%]
$Abs(t)$	amount of absorbed water for aggregates in a certain time "t" [%]
C	Portland cement content [kg]
w/c	water-to-cement ratio
$(w/c)_{eff}$	effective water-to-cement ratio
w_{add}	added water in the mix for (partially or totally) saturate the aggregates [kg]
δ	parameter that takes into account of the initial moisture condition of the aggregates
P_i	weight in the mixture of the ith aggregates fraction [kg]
V_i	volumetric fraction of the ith aggregates class respect to the total volume of the coarse aggregates [%].
A_{MIX}	average porosity of the coarse aggregates employed in the mix [%]
A_{NAT}	average porosity of the coarse aggregates employed in the mix made with only NAs [%]
r^*	correction factor for $R_{c,max}$
α^*	correction factor for α_0
α_{max}	maximum degree of hydration
a; b	numerical values for Eq. (2)
k_1; k_2	numerical values for Eq. (3)
β	numerical value for Eq. (4)
a_R; b_R	numerical values for Eq. (10)
a_α; b_α	numerical values for Eq. (11)
A_R; B_R	numerical values for Eq. (12)
A_α; B_α	numerical values for Eq. (13)

concrete members and structures: the latter are usually referred to as Recycled Concrete Aggregates (RCAs) [10–13]. As a matter of fact, huge amounts of waste concrete derive from various activities, such as construction and rehabilitation actions, demolitions, concrete production and testing laboratories [9].

Recycling these waste materials is a viable solution for contributing to make construction activities more sustainable [14–16]. However, the definition of reliable relationships capable of predicting the relevant properties of concrete made out of these non-conventional constituents, often referred to as Recycled Aggregates Concrete (RAC), is still considered as an open issue in concrete technology [17,18]. This is mainly to the lack of knowledge about the peculiar properties of RCAs [19,20] and their consequences on the resulting mechanical performance of RAC [21,22].

As a matter of fact, RCAs can be regarded as a two-phase composite made of "original" Natural coarse Aggregates (NAs) and the adhering mortar (made of sand, hydration products and fractions of un-hydrated cement), the latter being generally referred to as Attached Mortar (AM) [23]. Several studies highlight that RCAs are significantly more porous than NAs [9,13,16]: this higher porosity is due to AM, which is characterised by micro cracks and pores that are accessible by water [24,25].

The actual porosity of RCAs depends on two variables: the composition of the original concrete and the processing procedure adopted for transforming concrete debris into recycled concrete aggregates [26]. The presence of a constituent characterised by a higher porosity has a twofold influence on the strength of RAC. On the one hand, higher porosity of RCAs results in higher water absorption capacity of aggregates, which affects the actual water-to-cement ratio [27] and, on the other hand, a porous constituent represents the weak "link" within the solid skeleton of the cementitious composite matrix [28–33]. Although plenty of studies have been devoted to characterising the properties of RCAs and investigating the mechanical performance of RACs, only few dedicated mix design procedures are currently available in the literature for concretes with recycled aggregates [34].

This paper proposes a rational mix design methodology for RACs (produced with RCAs derived both from demolished concrete structures and crushed concrete samples already tested in laboratory). Although being a conceptual formulation, it is based upon a significant number of experimental results intended at unveiling the correlations between the aforementioned properties of aggregates and the key phenomena (such as cement hydration) controlling the concrete strength. Section 2 describes the experimental procedures implemented for both characterising RCAs and unveiling the consequences of using them in concrete mixtures. The results of these tests, reported and analysed in Section 3, are the bases for the proposed conceptual mix design procedure, which is presented in Section 4.

Finally, taking explicitly into account the effects of the physical properties of RCAs (i.e. water absorption capacity and, indirectly, open porosity and attached mortar) on the resulting compressive strength is the main original contribution and novel aspect of the aforementioned mix design methodology. However, it is worth highlighting that the specific calibrations mentioned in this paper are restricted to the parametric field actually explored in the proposed experimental tests (i.e. they refer to concrete mixtures with CEM I type of cement) and, hence, further experimental activities are needed for extending this conceptual methodology to a wider class of concretes.

2. Materials and methods

2.1. Materials

2.1.1. Aggregates

According to ASTM C33 [35], three different size ranges were considered for aggregates: sand (nominal diameter smaller than 4.75 mm), coarse class 1 (C1, nominal diameter ranging between 4.75 mm and 9.5 mm) and coarse class 2 (C2, nominal diameter ranging between 9.5 and 19 mm). It is worth highlighting that only natural sand derived from cracking calcite limestone rocks is employed in this study. This is because, as it is well-known [36], fine aggregates obtained from recycled demolished concrete are too porous and do not seem appropriate for use in structural concrete. Conversely, both NAs and RCAs were employed as coarse aggregates.