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Enhancing mechanical and durability properties of recycled aggregate concrete

George Dimitriou, Pericles Savva *, Michael F. Petrou

[a] Department of Civil and Environmental Engineering, University of Cyprus, 75 Kallipoleos Av., P.O. Box 20537, 1678 Nicosia, Cyprus

HIGHLIGHTS

- Different methods were used to improve the quality of recycled aggregate concrete.
- A treatment method was applied on recycled aggregates to remove adhered mortar.
- Treated and non-treated recycled aggregate mixtures were compared with Control.
- Mineral admixtures were employed to improve recycled aggregate concrete quality.
- Internal curing methodology was tested using recycled aggregates.
- Recycled aggregate concrete quality was improved using the proposed methodologies.

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ABSTRACT

The main difference between Recycled Concrete Aggregate (RCA) and Natural Aggregate (NA) is the mortar adhered on RCA. This paper presents the effect of RCA to concrete and a treatment method utilized to improve the properties of RCA, by reducing the amount of the adhered mortar, and therefore the properties of the Recycled Aggregate Concrete (RAC). Mineral admixtures were used as partial replacement of cement. Three types of coarse RCA and two types of mineral admixtures were used (fly ash and silica fume). In addition, the RCA were employed as internal curing (IC) agents in concrete mixtures to assess their effectiveness in enhancing the properties of concrete. The mechanical properties and durability of RAC were improved using the proposed methodologies. Cost analysis showed that RAC mixtures could be less expensive than NA mixtures.

1. Introduction

According to the World Commission on Environment and Development (WCED), "sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. When considering the total amount of natural resources in a large scale, in Europe for example, the exploitation of resources might not be as significant as in a smaller scale, in Cyprus for instance, where the increased exploitation may reduce the resources to a crucial level, due to country's small size, compromising the needs of the following generations.

There is a significant research activity regarding the mechanical performance of recycled aggregate concrete (RAC) which shows that the strength of RAC is adequate for use as structural concrete. On the contrary, the replacement percentage of natural aggregates with recycled aggregates and the durability properties of RAC are still under investigation, since a wide variability in the results is reported [2]. In fact, the durability properties are still under examination and so the RCA are mainly used for secondary level construction activities, as road base and landfilling materials [3,4].

The microstructure of RAC is much more complicated than that of conventional concrete since it includes two kinds of interfacial transition zones, one between the RCA and the new mortar and a second one between the RCA and the adhered mortar. The old mortar includes many micro-cracks, formed during RCA production, and has high porosity [5], thus it becomes the weakest link in RAC and its strength is the upper limit of the strength of concrete. As the mortar-aggregate bond strength increases, the concrete

* Corresponding author.
E-mail addresses: dimitriou.georgios@ucy.ac.cy (G. Dimitriou), savva.pericles@ucy.ac.cy (P. Savva), petrou@ucy.ac.cy (M.F. Petrou).

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strength also increases [6,7]. RAC is weaker than Natural Aggregate (NA) concrete and its failure occurs through the aggregates themselves (including the old interfacial transition zone (ITZ)) instead of the new ITZ [8,9] similarly to the high strength concrete [3,5]. The presence of the adhered mortar is significant since recycled aggregates consist of 65–70% by volume of natural coarse aggregate and 30–35% by volume of old cement paste [7]. In order to enhance the properties of RCA, it is fundamental to elaborate a treatment method that is capable to remove the adhered mortar at such level that diminishes the negative effects.

In general, RCA are of lower quality than NA. RCA have higher water absorption values and lower densities. The water absorption of RCA ranges from 3 to 15% [3,7]. The presence of the mortar lowers the density values of the recycled aggregates (2200–2400 kg/m^3) [7]. Furthermore, the resistance to fragmentation is lower and their texture is more porous, rough and irregular due to crushing of the old concrete.

The lower quality aggregates have an immediate effect on the quality of the hardened concrete. The increase of the replacement ratio of RCA decreases the compressive strength of RAC. Generally, the compressive strength can be 10–25% lower than conventional for 100% replacement. Etxeberria et al. reported losses of 20–25% for 100% replacement, maintaining the same effective w/c ratio (0.50) and the same cement content [8]. However, the use of 20–30% RCA produces no significant changes with respect to the Control mixture with 0% RCA [8,10]. There is a drop of 10–35% of the splitting tensile strength using 100% RCA [5]. Tabsh and Abdelfatah found a 10–35% drop in tensile strength [11]. During the determination of splitting tensile strength, many researchers concluded that the failure initiated not only from the interfaces between the recycled aggregates and the mortar but also from the recycled aggregates themselves [5]. Regarding the modulus of elasticity, Chakradhara Rao et al. found a reduction of 34.8% using 100% RCA compared to the Control concrete [12]. Xiao et al. noticed a reduction up to 45% for modulus of elasticity with 100% replacement of RCA [5].

The durability properties of RAC deteriorate, at a higher rate than the mechanical properties, with the increase of RCA content. Thomas et al. noted that the open porosity of RAC increases with w/c ratio and the degree of replacement and concluded that a 20% replacement of NA with RCA decreases the density value around 5% compared to Control concrete [10]. Kou and Poon found 9.5% lower resistance to chloride permeability for a 100% RCA mixture [13]. Chakradhara Rao et al. reported 7.37% water absorption for concrete with 100% RCA and 6.54% for concrete with 50% RCA [12]. The open porosity, sorptivity and rapid chloride permeability (RCP) test values of RAC reached their maximum when percentage of natural aggregates replacement was 100% [14].

The use of fly ash and silica fume (or microsilica), creates some minor negative effects on the mechanical properties of the concrete but it improves substantially its durability properties. The use of fly ash reduces the permeability and improves the workability of RAC. Silica fume, due to its small size and its large surface area, improves the microstructure of concrete, creating a denser matrix. Although fly ash and silica fume have some drawbacks, such as reduced early strength and increased water demand, the synergistic effect using both mineral admixtures as cement replacements is important and beneficial [15].

The objective of this research is to determine whether a concrete mixture design incorporating RCA as replacement of NA and mineral admixtures as partial replacement of cement is able to achieve an adequate performance for structural applications. RCA are subjected to a treatment method to reduce the amount of the adhered mortar and improve their properties. In addition, RCA are utilized in concrete mixtures as internal curing (IC) agents in order to evaluate whether the material's performance could be further enhanced. Apart from the mechanical and durability properties, the economic aspects of the RAC are of equal importance and a comparison of NA with RCA is presented. The potential environmental and economic benefits could ameliorate RAC image to the public and boost its usage.

2. Experimental program

2.1. Materials and testing methods

The aggregates were subjected to a thermal treatment method as described, in detail, in Sánchez de Juan and Gutiérrez [16] in order to quantify the amount of adhered mortar. This method contains several cycles of high temperatures (500 °C) and soaking in water. The thermal method was selected as it can be used for all types of aggregates (including limestone), it is more consistent and it is easier to perform. It also proved to be the most effective method with lower variability compared to other methods [17].

Both mechanical and durability properties were determined according to international standards. The coarse aggregates were evaluated according to their resistance to fragmentation (EN 1097-2 [18]), weathering properties (EN 1367-2 [19]), absorption and density (EN 1097-6 [20]). The RAC mixtures were evaluated according to their compressive strength (EN12390-3 [21]), flexural (EN 12390-5 [21]) and splitting tensile strength (EN 12390-6 [21]), modulus of elasticity (ASTM C 469 [22]), rapid chloride permeability (ASTM C 1202 [23]), sorptivity (Capillary absorption [24]) and porosity (Open porosity [24]).

2.2. Concrete constituents

Four types of coarse aggregates were used in this research, namely three RCAs and one diabase NA. The RCAs tested are:

- RCA-L (laboratory) aggregates from crushed good quality laboratory concrete which represent the best-case scenario of RCA.
- RCA-F (field) aggregates from crushed field concrete coming from different sources, provided by a local supplier which represent the worst case scenario.
- RCA-T (treated), aggregates from crushed field concrete (same as RCA-F) that were subjected to a treatment method to remove the adhered mortar.

Coarse NA were used, with nominal sizes 4/10 mm and 8/20 mm. Only natural fine aggregates were used in all mixtures. The water used was drinkable tap water from the laboratory. All mixtures contained a superplasticizer. Three binders were used: ordinary portland cement, CEM I 42.5R, as the main binder, silica fume and fly ash as partial replacements of cement. Binders' properties are presented in Table 1.

2.2.1. Treatment method of RCA

A customized low-cost simple treatment method was utilized by Skyrra Vassas Ltd, a local NA and RCA supplier, on some of the field recycled aggregates in order to remove part of the adhered mortar. RCA-F aggregates were placed into an 8 m^3 modified concrete mixer (Fig. 1). The mixer was rotated at a speed of 10 rpm for 5 h. During this process water was added in order to remove the smaller particles, dust and the weaker adhering mortar. At the end of the treatment period, the aggregates were sieved through a modified sieve in order to discard aggregates with sizes lower than 4 mm. The final product was named RCA-T and exhibited substantially better properties, as it is described in the following sections.

2.3. Concrete mixtures

A total of 12 mixtures were cast. The mixture design is presented in Table 2. The same mixture design was adopted for all mixtures. The effective w/c ratio was kept constant at 0.48. All aggregates and cement replacements were made by weight and the design method used in this study was the Direct Weight Replacement (DWR) method, which has been used extensively throughout the literature, mainly because of its simplicity.

Table 1
Constituents of binders.

Property	Fly Ash	Silica Fume	Portland Cement
SiO_2 content, %	40	85–97	21
Al_2O_3 content, %	17	–	5
Fe_2O_3 content, %	6	–	3
CaO content, %	24	<1	62
Surface area, m^2/kg	420	15,000–30,000	370
Specific gravity	2.38	2.22	3.15