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Enhancing mechanical and durability properties of recycled aggregate concrete

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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

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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

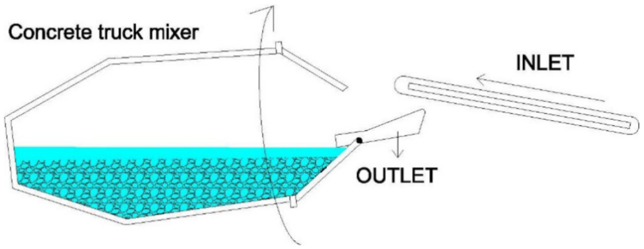

Fig. 1. Modified concrete mixer for RCA treatment.

Table 2
Mixture proportions.

Constituents	Quantity (kg/m^3)
Cement	400
Water	192
Coarse Aggregates 8/20 mm	655
Coarse Aggregates 4/10 mm	264
Sand 1 (natural sand) 0/4 mm	559
Sand 2 (extra fine limestone)	108
Superplasticizer	6.4

Two series of mixtures were cast. In the first series, of seven mixtures, there is a replacement of NA with different types of RCA while in the second series, of four mixtures, there is additionally a replacement of portland cement with mineral admixtures. The second series' specimens were also tested at 56 days due to the presence of mineral admixtures. For the mixtures without mineral admixtures, the 28-day period of curing was considered adequate. The replacement ratios of the mixtures are presented in Table 3. The code names of each mixture consist of "R" for RCA, "L" for laboratory, "F" for field, "T" for treated, "100″ or "50" represent the replacement percentage of NA, "F" for fly ash, "S" for silica fume, "25" and "5" represent the percentage replacement of portland cement, "cs" for the same amount of superplasticizer used in the Control mixture, "ps" for pre-soaked aggregates. Cubes of 100 mm were used to determine the compressive strength, the sorptivity and the porosity. Cylinders $\Phi 100 \times 200$ mm were used to determine the rapid chloride permeability, while the $\Phi 150 \times 300$ mm cylinders were used to determine the splitting tensile strength and the modulus of elasticity. Prisms $100 \times 100 \times 500$ mm were used to determine the flexural tensile strength.

2.4. Casting and curing

Concrete mixtures were prepared using a planetary mixer available in the Laboratory of Civil and Environmental Engineering, University of Cyprus. Aggregates were in air-dried condition (except for RF100ps mixture) and the proper water corrections were made, according to aggregates' moisture and absorption values. Slump tests were performed with a slump target of 200 ± 30 mm, aiming to create a relatively fluid and workable concrete. The desired slump was achieved by adjusting the amount of superplasticizer added in the concrete mixture. The vibration on a vibrating table was applied consistently and quite carefully to avoid segregation. The samples were removed from the molds after 24 h and were placed in water tanks at a constant temperature of 21 °C.

Table 3
Mixture design with replacement ratios.

	Mixtures	Replacement ratio of coarse aggregates	Type of aggregate	Fly Ash	Silica fume
Series 1	Control	0%	Natural	–	–
	RL100	100%	RCA-L	–	–
	RF100cs	100%	RCA-F	–	–
	RF100ps	100%	RCA-F	–	–
	RF100	100%	RCA-F	–	–
	RT100	100%	RCA-T	–	–
	RF50	50%	RCA-F	–	–
	RT50	50%	RCA-T	–	–
Series 2	RF100F25	100%	RCA-F	25%	0%
	RF100F25S5	100%	RCA-F	25%	5%
	RT100F25	100%	RCA-T	25%	0%
	RT100F25S5	100%	RCA-T	25%	5%

3. Experimental results and discussion

The test results are discussed in the following sections with an emphasis on the mechanical and durability properties of hardened concrete but also on the effect of the treatment method on aggregates.

3.1. Properties of aggregates

The mechanical and physical properties of the four types of aggregates used for this research are presented in Table 4.

NA in Cyprus present higher absorption values, reaching up to 4.5% [14] and thus the 2.5% is considered low. The RCA-T aggregates had much lower absorption values, compared to RCA-F and RCA-L (around 50%). From the tests performed on aggregates it is clear that:

- The density and absorption values are related to the amount of the adhered mortar.
- The treatment method, which resembled a prolonged Los Angeles test, removed not only a major amount of the adhered mortar but also some weaker or fractured aggregates keeping only the stronger and sounder ones producing the RCA-T aggregates that had very good resistance to fragmentation.
- The treatment method decreased the total amount of the adhered mortar by 62% and produced sounder and slightly rounder aggregates.
- RCA-T aggregates proved to be of a better quality than the other types of RCA and in some tests they performed even better than NA.

3.2. Workability

The shape and texture of the aggregates and the adhered mortar have an impact on the workability. The mixture RF100cs was cast in order to examine the effect of the shape and texture of aggregates on the workability, thus the amount of superplasticizer used was kept the same as in the Control mixture. This resulted in a low slump value of 50 mm, much lower than the slump target value of 200 mm. Table 5 presents the slump and superplasticizer values of each mixture.

The slump test results showed that:

- The mixtures containing RCA-T aggregates needed much less (up to 42% compared to the Control mixture) superplasticizer in order to reach the target slump value. Due to the rounder shape, RCA-T aggregates increased workability more effectively than any type of aggregates including the natural aggregates.
- The replacement of cement with mineral admixtures increased greatly the amount of the superplasticizer (up to 78% compared to the Control mixture) that was needed. Especially the microsilica-mixtures demanded the biggest amount. This occurred due to the higher surface area of microsilica particles that increased the superplasticizer demand.
- Presoaking the aggregates affected the workability since by keeping the same w/c ratio for both, RF100ps mixture needed 0.62% (of the amount of cement) superplasticizer and RF100 needed 1.15%.

3.3. Mechanical properties

Table 6 presents the results of the mechanical properties of all concrete mixtures tested.

Table 4
Mechanical and physical properties of aggregates.

Properties	NA	RCA-T	RCA-F	RCA-L
Los Angeles coefficient (LA) (%)	29	15	32	29
Apparent Particle Density (Mg/m^3)	2.69	2.74	2.72	2.60
Particle Density (Mg/m^3)	2.52	2.49	2.28	2.21
Particle Density in SSD (Mg/m^3)	2.58	2.58	2.44	2.37
Moisture Content (%)	0.5–0.6	2.6–2.8	2.7–2.9	2.1–2.2
Water absorption (WA) (%)	2.5	3.7	7.2	7.0
Soundness (%)	30	14	41	–
Mortar content (%) – by mass	0	9	24	23

Table 5
Slump and amount of superplasticizer.

Mixtures	Slump (mm)	Superplasticizer (kg/m^3)	Superplasticizer/cement ratio (%)
Control	200	3.50	0.87
RL100	220	3.00	0.75
RF100cs	50	3.50	0.87
RF100ps	190	2.50	0.62
RF100	170	4.60	1.15
RT100	185	2.50	0.62
RF50	195	3.25	0.81
RT50	195	2.00	0.50
RF100F25	170	5.90	1.48
RF100F25S5	190	6.25	1.56
RT100F25	195	2.58	0.65
RT100F25S5	195	2.90	0.73

3.3.1. Compressive strength

The compressive strength test results indicate that the use of RCA affected negatively the strength of the concrete. The results for the 100% substitution of NA coarse aggregates with RCA showed losses of 16.8%, 34.1% and 13.8% for RL100, RF100 and RT100 respectively, compared to the Control mixture. For a replacement ratio of 50%, the losses were 25.7% and 11.0% for RF50 and RT50, respectively (Table 6). The use of SSD aggregates (RF100ps) had only a minor impact on the 28-day strength. It should be noted that despite the decrease, the RAC mixtures manage to reach high compressive strength values (Table 6). The difference between the RCA-T and RCA-F aggregate mixtures is substantial; there is a 23.6% and 16.5% difference in compressive strength for replacement percentages of 100% and 50% respectively (Table 6).

In the second series, the difference between mixtures, consisted of the two different field aggregates (RCA-T, RCA-F), is also clearly noticed (Table 6). Regarding the use of mineral admixtures, although the 28-day compressive strength was low, the 56-day strength presented only a slight decrease compared to the mixtures without mineral admixtures. The lower early strength can be attributed to the slow pozzolanic reaction of fly ash. For the scenario of 100% NA replacement and 25% and 5% replacement of cement with fly ash and microsilica, respectively, RT100F25S5, the 56-day strength reached a compressive strength of 60.3 MPa (Table 6).

Taking into account all the compressive strength test results:

- All RAC mixtures provided good compressive strength values that decreased as the replacement ratio of NA with RCA increased (Table 6).
- Differences between RAC containing RCA-T and RAC containing RCA-F aggregates were particularly significant (31% on the average) for both series of mixtures (Fig. 2) and underlined the effect of the treatment method, as described in 2.2.1 section.
- The 28-day compressive strength of concrete mixtures decreased with the increase in recycled aggregate content (Table 6). This was due to the presence of the old ITZ that worsens the mechanical and physical properties of the recycled aggregates.
- Comparing the RF100ps with RF100, it can be concluded that presoaking the aggregates caused an increase in compressive strength by 7.4% (Table 6). It is presumed that the water added to the mixture RF100 based on the RCA-F absorption was not fully absorbed by the aggregates, resulting in an increased w/c ratio.
- The use of fly ash and microsilica as partial replacement of cement produced a low early strength but their 56-day strength was almost the same as the 28-day strength of mixtures without mineral admixtures (Table 6).
- Despite the use of recycled aggregates, that according to literature should exhibit high variability, the standard deviation was relatively low for all the tests (ranging between 1 and 6% of the mean values). However, standard deviation of compressive strength increased with the increase of recycled aggregates in concrete. The Control mixture exhibited the lowest standard deviation (0.8 Mpa).

Table 6
Summary of Results (f_{cm}: Mean compressive strength, f_{cf}: Flexural strength, f_{ct}: Splitting tensile strength, E: Modulus of elasticity, ρ: Density, P: Porosity, S: Sorptivity, RCP: Rapid chloride permeability).

Mixtures	f_{cm} (MPa)			f_{cf} (MPa)	f_{ct} (MPa)	E (GPa)	ρ (kg/m^3)	P (%)		S (mm/$\sqrt{}$min)		RCP (Coulombs)	
	7 days	28 days	56 days	28 days				28 days	56 days	28 days	56 days	28 days	56 days
Control	58.5	72.1	–	8.6	4.2	27.3	2169	17.4	–	0.092	–	3473	–
RL100	45.8	60.0	–	6.9	4.1	24.0	2017	22.3	–	0.122	–	4870	–
RF100cs	38.6	47.5	–	5.4	2.8	18.2	2035	22.2	–	0.120	–	4861	–
RF100ps	39.5	50.6	–	6.0	3.0	21.3	2049	21.0	–	0.109	–	5822	–
RF100	39.1	47.1	–	6.6	3.1	20.1	2033	21.3	–	0.116	–	5248	–
RT100	40.8	62.2	–	7.2	3.1	29.6	2157	18.2	–	0.101	–	3444	–
RF50	43.6	53.6	–	7.4	3.1	25.4	2076	19.6	–	0.098	–	4154	–
RT50	50.6	64.2	–	7.2	2.9	25.9	2139	18.0	–	0.091	–	3867	–
RF100F25	29.1	35.6	46.4	6.3	2.0	20.0	2000	22.5	22.4	0.120	0.116	5303	3095
RF100F25S5	26.0	38.2	45.8	6.3	2.2	19.9	2012	22.4	22.8	0.087	0.095	3466	1652
RT100F25	36.0	50.8	58.2	6.2	3.0	25.8	2122	18.9	18.7	0.095	0.083	4553	1887
RT100F25S5	34.2	50.9	60.3	6.9	2.3	23.0	2101	19.0	18.2	0.071	0.070	2989	1200

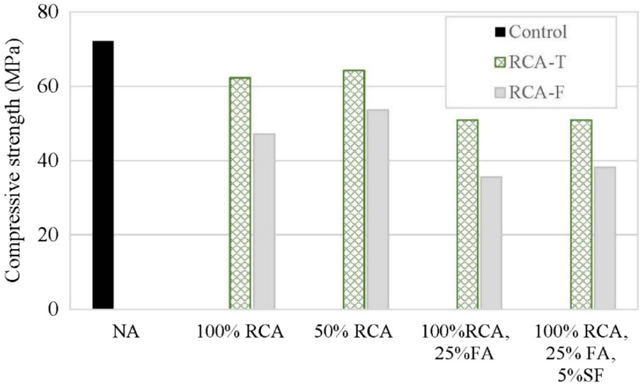

Fig. 2. Effect of treatment method on 28-day compressive strength.

3.3.2. Flexural strength

It can be seen that flexural strength decreased with the increase of recycled aggregate content. The results for the 100% substitution of NA with RCA showed losses of 19.6%, 23.7% and 16.7% for RL100, RF100 and RT100 respectively (Table 6). Like the compressive strength test, the RT100 presented the lowest loss in strength compared to the Control mixture. This is a result of the difference in the mechanical and physical properties of the aggregates. Regarding the SSD aggregates, there was a slight decrease in flexural strength. Etxeberria et al. noted that recycled aggregates should not be saturated because it would result in the failure of the interfacial transition zone between the saturated recycled aggregates and the new cement paste [8]. Regarding the use of mineral admixtures, there was only a slight effect in flexural strength with the incorporation of fly ash and silica fume.

3.3.3. Splitting tensile strength

There is a drop of 5–25% of the splitting tensile strength using 100% RCA compared to the Control mixture (Table 6). The RF100 presented higher tensile splitting strength than RT100. This shows, as expected, that the shape and texture of aggregates affect the strength of the concrete. Matias et al. concluded that the rough and angular contact area allows a better adherence to the new cement paste than NA [25]. As a result, RF100 had higher splitting tensile than RT100 with the rounder aggregates. The same pattern exists also for the 50% replacement level (RF50, RT50). The partial replacement of cement with mineral admixtures decreased the splitting tensile strength.

3.3.4. Modulus of elasticity

The modulus of elasticity of the recycled aggregate concretes was reduced when the recycled aggregates percentage increased except for the case of RT100 in which it increased by 9% (Table 6). “RT” mixtures exhibited on the average 22% higher modulus of elasticity compared to “RF” mixtures. It can be noted that the partial replacement of cement with mineral admixtures had a minor negative effect (0.7%) on the modulus of elasticity values for RF100 concrete but a greater negative effect (17.6%) for the RT100 concrete.

3.4. Durability properties

The durability tests results are presented in Table 6. The density of the Control mixture (2169 kg/m^3) is typical for normal concrete. The mixtures with RCA had lower density due to the lower density of the adhered mortar. RT100 however had almost the same density as the Control, indicating the use of good quality aggregates. The use of mineral admixtures did not have any serious impact on density. Porosity followed the same pattern as density, RT mixtures achieved values close to Control (3.5% higher) while the use of mineral admixtures had only a minor effect.

Using RCA, the reduction in permeability and the increase of sorptivity were expected since the recycled aggregates contained a certain amount of mortar and had undergone a crushing process, which was likely to leave cracks in the weaker mortar or weaker aggregates (Table 6). These cracks would in turn create paths for the fluids to pass through. The increase of the sorptivity coefficient of RAC can also be attributed to the higher absorption capacity of the recycled aggregates compared to natural aggregates. The difference though between RCA-T aggregates and RCA-F or RCA-L was evident. Especially the RT100 mixture presented around the same properties as the Control mixture while RL100 and RF100 presented lower quality. Comparing the RF100ps with RF100, it can be concluded that presoaking the aggregates caused an increase in RCP values by 11.0% and a reduction in sorptivity values by 6.0%. No effect was observed regarding the porosity. It is important to note that the durability (porosity, sorptivity and rapid chloride permeability) values of all the RAC mixtures was on the average 17% higher than the Control mixture as opposed to the corresponding average 28-day compressive strength which was 24% lower. “RT” mixtures exhibited only 4% higher durability values and 12% lower compressive strength.

For the second series of mixtures (with mineral admixtures), the RCP and sorptivity values were greatly improved since the used silica fume restructure the matrix leaving fewer paths for the liquid to pass through (Table 6). Silica fume, with high value of fineness, filled both the interfaces and the bulk paste and the capillary pores were reduced. Hence, the sorptivity and permeability of concrete decreased. The use of fly ash and microsilica refines the pore network and decreases the pore size. Specifically, the durability values of all the RAC mixtures (with mineral admixtures) was on the average 8% higher than the Control mixture as opposed to the corresponding average 28-day compressive strength which was 39% lower. “RT” mixtures exhibited 3% lower durability values and 30% lower compressive strength.

It is important to note that there is a good correlation among durability properties, especially between the sorptivity and porosity ($R^2 = 0.92$) for all mixtures without mineral admixtures, as seen in Fig. 3.

Similar observation was reported by Kanellopoulos et al. [14]. The mixtures with mineral admixtures exhibited good correlation also but only when the mixtures included silica fume were correlated separately. In such case, the coefficient of determination for mixtures with fly ash only was 0.95 and for mixtures with fly ash and silica fume was 0.94. Similar approach was followed for the correlation between sorptivity and Rapid Chloride Permeability that exhibited lower coefficient of determination values, as seen in Fig. 4.

4. Internal curing

The effort to improve RCA performance in concrete mixtures included the use of RCA-F and RCA-T as internal curing (IC) agents according to their absorption and desorption behavior. The technique of IC has arisen at the beginning of the last decade [26]. Concrete mixtures with low w/c ratio (<0.42) suffer underpressure within their sealed pore network, because the amount of water is not sufficient for full hydration [27]. The specific mechanism is widely known as self-desiccation. The underpressure develops a suction pressure that withdraws water from the IC medium pores. The majority of IC applications were conducted using lightweight aggregates and superabsorbent polymers [26,28–30].

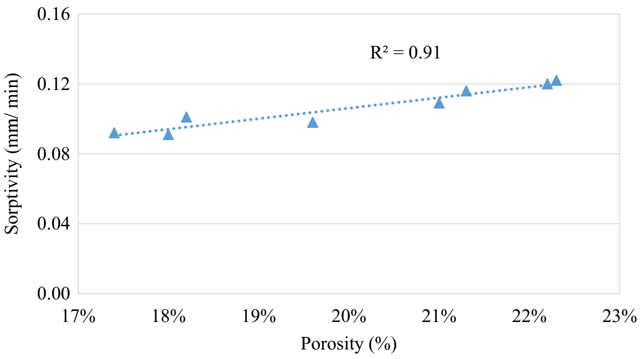

Fig. 3. Correlation between sorptivity and porosity.

A potential IC medium must have sufficiently high water absorption in order to deliver IC water within the material's structure. In addition, the water from the aggregate pores have to be released before RH levels drop internally below 85% [31]. Therefore, the IC medium desorption properties have to fulfill specific requirements. The water absorption of both RCA-F and RCA-T was measured according to EN 1097-6 [20]. Their desorption curves were determined by placing a sample of them, in a saturated surface-dry state, in an environmental chamber where the mass loss as a function of various RH values at constant temperature was recorded. It was shown that RCA-F and RCA-T had water absorption of 7.2% and 3.7% respectively whereas both type of aggregates released more than 50% of their water at RH levels higher than 90%. The higher water absorption was attributed to the larger amount of adhered mortar on the RCA-F. The RCA quantity was calculated according to Bentz equation [31]. Since the RCA-F and the RCA-T water absorption was different, the aggregates quantity had to vary in order to deliver the same amount of IC water. It was decided though, that the amount of aggregates will be based on the RCA-F properties and the RCA-T would carry a portion of the required IC water (Table 7). The reason was to maintain a similar mixture design in order to have comparable results.

Small trial mixtures were designed in order to verify RCA effectiveness, as IC agents, in concrete. A low w/c ratio was selected to reduce the water availability and intensify the IC action. Three concrete mixtures with 0.25 w/c ratio were designed (Table 7). The mixtures included a Control mixture with normal weight aggregates (NA) (4–10 mm and 0–4 mm), two mixtures with a 100% replacement of NA 4–10 mm with RCA-F and RCA-T.

4.1. Experiments and results

The compressive strength (EN 12390-3 [21]) of the mixtures was measured at the age of 1, 3, 7, 14, 28 and 56 days (Fig. 5) and chloride resistance (ASTM C-1202 [23]) at the age of 3, 7, 14 and 28 days (Fig. 6). All the results yielded from three different specimens and the average values presented herein fulfill the criteria reported in EN 12390-3 [21], ASTM C-1202 [23] and ASTM C 670 [32].

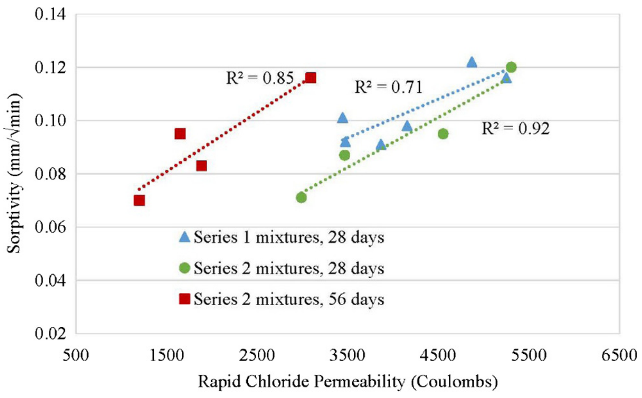

Fig. 4. Correlation between sorptivity and RCP.

Table 7
Constituents of IC mixtures using RCA-F and RCA-T.

	Control	RCA-F	RCA-T
	kg/m^3		
CEM II 42.5R	864	864	864
Water	216	216	216
Coarse Aggregates 4/10 mm	620	620	620
Sand 1 (natural sand) 0/4 mm	597	556	583
w/c	0.25		

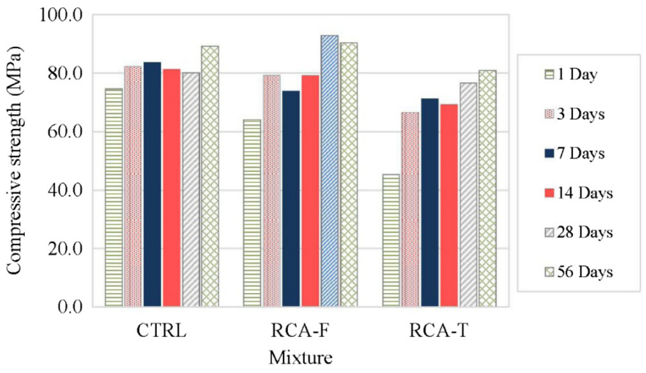

Fig. 5. Compressive strength of IC-RCA mixtures.

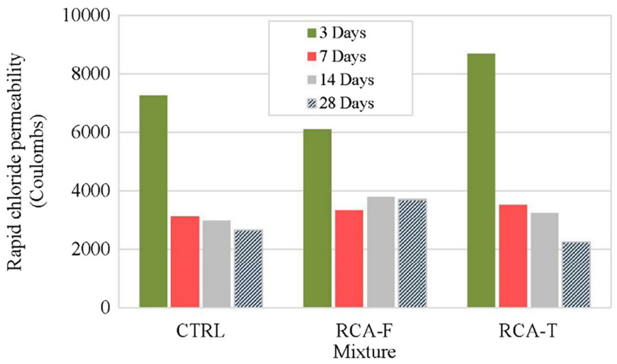

Fig. 6. Rapid chloride permeability of IC-RCA mixtures.

Due to the utilized type of cement, the Control mixture exhibited high compressive strength from the early ages and maintained the specific strength with small variations (Fig. 5). In the case of RCA mixtures, the compressive strength increased gradually which is attributed to the IC mechanism. The RCA mixtures exhibited an average increase of 39% in compressive strength from day 1 to day 28 as opposed to a 12% increase of the Control mixture. It is also worth noting that the compressive strength of the RCA mixtures was similar to the compressive strength of the Control mixture at the age of 56 days. RCA-F mixture exhibited higher compressive strength than the RCA-T mixture. It is presumed that the higher amount of IC water and the larger pores, due to the larger amount of adhered mortar in RCA-F mixture, contributed to an increased degree of hydration.

All mixtures exhibited high RCP values measured at the third day (Fig. 6). RCA-F mixture exhibited the lowest initial RCP value, which is attributed to the earlier initiation of IC. However, the

Table 8
Cost of mixtures (€).

	Unit cost (€/tn)	Control	RT100	RF100	RF50	RT50	RF100 F25	RF100 F25S5	RT100 F25	RT100 F25S5
Cement	84.00	33.60	33.60	33.60	33.60	33.60	25.20	23.50	25.20	23.50
Fly Ash	200.00	–	–	–	–	–	20.00	20.00	20.00	20.00
Microsilica	250.00	–	–	–	–	–	–	5.00	–	5.00
NA	9.30	6.20	–	–	3.00	3.00	–	–	–	–
RCA-F	3.50	–	–	2.30	1.10	–	2.30	2.30	–	–
RCA-T	6.50	–	4.30	–	–	2.10	–	–	4.30	4.30
Sand	10.80	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20	7.20
Superplasticizer (€/lt)	3.30	11.60	8.30	15.20	10.70	6.60	19.50	20.60	8.50	9.60
Water	0.90	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Total		58.5	53.4	58.3	55.7	52.6	74.2	78.70	65.30	69.60
€/Mpa		0.81	0.86	1.24	1.04	0.82	1.60	1.72	1.12	1.16

specific mixture, exhibited the highest 28-day RCP value, among the three mixtures, due to its interconnected pore network caused by excessive adhered mortar. The RCA-T mixture showed the lowest 28-day RCP value due to the combined effect of IC and improved aggregate quality (reduced adhered mortar).

5. Economic aspect

A cost analysis (see Table 8) was conducted in order to assess the financial aspect of the investigated scenarios. All mineral admixtures in Cyprus are imported and their cost is extremely high. The cost is much lower in countries where such mineral admixtures are produced locally, as industrial by-products. Table 8 presents the costs of the materials used and the final cost of the mixtures. RCA-F aggregates were the cheapest. The treatment method (for RCA-T) raised the cost of the aggregates but was still lower than the cost of NA. The 50% substitution level of NA with RCA-T (RT50 mixture) was the most cost-effective of all mixtures, in terms of €/MPa. RT50 mixture produced a cheaper concrete with similar quality as Control. Finally, although RCA-F aggregates were cheaper than RCA-T, due to the additional cost of the treatment method, the mixtures produced from RCA-F were more expensive since they required greater amount of superplasticizer in order to reach the same level of workability.

6. Conclusions

Some very useful conclusions were derived from this research aiming to dispel fears regarding the utilization of RCA into structural concrete. The key conclusion of this research is that the RAC can be enhanced in such a way to be used in some major construction activities. A simple treatment method, in the recycling process of RCA, is capable to reduce the adhered mortar at such level that diminishes the negative effects and to create a better quality RAC which is competitive to normal concrete. The main findings of the research are:

- Properties of aggregates
  - RCA-F aggregates consisted of 24% adhered mortar. A simple treatment method though can reduce mortar to 9%, producing aggregates with less amount of mortar, slightly rounder and sounder (RCA-T aggregates).
  - RCA had higher water absorption values, lower density and higher LA and soundness values. Treated recycled aggregates (RCA-T) showed great improvement in all of the tests that were performed, reaching or even surpassing the properties of natural aggregates.
- Replacement ratio of NA with RCA
  - Increasing the replacement ratio resulted in lower quality of concrete compared to normal concrete. Both mechanical and durability properties are negatively affected by the increase of the replacement ratio.
- Type of aggregates
  - RCA-F aggregates provided good quality concrete, taking into account the low quality of aggregates. RCA-T aggregates provided good quality concrete, competitive to Control concrete.
  - Presoaking aggregates had some positive effect on the compressive strength, modulus of elasticity and sorptivity of concrete.
- The combined effect of mineral admixtures (fly ash and silica fume) proved to be quite significant and improved substantially the durability properties. Especially, the use of silica fume had a crucial impact on sorptivity and chloride permeability values. The mechanical properties were relatively the same, though a low early compressive strength was presented due to the delayed pozzolanic activity of fly ash.
- The performance of concrete including RCA can be improved using the method of IC. It was shown that the RCA mixtures exhibited identical or even better properties with the conventional concrete mixture for both compressive strength and RCP values.
- RAC are cheaper than NA resulting to a slightly cheaper concrete. A 50% replacement of NA with RCA-T produces a less expensive mixture with almost the same quality as Control. In Cyprus, mineral admixtures are much more expensive than portland cement and their utilization resulted into a higher total cost.

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References

[1] Commision, Brundtland, Report of the World Commission on Environment and Development, United Nations, 1987.
[2] ACI Committee 555, Removal and Reuse of Hardened Concrete, 2001.
[3] A. Rao, K.N. Jha, S. Misra, Use of aggregates from recycled construction and demolition waste in concrete, Resour. Conserv. Recycl. 50 (2007) 71–81, https://doi.org/10.1016/j.resconrec.2006.05.010.

[4] Deloitte, Construction and Demolition Waste management in Cyprus V2, in: Deloite Touche Tohmatsu Limited, 2015, pp. 1–20.

[5] J. Xiao, W. Li, Y. Fan, X. Huang, An overview of study on recycled aggregate concrete in China (1996–2011), Constr. Build. Mater. 31 (2012) 364–383, https://doi.org/10.1016/j.conbuildmat.2011.12.074.

[6] S. Mindess, J.F. Young, D. Darwin, Concrete, Second, Pearson Education Inc., New Jersey, 2003.

[7] C.S. Poon, Z.H. Shui, L. Lam, Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates, Constr. Build. Mater. 18 (2004) 461–468, https://doi.org/10.1016/j.conbuildmat.2004.03.005.

[8] M. Etxeberria, E. Vázquez, A. Marí, M. Barra, Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete, Cem. Concr. Res. 37 (2007) 735–742, https://doi.org/10.1016/j.cemconres.2007.02.002.

[9] V. Corinaldesi, G. Moriconi, Behaviour of cementitious mortars containing different kinds of recycled aggregate, Constr. Build. Mater. 23 (2009) 289–294, https://doi.org/10.1016/j.conbuildmat.2007.12.006.

[10] C. Thomas, J. Setién, J.A. Polanco, P. Alaejos, M. Sánchez De Juan, Durability of recycled aggregate concrete, Constr. Build. Mater. 40 (2013) 1054–1065, https://doi.org/10.1016/j.conbuildmat.2012.11.106.

[11] S.W. Tabsh, A.S. Abdelfatah, Influence of recycled concrete aggregates on strength properties of concrete, Constr. Build. Mater. 23 (2009) 1163–1167, https://doi.org/10.1016/j.conbuildmat.2008.06.007.

[12] M. Chakradhara Rao, S.K. Bhattacharyya, S.V. Barai, Influence of field recycled coarse aggregate on properties of concrete, Mater. Struct. 44 (2011) 205–220, https://doi.org/10.1617/s11527-010-9620-x.

[13] S.C. Kou, C.S. Poon, Long-term mechanical and durability properties of recycled aggregate concrete prepared with the incorporation of fly ash, Cem. Concr. Compos. 37 (2013) 12–19, https://doi.org/10.1016/j.cemconcomp.2012.12.011.

[14] A. Kanellopoulos, D. Nicolaides, M.F. Petrou, Mechanical and durability properties of concretes containing recycled lime powder and recycled aggregates, Constr. Build. Mater. 53 (2014) 253–259, https://doi.org/10.1016/j.conbuildmat.2013.11.102.

[15] G. Kaur, S.P. Singh, S.K. Kaushik, Reviewing some properties of concrete containing mineral admixtures, Indian Concr. J. (2012) 35–51.

[16] M. Sánchez de Juan, P.A. Gutiérrez, Study on the influence of attached mortar content on the properties of recycled concrete aggregate, Constr. Build. Mater. 23 (2009) 872–877, https://doi.org/10.1016/j.conbuildmat.2008.04.012.

[17] L. Butler, J.S. West, S.L. Tighe, The effect of recycled concrete aggregate properties on the bond strength between RCA concrete and steel reinforcement, Cem. Concr. Res. 41 (2011) 1037–1049, https://doi.org/10.1016/j.cemconres.2011.06.004.

[18] EN 1097, Tests for mechanical and physical properties of aggregates Part 2: Methods for the determination of resistance to fragmentation, 2010.

[19] EN 1367 Test for thermal and weathering properties of aggregates, 2007, 2009.

[20] EN 1097, Tests for mechanical and physical properties of aggregates Part 6: Determination of particle density and water absorption, 2013.

[21] EN 12390, Testing hardened concrete, 2002.

[22] ASTM C469, Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete, 4 (2002) 1–5.

[23] ASTM C 1202, Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride, (2009) 1–6.

[24] A. Kanellopoulos, M.F. Petrou, I. Ioannou, Durability performance of self-compacting concrete, Constr. Build. Mater. 37 (2012) 320–325, https://doi.org/10.1016/j.conbuildmat.2012.07.049.

[25] D. Matias, J. De Brito, A. Rosa, D. Pedro, Mechanical properties of concrete produced with recycled coarse aggregates - Influence of the use of superplasticizers, Constr. Build. Mater. 44 (2013) 101–109, https://doi.org/10.1016/j.conbuildmat.2013.03.011.

[26] O.M. Jensen, P.F. Hansen, Water-entrained cement-based materials I. Principle and theoretical background, Cem. Concr. Res. 31 (2000) 1–13.

[27] T.C. Powers, T.L. Brownyard, Studies of the physical properties of hardened Portland cement paste, J. ACI. 18 (1947).

[28] P.D. Bentz, K.A. Snyder, Protected paste volume in concrete Extension to internal curing using saturated lightweight fine aggregates, Cem. Concr. Res. 29 (1999) 1863–1867.

[29] ACI Committee 308 and 213, Report on Internally Cured Concrete Using Prewetted Absorptive Lightweight Aggregate, 2013.

[30] H. Azarijafari, A. Kazemian, M. Rahimi, A. Yahia, Effects of pre-soaked super absorbent polymers on fresh and hardened properties of self-consolidating lightweight concrete, Constr. Build. Mater. 113 (2016) 215–220, https://doi.org/10.1016/j.conbuildmat.2016.03.010.

[31] D.P. Bentz, P. Lura, J.W. Roberts, Mixture proportioning for internal curing, Concr. Int. 27 (2005) 35–40. http://concrete.nist.gov/~bentz/Mixpropfin/CI2702Bentz.pdf.

[32] ASTM, Standard practice for preparing precision and bias statements for test methods, Am. Soc. Test. Mater. 4 (2013) 1–12, https://doi.org/10.1520/C0670-10.2.