THE IMPROVEMENT OF RECYCLED CONCRETE AGGREGATE – A REVIEW PAPER

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Summary: *Recycled aggregate consists of the original aggregate and cement mortar layer remaining of the old concrete. Physical and mechanical properties of recycled aggregate dependent on the properties, as well as on the quantity of remaining mortar. Removing and strengthening the adhered mortar are the two main methods for improvement the properties of recycled concrete aggregate. This paper reviews the published improvement methods for recycled concrete aggregate, and points out their advantages and disadvantages so as to facilitate the selection and further development of suitable enhancement methods for recycled concrete aggregate.*

Keywords: *recycled concrete aggregate, adhered cement mortar, improvement*

1. INTRODUCTION

The ambition of reducing the use of natural materials in construction and the aim of reducing the environmental impact of the concrete industry has recently driven Europe to adopt a policy that strongly promotes the use of recycled aggregates in concrete production. The European Directive n.98 of 19/11/2008 [1] calls on member states to take ''the necessary measures to promote the reuse of products and the preparing measures for re-use activities, particularly by promoting the establishment of economic tools and criteria about tenders, quantitative targets or other measures''. Particularly, it specifies that preparations for re-use, recycling and other types of recovery of material, including construction and demolition waste, shall be increased up to at least 70% (by weight) by 2020 [2].
Recycled Concrete Aggregate (RCA), derived from Concrete & Demolition waste generally consists of natural coarse aggregate and adhered mortar which makes it porous due to high mortar content, inhomogeneous and less dense [3,4]. The volume of the residual mortar in RA varies from 25% to 60% according to the size of aggregate [5]. Some researchers have reported in their studies that around 20% of cement paste is found attached to the surface of RA for particle size range from 20 to 30 mm [6,7]. What is specific for RCA is a presence of several types of interfacial transition zone (ITZ) - between the ''old'' and ''new'' compounds, that may play a key role in the internal microstructure of a concrete (Figure 1).

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Therefore, it will facilitate the applications of RCA if the adhered cement mortar can be enhanced. Removing and strengthening the adhered mortar are the two main methods for enhancing the properties of RCA.

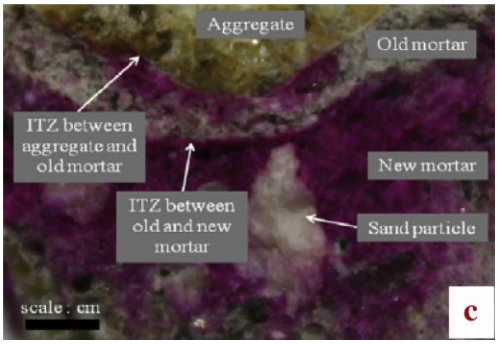

Figure 1. Sectional view of RCA [18]

2. MECHANICAL GRINDING

The adhered mortar can be separated as much as possible from the natural aggregate using crushing and ball – milling. It is a simple and popular treatment which has a lot of variations. However, during mechanical grinding recycled concrete aggregate could be damaged (micro – cracks by grinding).

Autogenous cleaning [2] - with this process RCAs are placed in a rotating mill drum and collide against each other while removing pieces of attached mortar. The mill drum, 30 cm in diameter and 50 cm in depth (Figure 2), was filled up to 33% with ‘‘raw’’ recycled aggregates and the rotation rate was imposed to 60 rotations for minute. After the autogenous cleaning process, aggregates were cleaned with water and subsequently dried to remove all the produced fine remainings and impurities. The results of autogenous cleaning, showed a progressive decrease of the water absorption capacity, with increasing durations from 2 to 10 or 15 min. The results highlight that after the autogenous cleaning, the amount of absorbed water was reduced by 50% and 20%, the amount of fine particles increased.

Figure 2. The mill drum [2]

Furthermore, uncleaned recycled aggregates show an attached mortar content equal of about 30% while the aggregates cleaning led to a decrease of the attached mortar up to about 15%.
Heat treatment method [8,9] - The coarse recycled concrete aggregate samples were heated at four different temperatures: 250˚C, 350˚C, 500˚C and 750˚C for a period of one hour in a conventional electric oven. The use of heat treatment method is successful in improving various physical properties including water absorption, specific gravity, porosity and freezing and thawing. However, it is recommended to use this method at temperatures between 300˚C and 350˚C because of the noticeable negative effects of higher temperatures on coarse recycled concrete aggregate characteristics. The aggregate suffers from thermal expansion followed by internal stresses due to exposure to high temperature between 400˚C and 600˚C. Whereas there is serious microcracking of the cement matrix when the material is exposed to a higher temperature range between 600˚C and 800˚C resulting in degradation, breakdown and mass loss of aggregate.

3. PRE-SOAKING IN WATER (PRE–SATURATION)

The results obtained in [10] verified that if recycled aggregates are immersed in water for short intervals the consistency of the fresh recycled concrete improved at the expense of an insignificant decrease in the compressive strength. This loss ranged from 11%, for the 3 min soaking period, to 13%, for 5 min pre-saturation interval.

4. PRE-SOAKING IN ACID

The hydration products of cement in hardened paste can be dissolved in acid solution. The procedure [11] is first to soak the recycled aggregate in an acidic environment at around 20˚C for 24 h and then watering with distill water to remove the acidic solvents afterward. Before concrete mixing, 24 h water soaking of recycled aggregate is stipulated. Three acidic solvents are experimented: hydrochloric acid (HCl), sulfuric acid (H_2SO_4) and phosphoric acid (H_3PO_4) with concentration of 0.1 mole which can provide a suitable acidic environment for the aggregate to remove the old cement mortar and will not lower the aggregate quality. Experimental results show that the values of water absorption of the pre-treated RA have been significantly reduced with improved mechanical properties for the recycled aggregate concrete. Meanwhile, the alkalinity of recycled aggregate concrete, chloride and sulphate contents of recycled aggregate have not been adversely affected.
In the procedure shown in [12], the coarse recycled concrete aggregates were kept immersed in HCl with a molarity of 0.5 mole for 24 h. The container was occasionally shaken to ensure a more efficient reaction of the acid in the degradation of weak mortar. After the immersion, the aggregates were watered with distilled water and drained, and then impregnated with calcium metasilicate ($CaSiO_3$) solution for 24 h . The purpose of this step was to coat the surface of coarse recycled concrete aggregate with calcium metasilicate particles to refill the pores and cracks throughout its physical surface. Simultaneously, the present calcium metasilicate particles that was used to coat the

recycled concrete aggregate surface would be dissolved during mixing and are expected to function as a filler with the product of cement hydration for the densification of the interface structure, which improves bond strength at contact between the aggregate surface and the cement matrix.

Table 1: Properties of recycled aggregate before and after pre-soaking treatments [11]

Properties of recycled aggregate	Sizes of aggregate	Before pre-soaking treatment	After pre-soaking treatment		
			ReMortarHCl	ReMortarH_2SO_4	ReMortarH_3PO_4
Water absorption (%)	20 mm 10 mm	1.65 2.63	1.45 2.31	1.48 2.37	1.53 2.41
Chloride content (%)	20 mm 10 mm	0.0016 0.0012	0.0025 0.0056	0.0001 0.0001	0.0001 0.0001
Sulphate content (%)	20 mm 10 mm	0.0025 0.0025	0.0076 0.0082	0.1090 0.1040	0.0110 0.0109
Value of pH	20 mm 10 mm	10.46 11.63	9.07 9.34	8.95 9.35	8.55 9.33

In [9] the coarse recycled concrete aggregate was soaked in an acidic solution composed of hydrochloric acid (HCl) (37%) and acetic acid ($C_2H_4O_2$) (99.7%) at a low concentration of 0.1mole for 24 h at room temperature around 20˚C.
In [13] the aggregates were submerged in HCI (hydrochloric acid) solution at 0.1 molarity for 24 h at 20˚C. After then, they were submerged in distilled water in order to remove acidic solution. The second method at the same paper was that the aggregates were submerged in water glass ($Na_2O \cdot nSiO_2$ sodium silicate) for 30 min. After then, they were held in suspension for 10 min to provide leakage of excess water glass from the aggregates which were taken out of the solution and then dried in oven for 1 h by preventing bonding the aggregate particles. The use of HCl concentration at 0.1 molarity has the potential to remove the loose adhered mortar and certain loose substances on recycled concrete aggregate surface as demonstrated by the SEM analysis. The properties of recycled concrete aggregate such as density and water absorption have improved after HCl treatment as compared to untreated recycled concrete aggregate. Water glass treated aggregates considerably reduce the water absorption providing the minimal value compared to the other treatments applied. The SEM analysis has demonstrated that new ITZs in SCCs containing treated recycled concrete aggregate provide less porous, more dense and connected microstructure (Figure 3) .
The study [14] include assessing the influence of different acid concentrations and durations of treatment on the physical and mechanical properties of coarse RCA, as well as effects of using treated aggregate on concrete's compressive strength. Three types of acid molarity, 0.1, 0.5 and 0.8 mole, of HCl were used in this study.
The aggregates were immersed in acidic solvents for 1, 3, and 7 days. The use of low concentration HCl has the potential to remove the loose adhered mortar on RCA surface. The results show a linear correlation between the amount of mortar loss with the increase of the molarity of acid. However, the immersion time of RCA with acid did not have significant influence on the amount of mortar lost. The results indicate that incorporating concrete mix with treated RCA at a proportion of up to 45% achieves the optimum strength in the mix design of concrete compressive strength.

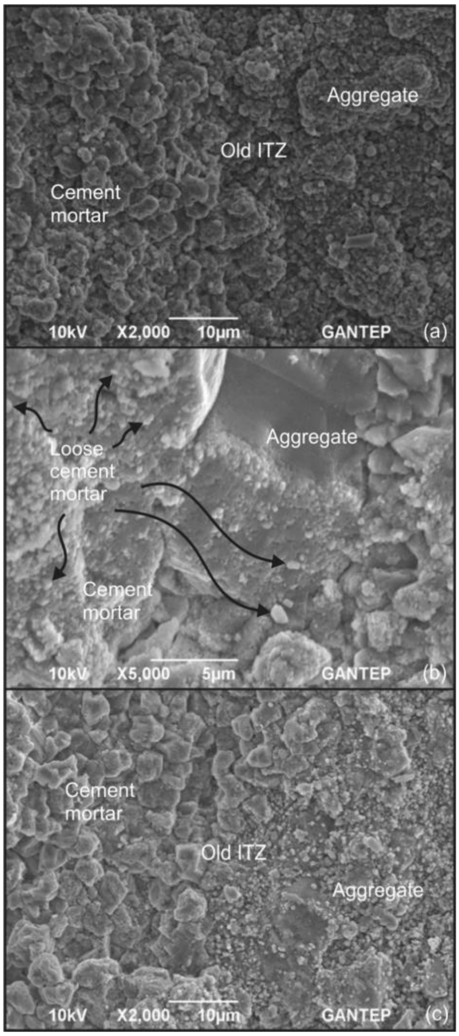

Figure 3. Surface microstructure views of RCAs: (a) untreated RCA with old ITZ, (b) untreated RCA with loose cement mortar, and (c) treated RCA with HCl solution [13]

5. TWO – STAGE MIXTURE APPROACH

In order to improve the quality of recycled aggregate concrete, a mixing method: two-stage mixing approach (TSMA) was developed by Tam et al. [15], which divides the mixing process into two parts and proportionally splits the required water into two parts which are added after mixing one part with fine and coarse aggregate and cement; while the normal mixing approach only puts all the ingredients of concrete and mix them. In TSMA, during the first stage of mixing, the use of half of the required water for mixing leads to the formation of a thin layer of cement slurry on the surface of RCA which permeates into the porous old cement mortar, filling up the old cracks and voids. In the second stage of mixing, the remaining water is added to complete the cement hydration process. Improvement of strength can be achieved up to 21.19% for 20% of RCA under 28-day curing conditions using TSMA.

6. THREE STEP METHOD

The method was divided into three steps: rough crushing of the concrete, thermal treatment of the crushed concrete to separate the paste from the aggregates and chemical attack of the remaining attached paste with salicylic acid. Two variants were tested for the thermal treatment: a soundness test (ST) consisting in apply cycles of freezing (-17˚C) and heating (+60˚C) of the sample immersed in a 26% Na_2SO_4 solution, and liquid nitrogen – microwave heating cycles (LNMO). These two methods showed similar efficiency, i.e. a direct recovery rate of 84% of clean aggregates of the size class 4/20 mm (52% recovered compared to 62% of 4/20 mm aggregates initially present in the concrete). The soundness test was kept in the final method due to its easier application in the laboratory. The chemical treatment of the remaining aggregates covered by cement paste by means of salicylic acid successfully dissolved the paste, with an efficiency of around 67–69%. Only thin layers of pasteremained on the 31–33% of final aggregates (size classes 0/1 and 1/4 mm). The overall efficiency of the three-step method, evaluated by comparing the amounts of recovered aggregates and natural aggregates, reached 90–92% on quartzite and siliceous limestone aggregates, respectively.

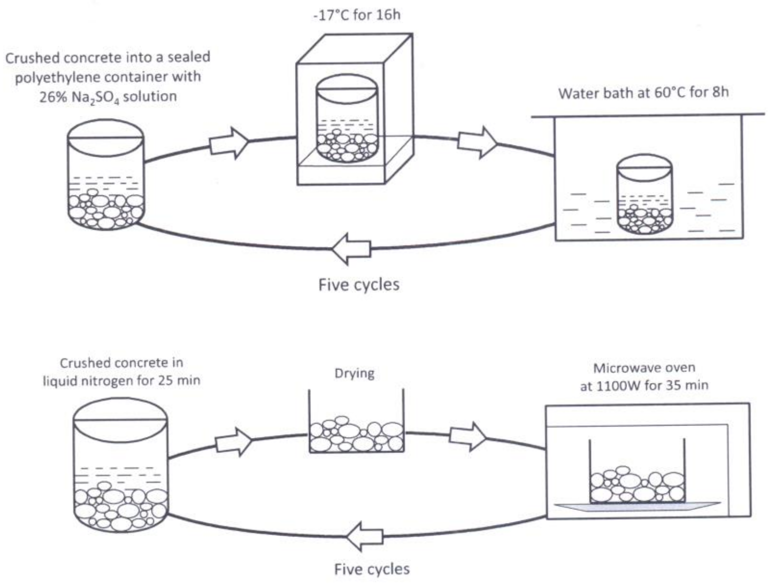

Figure 4. Three step method: soundness test and liquid nitrogen – microwave heating cycles [16]

7. SELF – HEALING

Self healing process was achieved by immersing the recycled aggregates in water for 30 days. This period gives good chance to the unhydrated cement particles to react again with water to enhance the properties of concrete particles. The efficiency of this process to enhance the mechanical properties of hardened concrete had been documented [17].

8. MINERAL ADMIXTURE SOLUTION

Some approaches like surface coating of recycled concrete aggregate with low w/c ratio paste or by impregnating it in silica fume solution or in other mineral admixture solution also helped in healing the pores or cracks present in RCA. Impregnation of the RCA with a solution of silica fume or any other mineral admixtures helps in penetrating the silica fume particles into the cracked and loose layer of this aggregate.
Due to the filling effect of silica fume, it helps in improving the ITZ during the hardening process of concrete. Furthermore, the pozzolanic reaction of silica fume with $Ca(OH)_2$ produces secondary C–S–H gel which in turn strengthened the weak structure of the RA to form an improved zone, penetrates from the RCA through the residues of the old cement paste into the new cement matrix.
Silica fume treatment at early age has a stronger effect on filling than the pozzolanic reaction, which is known to develop more slowly. The similar effect is also shown by other pozzolanic substances like GGBS, fly ash etc. This ultimately helps in improving the performance of recycled aggregate concrete regarding strength and durability [13,17-23].

9. POLYMER EMULSION

Silicon based additives are emulsions composed of alkylalkoxysilanes (silane), polydiorganosiloxanes (siloxane) or both of them. The treatment process can be simple impregnation (the aggregate samples were impregnated by each polymer solution for 5 min, then dried at room temperature maintained at 20˚C and about 50% relative humidity (RH) for 24 h, then in ventilated oven at a temperature of 50±5˚C until the difference in mass during 24h is less than 0.1%) and double impregnation and heat treatment process: the aggregate samples were impregnated by soluble sodium silicate for 3 min followed by drying for 20 h at room temperature maintained at 20˚C and 50% relative humidity (RH), then the samples were again impregnated in each polymer solution (different siloxane/silane emulsions) for 5 min followed by drying during 24 h in a room maintained at 20˚C and in ventilated oven at a temperature of 50±5˚C until the difference in mass is less than 0.1%.
The results showed that these kinds of treatment emphasize the formation of polymeric film in pore network. This film allows the significant reduction of water absorption capacity.
The film formed is efficient and resistant in alkali environment. Few amount of polymer-based treatment is necessary to achieve the water repellent performance [24].

10. CALCIUM CARBONATE BIODEPOSITION

The method of biodeposition of calcium carbonate (Figure 5) conducted through the participation of Sporosarcina pasteurii bacteria, should constitute an alternative method. Biodeposition, as opposed to other concepts, is a natural method and, in principle, makes less severe with the environment, because all the components used for cultivating the substrates as well as and the strain itself, naturally occur in the environment. The biodeposition concept is based on the ability of bacteria to precipitate calcium carbonate on the outer surface of the cell wall, due to occurrence of negative zeta potential of adequate strength. Biodeposition process has been described as follows:

$$Sp.cell + Ca^{2+} \rightarrow Sp.cell\text{-}Ca^{2+}$$
$$CO(NH_2)_2 \rightarrow 2NH_4^+ + CO_3^{2-}$$
$$Sp.cell\text{-}Ca^{2+} + CO_3^{2-} \rightarrow Sp.cell – CaCO_3$$

S. pasteurii cell (Sp. cell) can attract Ca ions (Ca^{2+}), which react with carbonate ions $CaCO_3^{2-}$ originating from urea ($CO(NH_2)_2$) hydrolysis. Simultaneously, ammonia ions NH_4^+ increase pH value in surrounding medium which improves calcite precipitation efficiency. The results showed that this procedure led to reduction in the water absorption of aggregate and this was even more effective when finer fractions derived from inferior quality concrete were used [25].

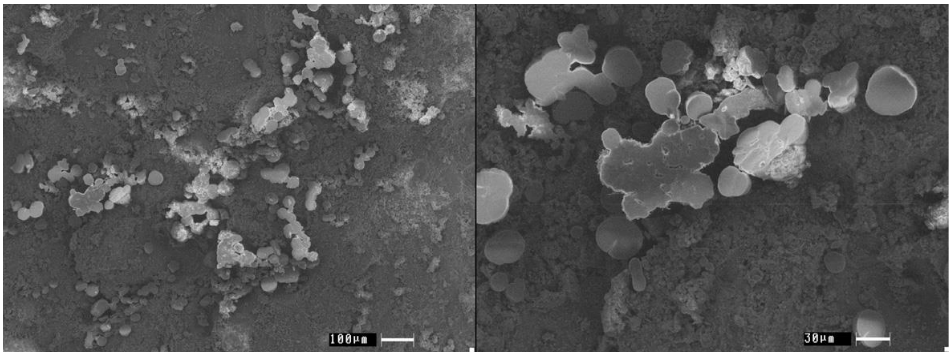

Figure 5. Scanning electron micrograph of recycled aggregate grain (w/c = 0.45, fraction 12/16 mm) after biodeposition treatment [25]

11. CARBONATION

In consideration of the constituent of the old cement mortar adhering to the surface of RCA, improving the low quality of RCA through accelerated carbonation is possible to some extent because the calcium hydroxide, which is one of the main cement hydration products in the old cement mortar adhering to the surface of RCA, can react with carbon dioxide accompanied by an increase in solid volume, which is formulated by the following reaction: $Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$

The other hydration products, such as CSH (calcium silicate hydrate gel), also appears to be converted to calcium carbonate, water and a modified CSH gel with a lowered Ca/Si ratio or a higher degree of polymerized silica gel. For the reinforced concrete structure, natural carbonation can reduce the alkalinity of concrete leading to corrosion of steel reinforcement, and thus can limit the lifetime of reinforced concrete structures. However, the most direct consequence of carbonation is decrease in pore volume of concrete.
The experimental results confirmed that the CO_2 curing process can densify the mortar adhered on the RCA. After the CO_2 curing process, there was a significant reduction in water absorption and porosity of the RCA. Owing to the large specific surface area, RCA with smaller particle sizes was more easily to be carbonated. The moisture content of RCA significantly influenced the carbonation percentage since the dry matrix could not provide sufficient water for the carbonation reactions and the pores in the water saturated matrix was filled with water blocking CO_2 penetration. Furthermore, the carbonation process proceeded rapidly within the first 2 h but slowed down sharply after that [26-30].

12. CONCLUSION

Various methods for enhansing the properties of recycled concrete have been developed and studied. The two common methods for improving the properties of recycled concrete aggregate are removing and strengthening the adhered mortar. Every method shows good results in aggregate enhansing and has its own characteristics, so other parameters (like use of concrete, cost, etc.) should be taken into account.

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NAČINI POBOLJŠANJA RECIKLIRANOG AGREGATA – PREGLEDNI RAD

Rezime: *Reciklirani agregat se sastoji iz zrna prirodnog agregata i sloja cementnog maltera preostalog od starog betona. Fizičke i mehaničke osobine recikliranog agregata zavise od kako od karakteristika tako i od količine preostalog maltera. Uklanjanje i ojačavanje preostalog maltera su dva glavna načina za poboljšanje karakteristika recikliranog betonskog agregata. U radu je dat pregled objavljenih metoda za* *poboljšanje recikliranog agregata uz isticanje njihovih prednosti i nedostataka, kako bi se olakšao izbor i dalja razrada odgovarajuće metode.*

Ključne reči: *reciklirani betonski agregat, preostali cementni malter, poboljšanje*