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Quality Improvement Techniques for Recycled Concrete Aggregate: A review

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Abstract

The main problem in using recycled concrete aggregate (RCA) as a construction material is due to the weak adhered mortar which usually has higher porosity and water absorption. It also has lower strength compared to natural aggregate (NA), and it often forms weak interfacial transition zones in the recycled aggregate concrete (RAC). These weak zones lead to negative effects on the mechanical properties and durability performance of RAC. In order to utilize RCA in more effectively as aggregate in concrete, it is necessary to improve the quality and enhance the properties of the attached weak mortar. This paper reviews different treatment methods of RCA based on the published research, and systematically analyses the strengths and weaknesses as well as the applicability and limitations of each method. The advantages and disadvantages of each treatment method, in terms of their technical feasibility, efficiency, economic and environmental impacts, are also discussed, in view of facilitating the selection of the most suitable treatment method for RCA. Although most techniques have been examined and trialed under laboratory conditions, further investigations are required to determine the most effective approach for treating RCA, with consideration not only given to the laboratory scale, but also on a commercial production scale.

1. Introduction

The construction sector has seen tremendous expansion recently. This sector is considered the largest carbon dioxide emitter and energy consumer, accounting for up to 45% of the total global CO₂ and about 40% of the global energy consumption (Peng 2016). In China, about 73% of total energy consumption of building comes from

manufacturing the raw materials (Zhang and Wang 2016). As one of the most used construction materials, concrete not only contributes to the carbon emission and energy consumption, it also excessively uses the nature materials such as sand, stone or gravels. In concrete, both coarse and fine aggregates account for 60 to 75% of the total volume. World demand for concrete aggregates will rise 5.2% annually to 51.7 billion metric tons in 2019 and China remains the largest national consumer of aggregates, representing nearly half of global demands (Freedonia 2016). Therefore, aggregates have a significant effect on environment and on the sustainability feature of structures. On the other hand, the construction and demolition (C&D) waste generated by the construction sector is one of the most voluminous waste streams world widely. According to Construction and Demolition Recycling Association (CDRA), more than 583 million tons of C&D wastes were generated in 2015 (Turley 2018). If not recycled, most of them will be sent to landfills, which also creates significant impact on environment. Such dilemma leads to the perfect necessity to recycle C&D concrete waste and replace the natural aggregates (Yang *et al.* 2018).

Using recycled concrete aggregates (RCA) retrieved from C&D wastes in new concrete mixes is becoming a popular application (Rahal 2007; Leite *et al.* 2011; Pan *et al.* 2017; Tripura *et al.* 2018). After the Second World War, European countries started using C&D concrete wastes for concrete production. Approximately 200 million tons of construction wastes are generated every year in Europe, but only 30% of the waste is recycled at present (Tabsh and Abdelfatah 2009). In USA, almost 100 million tons of RCA are produced every year. However,

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Table 1 Current situation of using RCA based on the standards adopted in different countries.

Country/Standard	Classification	Maximum replacement ratio of NA		Applications	Maximum strength
		Fine	coarse		
Germany, DIN 4226-100	RCA	0%	20-35%	Structural concrete, prestressed concrete not allowed	C30/37 (20% replacement), C25/30 (35% replacement)
	RMA & RA	-	-	Non-structural concrete	-
UK, BS 8500:2	RCA	0%	20%	Structural concrete	C40/50
	RA	0%	-	Non-structural concrete	-
HK, WBTC No.12/2002	RCA	0%	100%	Less demanding applications structural concrete,	20 MPa
			20%		35 MPa
Japan, BCSJ	MRA	100%	100%	Foundations and less demanding situations	18 MPa
Japan, JIS A5021	MRA - Class H	-	-	No limitations	45 MPa
Japan, JIS A5022	MRA – Class M	-	-	Members not subjected to drying or freezing and thawing action	-
Japan JIS A5023	MRA – Class L	-	-		-
USA, ACI 555R-01	BA	0%	50%	Non-structural concrete	-
	RCA	50%	50%	Non-structural concrete	-

RCA: recycled concrete aggregate; RMA: recycled masonry aggregate; MRA: mixed concrete and masonry recycled aggregate; MRA - Class H: high-quality recycled aggregate; MRA - Class M: medium-quality recycled aggregate; MRA - Class L: low-quality recycled aggregate; BA: blending aggregate.

this huge amount is primarily for the application of road construction as base or the filler material (Smith *et al.* 2008). In Canada, the use of RCA is very uncommon and limited and only 3% RCA is used (Miller 2005). In Japan, the recycling law was established in 1991, which has hugely encouraged the reuse of C&D concrete wastes. Owing to this initiative, the rate of using RCA as a sub-base material for concrete pavement increased from 48% to 96% in 2000 (Saotome 2007). Every year, 14 million tons of wastes are generated in Hong Kong and RCA is successfully used in many government projects (Rao *et al.* 2007). To facilitate such growing applications, those countries have also produced the standards/codes, which usually classify the type of RCA, specify their respective maximum replacement to natural aggregates, the maximum concrete strength at such replacement and the typical engineering applications. Table 1 summarizes the comparison amongst those standards from Germany, UK, HK, Japan, and USA.

It is found that the main problem of using RCA is the weak adhered mortar and the interfacial transition zone (ITZ) between the original aggregate and the weak adhered mortar, which distinguishes RCA from the natural aggregate (NA), resulting in a poorer quality concrete (Malesev *et al.* 2010; Henry *et al.* 2011; Qiu *et al.* 2014; Zhang *et al.* 2015d; Mukharjee and Barai 2017). Previous research (Etcheberria *et al.* 2007; Lee *et al.* 2012; Pasandin and Perez 2014; Choi *et al.* 2016) have confirmed that the weak adhered mortar in RCA has some inferior characteristics such as lower density, and higher porosity as well as increased water absorption compared to NA. Moreover, the quality and the amount of attached mortar present, in addition to the weak adhesion between mortar and aggregate, are also major contributing factors

to the poor quality of RCA. These factors have a negative effect not only on the physical and mechanical properties of RCA (Menard *et al.* 2013; Silva *et al.* 2015; Martirena *et al.* 2017; Jin *et al.* 2018), but also on its durability (Saravanakumar and Dhinakaran 2013; Zhu *et al.* 2013; Guo *et al.* 2018).

Consequently, it is necessary to enhance and improve the physical and mechanical properties of RCA such that it is more comparable to those of NA. The challenges in making such improvements mainly include how to reduce the water absorption and porosity of RCA, as well as to improve the strength and enhance the durability performance of the resultant concrete.

Numerous researchers have explored various approaches and techniques to reduce or partially compensate the detrimental effects of RCA, or to improve the characteristics of the resultant concrete. These approaches include adjusting and trialing different mixing methods, materials and processes, such as varying the water/cement (W/C) ratio (Eckert and Oliveira 2017; Pandurangan *et al.* 2016; Saravanakumar and Dhinakaran 2012), blending RCA with NA at various replacement ratios (Abdel-Hay 2015; Haghghatnejad *et al.* 2016; Yang *et al.* 2011), as well as cement coating (Binyu and ChiSun 2015; Martirena *et al.* 2017; Tam *et al.* 2005). Likewise, the properties of RCA can be improved by undertaking several quality improvement treatments. Such treatment methods include eliminating the adhered mortar from RCA surfaces and improving the adhered mortar by enhancing its properties. Thus, this study conducts a review of the reported treatment techniques for RCA, identifying the applicability, limitations, strengths and weaknesses of each technique. This study also provides evidence to assist in the selection of suit-

able treatment methods for different applications, and to assess their potential for enhancing the quality of RCA.

2. Treatment techniques of RCA

Due to the widely varying effects of adhered mortar on the quality of RCA, there are several approaches and techniques that have been considered to improve the characteristics of RCA. These approaches and techniques can be primarily classified into two categories (Purushothaman *et al.* 2015). The first category mainly includes eliminating the adhered mortar from the RCA surface using different methods while the second category includes modifying and improving the properties of RCA by improving the quality of the adhered mortar. Several treatment techniques of RCA are reviewed in detail in the following sections and their categorizing relationship are summarized in Fig. 1.

3. Eliminating the adhered mortar

A large amount of weak adhered mortar is considered as the major factor compromising the quality of RCA (Ajdukiewicz and Kliszczewicz 2002; Shayan and Xu 2003; De Juan and Gutiérrez 2009). The attached weak mortar results in poor qualities for RCA, such as low density, high water absorption and porosity. The weak adhered mortar can be removed from the RCA surface by using either one or a combination of thermal, mechanical and chemical treatments. These treatment methods are described in detail in the following sections.

3.1 Thermal treatment technique

Thermal treatment is considered as a favorable treatment method for eliminating the attached weak adhered mortar, mainly due to its operational simplicity and cost effectiveness. The thermal technique that was explored in the past mainly consists of two methods, namely, traditional heating and microwave heating.

(1) Traditional heating

In this technique, RCA particles are heated at various temperatures for about 2 hours. The thermal stresses generated through differing thermal expansion of the original aggregate and the attached mortar are used to loosen the attached weak mortar from the surface so that the mortar can then be removed. Shima *et al.* (2005) observed that when RCA is heated at temperatures higher than 300°C, the aggregate-mortar interface becomes weak due to dehydration, and loses its bond under the induced thermal stresses. Mulder and Feenstra (2007) heated RCA from C&D concrete waste at 700°C to separate the original aggregate from the adhered cement paste. After treatment, only 2% of the hardened cement paste remained attached to the original aggregate particles. This finding also agreed well with Ma *et al.* (2009), in which concrete from C&D wastes was heated at 750°C to separate aggregates from the adhered mortar. Results clearly indicated that the higher heating temperature, the easier the adhered mortar can be removed. However, it is worth noting that when the heating temperature is higher than 500°C, the properties of RCA may be degraded (Al-Bayati *et al.* 2016), so the heating temperature should be carefully selected when implementing this method.

It is accepted that soaking the RCA before heating can further increase the efficiency of mortar separation because of the higher internal pore vapor pressure developed in the adhered mortar or the mortar-aggregate interface zone, leading to a higher mortar removal rate when RCA is exposed to temperatures above 100°C (Al-Bayati *et al.* 2016; De Juan and Gutiérrez 2009). Furthermore, immersing the heated RCA in cold water immediately after heating can also lead to higher rate of mortar removal. This is due to the fact that the near-surface material will cool down faster than the inner material and will contract rapidly. The original aggregate will cool down slowly and its contraction will be hindered by the external layer of mortar surrounding the aggregate particles which will induce tension and encourage the separation of the external mortar (De Juan and Gutiérrez 2009).

Fig. 1 Treatment techniques of recycled concrete aggregate.

(2) Microwave heating

The microwave heating technique benefits from the differences in the electromagnetic properties between the original aggregate and the adhered mortar (Like *et al.* 2016). Microwave heating results in fracturing and separates the adhered mortar without harming the original aggregate, and consequently reduces the content of adhered mortar in the RCA (Akbarnezhad *et al.* 2011; Akbarnezhad and Ong, 2010). The process comprises two stages. First, microwave heating is used to generate high differential thermal stresses in the adhered mortar, particularly at the interfacial transition zones (ITZs) between the aggregate and the adhered mortar, and this separates the adhered mortar from Type I RCA particles (which consist of a natural aggregate particle surrounded by a layer of mortar), as shown in **Figs. 2(a)** and **2(b)**. Secondly, additional microwave heating is used to break up and weaken the adhered mortar in the Type I RCA particles into smaller pieces (Type II RCA particles, which just consist of mortar) that can be easily collected through sieving, as shown in **Fig. 2(c)**. Akbarnezhad *et al.* (2011) attempted to increase the quality of RCA by removing adhered mortar using the microwave heating technique. RCA samples were heated in a prototype industrial microwave heating system (2.45 GHz, 10 kW). The results confirmed that microwave heating could

eliminate the adhered mortar by creating high temperature gradients, especially at the ITZs between the aggregate and the adhered mortar. Similar results have been achieved by other researchers (Bru *et al.* 2014; Lippiatt and Bourgeois 2012), who attempted to retrieve the original aggregate from concrete waste by using the cavity microwave equipment (2.45 GHz, 6 kW) to assess the potential and the effectiveness of this process. Results revealed a thorough embrittlement of RCA particles using the microwave treatment. Results also suggested that the larger aggregates were more efficient in the microwave heating treatment as evidenced by the increase in the separation degree, i.e. the mortar-free aggregates accounted 29.7% for fine aggregates (< 2 mm) and 65.1% for large aggregates (> 20 mm). Thus the microwave heating would be more effective for coarse aggregates in terms of mortar removal.

3.2 Mechanical treatment technique

Mechanical treatment is a common treatment method for producing high quality RCA by separating adhered mortar from the NA. In this method, mechanical forces are used to pulverize and remove the adhered mortar. There are two techniques that have been suggested in this method: an eccentric-shaft rotor method and mechanical grinding, as shown in **Fig. 3**. In the eccentric-shaft rotor

Fig. 2 Various types of RCA particles: (a) RCA particle surrounded by adhered mortar; (b) three RCA particles held together and surrounded by adhered mortar, (c) only mortar (Akbarnezhad *et al.* 2011).

Fig. 3 Mechanical treatment techniques: (a) eccentric-shaft rotor; (b) ball-milling (Yoda *et al.* 2003).

Table 2 Improvement percentage of apparent particle of RCA after thermal-mechanical treatment (Sui and Mueller 2012).

Treatment temperature (°C)	Improvement percentage in apparent particle density of RCA (%)
100	0.50
200	1.60
300	2.78
400	3.54
500	3.92
600	4.67

Table 3 Improvement percentage of RCA properties after acid soaking treatment (Tam *et al.* 2007).

Property	Particle size (mm)	Improvement percentage (%)		
		HCl-treated RCA	H ₂ SO ₄ -treated RCA	H ₃ PO ₄ -treated RCA
Water absorption (%)	10	12.17	9.89	8.37
	20	12.12	10.30	7.27

method, RCA lumps are passed between an outer cylinder and an inner cylinder that rotates eccentrically at a high speed. The adhered mortar can be removed from RCA by this action (Yonezawa *et al.* 2001). In the mechanical grinding method (ball-milling), a drum is divided into small sections. The adhered mortar in the RCA is removed by scrubbing against the iron balls placed in each part of the drum (Yoda *et al.* 2003). Mechanical grinding can also improve the shape of the RCA particles due to the effects of peeling and collision. However, the process might easily damage the RCA particles due to collision and grinding actions leading to changes in the geometric characteristics of RCA particles, and as such may introduce micro-cracks (Ogawa and Nawa 2012; Sun and Xiao 2004).

3.3 Thermal-mechanical technique

This technique is a combination of two treatment processes. The first process involves a traditional heating technique at temperatures ranging from 300°C to 500°C to dry out the adhered mortar and to weaken it as a result of the generated thermal stresses. The second process includes mechanical grinding to totally eliminate the adhered mortar from the RCA particles. Sui and Mueller (2012) studied the effect of combining two different treatment methods, namely the traditional heating treatment at various temperatures (from 100°C to 600°C) for 30 min, and a mechanical ball-milling treatment for different milling times (3 min to 14 min), on the properties of RCA. Results show that the adhered mortar can be removed by heating at a temperature ranging from 200°C to 600°C, followed by vigorous mechanical treatment for an appropriate duration. **Table 2** shows the improvement percentage of the apparent particle density of RCA treated with combination of heating and mechanical treatment. As can be seen, the combination of heating treatment at (200 - 600°C) and the short mechanical treatment for 5 minutes achieved a satisfactory performance for improving the physical properties of RCA (i.e. increasing the apparent particle density).

3.4 Water cleaning technique

Pre-soaking in water can wash away impurities, loose

particles and weak adhered mortar, and achieve a higher quality RCA. Katz (2004) used ultrasonic water cleaning to remove the weak adhered mortar, and found this method to be successful. The RCA made with cleaned RCA by ultrasonic water cleaning has an increase of 3% and 7% in compressive strength for 7 days and 28 days, respectively. Abd ELhakam *et al.* (2012) attempted to enhance the quality of RCA by impressing RCA in water up to 30 days. It was found that this soaking duration enhanced the RCA quality and increased the compressive strength of the resulting concrete by 4.8% and 15.7% for 7 days and 56 days, respectively.

3.5 Chemical treatment technique (acid soaking)

More recently, the technique of pre-soaking in acid has been developed as an effective treatment method for eliminating adhered mortar and enhancing the quality of RCA. However, a major drawback of this technique is the possible increase in the chloride and sulphate content of the aggregate after treatment with hydrochloric or sulphuric acid. An increase in the chloride and sulphate content of aggregate may affect the durability of the resulting concrete. Tam *et al.* (2007) soaked RCA in three different strong acid solutions (hydrochloric (HCl), sulphuric (H₂SO₄), and phosphoric (H₃PO₄)) at the low concentration of 0.1 mol for 24 hours at 20°C. The obtained results indicated that the water absorption have been reduced after the acid soaking treatments with improvements between 7.27% and 12.17% for the different particle sizes of RCA, as summarized in **Table 3**. The different acids can react with the main composition of RCA such as calcium oxide (CaO), aluminium oxide (Al₂O₃) and iron oxide (Fe₂O₃). Various reaction products such as (Ca²⁺, Al³⁺, Fe³⁺, etc.) can be generated and these products can weaken the attached mortar, making it possible to remove. Thus, this treatment could remove a large proportion of the adhered mortar from the original aggregate, which helps to improve the weak ITZ between the RCA and the adhered mortar.

Pre-soaking in acid was also investigated by Ismail and Ramli (2013) who studied the effect of using different concentrations of HCl solution (0.1, 0.5, 0.8 mol)

Table 4 Physical properties of RCA before and after chemical treatment (Al-Bayati *et al.*, 2016).

RCA Treatment	Bulk Relative Density (BRD)	Apparent Specific Gravity	Saturated Surface Dry Density (SSD)	Absorption (%)
Untreated RCA	2.295	2.638	2.425	5.91
Soaking in $C_2H_4O_2$	2.299	2.651	2.432	5.79
Soaking in HCl	2.305	2.651	2.435	5.66

with different soaking durations (1, 3, 7 days) to improve the quality of the RCA. The results show a linear correlation between the amounts of mortar loss and increasing concentration of acid; whilst the length of soaking time had no substantial effect.

Saravanakumar *et al.* (2016) also attempted to improve the quality of RCA by removing adhered mortar via pre-soaking in acid solutions. The RCA samples were soaked in three different 0.1 mol acid solutions (HCl, nitric acid (HNO_3), and H_2SO_4) for 24 hours at room temperature. The results showed that the treated RCA by HCl, HNO_3 , and H_2SO_4 have improved the water absorption of RCA by 10%, 11%, and 13%, respectively, compared with untreated RCA. This finding agreed with (Purushothaman *et al.* 2015) that studied the effect of treated RCA with HCl and H_2SO_4 acid solutions. This treatment technique improved the water absorption of RCA by 10% and 19.5% for HCl-treated RCA and H_2SO_4 -treated RCA, respectively, compared with un-

treated RCA. Additionally, (Saravanakumar *et al.* 2016) treated again the HCl-treated RCA with silica fume by immersing it in silica fume solution for 24 hours at room temperature. The findings showed that the silica fume impregnation after HCl treatment filled the pores and the voids in the RCA. Hence, the quality of the RCA could be improved by soaking HCl-treated RCA in silica fume solution, as shown in Fig. 4.

Al-Bayati *et al.* (2016) also attempted to enhance the quality of RCA by soaking it in 0.1 mol strong acid (HCl) and 0.1 mol weak acid (acetic acid ($C_2H_4O_2$)) for 24 hours at 20°C. Results indicated that using the two different types of acids appeared to result in almost similar performance in improving the properties of RCA, as summarized in Table 4. Therefore, the use of the weak acid instead of the strong one is recommended to improve the quality of RCA and to mitigate the influence of acid attacks on the RCA surface and the hazardous of waste solution.

Fig. 4 Microstructure of RCA before and after treatment (Saravanakumar *et al.* 2016).

3.6 Chemical-mechanical technique

Abbas *et al.* (2008) proposed a method combining chemical and mechanical treatments to separate adhered mortar from RCA. The chemical treatment is achieved through soaking RCA in a sodium sulphate solution (Na_2SO_4) for 16 to 18 hours. The mechanical treatment is implemented by subjecting the RCA to a freeze-and-thaw action. Results indicated that the proposed method is capable of removing the attached residual mortar from RCA without significantly damaging the original aggregate. Wang *et al.* (2017) used the similar method to improve the quality of RCA by soaking it in the acetic acid solution at 1%, 3%, and 5% concentrations respectively followed by the mechanical rubbing. During the soaking process, the acetic acid reacted with the main composition of RCA in the adhered mortar, namely, calcium carbonate (CaCO_3) and calcium hydroxide (CH) as well as the hydrated calcium silicate (C-S-H). This reaction weakened the adhered mortar, making it possible to separate from RCA by the mechanical rubbing. Results showed that the treated RCA has lower water absorption and less attached adhered mortar after conducting the mechanical treatment than only applying the chemical treatment at the different acetic acid concentrations, as shown in Fig. 5.

4. Quality-improving the adhered mortar

This section introduces an alternative approach to enhance the performance of RCA. Rather than removing the weak mortar, these methods retain the mortar on the original aggregate and strengthen it before the aggregate is recycled. The key quality improvement techniques are to improve the characteristics of adhered mortar by filling and condensing the weak portions and achieving stronger ITZs. Several techniques can be used, such as polymer treatment, the use of pozzolanic materials as

surface coating binders to improve the bonding strength between the RCA and the new mortar through a pozzolanic reaction, as well as the carbonation technique.

4.1 Polymer treatment technique

Polymers are used to enhance the durability performance of concrete because some polymers can react chemically with the hydration products of the adhered mortar, whilst others form a coating surrounding it (Singh and Rai 2001). Calcium complexes formed by the chemical interaction are able to fill the pores and voids in the adhered mortar and seal the RCA surface. Therefore, the water absorption and the porosity could be decreased, and subsequently the durability performance improves. Different types of polymers have been used for improving the properties of RCA, such as water soluble polymers such as polyvinyl alcohol (PVA) and silicon-based water repellent polymers.

Water soluble polymers have adhesive properties and can solidify in a short time. Thus, if RCA is submerged in a water soluble polymer, the polymer molecules can fill the voids in the weak adhered mortar. PVA solution is a water soluble polymer that can be used to decrease the water absorption of porous materials such as RCA (Mansur *et al.* 2007). Kou and Poon (2010) studied the physical and mechanical properties of RCA that was treated with 6, 8, 10 and 12% PVA solution. Results indicated that the water absorption of PVA-treated RCA decreased as the concentration of PVA increased, and 10% PVA solution was the recommended optimum concentration for RCA impregnation. Table 5 summarizes the percentage improvement of the RCA properties (i.e., density, water absorption, and 10% fine value) and the mechanical properties of the concrete made with RCA treated with 10% PVA solution (i.e., compressive strength, drying shrinkage, and chloride ion penetration). As can be seen from this table, PVA impregnation not only improves the physical and mechanical properties of

Fig. 5 Physical properties of treated RCA with chemical and chemical-mechanical treatments: (a) water absorption; (b) adhered mortar loss (Wang *et al.* 2017).

Table 5 Improvement percentage of the physical and mechanical properties of RCA treated by 10% PVA solution and resultant concrete (Kou and Poon, 2010).

Property	Particle size (mm)	Improvement percentage (%)	
		PVA-modified RCA in oven-dried	PVA-modified RCA in air-dried
Density	10	1.0	1.22
	20	1.74	2.0
Water absorption	10	44	69
	20	62	74
10% fine value	14	22	24
Compressive strength		6	11
Drying shrinkage		15	11
Chloride ion penetration		35	32

RCA but the mechanical properties of the resultant concrete also are enhanced.

Silicon-based water repellent polymers are considered as effective enhancement materials and include silane, siloxane or both. Since the particle size of silane-based polymer is smaller than that of siloxane based polymer, the silane-based polymer can penetrate easily into the adhered mortar and form a coating surrounding it with good water repellent capacity (Zhao *et al.* 2011). Zhu *et al.* (2013) treated RCA using silane-based polymer by applying two treatment methods (i.e. integral mixing and surface coating). Findings show that the surface coating treatment is more efficient than the integral matrix treatment in reducing the water absorption of RCA. Tsujino *et al.* (2007) conducted experiments on the application of two types of surface improving agent, namely an oil-type (paraffin) and a silane-type, to improve the properties of RCA through repeated spraying and drying cycles. The results showed that the RCA treated with the oil-type agent showed a greater reduction in water absorption for RCA than RCA treated with silane-type. This is because the oil-type agent containing paraffin that can react with calcium hydroxide in the adhered mortar and produce alkali metal salts which form a water-repellent layer on the RCA surface. Although the treatment using the silane-type agent reduced the water absorption of the RCA, the compressive strength of the resultant concrete was lowered because the positive silane groups could permeate into the cement paste and make it hydrophobic (Spaeth *et al.* 2008). Spaeth and Djerbi Tegguer (2013) attempted to solve the problem of silane hydrolysis by soaking RCA in silane and various combinations of silane and siloxane polymer solution at different concentrations, and then adding sodium silicate to the silane or combined siloxane/silane solutions. It was found that silane-based polymer decreased the water absorption of the RCA. Also, the addition of sodium silicate reduced the hydrolysis effect by forming a thinner hydrophobic layer.

4.2 Calcium carbonate biodeposition

Calcium carbonate biodeposition is also a developing technique for improving the quality of RCA, in particular by reducing water absorption in the adhered mortar. This technique is conducted using bacteria, and is based on the

ability of these bacteria to accelerate the formation of calcium carbonate on the aggregate surface due to the negative zeta potential of the bacterial cell wall surface (Achal *et al.* 2009). Moreover, the biodeposition technique is a natural method compared with other concepts. Also, this technique has a less acute environmental impact because all of the components used for seeding the substrates occur naturally in the environment (Qiu *et al.* 2014). Grabiec *et al.* (2012) proposed a biodeposition technique for treating RCA using the bacteria *Sporosarcina pasteurii*, which were cultivated in a liquid medium resulting from urea hydrolysis, as follow (Qian *et al.* 2009):

The bacterial cell wall surface (*Sp.cell*) can attract (Ca^{2+}), which reacts with the calcium carbonate ions ($CaCO_3$) produced as a result of urea hydrolysis. Concurrently, ammonia ions (NH_4^+) increase the pH value of the surrounding medium, which improves calcium carbonate precipitation efficiency. The growing substance containing bacteria was stored at either 25°C or 35°C for 72 h for calcium carbonate precipitation. After three days of calcium carbonated precipitation, RCA was impressed in this substance for 72 h. Results indicated that the biodeposition can reduce the water absorption up to 21%, particularly for finer RCA derived from lower quality concrete, as displayed in Fig. 6. Furthermore, the precipitated $CaCO_3$ filled the pores and voids in the adhered mortar and exhibited a good bond in the aggregate surface, as shown in Fig. 7.

4.3 Incorporating pozzolanic materials

Using pozzolanic materials such as fly ash or silica fume is considered to be a more efficient technique to improve the properties of adhered mortar. If RCA is immersed in

pozzolanic material slurry, or sprayed with pozzolanic materials (surface coating), the pozzolanic materials react with calcium hydroxide (CH) remaining in the adhered mortar to form hydrated calcium silicate (C-S-H) gel. These hydrated products can modify the RCA surface and the properties of the adhered mortar to improve the bonding characteristics of RCA. Tam *et al.* (2005) suggested a two-stage mixing approach (DM) to treat RCA, in which it divides the mixing process into two parts. During the first part of mixing, the cement and half of the required water were added to the RCA. By doing this, a thin layer of cement slurry is produced on the RCA surface and the quality of the adhered mortar is improved. In the second part, the remaining water is added to complete the concrete mixing process. This method increased the compressive strength of RAC up to 21% for 20% RCA replacement at 28-day curing in comparison to the normal mixing approach (NM). Tam and Tam (2008) tried two alternative DM, one with silica fume and the other with silica fume and cement. The

Fig. 6 Water absorption of RCA before and after biodeposition (a: w/c of parent concrete = 0.45, fraction 6-8 mm; b: w/c = 0.45, fraction 12-16 mm; c: w/c = 0.70, fraction 6-8 mm; d: w/c = 0.70, fraction 12-16 mm) (Grabiec *et al.* 2012).

pozzolanic reaction and filler effect of the silica fume performed effectively due to its high specific surface area. Thus, the microstructure of the RCA was much denser. Kong *et al.* (2010) proposed a triple mixing method (TM) based on DM that was suggested by Tam *et al.* (2005) to further strengthen the ITZ between the aggregate and the adhered mortar and improve the properties of the resultant concrete. **Figure 8** summarizes the different mixing methods of RCA treated by adding pozzolanic materials. Using TM proposed by (Kong *et al.* 2010) enhanced the properties of RCA. The pozzolanic particles can react with the CH accumulated in the pores and on the surface of the adhered mortar to produce new hydrated products (e.g. C-S-H). These products can not only density the adhered mortar in RCA, but also improve the bond in existing ITZ. Thus the compressive strength of the resultant concrete at different curing ages was further enhanced. **Figure 9** shows the percentage improvement of the compressive strength for new concrete containing RCA after applying the different mixing approaches (DM and TM) with pozzolanic materials (fly ash (F) and slag (S)) compared to NM. Padhi *et al.* (2018) studied the effect of using 5 - 35% rice husk ash (RHA) in designing concrete mixes with 100% RCA. The experimental results showed that the behavior of RAC was substantially influenced by the incorporation of RHA. However, concrete mixes containing 100% RCA and 10 - 15% RHA met the design requirements for application in construction industry.

Moreover, the benefits of the treatments using pozzolanic materials, especially those containing silica are due to their finer particle size and the presence of the rich silica on the RCA surface, which could improve the ITZ between the RCA and the cement paste via pozzolanic reaction as described in previous research (Katz 2004; Tam and Tam, 2008), and as shown in **Fig. 10**. These results agree with those obtained by Li *et al.* (2009) who determined that surface coating with pozzolanic materials (silica fume, fly ash, and slag) modified the RCA surface and enhanced the properties of the resultant concrete.

A number of researchers (Archontas and Pantazopoulou, 2015; Miyandehi *et al.* 2016; Mohseni *et al.*

Fig. 7 SEM of RCA: (a) before biodeposition treatment; (b) after biodeposition treatment (Grabiec *et al.* 2012).

Fig. 8 Different mixing methods of the recycled aggregate concrete (Kong *et al.* 2010).

DM-F: two-stage mixing with fly ash; DM-S: two-stage mixing with slag; TM-F: triple mixing with fly ash; TM-S: triple mixing with slag for RAC.

Fig. 9 Improvement percentage in compressive strength of the resultant concrete after incorporating pozzolanic materials (Kong *et al.* 2010).

2015; Yang *et al.* 2015) have studied the modification effect of nano-silica on the properties of normal concrete. In general, nano-silica powder has a filler effect by filling up the pores and voids in the mortar. With the optimum content, the nano-silica powder contributes in enhancing

the strength due to the reduced porosity. In addition to this filling effect, nano-silica has a higher pozzolanic reactivity. The pozzolanic reaction of nano-silica with CH that formed during the cement hydration produces additional C-S-H gel which is the main contributing for strength development. In contrast, few researchers have attempted to use nano-silica to enhance the properties of RCA. Zhang *et al.* (2016) examined the effects of the surface treatment on the microstructure and macro-properties of RCA using two slurries containing nano-materials. The first slurry contained nano-Si and nano-Ca, while the other slurry contained cement and nano-Si. The results indicated that although both nano-slurries enhanced the new ITZs between the old adhered mortar and the new mortar, these nano-slurries could not modify the old ITZs between the aggregate and the old adhered mortar. This primarily is because the contained unhydrated cement particles in the old ITZs are beyond the reach of nanomaterials (Zhang *et al.* 2015c).

4.4 Carbonation technique

It is known that the main hydration products of adhered mortar on RCA are calcium hydroxide and hydrated calcium silicate. Carbonation is the process of carbon dioxide (CO_2) entering the pores and voids of adhered mortar and its interaction with those hydration products (Castellote *et al.* 2009). The carbonation of calcium hydroxide begins when CO_2 reacts with calcium hy-

Table 6: Physical and mechanical properties of RCA before and after carbonation treatment (Kou *et al.* 2014).

Type of RCA	Carbonation curing time (h)	Property				
		Density (kg/m ³)		Water absorption (%)		10% fine value (kN)
		10 mm	20 mm	10 mm	20 mm	14 mm
Untreated RCA		2326	2326	12.25	11.82	96
	6	2339	2330	10.86	10.12	98
	12	2346	2337	8.77	8.03	101
Treated RCA	24	2351	2345	7.57	7.32	108
	48	2352	2347	7.42	7.13	109
	72	2354	2349	7.28	6.99	111

droxide in the adhered mortar and forms a dense coating around the reacted calcium hydroxide crystals as well as filling the pores and voids of the cement paste (Thiery *et al.* 2007). Carbonation of C-S-H begins with decalcification of the calcium ions between layers reacting with carbonate ions. Decalcification can cause formation of Si-OH groups and consequently the formed silica gel improves the bond between the cement paste and the RCA (Chen *et al.* 2006). Borges *et al.* (2010) indicated that the carbonation rate of calcium hydroxide could be higher than that of C-S-H, while during the formation of calcium carbonate, the calcium hydroxide carbonation rate decreased conversely.

Recently, some researches have attempted to use CO₂ to cure RCA. Thiery *et al.* (2013) studied the carbonation kinetics, including maximum CO₂ absorption and absorption rate, of RCA using CO₂ concentrations of 10% and 50%. Results indicated that RCA could have a maximum CO₂ absorption of 65% at a CO₂ concentration of 50%, and the absorption rate increased when the particle size of the RCA was below 2 mm and the water saturation was less than 0.4. Kou *et al.* (2014) treated RCA in a 100% CO₂ environment under a modest pressure (0.1 Bar above atmospheric) for 6, 12, 24, 48 and 72 hours, to study the influence of carbonation treatment on the properties of RCA. It was found that the carbonation treatment improved the physical and mechanical properties of the treated RCA at the different curing time and for different particle size of RCA, as summarized in

Table 6. Zhang *et al.* (2015a) attempted to improve the quality of RCA through carbonation of the adhered mortar. RCA was treated in a CO₂ concentration of 20% under a pressure of 0.2 MPa for 7 days. The results indicated that carbonation treatment increased the density up to 5%, and decreased the water absorption up to 28% as well as crushing values up to 9% of RCA compared with untreated RCA. Furthermore, the carbonation treatment not only improved the new ITZs between the old adhered mortar and new mortar, but also improved the old ITZs between the aggregate and the old adhered mortar, as shown in **Fig. 11** (Zhang *et al.* 2015b). These findings agreed with Shi *et al.* (2018), who explained that the carbonation treatment enhanced the quality of both old and new ITZs by achieving a greater micro-hardness and denser structure. Xuan *et al.* (2017) studied the durability properties of RAC prepared with carbonated RCA in a 100% CO₂ environment. Results indicated that the CO₂ curing treatment of RCA had a greater beneficial effect on the durability properties of the RAC. The improvement of impermeability for the treated concrete was 15.1%, 36.4% and 42.4% for bulk electrical conductivity, chloride ion permeability and gas permeability, respectively.

4.5 Sodium silicate solution

Cheng and Weng (2004) soaked RCA for 1, 5, and 24 hours in different concentrations (0.05, 0.1, 0.2, 0.3, and 0.4) of sodium silicate solution. Findings showed that the

Fig. 10 Microstructure of RCA after adopting: (a) NM; (b) DM with silica fume; (c) DM with silica fume and cement (Tam and Tam 2008).

sodium silicate reduced significantly the water absorption of RCA. This is attributed to the silicic acid gel that is precipitated from the sodium silicate solution filling the pores and voids of RCA. Also, the sodium silicate reacted with calcium hydroxide and produced C-S-H gel that improved the bond between the adhered mortar and RCA (Yang *et al.* 2016).

5. Discussion

Numerous treatment techniques for removing adhered mortar or enhancing the properties of RCA have been described and explained in this study. There are many economic and environmental aspects that should be taken into consideration during the application of these techniques, such as the cost of treatment, the processing time, and the amount of embodied energy or carbon emission to achieve the most acceptable results for treating the RCA. Based on the preceding review, the strengths and weaknesses as well as the applicability and limitations of each method are summarized in **Table 7**, and discussed as follows.

(1) Comparison of the treatment approaches for eliminating adhered mortar

Based on previous studies, the microwave heating technique has the advantages of rapid heating, selective heating, internal heating and easy control compared to the traditional heating techniques. Therefore microwave heating can increase the removal efficiency of the weak adhered mortar from the RCA surface. Also, quick selective heating by microwave can separate the adhered mortar from the RCA by generating differential expansion. Microwave heating can reduce energy consumption compared to the mechanical crushing, but it is not considered preferable when applied on a large scale. Despite the advantages of lower energy consumption and shorter processing time, the microwave heating technique can have a better removal effect if it can be followed by a

short mechanical treatment. It may be argued that using a chemical treatment technique (pre-soaking in acid) may be considered more efficient for eliminating the adhered mortar and enhancing the quality of RCA. However, the major problem of this technique is the influence of the chloride and sulphate ions that may be introduced through the treatment process. The higher cost of some treatment acids may also make such methods economically impractical on a large scale.

(2) Comparison of the treatment approaches for quality improvement of the adhered mortar

In general, the polymer treatment can reduce water absorption, fill pores and voids in the adhered mortar, and coat the RCA surface. The polymer treatment can improve the workability and durability of RCA concrete. In addition, the development of the water-repellent characteristic impairs the bond between the RCA and cement paste. Using pozzolanic materials such as fly ash, silica fume, and nano-silica is considered as an effective treatment in improving the properties and modifying the surface of RCA, because these materials can fill the pores and voids in the adhered mortar and react with CH to produce C-S-H gel that improves the bond between the RCA and the cement paste. The efficiency of pozzolanic materials in improving the properties of RCA depends on the calcium hydroxide content in the adhered mortar, the particle size and the reaction of the pozzolanic materials. Therefore, nano-silica is more efficient in improving the properties of RCA due to its high specific area and higher reaction rate. As mentioned before, it is important to provide an effective and economical treatment technique, and using nano-silica is considered as an effective technique, but not an economical technique because of its high cost. Using CO_2 to treat RCA is not only an efficient technique for improving the characteristics of RCA, but also an environmentally friendly approach. Therefore, the carbonation treatment technique is considered as an effective and sustainable method for enhancing the mechanical properties and durability performance of the resulting concrete, but the major drawback of this method is that it is time-consuming.

Fig. 11 Microstructure of the RCA surface: (a) un-carbonated RCA; (b) carbonated RCA (Zhang *et al.* 2015b).

Table 7 Treatment techniques of recycled concrete aggregate and their effects.

Treatment Techniques	% improvement in water absorption of RCA	% improvement in compressive strength of RAC concrete at 28 days	Economic, environmental, and practicality aspects
Traditional heating	↓ up to 10%	-	<ul style="list-style-type: none"> • Increase energy consumption • Time-consuming • Inconvenient on a large scale
Microwave heating	↓ up to 33%	↑ up to 27%	<ul style="list-style-type: none"> • Time-consuming • Inconvenient on a large scale
Mechanical treatment	↓ up to 50%	↑ up to 39%	<ul style="list-style-type: none"> • Need special device • Increase energy consumption • Increase CO₂ emission
Thermal-mechanical treatment	↓ up to 55%	↑ up to 18%	<ul style="list-style-type: none"> • Increase energy consumption • Time-consuming • Increase CO₂ emission • Need to dispose of fine particles
Water cleaning treatment	-	↑ up to 7%	<ul style="list-style-type: none"> • Time-consuming • Need to dispose more waste water
Chemical treatment (Pre-soaking in acid)	↓ up to 19%	↑ up to 19%	<ul style="list-style-type: none"> • High cost • Increased chloride and sulphate contents • Need to dispose of waste acids
Chemical-mechanical and thermal treatment	↓ up to 50%	↑ up to 23%	<ul style="list-style-type: none"> • Cost-intensive • Increase energy consumption • Increase CO₂ emission • Need to dispose of waste acid and fine aggregate
Polymer treatment	↓ up to 74%	↑ up to 11%	<ul style="list-style-type: none"> • Cost-intensive • Time-consuming • Need to dispose of waste solution • Inconvenient on a large scale
Calcium carbonate bio-deposition	↓ up to 21%	↑ up to 40%	<ul style="list-style-type: none"> • Cost-intensive • Time-consuming • Inconvenient on a large scale
Pozzolanic materials	↓ up to 50%	↑ up to 23%	<ul style="list-style-type: none"> • Time-consuming
Carbonation	↓ up to 22%	↑ up to 20%	<ul style="list-style-type: none"> • Time-consuming • Need special device • Inconvenient for reinforced concrete
Sodium silicate solution	↓ up to 39%	↑ up to 29%	<ul style="list-style-type: none"> • Cost-intensive • Increase the risk of alkali-silica reaction

6. Summary and conclusions

This paper presents a state-of-the-art review of treatment techniques for improving the qualities of RCA. The advantages and disadvantages of each method, in terms of their technical feasibility, economy, efficiency and environmental impact, are also illustrated, and this can facilitate the selection of suitable treatment methods for RCA. The recommended removal technique is the more controllable heating process, for example by means of microwave or solar heating, followed by short-term mechanical treatment, such as mechanical grinding (ball-milling). This technique will be the most effective in removing adhered mortar. The carbonation technique and the employment of low-cost nano-type pozzolanic materials have great huge potential to enhance the properties of RCA. Most of the treatments are currently being examined on a small scale under laboratory conditions. How these techniques can be applied to large scale

commercial production requires further research and investigation.

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