Quality Improvement Techniques for Recycled Concrete Aggregate: A review

Wafaa Mohamed Shaban¹, Jian Yang²*, Haolin Su³, Kim Hung Mo⁴, Lijuan Li⁵ and Jianhe Xie⁶

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 Abdelghafar 2009). In USA, almost 100 million tons of RCA are produced every year. However,
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 respective maximum replacement to natural aggregates, as to improve the strength and enhance the durability 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 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; Haghighatnejad 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-

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 |
|------------------|----------------|----------------------------------|--------------|------------------|
| 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 | - | - | Non-structural concrete | - |
| HK, WBTC No.12/2002 | RCA | 0% | 100% | Less demanding applications structural concrete, | 20 MPa |
| | - | 20% | - | - | |
| 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 draining or freezing and thawing action | - |
| Japan JIS A5023 | MRA - Class L | - | - | Backfill concrete, blending concrete, leveling concrete | - |
| 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.
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 the original aggregate 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).
(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 technique, the adhered mortar is separated from the aggregate by creating high differential thermal stresses. In mechanical grinding, the adhered mortar is removed by applying mechanical forces to break up and weaken the adhered mortar in the RCA particles. The results confirmed that mechanical treatment could effectively remove the adhered mortar from the RCA particles. The effectiveness of the mechanical treatment technique depends on the type of aggregate and the size of the aggregates.
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 RAC 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.

**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) | HCl-treated RCA Improvement percentage (%) | H2SO4-treated RCA Improvement percentage (%) | H3PO4-treated RCA Improvement percentage (%) |
|----------|--------------------|-------------------------------------------|---------------------------------------------|---------------------------------------------|
| Water absorption (%) | 10 | 12.17 | 9.89 | 8.37 |
|                  | 20 | 12.12 | 10.30 | 7.27 |
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 (HNO₃), and H₂SO₄) for 24 hours at room temperature. The results showed that the treated RCA by HCl, HNO₃, and H₂SO₄ 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 H₂SO₄ acid solutions. This treatment technique improved the water absorption of RCA by 10% and 19.5% for HCl-treated RCA and H₂SO₄-treated RCA, respectively, compared with untreated 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 (C₂H₄O₂)) 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.

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 C₂H₄O₂ | 2.299                      | 2.651                     | 2.435                               | 5.79           |
| Soaking in HCl    | 2.305                      | 2.651                     | 2.435                               | 5.66           |
| Soaking in HNO₃   | 2.305                      | 2.651                     | 2.435                               | 5.66           |
| Soaking in H₂SO₄  | 2.305                      | 2.651                     | 2.435                               | 5.66           |
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 (Na₂SO₄) 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 (CaCO₃) 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).](image)
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) | 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                             |
| 10% fine value         | 20                 | 62                             | 74                             |
| Compressive strength   | 14                 | 22                             | 24                             |
| Drying shrinkage       |                    | 6                              | 11                             |
| Chloride ion penetration|                   | 15                             | 11                             |

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 repellant 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):

$$Sp.cell + Ca^{2+} \rightarrow Sp.cell - Ca^{2+}$$

(1)

$$CO(NH)_{2} + 2H_{2}O \rightarrow 2NH_{4}^{+} + CO_{3}^{2-}$$

(2)

$$Sp.cell - Ca^{2+} + CO_{3}^{2-} \rightarrow Sp.cell - CaCO_{3}$$

(3)

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 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.
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 (CO₂) 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 CO₂ reacts with calcium hy-
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.

| Type of RCA | Carbonation curing time (h) | Density (kg/m³) | Water absorption (%) | 10% fine value (kN) |
|-------------|----------------------------|-----------------|----------------------|---------------------|
|             |                            | 10 mm           | 20 mm                | 10 mm              | 20 mm              | 14 mm              |
| Untreated RCA | 6                         | 2326            | 2326                 | 12.25              | 11.82              | 96                 |
|             | 12                        | 2339            | 2330                 | 10.86              | 10.12              | 98                 |
| Treated RCA | 24                        | 2346            | 2337                 | 8.77               | 8.03               | 101                |
|             | 48                        | 2351            | 2345                 | 7.57               | 7.32               | 108                |
|             | 72                        | 2352            | 2347                 | 7.42               | 7.13               | 109                |
|             |                            | 2354            | 2349                 | 7.28               | 6.99               | 111                |

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...
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).

\[
Na_2SiO_3 + Ca(OH)_2 + H_2O \rightarrow C-S-H + NaOH \quad (4)
\]

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\textsubscript{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).
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.

Acknowledgement

The corresponding author would like to thank the supports from Science and Technology Program of Guangzhou, China [Grant No. 201704030057].

References

Abbas, A., Fathifazl, G., Burkan Isgor, O., Razaqpur, A. G., Fournier, B. and Foo, S., (2008). “Proposed method for determining the residual mortar content of recycled concrete aggregates.” J. ASTM Int., 5(1), 1-12.
Abd Elhakam, A., Mohamed, A. E. and Awad, E., (2012). “Influence of self-healing, mixing method and adding silica fume on mechanical properties of recycled aggregates concrete.” Constr. Build. Mater., 35, 421-427.
Abdel-Hay, A. S., (2017). “Properties of recycled
concrete aggregate under different curing conditions.”  
*HBRC J.*, 13(3), 271-276.

Achal, V., Mukherjee, A., Basu, P. C. and Reddy, M. S., (2009). “Lactose mother liquor as an alternative nutrient source for microbial concrete production by Sporosarcina pasteurii.” *J. Ind. Microbiol. Biotechnol.*, 36(3), 433-438.

ACI Committee 555, (2001). “Removal and reuse of hardened concrete.” ACI 555R-01, ACI committee 555 report, American Concrete Institute, Farmington Hills, Michigan.

Ajdukiewicz, A. and Kłiszczewicz, A., (2002). “Influence of recycled aggregates on mechanical properties of HS/HPC.” *Cem. Concr. Compos.*, 24, 269-279.

Akbarnezhad, A. and Ong, K. C. G., (2010). “Microwave decontamination of concrete.” *Maga. Concr. Res.*, 62(12), 879-885.

Akbarnezhad, A., Ong, K. C. G., Zhang, M. H., Tam, C. T. and Foo, T. W. J., (2011). “Microwave-assisted beneficiation of recycled concrete aggregates.” *Constr. Build. Mater.*, 25(8), 3469-3479.

Al-Bayati, H. K. A., Das, P. K., Tighe, S. L. and Baaj, H., (2016). “Evaluation of various treatment methods for enhancing the physical and morphological properties of coarse recycled concrete aggregate.” *Constr. Build. Mater.*, 112, 264-298.

Archontas, N. D. and Pantazopoulou, S. J., (2015). “Microstructural behavior and mechanics of nano-modified cementitious materials.” *Adv. Concr. Constr.*, 3(1), 15-37.

BCSJ, (1977). “Proposed standard for the use of recycled aggregate and recycled aggregate concrete.” Committee on disposal and reuse of construction waste, Building Con-tractors Society of Japan, Japan.

Binuy, Z. and Chi Sun, P., (2015). “Use of furnace bottom ash for producing lightweight aggregate concrete with thermal insulation properties.” *J. Clean. Prod.*, 99, 94-100.

Borges, P. H. R., Costa, J. O., Milestone, N. B., Lynsdale, C. J. and Streffield, R. E., (2010). “Carbonation of CH and C-S-H in composite cement pastes containing high amounts of BFS.” *Cem. Concr. Res.*, 40(2), 284-292.

Bru, K., Touzé, S., Bourgeois, F., Lippiatt, N. and Ménard, Y., (2014). “Assessment of a microwave-assisted recycling process for the recovery of high-quality aggregates from concrete waste.” *Int. J. Mineral Process.* 126, 90-98.

BS 8500-2, (2002). “Concrete - complementary British standard to BS EN 206-1, Part 2: Specification for constituent materials and concrete.” British Standards Institution, United Kingdom.

Castellote, M., Fernandez, L., Andrade, C. and Alonso, C., (2009). “Chemical changes and phase analysis of OPC pastes carbonated at different CO₂ concentrations.” *Mater. Struct.*, 42(4), 515-525.

Chen, J. J., Thomas, J. J. and Jennings, H. M., (2006). “Decalcification shrinkage of cement paste.” *Cem. Concr. Res.*, 36(5), 801-809.

Cheng, H. L. and Wang, C. Y., (2004). “Improvement of recycled aggregate quality by pre-soaking with water glass.” *Gypsum Cem. Build.*, 12, 12-14.

Choi, H., Choi, H., Lim, M., Inoue, M., Kitagaki, R. and Naguchi, T., (2016). “Evaluation on the mechanical performance of low-quality recycled aggregate through interface enhancement between cement matrix and coarse aggregate by surface modification technology.” *Int. J. Concr. Struct. Mater.*, 10(1), 87-97.

DIN 4226-100, (2002). “Aggregates for mortar and concrete, Part 100: Recycled aggregates.” Deutsches Institut für Normung E.V., Germany.

De Juan, M. S. and Gutiérrez, P. A., (2009). “Study on the influence of attached mortar content on the properties of recycled concrete aggregate.” *Constr. Build. Mater.*, 23(2), 872-877.

Eckert, M. and Oliveira, M., (2017). “Mitigation of the negative effects of recycled aggregate water absorption in concrete technology.” *Constr. Build. Mater.*, 133, 416-424.

Etxeberría, M., Vazquez, E., Mari, A. and Barra, M., (2007). “Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete.” *Cem. Concr. Res.*, 37, 735-742.

Freedonia, (2016). “World construction aggregates – demand and sales forecasts, market share, market size, market leaders.” Cleveland, The Freedonia Group Inc, (Study No 3389).

Grabiec, A. M., Klama, J., Zawal, D. and Krupa, D., (2012). “Modification of recycled concrete aggregate by calcium carbonate biodeposition.” *Constr. Build. Mater.*, 34, 145-150.

Guo, H., Shi, C., Quan, X., Zhu, J., Ding, Y. and Ling, T-C., (2018). “Durability of recycled aggregate concrete - A review.” *Cem. Concr. Compos.*, 89, 251-259.

Haghhighatnejad, N., Mousavi, S. Y., Khaleghi, S. J., Tabarsa, A. and Yousefi, S., (2016). “Properties of recycled PVC aggregate concrete under different curing conditions.” *Constr. Build. Mater.*, 126, 943-950.

Henry, M., Pardo, G., Nishimura, T. and Kato, Y., (2011). “Balancing durability and environmental impact in concrete combining low-grade recycled aggregates and mineral admixtures.” *Resour. Conserv. Recycl.* 55(11), 1060-1069.

Ismail, S. and Ramli, M., (2013). “Engineering properties of treated recycled concrete aggregate (RCA) for structural applications.” *Constr. Build. Mater.*, 44, 464-476.

JIS A 5021, (2005). “Recycled aggregate for concrete-class H.” Japan Standards Association, Japan.

JIS A 5022, (2006). “Recycled aggregate for concrete-class M.” Japan Standards Association, Japan.

JIS A 5023, (2007). “Recycled aggregate for concrete-class L.” Japan Standards Association, Japan.
Jin, R., Li, B., Elamin, A., Wang, S., Tsiofoulou, O. and Wanatowski, D., (2018). “Experimental investigation of properties of concrete containing recycled construction wastes.” *Int. J. Civ. Eng.*, 16(11), 1621-1633.

Katz, A., (2004). “Treatments for the Improvement of Recycled Aggregate.” *J. Mater. Civ. Eng.*, 16(6), 597-603.

Kong, D., Lei, T., Zheng, J., Ma, C., Jiang, J. and Jiang, J., (2010). “Effect and mechanism of surface-coating pozzolanic materials around aggregate on properties and ITZ microstructure of recycled aggregate concrete.” * Constr. Build. Mater.*, 24(5), 701-708.

Kou, S. C. and Poon, C. S., (2010). “Properties of concrete prepared with PVA-impregnated recycled concrete aggregates.” *Cem. Conc. Compos.*, 32(8), 649-654.

Kou, S. C., Zhan, B. J. and Poon, C. S., (2014). “Use of a CO2 curing step to improve the properties of concrete prepared with recycled aggregates.” *Cem. Conc. Compos.*, 45, 22-28.

Lee, C.-H., Du, J.-C. and Shen, D.-H., (2012). “Evaluation of pre-coated recycled concrete aggregate for hot mix asphalt.” * Constr. Build. Mater.*, 28(1), 66-71.

Leite, F. D. C., Motta, R. D. S., Vasconcelos, K. L. and Bernucci, L., (2011). “Laboratory evaluation of recycled construction and demolition waste for pavements.” * Constr. Build. Mater.*, 25, 2972-2979.

Li, J., Xiao, H. and Zhou, Y., (2009). “Influence of coating recycled aggregate surface with pozzolanic powder on properties of recycled aggregate concrete.” * Constr. Build. Mater.*, 23(3), 1287-1291.

Like, Q., Yong, L., Jun, D. and Pengfei, T., (2016). “Thermal stress distribution and evaluation of concrete particles under microwave irradiation.” *J. Eng. Technol. Rev.*, 9(3), 148-154.

Lippiatt, N. and Bourgeois, F., (2012). “Investigation of microwave-assisted concrete recycling using single-particle testing.” *Mineral Eng.*, 31, 71-81.

Malešev, M., Radonjanin, V. and Marininković, S., (2010). “Recycled concrete as aggregate for structural concrete production.” *Sustain.*, 2(5), 1204-1225.

Ma, X. W., Han, Z.X., Li, X. Y. and Meng, F. N., (2009). “Thermal treatment of waste concrete and the hydration properties of the dehydrated cement paste.” *J. Qingdao Technol. Univ.*, 3(4), 93-97.

Mansur, A. A. P., Santos, D. B. and Mansur, H. S., (2007). “A microstructural approach to adherence mechanism of poly(vinyl alcohol) modified cement systems to ceramic tiles.” *Cem. Conc. Res.*, 37(2), 270-282.

Martirena, F., Castaño, T. and Alujas, A., Orozco-mora los, R., Martínez, L. and Linsel, S., (2017). “Improving quality of coarse recycled aggregates through cement coating.” *J. Sustain. Cement-Based Mater.*, 6(1), 69-84.

Menard, Y., Bru, K., Touze, S., Lemnoign, A., Poirier, J. E., Ruffie, G. and Von Der Weid, F., (2013). “Innovative process routes for a high-quality concrete recycling.” *Waste Manage.*, 33(6), 1561-1565.

Miller, G., (2005). “Running out of gravel and rock.” *Toronto Star*, January 6, A22.

Miyandedi, B. M., Feizbakhash, A., Yazdi, M. A., Liu, Q. F., Yang, J. and Alipour, P., (2016). “Performance and properties of mortar mixed with nano-CuO and rice husk ash.” *Cem. Conc. Compos.*, 74, 225-235.

Mohseni, E., Miyandedi, B. M., Yang, J. and Yazdi, M. A., (2015). “Single and combined effects of nano-SiO2, nano-Al2O3 and nano-TiO2 on the mechanical, rheological and durability properties of self-compacting mortar containing fly ash.” * Constr. Build. Mater.*, 84, 331-340.

Mukharjee, B. B. and Barai, S. V., (2017). “Mechanical and microstructural characterization of recycled aggregate concrete containing silica nanoparticles.” *J. Sustain. Cement-Based Mater.*, 6(1), 37-53.

Mulder, E. and Feenstra, L., (2007). “Closed cycle construction - A process for the separation and reuse of the total C&D waste stream.” In: *Proc. of Sustain. Constr. Mater. Technol.*, London, Taylor & Francis Group, 27-34.

Ogawa, H. and Nawa, T., (2012). “Improving the quality of recycled fine aggregates by selective removal of brittleness defects.” *J. Adv. Concr. Technol.*, 10, 395-410.

Padhi, R. S., Patra, R. K., Mukharjee, B. B. and Dey, T., (2018). “Influence of incorporation of rice husk ash and coarse recycled concrete aggregates on properties of concrete.” * Constr. Build. Mater.*, 173, 289-297.

Pan, G., Zhan, M., Fu, M., Wang, Y. and Lu, X., (2017). “Effect of CO2 curing on demolition recycled fine aggregates enhanced by calcium hydroxide pre-soaking.” * Constr. Build. Mater.*, 154, 810-818.

Pandurangan, K., Dayanithy, A. and Om Prakash, S., (2016). “Influence of treatment methods on the bond strength of recycled aggregate concrete.” * Constr. Build. Mater.*, 120, 212-221.

Pasandin, A. R. and Pérez, I., (2014). “Mechanical properties of hot-mix asphalt made with recycled concrete aggregates coated with bitumen emulsion.” * Constr. Build. Mater.*, 55, 350-358.

Peng, C., (2016). “Calculation of a building’s life cycle carbon emissions based on Ecotect and building information modeling.” *J. Clean. Prod.*, 112, 453-465.

Purushothaman, R., Amirthavalli, R. R. and Karan, L., (2015). “Influence of treatment methods on the strength and performance characteristics of recycled aggregate concrete.” *J. Mater. Civ. Eng.*, 27(5), 04014168.

Qian, C., Wang, J., Wang, R. and Cheng, L., (2009). “Corrosion protection of cement-based building materials by surface deposition of CaCO3 by Bacillus pasteurii.” *Mater. Sci. Eng. C.*, 29(4), 1273-1280.

Qiu, J., Qin, D., Sheng-Tng, D. Q. and Yang, E., (2014). “Surface treatment of recycled concrete aggregates through microbial carbonate precipitation.” * Constr. Build. Mater.*, 57, 144-150.

Rahal, K., (2007). “Mechanical properties of concrete...
with recycled coarse aggregate.” Build. Environ., 42(1), 407-415.
Rao, A., Jha, K., N. and Misra, S., (2007). “Use of aggregates from recycled construction and demolition waste in concrete.” Resour. Conserv. Recycl., 50, 71-81.
Saotome, T., (2007). “Development of construction and demolition waste recycling in Ontario.” School of Engineering Practice SEP 704, McMaster University, Hamilton, ON, Canada.
Saravanakumar, P and Dhinakaran, G., (2012). “Effect of admixed recycled aggregate concrete on properties of fresh and hardened concrete.” ASCE J. Mater. Civ. Eng., 24(4), 494-498.
Saravanakumar, P and Dhinakaran, G., (2013). “Durability characteristics of recycled aggregate concrete.” Struct. Eng. and Mech., 47(5), 701-711.
Shayan, A. and Xu, A., (2003). “Performance and properties of structural concrete made with recycled concrete aggregate.” ACI Mater. J., 100(5), 371-380.
Shi, C., Wu, Z., Cao, Z., Ling, T., C. and Zheng., J., (2018). “Performance of mortar prepared with recycled concrete aggregate enhanced by CO₂ and pozzolan slurry.” Constr. Build. Mater., 86, 130-138.
Shima, H., Tateyashiki, H., Matsuhashi, R. and Yoshida, Y., (2005). “An advanced concrete recycling technology and its applicability assessment by the input-output analysis.” J. Adv. Concr. Technol., 3(1), 53-67.
Silva, R. V., Neves, R., De Brito, J. and Dhir, R. K., (2015). “Carbonation behaviour of recycled aggregate concrete.” Cem. Concr. Compos., 62, 22-32.
Singh, N. B. and Rai, S., (2001). “Effect of polyvinyl alcohol on the hydration of cement with rice husk ash.” Cem. Concr. Res., 31(2), 239-243.
Smith, J.T., Tighe, S.L., Norris, J., Kim, E. and Xu, X., (2008). “Coarse recycled aggregate concrete pavements-design, instrumentation, and performance.” In: Proceedings of annual conference of the Transportation Association of Canada, Toronto, ON, Canada.
Spaeth, V. and Djerbi Tegguer, A., (2013). “Improvement of recycled concrete aggregate properties by polymer treatments.” Int. J. Sustain. Built Environ. 2(2), 143-152.
Spaeth, V., Delplancke-Ogletree, M. P. and Lecomte, J. P., (2008). “Hydration process and microstructure development of integral water repellent cement based materials.” In: Proceeding of 5th International Conference on Water Repellent Treatment of Building Materials, 254, 245-254.
Sui, Y. and Mueller, A., (2012). “Development of thermo-mechanical treatment for recycling of used concrete.” Mater. Struct., 45, 1487-1495.
Sun, Y. D., Xiao, J. Z., (2004). “Aggregate of recycled concrete.” Concrete, 176(6), 33-36.
Tabsh, S., W. and Abdel fattah, A., S., (2009). “Influence of recycled concrete aggregates on strength properties.” Constrstr. Build. Mater., 23, 1163-1167.
Tam, V. W. Y., Gao, X. F. and Tam, C. M., (2005). “Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach.” Cem. Concr. Res., 35, 1195-1203.
Tam, V. W. Y., Tam, C. M. and Le, K. N., (2007). “Removal of cement mortar remains from recycled aggregate using pre-soaking approaches.” Resour. Conserv. Recycl., 50, 82-101.
Tam, V. W. Y. and Tam, C. M., (2008). “Diversifying two-stage mixing approach (TSMA) for recycled aggregate concrete: TSMAs and TSMAsc.” Constr. Build. Mater., 22, 1068-2077.
Thiery, M., Danla, P., Belin, P., Habert, G. and Roussel, N., (2013). “Carbonation kinetics of a bed of recycled concrete aggregates: A laboratory study on model materials.” Cem. Concr. Res., 46, 50-65.
Tripura, D., D., Raj, S., Mohammad, S. and Das, R., (2018). “Suitability of recycled aggregate as a replacement for natural aggregate in construction.” ACI Mater. J., 326, 37-1-37-10.
Tsujino, M., Noguchi, T., Tamura, M., Kanematsu, M. and Maruyama, I., (2007). “Application of conventionally recycled coarse aggregate to concrete structure by surface modification treatment.” J. Adv. Concr. Technol., 5(1), 13-25.
Turley, W., (2018). “Construction recycling & demolition recycling information by material: concrete.” Chicago, 5(2).
WBTc, (2002). “Specifications facilitating the use of recycled aggregates.” Works Bureau Technical Circular 12/2002, 209/32/105, Hong-Kong.
Wang, L., Wang, J., Qian, X., Chen, P., Xu, Y. and Guo, J., (2017). “An environmentally friendly method to improve the quality of recycled concrete aggregates.” Constr. Build. Mater., 144, 432-441.
Xuan, D., Zhan, B. and Poon, C. S., (2017). “Durability of recycled concrete prepared with carbonated recycled concrete aggregates.” Cem. Conc. Compos., 84, 214-221.
Yang, J., Du, Q. and Bao, Y., (2011). “Concrete with recycled concrete aggregate and crushed clay bricks.” Constr. Build. Mater., 25, 1935-1945.
Yang, J., Mohseni, E., Behforouz, B. and Khotbehsara, M. M., (2015). “An experimental investigation into the effects of Cr₂O₃ and ZnO₂ nanoparticles on the mechanical properties and durability of self-compacting mortar.” Int. J. Mater. Res., 106(8), 886-892.
Yang, L., Qian, Y., Fang, Q. and Han, Y., (2016). “Effects
of recycled coarse aggregate reinforcing treated by water-glass on the performance of recycled concrete.”
In: *Proceedings of the 3rd International Conference on Material Engineering and Application (ICMEA 2016)*, Adv. Eng. Res. 103, 181-186.

Yang, Y., Ying, C., Sierens, Z., Fan, H. and Li, J., (2018). “Efficient recycling and reuse of waste concrete on a construction site.” *ACI Mater. J.*, 326, 38.1-38.10.

Yoda K., Harada M. and Sakuramoto F., (2003). “Field application and advantage of concrete recycled in-situ recycling systems.” London, E14 4JD, United Kingdom: Thomas Telford Services Ltd.

Yonezawa T., Kamiyama Y. and Yanagibashi K., (2001). “A study on a technology for producing high quality recycled coarse aggregate.” *Zairyo/J Soc Mater Sci Jpn.*, 50(8), 835-42.

Zhang, J., Shi, C., Li, Y., Pan, X., Poon, C. and Xie, Z., (2015a). “Performance enhancement of recycled concrete aggregates through carbonation.” *J. Mater. Civ. Eng.*, 27(11), 04015029.

Zhang, J., Shi, C., Li, Y., Pan, X., Poon, C. S. and Xie, Z., (2015b). “Influence of carbonated recycled concrete aggregate on properties of cement mortar.” *Constr. Build. Mater.*, 98, 1-7.

Zhang, H., Zhao, Y., Meng, T. and Shah, S. P., (2015c). “The modification effects of a nano-silica slurry on microstructure, strength, and strain development of recycled aggregate concrete applied in an enlarged structural test.” *Constr. Build. Mater.*, 95, 721-735.

Zhang, J., Taylor, P. and Shi, C., (2015d). “Investigation of approaches for improving interfacial transition zone related freezing-and-thawing resistance in concrete pavements.” *ACI Mater. J.*, 112(5), 613-618.

Zhang, Z. and Wang, B., (2016). “Research on the life-cycle CO₂ emission of China’s construction sector.” *Energy Build.*, 112, 244-255.

Zhao, T., Wittmann, F. H., Jiang, R. and Li, W., (2011). “Application of silane-based compounds for the production of integral water repellent concrete.” In: *Hydrophobe VI, 6th International Conference on Water Repellent Treatment of Building Materials*. 137-144.

Zhu, Y. G., Kou, S. C., Poon, C. S., Dai, J. G. and Li, Q. Y., (2013). “Influence of silane-based water repellent on the durability properties of recycled aggregate concrete.” *Cem. Concr. Compos.*, 35(1), 32-38.