International Journal of Environmental Science and Technology (2023) 20:521–536
https://doi.org/10.1007/s13762-022-04015-z

ORIGINAL PAPER

Feasible techniques for valorisation of construction and demolition waste for concreting applications

H. M. S. C. H. Bandara[1] · G. Thushanth[1] · H. M. C. C. Somarathna[1] · D. H. G. A. E. Jayasinghe[2] · S. N. Raman[3]

Received: 22 November 2021 / Revised: 12 January 2022 / Accepted: 3 February 2022 / Published online: 26 February 2022

Abstract

Considering that the production of concrete is a resource and energy intensive process, the utilisation of recycled aggregates is one of the approaches that can be adopted to circumvent the issue of high extraction of natural aggregates (NA). In addition, construction and demolition (C&D) wastes are dumped in landfills, resulting in social, environmental and economic difficulties. The present study focuses on the use of recycled concrete aggregates (RCA) from C&D waste as coarse aggregates for concreting applications. A low-cost and simplified treatment method was used for valorise waste generated from demolition of concrete structures. Crushed RCA were placed in a drum type concrete mixer and rotated with water at a speed of 10 rpm for 30 min. Results showed that the remaining adhered mortar adversely affects aggregate properties, with a reduction in density and increases in porosity, aggregate impact value, Los Angeles abrasion value and water content compared with those of NA. The complete substitution of coarse aggregates with RCA reduced slump, density, dry and wet compressive strength by 47%, 1.8%, 28% and 27%, respectively, but enhanced water absorption by up to 5.6%. Results showed that proposed technique provides feasible and cost-effective way for valorisation. The manufacture of quality RCAs is essential and the removal level of adhered mortar will determine RCA quality, and consequently, the quality of concrete. To meet standard requirements for structural concrete, RCA can be used to replace NA by implementing proper control of the proposed valorisation technique, subsequently conserving natural resource for sustainable future.

Keywords Construction and demolition (C&D) waste · Resource conservation · Recycled concrete aggregates (RCA) · Valorisation of waste · Structural concrete · Sustainability

Introduction

Ensuring sustainable consumption and production patterns were pointed out as a key goal by United Nations Development Programme due to the high global consumption of the natural environment and resources in a way that leads to having destructive impacts on the planet. Conservation of resources and sustainable consumption is mandatory towards achieving a sustainable and resilient future, and waste reduction and recycling is a highly viable approach to attain it. Concrete is recognised as one of the most highly consumed materials, and it is associated with a relatively high global carbon footprint due to the massive amount of concrete produced worldwide and the relatively high embodied carbon (Xiao et al. 2018). The total aggregates of concrete account for approximately 70% to 80% of its total volume, and coarse aggregates comprise up to 40%–50% total concrete volume (Mcginnis et al. 2017; Shetty 2008). The production of natural aggregates (NA), such as a mining process, generally occurs in vast aggregate quarries, involves heavy equipment and consumes an excessive amount of energy. Challenges may develop in the construction industry due to depletion and scarcity of sources, high extraction rates of natural resources, natural resource conservation, restrictions on opening new sources and increased production cost

Editorial responsibility: J Aravind.

✉ H. M. C. C. Somarathna
hmccsomarathna@eng.jfn.ac.lk

[1] Department of Civil Engineering, Faculty of Engineering, University of Jaffna, Ariviyal Nagar, Killinochchi 44000, Sri Lanka

[2] Department of Engineering Technology, Faculty of Technology, University of Jaffna, Ariviyal Nagar, Killinochchi 44000, Sri Lanka

[3] Civil Engineering Discipline, School of Engineering, Monash University Malaysia, Jalan Lagoon Selatan, 47500 Bandar Sunway, Selangor, Malaysia

(Kurda et al. 2018; Mcginnis et al. 2017; Tam et al. 2018). In recent decades, recycled aggregates (RAs) have gradually gained attraction because of their benefits for a sustainable future due to the reduction of environmental impact associated with NA production (Almeida et al. 2007). The use of RAs was first reported in Europe after World War II (Le and Bui 2020). In the past few decades, however, awareness and tendency towards using RAs in concrete are increasing globally with a goal of conserving natural resource towards their responsible consumption and production (González-Fonteboa and Martínez-Abella 2008). Several recent studies have confirmed the viability of using alternatives to aggregates, such as manufactured sand (Shen et al. 2018, 2016), agricultural waste (Jaya and Sekar 2016; Kanojia and Jain 2017), clay bricks (Zhang et al. 2020), crumb rubber (Li et al. 2019; Sofi 2017), glass wastes (Arabi et al. 2019; Belouadah et al. 2019), tiles and ceramics (Kumar et al. 2017), in addition to or as replacements for NA in concrete.

Construction and demolition (C&D) activities are currently amongst the major contributors to environmental damage globally, because these activities produce an enormous amount of waste, making waste management a challenging task (Bravo et al. 2017; Fan et al. 2016; Mcginnis et al. 2017; Omary et al. 2016; Robert et al. 2018; Seara-paz et al. 2018; Silva et al. 2018; Tahar et al. 2017; Tam et al. 2018). The high production of C&D wastes has exerted a huge impact on the society and the environment; accordingly, proper waste management, such as recycling and reusing waste concrete, valorisation of waste and responsible consumption have been promoted (Li et al. 2017; Munir et al. 2019). Waste concrete recycling is a highly acceptable approach worldwide due to its simplicity of operation and implementation and the availability of markets for these products (Wijayasundara et al. 2016; Xiao et al. 2018). RAs derived from waste concrete are called recycled concrete aggregates (RCA). As one of the solutions for conserving natural resource and considering its high potentials, the use of RCA has been increasing and is being encouraged (Brito et al. 2020; Fan et al. 2016; Le and Bui 2020). Furthermore, using RCA provide economical solutions, depending on the local conditions (Arrigoni et al. 2018; Wijayasundara et al. 2016). For example, sorting and selling concrete waste from a construction site to a recycler may be cheaper than dumping the waste on a landfill (Marinković et al. 2010). In addition, demolition cost may be less than the cost of using new materials on the same site. Recycling cost depends on several factors, such as the recycling method, sorting level and sorting method for C&D wastes and the machinery and processing used for RAs (Aslani et al. 2018; Martínez-Lage et al. 2020; Omary et al. 2016).

The performance of RCA as a substitute for NA has been studied by various researchers worldwide (Bravo et al. 2017; Bravo and De Brito 2012; Kou and Poon 2012; Mcginnis et al. 2017; Mefteh et al. 2013). When aggregates were replaced completely, most of the aforementioned studies found that the loss of concrete compressive strength reached up to 30%; moreover, water demand increased to overcome the flow difficulties of fresh concrete (Berredjem et al. 2020; Mcginnis et al. 2017; Mefteh et al. 2013). The performance of concrete with RCA varies depending on the source of the original aggregates and the adopted recycling process for RCA to remove the adhered mortar content (Mcginnis et al. 2017; Puthussery et al. 2017; Rahal 2007). Thus, the production process of RCA is a main criterion that affects the remaining adhered mortar content and properties of the final product (Fan et al. 2016). Some researchers have studied various methods for producing RCA to achieve improved properties, mostly methods for removing adhered mortar paste via heat treatments (Akbarnezhad et al. 2011), and acetic acid (Wang et al. 2017), and further enhancement of the quality with polymer emulsion (Kou and Poon 2010). Summary of the valorisation techniques used to remove adhered mortar from RCAs and their key findings are listed in Table 1. To enhance the properties of RCA, a treatment method that is capable of removing the adhered mortar at the maximum level is required to reduce the negative effects. In addition, such method will enhance bonding between RCA and the new mortar and decrease the pore size of the remaining adhered mortar and the width and length of cracks in the old interfacial transition zone; consequently, the quality of RCA is improved. Available studies have concluded that the attached mortar content increases with a decrease in RCA particle size (Bai et al. 2020; Berredjem et al. 2020; Wang et al. 2020). Most of the above valorisation methods required high cost for the material, equipment and expertise.

The development of concrete with RCA is still in infancy in many developing countries, like Sri Lanka. Therefore, a study on the feasibility of developing concrete with RCA obtained with simple techniques will provide new knowledge to the scientific, social and technical aspects of the construction industry and waste management for developing economies. Very limited studies have been conducted in Sri Lanka to evaluate the feasibility of using RAs in concrete (Gobieanandh and Jayakody 2016; Jayakody et al. 2018; Karunaratne et al. 2013; Mithushan et al. 2017). Given the limited number of studies conducted in this area, the use of RCA in construction in Sri Lanka remains behind compared with those in other countries worldwide. Consequently, understanding the characteristics of RCA with new valorisation techniques is critical for assuring the feasibility of RCA application (Puthussery et al. 2017). In the current study, RCA were produced with simple valorisation technique and used as a replacement for NA in concrete to produce normal-grade concrete with a target compressive strength of 30 MPa. Feasible techniques for valorisation of C&D waste for concreting applications RCA were produced

Table 1 Summary of the valorisation techniques used to remove adhered mortar from RCAs and their key findings

Study	Valorisation technique used to remove adhered mortar from RCAs	Key observations
Sim and Park (2011)	Advanced recycling process that involved water floatation and air blowing to produce RCAs	Satisfied the requirements of aggregates except for the relatively higher water absorption of the RCA
Juan and Gutiérrez (2009)	Thermal treatment method (involved a number of cycles of heating up to 500 °C and soaking in water)	It is easier to perform and can be used for all types of aggregates, including limestone. However, the cost for the production was higher due to the heat treatment
Al-Bayati et al. (2016)	Pre-soaking in an acidic solution, followed by heating	Excessive acid solution concentration and high temperature for heating RCA are not good for reducing the porosity of RCA
Montgomery, (1998)	Ball milling and hot grinding technique	One of the most effective, with lower variability compared with other methods
Ma et al. (2009)	Heating technique, followed by grinding	Adverse performance of RCAs due to the formation of microcracks during the grinding process
Katz (2004)	Ultrasonic water cleaning process,	Suitable for separating mortar with weak adhesion but not mortar with strong adhesion
Shi et al. (2016)	Ultrasonic cleaning method	Cannot remove the attached strong mortar on the surface of RCA, and require high energy consumption
Dimitriou et al. (2018)	Crushed and washed, then, submerged into a 0.1 M hydrochloric acid solution for 24 h	Removed adhered mortar by 54%–76% of the initial mass of RCAs
	Crushed and washed, then submerged into a 2 M sulphuric acid solution for 5 days and then washed and filtered through a 4.75 mm sieve,	Removed adhered mortar by 12%–20% of the initial RCA mass
Tam et al. (2007)	Immersed RCAs into an acid solution,	Increasing the acid content of RCAs and exhibiting low feasibility with high cost
Fan et al., (2016)	Roller sand washing, and wheeled sand washing	Roller sand washing gives a larger amount of cement paste than does wheeled sand washing and therefore has lower density and higher water absorption
Choi et al. (2014)	Microwave heating	Effectively heated the iron oxide contained in the surface modification coarse paste of RCA
Wang et al. (2017)	RCAs are first soaked in acetic acid solution, followed by mechanical rubbing	Zero hazardous waste solution is generated, the waste solution of the treatment can be used as admixture for new concrete
Tam et al., (2020)	Injection of CO2 into recycled aggregate	Carbon-conditioning permits a prompt and complete carbonation of recycled aggregate

using simple techniques that are attainable in any region worldwide. Investigations were performed to study the influenced of the proposed valorisation technique on the major characteristics of RCA and concrete with RCA.

Materials and methods

Materials

Ordinary Portland cement (strength class: 42.5 N; UltraTech Cement, India) and normal tap water (pH of the water is 7.11) were used throughout the experimental programme. 19.5 mm downgraded crushed stones and 4.75 mm downgraded river sand were used as natural coarse aggregates, and fine aggregates, respectively. Natural coarse and fine aggregates were obtained from Mannar region, Sri Lanka. Natural coarse aggregates used can be classified as angular crushed rocks with well-defined edges formed at the intersections of roughly planar faces (Shetty 2008).

Recycled concrete aggregates (RCA)

The C&D waste required to produce the RCA were sourced from Oddusuddan region in Sri Lanka. All the processes for obtaining RCA from waste concrete were performed in collaboration with Business Promoters & Partners Engineering (Pvt) Ltd. The preparation of RCA involved six major steps as illustrated in Fig. 1.

During the identification of waste concrete, the strength of waste concrete was firstly checked before producing RCA. The core test was conducted using a 100 mm-diameter concrete core, and the density and strength were measured. The average cylinder compressive strength and waste concrete density were 18.6 MPa and 1326 kg/m^3, respectively. In the second step, waste concrete components were separated from C&D wastes because they consist of several waste categories, such as concrete, masonry, timber, paper, plastics, metals, glass and rubble. Larger concrete blocks were broken into concrete parts (1–2 feet) using concrete breakers, and reinforcements were removed up to an acceptable level for further crushing. A primary jaw crusher was used to crush concrete debris into concrete parts measuring approximately 75 mm (3 inch). A cone crusher was used to break the broken particles into a maximum size of between 19 mm (0.75 inch) and 50 mm (2 inch) in accordance with the requirement. Screening was conducted after the crushing process, and the remaining aggregates from the 40 mm sieve were returned to the crushing process.

In the present study, a low-cost simple valorisation method was used to remove the remaining adhered mortar. Crushed RCA aggregates were placed in a drum type of concrete mixer and rotated with water at a speed of 10 rpm for 30 min. Water was added to break the bond between the virgin aggregates and the adhered mortar, and to remove dust and fine particles. Subsequently, the aggregates were dried and passed through a 19.5 mm sieve to discard aggregates with sizes larger than 19.5 mm. Figure 2 shows the morphological appearance of natural coarse aggregates and RCA.

Investigation of aggregate characteristics

Specific gravity and water absorption were determined in accordance with ASTM C-127 (2015). Density was calculated, and relative density (specific gravity) was found on the basis of the obtained masses. Water absorption was determined in accordance with the continuous hydrostatic weighing method. Sieve analysis was conducted in accordance with the specifications of ASTM C-136 (2015). Meanwhile, ASTM C-131 (2015) was adopted to assess the aggregate impact value (AIV) of both aggregate types. The Los Angeles abrasion value (LAAV) test was conducted in accordance with ASTM C-131 (2015).

Preparation of concrete specimens with RCA

The potential of using RCA manufactured with proposed valorisation technique as a replacement for NA in concrete was studied by preparing concrete with different mix proportions of RCA. The concrete mix design was established in accordance with the British design of experiment method, and the target concrete strength was 30 MPa. NA were replaced with RCA at different volume percentages ranging from 0 to 100% to the total coarse aggregate volume. Six different mixtures were prepared by varying NA and RCA as mix and the details of the six mixtures are provided in Table 2. The water/cement (W/C) ratio was set as 0.5 throughout the study.

The grading of RCA was brought similar to the grading of particle size in NA (coarse) to minimise the effect of aggregate grading on concrete properties. Different particle size distributions affect the packing of concrete, which influences the overall performance of concrete properties. Concrete cubes with dimensions of 150 × 150 × 150 mm were prepared. The test specimens were stored under ambient condition for 24 h. Subsequently, the specimens were labelled, removed from the moulds and submerged in clear freshwater at ambient temperature until the testing day.

Investigation of concrete characteristics

The workability of concrete was determined by analysing the slump value of each concrete mix in accordance with

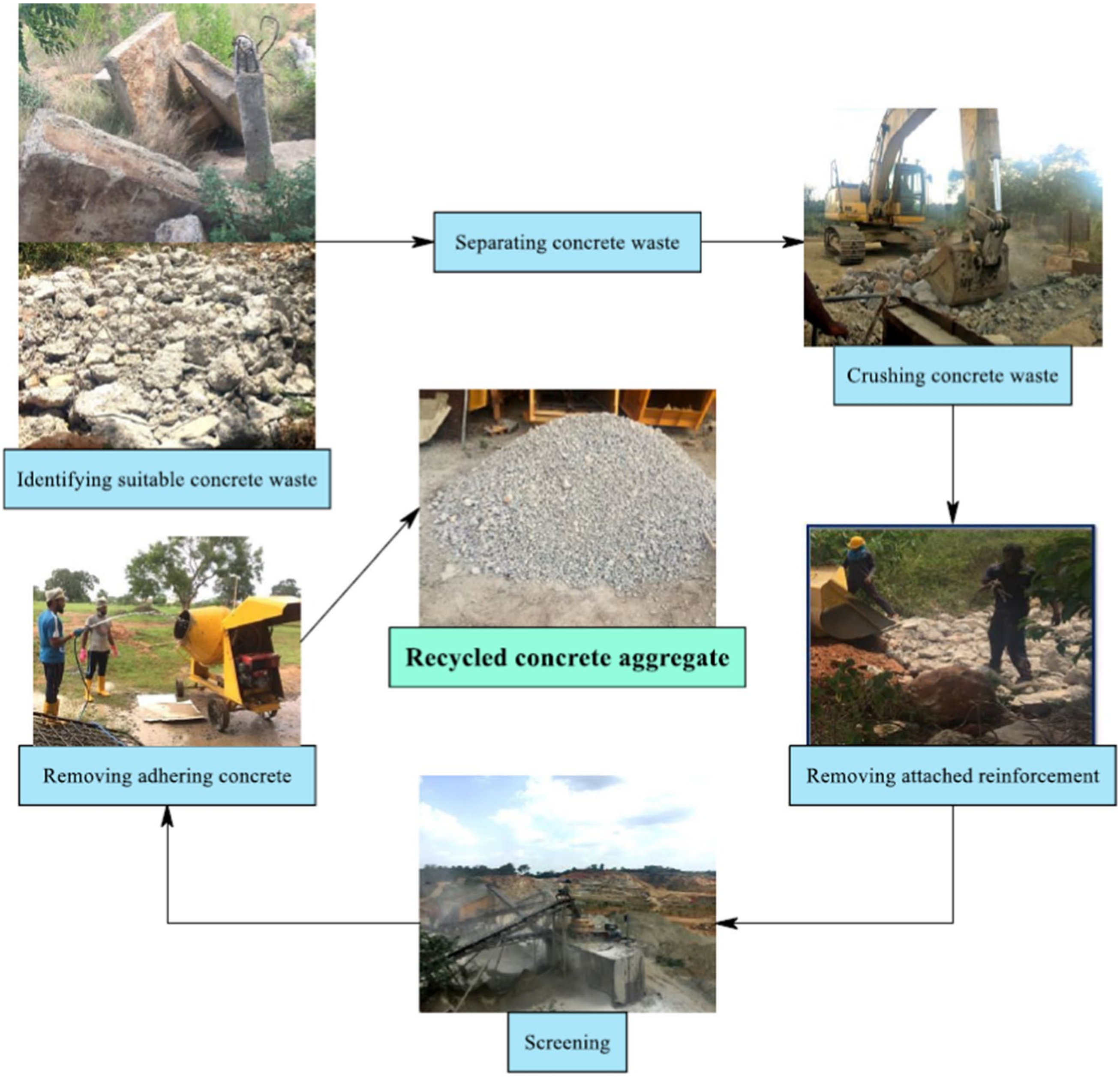

Fig. 1 Major steps in RCA preparation

ASTM C-143 (2015). The density of the hardened concrete was determined in accordance with ASTM C138/C138M (2017) using cube specimens with dimensions of 150 × 150 × 150 mm. The specimens were weighed at 28 days under dry and wet conditions. The weight of the specimens was measured using an electronic weighing scale with an accuracy of 0.005 kg. The dimensions of the specimens were measured using a Vernier calliper with a minimum scale of 0.01 mm. The concrete cube specimens (150 × 150 × 150 mm) were used to determine the compressive strength in accordance with ASTM C-39 (2014) at three ages: 7, 14 and 28 days. A water absorption test was conducted following the ASTM C-1585 (2013) standard. The specimens at 28 days were firstly placed in an oven at 105 ± 5 °C and then dried until they achieved a constant weight. The specimens were immersed in water to achieve a saturated surface dry condition before being weighed.

Fig. 2 Morphological appearance of NA (coarse) and RCA

NA (coarse) RCA

Table 2 Details of the mix design proportions of coarse aggregates

Concrete type	Aggregate ratio NA/RCA (v/v)	Cement [kg/m^3]	Water [kg/m^3]	Fine aggregate [kg/m^3]	Coarse aggregates [kg/m^3]	
					NA	RCA
1	100:0	380	190	695	1253	0
2	80:20	380	190	695	1002	226
3	60:40	380	190	695	752	452
4	40:60	380	190	695	501	677
5	20:80	380	190	695	251	903
6	0:100	380	190	695	0	1129

Results and discussion

Characteristics of aggregates

RCA obtained from C&D wastes contain the original aggregates with bonded hydrated cement paste around them. As shown in Fig. 2, RCA have a rougher surface than NA (coarse) and a more greyish colour. Colour of the parent rock of RCA were observed by crushing them and compared with NA (coarse) and showed almost similar colour. The difference in surface roughness and colour is primarily caused by the remaining adhered mortar paste around RCA. Moreover, the remaining mortar adhered on RCA makes the aggregates slightly larger than their original size. The surface of NA is smooth and has few pores. By contrast, the surface of RCA has many irregular pores and loose particles, which may affect the hydration of cement and the formation of $Ca(OH)_2$ and ettringite, and consequently, the properties of concrete (Wang et al. 2020). The adhered amount of mortar is not uniform in RCA, and thus, a proper control of the removal process is necessary to obtain a uniform surface condition for RCA, such that rpm value of the concrete mixture or rotating time should be controlled properly. Furthermore, the attached mortar content increases with a decrease in aggregate size as a percentage of the weight of virgin aggregates.

Table 3 Comparison of characteristics of natural and recycled aggregates

Aggregate characteristic	Natural aggregates		Recycled concrete aggregates	
	Avg	Stdv	Avg	Stdv
Density (compacted) (Kg m^{-3})	1580	18	1544	24
Density (loose) (Kg m^{-3})	1375	16	1371	14
Water absorption (%)	1.12	0.06	5.67	0.19
Fineness modulus	7.29	0.16	6.78	0.22
AIV (%)	21.92	0.67	28.67	0.02
LAAV (%)	18.81	1.32	36.44	2.61

Experimental analysis conducted in this study showed that RCA exhibited lower densities than NA under loose and compacted conditions, as indicated in Table 3. RCA present less relative density than NA, and their relative densities are 2.54 and 2.82, respectively. The bulk density of both aggregate types is within the required limits on the basis of the ACI E-701 standard, with both values within 1200–1700 kg/m^3. A conclusion can be drawn that the density of RCA is lower than that of NA primarily due to the old cement paste attached to virgin aggregates which increase the porosity of the aggregates. Past studies have indicated a reduction in specific gravity, and it is reduced with the percentage of the remaining mortar content, with the specific gravity of RCA ranging from 1.91 to 2.70 (Deiyagala et al. 2017). However, some researchers have asserted that the low relative density of RCA can be attributed more to the quality of virgin aggregates than to the amount of adhered mortar paste (Duan and Poon 2014; Omary et al. 2016; Younis and Pilakoutas 2013).

As presented in Table 2, the RCA used in this study have greater water absorption than NA (coarse). Higher water absorption indicates the high porosity of RCA as a result of the remaining attached mortar paste. It can also be due to the cracks in the old interfacial transition zone, which increase water demand. Consequently, density is lower and water absorption is higher. This phenomenon has been observed by others researchers, i.e. water absorption is increased by increasing the mortar content of RCA (Duan and Poon 2014; Younis and Pilakoutas 2013; Zega et al. 2010). Deiyagala et al. (2017), Mithushan et al. (2017) and Karunaratne et al. (2013) observed 3.60%, 4.39% and 2.82% water absorption values for RCA in their respective research. Fakitsas et al. (2012) submerged RCA in water for 3 days and then surface-dried them for 12 h prior to use, resulting in 80%–90% saturation degree, and their results of the compressive tests showed the strength enhancement of concrete with RCA at 28 days and 90 days. This positive result was attributed to the internal curing due to the higher water absorption and retention abilities of RCA. In particular, water absorbed by RCA may weaken the initial hydration process. However, the slow release of absorbed water can accelerate the late hydration process, reducing the self-drying of the new cement matrix and densifying the interfacial transition zones (Wang et al. 2020). To minimise the effect of the higher water absorption of RCA, the pre-wetting of RCA or adjusting water addition to the concrete mix is possible. However, Matias et al. (2014) observed an increment in dry shrinkage after pre-soaking RCA for 24 h because this process will increase the amount of entrained water in RCA. Recently, CO_2 treatment has been used for RCA to reduce porosity and water absorption. Thereafter, CO_2 is chemically and permanently converted into stones. CO_2 treatment can provide the same physical and mechanical properties to concrete with RCA as NA (Tam et al. 2020).

Sieve analysis was conducted for NA (coarse), RCA and fine aggregates (river sand). Figure 3 compares their particle size distribution curves, including the maximum and minimum limits of BS 882:1992. In NA (coarse), 98.3% of the particles are within the 10–37.5 mm range due to the grading process that was performed during manufacturing. RCA contain 12.16% particles smaller than 5 mm, which did not undergo a grading process. Particles smaller than 5 mm should be less than 5% in accordance with BS 882:1992, indicating the necessity of proper screening to remove excess fine particles to achieve acceptable levels. The adhered mortar in waste concrete is the primary reason for the high content of fine particles in crushed RCA. This behaviour and the fine content are dependent on the processing techniques, particularly in this method, speed of the concrete mixture (rpm value) and duration of the rotation. The adhered mortar on RCA was separated in the beginning of the mechanical processing, and subsequently, crumbled and accumulated as fine particles. The fineness modulus was calculated for NA (coarse) and RCA, as shown in Table 3. The findings indicate the higher content of fine particles in RCA due to the crushed mortar during RCA production. The crushing process of the mortar produced fine particles less than 5 mm.

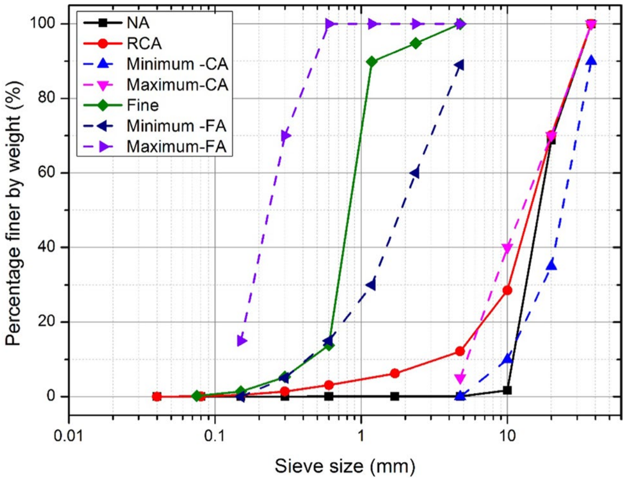

Fig. 3 Particle size distribution curves of NA (coarse) and RCA

AIV is a measure of resistance to sudden impact or shock of aggregates. The AIV values of RCA and NA (coarse) were determined and the findings are listed in Table 3. The significant deviation in AIV was caused by the remaining mortar adhered on RCA. The bond within aggregate particles is considerably higher than the bond between adhered mortar particles and aggregate particles. Therefore, impact forces break the bond between the adhered mortar and the coarse aggregates. This bond is easier to break than aggregate particles. Hence, adhered mortar also plays a major role in AIV, and the control removal of adhered mortar is essential. The required AIV for concrete applications should be less 30% in accordance with BS 882:1992. Both types of aggregates presented acceptable AIVs that are within the standard limits. Table 3 provides the average LAAV of NA and RCA obtained from three samples for each type of aggregates. RCA have higher LAAV values than NA probably because they are surrounded by old cement mortar paste with lower wear resistance than rocky materials. Spanish standards specify that LAAV should be less than 40% for structural concrete. LAAV should be less than 50% for structural concrete and less than 40% for pavement concrete in China (Bai et al. 2020). Previous studies have recorded that the LAAV limits for NA and RCA are 11.5%–38.9% and 20%–51.5%, respectively (Karunaratne et al. 2013). Therefore, the obtained results are compatible with the standards and results reported by other researchers. Several studies have asserted that LAAV increases gradually with a decrease in particle size of RCA because the remaining adhered mortar content is high in small aggregate particle size, subsequently increasing the worn parts (Bai et al. 2020).

Characteristics of concrete with RCA

Concrete with RCA is a composite material in which NA are completely or partially replaced with RCA. It contains four zones: NA, RCA, old cement paste and new cement paste. The interfacial transition zone is an interphase in the microstructure between cement paste and aggregates, and the microstructure of concrete with RCA contain five interfacial transition zones: interfacial transition zones between NA and old cement matrix, NA and new cement matrix, RCA and old cement matrix, RCA and new cement matrix and new and old cement matrices (Le and Bui 2020).

All the concrete mixes presented adequate consistency, and the workability of concrete with different RCA contents was measured by slump. The average slump values of the six concrete types are presented in Fig. 4, which shows a gradual reduction in slump with an increase in RCA replacement amount. An adjustable workability was demonstrated until a replacement of 40% RCA (Type 3). When the replacement ratio was 100%, the concrete produced using RCA lost 47% of its workability compared with that produced using NA. This finding can be attributed to RCA having a rougher surface texture, which increases friction among particles. Accordingly, when the RCA replacement ratio was increased, the higher RCA content in the concrete mix produced more friction between particles, reducing slump in concrete. In addition, RCA have higher water absorption due to the remaining mortar adhered on the particles, resulting in low water content during the fresh mortar phase, and subsequently, low workability. Given the high absorption, RCA also have higher water demand than NA. Moreover, the required workability is achievable with high possibility through the addition of admixtures with a low water volume, modifications to the water content and pre-soaking of the aggregates. Furthermore, the removal of adhered mortar on RCA will help the workability of RCA to approach that of NA. Verian et al. (2018) observed that concrete with complete RCA replacement requires 5% to 15% additional water to attain workability similar to that of NA. Falek et al. (2017) reported that concrete with smaller RCAs absorbs a higher quantity of water than concrete with coarse RCAs because adhered mortar content is high in small RCAs.

Figure 5 shows the average densities of six concrete types at 28 days. As shown in the figure, dry density decreased with an increase in RCA replacement ratio. This finding agrees with those of previous studies (Dimitriou et al. 2018). The highest wet density was recorded in 0% RCA, and gradual reduction in wet density is also demonstrated with an increase in RCA replacement. The low specific gravity of RCA compared with that of NA results in the low density of concrete with RCA, and reduction increases with RCA

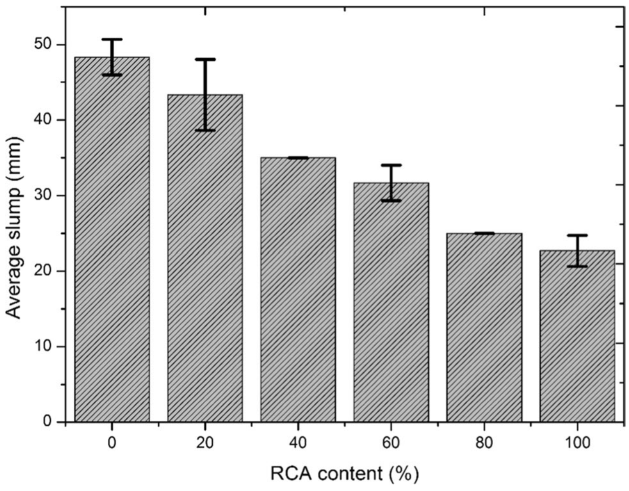

Fig. 4 Slump value variation of concrete with RCA in different types of concrete

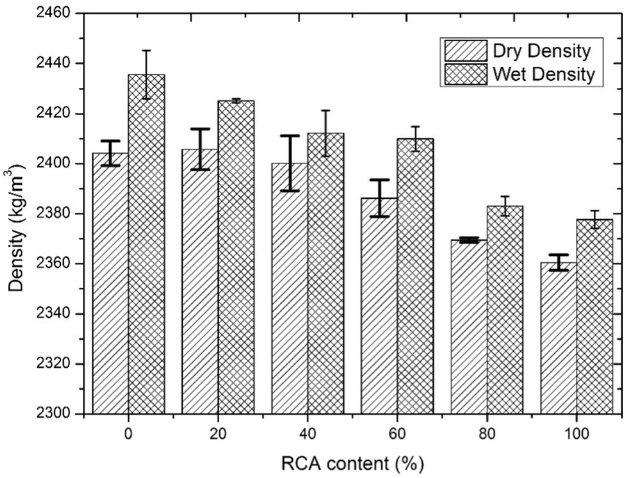

Fig. 5 Density variation of different types of concrete at 28 days

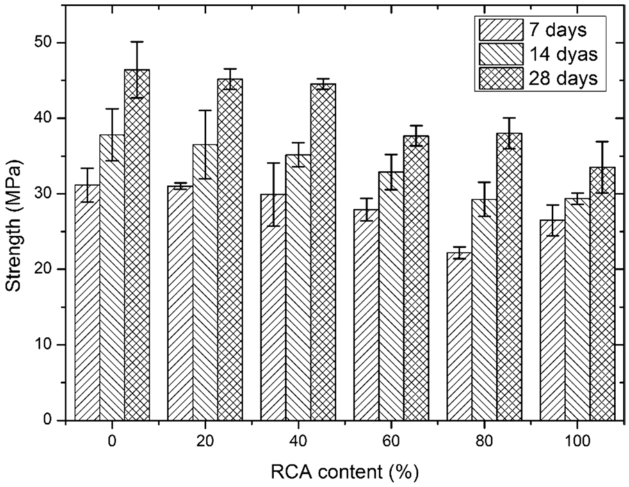

Fig. 6 Dry compressive strength of different types of concrete

Table 4 Relationship between the replacement ratio of RCA and relative compressive strength

Category	Equation	The coefficient of determination, R^2
7 days—Dry	$y = -0.0021x + 1$	0.65
14 days—Dry	$y = -0.0024x + 1$	0.95
28 days—Dry	$y = -0.0025x + 1$	0.90
28 days—Wet	$y = -0.0031x + 1$	0.76

replacement content. In addition, a rougher surface texture and the remaining adhered mortar reduce the packing process, decreasing the final density of the concrete. Furthermore, the high water absorption capacity of RCA reduces workability, and subsequently, a decrease in compaction leads to low density. As shown in Fig. 5, the dry density at 28 days is lower than the wet density at 28 days for each type of concrete due to the absorbed water.

Figure 6 shows the average compressive strength of the six types of concrete. The target compressive strength (i.e. Grade 30) was achieved at 28 days for all concrete types with different RCA replacement ratios. However, an increase in RCA content adversely affected the compressive strength of concrete. The 7-day compressive strength was reduced gradually with an increase in RCA replacement ratio, except for a deviation found in concrete with 80% RCA. A gradual reduction of the 14-day compressive strength was also exhibited with an increase in RCA replacement content, and no difference was observed amongst the 80% and 100% replacement ratios. The 28-day compressive strength variation also presented a steady decrease, with a minor deviation in the 60% and 80% RCA replacement ratios. Concrete with 100% RCA demonstrated 15.0%, 22.3% and 27.8% losses of its compressive strength at 7, 14 and 28 days, respectively. The relationships between RCA replacement ratio and relative dry compressive strength of the three ages were established by considering the linear correlation of RCA replacement ratio and the fraction of compressive strength with respect to the compressive strength of concrete with 100% NA, as plotted in Fig. 7. The respective equation and the coefficient of determination, R^2, obtained for each category are listed in Table 4. These equations can be used as reference for estimating the acceptable RCA replacement ratio for a target compressive strength with a specified mix design. As indicated in available studies, a 95% probability exists that concrete specimens with 100% RCA (coarse) can have approximately 0.766 times lower compressive strength than that of the corresponding concrete specimen with NA (Deiyagala et al. 2017; Karunaratne et al. 2013; Mithushan et al. 2017); this finding agrees with the results obtained from the current study, by indicating the proposed valorisation method of removing adhered mortar with a concrete mixture is an acceptable method (Bai et al. 2020).

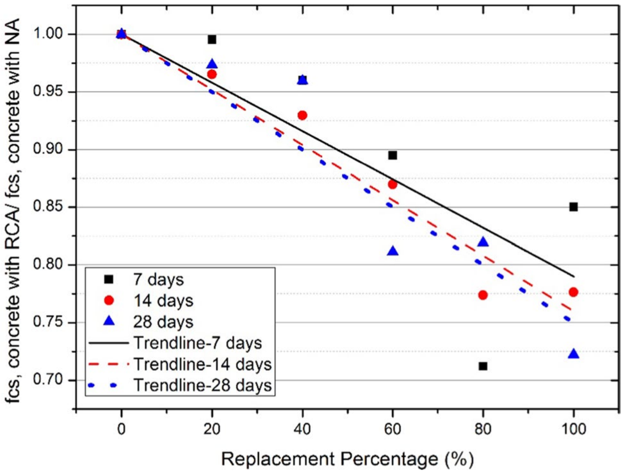

Fig. 7 Relationship between the replacement ratio of RCA and relative dry compressive strength

As a comprehensive observation, strength was reduced with the RCA replacement percentage of NA. This phenomenon may be attributed to several reasons. Firstly, the remaining mortar adhered on RCA results in low workability and a weak bond between aggregates and the cementitious paste phase. Moreover, the surface of RCA contains loose particles that weaken the physical and chemical bonding between RCA and cement paste. Concrete with RCA is more porous than concrete with 100% NA due to the higher porosity of RCA than NA. Therefore, concrete produced with RCAs tends to have less compressive strength than concrete produced with NA. The old mortar has many microcracks that were formed during RCA production, resulting in high porosity. Accordingly, these cracks become the weakest link in RCAs and act as initiators for crack propagation, decreasing the compressive strength of concrete. Given that RCAs have microcracks, a weak bond between RCA and the cement matrix is formed between the old and new interfacial transition zones, causing failure. Furthermore, RCA are weaker than NA, and failure may occur through RCA themselves (i.e. in the interfacial transition zone between RCA and the old cement matrix) instead of in the other interfacial transition zones. Meanwhile, a water film is formed near the aggregates, and a porous Ca $(OH)_2$-rich layer is developed between RCA and cement paste perpendicular to the aggregate surface due to the high water absorption of RCA. These defects in microstructure lead to weak physical and chemical bonding between RCA and cement paste, and consequently, the presence of cracks and pores, weakening mechanical and durability properties (Wang et al. 2020).

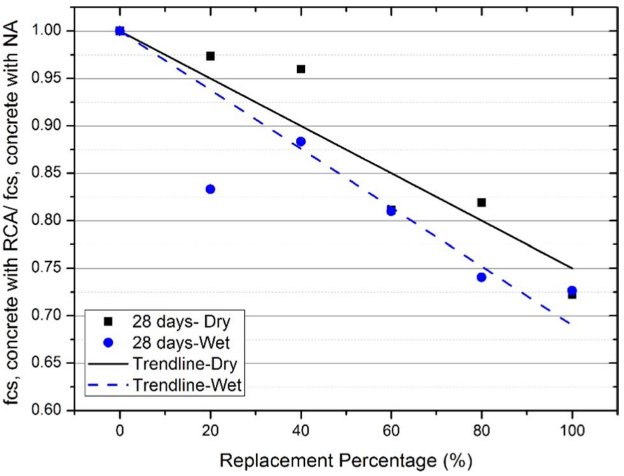

Fig. 9 Relationship between the replacement ratio of RCA and the relative wet and dry compressive strengths

Nevertheless, concrete with RCA can be used as a structural material, depending on compressive strength requirements. For example, when the required compressive strength is 30 MPa, then NA can be replaced with RCA as a structural material in concrete at W/C = 0.5, and the aforementioned mix design, regardless of the replacement ratio. However, if the required compressive strength is higher than 30 MPa, then adjustments can be made to the replacement ratio and the W/C with an appropriate mix design. The comparison of the 28-day dry and wet compressive strengths is illustrated in Fig. 8. With an increase in RCA replacement, wet compressive strength is reduced due to the aforementioned reasons. In addition, a linear relationship is exhibited by wet compressive strength reduction, as shown in Fig. 9 and Table 3. However, only a few studies have reported an enhancement in the compressive strength of concrete with a small proportion of RCA; this finding can be primarily attributed to the good control of RCA grading (Etxeberria et al. 2007; Fonseca et al. 2011).

The results of the water absorption test of the concrete specimens with varying RCA replacement ratios are presented in Fig. 10. Concrete with NA exhibited minimum water absorption capacity, and an increase in absorption was observed with an increment in RCA percentage. The attributes obtained via RCA replacement indicated that RCA have lower density, higher water absorption and higher porosity than NA. Consequently, concrete with RCA presented lower density and higher water absorption than concrete with NA. In particular, the remaining adhered mortar increased the total mortar volume within the concrete, increasing the total voids, and consequently,

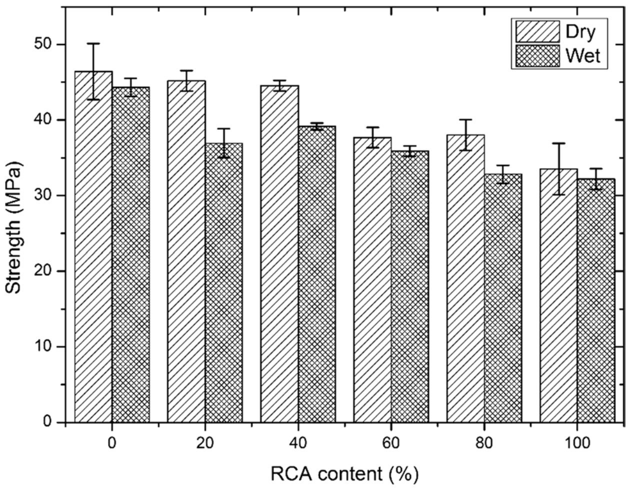

Fig. 8 Dry and wet compressive strengths of different types of concrete at 28 days

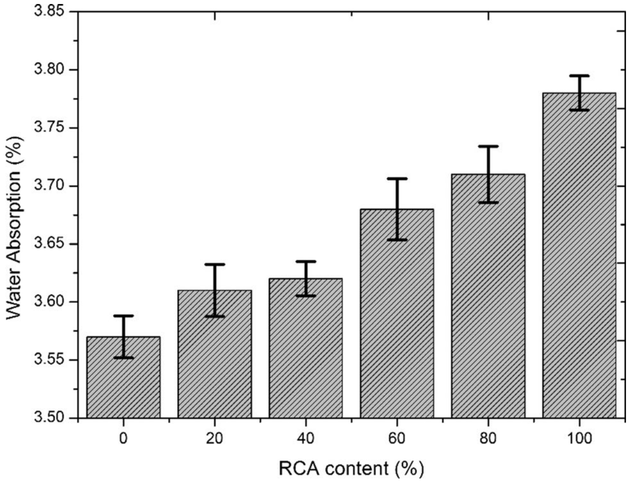

Fig. 10 Comparison of the water absorption of each concrete type

Table 5 Comparison of the present study with the findings of recent literature

Concrete characteristics	Findings of the present study	Findings of the recent studies	
Dry density	1.8% reduction with 100% replacement	3.2, 3.3, 4.0, 4.5% reductions in four different types of RCA with 100% replacement	Fan et al., (2016)
		1% reduction with 100% replacement	Deiyagala et al., (2017)
		3.3% reduction with 100% replacement	Etxeberria et al., (2007)
		4.9% reduction with 100% replacement	Poon et al., (2002)
		6.07% reduction with 100% replacement	Puthussery et al., (2017)
Wet density	2.4% reduction with 100% replacement	Not reported	
Workability (concrete slump)	An adjustable workability until 40% replacement. 47% of lost with 100% replacement	36.4% reduction with 100% replacement	Karunaratne et al. (2013)
		38.3% reduction with 100% replacement	Karunaratne et al., (2013)
Dry compressive strength (7 days)	15% increment with 100% replacement	14.4%, 20.9%, 35.7%, 51.2% reductions for four different types of RCA with 100% replacement	Fan et al., (2016)
		25% reduction with 60% replacement	Jayakody et al., (2018)
		7.1% reduction with 100% replacement	Deiyagala et al., (2017)
		19.2% reduction with 100% replacement	Kou and Poon, (2012)
Dry compressive strength (14 days)	22.4% increment with 100% replacement	12.0%, 18.0%, 21.0%, 46.1% reductions for four different types of RCA with 100% replacement	Fan et al., (2016)
		5.6% reduction with 100% replacement	Deiyagala et al., (2017)

Table 5 (continued)

Concrete characteristics	Findings of the present study	Findings of the recent studies	
Dry compressive strength (28 days)	27.8% increment with 100% replacement	Reduction of 22% with 100% replacement	Deiyagala et al. (2017)
		Reductions of 5% and 15% for the target strengths of 30 MPa and 25 MPa with 100% replacement	Mithushan et al. (2017)
		17.9% reduction with 100% replacement	Karunaratne et al. (2013)
		26.4% losses with 100% replacement	Mcginnis et al. (2017)
		11.8%, 20.1%, 32.9%, 47.9% reductions for four different types of RCA with 100% replacement	Fan et al., (2016)
		46% reduction with 60% replacement	Jayakody et al., (2018)
		2.8% reduction with 100% replacement	Deiyagala et al., (2017)
		15.5% and 5.1% reductions for concrete grade 25 and 30 with 100% replacement	Mithushan et al., (2017)
		18.8% reduction with 100% replacement	Karunaratne et al., (2013)
		30.82% reduction with 100% replacement	Bahrami et al., (2020)
		28.9% reduction with 100% replacement	Falek et al., (2017)
		3.4% reduction with 100% replacement	Etxeberria et al., (2007)
		13.1% reduction with 100% replacement	Poon et al., (2002)
		21.6% reduction with 100% replacement	Kou and Poon, (2012)
Wet compressive strength	27.4% increment with 100% replacement	Not reported	
Water absorption	5.9% increment with 100% replacement	Enhancement of 63% and 70% for concrete with 25 MPa and 30 MPa target strength	Mithushan et al., (2017)
		24%, 47%, 61%, 110% increments for four different types of RCA with 100% replacement	Fan et al., (2016)
		24% enhancement with 100% replacement	Puthussery et al., (2017)

water absorption. An increase in water absorption is an indicator of high porosity. An increase in capillary porosity and its interconnection increases capillary suction, making concrete with RCA vulnerable to various aggressions. Mithushan et al. (2017) reported that the enhancement of water absorption values was 4.14% and 4.38% for concrete with 25 MPa and 30 MPa target strength, respectively, when NA were completely replaced with RCA. Table 5 provides a comparison of the present study with the findings of recent literature. These findings clearly draw attention to how the production process of RCA can influence the properties of concrete with RCA, and removing the adhered mortar will directly influence the properties of final concrete with RCA. Proposed techniques for valorisation of C&D waste for concreting applications are feasible with the equipment for a production of reasonable quantity of RCA for small-scale application. However, further implementation of equipment is required for production of lager quantity for industrial application.

Conclusion

This research was initiated to evaluate the feasibility of using RCA in place of NA as a structural construction material with a low-cost and simple valorisation method to remove the remaining adhered mortar. Crushed RCA aggregates were placed in a concrete mixer and rotated with water at a speed of 10 rpm for 30 min. The behaviour of RCA (coarse) and six types of concrete with varying RCA contents as a replacement for NA were investigated. RCA exhibit well-spread particle size distribution with higher fine particle content than NA. Therefore, RCA should undergo a screening process to remove excess fine particles prior to being used. The remaining adhered mortar negatively affects aggregate properties, such as lower density, higher AIV, higher LAAV and higher water absorption. Hence, proposed techniques should be done with proper control to remove adhered mortar effectively. The RCA replacement ratio is a major factor that influences the physical, mechanical and durability characteristics of the resulting concrete. Concrete specimens with RCA have a lower density than specimens with the same amount of NA. The workability of concrete with RCA decreased with increase in RCA content due to the high water absorption capacity and rough surface texture of RCA. Compressive strength was reduced with an increase in RCA replacement ratio. When NA were completely replaced with RCA, 28% and 27% reductions were exhibited in the dry and wet compressive strengths, respectively. The proposed technique using a concrete mixture with water flow showed as an acceptable approach to valorise waste concrete by removing the adhered mortar. With proper control in the proposed technique, concrete with RCA can provide a sustainable alternative by minimising the environmental impact associated with NA production, natural resource conservation, and C&D waste management. C&D waste reduction and recycling lead towards sustainable consumption in construction, and subsequently global environmental sustainability.

Acknowledgements The authors would like to extend their gratitude to University of Jaffna for providing the necessary funding for this research through URG/2018/SEIT/09, and to the Department of Civil Engineering, University of Jaffna for the generous supply of materials and laboratory facilities.

Author contribution statement Conceptualization (H.M.C.C. Somarathna, H.M.S.C.H. Bandara, G. Thushanth), Data curation (H.M.S.C.H. Bandara, G. Thushanth, H.M.C.C. Somarathna), Formal analysis (H.M.S.C.H. Bandara, G. Thushanth, H.M.C.C. Somarathna), Funding acquisition (H.M.C.C. Somarathna), Investigation (H.M.S.C.H. Bandara, G. Thushanth, H.M.C.C. Somarathna), Methodology (H.M.S.C.H. Bandara, G. Thushanth, H.M.C.C. Somarathna, S.N. Raman), Project administration (H.M.C.C. Somarathna), Supervision (H.M.C.C. Somarathna, D.H.G.A.E Jayasinghe, S.N. Raman), Validation (H.M.S.C.H. Bandara, G. Thushanth, H.M.C.C. Somarathna, S.N. Raman), Visualization (H.M.S.C.H. Bandara, G. Thushanth, H.M.C.C. Somarathna), Writing - original draft (H.M.S.C.H. Bandara, G. Thushanth, H.M.C.C. Somarathna), Writing - review & editing (H.M.C.C. Somarathna, D.H.G.A.E Jayasinghe, S.N. Raman).

Declarations

Conflict of interest The authors declare no conflict of interest.

References

ACI-E-701, n.d. E-701 Cementitious materials for concrete. American Concrete Institute, Michigan, United States, p. 25

Akbarnezhad A, Ong KCG, Zhang MH, Tam CT, Foo TWJ (2011) Microwave-assisted beneficiation of recycled concrete aggregates.

Constr Build Mater 25:3469–3479. https://doi.org/10.1016/j.conbuildmat.2011.03.038

Al-Bayati HKA, Das PK, Tighe SL, Baaj H (2016) Evaluation of various treatment methods for enhancing the physical and morphological properties of coarse recycled concrete aggregate. Constr Build Mater 112:284–298. https://doi.org/10.1016/j.conbuildmat.2016.02.176

Almeida N, Branco F, Santos JR (2007) Recycling of stone slurry in industrial activities: Application to concrete mixtures. Build Environ 42:810–819. https://doi.org/10.1016/j.buildenv.2005.09.018

Arabi N, Meftah H, Amara H, Kebaïli O, Berredjem L (2019) Valorization of recycled materials in development of self-compacting concrete: mixing recycled concrete aggregates – windshield waste glass aggregates. Constr Build Mater 209:364–376. https://doi.org/10.1016/j.conbuildmat.2019.03.024

Arrigoni A, Beckett CTS, Ciancio D, Pelosato R, Dotelli G, Grillet AC (2018) Rammed earth incorporating recycled concrete aggregate: a sustainable, resistant and breathable construction solution. Resour Conserv Recycl 137:11–20. https://doi.org/10.1016/j.resconrec.2018.05.025

Aslani F, Ma G, Law D, Wan Y, Muselin G (2018) Development of high-performance self-compacting concrete using waste recycled concrete aggregates and rubber granules. J Clean Prod. https://doi.org/10.1016/j.jclepro.2018.02.074

ASTM C127, (2015) Standard test method for density, relative density (specific gravity), and absorption. In: ASTM standard book. ASTM International, West Conshohocken, PA, pp. 1–6. https://doi.org/10.1520/C0127-15

ASTM C131, (2015) Standard test method for resistance to degradation of small-size coarse aggregate by abrasion and impact in the los angeles machine In: ASTM standard book. ASTM International, West Conshohocken, PA.

ASTM C136, (2015) Standard test method for sieve analysis of fine and coarse aggregates. In: ASTM standard book. ASTM International, West Conshohocken, PA.

ASTM C143, (2015) Standard test method for slump of hydraulic-cement concrete. In: ASTM standard book. West Conshohocken, PA.

ASTM C1585, (2013) Standard test method for measurement of rate of absorption of water by hydraulic-cement concretes. In: ASTM Standard Book. ASTM International, West Conshohocken, PA

ASTM_C138/C138M, (2017) Standard test method for density (unit weight), yield, and air content (gravimetric) of concrete. In: ASTM standard book. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/C0138_C0138M-17A

ASTMC39, 2014. ASTM C-39. In: standard test method for compressive strength of cylindrical concrete specimens. ASTM International, West Conshohocken, PA

Bahrami N, Zohrabi M, Mahmoudy SA, Akbari M (2020) Optimum recycled concrete aggregate and micro-silica content in self-compacting concrete: rheological, mechanical and microstructural properties. J Build Eng 31:101361. https://doi.org/10.1016/j.jobe.2020.101361

Bai G, Zhu C, Liu C, Liu B (2020) An evaluation of the recycled aggregate characteristics and the recycled aggregate concrete mechanical properties. Constr Build Mater 240:117978. https://doi.org/10.1016/j.conbuildmat.2019.117978

Belouadah M, Rahmouni ZEA, Tebbal N (2019) Experimental characterization of ordinary concretes obtained by adding construction waste (glass, marble). Procedia Comput Sci 158:153–162. https://doi.org/10.1016/j.procs.2019.09.038

Berredjem L, Arabi N, Molez L (2020) Mechanical and durability properties of concrete based on recycled coarse and fine aggregates produced from demolished concrete. Constr Build Mater 246:118421. https://doi.org/10.1016/j.conbuildmat.2020.118421

Bravo M, De Brito J (2012) Concrete made with used tyre aggregate: durability-related performance. J Clean Prod 25:42–50. https://doi.org/10.1016/j.jclepro.2011.11.066

Bravo M, Brito JD, Evangelista L, Pacheco J (2017) Superplasticizer's efficiency on the mechanical properties of recycled aggregates concrete : influence of recycled aggregates composition and incorporation ratio. Constr Build Mater 153:129–138. https://doi.org/10.1016/j.conbuildmat.2017.07.103

Brito LD, Vieira P, Domingues A, Figueiredo D, Moacyr V (2020) Evaluation of the use of crushed returned concrete as recycled aggregate in ready-mix concrete plant. J Build Eng 31:101408. https://doi.org/10.1016/j.jobe.2020.101408

BS 882:1992 Specification for aggregates from natural sources for concrete, 1992. British Standards Institution, London, W4 4AL, UK

Choi H, Lim M, Choi H, Kitagaki R, Noguchi T (2014) Using microwave heating to completely recycle concrete. J Environ Prot (Irvine, Calif) 5:583–596. https://doi.org/10.4236/jep.2014.57060

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

Deiyagala DATH, Priyadarshani PGN, Perera MAN, Pallewatta TM, Samarawickrama MNC, Tibbotuwawa DPMB (2017) Engineering and economic viability of using crushed construction waste in the production of concrete and mortar. Eng J Inst Eng Sri Lanka 50:41–53. https://doi.org/10.4038/engineer.v50i3.7264

Dimitriou G, Savva P, Petrou MF (2018) Enhancing mechanical and durability properties of recycled aggregate concrete. Constr Build Mater 158:228–235. https://doi.org/10.1016/j.conbuildmat.2017.09.137

Duan ZH, Poon CS (2014) Properties of recycled aggregate concrete made with recycled aggregates with different amounts of old adhered mortars. Mater Des 58:19–29. https://doi.org/10.1016/j.matdes.2014.01.044

Etxeberria M, Vázquez E, Marí A, 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. https://doi.org/10.1016/j.cemconres.2007.02.002

Fakitsas CG, Papakonstantinou PEA, Kiousis PD, Savva A (2012) Effects of recycled concrete aggregates on the compressive and shear strength of high-strength self-consolidating concrete. J Mater Civ Eng 24:356–361. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000397

Falek K, Aoudjane K, Kadri EH, Kaoua F (2017) Influence of recycled aggregates on the mechanical and tribological behavior of concrete. Energy Procedia 139:456–461. https://doi.org/10.1016/j.egypro.2017.11.237

Fan CC, Huang R, Hwang H, Chao SJ (2016) Properties of concrete incorporating fine recycled aggregates from crushed concrete wastes. Constr Build Mater 112:708–715. https://doi.org/10.1016/j.conbuildmat.2016.02.154

Fonseca N, Brito JD, Evangelista L (2011) Cement & concrete composites the influence of curing conditions on the mechanical performance of concrete made with recycled concrete waste. Cem Concr Compos 33:637–643. https://doi.org/10.1016/j.cemconcomp.2011.04.002

Gobieanandh, V., Jayakody, S., (2016) Evaluate the strength of cement treated recycled construction. In: The 7th international conference on sustainable built environment. Earl's Regency Hotel, Kandy, Sri Lanka, pp. 62–67

González-Fonteboa B, Martínez-Abella F (2008) Concretes with aggregates from demolition waste and silica fume. Mater Mech Prop Build Environ 43:429–437. https://doi.org/10.1016/j.buildenv.2007.01.008

Jaya A, Sekar SK (2016) Mechanical and fracture characteristics of Eco-friendly concrete produced using coconut shell, ground granulated blast furnace slag and manufactured sand. Constr Build Mater 103:1–7. https://doi.org/10.1016/j.conbuildmat.2015.11.035

Jayakody S, Zimar AMZ, Ranaweera RALM (2018) Potential use of recycled construction and demolition waste aggregates for non-structural concrete applications. J Natl Sci Found Sri Lanka 46:205–216

Kanojia A, Jain SK (2017) Performance of coconut shell as coarse aggregate in concrete. Constr Build Mater 140:150–156. https://doi.org/10.1016/j.conbuildmat.2017.02.066

Karunaratne, S., Premasiri, E.S.Y., Kariapper, A., Abeysinghe, A.M.G.G.M.B., (2013) Use of recycled aggregates in structural concrete. In: world construction symposium 2013: socio-economic sustainability in construction. Colombo, Sri Lanka, pp 9

Katz A (2004) Treatments for the improvement of recycled aggregate. J Mater Civ Eng 16:597–603. https://doi.org/10.1061/(ASCE)0899-1561(2004)16:6(597)

Kou SC, Poon CS (2010) Properties of concrete prepared with PVA-impregnated recycled concrete aggregates. Cem Concr Compos 32:649–654. https://doi.org/10.1016/j.cemconcomp.2010.05.003

Kou SC, Poon CS (2012) Enhancing the durability properties of concrete prepared with coarse recycled aggregate. Constr Build Mater 35:69–76. https://doi.org/10.1016/j.conbuildmat.2012.02.032

Kumar VP, Pradesh A, Pradesh A (2017) Durability aspects of concrete by partial replacement of cement by ceramic waste. Int J Civ Eng Technol 8:22–30

Kurda R, Silvestre JD, de Brito J (2018) Life cycle assessment of concrete made with high volume of recycled concrete aggregates and fly ash. Resour Conserv Recycl 139:407–417. https://doi.org/10.1016/j.resconrec.2018.07.004

Le H, Bui Q (2020) Recycled aggregate concretes – a state-of-the-art from the microstructure to the structural performance. Constr Build Mater 257:119522. https://doi.org/10.1016/j.conbuildmat.2020.119522

Li LG, Lin CJ, Chen GM, Kwan AKH, Jiang T (2017) Effects of packing on compressive behaviour of recycled aggregate concrete. Const Build Mater 157:757–777. https://doi.org/10.1016/j.conbuildmat.2017.09.097

Li Y, Zhang S, Wang R, Dang F (2019) Potential use of waste tire rubber as aggregate in cement concrete – a comprehensive review. Constr Build Mater 225:1183–1201. https://doi.org/10.1016/j.conbuildmat.2019.07.198

Ma XW, Han ZX, Li XY, Meng FL (2009) Thermal treatment of waste concrete and the rehydration properties of the dehydrated cement paste. J Qingdao Technol Univ 30:93–97

Marinković S, Radonjanin V, Malešev M, Ignjatović I (2010) Comparative environmental assessment of natural and recycled aggregate concrete. Waste Manag 30:2255–2264. https://doi.org/10.1016/j.wasman.2010.04.012

Martínez-Lage I, Vázquez-Burgo P, Velay-Lizancos M (2020) Sustainability evaluation of concretes with mixed recycled aggregate based on holistic approach: technical, economic and environmental analysis. Waste Manag 104:9–19. https://doi.org/10.1016/j.wasman.2019.12.044

Matias D, de Brito J, Rosa A, Pedro D (2014) Durability of concrete with recycled coarse aggregates: influence of superplasticizers. J Mater Civ Eng 26:1–5. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000961

Mcginnis MJ, Davis M, De A, Weldon BD, Kurama YC (2017) Strength and stiffness of concrete with recycled concrete aggregates. Constr Build Mater 154:258–269. https://doi.org/10.1016/j.conbuildmat.2017.07.015

Mefteh H, Kebaïli O, Oucief H, Berredjem L, Arabi N (2013) Influence of moisture conditioning of recycled aggregates on the properties of fresh and hardened concrete. J Clean Prod 54:282–288. https://doi.org/10.1016/j.jclepro.2013.05.009

Mithushan, S., Nishanthan, J.A., Niwunhella, A.G.M.A., Perera, S.V.T.J., (2017) Effect of partial replacement of conventional ingredients in concrete with alternative materials. In: 5th international symposium on advances in civil and environmental engineering practises for sustainable development (ACEPS-2017). pp. 426–433

Montgomery D (1998) Workability and compressive strength properties of concrete containing recycled concrete aggregate. Sustain Constr Use Recycl Concr Aggreg. https://doi.org/10.1680/scuorca.27268.0025

Munir MJ, Wu YF, Kazmi SMS, Patnaikuni I, Zhou Y, Xing F (2019) Stress-strain behavior of spirally confined recycled aggregate concrete: an approach towards sustainable design. Resour Conserv Recycl 146:127–139. https://doi.org/10.1016/j.resconrec.2019.03.043

Omary S, Ghorbel E, Wardeh G (2016) Relationships between recycled concrete aggregates characteristics and recycled aggregates concretes properties. Constr Build Mater 108:163–174. https://doi.org/10.1016/j.conbuildmat.2016.01.042

Poon CS, Kou SC, Lam L (2002) Use of recycled aggregates in molded concrete bricks and blocks. Constr Build Mater 16:281–289. https://doi.org/10.1016/S0950-0618(02)00019-3

Puthussery JV, Kumar R, Garg A (2017) Evaluation of recycled concrete aggregates for their suitability in construction activities: an experimental study. Waste Manag 60:270–276. https://doi.org/10.1016/j.wasman.2016.06.008

Rahal K (2007) Mechanical properties of concrete with recycled coarse aggregate. Build Environ 42:407–415. https://doi.org/10.1016/j.buildenv.2005.07.033

Robert MJ, Gaurav G, Singh B (2018) Splice strength of steel reinforcement embedded in recycled aggregate concrete. Constr Build Mater 160:156–168. https://doi.org/10.1016/j.conbuildmat.2017.11.007

Seara-paz S, González-fonteboa B, Martínez-abella F, Carro-lópez D (2018) Long-term flexural performance of reinforced concrete beams with recycled coarse aggregates. Constr Build Mater 176:593–607. https://doi.org/10.1016/j.conbuildmat.2018.05.069

Shen W, Yang Z, Cao L, Cao L, Liu Y, Yang H, Lu Z, Bai J (2016) Characterization of manufactured sand: particle shape, surface texture and behavior in concrete. Constr Build Mater 114:595–601. https://doi.org/10.1016/j.conbuildmat.2016.03.201

Shen W, Liu Y, Wang Z, Cao L, Wu D, Wang Y, Ji X (2018) Influence of manufactured sand's characteristics on its concrete performance. Constr Build Mater 172:574–583. https://doi.org/10.1016/j.conbuildmat.2018.03.139

Shetty MS (2008) Concrete technology: theory and practice. S Chand Publishing, New Delhi

Shi C, Li Y, Zhang J, Li W, Chong L, Xie Z (2016) Performance enhancement of recycled concrete aggregate – a review. J Clean Prod 112:466–472. https://doi.org/10.1016/J.JCLEPRO.2015.08.057

Silva RV, de Brito J, Dhir RK (2018) Fresh-state performance of recycled aggregate concrete: a review. Constr Build Mater 178:19–31. https://doi.org/10.1016/j.conbuildmat.2018.05.149

Sim J, Park C (2011) Compressive strength and resistance to chloride ion penetration and carbonation of recycled aggregate concrete with varying amount of fly ash and fine recycled aggregate. Waste Manag 31:2352–2360. https://doi.org/10.1016/j.wasman.2011.06.014

Sofi A (2017) Effect of waste tyre rubber on mechanical and durability properties of concrete – a review. Ain Shams Eng J. https://doi.org/10.1016/j.asej.2017.08.007

Tahar Z, Ngo T, Hadj E, Bouvet A, Debieb F, Aggoun S (2017) Effect of cement and admixture on the utilization of recycled aggregates in concrete. Constr Build Mater 149:91–102. https://doi.org/10.1016/j.conbuildmat.2017.04.152

Tam VWY, Tam CM, Le KN (2007) Removal of cement mortar remains from recycled aggregate using pre-soaking approaches. Resour Conserv Recycl 50:82–101. https://doi.org/10.1016/j.resconrec.2006.05.012

Tam VWY, Soomro M, Catarina A, Evangelista J (2018) A review of recycled aggregate in concrete applications (2000–2017). Constr Build Mater 172:272–292. https://doi.org/10.1016/j.conbuildmat.2018.03.240

Tam VWY, Butera A, Le KN, Li W (2020) Utilising CO 2 technologies for recycled aggregate concrete: a critical review. Constr Build Mater 250:118903. https://doi.org/10.1016/j.conbuildmat.2020.118903

Verian KP, Ashraf W, Cao Y (2018) Properties of recycled concrete aggregate and their influence in new concrete production. Resour Conserv Recycl 133:30–49. https://doi.org/10.1016/j.resconrec.2018.02.005

Wang L, Wang J, Qian X, Chen P, Xu Y, Guo J (2017) An environmentally friendly method to improve the quality of recycled concrete aggregates. Constr Build Mater 144:432–441. https://doi.org/10.1016/j.conbuildmat.2017.03.191

Wang R, Yu N, Li Y (2020) Methods for improving the microstructure of recycled concrete aggregate: a review. Constr Build Mater 242:118164. https://doi.org/10.1016/j.conbuildmat.2020.118164

Wijayasundara M, Mendis P, Zhang L, Sofi M (2016) Financial assessment of manufacturing recycled aggregate concrete in ready-mix concrete plants. Resour Conserv Recycl 109:187–201. https://doi.org/10.1016/j.resconrec.2016.02.007

Xiao J, Wang C, Ding T, Akbarnezhad A (2018) A recycled aggregate concrete high-rise building: structural performance and embodied carbon footprint. J Clean Prod. https://doi.org/10.1016/j.jclepro.2018.07.210

Younis KH, Pilakoutas K (2013) Strength prediction model and methods for improving recycled aggregate concrete. Constr Build Mater 49:688–701. https://doi.org/10.1016/j.conbuildmat.2013.09.003

Zega CJ, Villagrán-Zaccardi YA, Di Maio AA (2010) Effect of natural coarse aggregate type on the physical and mechanical properties of recycled coarse aggregates. Mater Struct Constr 43:195–202. https://doi.org/10.1617/s11527-009-9480-4

Zhang S, He P, Niu L (2020) Mechanical properties and permeability of fiber-reinforced concrete with recycled aggregate made from waste clay brick. J Clean Prod 268:121690. https://doi.org/10.1016/j.jclepro.2020.121690