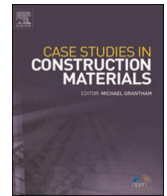




ELSEVIER

Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

## Case Studies in Construction Materials

journal homepage: [www.elsevier.com/locate/cscm](http://www.elsevier.com/locate/cscm)

# Enhancing the aggregate impact value and water absorption of demolition waste coarse aggregates with various treatment methods

Qusai Al-Waked<sup>\*</sup>, Jiping Bai, John Kinuthia, Paul Davies

Faculty of Computing, Engineering and Science, University of South Wales, Treforest Campus, CF37 1DL, UK

## ARTICLE INFO

## Keywords:

Recycled aggregate  
Demolition waste aggregates  
Treatments  
Adhered mortar  
Water absorption  
Aggregate impact value

## ABSTRACT

Recycled aggregate (RA) from construction and demolition waste can readily be used to replace natural aggregate in concrete. Nonetheless, the poor quality of RA adversely affects the properties of recycled aggregate concrete, limiting its use to only non-structural applications. This study examined the effects of various treatment methods by testing the aggregate impact value (AIV) and water absorption (WA) of recycled coarse aggregate before and after treatments as an indicator to examine the efficiency of these treatments. The results showed that the untreated RA achieved 17% and 6.1% for AIV and WA, respectively. Accelerated carbonation treatment at 50% CO<sub>2</sub> concentration level for six days of CO<sub>2</sub> exposure time achieved the best results among other carbonation conditions, showing 11% and 46% enhancements in the AIV and WA, respectively. The RA treated with cyclic limewater combined with accelerated carbonation exhibited better improvement in the AIV and WA compared to the sole use of accelerated carbonation treatment. Coating RA with cement-silica fume slurry at 0.1 mm coating thickness was found to be optimal, achieving 12% and 54% enhancements in the AIV and WA, respectively. Soaking RA in a 10% Portland cement - pulverized fuel ash - silica fume solution for 4 h was found to be optimal, recording enhancements of 13% and 54% in the AIV and the WA, respectively among other soaking solutions. Soaking RA in 5% sodium silicate - silica fume solution for 4 h was found to be optimal, obtaining 8% and 33% enhancements in the AIV and the WA, respectively. The treatment techniques proposed can be a powerful tool for promoting the use of RA in the construction industry.

## 1. Introduction

Construction industry activities generate large amounts of waste. According to Akhtar and Samarah [1], about 3 billion tonnes of construction and demolition waste (C&DW) is annually generated worldwide until 2012, and this figure is expected to constantly increase. Europe produces approximately 850 million tonnes of C&DW [2], while, nearly 18.8 and 21.2 million tonnes of hard demolition waste were generated in the UK in 2014 and 2015 respectively, and this quantity is predicted to continue to increase annually

*Abbreviations:* RA, Recycled aggregate; NA, Natural aggregate; C&DW, Construction and demolition waste; ITZ, Interfacial transition zone; WA, Water absorption; AIV, Aggregate impact value.

*\* Corresponding author.*

*E-mail addresses:* [qusai.al-waked@southwales.ac.uk](mailto:qusai.al-waked@southwales.ac.uk) (Q. Al-Waked), [jiping.bai@southwales.ac.uk](mailto:jiping.bai@southwales.ac.uk) (J. Bai), [john.kinuthia@southwales.ac.uk](mailto:john.kinuthia@southwales.ac.uk) (J. Kinuthia), [paul.davies7@southwales.ac.uk](mailto:paul.davies7@southwales.ac.uk) (P. Davies).

<https://doi.org/10.1016/j.cscm.2022.e01267>

Received 7 April 2022; Received in revised form 30 May 2022; Accepted 22 June 2022

Available online 25 June 2022

2214-5095/© 2022 Published by Elsevier Ltd.

This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

[3]. The dumping and landfilling of C&DW have rapidly and enormously led to a series of issues to the environment because C&DW may contain hazardous materials [4].

Despite that there are several countries that recycle around 80% of C&DW such as Japan, the Netherlands, Germany etc., developing countries have an average rate of recycling of 20–40% [5]. Accordingly, promoting the use of recycled aggregate (RA) from the C&DW into new concrete as a replacement for natural aggregate (NA) is an essential priority. This would lead to a reduction in carbon dioxide emissions and contribute significantly towards preserving the environment by minimizing the depletion of natural resources, thus leading to a sustainable and green future [6].

Kim [7] stated that the recycling of concrete waste is crucial for the sustainable development of the construction industry. With advances in technology in the manufacture of crusher machines and the developed recycling process of plants, it is now possible to obtain RA from large portions of C&DW at a reasonable cost. In line with this, recently, the utilization of RA from the C&DW in civil engineering applications has gained a huge interest worldwide, and studies on their possible use in new concrete have been carried out extensively over the last two decades.

Recently, a significant number of studies examined the effects of RA on concrete [8-11,7] and revealed that replacing NA with RA in concrete adversely affects the mechanical properties of concrete. This negative effect of RA on concrete performance has limited its utilization in the construction industry to non-structural applications, road bases, blinding concrete, and footpaths [12].

According to [13], the reduced attraction towards RA is mainly due to their poor engineering properties as a result of numerous factors, primarily the presence of the adhered mortar and the weak old interfacial transition zone on the RA surface. Other factors may include, pre-loading, accelerated weathering, processing costs, and the constituents of different materials with various engineering properties (i.e., bricks, glass, rounded stones, and recycled concrete aggregates) [13]. Therefore, RA possesses low density, low aggregate impact value, low crush value, high water absorption, weak ITZ, weak bonding, micropores, and microcracks compared to NA [14].

Consequently, studies with the aim of enhancing the quality of RA have been carried out extensively over the past decade to produce high-quality RA and ultimately expand RAC application into structural concrete [15,14,9,10]. The current methods used for treating RA can be categorized into two main approaches; (i) removing the adhered mortar, and (ii) strengthening the adhered mortar.

Removing the adhered mortar techniques can offer great results through practical treatment procedures such as soaking in acid [11], thermal or traditional heating [16], microwave heating [14], and mechanical treatment [9].

Although removing the adhered mortar technique has been observed to offer promising results, it showed some negative side effects, for instance, soaking in acid and mechanical treatments may introduce micro-cracks and damage to the RA surface [17,18]. In addition, removing the adhered mortar methods tends to increase the cost of recycled aggregates, not to mention it may result in fine aggregates which in turn may be considered as another waste material generation especially if it is not utilized.

The approach of strengthening the adhered mortar offers greater advantages than removing the adhered mortar [18]. Strengthening the adhered mortar include methods such as coating RA with pozzolan slurry [19], calcium carbonate biodeposition [20], soaking RA in sodium silicate solution [21], and accelerated carbonation [22]. The latter treatment is thought to have more advantages over the other treatments in terms of the environmental impact. Mazurana et al., [23] stated that RAs from the C&DW are capable of absorbing CO<sub>2</sub> through the reaction of the available calcium hydroxide on their surface and their high surface area. Thus, the utilization of carbonation treatment in the construction industry for enhancing RA can help reduce the global CO<sub>2</sub> emission by the deployment of carbon capture of RA via carbonation treatment [24].

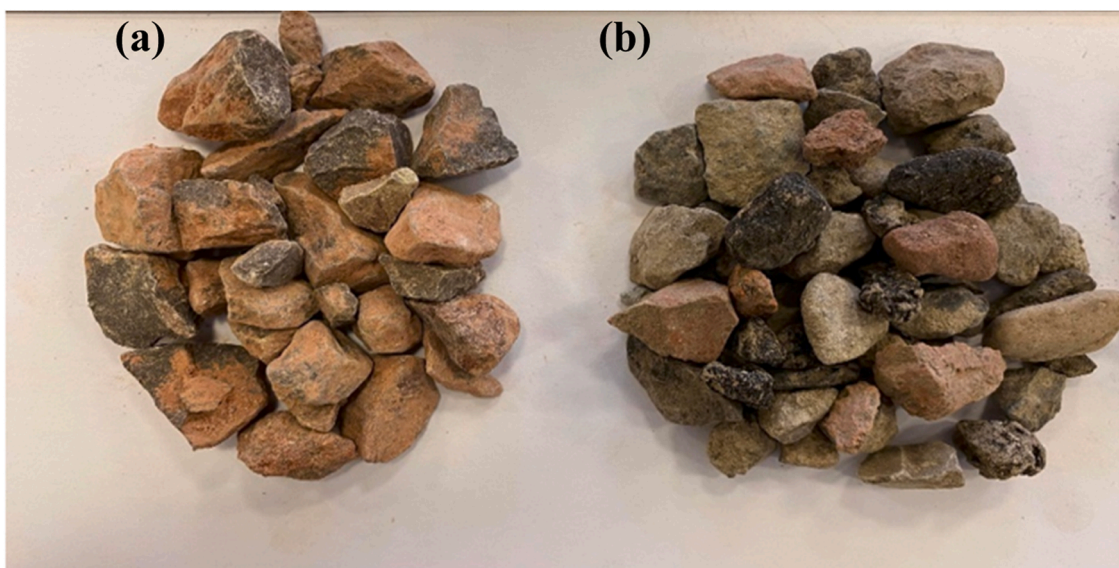


Fig. 1. (a) coarse NA, (b) coarse untreated RA (URA).

There are a significant amount of studies that have dealt with the effects of different treatments on the performance of recycled aggregate concrete, little attention, however, has been devoted to the effects of these treatments on RA properties.

Aggregates as inert fillers in concrete take around 80% of the concrete volume. Its physical properties, such as aggregate impact value (AIV) and water absorption (WA) affect the properties of fresh and hardened concrete. To this end, the present study aims at evaluating the effects of accelerated carbonation, cyclic limewater-accelerated carbonation, soaking RA in sodium silicate-silica fume solution, coating RA with cement-silica fume slurry, and soaking RA in cement-pozzolan solutions on the aggregate impact value (AIV) and water absorption (WA) of RA.

## 2. Materials characteristics

### 2.1. Aggregates

Two particle sizes of crushed limestone coarse aggregate (NA) were used throughout this study, 20/10 mm, and 10/4 mm. The limestone aggregate was sourced in bulk from Jewson UK Limited in Caerphilly, South Wales, UK, confirming BS EN 12620:2002 +A1: 2008 [25]. The untreated recycled aggregate (RA) utilized was sourced from Derwen Group, Neath Abbey, UK. It is a mix of construction and demolition waste with a size range of clean 20/10 mm and 10/4 mm. According to Derwen Group, the RA provided was produced to industry standards, in accordance with WRAP Quality protocol and BS EN 13242: 2013 [26] specifications [27]. The RA consisted of different recycled materials i.e., brick, glass, bituminous, rounded stones, and recycled concrete aggregates. Fig. 1 shows the NA and RA utilized throughout this study. Table 1 shows the compositions of RA in accordance with BS 8500-2: 2015 +A2: 2019 [28]. The mechanical and physical properties of the NA and RA are given in Table 2, while the particle size distribution of NA and RA is given in Fig. 2 in accordance with BS EN 933-1:2012 [29]

### 2.2. Portland cement

A commercially available Portland cement (CEM I-42.5 N) which was manufactured in accordance with BS EN 197-1: 2011 [34] was used throughout the study. The CEM I was sourced from Jewson UK limited based in Caerphilly, South Wales, UK. The oxide and physical composition of the cement used are shown in Table 3.

### 2.3. Pozzolanic materials

The pulverized fuel ash (PFA) used throughout this study was supplied by a local supplier and was compliant with BS EN 450-1:2012 [35]. The silica fume (SF) utilized throughout this study was an un-densified silica fume with a commercial code 971 U and was to the conformity of BS EN 13263-2:2005 +A1:2009 [36]. It was manufactured by Elkem Silicon Materials based in Norway and had a 97.1% purity. The ground granulated blast-furnace slag (GGBS) used is a by-product material and was supplied from the Port Talbot steelworks in South Wales, UK, in compliance with BS EN 15167-1:2006 [37]. Metakaolin (MK) used was an industrial type of the Metastar 501 brand manufactured by IMERYS company in the UK. The oxide and physical composition of the pozzolana used are given in Table 2.

### 2.4. Other materials

Sodium silicate also known as water-glass or sodium metasilicate was supplied by fisher scientific, Leicestershire, UK as a commercial white powder with a molar ratio  $\text{SiO}_2/\text{Na}_2\text{O} = 2$ . Commercially available calcium hydroxide white powder with a purity of 99.995% and 2.24 g/mL density, was also supplied by fisher scientific, Leicestershire, UK. Limewater solution was prepared by mixing 1.65 g of calcium hydroxide in 1 L of water at 25° C.

**Table 1**  
Compositions of recycled aggregates in this study (BS 8500-2:2015 +A2: 2019) [28].

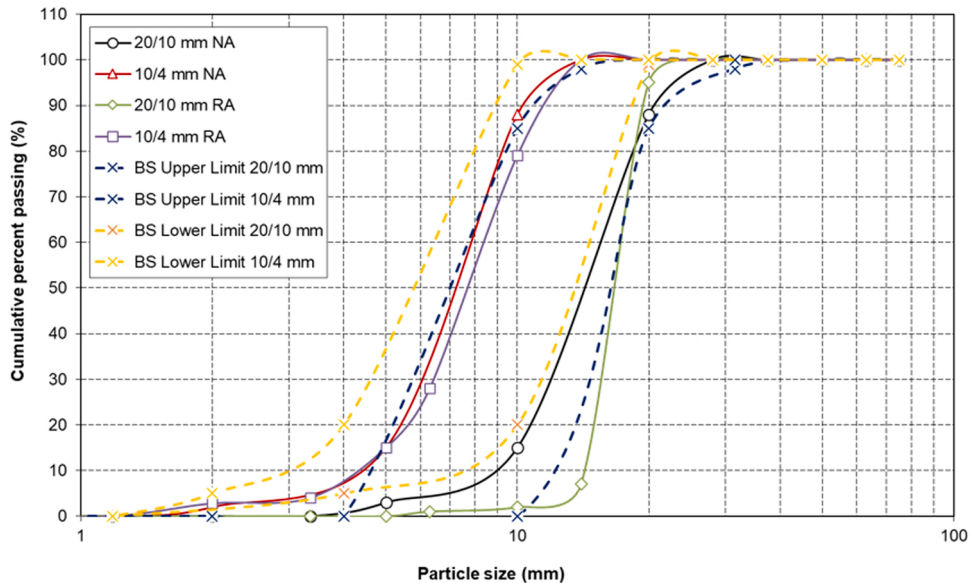
	R <sub>c</sub> (%)	R <sub>n</sub> (%)	R <sub>b</sub> (%)	R <sub>g</sub> (%)	R <sub>a</sub> (%)	X (%)
Sample 1	49.14	29.47	12.51	0.17	8.38	0.34
Sample 2	47.5	28.06	11.5	1.12	11.00	0.48
Sample 3	50.6	25.8	13.4	0.00	9.5	0.37
BS limits	–	–	–	–	≤ 10%	≤ 1%
Mean	49.08	27.78	12.47	0.42	9.6	0.39

Notes: R<sub>c</sub> - cement-based products, R<sub>n</sub> - unbounded aggregates and/or natural stones, R<sub>b</sub> - clay masonry units i.e., bricks and tiles, calcium silicate masonry unit, R<sub>a</sub> - bituminous materials, and X - miscellaneous materials and/or non-floating wood, plastic, and rubber, R<sub>g</sub> - crushed glass.

**Table 2**

Characteristics of the untreated RA (URA) compared with NA and relevant BS EN standards.

Characteristic	NA	URA	BS limits	Standard
Flakiness Index (FI) (%)	18	27	< 40	BS EN 933-3:2012 [30]
Shape Index (SI) (%)	12	18	< 55	BS EN 933-4:2008 [31]
Water Absorption (WA) (%)	1.5	6.1	< 8	BS EN 1097-6:2013 [32]
Density kg/m <sup>3</sup>	2480	2120	–	BS EN 1097-6:2013 [32]
Aggregate Impact Value (AIV) (%)	14	17	< 32	BS EN 1097-2:2020 [33]
LA (%)	18	26	< 50	BS EN 1097-2: 2020 [33]

**Fig. 2.** Particle size distribution of coarse RA and coarse NA [29].**Table 3**

Oxide compositions and physical properties of materials used throughout this study.

Oxide	Composition by (wt%)				
	PC	SF	PFA	GGBS	MK
CaO	61.49	–	0.22	37.99	0.07
SiO <sub>2</sub>	18.84	97.1	59.04	35.54	52.1
Al <sub>2</sub> O <sub>3</sub>	4.77	0.1	34.08	11.46	41.0
Fe <sub>2</sub> O <sub>3</sub>	2.87	0.2	2.00	0.42	4.32
SO <sub>3</sub>	3.12	0.06	0.05	1.54	–
Na <sub>2</sub> O	0.02	–	1.26	0.37	0.26
	<b>Physical properties</b>				
Colour	Grey	Dark Grey	Light Grey	Off-white	Off-white
Bulk density (kg/m <sup>3</sup> )	1400	120–220	800–1000	1200	500
Specific gravity (Mg/m <sup>3</sup> )	3.16	2.20	2.90	2.85	2.50

### 3. Experimental work of aggregate treatments

#### 3.1. Testing methods

Aggregate impact value (AIV) and water absorption (WA) were carried out on RA before and after treatment to evaluate the effects of treatments on enhancing these two properties. AIV was carried out in accordance with BS EN 1097-2:2020 [33]. AIV was performed on coarse RA passing the 12.5 mm sieve and retaining on the 10 mm BS test sieve. The test specimen was then poured into a cylindrical cup, followed by subjecting it to 25 gentle blows with a tamping rod to get it compacted at three layers. Thereafter, any surplus aggregates were stuck off, and the net weight of the aggregate was determined as (W1). The aggregates were then poured into another cylindrical cup attached to the impact apparatus base, where 25 strokes were then applied with a tamping rod to compact the test sample. The hammer of the machine was raised until its lower face was 380 mm above the upper surface of the test sample in the cup

and was allowed to fall freely on the test sample for 15 blows. The crushed test sample was then removed and sieved through the 2.36 mm BS sieve, and the passing particles were weighed ( $W_2$ ). The Aggregate Impact Value (AIV) was calculated according to Eq. (1).

$$AIV = (W_2/W_1) \times 100\% \quad (1)$$

### 3.2. Treatment techniques

Five treatment methods were employed in this study, accelerated carbonation, cyclic limewater-accelerated carbonation, soaking in sodium silicate-silica fume solution, coating with cement-silica fume slurry, and soaking in cement-pozzolan solutions.

#### 3.2.1. Accelerated carbonation

Prior to carbonation treatment, the RA was firstly air-dried at room temperature and monitored to achieve the desired moisture content of 5–7% for the required experimental work as recommended by Zhan et al. [38] and Pan et al. [39], with a view to accelerating the carbonation reaction through dissolving the  $\text{CO}_2$  gas and  $\text{Ca}^{+2}$  contained in RA (especially in the adhered mortar), while reducing the moisture content of the recycled aggregates. The RA was then placed into the carbonation chamber at a controlled temperature and relative humidity set at  $22 \pm 2^\circ\text{C}$  and  $50 \pm 5\%$ , respectively. Thereafter, the RA underwent carbonation for 7 days at 3 different  $\text{CO}_2$  concentration levels 20%, 50%, and 100% and at + 0.1 bar gas pressure. A sufficient quantity of silica gel was put at the bottom of the chamber and regularly replenished to remove the evaporated water from the aggregates during the carbonation process. The carbonation device used in this study was a Galaxy 170 R  $\text{CO}_2$  incubator as shown in Fig. 3.

#### 3.2.2. Cyclic limewater-accelerated carbonation

In this treatment approach, the following steps were repeated for three cyclic periods, (i) the RA were firstly pre-soaked in limewater solution for three days, and then (ii) pre-dried in a chamber at  $20 \pm 2^\circ\text{C}$  and relative humidity of  $50 \pm 5\%$  for 3 days. (iii) The RA were then placed into the  $\text{CO}_2$  chamber and underwent carbonation at 100%  $\text{CO}_2$  concentration level at a pressure of + 0.1 bar for 24 h.

#### 3.2.3. Soaking RA in sodium silicate-silica fume solution

The Recycled aggregates were impregnated in sodium silicate-silica fume solution for 1 h, 4 h, and 24 h. The solutions selected for this treatment were prepared with three different replacement levels in which sodium silicate-silica fume replaced water at 5 wt%, 10 wt%, and 15 wt%, and the mixing proportion of these two combined materials was worked out using a ratio of 0.6 of sodium silicate powder to silica fume powder. Table 4 shows a sample mix proportion design of the solution for treating 1000 g of recycled aggregate.

The methodology adopted involved the following procedures, the recycled aggregates were firstly dried in an oven for 24 h at  $105^\circ\text{C}$ , and then cooled at room temperature. After the sodium silicate-silica fume solution was prepared, it was stirred for 2 mins to reach homogeneity and ensured an appropriate diffusion of sodium silicate and silica fume particles. The recycled aggregates were then immersed in the solutions prepared for 1 h, 4 h, and 24 h. Thereafter, the RA was then drained for 10 min. Finally, the recycled aggregates were dried in an oven at  $105^\circ\text{C}$  for 24 h and cooled down at room temperature for one day.



Fig. 3.  $\text{CO}_2$  incubator used for the  $\text{CO}_2$  treatment of recycled aggregates.

**Table 4**  
Proposed solution ingredient for soaking RA in sodium silicate-silica fume solution.

Replacement level %	Sodium Silicate (g)	Silica Fume (g)	Water (g)
5%	19	31	950
10%	37.5	63	900
15%	56	94	850

### 3.2.4. Coating RA with cement slurry or cement-silica fume slurry

This treatment method involved the following procedures, firstly, the cement slurry or cement-silica fume slurry was prepared with the required cement or cement-silica fume and water then properly stirred. RA was then added to the slurries prepared and properly mixed using a mixer machine for 10 mins. The aggregates coated were then placed on trays to dry for 1 day at room temperature of  $20 \pm 2^\circ\text{C}$  and then cured in water for 7 days holding time to ensure the cement paste of the coated RA was fully hydrated. In this present study, the RA was coated with cement slurry or cement-silica fume slurry to reinforce its ability in resisting impact and enhance its water absorption. Two methods of coating the RA with cement and/or cement-silica fume slurry were adopted in this study: (i) coating of individual RA size fractions separately, and (ii) coating of the total combined RA particle sizes fraction.

#### (i) Coating the individual particle size fractions with cement or cement-silica fume slurry

The calculation steps that were set by Lee et al., [40] to determine the required volume of the coating paste for coating the RA, were followed in this study. The water-to-binder ratio for the preparation of the slurries was set at 0.45. Silica fume replaced 15% of cement weight in the cement-silica fume slurry. Three different theoretical thicknesses (*tth*) were proposed to coat the RA; 0.1 mm, 0.2 mm, and 0.3 mm.

#### (i) Coating the total combined gradation with cement or cement-silica fume slurry

In this technique, the total combined gradation of RA was coated with a coating level of 5% of cement content by the weight of the utilized RA. The set water-to-binder ratio for the coating slurry was 0.55. Silica fume replaced 15% of the cement-silica fume slurry.

### 3.2.5. Soaking RA in different cement-pozzolanic solutions

The recycled aggregates were treated by soaking in different types of cement-pozzolan solutions. Different solutions were designed for the RA treatment at different dosages as given in Table 5. The ingredients selected for the different solutions were Portland cement (PC), silica fume (SF), metakaolin (MK), and pulverised fuel ash (PFA). These pozzolan materials were selected with the aim of fulfilling the environmental and economic criteria. The solutions were prepared by blending the raw materials with water (twice the weight of RA) for several minutes. Then recycled aggregate was added into each solution and soaked for 1 h and 4 h at 5%, 10% and 15% concentration levels. Thereafter, the recycled aggregates were removed from the solution bath and let drain for 10 min and then air-dried at room temperature for 24 h prior to testing.

## 4. Results and discussion

### 4.1. Effects of accelerated carbonation on the AIV and WA

Fig. 4 shows the effects of different  $\text{CO}_2$  concentration levels on the aggregate impact value (AIV) of the RA. Fig. 4 demonstrates that the AIV of the RA was significantly enhanced by the accelerated carbonation treatment.

During the first 3 days of carbonation treatment, the AIV of the RA treated with 100%  $\text{CO}_2$  concentration showed the highest reduction from 17% to 15.7% (7.6% enhancement). This can be explained as the diffusion rate of  $\text{CO}_2$  is influenced by the concentration level of  $\text{CO}_2$  and the transport paths. Thus, a higher  $\text{CO}_2$  concentration level such as 100% is more beneficial for the diffusion of

**Table 5**  
Proportions of treatment solutions for 1000 g of RA prepared in this study.

Notation	Treatment solutions PC- pozzolan	Binder (g)				Water (g)	Replacement level (Binder to water)
		PC	PFA	SF	MK		
Group 1	PFA+MK	40	30	–	30	2000	5%
	PFA+SF	40	30	30	–	2000	5%
	MK+SF	40	–	30	30	2000	5%
Group 2	PFA+MK	80	60	–	60	2000	10%
	PFA+SF	80	60	60	–	2000	10%
	MK+SF	80	–	60	60	2000	10%
Group 3	PFA+MK	120	90	–	90	2000	15%
	PFA+SF	120	90	90	–	2000	15%
	MK+SF	120	–	90	90	2000	15%

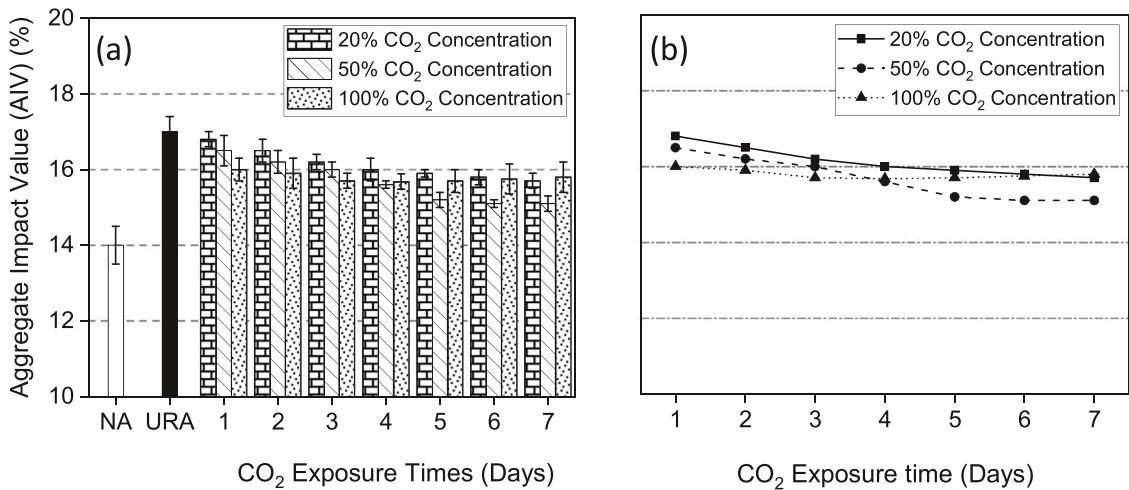


Fig. 4. The impact of carbonation treatment at different concentration levels and CO<sub>2</sub> exposure time on the AIV of the RA shown in (a) clustered column chart, and (b) scatter chart, note: NA – natural coarse aggregate, URA – untreated recycled coarse aggregate.

CO<sub>2</sub> prior to the pores being blocked up by calcium carbonates. Moreover, during the initial period of reaction, carbonation occurs intensely in a rapid growth stage. These two aspects contributed to a higher enhancement of 100% concentration level during the first 3 days of carbonation [41].

Accordingly, the results demonstrate that the observed optimal CO<sub>2</sub> exposure time for 100% CO<sub>2</sub> concentration was 3 days. After three days of CO<sub>2</sub> carbonation, there was no further improvement in the AIV at a 100% CO<sub>2</sub> concentration level. Anstice et al. [42] and Hyvert et al. [43] confirmed that increased concentration in CO<sub>2</sub> level may lead to C-S-H gel decalcification, while increasing the CO<sub>2</sub> level up to 100% may lead to complete disappearance of C-S-H gel, which results in adverse effects on the RA properties. Similarly, Kashef-Haghighi et al. [44] also observed that there was no further increase in RA carbonation percentages when the CO<sub>2</sub> concentration level reached 100%.

After 3 days of carbonation, RA treated with 50% CO<sub>2</sub> concentration started to achieve lower AIV compared to the RA treated with 100% and 20% CO<sub>2</sub> concentration levels. This can be attributed to the high concentration level of CO<sub>2</sub> which increased the degree of decalcification of calcium-silicate-hydrate. Thus, a large amount of CO<sub>2</sub> was allowed to react with C-S-H which formed a phase of a lower Ca/Si ratio, hence achieving better enhancement in AIV. The highest AIV enhancement at 50% CO<sub>2</sub> concentration level was reached at 6 days of carbonation, the AIV was reduced from 17% to 15.1% (11.2% enhancement). Thus, the optimal CO<sub>2</sub> exposure time at a 50% CO<sub>2</sub> concentration level is at 6 days of carbonation.

Treating RA with a 20% CO<sub>2</sub> concentration level offered better quality results over time but with slow AIV enhancements because of the lower CO<sub>2</sub> concentration level. The highest AIV enhancement at a 20% CO<sub>2</sub> concentration level was recorded at 7 days of CO<sub>2</sub> exposure time, where the AIV of RA was reduced from 17% to 15.9% (6.5% enhancement). This is thought to be due to carbonation

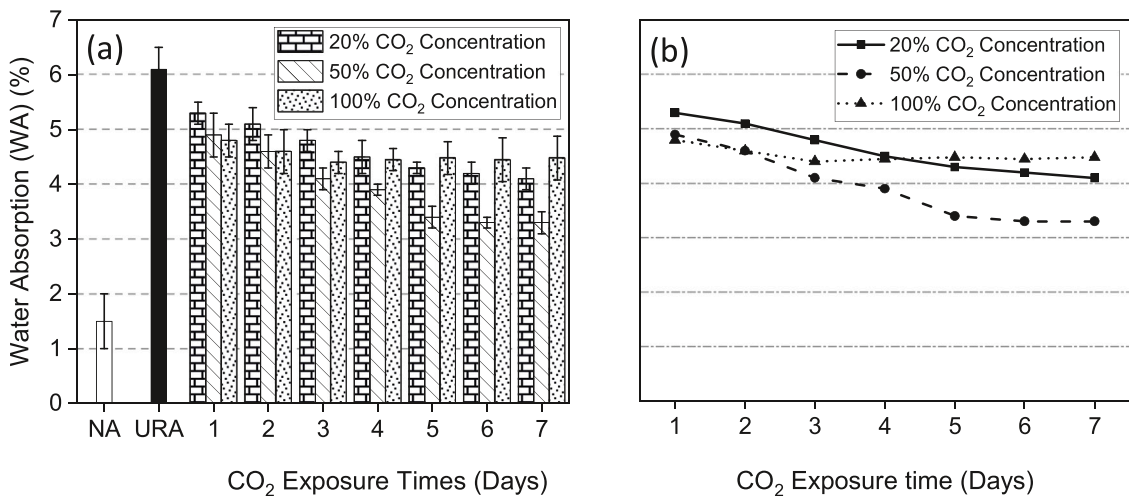


Fig. 5. The impact of carbonation treatment at different concentration levels and CO<sub>2</sub> exposure times on the WA of RA shown in (a) clustered column chart, and (b) scatter chart, note: NA – natural aggregate, URA – untreated recycled aggregate.

treatment that led to a denser particle surface of the RA which in turn reduced the rate of diffusion of CO<sub>2</sub> into RA pores, hence slowing down the efficiency with time. This is in line with Pu et al. [41] who reported a 9.14% reduction in the AIV of the RA after carbonation treatment at a 20% CO<sub>2</sub> concentration level for 7 days of carbonation.

Generally, the main reason behind the enhancement/ reduction of the AIV value of the RA after carbonation treatment is that the old ITZ was filled by the calcium carbonate that was produced during the carbonation treatment. Furthermore, the efficiency of accelerated carbonation treatment in enhancing the properties of the RA stems from the chemical reaction of CO<sub>2</sub> with the hydrated products within the adhered mortar on the RA surface. The pores and micro-cracks of the RA can be filled through the process of carbonation [45]. At the start of carbonation, the carbonation of Ca(OH)<sub>2</sub> starts first, and it is rate initially higher compared to that of C-S-H as it is shown in Eq. (2). The reaction between CO<sub>2</sub> and C-S-H begins (Eq. 3) with decalcification, in which the Ca<sup>2+</sup> reacts within the interlayer with CO<sub>3</sub><sup>2-</sup> [46].



Fig. 5 demonstrates the effects of the different CO<sub>2</sub> concentration levels on the enhancement of the water absorption (WA) of the RA. The RA treated at a 100% CO<sub>2</sub> concentration level achieved the highest reduction in the WA value from 6.1% to 4.4% (27.9% improvement) during the first day of carbonation. The highest reduction in the WA was at a 50% CO<sub>2</sub> concentration level at 6 days of carbonation, the WA of the RA was reduced from 6.1% to 3.3% (46% enhancement). At a 20% CO<sub>2</sub> concentration level and 7 days of carbonation, the WA was reduced from 6.1% to 4.1% (32.8% enhancement). It can be concluded that the optimal CO<sub>2</sub> concentration level was 50% at an optimal CO<sub>2</sub> exposure time of 5 days.

These results can be attributed to the reduction of the porosity of the cement paste after carbonation treatment, the refinement of pore structures, the transformation of portlandite into calcite, and the formation of amorphous carbonation products during accelerated carbonation treatment. A similar observation was reported by [47], Li [48], and Ying et al. [49], who reported a 22.6–40.3% enhancement in water absorption after carbonation treatment at various CO<sub>2</sub> concentration levels.

#### 4.2. Effects of cyclic limewater-accelerated carbonation on the AIV and WA

The recycled aggregates treated with three cyclic limewater-accelerated carbonation treatment achieved further and better improvement compared to the sole use of accelerated CO<sub>2</sub> at 100% concentration level for 3 days. The AIV of RA was reduced by 9% (17–15.4%) and water absorption was reduced by 36% (6.1% to 3.9%). This is mainly due to the introduction of the limewater pre-soaking technique resulting in additional carbonatable compounds into the pores of the RA, thus leading to more CO<sub>2</sub> uptake and more calcium carbonate precipitates, hence, resulting in a denser microstructure of the adhered mortar on the RA surface [50]. These findings are in line with Zhan et al. [38] who observed that carbonated RA achieved 44% enhancement in AIV after pre-soaking followed by accelerated carbonation. Similarly, Zhan et al. [50] reported that a 50% reduction in water absorption can be achieved when cyclic lime water-carbonation treatment is repeated for three cycles.

#### 4.3. Effects of Soaking RA in sodium silicate-silica fume solution on the AIV and WA

Fig. 6 shows the RA after soaking in sodium silicate-silica fume solution. Figs. 7 and 8 show the effects of soaking RA in different sodium silicate-silica fume solution concentrations and time on the AIV and the WA of the RA, respectively.

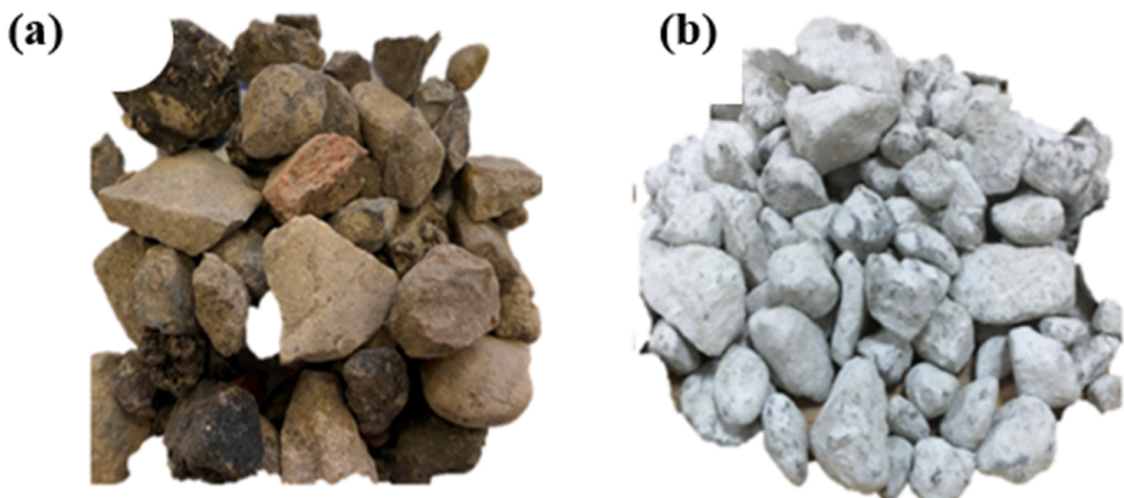


Fig. 6. (a) untreated RA, (b) treated RA with soaking in sodium silicate-silica fume solution.



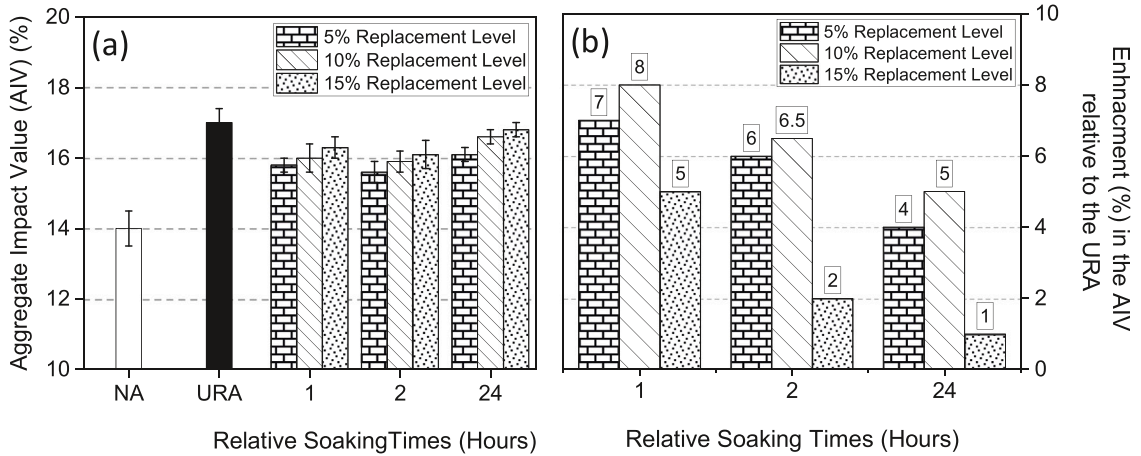


Fig. 7. (a) effects of soaking the RA in sodium silicate-silica fume solution at various replacement levels and soaking times on the AIV of the RA, (b) enhancement values in the AIV relative to the untreated RA.

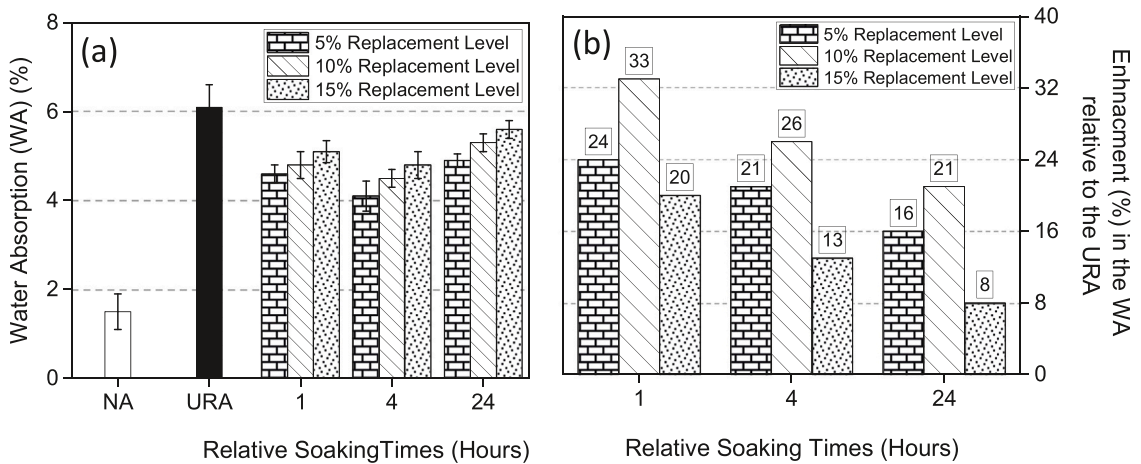


Fig. 8. effects of soaking the RA in sodium silicate-Silica Fume solution at various replacement levels and soaking times on the WA of the RA, (b) enhancement values in the WA relative to the untreated RA.

During the first 1 h of soaking treatment, the AIV of the RA treated in the sodium silicate-silica fume solution with a 5% replacement level showed the highest reduction from 17% to 15.8% (7% enhancement), whereas the AIV of the RA treated in the solution with 15% replacement level, recorded the lowest enhancement, the AIV was reduced from 17% to 16.3% (4% enhancement). After 4 h of soaking, an increase in the reduction trend of the AIV of the RA is evident for all the solutions with different replacement levels. The highest AIV enhancement was obtained by the solution with a 5% replacement level, the AIV was reduced from 17% to 15.6% (8% enhancement). Further soaking times of up to 24 h showed lower enhancements in the AIV of the RA compared to 1 h and 4 h soaking times.

A similar trend can be seen for the WA of the RA with a significant reduction in the WA after treating RA by soaking in sodium silicate – silica fume solution. At the first hour of soaking, a solution with a 5% replacement level showed the highest reduction in the WA, the WA of the RA treated in this solution was reduced from 6.1% to 4.6% (24.6% enhancement). A significant increase in the reduction of the WA can be observed after 4 h of soaking for all the solutions with different replacement levels. The highest reduction in the WA at this soaking time was obtained by the solution with a 5% replacement level, where the WA was significantly reduced from 6.1% to 4.1% (33% enhancement). Further observations also indicated that, after 24 h of soaking time, lower enhancement can be seen in the WA for all the prepared solutions with different sodium silicate-Silica Fume replacement levels, compared to 1 h and 4 h soaking times. It can be concluded that, among all the concentration solutions utilized, the solution with a 5% replacement level achieved the best enhancements in the AIV and the WA of the RA, whereas solutions with a higher replacement level of 15% achieved the lowest enhancement results. Among all the soaking times, soaking for 4 h achieved the highest enhancements. Consequently, soaking in solution with a replacement level of 5% for 4 h of soaking time is considered to be optimum.

Immersing RA in a pozzolanic solution can improve the microstructure and the engineering properties of the RA in two aspects; pozzolana acts as a micro-filler that fills in the pores and micro-cracks of RA, these materials will form C-S-H gel through reacting with

CH crystals in RA that fill up the voids with RA. A thin layer called water repellent is formed by impregnating the RA in sodium silicate-silica fume solution for a certain time, resulting in filling the pores and the voids within the adhered mortar when. When RA is immersed in this solution, both materials can react with the calcium hydroxide existing in the adhered mortar to form C-S-H gel, according to Eq. (4) [51]:



Furthermore, further improvement can be achieved in this method, as a result of the pozzolanic reaction between silica fume and the  $\text{Ca}(\text{OH})_2$  which produces secondary C-S-H gel, hence a stronger interfacial transition zone will be developed on the RA surface.

Soaking RA in sodium silicate-silica fume solution significantly enhanced the AIV and the WA of the RA. This may be ascribed to the thin film layer formed of sodium silicate and pozzolana particles on the surface of RA through consuming the CH product in the AM which in return made RA a denser structure by filling up and sealing the pores and cracks of RA. This is in line with the outcome of Shaban et al. [52] study who stated that soaking RA in sodium silicate solution significantly reduced the WA of the RA. They added that this is attributed to the silicic acid that filled up the pores and voids of the RA surface along with the chemical reaction between the sodium silicate and CH that produced C-S-H gel which enhanced the bond between the adhered mortar and RA.

Among all the utilized concentration solutions, solutions with 5% concentration achieved the best performance, whereas solutions with a higher concentration of 15% achieved the lowest enhancement results. Among all the soaking periods of time, soaking for 4 h achieved the highest enhancement values in terms of RA engineering properties. This might be because the pozzolan materials could not penetrate deeply into the surface of RA and efficiently strengthen it in the case of short soaking times [52]. Moreover, long soaking times i.e., 24 h would result in removing the hydration products and eroding the surface of RA and thus lower enhancements to the AIV and WA of RA will be achieved [53]. Higher concentration levels also are not beneficial to the enhancement of RA as the solution may be too thick to penetrate the surface of RA and it would also reduce the degree of hydration of the pozzolan products. Ouyang et al. [53] stated that excessive treatment methods should be avoided, such as high concentration of the treatment solutions, and long soaking times, which could erode the surface of RA, leading to reducing the efficiency of the treatment employed.

This is in line with Yang et al. [51] who soaked RA in water-glass (sodium silicate) solution with different concentrations of 3%, 5%, 8%, 10%, 20%, and 40% for 10 min, 1 h, 2 h, and 5 h. Yang et al. [51] found that the treated RA obtained enhanced water absorption by 36% when RA was soaked in water-glass solution with 40% concentration for 1 h, whereas soaking the RA in water-glass solution with 5% for 1 h achieved the best performance in terms of concrete 3-, 7-, and 28-day compressive strength at about 22%, 28% and 29% enhanced performance respectively.

Bui et al. [54] soaked RA in three main solutions; solution type G, solution type S, and sodium silicate SS. Solution type G included; GFA (fly ash +  $\text{NaSiO}_3$  +  $\text{NaOH}$ ), GSF (silica fume +  $\text{NaSiO}_3$  +  $\text{NaOH}$ ), GMK (metakaolin +  $\text{Na}_2\text{SiO}_3$  +  $\text{NaOH}$ ). Solution type S included; SFA (fly ash +  $\text{Na}_2\text{SiO}_3$ ), SSF (Silica fume +  $\text{Na}_2\text{SiO}_3$ ), and SMK (metakaolin +  $\text{Na}_2\text{SiO}_3$ ). Solution type SS was sodium silicate. RA was soaked for 24 h and at three different solution concentrations 10%, 20%, and 30%. Among all the treatment solutions, RA soaked with sodium silicate (SS) solution at 30% concentration achieved the best performance in terms of water absorption, RA attained 34% enhanced water absorption. Bui et al. [54] stated that, among all the utilized solutions, the combination between silica fume and sodium silicate achieved the best 28-day compressive strength, whereas concrete produced with treated RA in silica fume-sodium silicate solution achieved 36% enhancement. (Fig. 9).

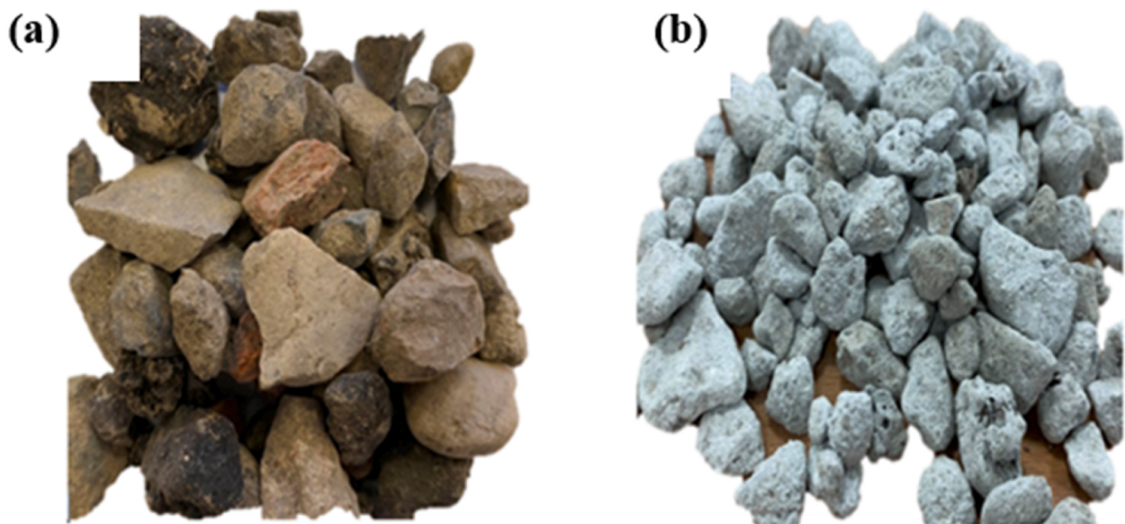


Fig. 9. shows RA before and after coating with cement-silica fume slurry. (a) untreated RA, (b) treated RA with coating with cement-silica fume slurry.

4.4. Effects of coating RA with cement or cement-silica fume slurry on the AIV and WA

Figs. 10 and 11 show the effects of coating the individual particle size fraction with cement slurry or cement-silica fume slurry, along with the effects of coating the total combined gradation of RA, on the AIV and the WA of the RA, respectively. As can be seen from Figs. 10 and 11, among all the coating thicknesses and coating materials, the treated RA with cement-silica fume slurry and coating thickness of 0.1 mm recorded the highest reduction in the AIV and the WA, from 17% to 14.9% (12% enhancement), and from 6.1% to 2.8% (54% enhancement), respectively, compared to the other coating thicknesses. In addition to that, via visual inspection, coating RA particles smaller than 10 mm with a thickness of 0.3 mm, results in getting the RA cemented to each other and hence, they cannot be separated easily. According to Lee et al. [40], when the coating paste around RA of 4.75 mm size exceeds the designated theoretical thickness of 0.65 mm, then the coating paste may get cemented into lumps and cannot be separated easily, while the coating paste cannot entirely coat the surface of RA when the coating paste around the surface of RA of 12.5 mm size is less than 0.25 mm of the coating thickness.

Accordingly, based on these results, it can be concluded that 0.1 mm is the optimum coating thickness to coat the individual RA grain sizes. This may be attributed to the small coating thickness resulting in filling the pores/cracks and thus leading to strengthening the weak RA particles. These findings are in line with Kareem et al. [55] who found that coating the individual RA at 0.1 mm coating thickness with cement slurry resulted in better AIV by 7% enhancement compared to 0.05, 0.2, and 0.4 mm coating thicknesses. RA treated with cement-silica fume slurry showed better AIV and WA compared to the ones treated with cement slurry only, this may be attributed to the additional produced C-S-H gel which effectively filled the pores and voids in the weak adhered mortar [40].

Coating the total combined RA with cement slurry only achieved 7% enhancement in the AIV (from 17% to 15.8%) and 36% enhancement in the WA (from 6.1–3.9%), whereas coating with cement and silica fume slurry offered slightly higher enhancement of 9% in the AIV (from 17% to 15.4%) and 41% enhancement in the WA (from 6.1% to 3.6%). Overall, the results of the effects of different coating methods on the AIV and the WA of the RA indicated significant enhancement in the AIV and the WA for all the coated RA with cement and/or cement-silica fume slurry regardless of the coating method.

It was also found that the increase in coating thickness layer results in adverse effects on the AIV and the WA. The RA treated with cement-silica fume slurry showed better enhancements in the AIV and the WA compared to the ones treated with cement slurry only. The method of coating the RA particle size fraction individually performed better in enhancing the AIV and the WA of the RA, in comparison with the method of coating the total gradation of the RA. This is in line with Zhihui et al. [56] who reported a 9% enhancement in AIV and a 39% enhancement in the WA of RA after coating the total combined RA size fraction with cement slurry.

Overall, this surface treatment method aims at altering the micro-surface structure of RA and then strengthen it by the touch-up of new materials (i.e., cement, silica fume, fly ash) and coating of the older material via patching and bonding of the smaller pores on the surface of RA to enhance its quality and properties, hence, reinforcing the bonding force and mechanical strength of the interface between coating materials and RA [40]. It can also be added that the basic premise of this treatment is to coat RA with hydrated cement film which is thick enough to act as a shield on the surface of RA.

4.5. Effects of soaking RA in different cement-pozzolan solutions on the AIV and WA

Fig. 12 shows RA after soaking in different cement-pozzolan solutions. The results shown in Figs. 13 and 14 show the effects of soaking RA in different cement-pozzolan solutions on the AIV and WA of RA, respectively.

At the first 1 h of soaking time, the RA treated with the combination of PFA+MK solution with a 10% replacement level exhibited the highest reduction in the AIV, the AIV was reduced from 17% to 15.3% (10% enhancement). Whereas the RA treated with the combination of PFA+SF solution with a 10% replacement level, recorded the highest reduction in the WA, the WA was reduced from

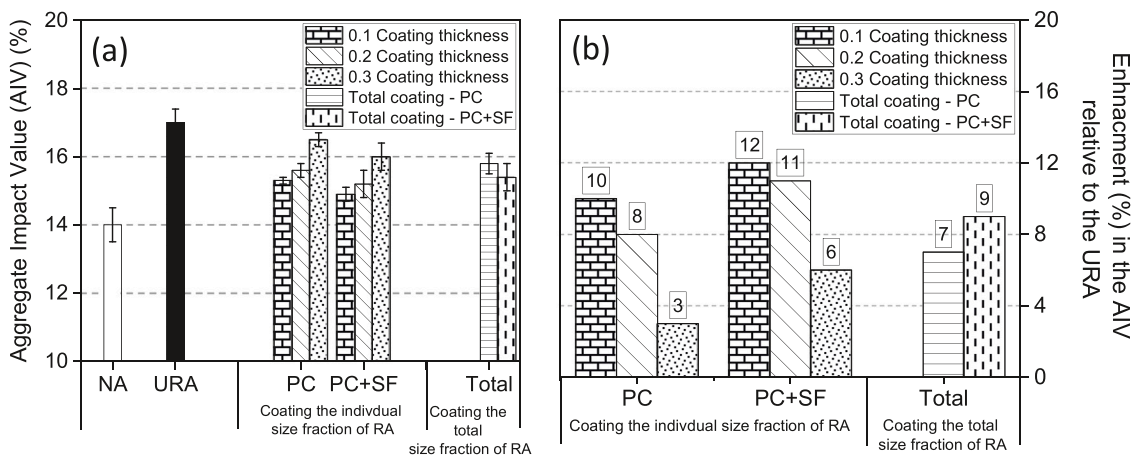


Fig. 10. (a) the effects of the different coating with cement and/or cement-SF methods on the AIV of the RA, (b) enhancement values in the AIV relative to the untreated RA.

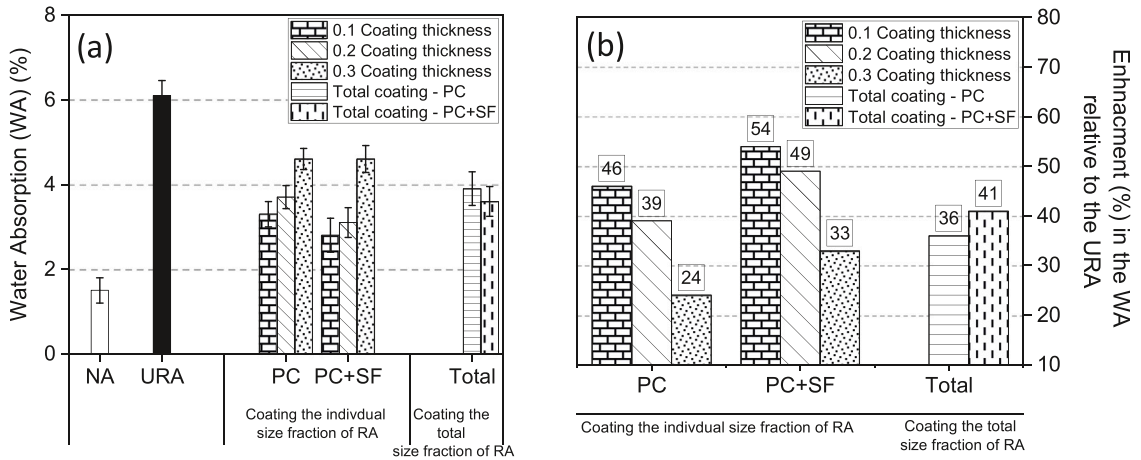


Fig. 11. (a) the effects of the different coating with cement and/or cement-SF methods on the WA of the RA, (b) enhancement values in the WA relative to the untreated RA.

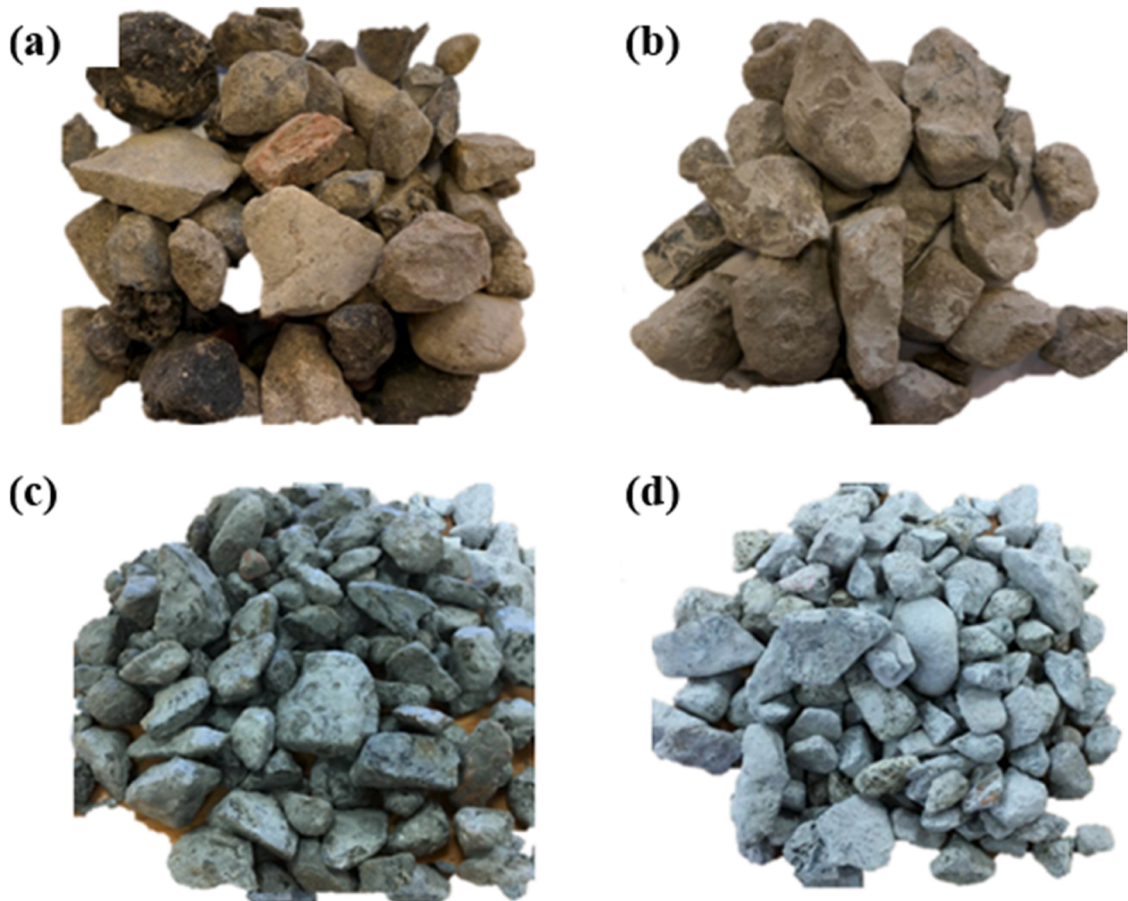


Fig. 12. (a) untreated RA, (b) treated RA with soaking in PFA+SF solution, (c) treated RA with soaking in PFA+MK solution, (d) treated RA with soaking in SF+MK solution.

6.1% to 3.2% (47% enhancement). These results are ascribed to the pozzolan thin layer formed on the RA surface after the treatment which filled the pores and the micro-cracks of the RA.

Further soaking time of the RA for up to 4 h resulted in better enhancement in the AIV and the WA of the RA regardless of the

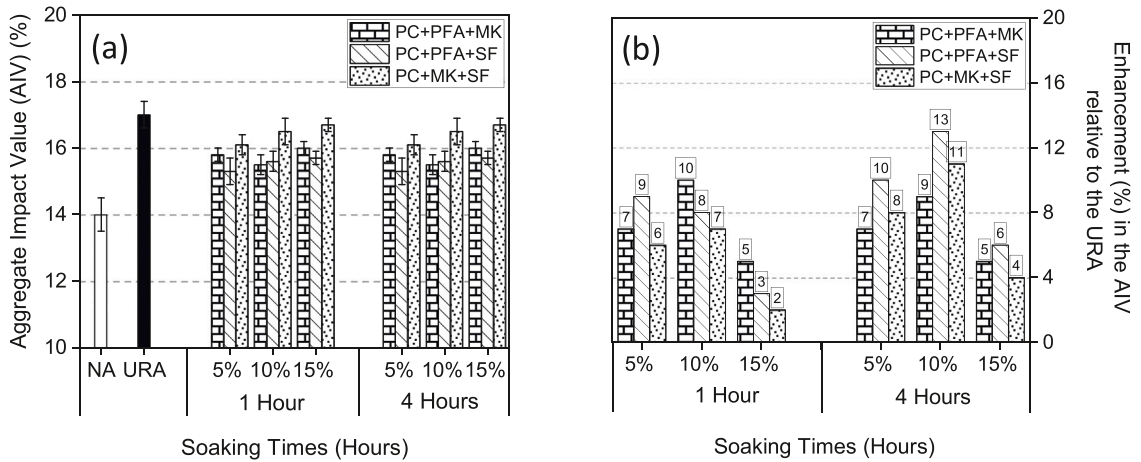


Fig. 13. (a) the effects of different soaking solutions at different replacement levels and soaking times on the AIV of the RA, (b) enhancement values in the AIV relative to the untreated RA.

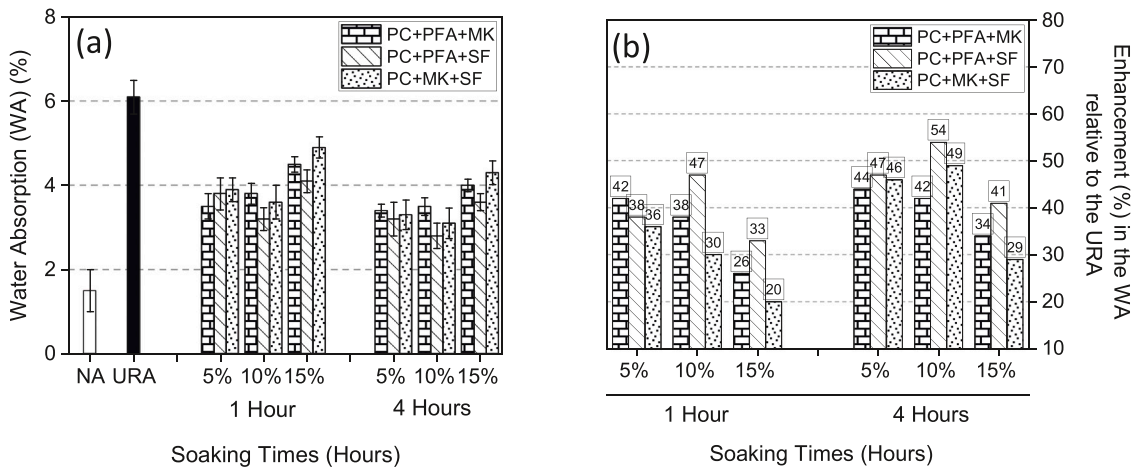


Fig. 14. (a) the effects of different soaking solutions at different replacement levels and soaking times on the WA of the RA, (b) enhancement values in the WA relative to the untreated RA.

replacement level and combination of materials, compared to 1 h of soaking. This might be because the pozzolanic materials need a longer time to deeply penetrate the adhered mortar and efficiently strengthen it. This finding is in line with Shaban et al. [52] who reported a 51.4% reduction in water absorption of RA after soaking in pozzolan solution. Li et al. [57] examined the effect of soaking of RA by pozzolanic powder (fly ash, silica fume, and GGBS), and found that the combination of Portland cement along with fly ash and silica fume is more efficient for high strength recycled aggregate concrete with better packing density and denser interfacial transition zone.

The highest reduction in the AIV and the WA was obtained by the PFA+SF solution at a 10% replacement level. The AIV was reduced from 17% to 14.7% (13% enhancement), while the WA was reduced from 6.1% to 2.8% (54% enhancement). This may be attested to the high reactivity of this pozzolan solution [45]. A similar finding was observed by Shaban et al. [52], who reported an approximate reduction of 40% in AIV after soaking RA in cement-pozzolan solutions.

Overall, it can be seen that soaking the RA in the solutions adopted for 4 h provided better enhancements in the AIV and the WA of the RA regardless of solutions replacement levels, compared to the 1 h of soaking time. Among all the replacement levels used, solutions with a 10% replacement level offered higher enhancements in the AIV and the WA of the RA, in comparison with solutions prepared with 5% and 15% replacement levels. In addition, the AIV and the WA of the RA soaked in the solutions prepared with a 15% replacement level exhibited lower enhancement values compared to solutions prepared with a 5% and 10% replacement levels regardless of the soaking time and the materials used. Consequently, it can be concluded that the optimal soaking time is 4 h, and the optimal replacement level is 10%. Among all the combinations of materials used for solution preparation, the solution prepared with PFA+SF solution achieved somewhat the best results regardless of soaking time and replacement level.

The main principle behind soaking RA in cement-pozzolan treatment is to cover the RA surface with a thin layer of hydration

products, hence strengthening RA engineering properties. After the treatment, a dense coated layer is formed around the RA surface after the reaction of the pozzolanic materials with the  $\text{Ca}(\text{OH})_2$  in the adhered mortar.

According to Singh et al. [58], the additional hydrated calcium silicate (C-S-H) gel fills the pores and voids of the adhered mortar as shown in Eq. (5). The incorporation of cement in the solutions is important for the treatment because it releases additional (C-S-H) gel and  $\text{Ca}(\text{OH})_2$  during hydration, as given in Eq. (6).



This additional production of C-S-H gel efficiently fills the voids and pores of the weak adhered mortar, resulting in a much denser microstructure of RA. Singh et al. [58] stated that particle size, the content of calcium hydroxide in the adhered mortar, the alkalinity of pore solution, and the reactivity of the pozzolanic materials are the main factors affecting the efficiency of the pozzolan solution treatment.

## 5. Conclusions

Recycled coarse aggregates demonstrated relatively low-quality characteristic performance compared to NA due to several factors. One of the major factors is the adhered mortar that results in a weak old interfacial transition zone. Other concerns include variation in composition, previous loading, processing, and weathering compared to freshly crushed natural aggregates. This paper has presented laboratory-based investigations on the effects of different treatments including, accelerated carbonation treatment, cyclic limewater-accelerated carbonation, soaking in sodium silicate-silica fume solution, coating with cement and/or cement-silica fume slurry, and soaking in cement-pozzolan solutions on enhancing the aggregate impact value and water absorption of RA. The following specific conclusions can be drawn:

Accelerated carbonation treatment is an environmentally friendly viable treatment through its mechanism in terms of carbon capture. Accelerated carbonation treatment at 50%  $\text{CO}_2$  concentration level for six days of  $\text{CO}_2$  exposure time achieved the best results among carbonation conditions, giving 11% and 46% enhancement in the AIV and WA, respectively. The recycled aggregates treated with three cyclic periods of pre-soaking in limewater followed by accelerated carbonation at 100%  $\text{CO}_2$  concentration level for 24 h, exhibited better improvement in the AIV and WA compared to the sole use of accelerated carbonation treatment under the same carbonation conditions. The observed enhancements in the AIV and the WA after accelerated carbonation treatment was mainly due to the carbonation process through the chemical reactions between  $\text{CO}_2$ , the available calcium hydroxide, and the calcium silicate hydrates on the RA surface. This carbonation process filled the pores and the cracks on the RA surface and sealed its surface.

Coating the individual size fraction of RA with cement or cement-silica fume achieved better enhancement in the AIV and WA compared with coating the whole size fraction of RA. Among all the coating thicknesses, coating the individual size fraction of RA with cement-silica fume slurry at 0.1 mm coating thickness led to the best enhancements of 12% and 54% in the AIV and the WA, respectively. Coating RA with cement and silica fume slurry was observed to provide better enhancement in the AIV and the WA, compared to coating RA with only cement slurry. The enhancements observed in the AIV and WA were mainly due to the RA surface being covered with a thick layer of hydration products and C-S-H gel that acted as a shield that strengthened the adhered mortar and reduced its porosity.

Soaking RA in 5% sodium silicate-silica fume solution for 4 h soaking time was found to be optimal. The treated RA achieved 8% and 33% enhancement in the AIV and the WA, respectively. This was ascribed to the produced C-S-H gel by the chemical reaction between sodium silicate and calcium hydroxide with the presence of water and between silica fume and calcium hydroxide simultaneously. The produced C-S-H gel and the secondary C-S-H gel effectively filled the micro-pores, voids, and micro-cracks on the RA surface, which reflected in the reduced WA and enhanced AIV.

Soaking RA in 10% Portland cement-pozzolan solution for 4 h soaking time was found to be optimal, among all the examined conditions, achieving enhancements of 13% and 54% in the AIV and the WA, respectively. This enhancement resulted from the pore filling and sealing effects of this treatment on the surface of RA.

## Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or non-profit sectors.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

- [1] Ali Akhtar, Ajit Samarah, Construction and demolition waste generation and properties of recycled aggregate concrete: a global perspective, 262-28, J. Clean. Prod. 186 (2018), <https://doi.org/10.1016/j.jclepro.2018.03.085>.
- [2] N. Tošić, S. Marinković, A. Stojanović, Sustainability of the concrete industry – current trends and future outlook, Tehnika Naše Građevinarstvo 71 (1) (2017) 38–44, <https://doi.org/10.5937/tehnika1701038T>.

- [3] Sharman, J., 2018. Construction Waste and materials Efficiency. [online] Available at: (<http://www.thenb.com>). [Accessed 20 February 2022].
- [4] W. Lu, Big data analytics to identify illegal construction waste dumping: a Hong Kong study, *Resour. Conserv. Recycl.* 141 (2019) 264–272, <https://doi.org/10.1016/j.resconrec.2018.10.039>.
- [5] V. Tam, M. Soomro, A. Evangelista, A review of recycled aggregate in concrete applications (2000–2017), *Constr. Build. Mater.* 172 (2018) 272–292, <https://doi.org/10.1016/j.conbuildmat.2018.03.240>.
- [6] R. Silva, J. Brito, R. Dhir, Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production, *Constr. Build. Mater.* 65 (2014) 201–217, <https://doi.org/10.1016/j.conbuildmat.2014.04.117>.
- [7] J. Kim, Influence of quality of recycled aggregates on the mechanical properties of recycled aggregate concrete: an overview, *Constr. Build. Mater.* 328 (2022), 127071, <https://doi.org/10.1016/j.conbuildmat.2022.127071>.
- [8] H. Dabiri, et al., Compressive strength of concrete with recycled aggregate; a machine learning-based evaluation, *Clean. Mater.* 3 (2022), 100044, <https://doi.org/10.1016/j.clema.2022.100044>.
- [9] H. Dilbas, O. Cakir, C. Atis, Experimental investigation on properties of recycled aggregate concrete with optimized Ball Milling Method, *Constr. Build. Mater.* 212 (2019) 716–726, <https://doi.org/10.1016/j.conbuildmat.2019.04.007>.
- [10] G. Dimitriou, P. Savva, M. Petrou, Enhancing mechanical and durability properties of recycled aggregate concrete, *Constr. Build. Mater.* 158 (2018) 228–235, <https://doi.org/10.1016/j.conbuildmat.2017.09.137>.
- [11] H. Katkhuda, N. Shatarat, Improving the mechanical properties of recycled concrete aggregate using chopped basalt fibers and acid treatment, *Constr. Build. Mater.* 140 (2017) 328–335, <https://doi.org/10.1016/j.conbuildmat.2017.02.128>.
- [12] V. Tam, Comparing the implementation of concrete recycling in the Australian and Japanese construction industries, *J. Clean. Prod.* 17 (7) (2009) 688–702, <https://doi.org/10.1016/j.jclepro.2008.11.015>.
- [13] A. Gonzalez-Corominas, M. Etxeberria, Properties of high-performance concrete made with recycled fine ceramic and coarse mixed aggregates, *Constr. Build. Mater.* 68 (2014) 618–626, <https://doi.org/10.1016/j.conbuildmat.2014.07.016>.
- [14] K. Bru, et al., Assessment of a microwave-assisted recycling process for the recovery of high-quality aggregates from concrete waste, *Int. J. Miner. Process.* 126 (2014) 90–98, <https://doi.org/10.1016/j.minpro.2013.11.009>.
- [15] H. Al-Bayati, P. Das, S. Tighe, H. Baaj, Evaluation of various methods for enhancing the physical and morphological properties of coarse recycled concrete aggregate, *Constr. Build. Mater.* 112 (2016) 284–298, <https://doi.org/10.1016/j.conbuildmat.2016.02.176>.
- [16] E. Pawluczuk, K. Wichrowska, M. Boltryk, J. Rodriguez, The influence of heat and mechanical treatment of concrete rubble on the properties of recycled aggregate concrete, *Materials* 12 (3) (2019) 1–24, <https://doi.org/10.3390/ma12030367>.
- [17] H. Al-Bayati, S. Tighe, Utilizing a Different Technique for Improving Micro and Macro Characteristics of Coarse Recycled Concrete Aggregate, Transportation Association of Canada, Toronto, 2016. ([https://www.tac-atc.ca/sites/default/files/conf\\_papers/al-bayati](https://www.tac-atc.ca/sites/default/files/conf_papers/al-bayati)).
- [18] V. Tam, C. Tam, K. Le, Removal of cement mortar remains from recycled aggregate using pre-soaking approaches, *Resour. Conserv. Recycl.* 50 (1) (2007) 82–101, <https://doi.org/10.1016/j.resconrec.2006.05.012>.
- [19] S. Kou, C. Poon, Enhancing the durability properties of concrete prepared with coarse recycled aggregate, *Constr. Build. Mater.* 35 (2012) 69–76, <https://doi.org/10.1016/j.conbuildmat.2012.02.032>.
- [20] A. Grabiec, J. Klama, D. Zawal, D. Krupa, Modification of recycled concrete aggregate by calcium carbonate bio-deposition, *Constr. Build. Mater.* 34 (2012) 145–150, <https://doi.org/10.1016/j.conbuildmat.2012.02.027>.
- [21] J. Chen, J. Thomas, H. Jennings, Decalcification shrinkage of cement paste, *Cem. Concr. Res.* 36 (5) (2006) 801–809, <https://doi.org/10.1016/j.cemconres.2005.11.003>.
- [22] S. Kou, B. Zhan, C. Poon, Use of a CO<sub>2</sub> curing step to improve the properties of concrete prepared with recycled aggregates, *Cem. Concr. Compos.* 45 (2014) 22–28, <https://doi.org/10.1016/j.cemconcomp.2013.09.008>.
- [23] L. Mazurana, P. Bittencourt, F. Scremin, A. Junior, E. Possan, Determination of CO<sub>2</sub> capture in rendering mortars produced with recycled construction and demolition waste by thermogravimetry, *J. Therm. Anal. Calorim.* 147 (2020) 1071–1080, <https://doi.org/10.1007/s10973-020-10436-0>.
- [24] Mazurana, L. CO<sub>2</sub> uptake in rendering mortars by carbonation [Internet]. Universidade Tecnológica Federal do Paraná; 2019. Available from: (<https://repositorio.utfpr.edu.br/jspui/handle/1/4733>). Accessed 21 May 2022.
- [25] British Standards Institution, BS EN 12620:2002+A1:2008—Aggregates for Concrete, British Standards Institution, London, UK, 2008.
- [26] British Standards Institution, BS EN 13242:2013—Aggregates for Unbound and Hydraulically Bound Materials for Use in Civil Engineering Work and Road Construction, British Standards Institution, London, UK, 2013.
- [27] Derwen, 2016. Recycled Aggregate. [Online] Available at: (<https://www.derwengroup.co.uk>) [Accessed 10 February 2022].
- [28] British Standards Institution, BS 8500-2:2015 +A2: 2019—Concrete-complementary British standard to BS EN 206. Part 2: Specification for Constituent Materials and Concrete, British Standards Institution, London, UK, 2019.
- [29] British Standards Institution, BS EN 933-1:2012—Tests for geometrical properties of aggregates. Part 1: Determination of Particle Size Distribution—Sieving Method, British Standards Institution, London, UK, 2012.
- [30] British Standards Institution, BS EN 933-3: 2012—Tests for geometrical properties of aggregates. Part 3: Determination of Particle Shape—Flakiness Index, British Standards Institution, London, UK, 2012.
- [31] British Standards Institution, BS EN 933-4:2008—Tests for geometrical properties of aggregates. Part 4: Determination of Particle Shape—Shape Index, British Standards Institution, London, UK, 2008.
- [32] British Standards Institution, BS EN 1097-6:2013—Tests for mechanical and physical properties of aggregates. Part 6: Determination of Particle Density and Water Absorption, British Standards Institution, London, UK, 2013.
- [33] British Standards Institution, BS EN 1097-2:2020—Tests for mechanical and physical properties of aggregates. Part 2: Methods for Determination of Resistance to Fragmentation, British Standards Institution, London, UK, 2020.
- [34] British Standards Institution, BS EN 197-1:2011 - Cement. Composition, Specifications and Conformity Criteria for Common Cements, British Standards Institution, London, UK, 2011.
- [35] British Standards Institution, BS EN 450-1:2012 - Fly ash for concrete. Definition, Specifications and Conformity Criteria, British Standards Institution, London, UK, 2012.
- [36] British Standards Institution, BS EN 13263-2:2005+A1:2009 - Silica fume for concrete. Conformity evaluation, British Standards Institution, London, UK, 2009.
- [37] British Standards Institution, BS EN 15167-1:2006 - Ground granulated blast furnace slag for use in concrete, mortar and grout. Definitions, Specifications and Conformity Criteria, British Standards Institution, London, UK, 2006.
- [38] B. Zhan, D. Xuan, C. Poon, C. Shi, Effect of curing parameters on CO<sub>2</sub> curing of concrete blocks containing recycled aggregates, *Cem. Concr. comp.* 71 (2016) 122–130, <https://doi.org/10.1016/j.cemconcomp.2016.05.002>.
- [39] G. Pan, et al., Effect of CO<sub>2</sub> curing on demolition recycled fine aggregates enhanced by calcium hydroxide pre-soaking, *Constr. Build. Mater.* 154 (2017) 810–818, <https://doi.org/10.1016/j.conbuildmat.2017.07.079>.
- [40] C.-H. Lee, J. C. Du, D.-H. Shen, Evaluation of pre-coated recycled concrete aggregate for hot mix asphalt, *Constr. Build. Mater.* 28 (1) (2011) 66–71, <https://doi.org/10.1016/j.conbuildmat.2011.08.025>.
- [41] Y. Pu, L. Li, Q. Wang, X. Shi, C. Luan, G. Zhang, L. Fu, A. Abomohra, Accelerated carbonation technology for enhanced treatment of recycled concrete aggregates: a state-of-the-art review, *Constr. Build. Mater.* 282 (2021), 122671, <https://doi.org/10.1016/j.conbuildmat.2021.122671>.
- [42] D. Anstice, C. Page, M. Page, The pore solution phase of carbonated cement pastes, *Cem. Concr. Res.* 35 (2005) 377–383, <https://doi.org/10.1016/j.cemconres.2004.06.041>.
- [43] N. Hyvert, et al., Dependency of C-S-H carbonation rate on CO<sub>2</sub> pressure to explain transition from accelerated tests to natural carbonation, *Cem. Concr. Res.* 40 (2010) 1582–1589, <https://doi.org/10.1016/j.cemconres.2010.06.01027>.

- [44] S. Kashef-Haghighi, Y. Shao, S. Ghoshal, Mathematical modeling of CO<sub>2</sub> uptake by concrete during accelerated carbonation curing, *Cem. Concr. Res.* 67 (2015) 1–10, <https://doi.org/10.1016/j.cemconres.2014.07.020>.
- [45] A. Mistri, S. Bhattacharyya, N. Dhami, A. Mukherjee, S. Barai, A review on different treatment methods for enhancing the properties of recycled aggregates for sustainable construction materials, *Constr. Build. Mater.* 233 (2020) 117–894, <https://doi.org/10.1016/j.conbuildmat.2019.117894>.
- [46] P.H.R. Borges, J.O. Costa, N.B. Milestone, C.J. Lynsdale, R.E. Streatfield, Carbonation of CH and C–S–H in composite cement pastes containing high amounts of BFS, *Cem. Concr. Res.* 40 (2010) 284–292, <https://doi.org/10.1016/j.cemconres.2009.10.020.25>.
- [47] J. Zhang, C. Shi, Influence of carbonated recycled concrete aggregate on properties of cement mortar, *Constr. Build. Mater.* 98 (2015) 1–7, <https://doi.org/10.1016/j.conbuildmat.2015.08.087>.
- [48] Li, Y., 2014. Improvement of Recycled Concrete Aggregate Properties by CO<sub>2</sub> Curing, Changsha: Hunan University. 28.
- [49] J. Ying, Q. Men, J. Xia, The effect of cumulative aggregate treatment by carbon dioxide levels on properties of concrete, *J. Build. Mater.* 20 (2017) 277–282.
- [50] M. Zhan, G. Pan, Y. Wang, M. Fu, X. Lu, Effect of presoak-accelerated carbonation factors on enhancing recycled aggregate mortars, *Mag. Concr. Res.* 69 (16) (2017) 838–849, <https://doi.org/10.1680/jmacr.16.00468>.
- [51] H. Yang, J. Xia, J. Thompson, R. Flower, Urban construction and demolition waste and landfill failure in Shenzhen, China, *Waste Manag.* 63 (2016) 393–396, <https://doi.org/10.1016/j.wasman.2017.01.026>.
- [52] W. Shaban, et al., Quality improvement techniques for recycled concrete aggregate: a review, *J. Adv. Concr. Technol.* 17 (2019) 151–167, <https://doi.org/10.3151/jact.17.151>.
- [53] K. Ouyang, C. Shi, H. Chu, H. Guo, B. Song, Y. Ding, G. Xuemao, J. Zhu, H. Zhang, Y. Wang, J. Zheng, An overview on the efficiency of different pretreatment techniques for recycled concrete aggregate, *J. Clean. Prod.* 263 (2020), 121264, <https://doi.org/10.1016/j.jclepro.2020.121264>.
- [54] N. Bui, T. Satomi, H. Takahashi, Enhancement of recycled aggregate concrete properties by a new treatment method, *Int. J. GEOMATE* 14 (41) (2018) 68–76, <https://doi.org/10.21660/2018.41.11484>.
- [55] A. Kareem, H. Nikraz, H. Asadi, Evaluation of the double coated recycled concrete aggregates for hot mix asphalt, *Constr. Build. Mater.* 172 (2018) 544–552, <https://doi.org/10.1016/j.conbuildmat.2018.03.158>.
- [56] Z. Zhihui, W. Shoude, L. Lingchao, G. Chenchen, Evaluation of pre-coated recycled aggregate for concrete and mortar, *Constr. Build. Mater.* 43 (2013) 191–196, <https://doi.org/10.1016/j.conbuildmat.2013.01.032>.
- [57] J. Li, H. Xiao, Y. Zhou, Influence of coating recycled aggregate surface with pozzolanic powder on properties of recycled aggregate concrete, *Constr. Build. Mater.* 23 (3) (2009) 1287–1291, <https://doi.org/10.1016/j.conbuildmat.2008.07.019>.
- [58] L. Singh, V. Bisht, M.S. Aswathy, L. Chaurasia, S. Gupta, Studies on performance enhancement of recycled aggregate by incorporating bio and nano materials, *Constr. Build. Mater.* 181 (2018) 217–226, <https://doi.org/10.1016/j.conbuildmat.2018.05.248>.