Enhancement of properties of recycled coarse aggregate concrete using bacteria

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**ABSTRACT**
Due to rapid construction, necessity for raw materials of concrete, especially coarse aggregate, tends to increase the danger of early exhaustion of the natural resources. An alternative source of raw materials would perhaps delay the advent of this early exhaustion. Recycled coarse aggregate (RCA) plays a great role as an alternative raw material that can replace the natural coarse aggregate (NCA) for concrete. Previous studies show that the properties of RCA concrete are inferior in quality compared to NCA concrete. This article attempts to study the improvement of properties of RCA concrete with the addition of bacteria named as *Bacillus subtilis*. The experimental investigation was carried out to evaluate the improvement of the compressive strength, capillary water absorption, and drying shrinkage of RCA concrete incorporating bacteria. The compressive strength of RCA concrete is found to be increased by about 20% when the cell concentration of *B. subtilis* is $10^6$ cells/ml. The capillary water absorption as well as drying shrinkage of RCA are reduced when bacteria is incorporated. The improvement of RCA concrete is confirmed to be due to the calcium carbonate precipitation as observed from the microstructure studies carried out on it such as EDX, SEM, and XRD.

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1. Introduction
Crushed concrete that results from the demolition of old structures is generated nowadays in large quantities. The current annual rate of generation of construction waste is 145 million tons worldwide [1]. The area required for land-filling this amount of waste is enormous. Therefore, recycling of construction waste is vital, both to reduce the amount of open land needed for land-filling and to preserve the environment through resource conservation [1]. It has been widely reported that recycling reduces energy consumption, pollution, global warming, greenhouse gas emission as well as cost [2–4]. Also, from the viewpoint of sustainable and green building technologies, the use of RCA in new concrete production has increased globally. Many attempts to develop structural concrete with RCA have been reported in the literature. From these studies, it is worth
noting that a certain amount of mortar from the parent concrete remains adhered to the stone particles in RCA. This adhered mortar forms a weak porous interface, which influences the strength and performance of RCA concrete [5–7] and subsequently results in concrete with lower quality [8–13]. This is considered to be one of the most significant differences between RCA and NCA concrete.

Use of urease-producing bacteria can address the problems associated with RCA concrete to some extent. *B. subtilis* bacteria can precipitate CaCO$_3$ through urease activity [14–16] which catalyzes the hydrolysis of urea into ammonium and carbonate. First, urea is hydrolyzed intracellular to carbamate and ammonia. Carbamate spontaneously hydrolyzes to form additional ammonia and carbonic acid. These products subsequently form bicarbonate, ammonium, and hydroxide ions. These reactions increase the ambient pH, which in turn shifts the bicarbonate equilibrium, resulting in the formation of carbonate ions. This leads to accumulation of insoluble CaCO$_3$, which fills up the pores of the concrete and improves the impermeability.

The rising tide of adoption of RCA for construction demands an investigation of methods to improve the quality of RCA concrete. Bacterial calcium carbonate mineralization using *B. subtilis* is proposed in the present study to improve the quality of RCA concrete.

2. Literature review

This section presents the state of the art review of published literature in two subjects required for understanding the present problem: (i) behavior of RCA concrete and (ii) improvement of mechanical and physical properties of RCA concrete as well as NCA concrete.

Katz [17] reported that concrete made with 100% recycled aggregates is weaker than concrete made with natural aggregates at the same water-to-cement ratio (w/c) and same cement type. Many published literature [17–20] reported that RCA concrete with no NCA reduces the compressive strength by a maximum of 25% in comparison with NCA concrete. A similar trend was observed in the case of tensile splitting strength and flexural strength [21].

The review of literature did not find any previous work on the mix design methodology for RCA concrete. It may be due to the high variability of the properties of RCA. Wardeh et al. [22] carried out an experimental program on RCA concrete according to the mix design method given in Eurocode 2. Sriravindrarajah et al. [23] proposed a mix design for pervious concrete and revealed an empirical relationship among porosity, compressive strength, and water permeability. Brito and Alves [24] studied the correlation of mechanical properties, density, and water absorption of RCA concrete.

Erik [25] and Dhir et al. [26] reported that RCA concrete requires more water for the same workability as compared to NCA concrete. Hansen [27] found that density, compressive strength, and modulus of elasticity of RCA concrete are relatively lesser than that of the parent concrete. RCA concrete results in higher permeability, rate of carbo- nation, and risk of reinforcement corrosion than NCA concrete for a given w/c ratio.

Fernando et al. [28] studied the variation of w/c ratio of some mechanical properties of concrete. The results showed a significant decrease in mechanical properties with an increase of w/c ratio when natural aggregates are completely replaced by recycled
aggregates. Fernando et al. [29] investigated the effect of different curing conditions on the compressive strength of RCA concrete and showed that the compressive strength of RCA concrete is reduced up to 20% when cured in open-air conditions.

There are several techniques available in the literature [30–34] to enhance the properties of RCA concrete such as partial replacement of cement with silica fume and fly-ash, addition of nanoparticles, etc. However, use of bacteria to enhance the properties of RCA concrete is not attempted by any previous researchers. Similar studies on NCA concrete are also found to be very limited.

Torgal and Labrincha [15] summarize that some bacteria are capable of naturally precipitating calcium carbonates. The precipitation is due to several activities of bacteria and fungi such as photosynthesis, ammonification, denitrification, sulfate reduction, and anaerobic sulfide oxidation [35,36]. From a majority of the experiments reported in literature, it is seen that bacteria of the genus Bacillus are used as an agent for the biological production of calcium carbonate based minerals.

Also, bacteria are found to be used in previous studies [37] for healing cracks by the precipitation of calcium carbonate. Ramachandran et al. [38] reported that the durability of concrete was enhanced with an increase in bacterial concentration. Chahal et al. [39,40] investigated the influence of the ureolytic bacteria (Sporosarcina pasteurii) on the compressive strength, water absorption, and chloride permeability of concrete incorporating silica fume and fly ash. A cell concentration of $10^5$ cells/ml was found to be the optimum dose of bacteria to enhance the compressive strength and reduce the permeability of NCA concrete. Kim et al. [41] investigated the characteristics of microbiological precipitation of calcium carbonate on normal and lightweight concrete by two types of bacteria, Sporosarcina pasteurii and Bacillus sphaericus. It is observed that B. sphaericus precipitated thicker calcium carbonate crystals than Sporosarcina pasteurii.

3. Research significance

It is found from an extensive review of literature that there is hardly any research on the use of bacteria to improve the properties of RCA concrete. The main objective of this study was to investigate the improvement of RCA concrete (made by 100% replacement of natural coarse aggregates) by adding bacteria. B. subtilis, which is widely available and most efficient in calcite production in an alkaline environment [15], was chosen in the present study. This bacteria is generally found in soil, non-pathogenic by nature [42–44], and cost effective.

4. Experimental investigation

4.1 Culture of Bacillus subtilis

B. subtilis (MTCC.736), which facilitates the precipitation of calcium carbonate, was collected from the Institute of Microbial Technology (IMTECH), Chandigarh, India, and was constantly maintained on nutrient agar slant. A single colony of the culture was taken and inoculated into nutrient broth and incubated at 37°C with constant shaking at 150 rpm. The medium composition of nutrient broth used for routine culture is shown in Table 1.
4.2 Growth kinetic study

Growth kinetic study of *B. subtilis* was done using UV-V spectrophotometer (Lambda 35, Singapore). One loop of bacterial culture from preserved slant is inoculated into the nutrient broth. The turbidity of the culture medium is measured by observing the optical density (O.D.) every 1 hour, and a graph is plotted to obtain the growth curve of the test organism. Figure 1 shows the growth curve of the test organism marked by different phases such as lag phase, log phase, and stationary phase. The bacteria concentrations required for addition in the concrete are selected considering the growth kinetics of *B. subtilis*. The lag phase of the growth kinetics corresponds to low concentration of bacterial cells (~$10^1$ cells/ml), whereas the mid-log phase of growth kinetics corresponds to the concentration of ~$10^3$ cells/ml. Generally, the highest number of live active cells was found in the late log phase or early stationary phase of growth kinetics, which corresponds to about $10^6$ cells/ml. At a concentration of about $10^7$ cells/ml the number of live cells is found to be less, and the activity decreases. The present study used four cell concentrations, $10^1$, $10^3$, $10^6$, and $10^7$ cells/ml, considering the growth kinetics of *B. subtilis*.

4.3 Properties of cement

Portland slag cement (PSC) made from waste blast furnace slag is popular in the regions adjacent to steel industries. The present study uses PSC cement conforming to IS:
455-1989 [45] for making concrete. The chemical composition and the physical properties of the cement used are given in Tables 2 and 3, respectively.

### 4.4 Properties of fine and recycled coarse aggregate

Locally available sand (fine aggregate) conforming to IS: 383-1970 [46] is collected from a nearby river and used in the present study. For recycled coarse aggregate, the parent concrete is crushed through a mini jaw crusher maintaining the size of aggregate between 20 and 4.75 mm. The particle size distribution curve of RCA is presented in Figure 2. The physical properties of fine aggregate, RCA, and NCA were evaluated as per IS: 2386 (Part III)-1963 [47] and reported in Table 4.

### 4.5 Mixture proportion

In order to study the improvement of compressive strength of RCA concrete, various concrete mixes were considered with and without bacteria. The mix design was applied as per the normal concrete design procedure available in IS: 10262-1982 [48] following a weight batching. The RCA concrete mixes were prepared by full

| Chemical composition of Portland slag cement. | Percentage (%) |
|---------------------------------------------|----------------|
| SiO₂                                        | 12             |
| CaO                                         | 43             |
| MgO                                         | 6.7            |
| Fe₂O₃                                       | 12             |
| Al₂O₃                                       | 26             |

| Physical properties of Portland slag cement. | Value |
|---------------------------------------------|-------|
| Specific gravity                            | 3.015 |
| Fineness by sieve analysis                  | 2%    |
| Normal consistency                          | 32%   |

![Figure 2. Coarse aggregate size distribution curve for RCA.](image-url)
(100%) replacement of NCA with RCA. The cement content was kept constant at 372 kg/m$^3$ with a constant total w/c ratio of 0.5. Concrete with NCA was prepared and considered as a reference to study the properties of other mixes. Four different bacterial concrete with cell concentrations of $10^1$, $10^3$, $10^6$, $10^7$ cells/ml were prepared and these mixes are represented as B-1, B-2, B-3, and B-4, respectively. The concentration of the bacteria was obtained by growing the culture for different time followed by centrifugation at 10,000 rpm for 10 min at 4°C. In order to study the effect of bacteria, a control mix of RCA without bacteria was also cast. The details of all the mixtures are presented in Table 5.

In order to avoid the extra water absorption by RCA, it was soaked in water for 1 hour and removed 24 hours before casting to have the same saturated surface dry condition as that of NCA. Under laboratory conditions, both coarse and fine aggregates were dry blended with cement for 2 min before adding water. Around 10% of total water was taken out and used for mixing the bacteria concentration. The remaining water (90%) was added and mixed with dry aggregates and cement for 1 min. The diluted bacterial solution was finally mixed with concrete for another 3 min.

### 4.6 Preparation of test specimens

For conducting compressive strength and capillary water absorption tests, concrete cubes of size $150 \times 150 \times 150$mm were cast. Three samples were tested for each category, and the average of the three was considered. For conducting drying shrinkage test, $150 \times 75 \times 75$mm concrete prisms were used. A rotary mixture was used for thorough mixing, and a table vibrator was used for good compaction. After successful casting, the concrete specimens were de-molded after 24 hours and immersed in water for 28 days maintaining $27\pm1$°C.

| Table 4. Properties of recycled coarse aggregate, natural coarse aggregate, and natural fine aggregate. |
|-----------------------------------------------|-----------------|-----------------|-----------------|
| Property                                      | RCA             | NCA             | Natural fine aggregate |
| Specific gravity                             | 2.48            | 2.83            | 2.658            |
| Bulk density (kg/l)                          | 1.409           | 1.97            | -               |
| Loose bulk density (kg/l)                    | 1.24            | 1.73            | -               |
| Water absorption (%)                         | 4.469           | 1.1             | 0.0651           |
| Impact value                                 | 26.910          | 23.84           | -               |
| Crushing value                               | 26.514          | 23.16           | -               |
| Fineness modulus                             | 3.38            | 3.14            | 2.84             |

| Table 5. Concrete mix proportion.            |
|-----------------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Mixture name                                  | RCA (Control Mix) | B-1 | B-2 | B-3 | B-4 | NCA concrete |
| Bacterial concentrations (cells/ml)           | 0               | $10^1$ | $10^3$ | $10^6$ | $10^7$ | 0               |
| Cement (kg/m$^3$)                             | 372             | 372 | 372 | 372 | 372 | 372             |
| Natural sand (kg/m$^3$)                       | 563.54          | 563.54 | 563.54 | 563.54 | 563.54 | 577.62          |
| Recycled coarse aggregate (kg/m$^3$)          | 1136.64         | 1136.64 | 1136.64 | 1136.64 | 1136.64 | 1232.75         |
| w/c ratio                                     | 0.5             | 0.5 | 0.5 | 0.5 | 0.5 | 0.5             |
| Water (kg/m$^3$)                              | 186             | 186 | 186 | 186 | 186 | 186             |
5. Test methods

The improvement of the physical properties of RCA concrete was evaluated by various tests that are described in the following sections.

5.1 Compressive strength test

The compressive strength of specimens was determined after 7 and 28 days of curing with surface dried condition as per Indian Standard IS: 516-1959 [49]. Three specimens were tested for typical category, and the mean compressive strength of three specimens was considered as the compressive strength of the specified category.

5.2 Drying shrinkage test

Drying shrinkage test was used to measure the shrinkage of concrete by determining the change in length of concrete specimens due to changes in moisture content. Initial drying shrinkage for the RCA concrete was measured as per Indian Standard IS: 1199-1959 [50]. The concrete prism was de-molded after 24 hours and left in the moist air for 7 days. At the end of moist curing, the specimens were put in a water tank at 27±1°C for 20 days. After the completion of curing, the length of the specimen was measured (to an accuracy of 0.005 mm) in wet condition. This length is termed the original wet measurement. Then the specimens were kept in the oven at 50±1°C for 44 hours. After this period of heating, it was allowed to cool for at least 4 hours. The reading that was taken after cooling was taken as dry measurements. Dry shrinkage was measured as the difference between the original wet measurement and the final dry measurement.

5.3 Air content of freshly mixed concrete

Pressure method was used for measuring the air content in freshly mixed concrete as per Indian Standard IS: 1199-1959 [51]. Freshly mixed concrete was kept inside a bowl after successive tamping. The required test pressure, which was slightly more than 0.02 kg/cm², was applied through hand pump after adding water. At this instant, the corresponding initial height of water was measured on the graduated precision bore tube or gauge glass of the standpipe. Then the test pressure was released gradually, and the final water height was measured. The air content ‘A’ is calculated as

\[ A = A_1 - G \]

where \( A_1 \) is the apparent air content in percentage by volume of concrete, and it is equal to the difference between the initial water height and the final water height. ‘G’ represents the aggregate correction factor, in percentage by volume of concrete, which was obtained as per IS: 1199-1959 [50].

5.4 Capillary water absorption

In the present study, capillary action through the concrete was found out by mass method using concrete cubes of size 150 x 150 x 150mm. After casting and successive
28-day curing, the cubes were allowed to dry in an oven at 105°C until attaining a constant weight. One-dimensional water flow was maintained for the measurement of capillary action by coating the cube with epoxy resins, except the top and bottom surfaces. The cubes were immersed in the water, and a minimum depth of immersion of 5 mm above the base of the cube was maintained. A gap of approximately 2 mm was maintained between the immersed face and the bottom of the water for good contact with water. The durations of immersion were 0.5, 1, 2, 4, 6, 24, 48, 72, and 96 hours. The capillary water absorption is measured by recording the respective weights of the cubes after successive immersion. Capillary action is calculated using the following relation as a function of time:

\[ \Delta W = S \times \sqrt{t} \]

where \( \Delta W \) is the cumulative amount of water absorbed per unit area (gm/mm\(^2\)) during the time of immersion (\( t \)) and \( S \) is the coefficient of capillary water absorption.

5.5 **SEM/EDX of the concrete samples**

The deposition of calcium carbonate precipitation was investigated by scanning electron microscopy (SEM) and X-ray diffraction (XRD). SEM micrographs were obtained using Jeol JSM-6480 LV SEM apparatus. Samples taken from the inner core of the concrete cube were dried at room temperature, and coated with platinum (JFC-1200 fine coat). During the examination, the accelerating voltage is maintained at a range of 20 kV. Mineral components of the isolates were further characterized by energy dispersive X-ray spectroscopy (EDX) analysis.

5.6 **X-ray diffraction (XRD) spectroscopy of concrete samples**

X-ray diffractometer with a Cu anode (40 kV and 30 mA) and scanning from 20° to 80° was used for XRD spectra. The samples were taken from the inner core area, well crushed and ground before mounting on a glass fiber filter using a tubular aerosol suspension chamber (TASC). The components of the sample were identified by comparing them with standards established by the International Center for Diffraction Data.

6. **Results and discussion**

6.1 **Compressive strength**

The addition of bacteria to the fresh concrete results in the formation of CaCO\(_3\) precipitation that can be observed through the naked eye as shown in Figure 3. Figures 3(a), 3(b), and 3(c) show bacterial RCA concrete with a concentration of 10\(^6\) cells/ml, and RCA and NCA concrete without bacteria, respectively. A white foam like material can be visualized on the outer surface of the bacterial concrete sample (Figure 3(a)) which is absent in other two (Figures 3(b) and 3(c)). The mean compressive strengths of specimens with different concentrations of bacteria after curing of 7 and 28 days are presented in Table 6. It can be seen that the compressive
strength of bacterial concrete increases with the increase of cell concentration for both 7 and 28 days’ strength. However, after cell concentration of 10^6 cells/ml, the trend reverses. The same results are plotted in Figure 4. The maximum increment of 28 days compressive strength of RCA concrete is found to be 20.93% (with respect to RCA control mix) with an optimum cell concentration of 10^6 cells/ml (B-3). The same trend is also reported for NCA concrete in the literature [39,40].

Table 6. Effect of bacteria on compressive strength (MPa) at 7 and 28 days.

| Mixture name   | 7 days | 28 days |
|----------------|--------|---------|
| RCA (Control Mix) | 29.06  | 38.22   |
| B-1 (10^1 cells/ml) | 31.27  | 41.02   |
| B-2 (10^3 cells/ml) | 32.70  | 43.13   |
| B-3 (10^6 cells/ml) | 34.15  | 46.22   |
| B-4 (10^7 cells/ml) | 32.80  | 44.60   |
| NCA            | 33.15  | 44.08   |

Figure 3. Photographs of fresh concrete indicating calcium carbonate precipitation. (a) Bacterial RCA concrete (10^6 cells/ml). (b) RCA concrete without bacteria. (C) NCA concrete without bacteria.

Figure 4. Effect of bacteria on compressive strength at 7 and 28 days.
This increase of compressive strength may be due to the precipitation of CaCO$_3$ by *B. subtilis* on the microorganism cell surfaces and within the inner side of the concrete, which is confirmed in the microstructure analysis (refer to Sections 6.5 and 6.6). By the successive microbiological precipitation of CaCO$_3$ in the micropores, the compressive strength is improved.

### 6.2 Drying shrinkage test

Drying shrinkage is measured after successive 28 days’ curing including 7 days’ moist air curing. The drying length and drying shrinkage obtained for three specimens, NCA, RCA, and B-3, are tabulated in Table 7. It is noticed that the addition of bacteria to RCA concrete decreases the percentage of drying shrinkage. This can be attributed to denser RCA concrete formed by bacterial activity. The drying shrinkage of RCA concrete (without bacteria) is more than that of NCA concrete. Similar observations are also reported in previous literature [51–54]. The increase of drying shrinkage of RCA concrete (without bacteria) is perhaps due to the shrinking of old mortar adhered to the surface of RCA. However, previous studies [30,51] show that it can be controlled by reducing the w/c ratio accordingly. Another cause for higher drying shrinkage of RCA concrete maybe its low elastic modulus, as compared to NCA concrete, which offer less restraint to the potential shrinkage.

### 6.3 Air content of freshly mixed concrete

Table 8 shows the results of air content in the three samples, NCA, RCA, and B-3. Air content of bacterial concrete sample B-3 is found to be slightly more than the control mix RCA concrete, probably due to the bacterial activity (such as photosynthesis, etc.). The shortcoming of slightly higher air content may be reduced by increasing the mixing time to allow the extra air to flow out of the concrete mix.

### 6.4 Capillary water absorption

The capillary water absorption, which is the cumulative amount of water per unit area (gm/mm$^2$), is plotted as a function of time of immersion in Figure 5. The slope of these curves is increasing in nature; similar behavior was observed in previous studies [55,56].

### Table 7. Drying shrinkage of NCA, RCA, and B-3 samples.

| Type of concrete | Drying length (mm) | Drying shrinkage (%) |
|------------------|--------------------|----------------------|
| RCA              | 0.260              | 0.17                 |
| Bacterial RCA (B-3) | 0.040          | 0.03                 |
| NCA              | 0.135              | 0.09                 |

### Table 8. Air content of NCA, RCA, and B-3 samples.

| Type of concrete | Air content (%) |
|------------------|-----------------|
| NCA              | 12              |
| RCA              | 12              |
| B-3 (bacterial RCA) | 13            |
The water absorption for RCA samples (RCA and B-3) is higher than NCA samples, which is due to the additional water absorbed by the old mortar adhered to RCA. Capillary water absorption of B-3 sample (bacterial RCA) is less than that of RCA control mix (without bacteria). This is attributed to the denser concrete formed by bacterial precipitation of CaCO$_3$.

6.5 SEM and EDX of the concrete samples

Both B-3 concrete and RCA control mix are examined through SEM, and the results are presented in Figures 6 and 7. Deposition of calcium carbonate as calcite in B-3 RCA concrete is observed through SEM. More crystalline calcium carbonate is observed in the pores of bacterial concrete than RCA concrete. Figure 8 shows the intensities of various compounds from EDX at a point in the region marked in the Figure 7. The intensities of various compounds indicate the presence of calcite precipitated in the form of calcium carbonate.

![Figure 5. Variation of capillary water absorption for NCA, RCA, and B-3.](image)

![Figure 6. SEM of B-3 concrete sample.](image)
6.6 X-ray diffraction (XRD) spectroscopy of concrete samples

The results of the XRD of both B-3 and RCA samples are presented in Figures 9(a) and 9(b), respectively. It can be seen that more calcite is precipitated with higher intensity in B-3 concrete, due to bacterial activity. Also, it has been seen that in the case of bacterial concrete, more calcite is formed in crystalline form.

7. Conclusions

The experimental investigation is carried out to study the enhancement of properties such as compressive strength, drying shrinkage, air content, and capillary water absorption of RCA concrete with the addition of *B. subtilis*. The salient conclusions of the present study are as follows:

(1) Properties of RCA concrete such as compressive strength, capillary water absorption, and drying shrinkage are improved by the addition of *B. subtilis*. 

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**Figure 7.** SEM of RCA control mix.

**Figure 8.** EDX of B-3 sample concrete at marked outlines.
(2) The maximum compressive strength of bacterial RCA is observed at an optimum concentration of $10^6$ cells/ml at both 7 and 28 days. The maximum increase of compressive strength is found to be about 20%.

(3) *B. subtilis* plays a vital role in the increment in compressive strength of RCA concrete by way of calcium carbonate precipitation in the pores. Calcium carbonate precipitation by *B. subtilis* in the form of calcite has been confirmed through microstructure analysis using SEM, EDX, and XRD.

(4) *B. subtilis* decreases the drying shrinkage strain and capillary water absorption of RCA concrete and thereby enhances the durability. This can be attributed to a denser RCA concrete formed by bacterial activity.

Figure 9. (a). XRD analysis of B-3 concrete. (b). XRD analysis of RCA.
(5) Air content in bacterial RCA concrete is found to be slightly more than control mix RCA concrete during the initial stage of mixing. This can be reduced perhaps by increasing the mixing time to allow the extra air to go out of the concrete mix. To draw generalized conclusions on this aspect would require further research.

In order to improve the quality of RCA concrete, calcium carbonate mineralization with the help of *B. subtilis* bacteria is proposed in this study. This method can address the problems associated with RCA concrete to some extent. The present study is focused on three properties of RCA concrete: compressive strength, capillary water absorption, and drying shrinkage (at 28 days). Other properties such as modulus of elasticity, creep, rapid chloride penetration tests, and long-term effects need to be investigated for an assessment of the general behavior of RCA concrete.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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