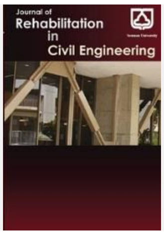

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Performance and Usability Assessment of Recycled Aggregate Extracted from Demolished Concrete Subjected to Multiple Recycling

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ABSTRACT

Concrete recycling is a growing trend in sustainable construction that aims to protect natural ingredients and reduce waste generation. However, most research focuses on first-generation recycled aggregates, and further evidence of recycled green concrete's potential for reuse is required. This investigation aims to evaluate the quality of aggregates through multiple recycling cycles and its impact on green concrete performance. Concrete blocks collected from a demolished highway culvert are broken into standard aggregate sizes. Green concrete prepared using these recycled aggregates is named first-generation green concrete. After attaining sufficient strength, the first-generation green concrete is broken to produce aggregates, which are said to be second-generation recycled aggregates, and concrete made with them as second-generation green concrete. In a similar manner, third and fourth-generation recycled aggregate and green concrete specimens are produced. Some quality parameters of aggregate, such as water absorption, aggregate crushing value (ACV), and Log Angeles abrasion resistance (LA), are monitored after each cycle of recycling. A maximum of 2nd generation recycled aggregates met the quality requirements of standard aggregates for concreting with an ACV of 27% (<30%) and LA of 39% (<40%). The compressive strength of green concrete built from first- to fourth-generation recycled aggregates is measured and investigated. The patterns of strength increase and loss are exhibited after each generation of recycling. It has been found that the first-generation green concrete may be useful as structural concrete in grades C-20 and C-25, while the second and third generation green concrete may be utilized for low-load bearing structures if longer curing is assured.

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1. Introduction

The exponential growth of the worldwide population and industrialization have an alarming impact on the environment. The concrete industry adds a huge amount of construction and demolition waste every year. Global construction and demolition waste generation was reported to be nearly 3 billion tons back in 2012, and it was expected to reach as high as 12.5 billion tons in the next ten years [1-2]. In 2016, the European Union contributed more than 2.5 billion tons of construction waste [3]. Several problems, including a shortage of raw materials for concrete, the occupancy of landfill areas [4,5], and pollution of the environment [6,7], are being encountered as a result of disposing of these wastes. A major portion of such construction and demolition waste is old, discarded concrete. Several studies indicated the potential of demolished concrete to be recycled for making aggregates, which are commonly known as recycled aggregates. Concrete made with recycled aggregates is usually called recycled concrete. As recycled concrete uses waste material as its ingredient, it can also be called green concrete [8–11]. A number of remarkable research works have been published on recycled aggregate in the past few years. In 2004, a study on the performance of recycled concrete reported some index properties of fresh and recycled aggregate when used with Portland cement [12]. A few years later, a regression analysis was presented correlating the properties of fresh and recycled aggregate concrete, and the study reported that recycled aggregate concrete (RAC) is generally suitable for moderate to low-strength construction applications. The researchers presented a prediction model for estimating the strength of recycled aggregate concrete [13]. The satisfactory performance of recycled aggregate to produce structural-grade concrete was also reported in the literature; researchers carried out load testing of reinforced concrete beams made of recycled concrete [14]. Besides the structural performance of recycled concrete, lower CO^2 emissions in the production of recycled concrete were also reported [15]. However, significant quality loss in subsequent concrete made with recycled aggregates is also mentioned in scholarly reports. In a study on the pre-treatment of recycled aggregate, about 10% more aggregate crushing value in recycled aggregate was found compared to its parent aggregate [16]. An experimental program with two variables (percentage of fine aggregate replacement and proportion of coarse aggregate replacement) found a strength loss of 15% to 32% with varying levels of recycled aggregate [17]. Another study on the influence of parent concrete strength on recycled concrete found that replacing 33% of the recycled aggregate reduces parent concrete strength by roughly 2 MPa, which is encouraging [18]. A study based on questionnaires about enablers and barriers related to the use of recycled aggregate in Australian construction industries was conducted to motivate builders to use recycled aggregate [19]. It is to be noted that most of the research work was concentrated on first-generation recycled aggregate. Multiple-time recycling is also a point of interest for current researchers. Recently, a study on the micro and macro-properties of multiple recycled aggregates was conducted, and the results showed that it is only possible to recycle concrete a limited number of times as the 3rd generation concrete had almost twice as much old mortar as the 1st generation had [20]. The compaction capacity of recycled aggregate was found to be reduced by successive recycling due to the addition of old mortar [21]. Up to three generations of recycled aggregate were found to meet the structural requirements for a 50-year life span [22]. Multiple recycling has also been found to have a detrimental effect on aggregate properties. In terms of aggregate crushing value (ACV) and aggregate impact value (AIV), the 3rd generation recycled aggregate was found to be quite inferior as compared to the 1st generation [23]. The continuous property deterioration may make the recycled aggregate unsuitable for a particular usage. Therefore, although the recycled aggregate generated by repeated recycling is a competitive and inventive green product, its quality parameters should be checked and compared to standard requirements to make its application suggestive. Moreover, there are several factors, such as the amount of old mortar, the presence of cracks, the age and configuration of the parent concrete, etc., that are responsible for the wide variability in the properties of recycled aggregate [21-22]. For this reason, recycled aggregates demand extensive studies and research for a better understanding of their behavior. For the same reason, multiple times recycled aggregate demands more research work to refine the acceptability of the research outcomes. Due to the absence of defined quality standards for recycled aggregate in established design codes, experimental investigations are the sole means to ascertain its potential and difficulties. This study focuses on the property changes in recycled aggregates after multiple recycling processes and the performance of green concrete produced with these repeatedly recycled aggregates, as there is a scarcity of research on this topic.

2. Materials and methods

2.1. Materials for the Study

2.1.1. Recycled aggregate

To produce recycled aggregates, concrete blocks were collected from a demolished culvert located at Kaharole, Dinajpur. The collected blocks were broken manually into standard aggregate sizes. Fig. 1 shows the demolition site and recycled aggregate processed from the waste concrete.

Fig. 1. Processing of recycled aggregate from demolished concrete.

2.1.2. Concreting ingredients

Other concreting ingredients such as fine aggregate, binder, and water were collected or managed locally. Table 1 shows the properties of the ingredients used in this study.

Table 1. Concreting ingredients and their properties.

Ingredient	Parameter	Details Information
Fine Aggregate (Natural coarse sand)	Fineness Modulus	2.40
	Specific Gravity	2.65
	Water absorption	2.0 %
Binder (Ordinary Portland Cement)	Specification and Standard	CEM-1, 52.5 N ASTM C150, Type – 1
Water		Potable tap water

2.1.3. Chemicals

Old connected mortar is a significant contributing element to the inferior quality of recycled aggregate, per earlier research [16]. Chemical separation using sodium sulfate was used to measure the quantity of old mortar affixed to the recycled aggregate of various generations. The salt solution was made using anhydrous sodium sulfate salt, as shown in Fig. 2.

Fig. 2. Anhydrous sodium sulfate.

2.2. Multiple times recycling

Coarse aggregates prepared by breaking the directly collected demolished concrete blocks were named 1st generation recycled aggregate (RAG1). The concrete specimens prepared with RAG1 were marked as 1st generation green concrete (GCG1). After attaining sufficient strength, the GCG1 specimens were broken into standard aggregate sizes and given the name 2nd generation recycled aggregate (RAG2). Concrete specimens prepared with RAG2 were named 2nd generation green concrete (GCG2). In a similar manner, 3rd generation recycled aggregates (RAG3), 4th generation recycled aggregates (RAG4), 3rd generation green concrete (GCG3), and 4th generation green concrete (GCG4) were produced. To avoid the possible effect of residual cementing properties in the freshly broken recycled aggregates, they were subjected to water immersion for 90 days before being used in making green concrete as guided in an earlier study [26].

2.3. Testing the properties of recycled aggregates

Key properties of recycled aggregates were tested in the laboratory. Specific gravity, water absorption, and bulk density were determined as they are required in the calculations of concrete mix design. In addition, some other quality indicator properties, such as old mortar content, aggregate crushing value, and Los Angeles abrasion value, were also tested to track the quality deterioration in aggregate after each cycle of recycling. Table 2 shows a list of tests conducted on the recycled aggregates and the standards followed.

Table 2. Tests of aggregate and their standards.

Property under test	Test Standard
Specific gravity	ASTM C127 – 15 [27]
Water absorption	ASTM C127 – 15 [27]
Bulk density	ASTM C29 / C29 M -17a [28]
Aggregate Crushing Value	BS 812-110:1990 [29]
Los-Angeles Abrasion Value	ASTM C131 / C131 M-14 [30]
Old mortar content test	Earlier research [16,25]

All the tests were conducted on RAG1, RAG2, RAG3, RAG4, and NA, keeping the test conditions identical. Fig. 3 shows some pictures taken during the laboratory tests.

Fig. 3. Different laboratory tests on the recycled aggregates.

2.4. Mix design and designations

The concrete mixes were designed following the guidelines of the American Concrete Institute (ACI) [31]. An earlier study on several methods of concrete mix design revealed that the ACI mix design method suits best for recycled concrete [32]. Three medium-strength grades of concrete such as C-20, C-25, and C-30 were selected for this study. A standard slump in the range of 75-100 mm was considered for all the mixes. The proportions of different ingredients are presented in Table 3.

Table 3. Designation of concrete mixes and proportion of ingredients.

Designation	Coarse aggregate Type	Strength Grade	Proportion (kg/m^3)			
			Water	Cement	Fine aggregate	Coarse aggregate
GCG1	RAG1	C-20	193	335	751	941
		C-25		387	707	941
		C-30		435	667	941
GCG2	RAG2	C-20		335	738	899
		C-25		387	694	899
		C-30		435	653	899
GCG3	RAG3	C-20		335	730	863
		C-25		387	687	863
		C-30		435	646	863
GCG4	RAG4	C-20		335	733	807
		C-25		387	689	807
		C-30		435	649	807
NC	NCA	C-20		335	700	1143
		C-25		387	656	1143
		C-30		435	616	1143

2.5. Preparation of concrete specimens and testing

Fig. 4 shows some instances of specimen preparation and testing. For the compressive strength test, 100 mm in diameter and 200 mm in height standard cylindrical concrete specimens were prepared and tested in accordance with ASTM C39 standard [33]. Tests were conducted after 7 days, 28 days, 56 days, 84 days, and 112 days of curing.

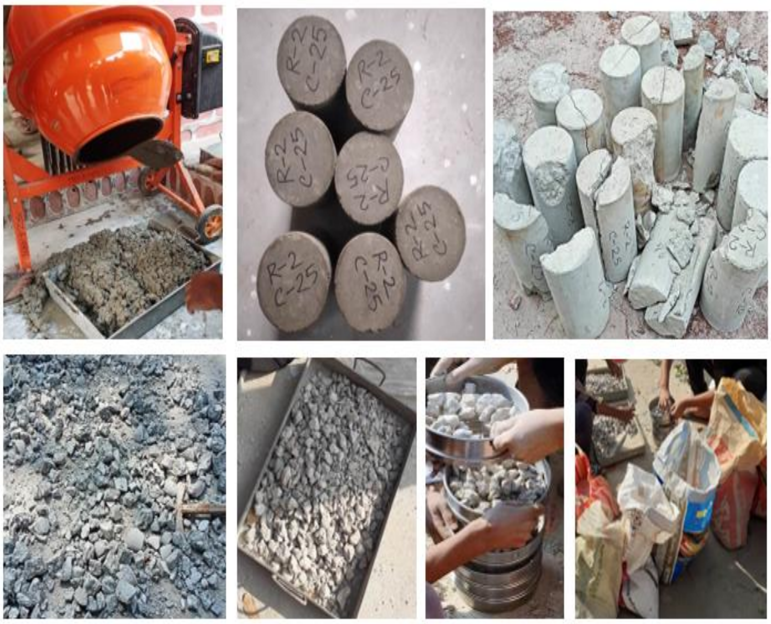

Fig. 4. Concrete specimen preparation and testing.

3. Results and discussion

3.1. Effect of multiple recycling on aggregate properties

3.1.1. Effect on specific gravity and bulk density

The change in specific gravity and bulk density is shown in **Figs. 5a-b.** Both the specific gravity and unit weight are found to decrease at higher generations of recycled aggregate. The specific gravity of normal weight aggregate lies between 2.5 and 3.0 [34].

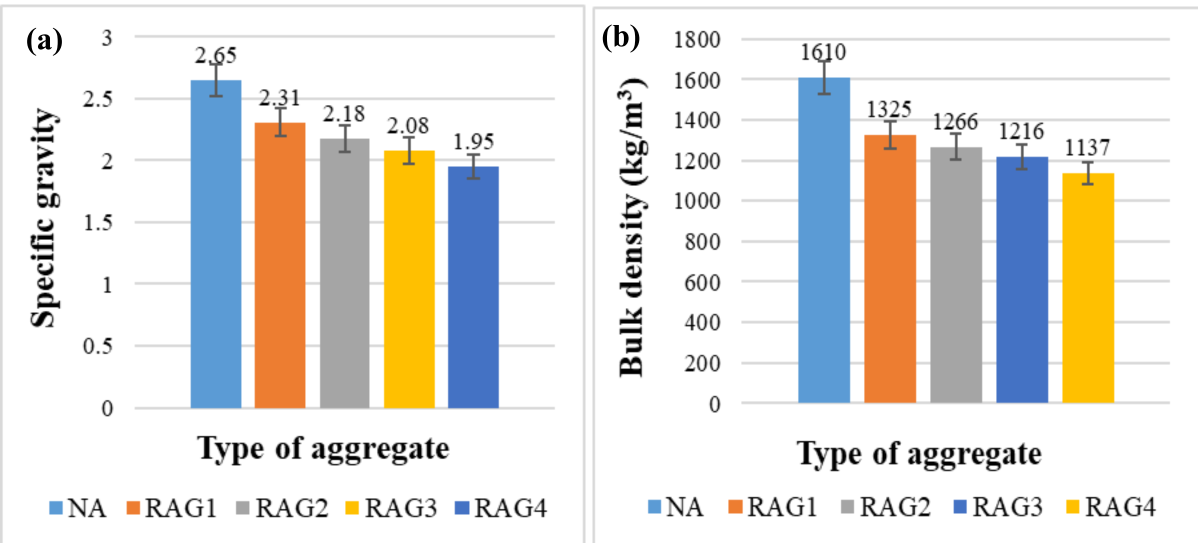

Fig. 5. (a) Specific gravity and (b) bulk density of recycled aggregates.

The natural stone aggregates used in this study had a specific gravity of 2.65, which was in that range, but the recycled aggregates of any generation had a lower specific gravity, which indicates that they are lighter than NA. A possible reason for this may be the addition of porous mortar in the recycled aggregates, which have a lower specific gravity than the stone particles. For the same reason, unit weight also decreased with successive repetitions of recycling.

3.1.2. Effect on water absorption

Water absorption is an important quality parameter of coarse aggregate. Ideal aggregates should have low water absorption. The natural aggregates used in this study had a water absorption of only 1.4%. As shown in Fig. 6, the water absorption values of recycled aggregates are considerably higher than those of NA. The 1st generation RCA had more than 4 times higher water absorption compared to NA. 2nd and 3rd generation RCA had almost equal water absorption, but the 4th generation RCA had the highest water absorption of 10.4%. The observation indicates a quality loss in RCA after successive repetitions of recycling. As more mortars are added after each cycle of concreting, it enables the aggregate to absorb more water through the porous surfaces of the attached old mortar.

3.1.3. Effect on strength of aggregate

Aggregate crushing value (ACV) is an indicator of its strength. Suitability of an aggregate in pavement application is judged by its ACV. Higher ACV indicates lower strength of aggregate. As shown in Fig. 7, ACV increases after each time of recycling. Since an additional interfacial transition zone is added after each cycle of recycling, the aggregates become weaker and for this reason breaking them into smaller pieces becomes easier resulting in a higher ACV.

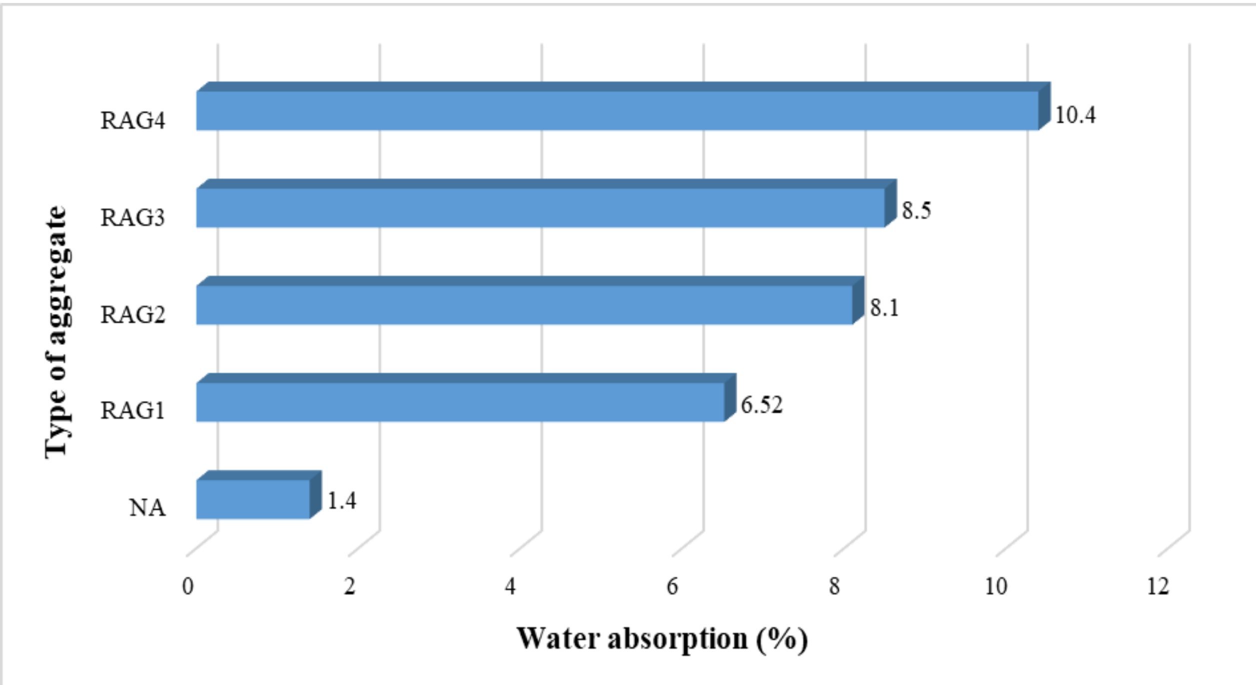

Fig. 6. Increase in water absorption for multiple recycling.

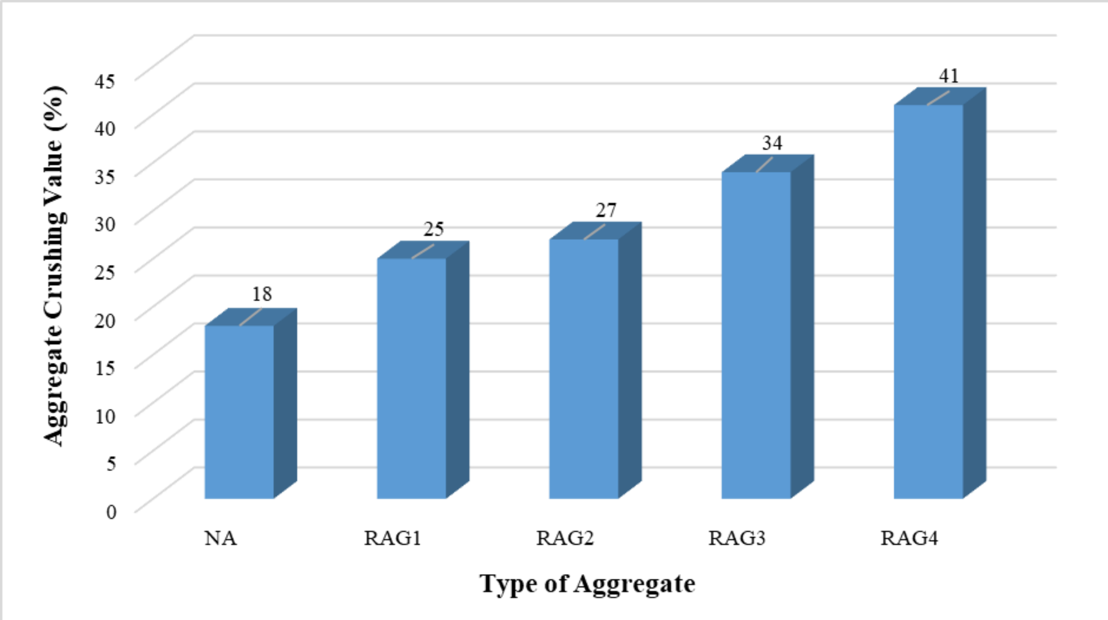

Fig. 7. Increase in ACV for multiple times recycling.

Also, in a previous study it was found that attached old mortar increases the ACV value [35]. Since, the RCA of higher generations are expected to contain more old mortar, their ACV should also be high. For concreting work, it is recommended to use aggregates having ACV less than 30% [33-34]. Therefore the 1st and 2nd generation RCA can be used for concrete work and the 3rd and 4th generations are not suitable.

3.1.4. Effect on abrasion resistance

Los Angeles Abrasion (LA) value indicates the resistance of the aggregate against degradation. An aggregate with a lower LA value usually possesses higher durability. **Fig. 8** shows the LA value for RCA of different generations. The RCA of higher generation contains more old mortar attached to the surfaces of stone particles and this mortar readily separates under the abrasive charges of LA machine resulting in a higher LA value. The LA value for structural concrete should be limited to 40% [38], and therefore, the 3rd and higher generation RCA should not be considered for concreting work. An earlier study also pointed that up to 2 times recycling may provide RCA of acceptable quality [39].

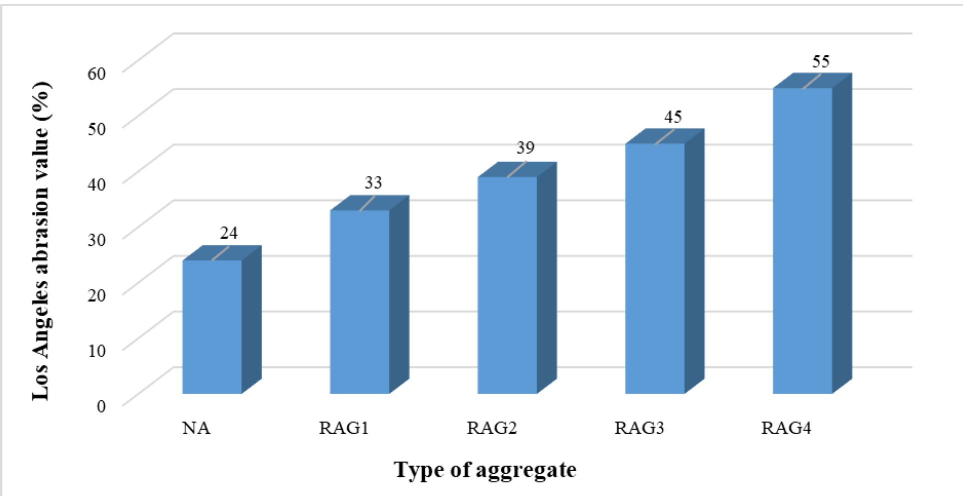

Fig. 8. Increase in LA for multiple times recycling.

3.1.5. Effect on residual mortar content

Old residual mortar is the most prominent factor that makes RCA inferior to NCA. With higher number of recycling, more mortars are adhered to the surfaces of aggregate increasing in its residual mortar (RM) content. RM content of RCA after each number of recycling is shown in Fig. 9.

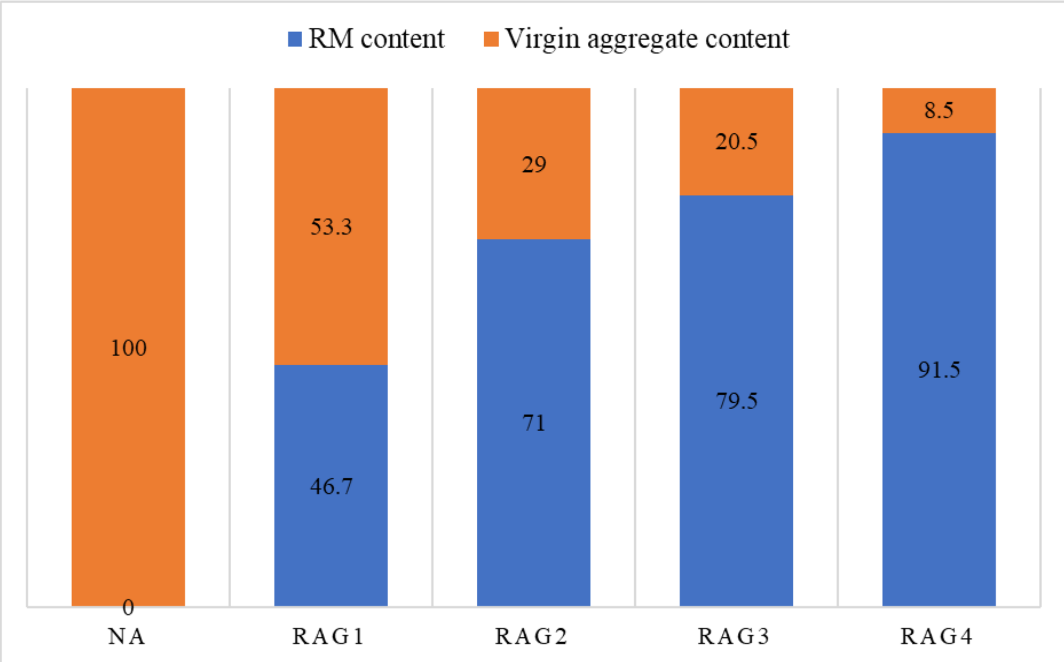

Fig. 9. Increase in RM content due to multiple times recycling.

Although about 1.2 times (by weight) mortar were added to the coarse aggregate after each number of recycling, the RM contents were not increased accordingly. A significant amount of old mortar is removed during its breaking process and the amount is more for the cases of weaker concrete [40–42]. However, as high as 91.5% old mortar was separated from RAG4. A high RM content leads to be requirement of pre-treatment which makes it uneconomical.

3.2. Effect of multiple recycling on concrete properties

3.2.1. Effect on compressive strength

As investigations on the qualities of recycled aggregates show that they are of lesser quality than natural aggregates, green concrete is expected to have lower strength than conventional concrete. The results in Section 3.1 reveal that when aggregates are recycled numerous times, their quality deteriorates with each cycle of recycling, and as a result, higher generations of green concrete had lower compressive strength at the same stage of curing. Fig. 10 depicts the compressive strength of normal and green concrete at different curing ages for various strength ratings. Fig. 10 shows a distinct trend of acquiring strength in green concrete. Usually, normal concrete gains strength rapidly at the early stages of its curing, and after a certain period its strength gaining becomes slow [42]. The experimental result for normal concrete (NC) is aligned with it and it was found to observe a rapid rise in compressive strength from 7 days to 28 days, but after 28 days of curing the additional strength gain was very slow and after 84 days the change was almost negligible.

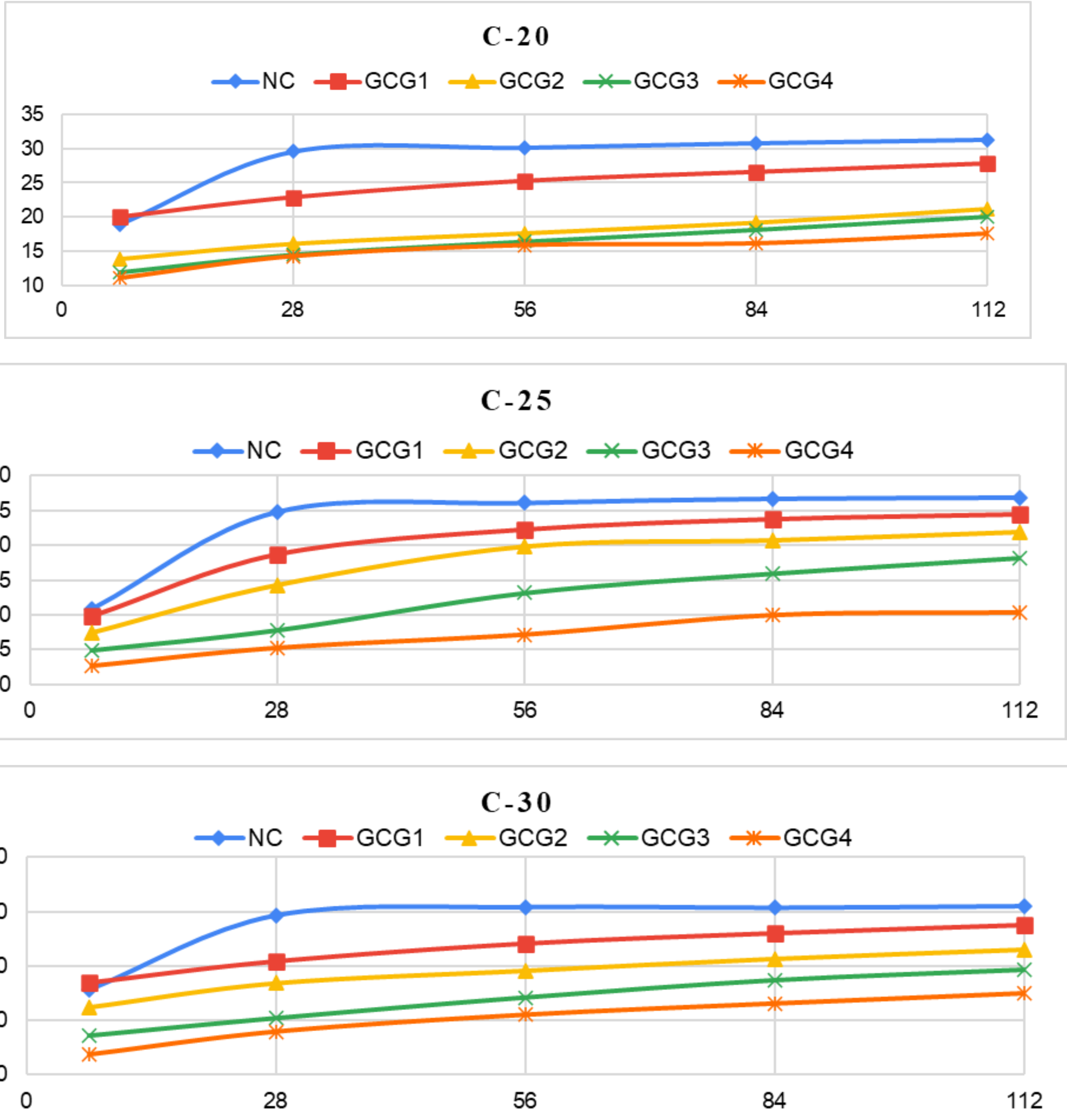

Fig. 10. Compressive strength of green concrete made with different generation of recycled coarse aggregate.

On the other hand, for green concrete, a significant increase in strength was observed from 28 days to 112 days. This delay in strength gain is possibly because of the interference of old ITZ with the hydration of cement. However, further research is necessary to confirm it. The effect of curing time is more prominent for green concrete. It can also be noted that the effect is more visible for higher-generation green concrete. And obviously, unlike normal concrete, 28-day strength may not be considered representative strength for green concrete, as it increases significantly and at a faster rate after 28 days. Compared to normal concrete, the compressive strength of green concrete of any generation was lower at any stage of curing for any of the tested strength grades. Considering their maximum attained strengths (after 112 days of curing), the GCG1 was found to be closest to the NC with a deviation of 10.99%, 6.69% and 8.69% less than the strength of NC for C-20, C-25 and C-30 grades, respectively. The deviation of compressive strength in green concrete from that of normal concrete at different ages of curing can be observed in Fig. 11.

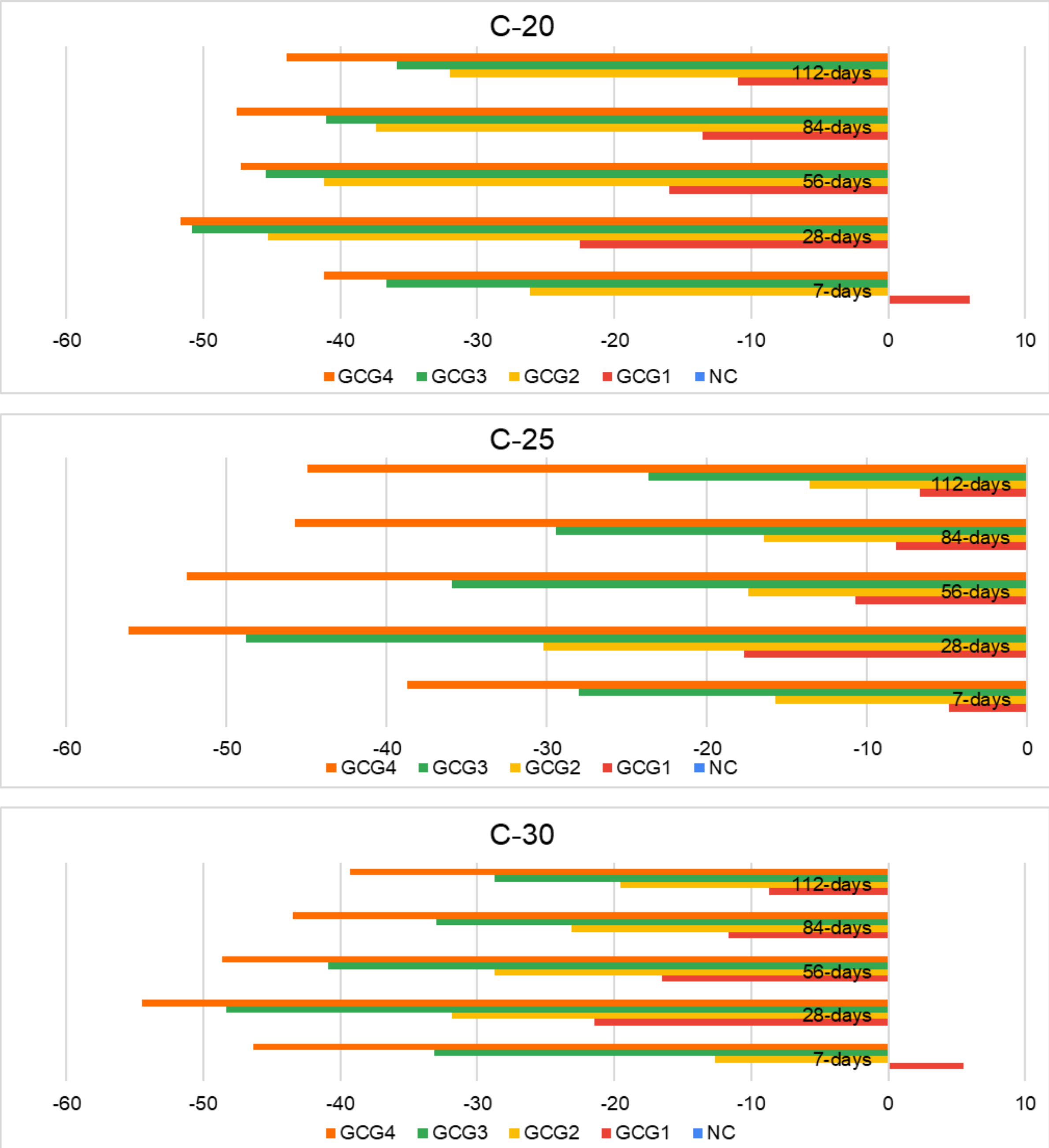

Fig. 11. Deviation of compressive strength in green concrete from that in normal concrete.

Table 1. Requirement of specified and average compressive strength [1].

Concrete Mix grade	Specified strength f'_c (MPa)	Required average strength, f'_{cr} (MPa)
C-20	20	20+7 = 27
C-25	25	25+8 = 33
C-30	30	30+8 = 38

There were two distinct occurrences for C-20 and C-30 in which the 7-day strength in GCG1 surpassed that of NC, showing that the green concrete had a high early strength. At 28 days, the difference in strength between NC and GC was greatest in all cases, and as the concrete matured, the difference decreased, indicating a delayed strength gain in green concrete. The green concrete of all generations followed similar patterns, although the variances were greater in subsequent generations. At 28 days, the C-25 GCG4 showed a maximum deviation of 56.14%. As structural concrete, the concrete should also meet the ACI strength requirement as prescribed in ACI 214R [43]. Strength requirement for designed concrete grade is presented in Table 4.

Fig. 12 and Fig. 13 shows the deviation of compressive strength in green concrete from f_c' and f_{cr}'. At the age of 7 days, none of the mixes meet the criteria for f_c' or f_{cr}' which is reasonable as sufficient strength is not gained at that little age. At 28 days, only normal concrete satisfied the requirement for both f_c' or f_{cr}' for all strength grades.

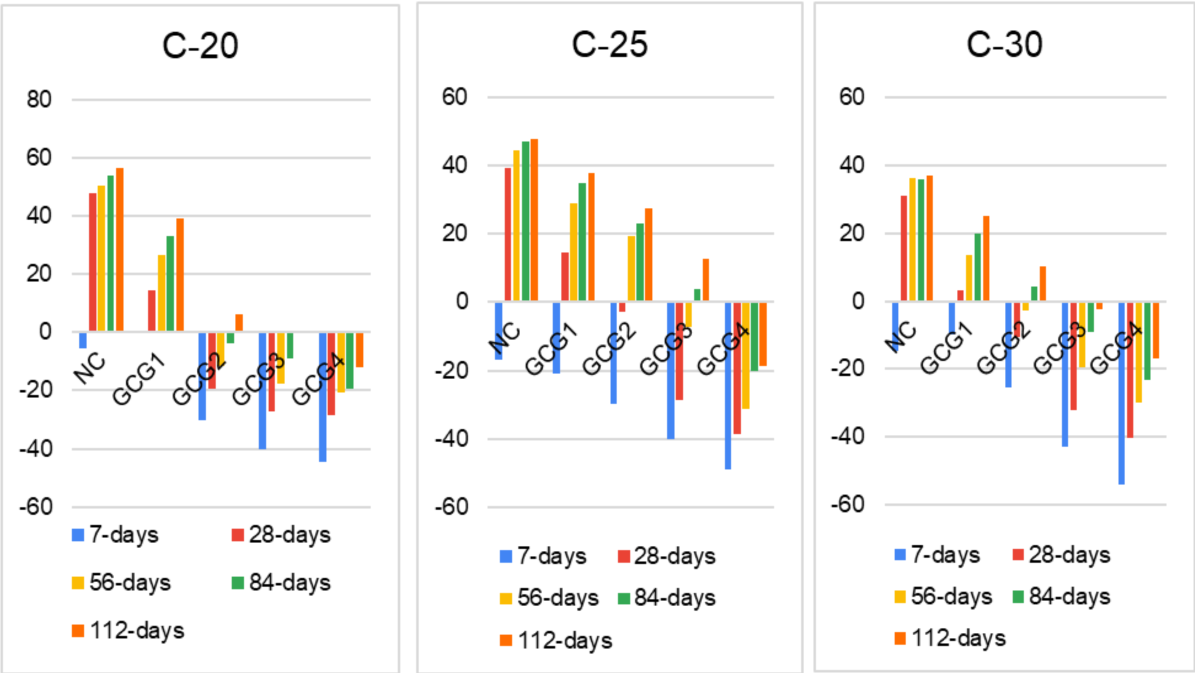

Fig. 12. Deviation of compressive strength from specified strength f_c'.

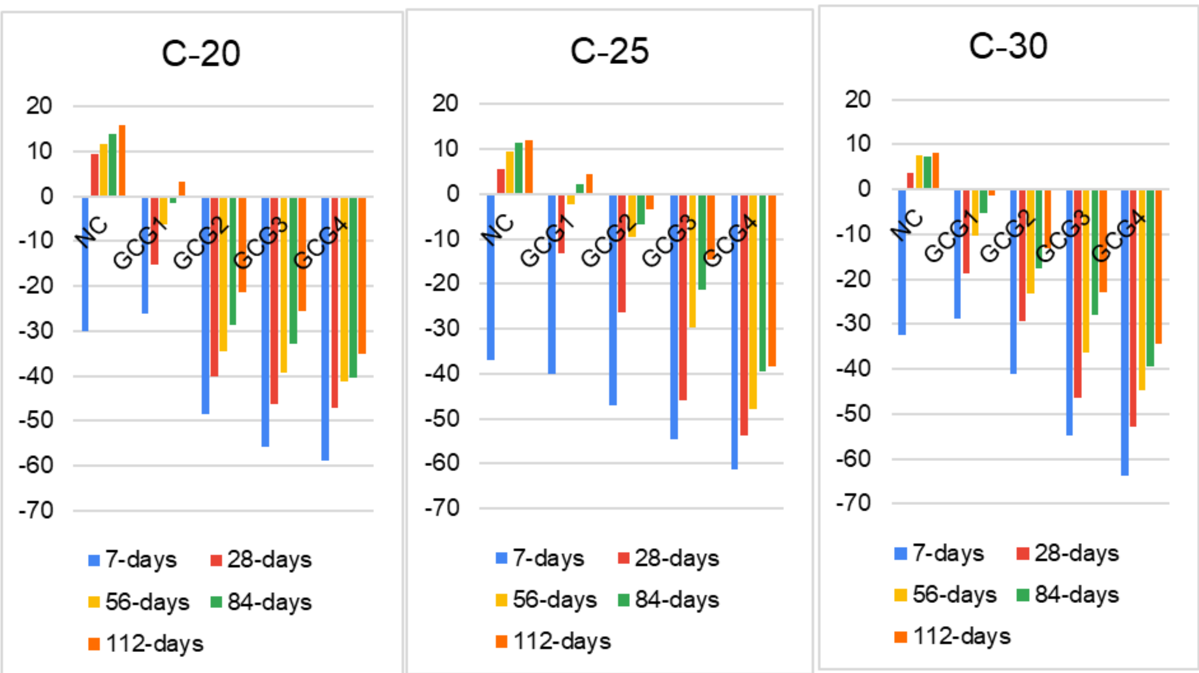

Fig. 13. Deviation of compressive strength from required average strength f_{cr}'.

The specified strength f_c' requirement was fulfilled by GCG1 at 7 days for C-20 and at 28 days for C-25 and C-30. GCG2 meets the same requirement in 112 days, 56 days, and 84 days as C-20, C-25 and C-30 respectively. GCG3 attained that strength in 112 days and 84 days as C-20 and C-25. It could not meet the f_c' requirement for C-30 at any stage. GCG1 satisfied the f_{cr}' requirement in 112 days 84 days as C-20 and C-25 grade. None of the other higher generation green concrete could attain sufficient strength to satisfy the f_{cr}' requirement. The pattern indicates a slower strength attainment in successive generation of recycling. However, the GCG1 was the only one to meet both of the requirement at 84 days (for C-25) or 112 days (for C-20). This indicates that the use of early strength admixtures may be advisable in the cases of green concrete made with recycled aggregates, to attain its strength faster. Another investigation showed that recycled concrete was acceptable up to three times recycling [44]. However, third-generation green concrete showed a more encouraging result in that investigation. The inferior performance of the parent RCA employed in this investigation might be attributed to its high RM content, which was around 46%.

4. Conclusions

This study investigates the change in quality of recycled aggregate and the green concrete made with them after several times of recycling. The following conclusions are drawn:

- In subsequent recycling cycles, the inclusion of ITZs and old mortar lowers the quality of the aggregates. However, as the first- and second-generation RCA satisfied the requirements of ACV and LA to be utilized in the production of concrete, recycling was determined to be safe twice. The higher generation RCA has ACV and LA values that exceed the limitation limits and should not be utilized in concrete work.
- The third and fourth-generation recycled aggregates are unsuitable for structural use; however, the higher-generation aggregates could be effectively used in pavement sub-base layers, non-structural fill, or landscape applications, with appropriate quality control measures.
- None of the green concrete could meet the average strength requirement for C-30 concrete, so such green concretes should be designed for a lower strength.
- 1st generation green concrete has compressive strength similar to conventional concrete and can meet the design requirements for C-20 and C-25 grades of concrete; however, the strength improvement necessitates a longer curing period.
- The average strength requirement was not met by the second or third generation green concrete, but they were able to achieve the minimum strength requirement after a longer curing period. The 4th generation green concrete failed to fulfill any of the strength requirements.
- The findings of the study denote that, with prolonged curing, the 1st generation green concrete can be used for regular concreting work, and the 2nd and 3rd generation concrete may be used for nonstructural and low load-bearing cases. To overcome the problem of a longer curing period, early strength-gaining admixtures may be used. However, further studies are required to establish the admixture usage.
- Using recycled aggregate also has environmental benefits, such as reducing waste generation. The production of raw material for brick aggregate, which emits harmful gases like CO_2, will also decrease when the use of recycled aggregate increases. So, the importance of recycled aggregates for a sustainable environment is greater.

The outcome of the present research enlightens a new way to recycle and reuse demolished concrete as new aggregates. However, extensive studies and research are required focusing on the durability and reinforcement interaction with green concrete to establish safety margins and to make the industry interested in using recycled aggregates. The energy consumption in breaking of concrete blocks and the life cycle assessment of recycled aggregate should also be performed to evaluate its total environmental impact. The current study's findings shed light on a novel method for recycling and reusing destroyed concrete as aggregates. However, substantial studies and research on the durability and reinforcing interaction with green concrete are necessary in order to establish safety margins and pique the industry's interest in employing recycled aggregates. The energy usage in breaking concrete blocks, as well as the life cycle evaluation of recycled aggregate, should be undertaken to determine the entire environmental effect.

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Conflicts of interest

The authors declare no conflict of interest.

Authors contribution statement

First Author: supervision, investigation, data analysis, validation, writing original draft.

Second Author: methodology, testing, data curation, visualization, writing review and editing.

Third Author: testing, data curation, writing review and editing.

Abbreviation	Description
RCA	Recycled coarse aggregate
ASTM	American Society for Testing and Materials
RAGi	i^{th} generation recycled aggregate
GCGi	i^{th} generation green concrete
RM	Residual mortar
NC	Normal concrete

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