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REVIEW ARTICLE

Sustainable Construction Exploration: A Review of Multi-Recycling of Concrete Waste

Jeonghyun Kim[1]

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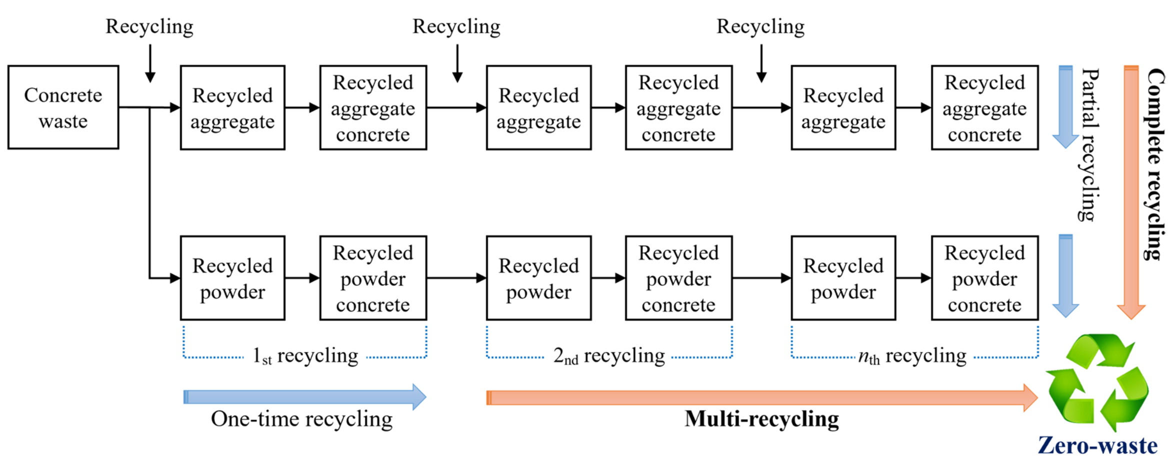
Abstract
This paper provides an overview of literature on the multiple-time recycling of concrete waste and meticulously analyzes the research findings. The paper begins by reviewing the characteristics of recycled materials such as recycled coarse aggregate, recycled fine aggregate, and recycled powder obtained from concrete waste in relation to the recycling cycle. The influence of each of these materials on the mechanical properties and durability of next-generation concrete is analyzed. Moreover, this paper introduces strategies reported in the literature that aim to enhance the performance of multi-recycled concrete. Lastly, this paper identifies and highlights limitations and research gaps, while providing insightful recommendations to drive future exploration of multi-recycling of concrete.

Graphical Abstract



Highlight

- Literature review on multi-recycling of concrete waste.
- Summary of effects of multi-recycling on properties of recycled materials/products.
- Review of strengthening methods for multi-recycled concrete.
- Identifying research gaps and proposing directions for future studies.

✉ Jeonghyun Kim
jeonghyun.kim@pwr.edu.pl

[1] Faculty of Civil Engineering, Wrocław University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

Keywords Multi-recycled concrete · Closed loop recycling · Concrete property · Concrete recycling · Sustainable development

Introduction

The utilization and recycling of concrete waste originated from the need for urban reconstruction following World War II (Buck 1977). In the present day, extensive research on recycling concrete waste has been undertaken to address issues such as landfill scarcity, the depletion of natural resources, and increased concern over environmental protection. Although most previous studies report that the performance of concrete containing recycled materials is inferior to that of concrete based on natural materials (Guo et al. 2018; Kim et al. 2016; Lin et al. 2023; Padmini et al. 2009), promising results have been reported, demonstrating the ability to produce concrete with performance similar to that of concrete made with natural materials through the application of various methods: reduced material replacement rate (Etxeberria et al. 2007; Ozbakkaloglu et al. 2018); improved mixing technique (Hiremath and Yaragal 2017; Sicakova and Urban 2018; Tam et al. 2007); material carbonation and CO_2 curing (Tam et al. 2020; Zhan et al. 2013); enhanced material quality (Kim 2022; Wei et al. 2021). Furthermore, replacing natural materials with recycled materials in concrete can reduce waste generation (Hossain et al. 2016; Martínez-Lage et al. 2020) and lower concrete production costs (Suárez Silgado et al. 2018). Due to these benefits, many studies have discussed various strategies to encourage the practical utilization of recycled concrete materials (De Brito and Silva 2016; Kim 2021; Ma et al. 2023; Makul et al. 2021).

Consequently, actual cases of utilizing recycled aggregates in real-scale concrete structures are being reported worldwide (Kim 2021; Li 2008; Poon and Chan 2007; Silva et al. 2019; Xiao et al. 2022a; Yoda and Shintani 2014). Concrete containing recycled materials can generally be referred to as recycled concrete, but the term 'recycled concrete' used in literature commonly implies one-time recycling. Tomosawa et al. (2005) emphasize that if a recycled product cannot be recycled again, it will merely contribute to waste generation for the next generation. Therefore, recycling should aim to reproduce identical products in the original sense of the term, creating a loop.

In this context, there has been a growing interest in the multi-recyclability of concrete waste as a genuine contribution to sustainable development, with studies on this subject being consistently documented (Brito et al. 2006; Kim and Jang 2024, 2022). The mechanical properties, durability, and economic and environmental benefits of multi-recycled concrete have been investigated by a few researchers. However, investigations into the repeated recycling of concrete have taken place relatively recently, resulting in a scarcity of comprehensive review on this topic. Therefore, the objective of this study is to conduct a thorough literature review on the multi-recycling of concrete waste. Commencing with an explanation of the conceptual distinctions between one-time and multiple-times recycling of concrete, this study reviews the effects of repeated recycling of concrete on the characteristics of recycled materials obtained from it. This paper also analyzes the effect of using these recycled materials on the properties of next-generation concrete and introduces methods to enhance the performance of multi-recycled concrete. Then, it reviews the environmental and economic analyses of multi-recycled concrete. To conclude, limitations and gaps of the literature are identified, and recommendations for further research are provided.

Multi-Recycling of Concrete

The concept of multi-recycling of concrete waste is presented in Fig. 1. After undergoing specific recycling technologies, often involving crushing, concrete waste turns into recycled materials. In general, concrete waste can yield recycled coarse aggregate (RCA), recycled fine aggregate (RFA), and recycled powder (RP) (hereafter, recycled materials mentioned in this article refer to RCA, RFA, and RP), and concrete incorporating them can be classified into recycled coarse aggregate concrete (RCAC), recycled fine aggregate concrete (RFAC), and recycled powder concrete (RPC), respectively. This recycled concrete, which has undergone recycling once, is referred to as first-generation recycled concrete (RCAC1, RFAC1 and RCP1 depending on the recycled material used). Crushing the first-generation recycled concrete yields recycled materials again, which have been recycled twice (RCA2, RFA2 and RP2). These are prefixed with 'multi' and are designated as multi-recycled coarse aggregate (multi-RCA), multi-recycled fine aggregate (multi-RFA) and multi-recycled powder (multi-RP). And concrete incorporating these multi-recycled materials is termed multi-recycled concrete: multi-recycled coarse aggregate concrete (multi-RCAC), multi-recycled fine aggregate concrete (multi-RFAC), multi-recycled powder concrete (multi-RPC). An explanation of the key terms used in this study is provided in Table 1.

Characteristics of Multi-Recycled Materials

Given that the quality of recycled concrete materials is one of the many factors influencing the properties of concrete (Kim 2022), it is of great significance to comprehend the influence of multi-recycling of concrete on material characteristics. Various indicators represent the quality of

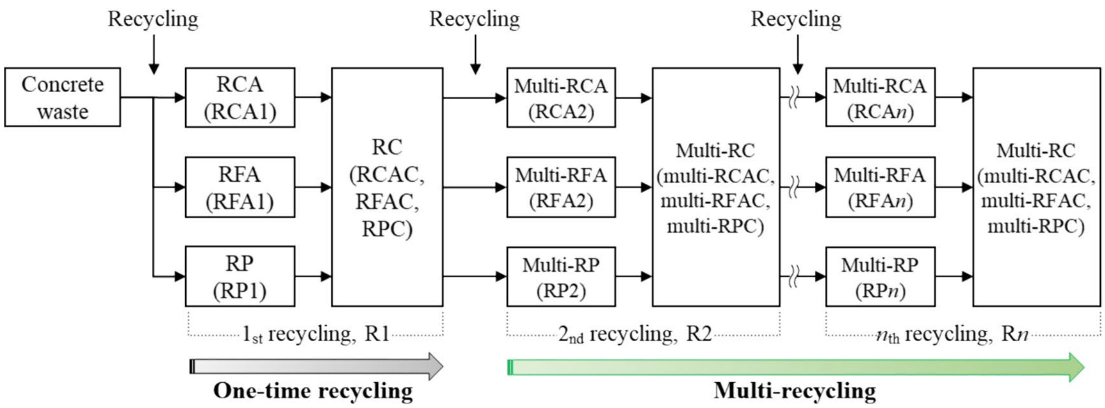


Fig. 1 Concept of multi-recycling of concrete (based on (Kim and Jang 2022))

Table 1 Terms and definitions for multi-recycled concrete

Category	Term	Definition
Recycled material	RCA_n*	Recycled coarse aggregate
	RFA_n	Recycled fine aggregate
	RP_n	Recycled powder
Recycled concrete	$RCAC_n$	Concrete with RCA_n
	$RFAC_n$	Concrete with RFA_n
	RPC_n	Concrete with RP_n
Recycling cycle	R1	Once-recycled materials and concrete
	R2	Twice-recycled materials and concrete
	R3	Thrice-recycled materials and concrete

**n* represents the number of recycling cycles. For instance, RCA1 describes once-recycled coarse aggregate, while RPC3 denotes concrete that includes thrice-recycled powder

aggregates, with density and water absorption being the most commonly reported, and occasionally, attached mortar content, Los Angeles abrasion, and crushing index are reported.

The fluctuations of density and water absorption of RCA are shown in Fig. 2a and b, respectively, clearly indicating a decrease in density and an increase in water absorption for increasing recycling cycles. Over three times of recycling, the density of multi-RCA can be reduced from 4.2% (Lei et al. 2023b) to up to 24% (Huda and Alam 2014) than that of natural coarse aggregate (NCA). For water absorption, NCA exhibits clustered values of 0.32–1.8%, whereas the values for RCA and MRCA vary from 4.45 to 11.2%. In the same recycling cycle, the difference between the minimum and maximum absorption values tends to gradually increase as the number of recycling cycles increased. In previous studies, apart from a study by Yang et al. (2022), the variation between the minimum and maximum absorption values for RCA1 was 1.95%, the value that escalated to 2.73% and 3.74% for the second and third generations RCAs (RCA2 and RCA3, respectively). In Fig. 2a and b, the lines representing both density and water absorption exhibit a steep slope during the first recycling (from NCA to RCA1) and then gradually level out during the second recycling (from RCA1 to RCA2) and the third recycling (from RCA2 to RCA3). As noted by Abreu et al. (2018), the characteristics of coarse aggregate stabilize as the recycling cycle increases.

Figure 2c and d show the Los Angeles abrasion and crushing index of coarse aggregates. As the recycling cycle increases, there is a corresponding increase in both the abrasion and crushing index. Higher values for these properties indicate that the aggregate is more susceptible to abrasion and (Mohajerani et al. 2017; Zhang et al. 2017), suggesting that repeated recycling weakens the aggregate. In contrast, in studies by Salesa et al. (2017a, b), the abrasion resistance of RCA1 was found to be stronger than that of NCA, but the studies did not note whether the RCA1 was obtained from concrete made with the NCA. Nonetheless, when comparing only RCA1, RCA2, and RCA3 used in these studies, it becomes clear that increasing the recycling cycle weakens the abrasion resistance of aggregate.

The above trend is also observed in RFA and RP. Figure 3a and b show the change in density and water absorption of fine aggregate, and Fig. 3c shows the change in powder density over the recycling cycle. The fine aggregate in the study by Jung (2023) and the powder in the study by Kim et al. (2023b) were obtained by crushing multi-RCAC, and the fine aggregate in the studies by Zhu et al. (2018, 2019a) was obtained from multi-RFAC. However, a common observation across these studies is that as the recycling cycle of concrete increases, density decreases and water absorption increases.

Based on the variations in the characteristic over recycling cycles (i.e., decreased density, increased water absorption, abrasion, and crushing index), it can be expected that multi-recycling of concrete diminishes recycled materials quality and is responsible for the poor performance of

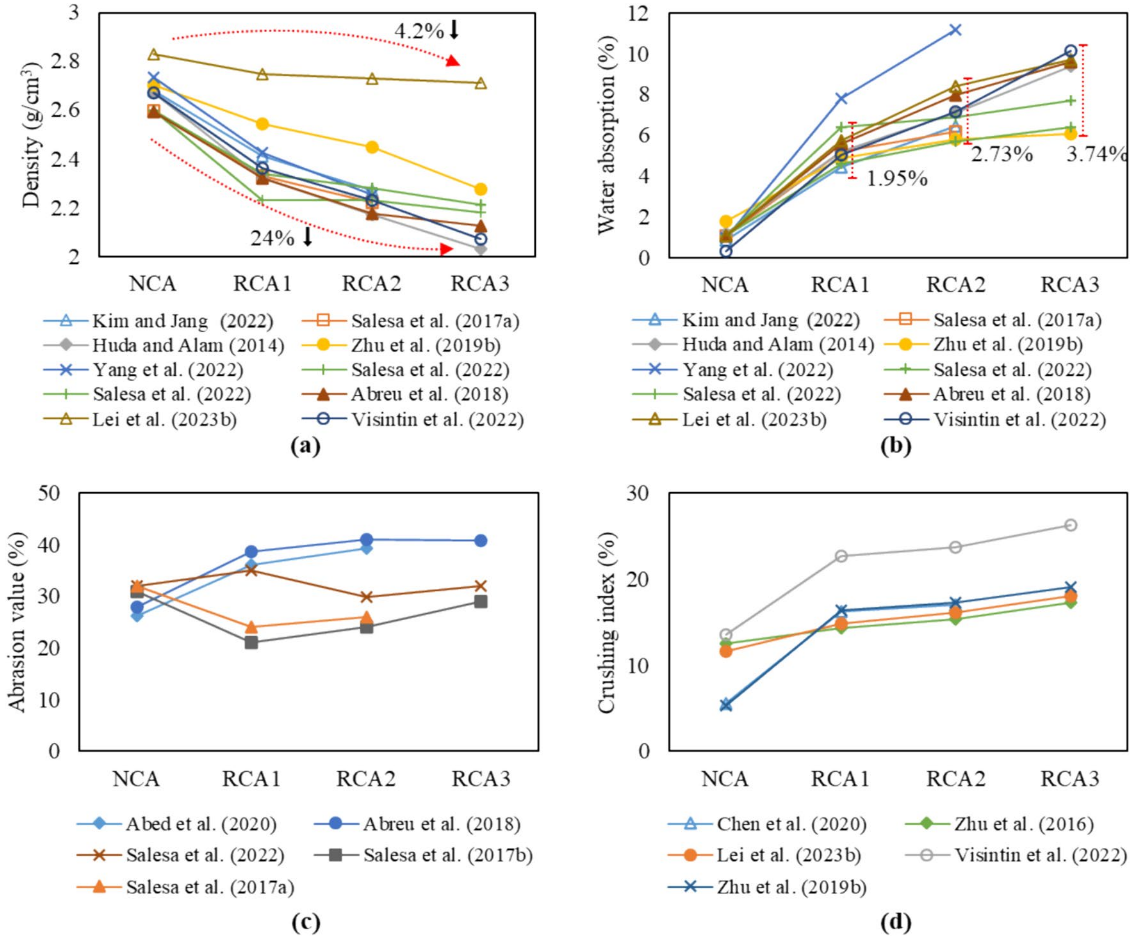


Fig. 2 Characteristics of coarse aggregates over the number of recycling cycles: **a** density; **b** water absorption; **c** LA abrasion; **d** crushing index (Abed et al. 2020; Abreu et al. 2018; Chen et al. 2020; Huda and Alam 2014; Kim and Jang 2022a; Lei et al. 2023b; Salesa et al. 2022, 2017a, b; Visintin et al. 2022; Yang et al. 2022; Zhu et al. 2016, 2019b)

concrete with those materials. This degradation is attributed to the attached mortar, which makes them looser, more porous, and less rigid than natural materials (Tam et al. 2021). Figure 4 shows the attached mortar content in RCA as a function of recycling cycles. Kim et al. (2023a) and Zhu et al. (2016, 2019b) reported attached mortar content of 32%, 55%, and 62% over three times of recycling, while Thomas et al. (2018) reported attached mortar content of up to 88% at the given recycling cycles.

The increase in attached mortar content with increasing recycling cycles is associated with changes in the proportion of materials that make up the concrete. Since recycled aggregate contains a certain amount of attached mortar, the volume fraction of recycled concrete is larger than that of natural aggregate concrete (NAC). As a result, as the recycling cycle increases, the fraction of aggregate in concrete decreases, and the fraction of total mortar (fresh mortar and attached mortar) increases. Therefore, more recycled concrete consists of a larger volume of mortar, and the aggregate obtained from it has a higher attached mortar content (Fig. 5).

Properties of Multi-Recycled Concrete

Slump

The attached mortar in RCA, RFA and RP increases their water absorption. Therefore, when water compensation methods, such as adding extra mixing water and increasing the plasticizer dosage, are not applied, the slump of recycled concrete is generally lower than that of natural concrete. Figure 6 shows the slump of RCAC, RFAC and RPC without the water compensation. As the number of recycling increases, the slump decreases noticeably. This can be attributed to the gradual increase in the water absorption of RCA and RFA, as reviewed in the previous section.

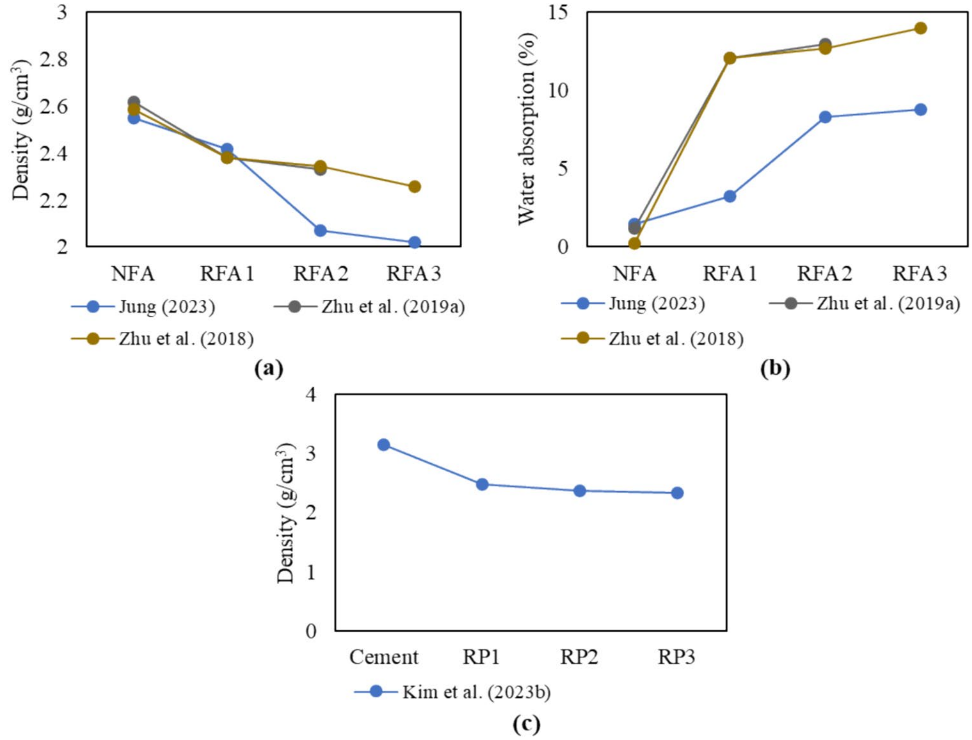


Fig. 3 Characteristics of recycled materials over the number of recycling cycles: **a** density; **b** water absorption of fine aggregate; **c** density of cement and recycled powder (Jung 2023; Kim et al. 2023b; Zhu et al. 2018, 2019a)

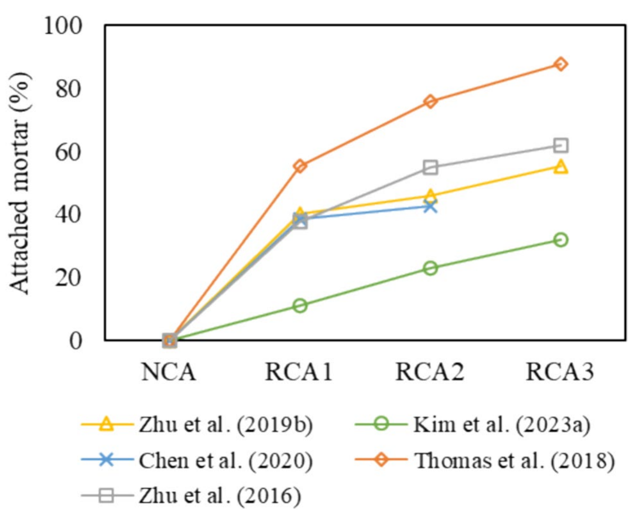


Fig. 4 Attached mortar content of coarse aggregate over the number of recycling cycles (Chen et al. 2020; Kim et al. 2023a; Thomas et al. 2018; Zhu et al. 2016, 2019b)

Hence, to achieve comparable slump values, additional water is demanded, and the quantities of additional water reported in previous studies are listed in Table 2. As expected, as the replacement rate and the number of recycling cycles increase, higher quantities of water are required. When replacing 25% of NCA with RCA, it demands 5.2% to 6.9% more mixing water during three times of recycling cycles, whereas 100% replacement requires 28.9% more water (Abreu et al. 2018). Similarly, RFA requires 6.4%, 19.2%, and 25.2% of additional water at replacement rates of 25%, 75%, and 100% to achieve similar slumps in the third recycling cycle (Zhu et al. 2018).

Due to the presence of additional factors influencing slump, such as particle shape and the moisture state of recycled materials, which were not addressed in the original research articles, an intercomparison between studies was not performed.

Air Content

An adequate level of air content in concrete improves its frost resistance (Hosseinzadeh and Suraneni 2021; Tanesi and Meininger 2007), while both insufficient and excessive air content can cause mechanical properties and durability-related issues (Özcan and Emin Koç, 2018; Wang et al. 2022a, b). Hence, some specifications specify permissible air content ranges for concrete under specific exposure conditions (e.g. 3.5–7.5% depending on aggregate size for ASTM C94 (ASTM C94/C94M-21b, 2021)).

Typically, recycled material-based concrete exhibits higher air content compared to natural material-based concrete. This is attributed to factors such as rough surface textures, greater angularity, and the presence of pores in the attached mortar (Silva et al. 2018). As the multi-recycling increases the attached mortar content, the air content in concrete increases progressively in proportion to the recycling cycle (Fig. 7). When concrete is recycled multiple times as coarse aggregate (i.e., multi-RCAC), the air content

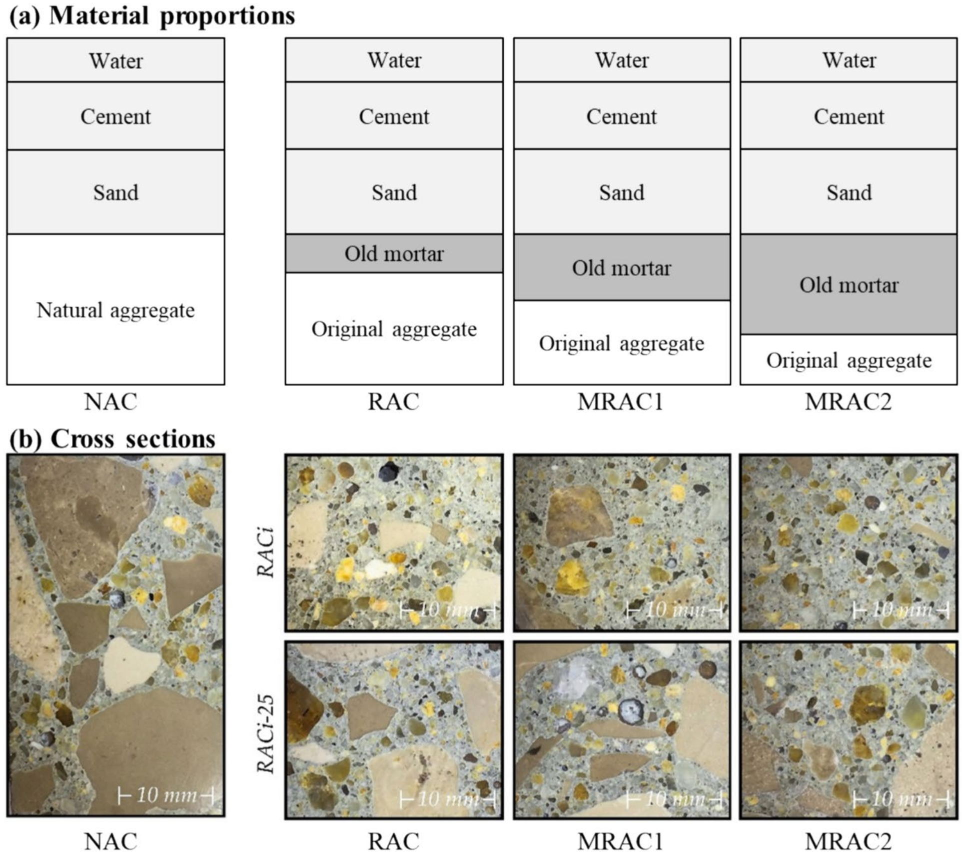


Fig. 5 Material proportions of various concretes: **a** illustration of concretes with natural-, recycled-, and multi-recycled aggregates; **b** cross-section of the concretes (Thomas et al. 2020)

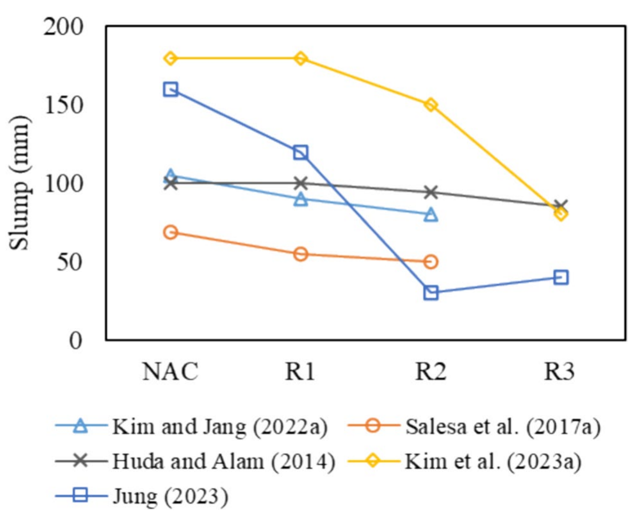


Fig. 6 Variation in concrete slump over recycling cycles (Huda and Alam 2014; Jung 2023; Kim et al. 2023a; Kim and Jang 2022; Salesa et al. 2017a)

increases gradually. Huda and Alam (2014) reported air content of 3.6%, 3.9%, and 4.4% for the 1st, 2nd, and 3rd generations, respectively. The air content of NAC was 3.4%. Similar results were also reported in the following literature (Yang et al. 2022). Salesa et al. (2017a) even reported no change in air content in the 1st and 2nd generations. Considering the tolerance of air content (e.g. ± 1.5% for ASTM C94 (ASTM C94/C94M-21b 2021)), the effect of repeated recycling on the air content of concrete can be acceptable. However, unlike RCA, RFA can significantly affect the air content (Silva et al. 2018). In a study conducted by Jung (Jung 2023), the air content of concrete containing 30% RFA during the three generations was 5.4%, 6.2%, and 7.3%, showing a sharp increase compared to NAC (4.3%).

Compressive Strength

The most fundamental property of hardened concrete is its compressive strength. Figure 8a and b show the 28-day compressive strength for multi-RCAC in absolute and relative scales, respectively. Most previous studies agree that multi-recycling has an unfavorable effect on the compressive strength of concrete. The compressive strength of RCAC decreases to 82.1–96.4% of NAC in the first recycling cycle, 83.4–93.8% in the second recycling cycle, and 57.6–90.1% in the third recycling cycle. The strength loss in RCAC is a consequence of the increased content of attached mortar in RCAs as the number of recycling cycles increases. As discussed earlier, RCAs become more porous with an increasing number of recycling cycles. Additionally, the

Table 2 Additional water for equivalent slump during repeated recycling

References	Type	Slump (mm)	Replacement (%)	Additional water (%)		
				R1	R2	R3
Zhu et al. (2019b)	RCA	150 ± 15	100	21.1	21.2	12.1
Yang et al. (2022)	RCA	80 ± 10	100	8.2	11.9	–
Abreu et al. (2018)	RCA	125 ± 15	25	5.2	6.3	6.9
	RCA	125 ± 15	100	20.8	25.4	28.9
Visintin et al. (2022)	RCA	85–100	100	11.3	4.7	12.5
Zhu et al. (2016)	RCA	132–148	70	8.2	10.8	11.9
Zhu et al. (2019a)	RFA	169–175	10	0.5	2.6	–
	RFA	165–170	20	4.2	5.3	–
	RFA	162–167	30	6.3	7.9	–
	RFA	157–160	40	8.5	10.6	–
Zhu et al. (2018)	RFA	181–188	25	7.2	6	6.4
	RFA	178–185	75	17.2	17.6	19.2
	RFA	168–185	100	22.8	23.6	25.2

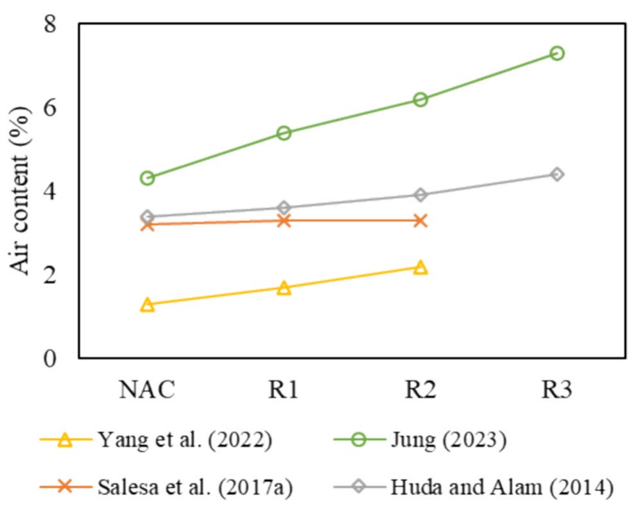


Fig. 7 Variation in concrete air content over recycling cycles (Huda and Alam 2014; Jung 2023; Salesa et al. 2017a; Yang et al. 2022)

compressive strength decreases with each recycling cycle due to a variety of complex factors, including the instability of the interfacial transition zone (ITZ) and the formation of micropores and cracks in RCA resulting from repeated crushing processes (Abreu et al. 2018; Huda and Alam 2014; Lee and Choi 2013; Zhu et al. 2019b).

Conflicting trends have been found in the following studies (Salesa et al. 2017a; Visintin et al. 2022). Salesa et al. reported an increase in compressive strength of 4.4–5.1% over three recycling cycles compared to that of NAC. The authors concluded that high-quality RCA obtained from precast members and the presence of unhydrated cement in the RCA contributed to the improvement in compressive strength. A similar case was also observed in the study by Kim et al. (2023a). In that study, in which precast concrete members were crushed and used as RCA in concrete repeatedly, the compressive strength of RCAC up to the second recycling cycles was 99–111% of that of NAC. In a study by Visintin et al. (2022), the compressive strengths of RCAC1, RCAC2 and RCAC3 were 3.1–9.8% higher than that of the control concrete. The authors noted that the internal curing by the additional mixing water to compensate for the high water absorption of RCA would have resulted in the similar compressive strengths over the three times of recycling. According to a study by Domingo-Cabo et al. (2009), when the effective water-cement ratio is constant, several properties of concrete (slump, compressive strength and elastic modulus) can be similar regardless of RCA replacement rate, and Eckert and Oliveira (2017) reported that extra mixing water can improve the ITZ structure without significantly affecting the effective water-cement ratio. However, other studies, where the effective water-cement ratio was kept constant for concretes by adjusting additional water, report a decrease in compressive strength with the recycling cycle (Abreu et al. 2018; Zhu et al. 2016, 2019b). While there may be various factors contributing to these conflicting results, Sosa et al. (2021) highlight the uncertainty arising from the absence of a reliable method to quantify the actual effective water-cement ratio.

The compressive strength of concrete containing RFA and RP is shown in Fig. 9. The change in compressive strength with respect to the recycling cycle is consistent with that of RCAC, i.e., a decrease in compressive strength as the recycling cycle increases. In particular, RP can cause significant strength loss at relatively low replacement rates, which is attributed not only to the micropores and cracks in RP itself but also to the replacement of cement by RP, reducing hydration products (Kim et al. 2023b; Kourounis et al. 2007).

Based on the above review, it can be concluded that, in general, multi-recycling has an unfavorable effect on the compressive strength of concrete. Identifying the factors that

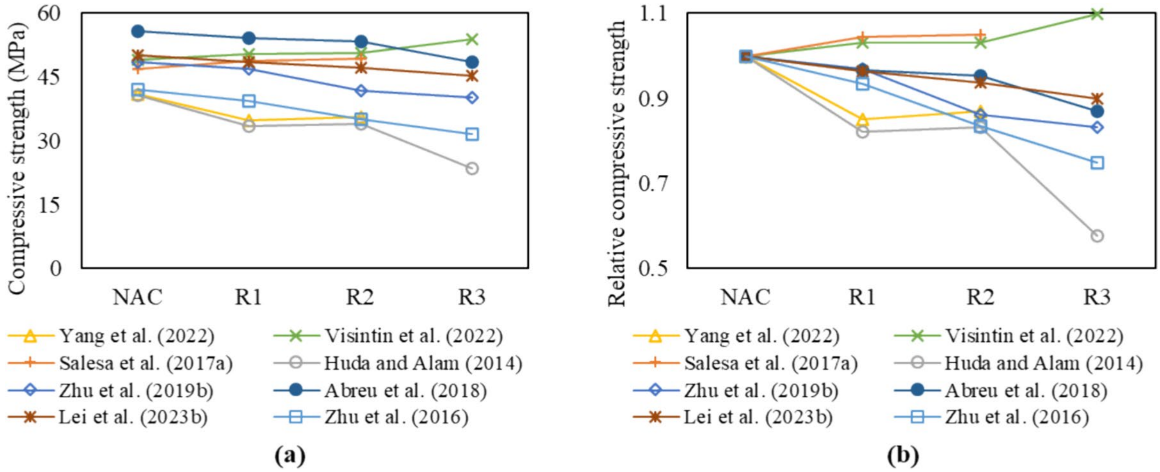


Fig. 8 Compressive strength of multi-recycled coarse aggregate concrete over recycling cycles in absolute (**a**) and relative scales (**b**) (Abreu et al. 2018; Huda and Alam 2014; Lei et al. 2023b; Salesa et al. 2017a; Visintin et al. 2022; Yang et al. 2022; Zhu et al. 2016, 2019b)

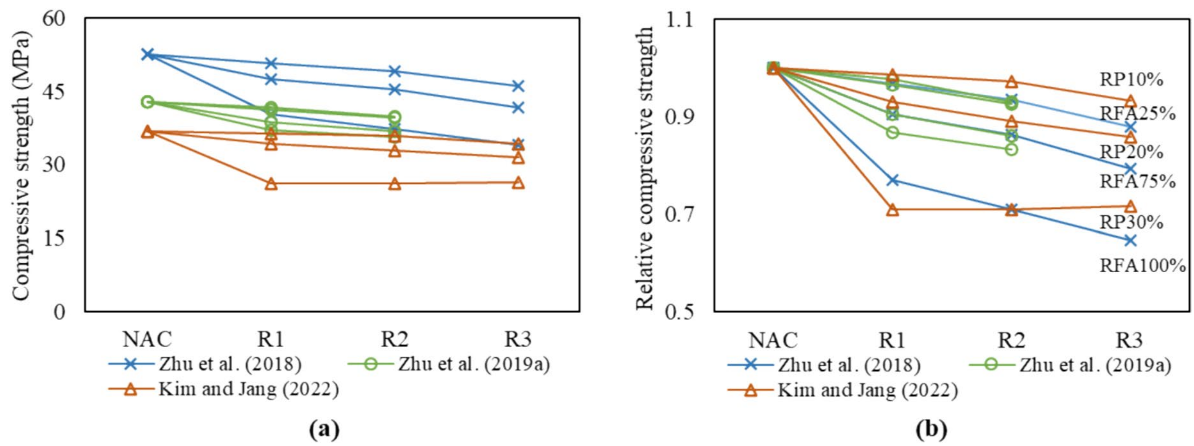


Fig. 9 Compressive strength of multi-recycled fine and powder concretes over recycling cycles in absolute (**a**) and relative scales (**b**) (Kim and Jang 2022; Zhu et al. 2018, 2019a)

contribute to the deterioration of properties in repeatedly recycled concrete is essential for sustainability. Practically, it is nearly impossible to track how many times concrete has been recycled. Although studies specifically designed to investigate the effects of multi-recycling may use 100% recycled aggregate, it is uncommon for recycled aggregate to entirely replace natural aggregate in real-world structures. Additionally, industrial regulations in some countries restrict high replacement rates (Tam et al. 2018). Due to this complexity, it is necessary to identify the factors that lead to the deterioration of properties in multi-recycled concrete. To understand the relationship between the characteristics of recycled aggregates and the properties of the concrete containing them, Fig. 10 illustrates how the density and water absorption of recycled aggregates correlate with the compressive strength of the concrete, irrespective of the number of recycling cycles. Generally, an increase in aggregate density enhances the compressive strength of the concrete, whereas a higher aggregate water absorption diminishes it.

Tensile Strength

Tensile strength is one of the crucial mechanical property of concrete since concrete cracks tend to occur in tension, exerting a significant influence on crack formation under load (Zain et al. 2002). Figure 11 illustrates the variation in tensile strength over recycling cycles. Generally, with an increase in the number of recycling cycles, the tensile strength decreases. This trend is commonly observed irrespective of the type of recycled materials. On rare occasions, some studies have reported an increase in tensile

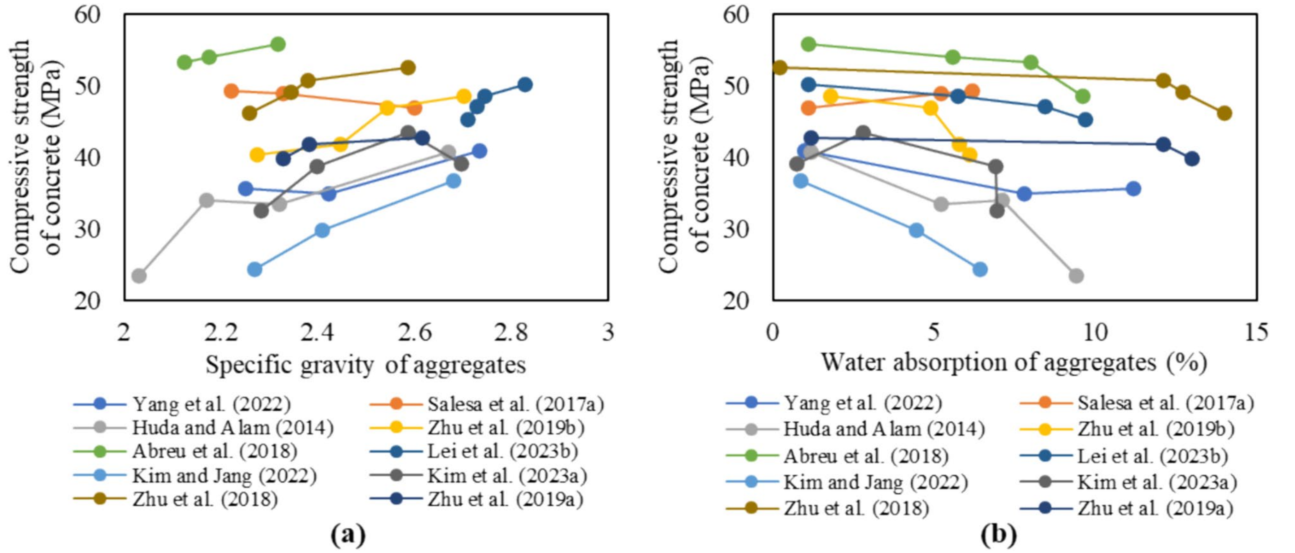


Fig. 10 Relationship between specific gravity of aggregates and compressive strength of concrete (**a**) and water absorption of aggregates and compressive strength of concrete (**b**) (Yang et al. 2022; Salesa et al. 2017a; Huda and Alam 2014; Abreu et al. 2018; Lei et al. 2023b; Kim et al. 2023a; Kim and Jang 2022; Zhu et al. 2016, 2018, 2019a, b)

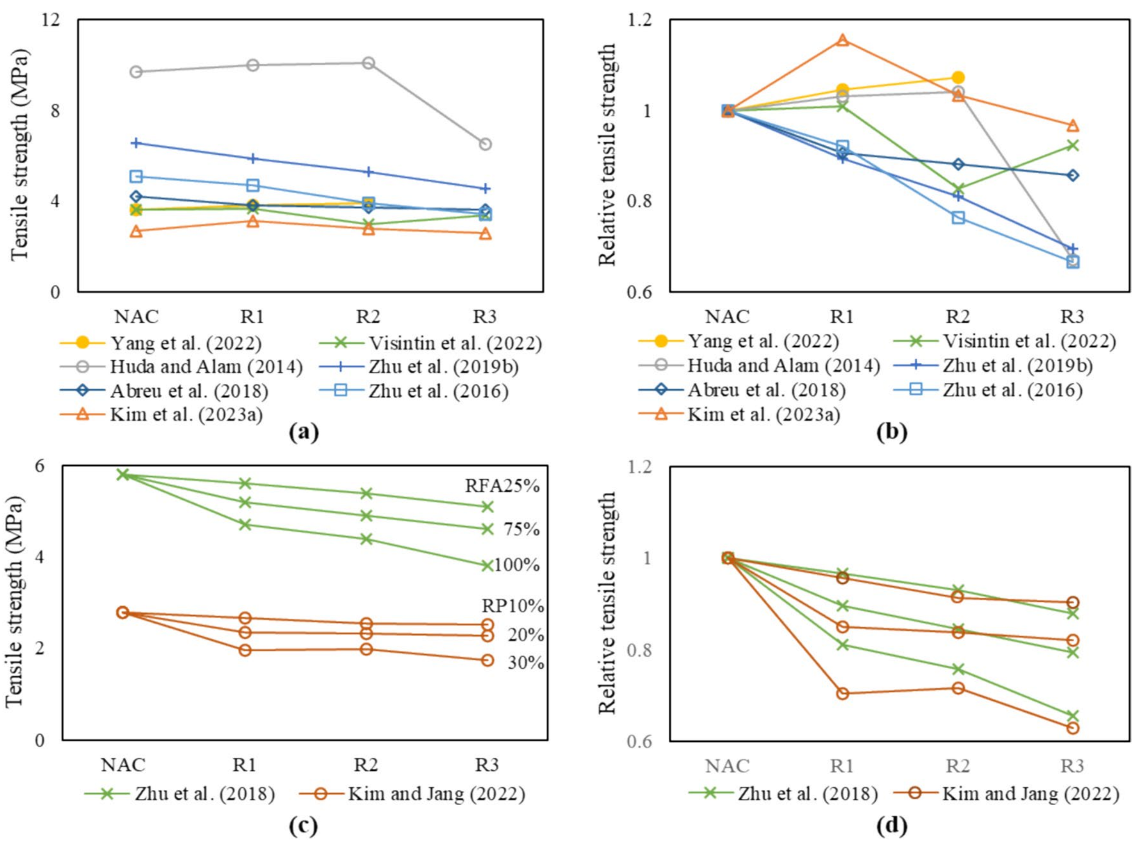


Fig. 11 Tensile strength of multi-recycled concretes over recycling cycles: **a** and **b** concrete with multi-recycled coarse aggregate in absolute and relative scale; **c** and **d** concrete with multi-recycled fine aggregate and powder in absolute and relative scale (Yang et al. 2022; Visintin et al. 2022; Huda and Alam 2014; Abreu et al. 2018; Kim et al. 2023a; Kim and Jang 2022; Zhu et al. 2016, 2018, 2019b)

strength with an increase in recycling cycles. For instance, in a study by Huda and Alam (2014), the tensile strength of RCAC1 and RCAC2 was observed to be 3–4% higher than that of NAC. The authors interpreted this phenomenon as a decrease in the water-cement ratio in the ITZ due to absorption of mixing water by the RCA. Consequently, the reduced water-cement ratio enhances the bond between RCA and the cement paste. However, in the case of R3, the tensile strength sharply decreased, and the authors attributed this to the low quality of RCA and the multiple layers of ITZ. Similar results were also reported by Yang et al. (2022).

Drying Shrinkage

Drying shrinkage occurs when water in the pores of the cementitious matrix evaporates in a dry environment (Wu et al. 2017). Due to the characteristics of recycled materials, such as low stiffness, high porosity, and water absorption, recycled concrete has weak resistance to shrinkage deformation (Mao et al. 2021; Wang et al. 2020; Wu et al. 2022; Xiao et al. 2022b). The characteristics of recycled materials further deteriorate with repeated recycling, causing concrete recycled for more cycles to exhibit greater shrinkage than concrete recycled for fewer cycles. Silva et al. (2021) and Kim et al. (2023a) recorded the drying shrinkage of multi-RCAC for 91 days, respectively. Silva et al. (2021) reported that drying shrinkage is associated with an increase in both aggregate replacement rates and recycling cycles (Fig. 12a). Similarly, Kim et al. (2023a) noted that drying shrinkage increases as the recycling cycle increases but suggested that the mix design method, so called an equivalent mortar volume (EMV) method (Fathifazl et al. 2009; Kim et al. 2016; Yang and Lee 2017), which deducts the amount of new mortar equal to the amount of mortar attached to RCA, can help suppress drying shrinkage. According to the study, the drying shrinkage of EMV-based concrete with 100% RCA in the 1st-, 2nd- and 3rd generations was 8.5%, 12.2%, and 5.5% lower than that of concrete proportioned by a traditional mix design (Fig. 12b).

One notable difference between the two studies is shrinkage deformation at early ages: Silva et al. (2021) found that the shrinkage behavior of NAC and RCAC was similar regardless of the recycling cycle up to 7 days, whereas the study by Kim et al. (2023a) showed clear differences in drying shrinkage deformation caused by the recycling cycle at 7 days. In the former study, the moisture compensation for achieving consistent workability was carried out at each recycling cycle, while in the latter case, it was not. Additional water absorbed into RCA is later released, acting as a moisture source for curing, and this internal curing effect can delay the initial drying shrinkage of multi-recycled concrete (Yildirim et al. 2015; Zhang et al. 2013; Zhutovsky and Kovler 2017).

Water Absorption

Water is the main transport medium for the penetration of harmful substances such as chlorides and sulfides into the pore structure of concrete (Wang et al. 2019). Therefore, understanding the movement of water in concrete is important from a durability perspective and some researchers have investigated the relevant properties. Figure 13 shows water absorption of concrete by immersion. As expected, the absorption capacity increases with the number of recycling cycles, and this trend is similarly observed in absorption through capillary action as shown in Fig. 14. Both of these properties are associated with porosity (Silva et al. 2021). Due to the presence of attached mortar, which increases with repeated recycling, recycled aggregates and RP exhibit higher porosity and water absorption capacity than natural aggregates and cement, respectively, leading to more permeable pores. These changes affect the absorption capacity of the next-generation concrete (Salesa et al. 2017b).

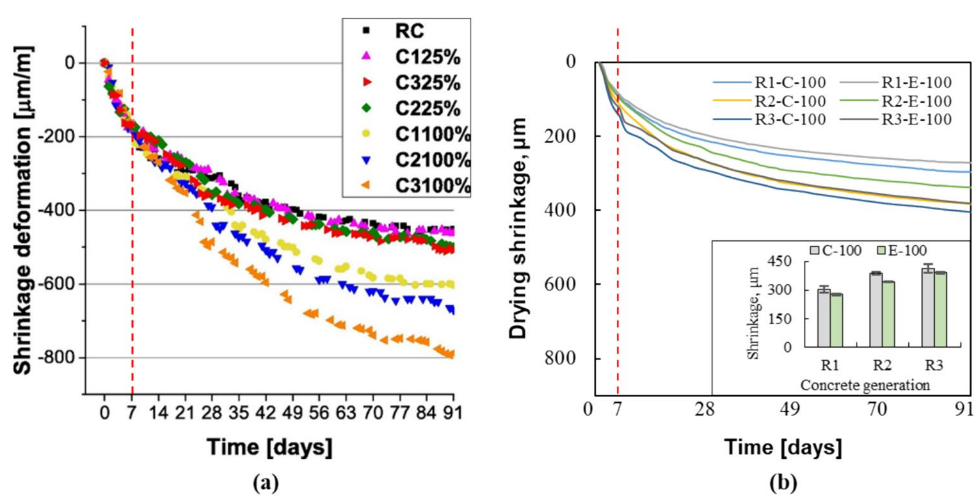


Fig. 12 Drying shrinkage of multi-recycled aggregate concrete by Silva et al. (2021) (**a**) and Kim et al. (2023a) (**b**)

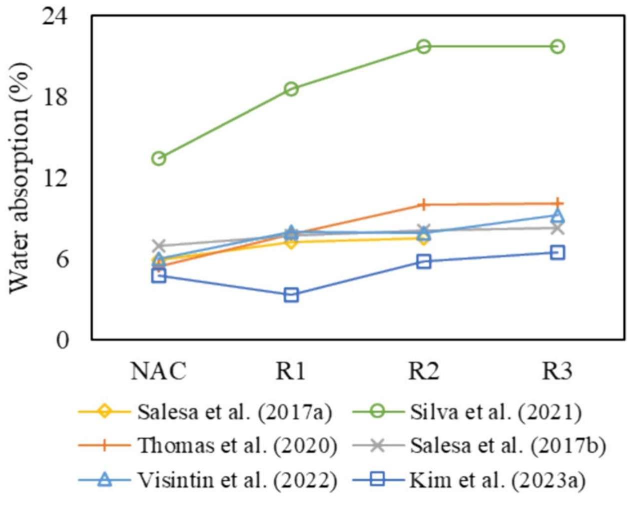


Fig. 13 Water absorption of multi-recycled concretes over recycling cycles (Kim et al. 2023a; Salesa et al. 2017a, b; Silva et al. 2021; Thomas et al. 2020; Visintin et al. 2022)

Chloride Penetration Resistance

Chloride resistance is a key indicator of concrete durability. Due to variations in the quality of recycled materials, as discussed in previous sections, the resistance of multi-recycled concrete to chloride penetration weakens with an increasing number of recycling cycles. Zhu et al. (2019b) and Kim et al. (2023a) demonstrated a weakening of chloride resistance in RCAC due to repeated recycling, based on the increase in electrical conductivity with recycling cycles. In the former study, the charge passed during three recycling cycles increased from 1537 to 3300 C, while in the latter study, it increased from 2931 to 4331 C over three recycling cycles. Silva et al. (2021) and Zhu et al. (2019b) also reported an increase in the chloride diffusion coefficient of RCAC by 47.4% and 85%, respectively, compared to that of NAC after three recycling cycles. The deterioration in chloride resistance can be more pronounced when RFA is repeatedly recycled. In another study conducted by Zhu et al. (2018), the diffusion coefficient of concrete using 100% RFA ranged from 1.33×10^{-12} m^2/s to 3.50×10^{-12} m^2/s over three recycling cycles, which was 233%, 419%, and 614% higher than that of NAC. Nevertheless, with the chloride diffusion coefficient of multi-RCAC and multi-RFAC satisfying the 100-year design life requirement in severe environments specified in the Chinese code (GB 50010-2010), the authors concluded that the feasibility of multi-recycling of concrete is promising.

Carbonation Resistance

Carbonation is a chemical reaction where hydrated cement paste reacts with CO_2. This promotes a decrease in the pH of concrete, which is also associated with the corrosion of reinforcement bars.

The lower quality of recycled materials, characterized by low density, high porosity, and microcracks compared to natural materials, is known to promote CO_2 influx, reducing the carbonation resistance of concrete containing them (Silva et al. 2015; Tang et al. 2018). As multi-recycling further deteriorates these characteristics of recycled materials, a gradual decrease in carbonation resistance of multi-recycled concrete with increasing recycling cycles is expected, and indeed, such experimental results have been reported in studies (Silva et al. 2021; Zhu et al. 2019a).

The carbonation resistance of multi-recycled concrete is further deteriorated in aggressive environments. After undergoing 300 freeze–thaw cycles, the carbonation depth of

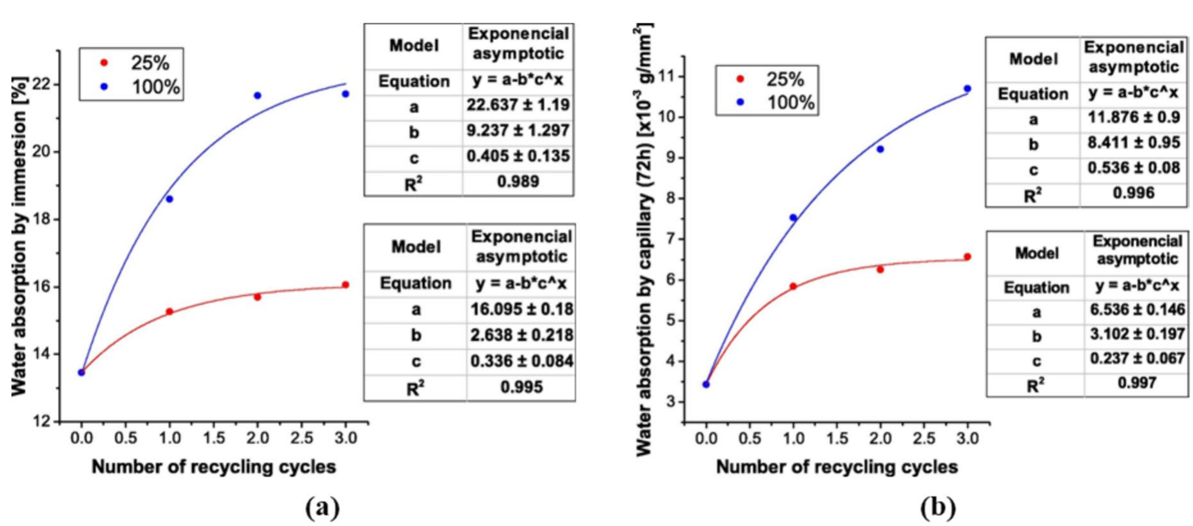


Fig. 14 Water absorption of multi-recycled concretes over recycling cycles by immersion (**a**) and capillary action (**b**) (Silva et al. 2021)

RCAC3 increased by more than double (117.3%) compared to the concrete before freeze–thaw action (Liu et al. 2021). Furthermore, the carbonation depth of RCAC1 and RCAC2, exposed to chloride ions, increased by 2.5 times and 2.7 times, respectively, compared to their pre-exposure levels (Chen et al. 2020). Both freeze–thaw action and chloride penetration loosen the pore structure of concrete, increasing its porosity. This increased porosity facilitates the CO_2 diffusion, resulting in a decrease in carbonation resistance. Nonetheless, the authors emphasize the promising result that the carbonation resistance of multi-recycled concretes exposed to harsh environments satisfied the 50-year design service life requirements of the design code (JGJ/T193-2009 and GB/T 50476-2019).

Frost Resistance

Frost resistance of concrete refers to the ability of concrete to withstand freeze–thaw cycles without significant damage and is a key parameter that determines the service life of concrete in cold regions. Generally, recycled materials absorb more water and this absorbed water is discharged into the cement paste, weakening its cold resistance. Zhu et al. (2019b) investigated the frost resistance of multi-RCAC. During 800 freeze–thaw cycles, both the dynamic elastic modulus and weight decreased in the order of NAC, RCAC1, RCAC2, and RCAC3 (i.e., NAC has the highest modulus and weight, while RCAC3 has the lowest). In particular, RCAC3 after 600 cycles showed a higher mass loss than RCAC2 after 800 cycles of freeze–thaw, clearly indicating a deterioration in frost resistance as concrete was repeatedly recycled. To complement this, Wang et al. (2022a, b) have stated that, in order to maintain a multi-cycle recycling system in an environment subject to freeze–thaw action, the parent concrete needs to be a high-performance concrete to prevent durability damage during its service life.

Microstructural Analysis

The scanning electron microscope results of concretes undergoing three cycles of recycling are shown in Fig. 15. For NAC, one ITZ between the NCA and the fresh mortar is observed, along with a few microcracks due to moisture evaporation (Fig. 15a). As recycling progresses multiple times, the cement matrix becomes complex. In RCAC1, there are two ITZs: ITZ1 between NCA and the existing hardened mortar, and ITZ2 between this RCA1 and the new mortar (Fig. 15b). RCAC2 has three ITZs, including the two observed in RCAC1 and ITZ3 between RCA2 and the fresh mortar (Fig. 15c). RCAC3 shows four ITZs, including the three observed in RCAC2 and ITZ4 between RCA3 and the fresh mortar (Fig. 15d) (Belabbas et al. 2024). The ITZ is a weak point where concrete is more prone to cracking. In particular, the ITZ between new and old mortar provides a weaker bond than the ITZ between aggregate and mortar (Zuo et al. 2020). This explains why the performance of concrete recycled more times is lower than that of concrete recycled fewer times.

Performance Enhancement of Multi-Recycled Concrete

Reduction in Replacement Rate of Recycled Materials

One of the simplest way to mitigate performance loss in recycled concrete is to reduce the replacement of natural materials with recycled ones (Bai et al. 2020; Kim et al. 2022). Some studies have attempted to compensate for the performance loss from multi-recycling by including natural aggregate in each recycling cycle (Abed et al. 2020; Marie and Quiasrawi 2012; Shmlls et al. 2022). For example, in a study by Marie and Quiasrawi (2012), RCAC1 was prepared with 20% RCA replacement rate (i.e., 80% of the coarse aggregate in RCAC1 was natural aggregate), from which RCA2 was obtained. RCAC2 was prepared with 20% RCA2 (i.e., 80% of the coarse aggregate in RCAC2 was natural aggregate) (Fig. 16). As shown in Table 3, this approach enhanced the workability, mechanical strength, and water absorption of the second generation RCAC. However, it should be noted that the environmental benefits diminish as natural aggregate is used for each recycling cycle. Furthermore, due to the 80% NCA used in RCAC1, the RCA2 obtained from RCAC1 does not truly represent 'multi-recycled' aggregate.

Carbonation of Recycled Materials

In recent times, numerous studies have emerged focusing on the utilization of CO_2 in concrete. When the hydration products in RCA, RFA, and RP are exposed to CO_2, calcium carbonate and silica gel are formed, and this reaction fills the pores and cracks of the recycled materials, making the microstructure dense (Fang et al. 2021; Lu et al. 2018; Luo et al. 2018; Xuan et al. 2017). Liu et al. (2022) applied this carbonation technique to second-generation RCA and investigated the effect of its use on the properties of concrete. The RCA2 was carbonated under the following conditions: a temperature of 20 °C; relative humidity of 55%; CO_2 concentration of 20%, and a CO_2 gas pressure of 0.5 MPa. Table 4 shows the characteristics of RCAs before and after carbonation treatment, and the properties of concrete containing the RCAs. The carbonated RCA2 has better characteristics (higher density, lower water absorption) as an aggregate for concrete than non-carbonated RCA2.

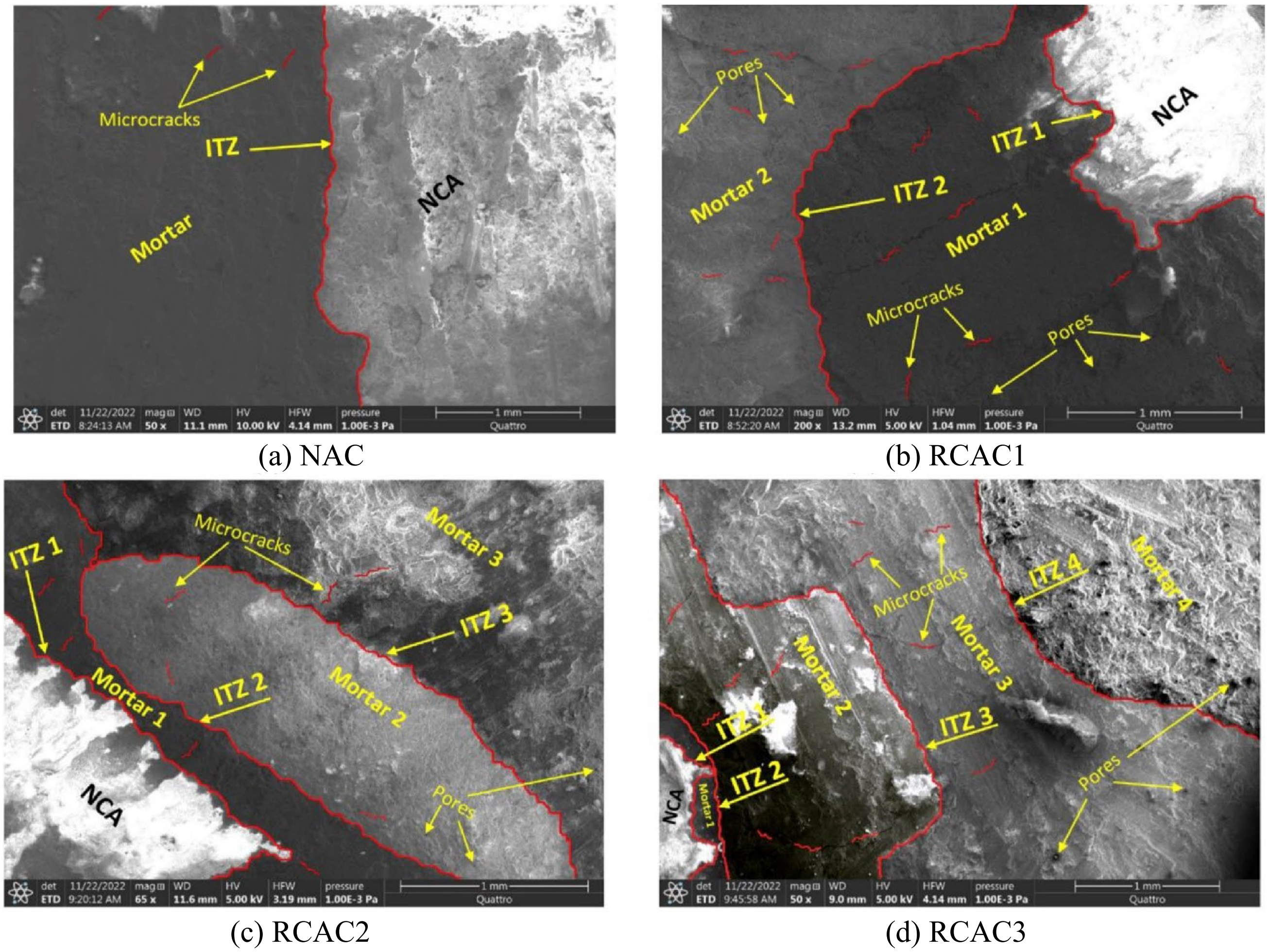


Fig. 15 Scanning electron microscopy analysis of concrete with various recycling cycles (Belabbas et al. 2024)

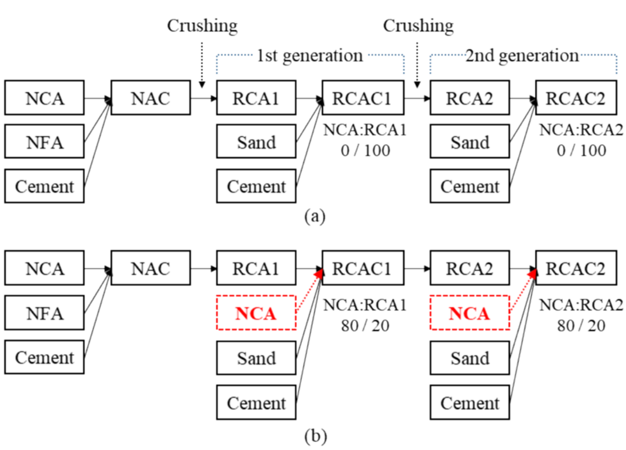


Fig. 16 Multi-recycling of concrete with and without natural aggregates

Table 3 Properties of RACs relative to NAC (Marie and Quiasrawi 2012)

	NAC	RCAC1	RCAC2
Slump	1	0.70	0.88
Compressive strength	1	0.80	0.88
Splitting tensile strength	1	0.90	0.95
Flexural strength	1	0.88	0.92
Water absorption	1	1.50	1.20

The quality of aggregates plays a crucial role in concrete performance (Kim 2022); consequently, concrete containing carbonated RCA2 exhibits higher compressive strength, a denser pore structure, and improved durability. In particular, it is worth noting that concrete containing carbonated RCA2 performed better than RCAC1, suggesting the possibility that carbonation treatment can offset performance losses by multi-recycling. A positive effect of carbonated RCA can also be found in other study (Wang et al. 2022a, b).

Table 4 Effect of carbonated multi-recycled coarse aggregate on concrete properties (Liu et al. 2022)

	RCA1	Non-carbonated RCA2	Carbonated RCA2
Density (g/cm^3)	2.486	2.242	2.366
Water absorption (%)	4.99	6.47	4.75
Soundness (%)	9.88	11.56	9.26
Crushing index (%)	15.2	24.5	18.7
	RCAC1	Non-carbonated RCAC2	Carbonated RCAC2
Water absorption (%)	3.86	4.3	2.82
Porosity (%)	10.0	15.2	7.9
Compressive strength (MPa)	47.0	38.9	52.2

Vibration Mixing

Yang et al. (2022) investigated the effect of vibration mixing on multi-recycled concrete. Table 5 summarizes the properties of vibrated and non-vibrated concretes, showing that the vibrated concrete exhibits better workability and strengths. This performance improvement is attributed to vibration breaking the viscous connection between cement particles, preventing the cement agglomeration and allowing RCA to be better coated with fresh mortar (Xiong et al. 2019; Zhao et al. 2021). This vibration mixing method has the advantage of being applicable without changing the mixing components of concrete.

Mix Design

As represented in Fig. 5, due to the presence of attached mortar, recycled concrete exhibits a larger volume of mortar compared to NAC, with a smaller proportion of original aggregates. To control this imbalance in material proportions, the EMV mix design method has been proposed (Fathifazl et al. 2009). The primary principle of the EMV method is to offset the volume of fresh mortar by the volume of attached mortar, thereby making the total mortar volume of recycled concrete equivalent to that of NAC. The performance efficiency and environmental benefits of this method have been reported in various literature (Fathifazl et al. 2011; Jiménez et al. 2014; Rajhans et al. 2019; Yang and Lee 2017). Kim et al. (2023a) applied the EMV method to multi-cycle recycling. The EMV-based concretes with the same material volume were prepared and tested over three recycling cycles. and the test results are summarized in Table 6. While concrete designed using conventional methods demonstrated a gradual loss of performance with increasing recycling cycles, the EMV-based concrete exhibited no obvious loss in the performance at each recycling cycle, indicating the importance of mix design that takes into account the characteristics of recycled aggregate.

Use of Plasticizer

As mentioned in the previous section, it was discussed that one of the consequences of multi-recycling is a reduction in concrete workability. In response, Kim et al. (2023c) aimed to improve the workability of RCAC3 by increasing the plasticizer dosage and investigated its influence on the concrete properties. In the study, plasticizer dosages in RCAC3 were increased from 0.8 to 1.2% of cement in 0.1% increments. Except for the plasticizer dosage, the rest of the mix design remained the same, and the control group was RCAC1 with 0.8% plasticizer. Table 7 summarizes the experimental results. The slump of RCAC3 increased with increasing plasticizer dosage. In addition, for the hardened properties, the density, mechanical strength, and capillary absorption

Table 5 Effect of vibratory mixing on concrete properties (Yang et al. 2022)

	RCAC1			RCAC2		
	Non-vibrated	Vibrated	Δ (%)	Non-vibrated	Vibrated	Δ
Slump (mm)	84	93	10.7	82	87	6.1
Air content (%)	1.7	2.1	23.5	2.2	2.7	22.7
Compressive strength (MPa)	34.9	38.9	11.5	35.7	38.8	8.7
Tensile strength (MPa)	3.79	3.95	4.2	3.89	4.25	9.3

Table 6 Effect of mix design on concrete properties (Kim et al. 2023a)

	Conventional-based RCAC			EMV-based RCAC		
	R1	R2	R3	R1	R2	R3
Water absorption (%)	3.34	5.84	6.44	2.87	5.13	5.17
Compressive strength (MPa)	43.4	40.6	32.5	43.5	42.3	44.7
Tensile strength (MPa)	3.12	2.79	2.61	3.16	3.06	3.31
Flexural strength (MPa)	5.85	5.50	5.40	6.22	5.73	5.79
Drying shrinkage (μm)	0.3035	0.3885	0.4135	0.2855	0.3335	0.2980
Electric charge (C)	2931	3384	4331	2826	3070	2874

Table 7 Properties of multi-recycled concrete with various plasticizer dosages

	R1-0.8	R3-0.8	R3-0.9	R3-1.0	R3-1.1	R3-1.2
Slump (mm)	180	80	100	120	160	200
Air content (%)	3.6	6	5.3	5.0	5.3	5.7
Density (kg/m^3)	2321	2218	2245	2284	2224	2196
Compressive strength (MPa)	43.4	32.5	34.8	37.2	34.7	33.5
Tensile strength (MPa)	3.12	2.61	2.84	3.26	3.06	2.59
Capillary absorption (mm)	1.73	2.19	1.89	1.84	1.87	2.12

were improved, and some properties (tensile strength and capillary absorption) achieved similar performance to that of the RCAC1 as the plasticizer dosage was increased to 1.0%. This is related to the fact that free water due to the increase in plasticizer is used to promote hydration of the cement (Zhao et al. 2021). However, this positive effect diminishes when the plasticizer dosage exceeds the threshold. Therefore, the authors recommended determining the appropriate dosage.

Environmental and Economic Analysis of Multi-Recycled Concrete

The environmental aspects of multi-recycling of concrete have been discussed in some studies. In a study by Visintin et al. (2022), it was found that the benefits of using RCA were insignificant as the process of recycling concrete waste into aggregate is similar to the process of converting natural stone into aggregate. However, the authors noted that the effect of transportation distance should be investigated. Generally, in urban areas, the generation of construction waste and the demand for concrete coexist, resulting in shorter transportation distances for RCA compared to NCA. In the life cycle assessment by Lei et al. (2024), RCAC1, RCAC2, RCAC3 demonstrated superior environmental performance compared to NAC in terms of Global Warming Potential (GWP), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP), Eutrophication Potential (EP), and Cumulative Energy Consumption (CED). For example, the GWP of RCACs with three different recycling cycles was 8.5%, 12.1%, and 15.8% lower than that of NAC. The authors attributed these environmental benefits to two main factors: (i) the shorter transportation distance of RCA from construction waste recycling plants to concrete production facilities (20 km) compared to NCA from quarries to concrete production facilities (380 km); (ii) avoiding landfilling of concrete waste through recycling. They particularly emphasized that these effects are amplified when concrete is repeatedly recycled. Similar results were reported in other study (Shmlls et al. 2023), where the use of RCAC1 and RCAC2 resulted in approximately 20% and 25% reduction in GWP. Kim and Jang (2022) analyzed the environmental impact of using multi-RP as a partial replacement for cement. According to their study, incorporating 20% RP recycled three times reduced GWP by 15% while achieving the target strength. Furthermore, it was observed that concrete containing 10% RP offered greater environmental benefits compared to concrete containing 100% RCA, which is due to the significantly higher CO_2 emissions from cement compared to other materials used in concrete.

The economic viability of multi-recycling of concrete has been relatively underexplored, and its benefits can vary depending on the circumstances. In the study by Kim and Jang (2022), the production cost of RCAC2 was approximately 5% lower than that of NAC. However, the compressive strength was 13% lower, leading the authors to emphasize that economic discussions should consider both intended properties and production costs together. The modification of multi-RAC for better performance could potentially worsen its economic viability. In a study (Shmlls et al. 2023), replacing NCA with RCA1 by 30% increased the cost per cubic meter of concrete from $147.4 to $152.9. Even with a 70% replacement rate of RCA1, the cost remained higher than that of NAC at $151.9. Similarly, replacing RCA1 with RCA2 resulted in the costs of $149.0 and $148.1 at 30% and 70% replacement rates, respectively, still higher than that of NAC. This is because natural aggregate is not inherently expensive material, and additionally, more additives are required proportionally to the number of recycling to enhance the workability of multi-RAC. While the primary purpose of recycling is environmentally driven, economic feasibility is essential for sustained implementation in actual industries. Further comprehensive research is necessary to understand the economic viability of multi-recycling.

Discussion

According to the findings of this review, multiple-time recycling is responsible for the performance loss in concrete, and the extent of this loss becomes more pronounced with an increase in the number of recycling cycles. Nevertheless, it is crucial to comprehend that the loss does not imply restricting the utilization of multi-recycled concrete. Even when no strengthening methods are applied, multi-recycled concrete can be used as normal strength (e.g., 20 MPa) as well as high strength concrete (e.g., 50 MPa) (see Figs. 9 and 10), and this strength range satisfactorily meets the requirements in many industry standards. For instance, Zhu et al. (Zhu et al. 2019b) reported that the 1st and 2nd generation concrete met the 100-year design life requirement in harsh and cold environments according to the Chinese design code, while the 3rd generation concrete satisfied the 50-year design life requirement.

Despite the limited number of publications on multi recycling, several research gaps could be identified. In most previous studies, concrete waste was recycled multiple times as coarse aggregate, and few studies treated it as fine aggregate and powder (Fig. 17a). Considering that fine particles are inevitably generated during the concrete multiple recycling process (Salesa et al. 2017b; Zhu et al. 2019b), further research on their utilization is needed to achieve multi-and-zero waste recycling. It is well known that the properties of concrete are significantly influenced by the materials used. Modern concrete may incorporate additives such as fibers, nanomaterials, water reducers and air-entraining agents to achieve optimal performance (Kidalova et al. 2012; Kowalik and Ubysz 2021; Sánchez-Pantoja et al. 2023). Furthermore, for environmental benefits, industrial by-products like fly ash and ground granulated blast-furnace slag, as well as industrial waste such as glass, brick, clay, plastic, and ceramic wastes, are used as supplementary cementitious materials (Shirdam et al. 2019; Sičáková et al. 2017; Tawfik et al. 2024). However, the effect of the repeated recycling of concrete containing these materials on the properties of next-generation concrete has not been investigated. Another research gap can also be clearly found in the types of concrete. The majority of previous studies have focused on conventional concrete, which requires compaction. Little study was carried out on self-compacting concrete and mortar (Fig. 17b). Additionally, very limited research has been conducted on steel and fiber reinforced concrete.

Table 8 summarizes the types of tests conducted in literature. Workability and compressive strength tests, as the most representative properties of fresh and hardened concrete, were the most frequently performed. Following these, properties such as tensile strength, water absorption and elastic modulus were also often measured. On the other hand, relatively little testing has been performed on the durability of concrete, such as abrasion resistance and freeze–thaw resistance.

In summary, current studies on multi- recycling of concrete primarily focus on the basic properties of traditional compacted concrete containing RCA, which may provide directions for further research. For example:

- The utilization of fine particles generated from multi-cycle recycling needs to be studied. The use of fine particles is directly related to achieving zero waste, and their counterparts, i.e., sand and cement, emit more CO_2 than coarse aggregates. Therefore, fine particles have the potential to make a significant contribution to reducing CO_2 emissions.

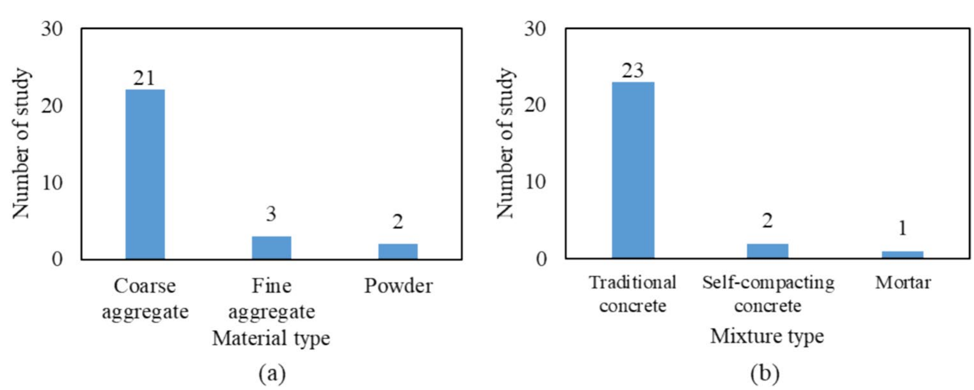


Fig. 17 Number of studies categorized by material type (**a**) and mixture type (**b**)

Table 8 A summary of properties of multi-recycled concrete reported in the literature

References	Slump	Air content	Strength				E-modulus	Water absorption		Porosity	Resistance			Shrinkage
			Compressive	Tensile	Flexural	Shear		Immersion	Capillary		Frost	Chloride	Carbonation	
Liu et al. (2021)	✓		✓										✓	
Brito et al. (2006)	✓		✓											
Marie and Quiasrawi (2012)	✓		✓	✓	✓			✓						
Shmlls et al. (2022)			✓	✓	✓									
Silva et al. (2021)			✓					✓	✓			✓	✓	✓
Zhu et al. (2019a)	✓		✓										✓	
Zhu et al. (2018)	✓		✓	✓								✓		
Jung (2023)	✓	✓	✓		✓									✓
Lei et al. (2023a)						✓								
Zhu et al. (2016)	✓		✓	✓										
Chen et al. (2020)			✓							✓			✓	
Kim et al. (2023a)	✓		✓	✓	✓			✓				✓		✓
Visintin et al. (2022)	✓		✓	✓			✓	✓		✓				
Lei et al. (2023b)			✓			✓								
Thomas et al. (2020)			✓					✓		✓				
Abed et al. (2020)	✓		✓		✓		✓			✓				
Kim and Jang (2022)	✓	✓	✓	✓			✓							
Kim et al. (2023b)	✓		✓		✓			✓	✓					✓
Kim et al. (2023c)	✓	✓	✓	✓					✓					
Salesa et al. (2017a)	✓	✓	✓				✓	✓						
Salesa et al. (2017b)	✓	✓	✓				✓	✓						
Huda and Alam (2014)	✓	✓	✓	✓			✓							
Zhu et al. (2019b)			✓	✓							✓	✓	✓	
Yang et al. (2022)	✓	✓	✓	✓										
Abreu et al. (2018)	✓		✓	✓			✓							
Wang et al. (2022a, b)											✓			
Count	**18**	**7**	**24**	**12**	**6**	**2**	**7**	**8**	**3**	**4**	**2**	**4**	**5**	**4**

- A more systematic investigation is needed into how the raw materials of parent concrete affect the properties of next-generation concrete. This will help identify which factors have favorable or unfavorable influences on repeated recycling.
- Examining various types of cementitious mixtures, including self-compacting mortar and concrete, can provide an expanded understanding of multi- recycling. Furthermore, given that concrete is often used in combination with fibers and rebar, it is essential to investigate the effect of multi-recycling on reinforced concrete.
- One notable weakness of recycled concrete is its low durability, which is a major impediment to using recycled materials in concrete. Thus, it is crucial to conduct various tests on the durability properties of multi-recycled cementitious mixtures and explore ways to enhance their performance.
- The environmental benefits of multi-recycling of concrete need to be better understood, and an investigation into establishing an economic model to sustain this recycling practice is also necessary.

These exemplary further studies are expected to build the body of knowledge on multi- recycling of concrete and contribute to better utilization of waste.

Conclusions

This paper has conducted a literature review on the multi-recycling of construction waste, and the following conclusions can be drawn:

- The number of times concrete is recycled affects the quality of the recycled material obtained from it. As the number of recycling increases, the recycled aggregate and powder have more micro cracks and pores.
- Recycled materials downgraded by multi-recycling have a negative influence on the workability, mechanical properties, and durability of concrete.
- Performance losses resulting from multiple cycles of concrete recycling can be offset by various strengthening methods, such as carbonation of recycled materials, modified mix design and mixing techniques.
- It should be noted that the lack of available data limits a clear assessment of the effect of multi-recycling of concrete and the identification of key contributing factors for the effect. Nevertheless, in this study, clear research gaps in existing studies were identified, and the limitations and potential of multi-recycling of concrete were discussed. Further comprehensive research is needed on the various types and properties of multi-recycled concrete.

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest The author has no relevant financial or non-financial interests to disclose.

Ethical Approval This article does not contain any studies with human participants or animals performed by any of the authors.

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