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Feasibility of utilizing recycled coarse aggregates in commercial concrete production

Ali Vahidi [a,*], Arsalan Mostaani [b], Abraham Teklay Gebremariam [a], Francesco Di Maio [a], Peter Rem [a]

[a] *Department of Engineering Structures, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands*
[b] *Faculty of Natural Sciences, Norwegian University of Science and Technology, Trondheim, Norway*

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ABSTRACT

This study addresses a critical gap in circular construction practices by assessing the use of high-quality Recycled Coarse Aggregates (RCA) from end-of-life concrete on an industrial scale. Unlike previous studies, which predominantly relied on theoretical mix designs or laboratory-level experiments, this research focuses on real-world applicability, employing commercially produced RCA and conventional production methods in industrial settings to identify upscaling challenges. Advanced Dry Recovery technology is utilized to produce high-quality RCA for both ready-mix and prefab concrete production. To ensure practical relevance, the research examines three water-to-cement ratios for ready-mix concrete and three strength classes for prefab concrete, all prepared and cast in a commercial setting using standard industrial practices. The results show that by selecting the appropriate application for RCA, there is potential for concrete companies to produce mixes using 100% RCA that meet standard requirements in terms of fresh, mechanical, and durability properties without the need for extra treatments or specific mixing methods, particularly when the water absorption of RCA is less than 4%. Achieving optimal performance requires adjustments in the mix design, specifically by considering the effective water-to-cement ratio. Additionally, the study underscores the impact of the parent concrete's properties on the RCA quality. This research not only demonstrates the feasibility of employing RCA in industrial-scale concrete production along with its associated challenges but also highlights the potential for enhancing circularity in the construction industry through large-scale adoption of RCA, thereby contributing to sustainable and circular construction practices.

1. Introduction

As part of efforts to attain circularity in the concrete industry, there is growing interest in employing Recycled Coarse Aggregates (RCA) in commercial concrete production (Wijayasundara et al., 2018). This shift is primarily motivated by the urgent need to address the environmental impacts and the depletion of resources linked to the use of Natural Coarse Aggregates (NCA) (Braga et al., 2017). In 2020, the global consumption of concrete reached approximately 26 Gt, necessitating the use of about 20 Gt of aggregates (Watari et al., 2023). This vast demand highlights the imperative to develop sustainable concrete production practices. However, the transition faces significant challenges due to the variability in RCA quality (De Brito and Silva, 2016). This variability, particularly in terms of residual mortar level, leads to water absorption rates that vary by up to 13% with an average value of 5.6% (Thomas et al., 2016), posing substantial obstacles to concrete manufacturing such as requiring time-consuming mix adjustments for expected consistency, increasing the need for frequent quality testing, and potentially leading to reduced trust among construction industry stakeholders in the reliability and performance of concrete made with recycled aggregates. These differences stem from the varying composition of parent concrete and the use of suboptimal crushers in transforming End-of-Life (EoL) concrete into coarse aggregates, resulting in notable amounts of residual mortar and microcracks on RCA surfaces (Gebre-Mariam et al., 2023; Akbarnezhad et al., 2013).

Several treatment approaches, including thermal, chemical, and

Abbreviations: ADR, Advanced Dry Recovery; EoL, End-of-Life; NCA, Natural Coarse Aggregates; PC, Prefab Concrete; RCM, Rapid Chloride Migration; RC, Ready-mix Concrete; URFA, Unprocessed Recycled Fine Aggregates; VP, Vacuum Porosity; WCR, Water-to-Cement Ratio; WWA, Wide Wheel Abrasion.

* Corresponding author.
E-mail address: a.vahidi@tudelft.nl (A. Vahidi).

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mechanical techniques such as pre-soaking in acidic media and compression casting have been used by researchers to reduce the amount and negative effect of residual mortar (Kazmi et al., 2020; Munir et al., 2022; Wu et al., 2024). Additionally, accelerated carbonation, mineral admixtures, and mixing approaches have been proposed to enhance the microstructure and quality of RCA, overcome their higher water absorption, and improve the performance of the produced concrete (Kazmi et al., 2020; Wu et al., 2024). While these techniques and methods can be effective, they often require substantial changes in the conventional operational processes of concrete companies on a case-by-case basis, demanding considerable time and resources (Munir et al., 2022). In response to these challenges and to enhance the use of recycled aggregates in industrial concrete production, technologies and methodologies have been developed to improve the quality and reliability of RCA at the recycling stage before delivery to concrete companies. These include Advanced Dry Recovery (ADR) and a Heating Air Classification System that recycles aggregates into coarse, fine, and ultrafine particles (Gebremariam et al., 2020), as well as automatic quality control systems and the implementation of material passports in the aggregates value chain (Vahidi et al., 2024).

Laboratory-scale studies have shown that by using high-quality RCA, it is possible to produce recycled aggregate concrete with properties similar to those of concrete made with natural aggregates (Gebremariam et al., 2021; Lotfi et al., 2014). However, the limited research on commercial RCA and recycled aggregate concrete at the industrial scale, coupled with a lack of confidence stemming from the inconsistent quality of RCA, presents challenges in achieving uniform concrete performance (Sagoe–Crentsil et al., 2001; Silva and Dhir, 2019). In this study, an extensive series of experiments was conducted using high-quality RCA produced by ADR technology. The selection of ADR was based on its effectiveness in enhancing the mechanical properties of recycled aggregates and minimizing impurities. These experiments, both fresh and hardened, took into account the requests and limitations of concrete companies and were designed to assess the feasibility of the conventional approach to producing recycled aggregate concrete. As part of these experiments, different mix designs of concrete were produced, including three different Water-to-Cement Ratios (WCR) for Ready-mix Concrete (RC) and three strength classes for Prefab Concrete (PC), which were then evaluated to investigate the impact of fully replacing NCA with RCA on the properties of the concrete.

1.1. Research significance

This study employs ADR technology to enhance the use of RCA in commercial concrete production. By conducting research in commercial settings, the findings validate and extend laboratory-scale results, addressing operational challenges and increasing industry trust in RCA's practical applications. The study demonstrates that RCA has the potential to be used in standard concrete mixes without additional treatments or significant changes to existing setups, directly addressing concerns about quality variability. Moreover, this research highlights the potential of using 100% RCA to promote sustainable construction practices. It explores how different parent concretes influence the quality of the produced concrete, providing insights that could refine recycling processes and improve aggregate quality. By demonstrating RCA's effectiveness in real-world settings this study encourages the wider adoption of recycled materials and supports the construction industry's transition towards sustainability. Ultimately, it bridges a critical gap in the literature and sets a foundation for future advancements in sustainable construction materials, marking a significant step towards circular economy practices in the construction sector.

2. Materials and methods

2.1. Concrete recycling procedure

In this study, two demolition sites were selected to produce RCA with different properties, including a two-story non-residential building in Almere (R) and a concrete bridge in Groningen (I) in the Netherlands. Selective demolition was adopted at these sites to minimize environmental impacts and optimize profitability (Andersen et al., 2022). To ensure consistency in processing the RCA, the EoL concrete from both the building and the bridge was transported to a recycling facility, where it underwent crushing and processing using ADR technology. ADR technology which is capable of processing up to 120 tons per hour at demolition sites, employs a spinning rotor to break water bonds between grains and an air sifter for mechanical separation, sorting crushed concrete waste into coarse and fine aggregates, as well as lighter contaminants like wood and plastics (Gebremariam et al., 2020) The properties of the resulting RCA types "R" and "I" were then analyzed as per EN standards 933-1, 1097-2, and 1097-6, with detailed results presented in Table 1.

Building upon this process, the recycling method resulted in a greater yield of fine aggregates (0–4 mm) compared to conventional sieving methods, attributable to the capability of ADR in breaking down loosely bonded coarse aggregates. Fig. 1 illustrates an increase in the fine aggregate fraction from 10.7% to 35.6% by weight. Additionally, changes in the proportions of the 4–8 mm and 8–16 mm particles within the coarse fraction were observed, indicating the effectiveness of ADR technology in processing weakly bonded aggregates. This suggests that ADR technology can enhance the overall quality and homogeneousness of recycled aggregates and may lead to a more consistent particle size distribution, thereby improving performance in applications like concrete production.

Following this advancement, the produced coarse fraction from type "R," ranging from 4 to 22 mm, was processed for use in RC, while the fraction, ranging from 4 to 16 mm from types "R" and "I" was utilized in PC production, as depicted in Fig. 2. The aggregates measuring 0–4 mm were directed to a secondary processing facility for further separation of fine aggregates from hydrated cement. However, the processed fine aggregates were not used in industrial-scale concrete production in this research.

2.2. Concrete production

In this study, commonly used concrete mix designs in the Dutch market were selected to evaluate the effects of RCA on the properties of RC and PC with varying WCR and strength classes. Cement types III/B 42.5 N LH and III/B 52.5 N LH-SR were used as the main binders for RC and PC, respectively, alongside marine coarse and fine natural aggregates. RCA was used in a dry state, similar to NCA, to replicate the casting procedure on an industrial scale. Each mix for both RC and PC was designed using computer-based software based on their reference mixes and mixed in a minimum batch of 4.5 m^3 at the industrial facility. It should be noted that conducting these tests on a large scale presents certain limitations, including the cost implications, availability of recycled aggregates, and selection of appropriate durability tests based on the database and requirements of the companies involved. Afterward, the concrete was transported to the laboratory, where samples were

Table 1
Properties of NCA and RCA types R and I.

Properties	NCA	R	I
Passing through 0.063 mm (%)	–	1.5	1.15
Los Angeles Abrasion (%)	21	24	26
Particle Density (g/cm^3)	2.5	2.35	2.25
Water Absorption (%)	1.2	3.8	6

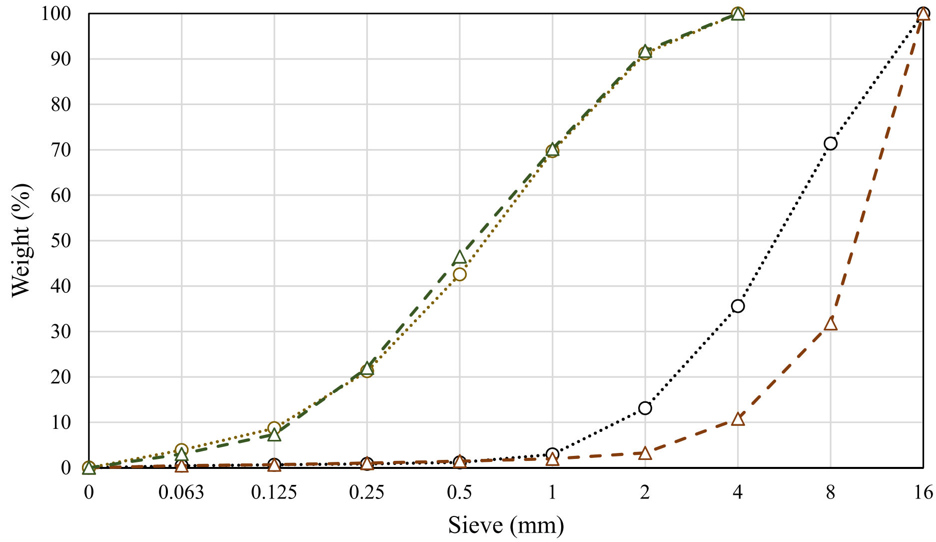

Fig. 1. Particle size distribution of recycled aggregates type R from crusher and ADR outputs.

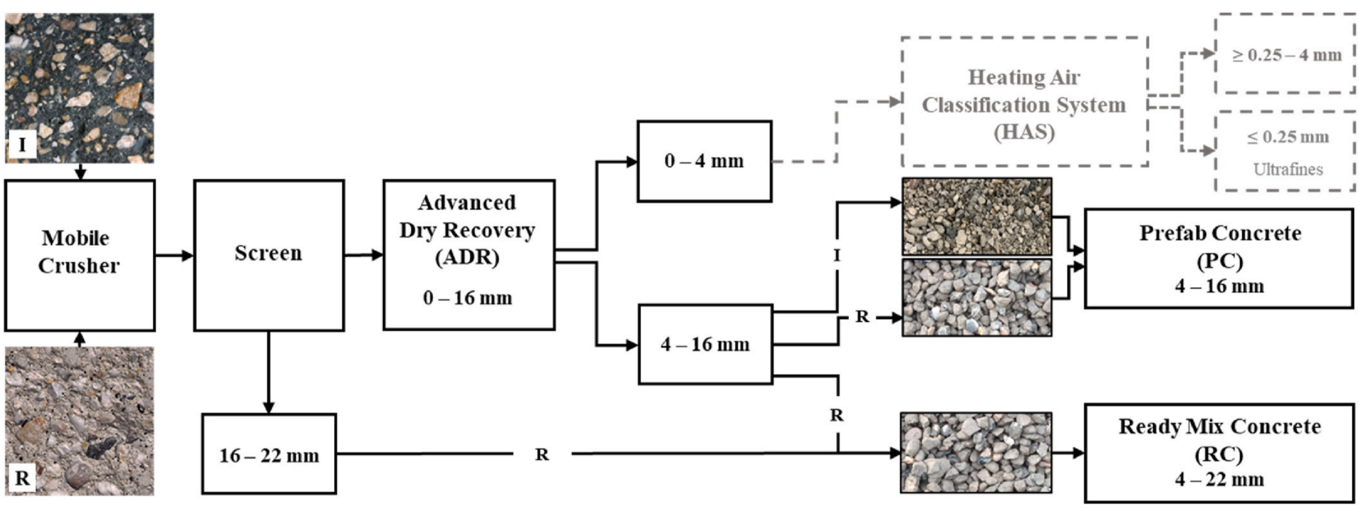

Fig. 2. Layout of concrete recycling for RC and PC.

taken for use in both fresh and hardened concrete testing procedures as requested by RC and PC companies. The specimens were cast in controlled laboratory settings and cured until the time of testing, in accordance with the guidelines set forth in EN-12390-2.

As shown in Table 2, the first part of this study focused on the production of RC mixes R0, R5, and R1, which involved replacing 0%, 50%, and 100% of NCA with RCA type "R," respectively. They were prepared with three levels of WCR (R4:0.45, R5: 0.55, and R6: 0.65) to assess the influence of WCR on the fresh, mechanical, and durability properties of commercially produced recycled concrete using conventional methods while maintaining an F4 consistency for RC companies. Following the production process, the fresh density of all RC mixes was measured, followed by conducting flow table tests on these mixes for up to 90 min, adhering to the NEN-EN 12350-5 standard. To further meet the requirements of the RC company, various hardened concrete performance parameters were assessed, including compressive strength (NEN-EN

Table 2
RC mixes of reference and recycled concrete for 1 m^3 for different WCRs.

WCR	RCA Type	RCA (%)	Concrete Mix	Cement (kg/m^3)	Fly Ash (kg/m^3)	Sand (0/4 mm)	Gravel (4/22 mm)	RCA (4/22 mm)	Water (kg)	SP (kg/m^3)
0.45	–	0	R4R0	366	0	819	1005	0	165	0.73
	R	50	R4R5	374	0	793	477	477	168	1.5
	R	100	R4R1	383	0	784	0	897	172	2.3
0.55	–	0	R5R0	315	0	831	1012	0	173	0
	R	50	R5R5	318	0	827	382	478	175	0
	R	100	R5R1	322	0	731	0	986	177	0.97
0.65	–	0	R6R0	258	42	831	1014	0	173	0
	R	50	R6R5	270	30	825	477	477	179	0
	R	100	R6R1	264	36	828	0	910	177	0.66

12390-3), water penetration (NEN-EN 12390-8), carbonation (CEN/TS 12390-10; 2007), rapid chloride migration (NT Build 492), and electrical resistivity (CUR guidance 1; part III; 2011). In a subsequent step, after obtaining samples for selected tests, the RCA content of the produced concrete was adjusted to dilute to 30% of the RCA replacement to comply with NEN-EN206/NEN8005 before being delivered to clients. This step was implemented to reduce the cost of concrete production for this research.

Given that the PC company had the capacity and capability to store the RCA for a longer time in its silos, the second part of this study was conducted in a series of three interconnected stages, each designed to address the specific requirements of PC companies. This phase of the research aimed to investigate the effects of using 100% RCA, sourced from two different types, "R" and "I." These types were selected for their varying water absorption rates to examine their impact on the performance of PC across high (PH), medium (PM), and normal (PN) strength classes. Initially, RCA type "R" was utilized to produce concrete mixes with three different strengths (PNR, PMR, and PHR). These mixes involved half to full replacement of NCA based on the reference mix (PHR0), which was designed for XF4-C53/65 to assess the level of different RCA replacements and their effect on the performance of recycled aggregate concrete. In the next phase, RCA type "I" was used to produce mixes PNI1 and PMI1, aiming to determine the influence of distinct parent concrete sources on the performance of recycled concrete, highlighting the role of differing water absorption properties. The final stage concluded with the full replacement of natural aggregates with both recycled fine and coarse aggregates of type "I" to produce mix PHI1, examining the effect of Unprocessed Recycled Fine Aggregates (URFA) on the performance of high-strength concrete. The PC mixes used in this study are listed in Table 3. For all mixes, in addition to measuring the fresh density, the slump flow test was conducted in two stages at 30-min intervals, according to NEN-EN 12350-8. Moreover, specimens were produced and tested for compressive strength (NEN-EN 12390-3), elastic modulus (EN 12390-13), water penetration (EN 12390-8), vacuum porosity (RILEM CPC11.3), wide wheel abrasion (EN 1338 Annex G), drying shrinkage up to 3 months (CUR report 94-12), accelerated carbonation (4% V/V CO2) up to 3 months (CUR recommendation 48), and rapid chloride migration (NT Build 492) based on the request of the PC company. In this part of the study, given the importance of the durability performance of concrete in meeting standard requirements, particularly for high-strength class concrete, only samples with a full replacement of NCA with RCA were produced to evaluate their performance based on these standards.

3. Results and discussion

3.1. Fresh concrete properties

3.1.1. Ready mix concrete (RC)

The results of the fresh concrete measurements for the RC and PC mixes are presented in Figs. 3 and 4, respectively. The data on fresh concrete for RC mixes show that while initial flowability remains in the standard range, mixes like R4R1 and R5R1 exhibit declines in flowability, particularly at 90 min, with reductions of up to 12% for R4R1 and 33% for R5R1, respectively. This diminished flowability is primarily attributed to conventional production methods that did not consider the effective WCR and the optimal use of superplasticizers (Mechtcherine et al., 2014). In contrast, mix R6R1, which utilized higher WCR levels along with fly ash and superplasticizers, demonstrated a 2% increase in flowability. This can be attributed to the spherical shape of the fly ash particles, which improve rheology, and the superplasticizer, which enhances particle dispersion, both contributing to increased flowability (Mechtcherine et al., 2014; Kurda et al., 2017). As shown in Fig. 3, the fresh density of produced concrete decreases with an increasing amount of RCA. This observation, consistently reported in the literature regardless of the methods used, indicates that the usage of RCA, based on the level of residual mortar, leads to a decrease in both the fresh and hardened density of the recycled aggregate concrete (Silva et al., 2018; Verian et al., 2018). In this study, employing 100% RCA resulted in an average density reduction of 5–6%.

3.1.2. Prefab concrete (PC)

The influence of RCA types "R" and "I" on the flowability of PC mixes shows that type "I," with approximately 35% higher water absorption than type "R," achieves the desired workability by using about three times more superplasticizer, as demonstrated by mixes PNI1 and PMI1 compared to PNR1 and PMR1 (Fiol et al., 2018). Additionally, adjustments in the cement content and strength class appear to equalize the flowability of mixes PHR0 and PHR1 at 30 min, while the PHI1 mix, incorporating URFA with high water absorption (8%), is unsuitable for industrial applications due to limited workability. The increased use of recycled aggregates results in decreased density in concrete due to higher porosity caused by residual mortar adhering to the recycled aggregate (Revilla-Cuesta et al., 2020). This trend is evident in all mixes when the replacement rate of RCA reaches 100%. Density is further reduced by up to 8% with RCA type "I," compared to 4% with type "R." This reduction can reach up to 10% for full replacement of aggregates with type "I" aggregates.

3.2. Mechanical properties

3.2.1. Ready mix concrete (RC)

The compressive strength of concrete mixes with varying RCA levels

Table 3
PC mixes of reference and recycled aggregate concrete for 1 m^3 for different strength classes.

Strength Class	RCA Type	RCA (%)	Concrete Mix	Cement kg	Limestone kg	Sand (0/4 mm)	URFA (0/4 mm)	Gravel (4/16 mm)	RCA (4/16 mm)	Water (kg)	SP % Cement
H	–	0	PHR0	325	185	829	0	1007	0	109	1.5
H	R	50	PHR5	326	184	704	0	504	504	102	1.8
H	R	100	PHR1	320	195	704	0	0	896	102	1.7
H	I	100	PHI1	320	195	0	540	0	920	165	5.6
M	–	0	PMR0	200	310	708	0	1008	0	114	1.5
M	R	50	PMR5	202	306	680	0	503	505	93	1.5
M	R	100	PMR1	200	310	666	0	0	876	114	1.5
M	I	100	PMI1	200	310	533	0	0	906	160	4.8
N	–	0	PNR0	186	325	704	0	1011	0	114	1.5
N	R	50	PNR5	186	324	696	0	504	512	95	1.9
N	R	100	PNR1	186	325	688	0	0	880	88	1.5
N	I	100	PNI1	186	325	530	0	0	903	160	5.6

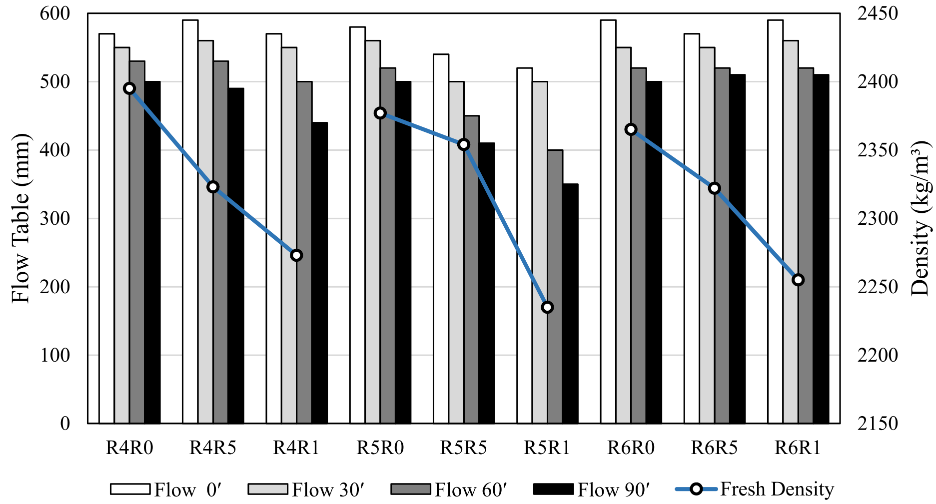

Fig. 3. Fresh concrete performance of RC mixes.

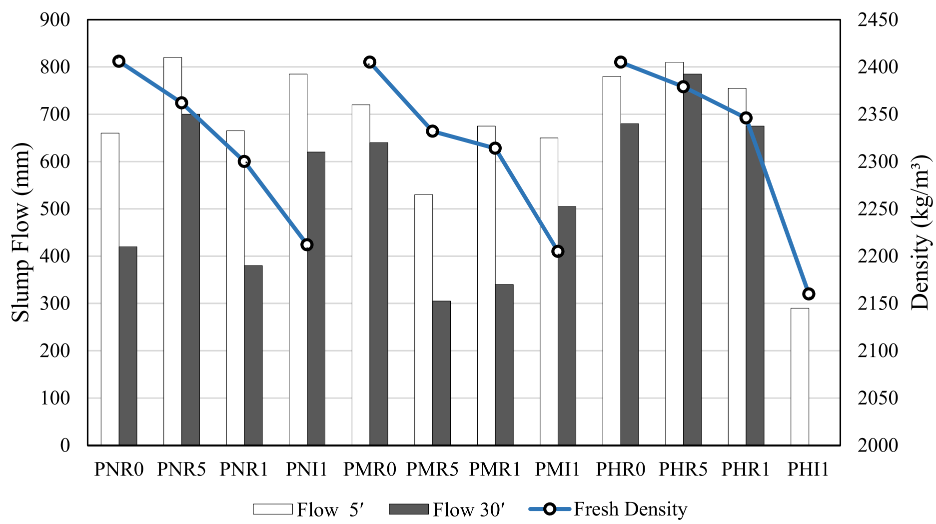

Fig. 4. Fresh concrete performance of prefab mixes.

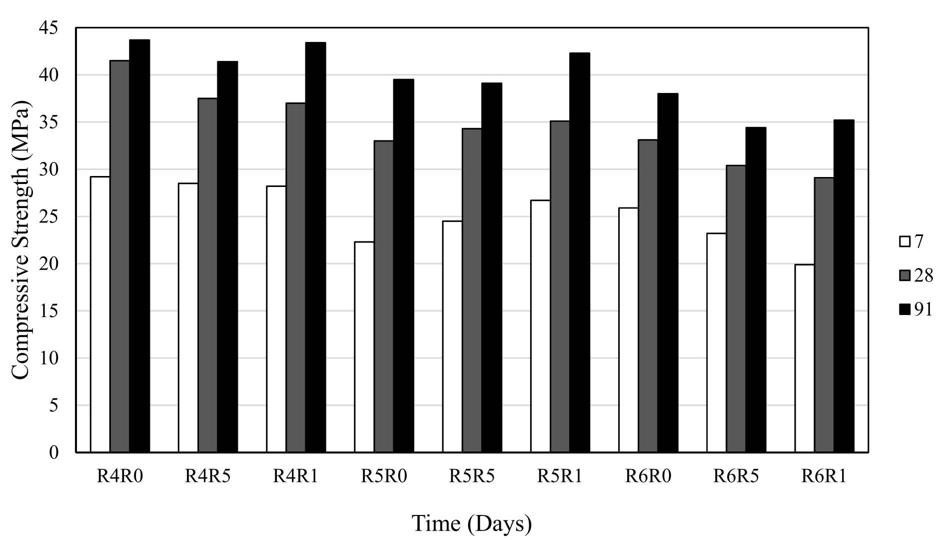

Fig. 5. Development of compressive strength of RC mixes with different WCRs.

and WCRs was investigated as detailed in Fig. 5. The literature indicates that using 100 percent RCA typically results in a reduction of concrete strength by about 20–30 percent (Silva et al., 2014). Corinaldesi recommends a maximum of 30 percent RCA for structural concrete classified up to C32/40, noting that the recycled aggregates in his study had a high water absorption rate of approximately 7% (Corinaldesi, 2010). In this investigation, for all mixes, the difference in compressive strength between the mix with full RCA replacement and the reference one was within 10% more or less at both 28 and 91 days. Based on the results, there is no clear correlation between the amount of RCA replacement and the mechanical performance of concrete. In particular, mixes with 50% RCA replacement exhibited the lowest compressive strength at 91 days, highlighting that factors beyond RCA percentage significantly influence concrete's mechanical properties. Additionally, the mix R5R1, which contains less cement and a higher WCR, demonstrated compressive strengths nearly matching those of R4R0 and R4R1. Furthermore, concrete with 100% RCA replacement showed strength either 6% higher than or equivalent to reference mixes for WCRs of 0.55 and 0.45 after 91 days, respectively. However, due to an unoptimized mix design, about 2%–4% more cement content was used compared with the reference mix.

3.2.2. *Prefab concrete (PC)*

The data in Fig. 6 show the compressive strength of PC mixes at different ages. The results indicate that the mixes containing 100% RCA type "R" have the potential to be used for both commercial and structural applications. In the mixes utilizing RCA type "I" with higher water absorption, mix PNI1 shows similar compression to PNR1 after 91 days, while mix PMI1 has about 27% less compressive strength than PMR1. This difference in higher strength classes suggests that the quality of RCA becomes more important in higher strength class concrete, particularly due to reduced water usage (Silva and Dhir, 2014; Wang et al., 2023). Mix PHI1, containing 100% recycled aggregates, including RCA and URFA, shows 36% and 32% less compression strength than PHR0 and PHR1, respectively. This emphasizes the negative effect of URFA, which can be attributed to its high water absorption and increased porosity (Gebremariam et al., 2021). It was anticipated that concrete made with RCA type "I" from a demolished bridge would have higher compressive strength due to the low level of contaminants and high-strength parent concrete (Kou and Poon, 2015). However, due to the higher level of residual mortar, this type of RCA exhibits lower performance in higher-strength class applications, highlighting the importance of concrete recycling. This variance in results and literature can be attributed to the method of crushing concrete samples after 28 days, compared to this study, where the EoL concrete from a bridge built at least 40 years ago presented greater challenges in separating aggregates from mortar during the recycling process.

The elastic modulus (E_c) of PC mixes fully replaced with RCA types "R" and "I" (PR and PI series) was compared with Neville's conventional equation for normal concrete (Neville, 1981), and with the empirical models developed by Xiao et al. based on statistical regression analysis (Xiao et al., 2006), and by Kakizaki et al. formulated based on the mass density of the concrete (Kakizaki et al., 2023). As shown in Fig. 7, a higher E_c is consistently exhibited by the PR series compared to the corresponding mixes in the PI series. In the PR series, an increase in E_c is observed with increasing strength class; it starts with a value higher than that estimated by Neville's equation, but this difference decreases by PMR1, and ultimately, a value approximately 7% lower is reached in PHR1. Conversely, PI samples with 100% RCA show an average deviation of −15% from Neville's equation, highlighting the significant impact of RCA quality on performance (Fiol et al., 2018; Manzi et al., 2017). Additionally, the proposed models were observed to be more effective for lower-quality RCA (type "I") in lower-strength classes.

3.3. *Durability properties*

The selection of different tests for RC and PC was performed based on the distinct expectations and usage requirements of the respective companies. For the RC, which is typically used in a range of standard construction applications, the focus was on assessing general durability and resistance to environmental elements such as water and chlorides. On the other hand, the PC, particularly the high-strength and self-compacting varieties, is employed in more demanding scenarios. Therefore, at the request of the company, the tests for this type of concrete went beyond basic durability for high-performance applications. This assessment was critical in determining the suitability of the RC and PC mixes for various construction applications. The results of these extensive durability tests are summarized in Table 4.

3.3.1. *Ready mix concrete (RC)*

Concrete exhibiting low permeability is more effective at preventing the penetration of corrosive agents and water (Tam et al., 2021). The literature suggests that increasing RCA content usually results in higher water penetration, particularly when the effective WCR is not

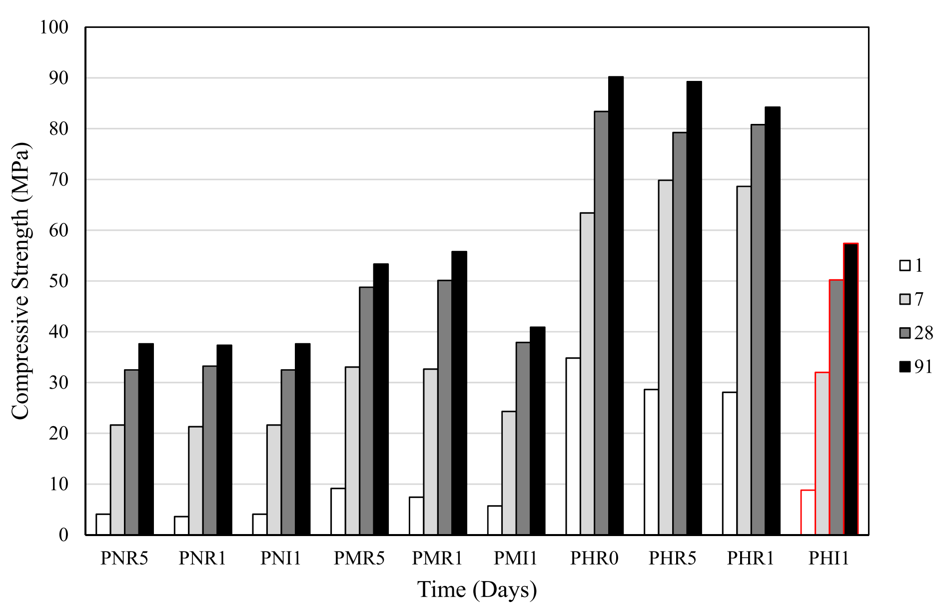

Fig. 6. Development of compressive strength of PC mixes with different strength classes.

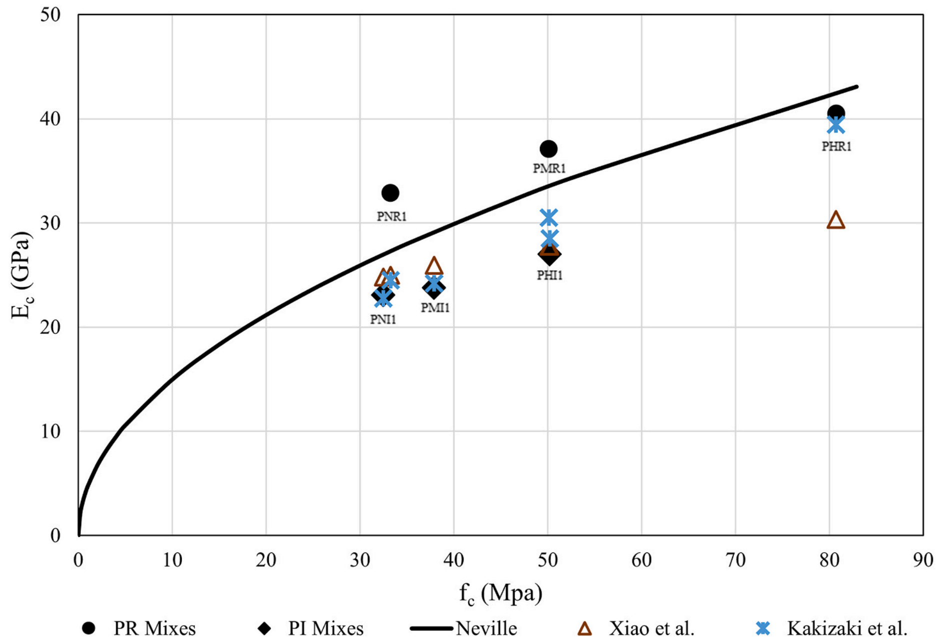

Fig. 7. Relationship between the elastic modulus (E_c), the compressive strength (f_c) of PC mixes and proposed models.

Table 4
Average results of durability tests for RC and PC selected mixes.

Property	Selected Mixes					
Ready Mix Concrete (RC)	R4R0	R4R1	R5R0	R5R1	R6R0	R6R1
Water Penetration (mm)	8	12	5	10	10	12
Carbonation (mm)	7.3	7.1	8.1	8.5	8.9	11.1
Electrical Resistivity (Ωm)	223	204	267	217	216	208
Chloride Migration Coefficient (10^{-12} m^2/s)	4.7	6.2	4.6	4.5	5.3	5
Prefab Concrete (PC)	PNR1	PMR1	PHR1	PNI1	PMI1	PHI1
Water Penetration (mm)	17	10	6	15	7	10
Vacuum Porosity (%V/V)	17	16.2	14.7	27	22.7	23.8
Wide Wheel Abrasion (mm)	20.5	19	18	23.9	23	23
Drying Shrinkage (mm/m)	0.34	0.28	0.17	0.82	0.74	0.64
Accelerated Carbonation (mm)	12	8.9	0.7	16.5	15.6	9.7
Chloride Migration Coefficient (10^{-12} m^2/s)	3.8	3.9	2.5	7	6	3

considered (Thomas et al., 2016). However, when considering the effective WCR, it is observed that a higher replacement rate of RCA can lead to lower water penetration, possibly due to the higher water absorption capacity of recycled aggregates (Martínez-Lage et al., 2012). The depth of water penetration shown in Table 4 indicates that RC mixes with 100% RCA exhibit higher penetration compared to NCA concrete. This increased penetration can be attributed to the higher porosity and microcracks often found in RCA. However, this difference decreases with increasing WCR to 0.65. Despite the higher penetration, all mixes remained within the acceptable range, with a maximum water penetration limit of 50 mm and an average of 25 mm, thus meeting the NEN-EN 12390-8 standard requirements for water penetration in concrete.

Key factors affecting carbonation depth include the aggregate's physical properties, as well as the concrete's chemical composition and porosity (Levy and Helène, 2004). According to the literature, RCA, particularly those with less than 5% water absorption, exhibit slightly higher carbonation depths than NCA at equivalent water-binder ratios (Otsuki et al., 2003). This is evidenced by results in Fig. 8, where mixes R4R1 and R5R1, containing 100% RCA, performed similarly to their corresponding NCA samples R4R0 and R5R0 after 182 days. Over a period of 547 days, the carbonation depth of all mixes increased, with those containing RCA gradually aligning with their NCA counterparts. However, the R6R1 mix with 0.65 WCR and 100% RCA replacement showed an increase in carbonation depth up to 11.1 mm, highlighting the significant impact of higher WCR on carbonation (Thomas et al., 2016). Additionally, findings indicate that lower WCR leads to reduced carbonation in both recycled and natural aggregate concrete due to decreased permeability.

The durability and long-term performance of concrete structures are commonly assessed using the Rapid Chloride Migration coefficient (RCM). While literature indicates that recycled aggregate concrete may exhibit lower resistance to chloride migration than natural aggregate concrete, the addition of additives such as superplasticizers and fly ash enhances this resistance by reducing its permeability (Gomes and De Brito, 2008). The RCM results displayed in Table 4 reflect this enhancement, showing that concrete mixes with 100% RCA replacement present similar or even slightly improved chloride migration resistance compared to those with NAC in higher WCR. For instance, R5R1 and R6R1 closely matches or surpasses the resistance observed in R5R0 and R6R0, and R4R1 only exceeds that of R4R0. These findings highlight the effectiveness of the mix design, particularly as all RC mixes demonstrate moderately high resistance to chloride ingress, with RCM values ranging between 2.5 and 7.5 × 10^{-12} m^2/s (Pontes et al., 2023). Additionally, Table 4 presents average electrical resistivities of RC mixes at 28 days, which vary from 204 Ωm to 267 Ωm. Electrical resistivity is an indicator of durability for corrosion resistance and is primarily influenced by the porosity of the concrete, which can be affected by WCR, binder quality and quantity, aggregate properties, and additives (Singh and Singh, 2019). The lower electrical resistivities observed in mixes with RCA compared to those with NCA are likely due to the higher capillary porosity and microcracks in RCA, which can increase electrical conductivity. However, all RC mixes fall within the same corrosion risk threshold (Alonso et al., 1988).

3.3.2. *Prefab concrete (PC)*

As presented in Table 4, the results of water penetration tests show that penetration increases as the strength class of concrete decreases. Unlike other durability results, mixes with RCA type "I," which have higher water absorption, exhibit superior performance. In this study, the

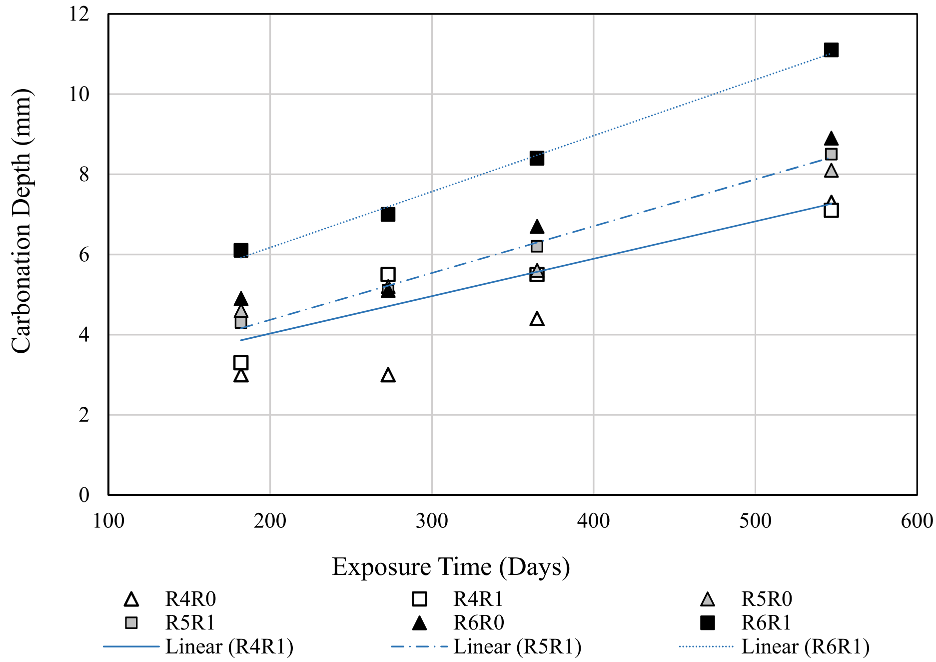

Fig. 8. Carbonation depth of RC mixes.

PNI1 mix has a water penetration of 15 mm, while the PMI1 mix shows 7 mm. Conversely, corresponding mixes with RCA type "R" exhibit higher water penetration, with PNR1 at 17 mm and PMR1 at 10 mm. The higher water absorption capacity of RCA type "I," compared to RCA type "R," can be attributed to the presence of a greater amount of residual mortar, which increases porosity. Consequently, RCA type "I" could be perceived as acting as an internal water reservoir, supplying water for continued cement hydration and leading to a more refined microstructure (Martínez-Lage et al., 2012). However, the PHI1 mix exhibits a penetration depth nearly 50% higher than PHR1 due to the use of UFRA.

The porosity of concrete, which significantly impacts its durability, was examined using the Vacuum Porosity (VP) test. The results showed a linear pattern, with values increasing as the strength class decreased and as the water absorption of aggregates increased. This pattern aligns with previously reported findings (Bahraq et al., 2022), supporting the theory that higher-strength concrete exhibits lower porosity due to its denser microstructure. Additionally, the decreased water absorption of aggregates indicates improved durability for the concrete. Moreover, the abrasion resistance of PC samples, assessed with the Wide Wheel Abrasion (WWA) test, demonstrates that the strength class of concrete and properties of RCA significantly influence this performance with a similar pattern to VP (Deng et al., 2023). The relationship between porosity and abrasion resistance is illustrated in Fig. 9, with a coefficient of determination (R^2) of 0.94. The proposed linear model for predicting WWA in the range of 14–28 for VP can be expressed as follows:

$$WWA = 0.48\ VP + 11.6 \tag{1}$$

The correlation between porosity and abrasion resistance highlights the importance of aggregate quality and concrete strength in determining the durability of concrete structures (Wang et al., 2021).

Shrinkage, leading to volumetric changes, is a significant factor in the formation of cracks in reinforced concrete and compromises its durability (Holt and Leivo, 2004). Recycled aggregate concrete typically exhibits higher shrinkage than natural aggregate concrete, primarily due to the presence of residual mortar and higher water absorption. Adjustments can be made by reducing the WCR and adding additives, which effectively mitigate concrete shrinkage (Xu-Ping, 2008), or by employing alternative mixing methods (Silva and Dhir, 2015). Fig. 10 illustrates the drying shrinkage of PC mixes with RCA types "R" and "I"

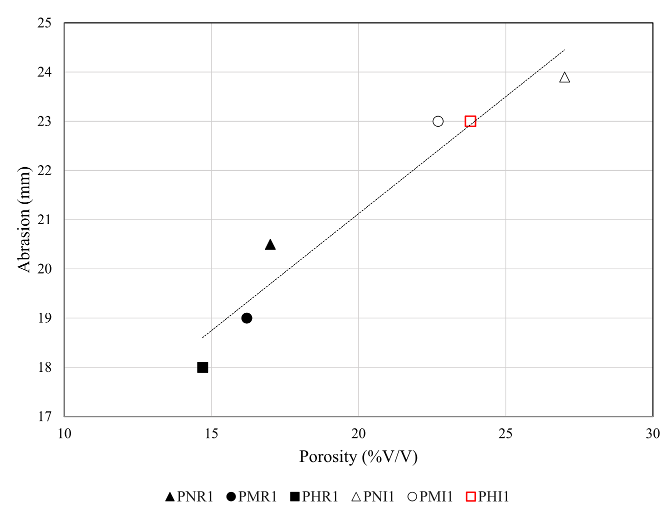

Fig. 9. Relationship between wide wheel abrasion and vacuum porosity in PC mixes.

over time. Within the PR and PI series, samples with a lower WCR and enhanced strength demonstrate improved shrinkage performance over time. Notably, mix PHI1, which utilizes UFRA with high water absorption and porosity, demonstrates unexpectedly lower shrinkage rates than other mixes in the "I" series, underscoring the significant influence of the concrete mixture on performance. After 91 days, PNI1 and PMI1 exhibit approximately 2.5 times higher shrinkage compared to PNR1 and PMR1, due to the higher porosity of RCA type "I," emphasizing the importance of RCA quality as reported in the literature (Yang et al., 2008; Yanagibashi et al., 2002).

After analyzing the carbonation depth across different mixes, as Fig. 11 demonstrates that PHR1 has the least susceptibility to carbonation, followed by PMR1, and PNR1 in the R series. This trend is attributed to the different strength classes of concrete, which lead to a more refined pore structure and a reduced depth of carbonation (Pedro et al., 2014; Corinaldesi and Moriconi, 2009). Additionally, a comparative analysis between the I (PNI1 and PMI1) and the R mixes (PNR1 and

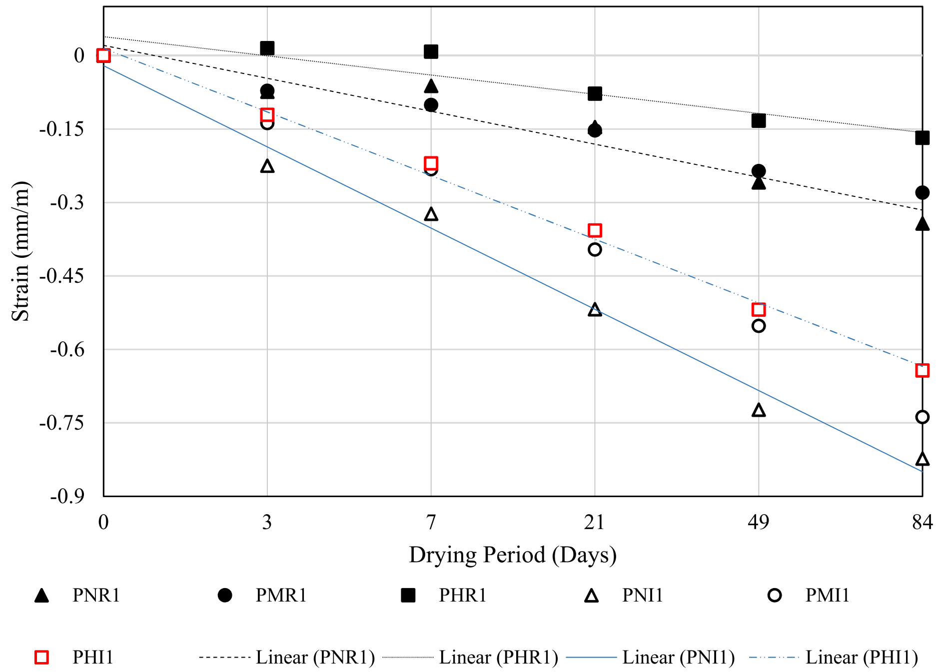

Fig. 10. Drying shrinkage as a function of time for PC mixes.

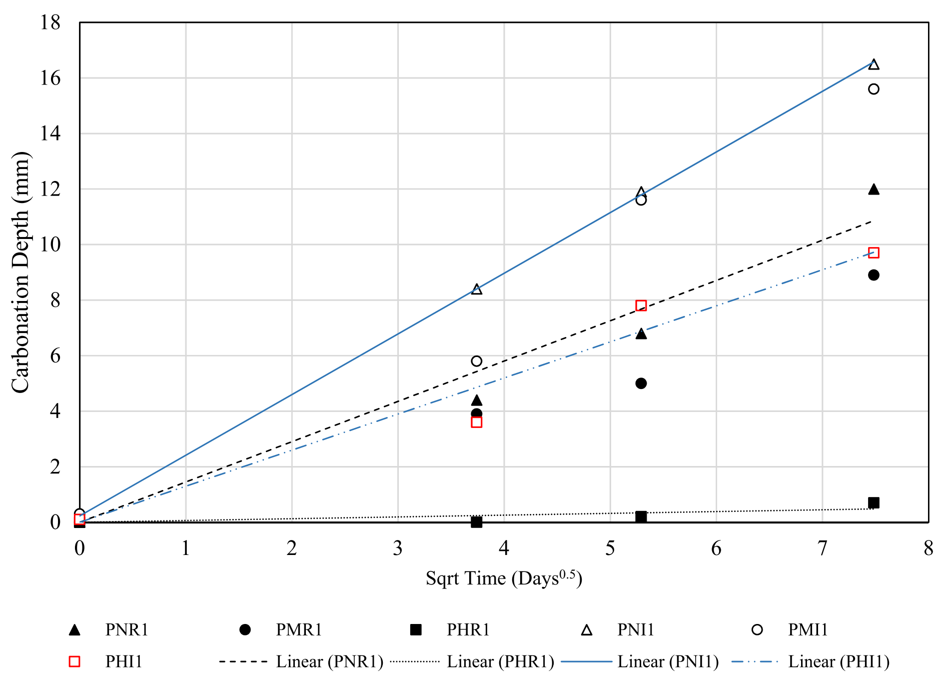

Fig. 11. Accelerated carbonation depth of PC mixes.

PMR1) highlights the significant role that the quality and water absorption of the produced RCA plays in influencing this property (Bravo et al., 2015). However, this could be compensated by using mineral addition and an improved concrete mix design (Lotfi et al., 2017; Silva et al., 2015). Although other studies have observed that RCA with higher-strength parent concrete performs better in carbonation properties, unlike this study, their samples were crushed shortly after casting, resulting in RCA with lower water absorption and less residual mortar (Xiao et al., 2012).

In this study, the resistance to chloride migration was assessed for PC mixes containing Type III cement with high slag content. As detailed in Table 4 and depicted in Fig. 12, all samples are classified as having moderately high resistance to chloride migration, similar to RC mixes (Singh and Singh, 2019). Enhanced durability was demonstrated by the mix PHR1, characterized by its high cement content and superior strength class. Further observations revealed a performance distinction based on the type of RCA used. Mixes containing RCA type "R" exhibited a chloride ion diffusion coefficient of 3.4×10^{-12} m^2/s, superior to those with RCA type "I," which averaged 5.3×10^{-12} m^2/s. This performance differential underscores the significant impact of RCA quality on concrete durability. Additionally, an increase in cement content coupled with a decrease in the WCR was correlated with enhanced chloride migration resistance. This improvement, particularly notable in the high-performance mixes PHR1 and PHI1, is attributed to a denser matrix

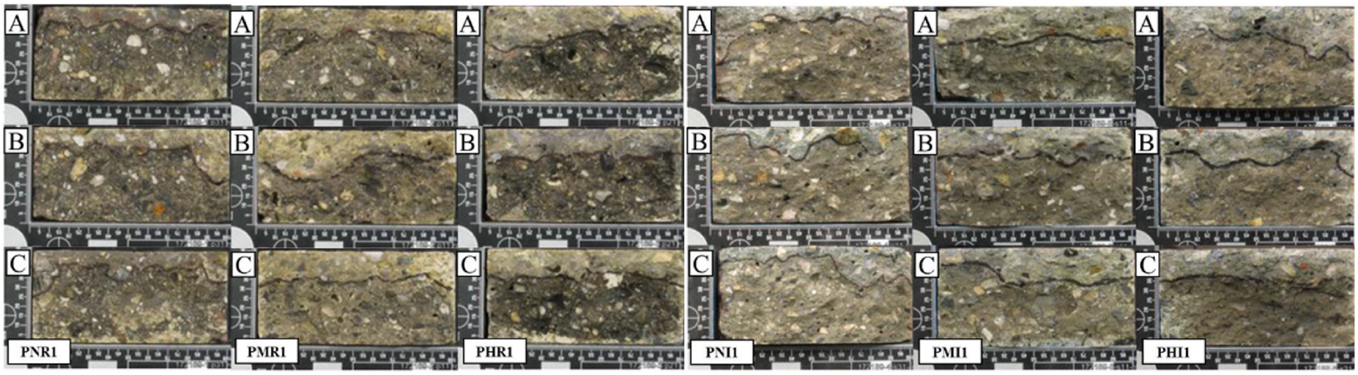

Fig. 12. Chloride migration of PC mixes produced by RCA types R and I.

that likely reduces the concrete's porosity and permeability to chloride ions (Dodds et al., 2017). These findings highlight the critical role of RCA and mix design selection in designing durable concrete mixes for aggressive environments.

Based on the durability results of RC and PC, concrete mixes with 100% RCA have the potential to be a sustainable choice for concrete companies. However, ensuring the quality of the aggregates and determining the appropriate application for different types of RCA is essential.

4. Conclusion

This study was conducted through two experimental series to assess the feasibility of incorporating 100% Recycled Coarse Aggregates (RCA) into concrete for large-scale industrial production. The commercially produced recycled aggregates, evaluated in both Ready-mix Concrete (RC) and Prefab Concrete (PC) settings, underwent tests for fresh, mechanical, and durability properties. Two types of RCA were produced using Advanced Dry Recovery technology to minimize loosely bonded aggregates. Initial tests at the RC facility examined the influence of the water-to-cement ratio, while subsequent tests evaluated the impact of two types of RCA across three different strength classes of concrete in PC applications, employing conventional production methods without using specific treatments for RCA or mixing methods. The findings indicate that high-quality RCA with a water absorption rate below 4% has the potential for use in concrete production without significant modifications of existing setups and production methods, remaining within acceptable standards for fresh, mechanical, and durability properties. Despite the suitable flowability of RC and PC mixes for industrial applications, particularly with mix design optimization and additive use, a reduction in density due to residual mortar ranging from 4% to 8% is inevitable, depending on the water absorption of the aggregates used. RC mixes with 100% RCA replacement exhibited strength either 5% higher than or equivalent to reference mixes with different water-to-cement ratios after 91 days. Nonetheless, 2%–4% more cement was used to achieve adequate consistency, highlighting the necessity for mix design optimization and considering an effective water-to-cement ratio. The PC results show that the influence of the RCA quality on recycled aggregate concrete is more significant in higher-strength classes. However, it is possible to use lower-quality aggregates and achieve sufficient consistency by using a higher amount of plasticizer, but the mechanical and durability properties are impacted by increased porosity. PC mixes incorporating RCA from high-strength parent concrete showed lower performance in higher strength classes of concrete. A decline in compressive strength in PC was observed due to the higher residual mortar and water absorption of RCA, especially when unprocessed recycled fine aggregates with higher porosity were used which decreased the compression to 35%. This emphasizes the need to consider the strength of parent concrete and the processing of fine aggregates to achieve 100% recycled aggregate concrete. The durability results of PC mixes showed that except for the better performance of RCA with higher water absorption in water penetration tests, RCA with lower water absorption demonstrated superior performance in other durability tests. In both cases, the durability performance improved by increasing the strength classes in PC production. The correlation between porosity and abrasion resistance underscores the importance of aggregate quality and concrete strength in determining the durability of concrete structures. Despite the technical feasibility of incorporating RCA in concrete, several aspects still require in-depth exploration to enhance sustainability in the construction industry. These insights are crucial for increasing stakeholders' confidence and for guiding the prioritization of further research, particularly in reducing the influence of aggregate quality and exploring potential labeling of aggregates based on quality and usage.

CRediT authorship contribution statement

Ali Vahidi: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Arsalan Mostaani:** Writing – review & editing, Visualization. **Abraham Teklay Gebremariam:** Writing – review & editing. **Francesco Di Maio:** Funding acquisition. **Peter Rem:** Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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