Effect of Mechanically Treated and Internally Cured Recycled Concrete Aggregates on Recycled Aggregate Concrete

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Abstract. Environmental concerns regarding Construction and Demolition Waste (CDW) and the introduction of a circular economy model, obligates the construction sector to incorporate Recycled Concrete Aggregates (RCA) in conventional concrete; nevertheless, RCAs have generally proven to decrease the overall characteristics due to their remnant mortar. Therefore, a mechanical treatment method was applied to RCA to partially remove the adhered mortar and improve Recycled Aggregate Concrete (RAC) properties. The main goal of this paper was to examine the combined effect of mechanically treated aggregates and internal curing (IC) method on the mechanical and durability characteristics of RAC. Several mixtures at 0.25 and 0.50 w/c ratio containing either untreated or mechanically treated RCA with various replacement percentages were cast and experimentally investigated. At the low w/c ratio, the incorporation of 25% untreated or mechanically treated RCA obtained the closest values compared to their corresponding reference mixture (0% RCA). The IC method proved highly effective in regard to chloride penetration since all values were significantly reduced regardless of the replacement percentage, w/c ratio and type of RCA. IC mixtures containing treated RCA experienced a notable decrease in drying shrinkage strain values compared to their reference mixtures.

Keywords: Adhered Mortar · Internal Curing · Recycled Aggregate Concrete · Recycled Concrete Aggregates · Treatment Method

1 Introduction

The mandatory and continuous demands of reducing waste materials or exploiting them, especially their reuse expands rapidly throughout all EU members. These concerns arise from factors such as the required transition to a circular economy and are applicable to Construction and Demolition Waste (CDW) especially, due to the significantly high quantities of yearly generated CDW (almost 40% and 50% in EU-members and Cyprus, respectively) [1]. However, instead of extending the life of CDW and enable

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re-using in added value applications, they are usually downgraded by being used in embankments or disposed in landfills. CDW could be upscaled by being re-used in new concrete by replacing conventional crushed aggregate, known as Recycled Concrete Aggregates (RCA). An environmentally friendlier concrete is thus created, commonly called Recycled Aggregate Concrete (RAC).

Due to the origin of RCA, besides fine and coarse aggregates with adhered surface mortar, they contain minor amounts of debris from asphalt, wood, ceramics, bricks, glass etc. Compared to Natural Aggregates (NA), RCA have the significant advantage of being environmentally friendly and cost-effective, while they can play an evident role in decreasing carbon footprint, energy and fuel consumption, lowering production cost and upgrading the value of CDW. Nevertheless, RAC properties are critically affected by the possible presence of harmful compounds (like chlorides) and the existence of highly porous remnant paste, which ultimately reduces the quality of the material by negatively affecting their surrounding Interfacial Transition Zone (ITZ) [2–6]. In an effort to improve RCA's influence on RAC properties, numerous treatment methods have been examined and developed by researchers [7–11].

The authors have developed and optimized [12, 13], a mechanical treatment procedure that includes the fragmentary removal of the remnant mortar by rotating RCA inside a concrete drum. The optimization of this technique was conducted by trials at different time intervals, where parameters like circularity alterations and mass loss, were evaluated, finally indicating that the 3 h treatment length was optimal. Furthermore, enhancement of RAC properties can also be achieved by the application of an effortless and cost-effective Internal Curing (IC) method. During this method, saturated and surface-dried RCA (pre-soaked in water for 24 h) are incorporated into RAC mixtures and followed by placement of the concrete specimens inside an environmental chamber in regulated conditions (65% RH and 25 ± 2 °C). As the concrete hydration process initiates, all the absorbed water particles, encircle the aggregate and transfer to the neighboring cement paste allowing for longer and sufficient curing, particularly considering the dense matrix in low w/c ratios. According to the literature, adaption of the IC procedure has proven beneficial in enhancing the overall properties of RAC, specifically by increasing the compressive strength and reducing early-age shrinkage [14–18].

Formerly published research by the authors [19], studying the effect of partial or full replacement of NA with mechanically treated RCA in water-cured RAC combinations, indicated that 25% RCA addition can be executed without compromising RAC properties. The main objective of this research was to further investigate the mechanical and durability enhancement of IC RAC mixtures when mechanically treated and internally cured RCA (also examined for their waste retainment abilities) were incorporated at various percentages. A total of 12 IC RAC formulations at 0.25 and 0.50 w/c ratio including 0%, 25%, or 50% of untreated or treated RCA were examined and compared for their mechanical (compressive strength) and durability (porosity, sorptivity, rapid chloride permeability and drying shrinkage) characteristics.

2 Materials and Methods

2.1 Materials

For all RAC formulations, the main binder was Ordinary Portland Cement (OPC) CEM I 52.5 N of specific gravity 3.1 Mg/m^3 provided by Vassilico Cement Works PCL. Retail accessible polycarboxylate based superplasticizer (SP) for workability adjustments was supplied by Ha-Be Betonchemie GmbH & Co. KG. Potable laboratory water free from hazardous compounds was utilized as mixing water. Four different types of aggregates were used: Natural crushed aggregates (NA) with coarse (8/20 mm and 4/10 mm) and fine (0/4 mm and 0/2 mm) gradations, Recycled Field Coarse Aggregates (RFC) and Recycled Treated Coarse Aggregates (RTC) of 8/20 mm and 4/10 mm and Recycled Fine Field Aggregates (RFF) of 0/4 mm. Figure 1 presents the particle size distribution, while Table 1 lists the physical and mechanical properties of all incorporated aggregate types. X-Ray Diffraction Analysis, petrographic analysis and Scanning Electron Microscope on natural aggregates revealed that they originated from fine to medium-grade diabase to dolerite crystalline igneous rocks consisting mainly of plagioclase, chlorites, amphiboles, zeolites and fewer quantities of quartz, pyrite, magnetite etc.). RCA were supplied by Skira Vassa Ltd, however the original material source was not identified. Water retainment abilities of RCA for their utilization as IC agents were also examined and are presented in Table 2. Pre-soaked NA, RFF and RFC aggregates were placed inside an environmental chamber in initial conditions of 100% moisture. After reducing the relative humidity (RH) to pre-determined values, entrapped water was calculated. RFF retained the highest amounts of absorbed water at 40% RH. RFC 8/20 m and 4/10 mm reserved 72% and 67% water respectively at 93% RH, significantly higher than their corresponding NA fractions, justifying RCA'S utilization in IC method.

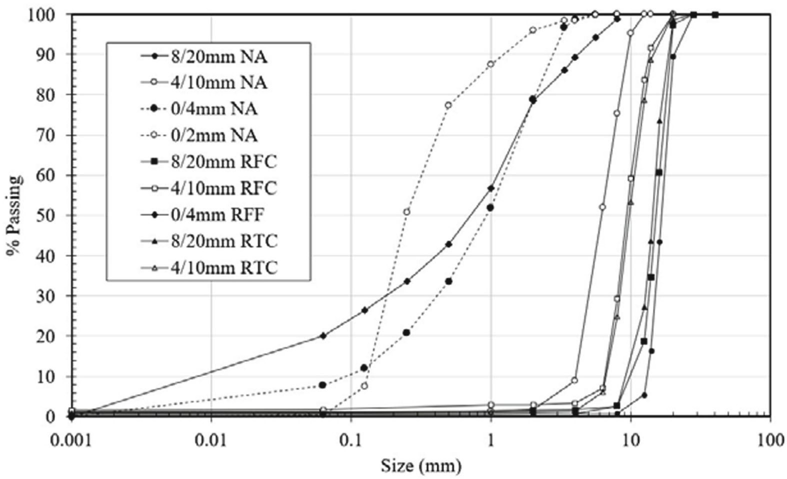

Fig. 1. Particle Size Distribution of natural and recycled aggregates

Table 1. Physical and Mechanical Properties of natural and recycled aggregates

	Particle Density (Kg/m^3)	Particle Density, SSD (Kg/m^3)	Water Absorption (%) (WA)	Flakiness Index	Shape Index	Los Angeles coefficient (LA) (%)
NA 8/20 mm (kg/m^3)	2500	2600	4.1	7	9	-
RFC 8/20 mm (kg/m^3)	2430	2530	4.4	5	16	-
RTC 8/20 mm (kg/m^3)	2400	2490	4.0	6	15	-
NA 4/10 mm (kg/m^3)	2473	2567	3.8	16	9	29
RFC 4/10 mm (kg/m^3)	2517	2681	6.5	5	7	32
RTC 4/10 mm (kg/m^3)	2430	2539	4.5	4	5	15
NA 0/4 mm (kg/m^3)	2267	2378	4.9	-	-	-
RFF 0/4 mm (kg/m^3)	2299	2413	5.0	-	-	-
NA 0/2 mm (kg/m^3)	2530	2580	1.8	-	-	-

Table 2. Water Retainment Abilities of NA, RFC and RFF aggregates

Relative humidity (%)	Mass retained (%)				
	8/20 mm - RFC	4/10 mm - RFC	0/4 mm - RFF	8/20 mm - NA	4/10 mm - NA
100%	100%	100%	100%	100%	100%
95%	75%	71%	98%	55%	70%
93%	72%	67%	94%	51%	55%
92%	71%	66%	93%	49%	51%
90%	69%	65%	91%	48%	47%
85%	67%	63%	87%	44%	44%
80%	65%	62%	82%	42%	41%
60%	60%	57%	67%	35%	35%
40%	56%	53%	60%	28%	27%
0%	0%	0%	0%	0%	0%

2.2 Methods

RAC Treatment Method. For improving RAC characteristics, RCA were mechanically treated for removing fragments of remnant mortar. The authors have previously published in detail this treatment method in [13]. The focus of this research was to optimize the treatment duration where RFC and equal quantities of water were left rotating and colliding inside a concrete mixture track (capacity of 10 m^3 and rotating speed of 12 rpm) for different time intervals (1, 2, 3, 4 and 5 h). after each treatment cycle, parameters such as total mass loss, circularity alterations (the rotating motion and collision alter the surface area), particle size distribution before and after treatment, environmental impact, as well as energy consumption and treatment cost were evaluated. The optimum treatment duration was conclusively selected at 3h.

RAC Formulation Proportions, Casting, Curing and Testing. As presented in Table 3, Two Water Cured (CWC) reference mixtures containing 0% rca and 10 ic rac mixtures of 0.25 and 0.50 w/c ratios were cast incorporating RFF, RFC or RTC aggregates at replacement percentages of 25% or 50% by mass. All mixtures were designed with similar to their corresponding reference mixture all-in-aggregate gradings. The following coding will be used for the identification of each mixture: XX-YYZZ (w/c), where XX is the type of curing (CWC and IC), YY represents the type of recycled aggregate (RFF, RFC, or RTC) and ZZ is the RCA replacement percentage (25% or 50%) and w/c ratio (0.25 or 0.50).

Table 3. Mixture Proportions for all designed mixtures.

	CWC-REF1 (0.25)	IC-RFF25 (0.25)	IC-RFF50 (0.25)	IC-RFC25 (0.25)	IC-RFC50 (0.25)	IC-RTC25 (0.25)	IC-RTC50 (0.25)	CWC-REF2 (0.50)	IC-RFC25 (0.50)	IC-RFC50 (0.50)	IC-RTC25 (0.50)	IC-RTC50 (0.50)
Water (kg/m^3)	216	216	216	216	216	216	216	200	200	200	200	200
CEM I 52.5N (kg/m^3)	864	864	864	864	864	864	864	400	400	400	400	400
NA 8/20 mm (kg/m^3)	-	-	-	-	-	-	-	629	471	314	471	314
RFC 8/20 mm (kg/m^3)	-	-	-	-	-	-	-	-	157	314	-	-
RTC 8/20 mm (kg/m^3)	-	-	-	-	-	-	-	-	-	-	157	314
NA 4/10 mm (kg/m^3)	730	730	730	548	365	547	365	386	289	192	289	193
RFC 4/10 mm (kg/m^3)	-	-	-	183	365	-	-	-	96	192	-	-
RTC 4/10 mm (kg/m^3)	-	-	-	-	-	182	365	-	-	-	96	193
NA 0/4 mm (kg/m^3)	355	251	167	334	334	335	335	266	266	266	266	266
RFF 0/4 mm (kg/m^3)	-	84	167	-	-	-	-	-	-	-	-	-
NA 0/2 mm)	184	183	184	183	184	184	184	406	407	407	406	406

Mixing was conducted with a Technotest AT 205 mixer (capacity of 150 L) in accordance with BS 1881-125:2013 [20]. Workability performance was evaluated through the slump test, with a target slump class of S3. Specimens were cast in conformity with EN 12390-2:2019 [21] and at a temperature of 25 ± 2 °C for 24 h. Reference mixtures were CWC at a controlled temperature of 22 ± 2 °C inside a water tank and IC to compare the effectiveness of the IC method with real-life manufacturing conditions. RCA-based mixtures were IC which requires the incorporated RCA to be saturated and surface-dried prior mixing. Specimens were then cured in a room with regulated environmental conditions (25 ± 2 °C and 65% RH), until testing.

Compressive strength was evaluated in conformity with EN 12390-3:2019 [22] at the ages of 7, 28, 90 and 365 days. Cubic samples (100 x 100 x 100 mm) were loaded under compression using a Controls Advantest-9 5000 kN compression machine at a load rate of 0.6 ± 0.2 MPa/s, until failure. Open porosity [3] and sorptivity coefficient [3] were measured on cubic specimens (100 x 100 x 100 mm) at the ages of 28 and 365 days. Rapid Chloride Permeability [23] was examined on cylindrical discs (100Ø50 mm) at the ages of 28, 90 and 365 days, following exposure to 0.3 N NaOH and 3% NaCl solutions. Subsequently, a potential difference flowed through the discs and the value of the electric charge was recorded. Drying shrinkage strains [24] were measured on 300 x 75 x 75 mm prismatic samples with attached metallic spheres on each opposite side using a length comparator for a total duration of 20 weeks.

3 Results and Discussion

This chapter discusses the experimental results of the compressive strength, porosity, sorptivity, rapid chloride permeability and drying shrinkage of the examined IC RAC formulations. Figure 2a and b demonstrate the relationship between compressive strength and porosity at the ages of 28 and 365 days at 0.25 and 0.50 w/c ratio respectively. We can initially observe that both reference mixtures achieved the highest compressive strength and lowest porosity values out of all IC RAC formulations at both w/c ratios. Incorporation of 25% RFC or RTC and internally cured aggregates achieved the closest compressive strength to CWC-REF1 (0.25), while IC-RTC50 had the lowest open porosity of RAC mixtures at 0.25 w/c ratio. Compressive strength for all IC RAC mixtures at 0.50 w/c fluctuated at similar levels, indicating that the treatment and curing method did not affect the compressive strength as profoundly as in the 0.25 w/c ratio case. The use of untreated aggregates increased the porosity in both w/c ratios. Adding treated aggregates decreased the porosity compared to formulations with untreated aggregates, a phenomenon highly intensified at the high w/c ratio and to a lesser extent at the low w/c ratio at the age of 365 days. Therefore, the treatment method seems beneficial in terms of removing parts of the highly porous adhered mortar, thus improving cohesiveness of the cementitious matrix.

Figure 3a and b presents the experimental results of compressive strength and capillary absorption for IC RAC mixtures at both w/c ratios. In contrast to porosity which correlates with the number of pores in the cement matrix, the sorptivity coefficient explains the interconnectivity of pores. We can observe that the combination of internally cured RCA and 25% mechanically treated, obtained almost similar sorptivity values (0.0079 mm/min$^{1/2}$) to CWC-REF1 (0.25), while IC-RFF50 (0.25) and IC-RTC50 0.25) also demonstrated sufficient performance. However, as indicated in Fig. 3b, capillary absorption increased when internally cured RCA except for RFC50 were added into the mixtures, which may imply that pre-soaking RCA does not have a positive effect on improving cohesiveness at high w/c ratio mixtures.

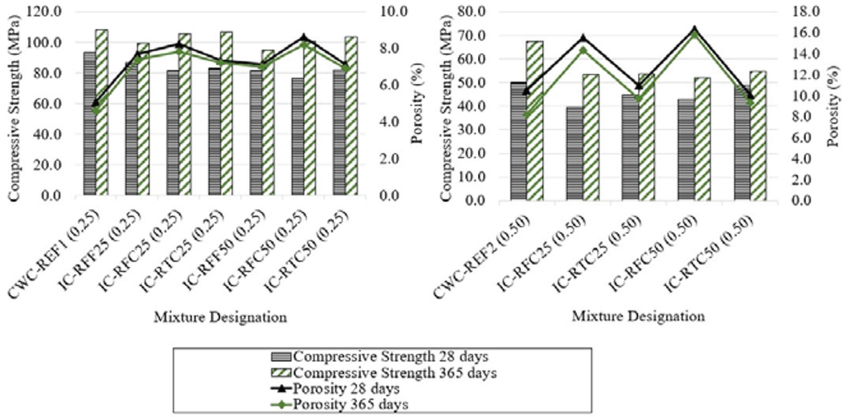

Fig. 2. Compressive strength and porosity at the ages of 28 and 365 days for all designated IC RAC mixtures at (a) 0.25 w/c ratio and (b) 0.50 w/c ratio.

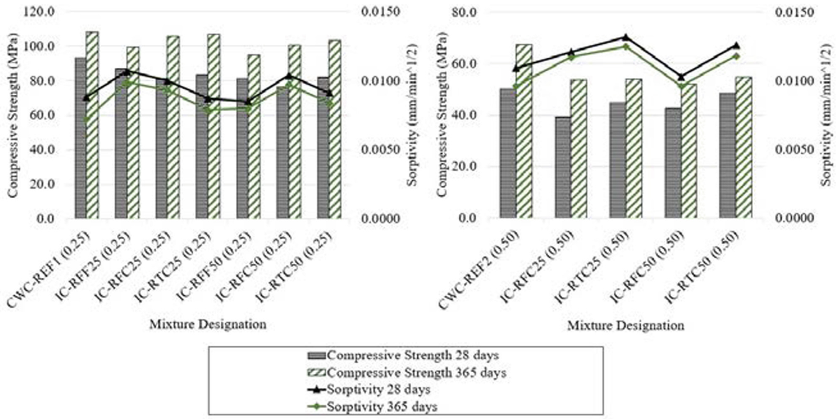

Fig. 3. Compressive strength and sorptivity at the ages of 28 and 365 days for all designated IC RAC mixtures at (a) 0.25 w/c ratio and (b) 0.50 w/c ratio.

Figure 4 illustrates the relationship between chloride penetration and compressive strength at the ages of 28, 90 and 365 days. Both reference mixtures, regardless of the w/c ratio, yielded the highest permeability values out of all IC RAC combinations; a behaviour attributed to numerous reasons, as explained in a previous publication []. Mixtures were clearly divided into two groups based on their w/c ratio (0.50 left and 0.25 right). At the low w/c ratio, the efficiency of IC was predominant at the initial stages, while at the high w/c ratio the effectiveness was demonstrated in the long-term. All RCA-based formulations at 365 days yielded significantly reduced chloride penetration values regardless of the w/c ratio, type and replacement percentage of RCA. IC-RTC25 (0.25) and IC-RTC50 (0.50) yielded reductions of 81.7% and 90.9% respectively, compared to their equivalent reference mixture. Figure 5a and b show the evolution of drying shrinkage over time across a period of 20 weeks. Shrinkage strain readings for the reference mixtures were balanced at approximately 7 weeks and IC RAC mixtures on average at 18 weeks (each data marking refers to 1-week long measurements). At both w/c ratios, the reference mixtures presented the highest dimensional changes, while altering the curing method from CWC to IC, drastically reduced the early-age shrinkage. IC-RTC25 (0.25) and IC-RTC50 (0.50) presented the lowest shrinkage since they yielded 75.7% and 69.2% decrease in correlation to their reference mixtures; nonetheless, the implementation of RFF and RFC also revealed to significantly reduce dimensional changes.

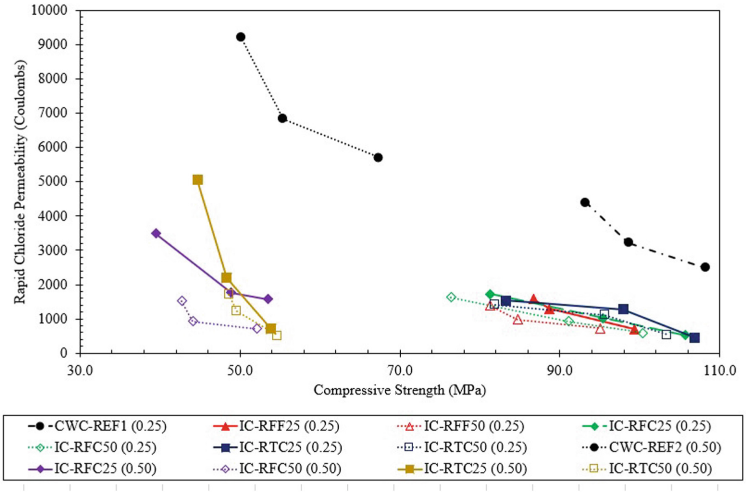

Fig. 4. Rapid chloride permeability vs compressive strength for all RAC mixtures at both 0.25 and 0.50 w/c ratio.

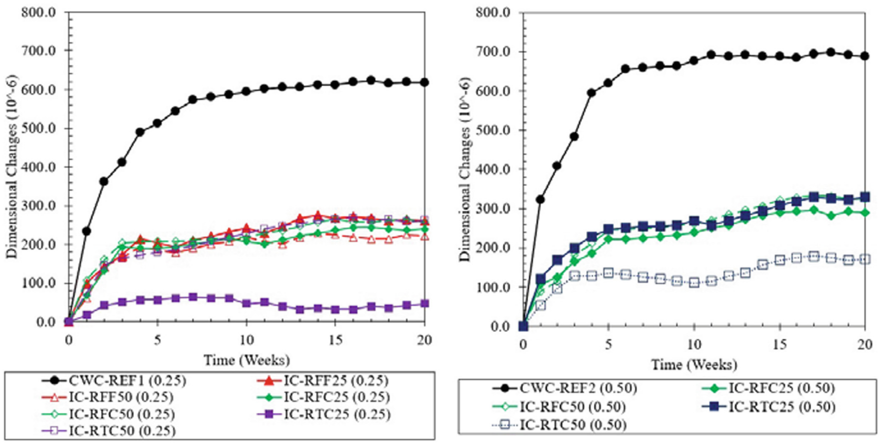

Fig. 5. Dimensional changes over time at (a) 0.25 w/c ratio and (b) 0.50 w/c ratio

4 Conclusions

The goal of this study was to examine the mechanical (compressive strength) and durability (porosity, sorptivity, rapid chloride permeability and drying shrinkage) characteristics of 12 IC RAC mixtures (0.25 and 0.50 w/c ratio) when mechanically treated and internally cured RCA were incorporated at various percentages (0%, 25% or 50%). At 0.25 w/c ratio, mixtures with 25% of either untreated or treated RCA yielded the closest performance to their equivalent reference mixture, while mixtures with 50% treated RCA demonstrated the lowest open porosity. In general, the addition of RTC was more beneficial and evident to porosity at a high w/c ration and to a lesser extent at a low w/c ratio. Altering the curing method (IC instead of CWC), has been proven to have a significant impact on dimensional changes, since all shrinkage strain values were drastically reduced compared to their corresponding reference mixture. At 365 days, all RAC mixtures despite of type and replacement percentage of RCA and w/c ratio yielded reduced chloride permeability measurements.

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References

1. Eurostat, Waste Statistics-Total waste generation (2021). https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics#Total_waste_generation
2. Thomas J, Thaickavil NN, Wilson PM (2018) Strength and durability of concrete containing recycled concrete aggregates. J. Build. Eng. 19:349–365

3. Kanellopoulos A, Petrou MF, Ioannou I (2012) Durability performance of self-compacting concrete. Constr Build Mater 37:320–325
4. Kou SC, Poon CS, Etxeberria M (2011) Influence of recycled aggregates on long term mechanical properties and pore size distribution of concrete. Cem Concr Compos 33:286–291
5. Adessina A, Ben A, Barthélémy J, Chateau C, Garnier D (2019) Cement and Concrete research experimental and micromechanical investigation on the mechanical and durability properties of recycled aggregates concrete. Cem Concr Res 126
6. Sasanipour H, Aslani F (2020) Durability assessment of concrete containing surface pretreated coarse recycled concrete aggregates. Constr Build Mater 264
7. Wang X, Yang X, Ren J, Han N, Xing F (2021) A novel treatment method for recycled aggregate and the mechanical properties of recycled aggregate concrete. J. Mater. Res. Technol. 10:1389–1401. https://doi.org/10.1016/j.jmrt.2020.12.095
8. Martinez-Echevarria MJ et al (2020) Crushing treatment on recycled aggregates to improve their mechanical behaviour for use in unbound road layers. Constr Build Mater 263:120517
9. Wang J, Zhang J, Cao D, Dang H, Ding B (2020) Comparison of recycled aggregate treatment methods on the performance for recycled concrete. Constr Build Mater 234:117366
10. Xuan D, Zhan B, Poon CS (2016) Assessment of mechanical properties of concrete incorporating carbonated recycled concrete aggregates. Cem Concr Compos 65:67–74
11. Ouyang K et al (2020) An overview on the efficiency of different pretreatment techniques for recycled concrete aggregate. J Clean Prod 263:121264
12. Dimitriou G, Savva P, Petrou MF (2018) Enhancing mechanical and durability properties of recycled aggregate concrete. Constr Build Mater 158:228–235
13. Savva P, Ioannou S, Oikonomopoulou K, Nicolaides D, Petrou MF (2021) A mechanical treatment method for recycled aggregates and its effect on recycled aggregate-based concrete. Materials (Basel) 14
14. Zhutovsky S, Kovler K (2012) Effect of internal curing on durability-related properties of high performance concrete. Cem Concr Res 42:20–26
15. Yang G, Li Q, Guo Y, Liu H, Zheng S, Chen M (2022) Study on the mechanical properties and durability of recycled aggregate concrete under the internal curing condition. Materials (Basel) 15
16. Xu F, Lin X, Zhou A (2021) Performance of internal curing materials in high-performance concrete: a review. Constr Build Mater 311:125250
17. Kim JH, Choi SW, Lee KM, Choi YC (2018) Influence of internal curing on the pore size distribution of high strength concrete. Constr Build Mater 192:50–57
18. Mao Y, Liu J, Shi C (2021) Autogenous shrinkage and drying shrinkage of recycled aggregate concrete: a review. J Clean Prod 295:126435
19. Oikonomopoulou K, Ioannou S, Savva P, Spanou M, Nicolaides D, Petrou MF (2022) Effect of mechanically treated recycled aggregates on the long term mechanical properties and durability of concrete. Materials (Basel). 15:1–16
20. BS 1881-125, (1986) Testing Concrete. Constr. Stand. 2(2010):1–14
21. CEN (European Commitee for Standardization), EN 12390-2 Testing hardened concrete-Part 2:Making and curing specimens for strength tests, Cyprus Stand (2019)
22. CEN (European Committee for Standardization), EN 12390-3 Testing hardened concrete-Part 3: Compressive strength of test specimens, Cyprus Stand (2009)
23. ASTM C1202 (2012) Standard test method for electrical indication of concrete's ability to resist chloride ion penetration. Am Soc Test Mater 1–8
24. CEN (European Commitee for Standardization), BS EN 1367-4 Tests for thermal and weathering properties of aggregates: Determination of drying shrinkage (2008)