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Examining the structural viability of recycled fine aggregates in sustainable concrete

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Abstract This study investigates the potential of incorporating recycled fine aggregates (RFA) into sustainable concrete. In this research, a conventional compaction technique is utilized to establish the order of compressive strength and, consequently, to assess particle packing density in terms of weight within a specific cylindrical volume and evaluate workability, compressive and flexural strengths, splitting tensile strength, elasticity modulus, and microstructural properties (analyzed through XRD, SEM, and EDAX). The study found that RFA can improve concrete properties, hardened characteristics, and microstructure up to an optimum 25 % RFA replacement threshold (RFA 25). Beyond this value, concrete strength and microstructure deteriorate. RFA 25 exhibits significantly higher compressive (14.75 %), flexural (6.61 %), and splitting tensile (13.14 %) strengths compared with the reference concrete, along with a 5.71 % decrease in the modulus of elasticity. Lower replacement levels promoted pozzolanic reactions, enhancing strength through additional hydration products, whereas higher replacements reduced strength.

1. Introduction

The construction industry, which is crucial for global economic growth, is simultaneously contributing to environmental degradation through the energy-intensive production of concrete, which has a substantial carbon footprint [1]. In addition, the surge in construction and demolition waste (CDW) disposal poses challenges [2], straining landfill space and causing negative ecological impacts [3]. This issue is addressed by incorporating recycled aggregate (RA) from CDW in fresh concrete, constituting 70 %–80 % of its volume, which presents economic and environmental advantages by reusing materials such as concrete, asphalt, bricks and tiles [4-6]. This research focuses on recycled fine aggregates (RFAs) generated through an impact crusher at the IL&FS CDW Recycling Plant in collaboration with the Delhi Metro Rail Corporation [7-9]. However, a comprehensive assessment of its performance and compliance with industry standards are necessary before this substitution is considered in civil engineering projects [10-12]. RA concrete (RAC), which employs RA instead of natural aggregate (NA), has been extensively studied. RAC tends to be less workable due to its porous structure and higher water absorption capacity [13]. Various factors, including the replacement ratio of NA, water-to-cement ratio, parent aggregate type, age, exposure conditions, number of crushing stages, and physical and mechanical characteristics of RA, influence its compressive strength [14-16]. Despite flaws in RAC's microstructure compared with that of NA concrete, adding RAs significantly enhances the strength of hardened concrete, offering a viable alternative to natural sand aggregates with lower permeability [17-19]. Concrete formulations containing RFAs and demolished coarse aggregates have shown effectiveness in replacing conventional concrete [20-22]. Studies incorporating fly ash with recycled concrete aggregates reveal increased water absorption and decreased electrical resistivity [23-25]. RFA concrete, with compressive strengths and modulus of elasticity (MOE) ranging from 70 % to 90 % of NA concrete, sur- passes traditional concrete in terms of CO_2 emissions and cost-effectiveness [24, 25]. Introducing waste carbon fibers into RFAs further improves mechanical performance [26, 27].

Various techniques such as freeze-thaw, mechanical grinding, ultrasonic treatment, heat treatment, and chemical treatment have been employed to enhance the performance of RAC in reducing adherent mortar [28, 29]. Researchers have explored methods such as adding mineral admixtures, altering mix designs, and adjusting the mixing procedure to improve compressive strength and mechanical properties in aggregates [30-32]. Aggregate replacement techniques such as direct weight replacement, equivalent mortar replacement, and direct volume replacement have been studied [31]. A multi-technique method that includes cement paste removal and fly ash treatment significantly enhances the compressive strength and elastic modulus of RFA concrete [33-35]. The choice of method impacts workability and performance [34, 35]. Despite various techniques applied in material processing, mix design, mixing, and curing stages to enhance RA concrete, the particle packing density (PPD) within a specific cylindrical volume using a conventional compaction technique has not been applied to RAC mix design. This study aims to implement this mixing approach because of its simplicity and effectiveness in producing RAC, aligning with circular economy principles of material reuse. However, ensuring industry-standard quality and performance remains crucial. While previous research involved substituting natural fine aggregates (NFAs) with varying proportions of RFA, a technique to determine the optimal replacement percentage for maximal strength has not been proposed. Our study addresses this gap while also exploring mechanical properties and other characteristics.

Our work's novelty lies in the following aspects:

- It investigates the efficient use of RFA for sustainable concrete production with five distinct RFA levels (0 %, 25 %, 50 %, 75 %, and 100 %) within the concrete mix.
- It examines the influence of various RFA ratios on concrete properties, such as workability, and hardened properties such as compressive strength, flexural strength, splitting tensile strength, and MOE, using established compacting procedures.
- It uses X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDAX) to analyze microstructural attributes and identify significant disparities with the control mixture.
- It examines the effects of RFAs on morphology and composition, encompassing chemical and mineralogical dimensions, to understand their role in generating microstructure. This insight can help formulate sustainable concrete with optimized RFA content.

2. Materials and mixing approach

2.1 Materials

The study utilizes ordinary Portland cement of grade 43, adhering to IS 269-2015 [36] standards. The cement's physical properties reveal a 31 % consistency, an initial setting time of 58 minutes—surpassing the minimum requirement of 30 minutes—and a final setting time of 435 minutes, significantly shorter than the standard's maximum limit of 10 hours. With a specific gravity of 3.11, insights into the density and quality of the cement can be derived. Fine aggregate is sourced from natural sand with a particle size of 4.75 mm and below, meeting IS 383–2016 [37] standards. Natural coarse aggregates (NCAs), conforming to IS 383–2016 [37], consist of crushed stone with sizes ranging from 4.75 mm to 20 mm. These aggregates pass through a 40 mm sieve but are retained on a 4.75 mm sieve. Of these, 90.76 % pass through a 20 mm sieve, and 4.52 % pass through a 10 mm sieve. RFAs, obtained from crushed concrete from CDW, undergo processing with an impact crusher. These RFAs meet size specifications, passing through a 4.75 mm sieve. A chemical admixture in accordance with IS 9103-1999 [38], namely, super-plasticizer (C-MAX), is added at a rate of 1 % by weight of cement. Potable water is utilized for the mixing and curing processes.

2.2 Mixing approach

In the formulation of concrete mixes, PPD is a pivotal tool, facilitating the development of high-performance and sustainable blends [39, 40]. This process entails the careful selection of an optimal aggregate mixture and the assessment of particle size distribution to emulate efficient packing. The objective is to attain maximum packing density and minimize void content, thereby yielding dense and durable concrete structures. Employing PPD not only improves workability but also enhances material efficiency and promotes compatibility with RAs, leading to heightened durability, reduced permeability, and enhanced strength in the resulting concrete.

Table 1 presents data on the weight of various fine aggregate mixtures at specific cylindrical volumes, considering a standard compaction effort. The table illustrates the impact of different ratios of RFA to NFA on the weight or density of the mixes after compaction. Notably, the mixture denoted as RFA 25 + NFA 75 exhibits the highest weight (15.27 units), signifying that this blend, comprising 25 % RFAs and 75 % NFAs, achieves the densest composition under standard compaction conditions. Conversely, the mixture labeled RFA 100 displays the lowest weight (13.27 units), indicating that a composition entirely composed of RFAs attains the lowest density given the

Table 1. Weight in specific cylindrical volume by giving the standard effect of compaction.

S. no	Fine aggregate mixtures	Weight (kg)
1	NFA	14.52
2	RFA 25 + NFA 75	15.27
3	RFA 50 + NFA 50	14.74
4	RFA 75 + NFA 25	13.84
5	RFA 100	13.27

Table 2. Different properties of aggregates.

Property	NFA	RFA	NCA	Standard limits
Bulk density (kg/m^3)	1625	1580	1740	1200–1750
Specific gravity	2.675	2.654	2.754	2.30–2.90
Water absorption (%)	0.51	1.12	0.62	≤ 2.0 (IS 2386 part 3) [41]
Abrasion loss (%)	15.52	18.44	25.43	< 30 (IS 2386 part 4) [42]
Crushing value (%)	16.21	17.34	26.24	< 30 (IS 2386 part 4) [42]
Impact value (%)	15.31	18.74	17.31	< 30 (IS 2386 part 4) [42]

Table 3. Concrete mixture composition (kg/m^3).

S. no.	Mixture ID	NFA	RFA	NCA	Cement	W/C Ratio	Admixture
1	RC	444.48	0	1511	400	0.5	4
2	RFA 25	333.36	111.12	1511	400	0.5	4
3	RFA 50	222.24	222.24	1511	400	0.5	4
4	RFA 75	111.12	333.36	1511	400	0.5	4
5	RFA 100	0	444.48	1511	400	0.5	4

RC – reference concrete NFA – natural fine aggregates NCA – natural coarse aggregates RFA – recycled fine aggregates

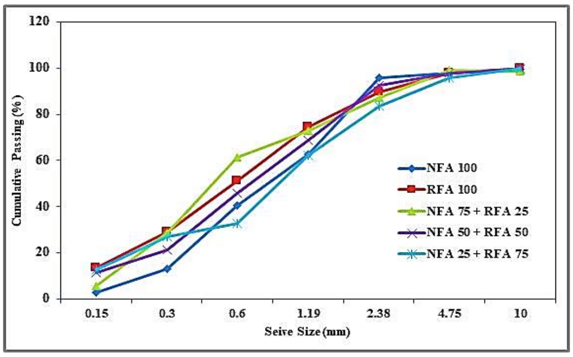


Fig. 1. Fine aggregate gradation curve for various mixtures.

specified compaction conditions. The remaining mixtures, namely, RFA 50 + NFA 50, NFA 100, and RFA 75 + NFA 25, exhibit intermediate weights, arranged in descending order of density. The densest mixture is attained with RFA 25 + NFA 75, and the other mixtures are listed in decreasing order of density. This finding succinctly summarizes the relative densities of the different mixtures. The reference to Fig. 1 suggests the existence of a complementary visual representation, likely in the form of a graph or chart, illustrating the distribution of particle sizes within the coarse aggregates used in the various combinations.

Such a figure would provide additional insights into the physical characteristics of the aggregates and how they influence the density and compaction behavior of the mixtures. The different properties of NFAs, RFAs and NCAs are shown in Table 2.

3. Mix proportions

Five concrete mixtures, with a target strength of 27 MPa, were formulated to examine the viability and influence of RFAs on the mechanical behavior of concrete. The compositions of these mixtures are outlined in Table 3. The reference concrete (RC) comprises NAs, whereas RFA 25, RFA 50, RFA 75, and RFA 100 integrate varying proportions of RFAs (25 %, 50 %, 75 % and 100 %, respectively) in lieu of NFAs. All mixtures maintain a consistent water–cement ratio of 0.50 and adopt the weight batching method [43].

4. Testing methodology

A series of experiments was conducted to comprehensively assess various facets of structural concrete. Key parameters such as compressive strength, flexural strength, splitting tensile strength, and MOE were meticulously measured. In addition, the workability of fresh concrete was evaluated, as depicted in Fig. 2. The microstructural characteristics of concrete samples from different combinations were further scrutinized through advanced techniques, including SEM, EDAX and XRD analyses.

4.1 Workability

The workability of concrete mixtures, incorporating various ratios of recycled CDW as fine aggregates, is evaluated using the IS 1199-1959 [44] standard through a slump test.

4.2 Compressive strength

A set of 30 specimens was generated utilizing steel cube molds with dimensions of 15×15×15 cm. These molds were filled with various concrete mixtures, cast, cured, and then subjected to compressive strength testing. The investigation

(a) (b) (c)

Fig. 2. Testing of various samples: (a) compressive strength cubes; (b) flexural strength beam; (c) splitting tensile strength cylinder.

involved assessing the compressive strength of distinct concrete compositions by utilizing a 2000 KN compression testing machine. Three specimens were tested for each mixture, and the average compressive strength value was computed from these results. The evaluations were performed at intervals of 7 and 28 days after casting.

4.3 Flexural strength

The experimental procedure encompassed the fabrication, curing, and examination of 30 concrete specimens, each shaped in steel rectangular molds measuring 50×10×10 cm. The primary objective of the study was to assess the flexural strength of each concrete blend, gauging its capacity to endure bending or deformation without fracture. With the use of a 2000 KN flexural testing apparatus, three specimens for each mixture were tested, and average flexural strength values were derived from the results. The testing occurred 7 and 28 days after the initial casting.

4.4 Splitting tensile strength

The research entailed the production of 30 concrete specimens utilizing steel cylindrical molds with a diameter of 15 cm and a height of 30 cm. Subsequently, these specimens underwent splitting tensile strength testing to assess the efficacy of diverse concrete mixtures. The tests were performed using a compression testing machine with a 2000 KN capacity, and the splitting tensile strength was determined based on the average value derived from three specimens.

4.5 Modulus of elasticity

This research delved into the nuances of concrete behavior by examining the MOE. Cylindrical specimens measuring 150×300 mm, with a height-to-diameter ratio of 2.0, were utilized for this assessment, following the guidelines specified in IS 516 part 6 of 2006 [45]. These meticulous evaluations yielded essential insights into the structural integrity and deformability of the concrete under various loads.

4.6 X-ray diffraction analysis

XRD is applied to scrutinize the phase characteristics and conduct mineralogical assessments of crystalline minerals present in concrete powder samples, particularly in diverse mixtures incorporating RFAs. The Bruker D-8 advanced diffractometer system is employed to scan the samples across an angular range of 3°–70°, with a scanning speed of 2° per minute and a sampling interval of 0.005° at an angle of 2°. Subsequently, the scans are analyzed using the JADE 7 X-ray diffraction software. The resulting peak intensities are visually represented against 2 theta degrees on the x-axis, spanning from 0° to 70°, with intensity plotted on the y-axis.

4.7 Scanning electron microscopy analysis

SEM analysis was conducted to characterize the materials of RFA, involving a comprehensive examination of the microstructure and surface morphology of concrete samples originating from various concrete mixtures. The analysis was carried out using the JSM 6610V scanning electron microscope at the University Science Instrumentation Centre in Delhi, operating at 30 kV.

5. Results and discussion

5.1 Workability

The slump values outlined in Table 4 indicate a diminishing trend in concrete slump as the proportion of RFAs increases.

This observation suggests that the workability of concrete incorporating RFA falls within a moderate range of 50 mm to 100 mm. This decline is attributed to RFA's higher water absorption capacity compared with NAs, primarily due to the presence of aged adhered mortar on its surface. As the content of RFA rises, the increased water absorption becomes more prominent, leading to a decrease in slump. This pattern aligns with findings from a prior study that noted a slump reduction with increased RCA content in concrete mixtures [46, 47]. The results of the slump test, along with the graphical representation in Fig. 3, provide compelling evidence that the incorporation of RFAs in concrete mixtures contributes to a slump reduction, influencing the concrete's flow and ease of handling.

Table 4. Slump value for various mixtures.

Concrete mix	Slump (mm)
RC	111
RFA 25	104
RFA 50	98
RFA 75	87
RFA 100	76

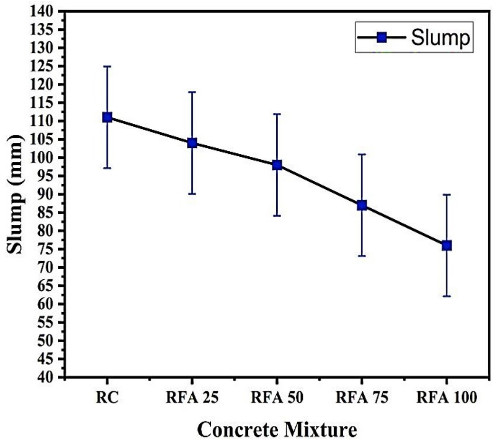


Fig. 3. Slump value for different concrete mixtures.

5.2 Compressive strength

The consolidated data are presented in Table 5, shedding light on how RFAs affect the compressive strength of concrete mixes. The results indicate that, in contrast to the reference mixture, the compressive strength of the concrete diminishes as the proportion of RFA in the mixes increases. Notably, RFA 25 exhibited the highest compressive strength, with a 25 % replacement of fine aggregates being identified as the optimal ratio for RFAs. The enhanced performance of RFA 25 is attributed to improved particle packing and reduced voids. The correlation between strength and the percentage of fine aggregates passing through the 600- to 150-micron range is significant, with a more substantial difference resulting in higher strength within certain limits. Higher replacement percentages of RFA increase void content and hinder strong bonding between aggregates, consequently leading to a reduction in strength. RFA 25 demonstrated the highest compressive strength at 36.71 MPa, while RFA 100 exhibited the lowest compressive strength at 23.01 MPa.

Drawing on the observations of Wagih et al. [48], the introduction of RFAs into concrete mixes led to a reduction in compressive strength of 20 %–34 % at 7 days and 30 %–38 % at 28 days when utilizing 100 % RFA replacement. However, the current study indicates a more moderate decrease in flexural

Table 5. Compressive strength variation in percentage for various combinations.

Concrete mix	Compressive strength (MPa)			
	7 days	% variation concerning RC	28 days	% variation concerning RC
RC	22.71	Reference	31.99	Reference
RFA 25	26.72	+17.65	36.71	+14.75
RFA 50	20.45	−9.95	29.78	−6.90
RFA 75	17.13	−24.57	24.86	−22.28
RFA 100	15.92	−29.89	23.01	−24.94

Note + sign represents an increase in strength and – sign represents a decrease in strength

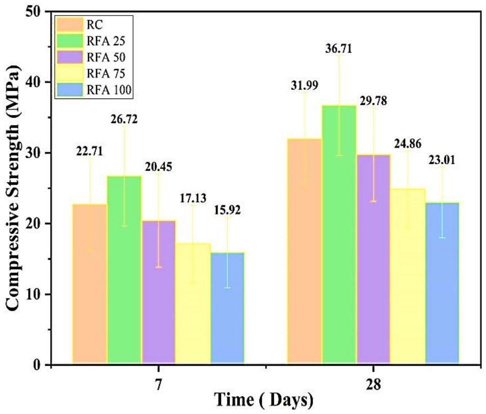


Fig. 4. Compressive strength variations for different concrete mixtures.

Table 6. Flexural strength variation in percentage for different mixtures.

Concrete mix	Flexural strength (MPa)			
	7 days	% variation concerning RC	28 days	% variation concerning RC
RC	3.18	Reference	3.92	Reference
RFA 25	3.41	+7.23	4.16	+4.59
RFA 50	3.12	−1.88	3.89	−0.76
RFA 75	2.89	−9.11	3.75	−4.33
RFA 100	2.60	−18.23	3.48	−11.22

+ Sign represents an increase in strength and – sign represents a decrease in strength

strength, with only a 7 %–10 % reduction after 50 % RFA replacement and a 25 %–29 % decrease with 100 % RFA replacement. These findings underscore the efficacy of the PPD mixing approach through standard compaction, considering weight within a specific cylindrical volume, in preserving flexural strength in concrete mixes. This study aligns with the outcomes of Kessal et al. [49] and lends support to the conclusions drawn by Vintimilla et al. [50]. These earlier studies also emphasized the crucial role of RFAs in achieving desirable concrete strength. Overall, this research contributes to the expanding body of knowledge on optimizing concrete mixtures for enhanced strength characteristics.

5.3 Flexural strength

The detailed outcomes in Table 6 provide a comprehensive understanding of the study. This investigation found that the flexural strength of concrete exhibits variations in terms of time and the amount of RFA replacement. The graphical representation illustrates a consistent pattern of flexural strength diminishing as the percentage of RFA replacement increases, indicating a negative correlation between higher RFA levels and concrete's flexural strength. Notably, after 28 days, RFA 25 demonstrated the highest flexural strength at 4.16 MPa, while RFA 100 exhibited the lowest strength at 3.48 MPa.

This study found a marginal reduction in flexural strength, with only a 1 %–2 % decrease following 50 % RFA replacement and a 10 %–15 % decrease with 100 % RFA replacement. This observation underscores the efficacy of the PPD mixing approach through standard compaction, considering weight within a specific cylindrical volume, in maintaining flexural strength in concrete mixes. This finding diverges from prior research that indicated a 5 %–10 % strength decrease after 50 % RFA replacement and a 15 %–20 % decrease for 100 % replacement [14]. Consistent with earlier research [11, 51], this study establishes a clear association between higher RFA replacement percentages and reduced flexural strength in concrete mixtures, as numerically depicted in Table 6 and visually presented in Fig. 5. These outcomes align with patterns observed in compressive strength studies, reaffirming and contributing to the existing body of knowledge by corroborating similar findings from other researchers.

Table 7. Splitting tensile strength variation in percentage for different mixtures.

Concrete mix	Splitting tensile strength (MPa)			
	7 days	% variation concerning RC	28 days	% variation concerning RC
RC	2.19	Reference	2.51	Reference
RFA 25	2.52	+15.0	2.84	+13.14
RFA 50	2.14	−2.28	2.48	−1.19
RFA 75	1.98	−9.58	2.34	−6.77
RFA 100	1.77	−19.17	2.19	−12.74

Note: + sign represents increase in strength and – sign represents decrease in strength

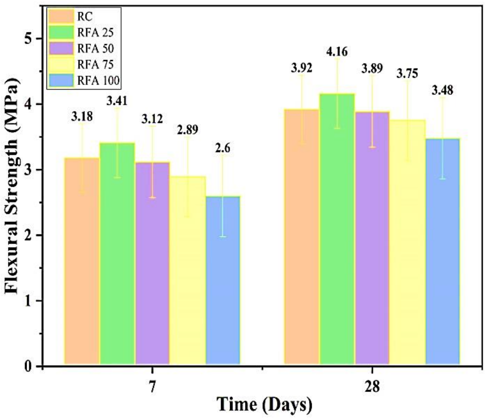


Fig. 5. Flexural strength variations for different concrete mixtures.

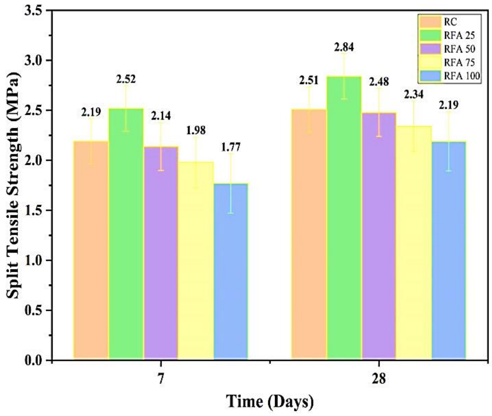


Fig. 6. Splitting tensile strength variations for different concrete mixtures.

5.4 Splitting tensile strength

The findings from these tests are systematically summarized in Table 7. The trends in splitting tensile strength variations over the 7- and 28-day periods are visually elucidated in Fig. 6. This figure effectively portrays the impact of varying percentages of RFA replacement on splitting tensile strength relative to

Table 8. Concrete MOE with different codes.

Concrete mix	Compressive strength (MPa)	Modulus of elasticity (GPa)		
		Experimental (E_c)	As Per IS 456-2000 (E_C)	As Per ACI code (E_C)
RC	31.99	31.42	28.27	26.77
RFA 25	36.71	29.61	30.29	26.68
RFA 50	29.78	24.04	27.28	25.83
RFA 75	24.86	22.68	24.92	23.61
RFA 100	23.01	20.31	23.98	22.72

the reference mixture. The observed trends in splitting tensile strength closely mirror those witnessed in compressive strength variations. Notably, as higher proportions of RFA replacement are employed, the splitting tensile strength of the concrete mixture tends to be lower than that of the reference mixture. Meticulous analysis of the results shows that the concrete mixture labeled "RFA 25" exhibits the highest splitting tensile strength (2.84 MPa) among all the tested mixtures. Conversely, the concrete mixture labeled "RFA 100" demonstrates the lowest splitting tensile strength (2.19 MPa) among the various mixtures examined.

In comparison to this study, where RFA is replaced using the PPD mixing approach through standard compaction in terms of weight within a specific cylindrical volume, only a 12 % reduction occurred at the 100 % replacement level. In contrast, Ashraf M. Wagih's work demonstrated a 24 % decline in splitting tensile strength at a 100 % replacement level [48]. These outcomes align with the findings of Kessal et al., establishing consistency with existing research [49, 50].

5.5 Modulus of elasticity

The MOE serves as a metric to assess the deformation capacity of both conventional concrete and RAC. MOE measures how much a material deforms when subjected to a load and subsequently returns to its original shape upon load release. The primary objective of this study is to ascertain the influence of RFA content on the deformation characteristics of concrete. The MOE at 28 days demonstrates a decline as the RFA content in the concrete increases. Table 8 delineates that RFA's brittleness and water absorption significantly contribute to this reduction, leading to more pronounced deformation in structural components made with RFA compared with those using NA. Consequently, an increase in RFA content correlates with a reduction in the MOE in concrete.

Fig. 7 visually presents the decline in the MOE with increasing RFA content, despite the potential benefits of the particle density method in enhancing strength and hydration. The comparison between compressive strength and the MOE of plain concrete for different RFA substitution percentages reinforces this observed pattern. The findings also suggest that various factors, including aggregate volume and stiffness, binder phase stiffness, and characteristics of the interfacial transition zone between aggregate and paste, contribute to the decrease in MOE with the increasing amount of RFA replacement. These results align with earlier studies that also identified a similar pattern of decreasing MOE as the quantity of RCA in concrete increased [48, 52].

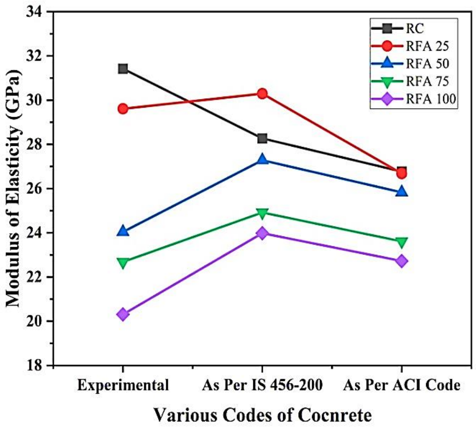


Fig. 7. Modulus of elasticity variation with different codes.

5.6 X-ray diffraction analysis

XRD is a robust technique for elucidating the phase characteristics and mineralogical composition of crystalline minerals in a concrete sample. This method is particularly valuable when examining the effects of diverse mixtures that integrate RFAs. The angles at which diffraction peaks appear for different compounds in the concrete mixtures are recorded in Table 9. This table provides the degree values for calcium silicate hydroxide (CSH), ettringite, and calcium hydroxide (CH) for each concrete mixture, offering in-depth insight into the mineralogical aspects of the specimens by elucidating the diffraction peak angles for various compounds. The interpretation and discussion noted that the angles for CSH exhibit minimal variation, suggesting a consistent presence of this compound. The slight decrease in angles for RFA 25 indicates a subtle alteration in CSH composition compared with the RC. Ettringite angles show some variation, with RFA 25 displaying a lower angle, suggesting potential modifications in the crystalline structure. Increasing angles with higher RFA content hint at changes in the formation or orientation of ettringite crystals.

CH angles undergo more pronounced changes, notably in RFA 75 and RFA 100, where a substantial increase is ob-

Table 9. Diffraction peak angles of various compounds for different concrete mixtures.

Concrete mix	CSH (degree)	Ettringite (degree)	CH (degree)
RC	26.450	36.780	47.299
RFA 25	26.337	34.146	50.175
RFA 50	26.596	36.606	50.110
RFA 75	26.575	39.385	60.001
RFA 100	26.571	39.523	59.930

Note: CSH – calcium silicate hydroxide CH – calcium hydroxide ettringite – hydrated calcium aluminum sulfate hydroxide

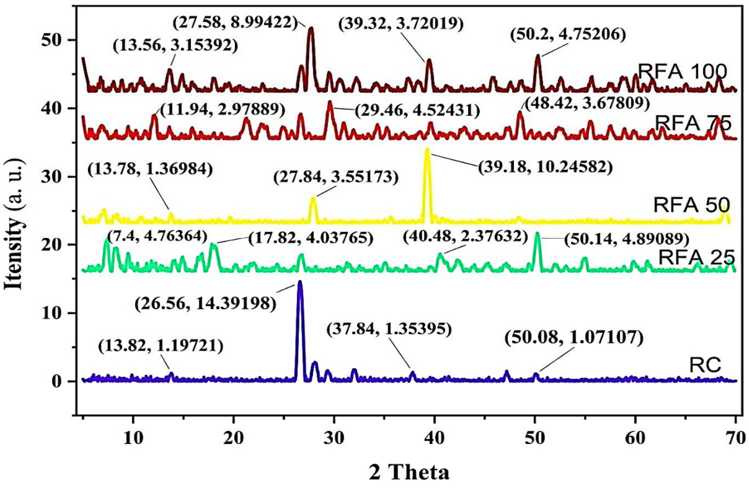


Fig. 8. XRD pattern for different concrete mixtures.

served, and potentially indicating variations in hydration products due to the presence of RFAs. Furthermore, the XRD results demonstrate the influence of RFAs on the phase composition of minerals within concrete. Specifically, the net intensity of peaks corresponding to CSH, CH, and ettringite decreases as the percentage of RFA replacement increases. This finding suggests a diminishing density of total CSH in the concrete with greater incorporation of RFAs. Fig. 8 presents the XRD patterns for various concrete mixtures, including RC, RFA 25, RFA 50, RFA 75, and RFA 100, offering a graphical depiction of how peak intensities and positions vary across these mixtures. These findings contribute to a comprehensive understanding of the effect of RFA on the mineralogical characteristics and overall composition of concrete mixtures.

As revealed by XRD studies, the addition of RFAs induces subtle changes in the phase composition of CSH, CH, and ettringite within concrete. The recorded data exhibit peaks at approximately 26.5°, 36°, and 50° for 2-theta angles, signifying the presence of various compounds such as CSH, ettringite, and CH across all combinations. While the strength of these peaks suggests the substantial presence of these substances, an important detail to note is that the concrete samples utilized in the investigation lacked microscopic homogeneity. This observation aligns with Silva et al.'s [53] study, which examined cement paste containing 12 % concrete floor polishing waste, highlighting comparable findings between the two studies [14].

In summary, XRD results imply that the incorporation of RFAs introduces subtle changes in the composition and crystalline structure of specific compounds, emphasizing the influence of RFA on the hydration process and overall mineralogical characteristics of the concrete. These nuanced insights are pivotal for evaluating the long-term durability and performance of concrete mixtures integrating RFAs.

5.7 Scanning electron microscopy analysis

In this investigation, SEM analysis is employed to scrutinize the characteristics of RFA concrete. Fig. 9 provides micrographs obtained after 28 days for distinct concrete mixtures that underwent SEM analysis.

These micrographs offer valuable insights into the microstructure of different concrete mixtures, revealing the formation of crucial hydration products at this stage. These hydration products, including CH, CSH, and ettringite, play a pivotal role in determining concrete strength. The micrographs illustrate distinctive characteristics: hexagonal crystal shapes correspond to CH, flower-like structures represent CSH gel, and needle-like structures denote ettringite. The test results reveal significant insights into the impact of different proportions of RFA on concrete microstructure and strength. The introduction of 25 % RFA into the concrete mixture enhances its microstructure, fostering the development of a dense cement paste. This improvement strengthens the bond between aggregates, consequently elevating the compressive strength of the concrete. Conversely, the inclusion of 50 % RFA results in less dense concrete compared with the reference mix, thereby reducing both density and compressive strength. At 75 % RFA replacement, the concrete structure exhibits voids and loose arrangements, further diminishing the compressive strength. A complete 100 % RFA replacement yields a porous microstructure, where the cement surrounding the RFAs undergoes incomplete hydration, resulting in fewer hydration products. SEM analysis elucidates that lower RFA mixture proportions generate a more substantial amount of CSH gel, contributing to a denser cement paste matrix and increased concrete strength. However, excessive RFA proportions weaken the mixture's structural integrity due to inadequate CSH production, resulting in reduced strength. These findings align with a previous study [28, 54], reinforcing the consistency of the results with existing research. In summary, the SEM analysis in this study provides valuable insights into how varying RFA proportions influence concrete microstructure and strength. The micrographs in Fig. 9 highlight distinct features corresponding to different hydration products, emphasizing that optimal RFA replacement proportions can enhance concrete properties, while excessive replacement can lead to weaker structures. These insights bear significance for the design of sustainable and high-performance concrete mixtures.

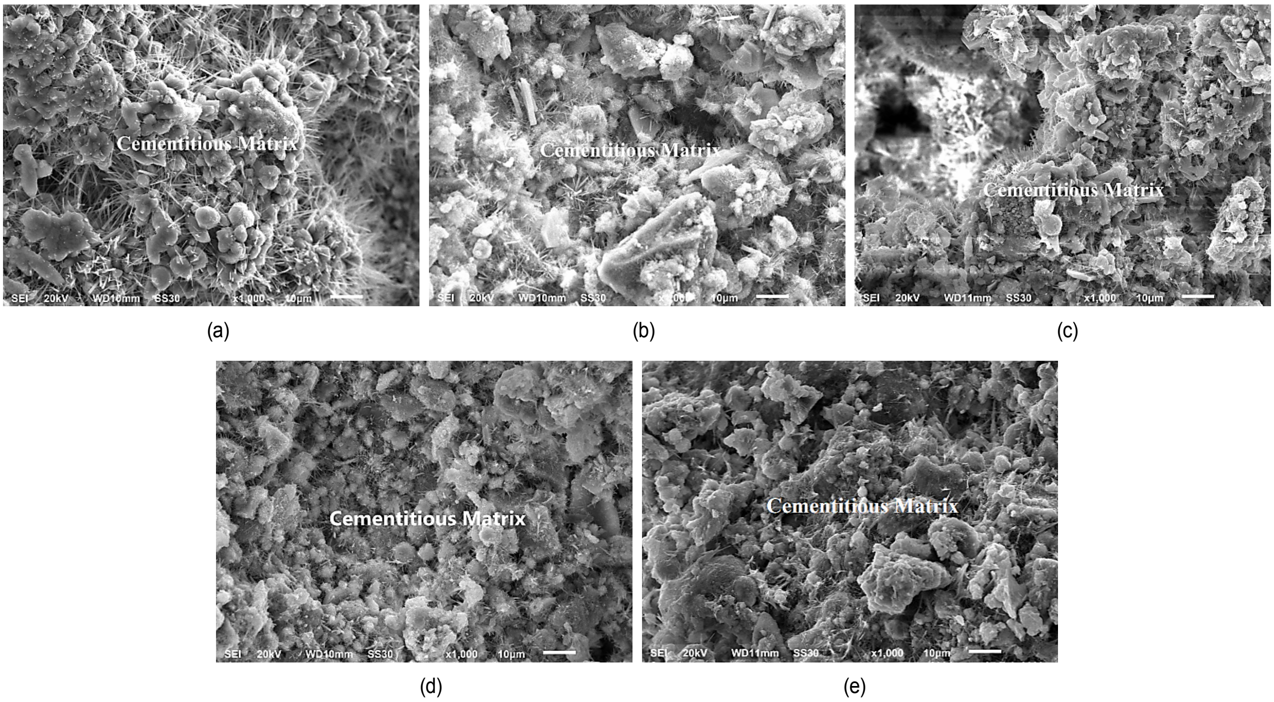
6. Cost–benefit analysis

Table 10 presents a comprehensive overview of the cost–benefit analysis conducted in this study, comparing the scheduled rate of the Road and Building Department Delhi Division, Government of Delhi with the prevailing market rates for various construction materials. The materials considered in this

Table 10. Cost of mixtures.

Elements	Unit cost per kg	RC (kg/m^3)	RFA 25 (kg/m^3)	RFA 50 (kg/m^3)	RFA 75 (kg/m^3)	RFA 100 (kg/m^3)
Cement	6.6	400	400	400	400	400
Admixture	0.9	4	4	4	4	4
NFA	0.75	444.48	333.36	222.24	111.12	0
NCA	0.65	1511	1511	1511	1511	1511
RFA	0.40	0	111.12	222.24	333.36	444.48
Total (INR)		3959.11	3920.21	3881.32	3842.43	3803.54
% variation concerned with RC		-	0.98	1.96	2.94	3.96

RC – reference concrete NFA – natural fine aggregates NCA – natural coarse aggregates RFA – recycled fine aggregates



(a) (b) (c)

(d) (e)

Fig. 9. Different concrete mixtures' SEM micrographs: (a) RC; (b) RFA 25; (c) RFA 50; (d) RFA 75; (e) RFA 100.

analysis include:

- Cement priced at INR 6.6 per kilogram.
- NFAs priced at INR 0.75 per kilogram.
- NCAs priced at INR 0.65 per kilogram.
- RFAs priced at INR 0.40 per kilogram.

RFAs are produced utilizing an impact crusher at the Delhi Metro Rail Corporation's IL&FS CDW Recycling Plant in Delhi, India, using discarded concrete.

The objective of this cost analysis is to quantify potential savings achievable through the utilization of CDW in comparison to NAs. Table 10 illustrates the material costs and the resultant expenses incurred by different mixtures. As depicted in the table, substituting NAs with RFAs can lead to cost savings ranging from 1 % to 4 %, depending on the quantity of replaced RFA. This approach not only offers cost savings but also delivers concrete of comparable quality to the control, making it a favorable choice from both economic and performance perspectives [55].

7. Conclusions

This paper investigates RFAs from CDW in sustainable concrete. The findings highlight reduced environmental impact without compromising structural integrity, emphasizing controlled particle size distribution. From the study, the following conclusions may be drawn:

1) The mechanical properties of concrete exhibit an optimum replacement percentage for RFAs at 25 %. Concrete achieves superior performance at this level, with a decline in strength characteristics observed at 100 % RFA replacement. Careful evaluation of the RFA replacement proportion is essential for ensuring intended concrete mixture performance.
2) A recommended replacement of 25 % RFAs in concrete yields higher strength compared with NFAs. RFA 25 demonstrates a 14.75 % increase in compressive strength, a 6.61 % increase in flexural strength, and a 13.14 % increase in splitting tensile strength compared with RC. The strength of 50 % RFA is comparable to that of 100 % NFAs.
3) The pozzolanic reaction enhances strength at lower replacement percentages by forming more hydration products, while higher levels result in decreased strength due to incomplete hydration. Optimal replacement percentage determination relies on microstructure and chemical composition analysis to achieve maximum strength.
4) The experimental MOE for concrete, incorporating both NA and RA, is lower than the theoretical value due to flaws, irregularities in recycled aggregates, and variations in composition.
5) RAs significantly reduce environmental impact by curbing natural resource demand, conserving resources, and minimizing carbon footprint. Their use promotes sustainable building methods, reduces landfill waste, and encourages resource reuse, resulting in a 10 % cost–benefit ratio and less negative environmental effects in construction projects.

Incorporating RFAs in concrete is a promising sustainable practice, with marginal mechanical property reduction. Microstructural analysis offers relevant insights. Further research is needed for optimal mix designs, long-term performance, and economic feasibility, marking a positive step in reducing construction's environmental impact.

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References

[1] O. Zaid, S. R. Zamir Hashmi, F. Aslam and H. Alabduljabbar, Experimental study on mechanical performance of recycled fine aggregate concrete reinforced with discarded carbon fibers, *Front. Mater.*, 8 (11) (2021) 1-12.

[2] D. Hoornweg and P. Bhada-Tata, A global review of solid waste management - review, global management, solid waste, *World Bank Urban Dev. Ser. Knowl. Pap.*, 1 (11) (2012) 1-116.

[3] O. E. Gjørv, Durability of concrete structures, *Arab. J. Sci. Eng.*, 36 (2) (2011) 151-172.

[4] T. R. Sonawane and S. S. Pimplikar, Use of recycled aggregate concrete, *IOSR J. Mech. Civ. Eng.* (2012) 52-59.

[5] S. R. Boyle, Evaluation of recycled concrete for use as aggregates in new portland cement concrete pavements, *Master's Thesis*, Washington State University, USA (2013).

[6] W. Z. Taffese, Suitability investigation of recycled concrete aggregates for concrete production: an experimental case study, *Adv. Civ. Eng.* (2018) 8368351.

[7] S. Bansal and S. K. Singh, A sustainable approach towards the construction and demolition waste, *Int. J. Innov. Res. Sci. Eng. Technol.*, 3 (2) (2013) 9226-9235.

[8] S. Bansal, S. K. Singh and J. Kurian, Construction and demolition (C&D) waste recycling in new delhi, *4th Int. Fib Congr. 2014 Improv. Perform. Concr. Struct. FIB 2014 - Proc.*, 6 (2014) 286-289.

[9] S. Bansal and S. K. Singh, Sustainable handling of construction and demolition (C & D) waste, *Int. J. Sustain. Energy Environ. Res.*, 4 (2) (2015) 22-48.

[10] Gagan and S. Arora, Recycled Aggregates: a sustainable solution of construction and demolished waste, *J. Mech. Civ. Eng.* (2015) 58-63.

[11] M. Surya, K. Rao VVL and P. Lakshmy, Recycled aggregate concrete for transportation infrastructure, *Procedia - Soc. Behav. Sci.*, 104 (11) (2013) 1158-1167.

[12] L. Evangelista and J. De Brito, Concrete with fine recycled aggregates : a review, *European Journal of Environmental and Civil Engineering*, 18 (2) (2014) 129-172.

[13] J. Yu, D. Liu and Z. Zhang, Durability and life prediction

analysis of recycled aggregate concrete with ceramic waste powder under freeze-thaw conditions based on impact-echo method and grey-markov model, *Front. Mater.*, 9 (10) (2022) 1-13.

[14] H. S. Joseph, T. Pachiappan, S. Avudaiappan and E. I. S. Flores, A study on mechanical and microstructural characteristics of concrete using recycled aggregate, *Materials (Basel).*, 15 (21) (2022) 15217535.

[15] L. Courard, M. Rondeux, Z. Zhao and F. Michel, Use of recycled fine aggregates from c & dw for unbound road sub-base, *Materials (Basel)*, 13 (2020) 2994.

[16] C. Shi, Y. Li, J. Zhang, W. Li, L. Chong and Z. Xie, Performance enhancement of recycled concrete aggregate - a review, *J. Clean. Prod.*, 112 (2016) 466-472.

[17] H. Yaprak, H. Y. Aruntas, I. Demir and O. Simsek, Effects of the fine recycled concrete aggregates on the concrete properties, *International Journal of Physical Sciences*, 6 (10) (2011) 2455-2461.

[18] A. Kumar and G. J. Singh, Improving the physical and mechanical properties of recycled concrete aggregate: A state-of-the-art review, *Eng. Res. Express*, 5 (1) (2023) 012007.

[19] D. D. Nguyen, Evaluating the possibility of replacing natural fine aggregates in concrete with recycled aggregates, *Eng. Technol. Appl. Sci. Res.*, 11 (6) (2021) 7805-7808.

[20] K. Naouaoui and T. Cherradi, A case study on the mechanical and durability properties of a concrete using recycled aggregates, *Civ. Eng. J.*, 7 (11) (2021) 1909-1917.

[21] K. Osterminski, R. B. Polder and P. Schießl, Long term behaviour of the resistivity of concrete, *Heron*, 57 (3) (2012) 211-230.

[22] H. Layssi, P. Ghods, A. R. Alizadeh and M. Salehi, Electrical resistivity of concrete, *Concr. Int.*, 2 (2015) 293–302.

[23] H. Oleiwi, Y. Wang, N. Xiang, L. Augusthus-Nelson, X. Chen and I. Shabalin, An experimental study of concrete resistivity and the effects of electrode configuration and current frequency on measurement, *6th Int. Conf. Durab. Concr. Struct. ICDCS 2018*, University of Leeds, UK., 6 (2018) 592-599.

[24] M. Quattrone, S. C. Angulo and V. M. John, Energy and CO_2 from high performance recycled aggregate production, *Resour. Conserv. Recycl.*, 90 (2014) 21-33.

[25] B. J. Zhan, D. X. Xuan and C. S. Poon, Enhancement of recycled aggregate properties by accelerated CO_2 curing coupled with limewater soaking process, *Cem. Concr. Compos.*, 89 (2018) 230-237.

[26] C. M. M. de A. e. Silva, M. M. L. Pereira, V. M. S. Capuzzo and J. de Brito, Concrete produced with recycled concrete aggregate exposed to treatment methods, *Case Stud. Constr. Mater.*, 18 (11) (2022) 01938.

[27] C. Cakiroglu and G. Bekdaş, Predictive modeling of recycled aggregate concrete beam shear strength using explainable ensemble learning methods, *Sustainability*, 15 (6) (2023) 15064957.

[28] V. W. Y. Tam, X. F. Gao and C. M. Tam, Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach, *Cem. Concr. Res.*, 35 (6) (2005) 1195-1203.

[29] J. paul Ntitanguranwa, J. Kabano and N. Gasingwa, Reuse of construction and demolished concrete waste by producing affordable high strength concrete block, *Rwanda J. Eng. Sci. Technol. Environ.*, 1 (1) (2018) 14.

[30] M. Ju, J. Jeong, M. Palou and K. Park, Mechanical behavior of fine recycled concrete aggregate concrete with the mineral admixtures, *Materials.*, 13 (10) (2020) 1-15.

[31] S. Pradhan, S. Kumar and S. V Barai, Recycled aggregate concrete: particle packing method (PPM) of mix design approach, *Constr. Build. Mater.*, 152 (2017) 269-284.

[32] S. Ismail and M. Ramli, Engineering properties of treated recycled concrete aggregate (RCA) for structural applications, *Constr. Build. Mater.*, 44 (2013) 464-476.

[33] M. K. Rao and D. C. N. S. Kumar, Durability assessment of concrete with class-F fly ash by chloride ion permeability, *Int. J. Recent Technol. Eng.*, 8 (4) (2019) 8831-8836.

[34] G. L. Golewski, Combined effect of coal fly ash (CFA) and nanosilica (nS) on the strength parameters and microstructural properties of eco-friendly concrete, *Energies*, 16 (1) (2023) 452.

[35] B. Uzbaş and A. C. Aydin, Analysis of fly ash concrete with scanning electron microscopy and X-Ray diffraction, *Adv. Sci. Technol. Res. J.*, 13 (4) (2019) 100-110.

[36] ISO 269:2015, *Indian Standard for Ordinary Portland Cement*, Bureau of Indian Standards, India (2017).

[37] ISO 383:2016, *Specification for Coarse and Fine Aggregate for Concrete*, Bureau of Indian Standards, India (2016).

[38] ISO 9103:1999, *Specification for Concrete Admixtures*, Bureau of Indian Standards, India (1999).

[39] S. Fennis and J. Walraven, Using particle packing technology for sustainable concrete mixture design, *Heron*, 57 (2) (2012) 72-102.

[40] B. Demolition, W. Bdw and S. Solution, Particle packing approach for proportioning recycled aggregate from particle packing approach for proportioning recycled aggregate from building demolition waste (BDW) — a sustainable solution, *J. Inst. Eng. Ser. A*, 11 (2022) 686-688.

[41] ISO 2386:1963 Part III, *Methods of Test for Aggregates for Concrete*, Bureau of Indian Standards, India (2021).

[42] ISO 2386:1963 Part IV, Methods of Test for Aggregates for Concrete, Part 4: Mechanical Properties, Bureau of Indian Standards, India (2016).

[43] ISO 10262:2009, *Guidelines for Concrete Mix Design Proportioning*, Bureau of Indian Standards, India (2009).

[44] ISO 1199:2018 Part 1, *Methods of Sampling, Testing, and Analysis for Fresh Concrete*, Bureau of Indian Standards, India (2018).

[45] ISO 516:2020 Part 6, Determination of Drying Shrinkage and Moisture Movement of Concrete Samples, Bureau of Indian Standards, India (2020).

[46] Z. Zhao, S. Remond, D. Damidot and W. Xu, Influence of fine recycled concrete aggregates on the properties of mortars, *Constr. Build. Mater.*, 81 (2015) 179-186.

[47] S. K. Kirthika, S. K. Singh and A. Chourasia, Performance of recycled fine-aggregate concrete using novel mix-proportioning method, *J. Mater. Civ. Eng.*, 32 (8) (2020) 1-13.

[48] A. M. Wagih, H. Z. El-Karmoty, M. Ebid and S. H. Okba, Re-

cycled construction and demolition concrete waste as aggregate for structural concrete, *HBRC J.*, 9 (3) (2013) 193-200.

[49] O. Kessal, L. Belagraa, A. Noui and N. Maafi, Performance study of eco-concrete based on waste demolition as recycled aggregates, *Mater. Int.*, 2 (2) (2020) 123-130.

[50] C. Vintimilla and M. Etxeberria, Limiting the maximum fine and coarse recycled aggregates-type a used in structural concrete, *Constr. Build. Mater.*, 380 (3) (2023) 131273.

[51] E. O. Aiyewalehinmi and T. E. Adeoye, Recycling of concrete waste material from construction demolition, *Am. J. Eng. Res.*, 5 (4) (2016) 182-191.

[52] M. Velay-Lizancos, I. Martinez-Lage, M. Azenha, J. Granja and P. Vazquez-Burgo, Concrete with fine and coarse recycled aggregates: E-modulus evolution, compressive strength and non-destructive testing at early ages, *Constr. Build. Mater.*, 193 (2018) 323-331.

[53] L. A. Silva, B. O. Nahime, E. C. Lima, J. L. Akasaki and I. C. Reis, XRD investigation of cement pastes incorporating concrete floor polishing waste, *Ceramica*, 66 (380) (2020) 373-380.

[54] H. S. Wong et al., Microscopy techniques for determining water–cement (w/c) ratio in hardened concrete: a round-robin assessment, *Mater. Struct. Constr.*, 53 (2) (2020) 1458.

[55] A. Al-Mansour, C. L. Chow, L. Feo, R. Penna and D. Lau, Green concrete: by-products utilization and advanced approaches, *Sustain.*, 11 (19) (2019) 1-30.

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