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RESEARCH ARTICLE

Environmental impacts and performance assessment of recycled fine aggregate concrete

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Abstract
Natural disasters and human demolition create vast amounts of construction and demolition waste (CDW), with a substantial portion being concrete waste. Managing this concrete waste is a daunting challenge for developing countries with limited resources, aiming to mitigate its harmful environmental effects. Therefore, the proposed approach involves using recycled fine aggregates (RFA) instead of fresh fine aggregates (FFA) in concrete, which aligns closely with achieving sustainable environmental objectives. Extensive laboratory tests were conducted to assess the effects of adding RFA to concrete. The influence of 0 to 100% RFA replacement and different curing times was investigated on compressive strength, tensile strength, resistance against chloride ion penetration and chemicals exposure, and quality of aggregates. So, around 30%, 35%, 20%, and 79% reductions in compression strength, tensile strength, modulus of elasticity, and workability were estimated when 100% RFA was used in recycled aggregate concrete (RAC). However, according to results analyses, the performance of RAC is reliable up to 50% of RFA in proposed conditions and mix design. In addition, major environmental impacts such as global warming potential, aquatic eutrophication, and aquatic acidification were reduced by 47%, 40%, and 18%, respectively, for concrete having 50% RFA than concrete having 100% FFA.

Keywords Construction and demolition waste · Environmental impacts assessment · Recycled fine aggregates · Concrete durability and strength · Chlorine ion penetration resistance · Resistance against chemicals exposure

Nomenclature

ASTM	American Society for Testing and Materials
ADB	Asian Development Bank (ADB)
CDW	Construction and demolition waste
CMRA	Construction Materials Recycling Association
CS	Crushed limestone
C_c	Coefficient of curvature
C_u	Coefficient of uniformity
D_{50}	Mean size diameter
EEA	European Environment Agency
E_c	Modulus of elasticity
FCA	Fresh coarse aggregates
FFA	Fresh fine aggregate
FTIR	Fourier transform infrared spectroscopy
f_c'	Compressive strength of concrete
f_{ctm}	Tensile strength of concrete
GTZ	German technical cooperation

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ITZ	Interface transition zone
k	Modulus of elasticity estimation factor
MTPA	Million tons per annum
RAC	Recycled aggregate concrete
RFA	Recycled fine aggregate
RCA	Recycled coarse aggregates
RCPT	Rapid chlorine penetration test
SDG	Sustainable Development Goals
UN	United Nations
UNDP	United Nations Development Program
OCHA	United Nations Office for the Coordination of Humanitarian Affairs
UTM	Universal testing machine
WB	World bank
w/c	Water cement ratio
XRD	X-ray diffraction

Introduction

The growth of a nation's economy is greatly reliant on its construction sector, which offers a plethora of employment opportunities, contributes to economic prosperity, and serves as a foundation for many other industries (Venugopal et al. 2020). The construction sector's role in sponsoring socio-economic evolution extends beyond its proportion of the national productivity (Lopes et al. 2011). It encompasses the construction of various infrastructures, including buildings, bridges, highways, railway lines, and hydraulic structures, which are critical to the growth of any developing country. In emerging economies, construction ventures make up approximately 10% of their gross domestic product (GDP), 80% of the total capital asset, and over 50% of the fixed asset investments (Jekale 2004).

At the same time, the construction sector has a significant environmental footprint because it relies on natural resources and the supplementing pollution generated during the manufacturing and processing phases (Nedeljković et al. 2021; Barragan-Ramos et al. 2022; Sattar et al. 2023). Moreover, the eventual demolition of structures that have outlived their usefulness results in substantial waste and debris production, and the generation of a gigantic quantity of construction and demolition waste (CDW) is also caused by natural hazards like earthquakes, floods, and tsunamis. The CDW accounts for a significant quantity of all waste, with a large volume that exceeds approximately one-third of total waste generation (Yuan et al. 2012; Gottsche and Kelly 2018; Mujtaba et al. 2022). The United States produces roughly 534 MTPA of CDW, primarily from dismantling structures, and similarly, in China, CDW accounts for 30 to 40% of the total waste, roughly amounting to 1130 MTPA (Swarna et al. 2022; Pereira and Vieira 2022). The detail of CDW generation in some populated countries is illustrated in Fig. 1. Furthermore, according to the World Bank, the amount of CDW generation is expected to reach 2.59 billion tons by 2030 and further increase to 3.40 billion tons by 2050 (Kaza et al. 2018; Guo et al. 2018). According to Polat et al. (2017), CDW makes up a sizable percentage, varying from 10 to 30%, of the total waste disposed of in landfills worldwide. Also, the construction sector releases up to 40% of CO_2 into the atmosphere and uses 35% of energy (Luangcharoenrat et al. 2019). Therefore, recycling of CDW in the construction sector receives attention from researchers and practitioners nowadays, and this approach has many advantages, more energy efficiency, less carbon footprint, extra economic benefit, and reduction in landfilling (Arabani and Azarhoosh 2012; Arulrajah et al. 2017; Ghorbani et al. 2020). The recycling of CDW in the construction sector is an old idea and its roots can be traced back to the Romans era, who frequently reused the stones in the construction of new roads. There is a big difference in the quantity of CDW being recycled in different regions of the world. Percentage recovery of CDW (recycling and backfilling) in developed countries is up to 100% (Pereira and Vieira 2022); however, in developing countries of Asia and Africa, the situation of CDW recycling is extremely bad.

Concrete waste is the major portion of CDW along soil and gravels, as illustrated in Fig. 2. Usually, this waste is divided into fine and coarse aggregates, and fine aggregates consist of fragments of concrete waste like hardened cement paste, calcium sulfate dihydrate, and other materials. A lot of studies have reported satisfactory results considering physical and mechanical characteristics under different conditions, on utilization of recycled concrete aggregates (RCA) in recycled aggregate concrete (RAC) (Kong et al. 2010; Hannawi et al. 2010; Babu et al. 2015;; Brito et al. 2016; Thomas et al. 2016; Bravo et al. 2018; Taffese 2018; Wichrowska and Morales 2020; Sivamani et al. 2021; Llanes et al. 2022; Abera 2022; Şimşek et al. 2022; Wang et al.

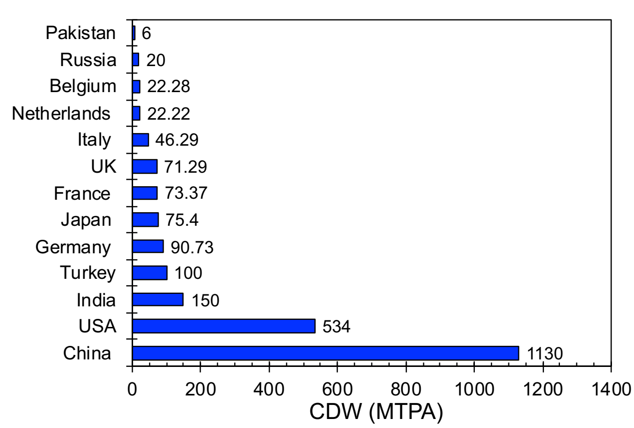

Fig. 1 CDW generation in some populated countries (Hoang et al. 2020; Haider et al. 2022; Swarna et al. 2022; Pereira and Vieira 2022)

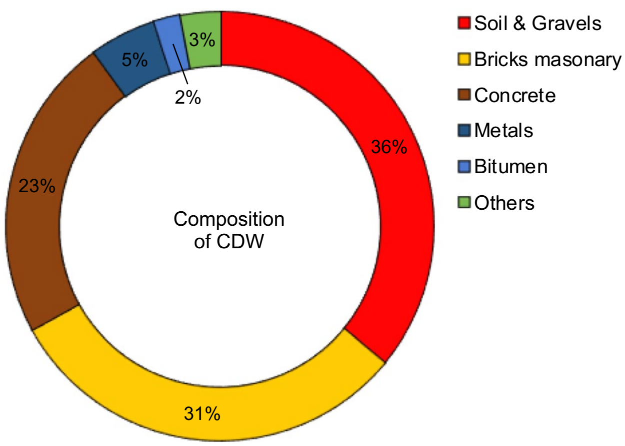

Fig. 2 Composition of CDW (Mohammadinia et al. 2016; Arulrajah et al. 2020; Abera 2022)

2023a, b; Yu et al. 2023; Wang et al. 2023a, b; Liu et al. 2023). On the other hand, many building codes limit the consumption of recycled fine aggregates (RFA) in RAC because of their substandard characteristics (Kong et al. 2010). Because the occurrence of mortar residue and high amounts of fines lead to poor physical and mechanical properties compared to fresh fine aggregates (FFA) (Evangelista et al. 2015; Etxeberria and Vegas 2015). Specifically, the presence of adhered mortar reduces the density and significantly raises the water absorption capacity of RAC, affecting its durability (Pedro et al. 2017). Since fine aggregates make up a major proportion of concrete by volume, it is logical to study the use of RFA as a replacement for FFA in RAC. The benefits of recycling fine aggregates from demolition waste include the lowering of environmental pollution, reduction in increasing demand for landfill space, and lessening the dependency on natural resources for new aggregate to limit the degradation of natural resources (Pedro et al. 2017; Zega and Maio 2011). A concrete structure must perform its intended functions of durability and serviceability throughout its expected life (Singh et al. 2018). Durability is defined as the ability of concrete to resist deterioration (Tang et al. 2015), and RFA has lower durability compared to FFA due to the presence of adhered mortar (Vieira et al. 2016) because deterioration of adhered mortar can occur easily through physical, chemical, or mechanical means (Shen et al. 2020).

However, chemical and mineral admixtures are also used to improve the performance of concrete containing RFA, and the effect of many admixtures, i.e., polymer emulsion, immersion in pozzolan slurry, calcium carbonate biodeposition, and sodium silicate solution, was investigated to strengthen the interface transition zone (ITZ) of RAC having RFA (Kou et al. 2011; Grabiec et al. 2012; Zhu et al. 2013; Cartuxo et al. 2015; Zhang et al. 2015; Shi et al. 2016; Barragan-Ramos et al. 2022). Limited studies have also been conducted to investigate the impact of RFA on mechanical characteristics considering compression strength, tensile strength, density, capillary absorption, modulus of elasticity, etc. of RAC without any additional admixture (Zega and Maio 2011; Lotfy and Al-Fayez 2015; Pedro et al. 2017; Kumar et al. 2018; Kirthika and Singh 2020; Tabsh and Alhoubi 2022). Zega and Maio (2011) explored the durability of structural concretes incorporating varying proportions of RFA, and the results regarding compressive strength and modulus of elasticity indicate that recycled concretes exhibit suitable durability and resistance, meeting international structural concrete standards. Pedro et al. (2017) discussed the strength and durability attributes of RAC by incorporating both RFA and RCA, comparing them with reference concrete, and found that RAC mixes exhibited results similar to regular concrete regarding compressive strength, splitting tensile strength, and modulus of elasticity. Kirthika and Singh (2020) investigated the performance of RFA in concrete considering different durability environments and found that increasing RFA content in concrete initially reduces its durability, but as the concrete ages, it shows improved resistance to water, chlorine, and carbonation. Tabsh and Alhoubi (2022) highlighted the cementitious properties of RFA, which can harden when mixed with water and left to dry, without additional cement, and concrete samples containing RFA showed compressive and tensile strengths comparable to at least 75% of control specimens. Generally, the impact of the proportion of RFA on various properties of concrete, like compressive strength, tensile strength, elastic modulus, and workability, is negative according to the literature. For compressive strength, as the percentage of RFA increases, there's a general trend of decreasing compressive strength (Evangelista and de Brito 2010; Cartuxo et al. 2015; Carro-López et al. 2015; Fan et al. 2016; Zhang et al. 2018). For example, this declined from approximately 59.3 to 54.8 MPa when the percentage of RFA varies from 0 to 100% (Evangelista and de Brito 2010). Similarly, the tensile strength tends to decrease with an increase in the proportion of RFA (Pereira et al. 2012; Kumar et al. 2023), and the tensile strength of RFA-based concrete reduced from about 3.97 to 3.71 MPa when the percentage of RFA varies from 0 to 100% (Kumar et al. 2023). Regarding the elastic modulus, there is also a consistent decline with an increase in the percentage of RFA. According to Pereira et al. (2012) and Kim and Yun (2014), the elastic modulus values dropped from 34,400 to 29,900 MPa and 21,300 to 2090 MPa, when the FFA is completely replaced with RFA, respectively. Generally, concrete workability decreases as RFA content rises due to its rough surface caused by adhered mortar. Moreover, RFA's higher water absorption diminishes concrete workability compared to FFA (Alves et al. 2014; Zhao et al. 2015).

Overall, the literature suggests that using RFA in RAC is beneficial for sustainability. Concrete properties mainly depend on percentage replacement, and the reduction in concrete properties attributed to RFA arises from various recycling challenges. These encompass fluctuations in the physical and chemical attributes of RFA, resulting in inconsistent material supply. Moreover, potential contamination by chlorides and sulfates can jeopardize durability. Lastly, the absence of standardized quality evaluation methods and limited research on appropriate treatment and utilization further constrain RFA's application in new concrete contexts (Nedeljković et al. 2021; Chandru et al. 2023).

To the authors' best knowledge, the literature is scarce on the comprehensive environmental impacts and performance assessment of RFA-based RAC without considering any supplementary additive. The current study aims to utilize the RFA in RAC as a replacement of FFA in a prudent manner to analyze its characteristics such as compressive and tensile strength, strength after chemical exposure, and resistance to rapid chlorine ion penetration. The study layout can be divided into four parts. Firstly, investigate the soundness and abrasion losses at different percentages of RFA by performing soundness and micro-Deval abrasion tests, respectively, and slump tests are also performed to evaluate the workability of fresh RAC. In the second part, a comprehensive study on the compressive strength and tensile strength of RAC is carried out by performing concrete cubes and cylinders considering different curing times and RFA percentages. In the third part, the performance of RFA-based RAC is determined against exposure to different chemicals, and residual compressive strength and mass loss are estimated to evaluate the durability after chemical exposure. Additionally, resistance against rapid chlorine ion penetration is also evaluated at different curing times. In the last part, considering a scenario, the fifteen environmental impacts are estimated and compared for concrete samples having different compositions of FFA and RFA. Moreover, a statistical analysis is also conducted to assess the impact of the partial replacement of FFA with RFA on the performance of concrete considering strength and durability parameters. A diagrammatical illustration of the scope of this study is presented in Fig. 3.

Experimental program

Materials

The RFA used in the current study was prepared after processing the demolished waste of a 45-year-old residential building, and conventional FFA, fresh coarse aggregates (FCA), and ordinary Portland cement were arranged from a local supplier. The sources of FCA and FFA were the Margalla Crush quarry and Lawrencepur quarry, respectively. Because these are considered one of the best sources of aggregates in Pakistan (Khan 2015). In Fig. 4, it can be observed that the grain size distributions of FFA and RFA were kept almost identical to avoid the impact of soil packing on strength, and grain size distributions of all selected aggregates fulfilled the requirements of concrete aggregates outlined by ASTM C33. The coefficient of uniformity (C_u), coefficient of curvature (C_c), and mean size diameter (D_{50}) are 4.67, 0.86, and 0.75 mm, respectively, for FFA and 4.4, 0.92, and 0.5 mm, respectively, for RFA. The C_u, C_c, and D_{50}

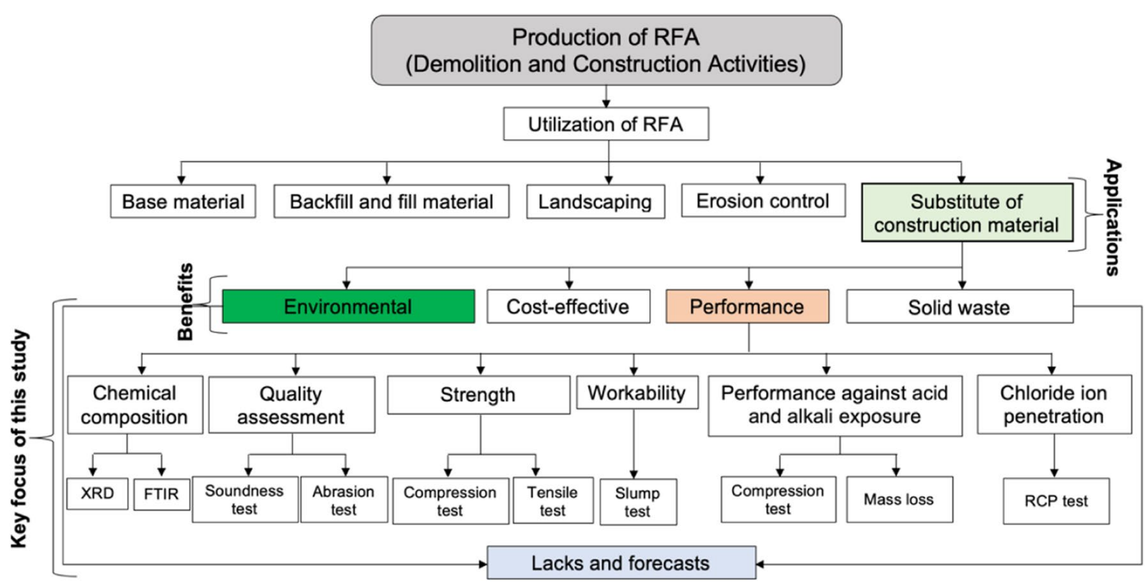

Fig. 3 Diagrammatical illustration of the scope of the current study

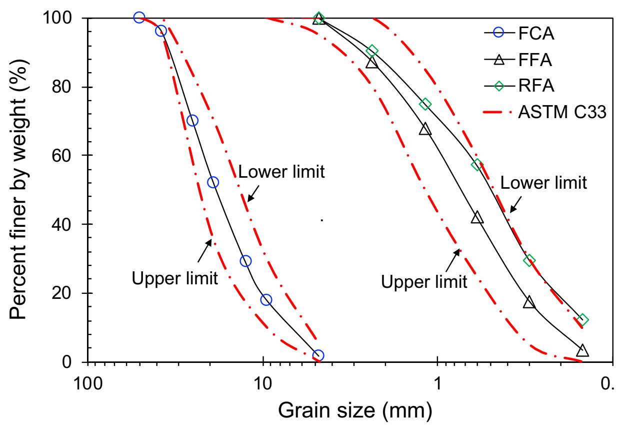

Fig. 4 Grain size distribution of selected materials

of FCA are 3.14, 1.27, and 19 mm, respectively. The physical characteristics of FFA and RFA are also presented in Table 1. To determine the chemical composition of FFA and RFA, wet chemical analysis, x-ray diffraction (XRD) analysis, and Fourier transform infrared spectroscopy (FTIR) were performed. The oxide composition of FFA and RFA is illustrated in Fig. 5 which shows that major oxides in FFA are 75.55% SiO_2, 12.13% Al_2O_3, and 3.38% CaO and dominant oxides in RFA are 67.75% SiO_2, 10.37% Al_2O_3, and 5.45% CaO. XRD analyses were performed to determine the mineralogy of FFA and RFA. The key mineral offered by the XRD analysis of FFA is quartz (Fig. 6a), and major peaks of this mineral are available in XRD spectra at several 2θ angles, including 27°, 30°, 50°, and 55°. Several transformations can be observed in the XRD spectra of RFA (Fig. 6b). The dominant minerals offered by the XRD spectra of RFA are quartz, calcite, and gypsum. The height of several peaks of quarts significantly diminished RFA as compared to FFA. Several small peaks of calcite in XRD spectra of RFA are available at several 2θ angles, including 36°, 43°, 50°, and 60° which indicates the presence of mortar residue and oxide composition of RFA also shows a similar result where the percentage of CaO of RFA is greater than that of FFA (Fig. 5). FTIR is a type of spectroscopic technique used to study the infrared absorption or transmission of a sample. FTIR is used to determine the composition and physical properties of materials, including their thickness, density, and chemical composition. Table 2 and Fig. 7 give the composition of FFA and RFA based on FTIR.

Table 1 Physical characteristics of FFA and RFA

Characteristics	FFA	RFA
Bulk unit weight (kN/m^3)	19.12	17.96
Apparent unit weight (kN/m^3)	28.38	27.81
Water absorption (%)	1.10	1.72
Fineness modulus	2.7	2.6
Specific gravity	2.62	2.48
Soundness loss (%)	8.7	13.3
Micro-Deval abrasion loss (%)	12	31

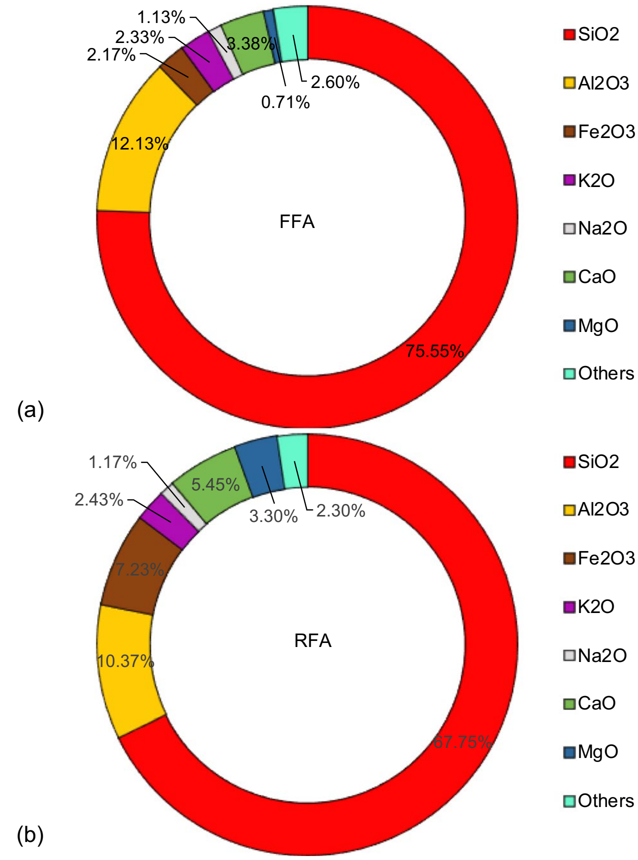

Fig. 5 Oxide compositions of **a** FFA; **b** RFA

Composition of concrete mixes

Several laboratory tests including micro-Deval abrasion test, soundness test, slump test, compression strength tests, tensile strength tests, and rapid chloride permeability test (RCPT) were performed. Additionally, residual compressive strength and mass loss of samples were also determined after chemical exposure to the samples. For this purpose, the detail of component dosages of concrete mixes considering the 1 m^3 concrete is illustrated in Table 3. A total of nine batches were prepared and the FFA was replaced by RFA in the proportion of 0%, 12.5%, 25%, 37.5%, 50%, 62.5%, 75%, 87.5%, and 100% in RAC. The water-to-cement ratio and mix design were kept at 0.5 and 1:2:4, respectively, for all batches. For strength tests, curing time was considered 1, 3, 7, 14, and 28 days. The early age curing periods are crucial to understanding the initial strength development and

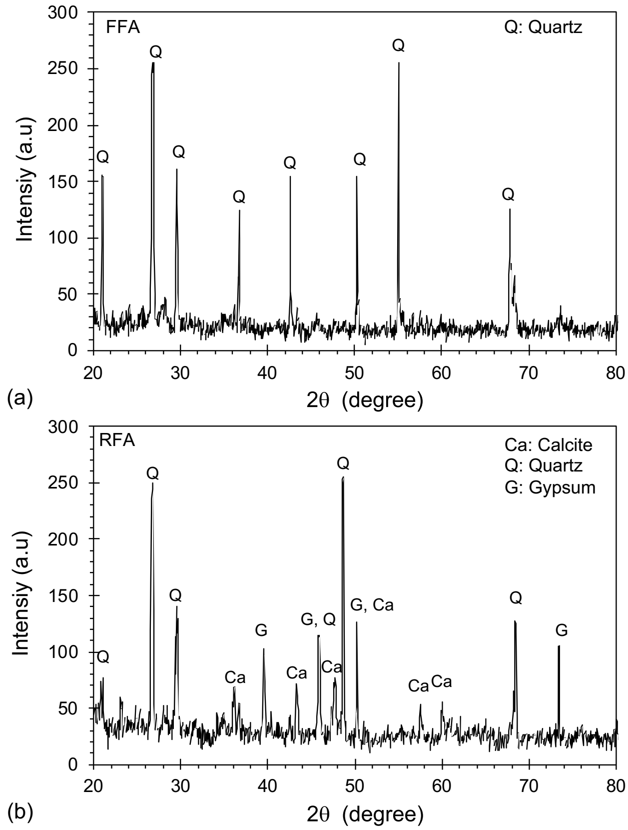

Fig. 6 XRD analyses of **a** FFA; **b** RFA

Table 2 Composition of materials based on FTIR analysis

Chemical composition	Useful range	Wavenumber observed (cm^{-1})
SiO_2	4000–600	2864
Al_2O_3	4000–600	1900
Fe_2O_3	4000–400	615 and 620
K_2O	4000–600	1604
Na_2O	4000–600	1394
CaO	4000–600	1160
MgO	4000–400	1402

durability of concrete structures, and additionally, studying the behavior of concrete during this early age provides valuable insights into the hydration process, which ultimately influences the long-term performance and durability of concrete structures. For RCPT, curing time was considered 28, 56, and 90 days. The 90-day immersion of concrete samples in chemicals was considered after 28 days of curing before estimating the mass loss and residual compressive strength. To evaluate the compressive and tensile strength, concrete cubes and cylinders were cast with sizes of 6″×6″×6″ and

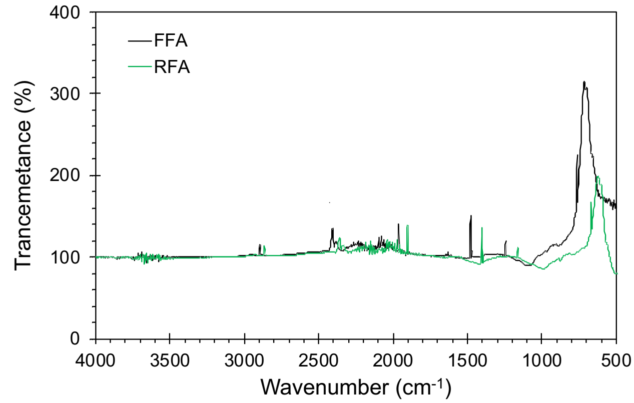

Fig. 7 FTIR analyses of FFA and RFA

6″×12″, respectively. The symbol (*NiRj*) was employed to represent the concrete batches, where *″i″* represents the percentage of FFA and *″j″* represents the percentage of RFA. For instance, the $N_{75}R_{25}$ denotes a batch of concrete composed of 75% of FFA and 25% of RFA.

Tests

The testing campaign comprised mechanical, durability, and aggregate quality tests, and all tests were performed according to ASTM standards. Regarding the mechanical characteristics, splitting tensile strength (ASTM C496), compressive strength of cylinders (ASTM C39), compressive strength of cubes (ASTM C109), and modulus of elasticity (ASTM C469) were determined. To estimate the durability of the concrete mixes, resistance to chloride ion penetration (ASTM C1202) and resistance to chemical exposure (ASTM C1898) concerning residual compressive strength and mass loss were evaluated. To evaluate the aggregate quality, soundness loss (ASTM C88) and micro-Deval abrasion loss (ASTM D6928) were estimated.

Results and discussion

Abrasion and soundness losses

The micro-Deval abrasion test is used to determine the abrasion loss of aggregates in the presence of water as the aggregates are more vulnerable in wet conditions. Recycled aggregates are generally weaker than fresh aggregates which occasionally affect the strength of concrete. Figure 8a illustrates the micro-Deval abrasion loss of samples having different percentages of RFA. With increasing the percentage of RFA, the abrasion loss also increases, and at 63.5% RFA addition, abrasion loss across the maximum permitted limit.

Table 3 Detail of component dosages for concrete mixes considering the 1 m^3 concrete

Batch no	Symbol	Samples	*w/c*	Water (kg)	Cement (kg)	Coarse aggregate (kg)	FFA (kg)	RFA (kg)
B-1	$N_{100}R_0$	Cubes and cylinders	0.5	164	328	1312	656	0
B-2	$N_{87.5}R_{12.5}$						574	82
B-3	$N_{75}R_{25}$						492	164
B-4	$N_{62.5}R_{37.5}$						410	246
B-5	$N_{50}R_{50}$						328	328
B-6	$N_{37.5}R_{62.5}$						246	410
B-7	$N_{25}R_{75}$						164	492
B-8	$N_{12.5}R_{87.5}$						82	574
B-9	N_0R_{100}						0	656

About 158% increment can be observed when RFA is totally replaced with FFA in RAC.

Concrete during its service life faces different environmental impacts such as relative humidity, temperature changes, acid rain, and CO_2 concentration, and these factors affect the durability of concrete over time. The long-term durability of concrete depends on the soundness of aggregates but the aggregates obtained from demolished waste have infrequent characteristics. Thus, the soundness test is essential to evaluate the durability of aggregates against weathering. The soundness loss is a sign of the resistance offered by the aggregates against weathering. It determines the resistance of the aggregates against their breakdown into fragments when dipped in a saturated solution of sodium sulfate (Na_2SO_4) for 18 h under constant temperature. Figure 8b illustrates the soundness loss of samples having different percentages of RFA. With increasing the percentage of RFA, the soundness loss also increases and these values remain within the permitted limit, even at 100% RFA addition. About 53% increment can be observed when RFA is replaced with FFA in RAC. Thus, RFA undergoes more abrasion and soundness losses as compared to FFA in RAC mixture because adhered mortar disintegrates easily under harsh environments. A comparison of soundness and abrasion losses against the replacement percentage of RFA is drawn in Fig. 8c. It can be observed that up to 50% of RFA replacement is beneficial for RAC in the current study and at this percentage of RFA, soundness and abrasion losses increased only about 25% and 46%, respectively.

Workability

To assess the workability of the fresh RAC, slump tests were performed on all concrete mixtures. Figure 9 shows the effect of RFA replacement percentages on the workability of RAC. The results indicated that workability is reduced with an increase in the percentage of RFA. This is caused by the rough surface of RFA as compared to the NFA due to the presence of adhered mortar on the surface of RFA. Secondly, RFA absorbs more water as compared to FFA which results in a reduction of the concrete workability made with RFA. Similar results were also reported by Zhao et al. (2015) and Alves et al. (2014). Approximately 79% reduction in workability is noted when FFA is replaced with RFA in RAC. Up to 40% RCA replacement, the workability of fresh RAC remains within a permitted limit.

Compressive strength

Compressive strength (f_c') of concrete is an essential characteristic to evaluate its performance and depends upon mix design, characteristics of aggregates, amount of water, and curing time (Tabsh and Alhoubi 2022). In the current study, concrete cubes and cylinders were tested to evaluate the f_c'. For concrete cubes, 1, 3, 7, 14, and 28-day curing times were considered, and for concrete cylinders, only 28-day curing was considered. Figure 10 illustrates the impact of curing time and RFA of f_c' determined from concrete cubes. A significant reduction in f_c' can be observed as the replacement of FFA with RFA increased. A similar response of f_c' is discussed in literature due to the addition of RFA (Lofty and Al-Fayaz 2015; Pedro et al. 2017). This decrement response of f_c' is due to the presence of adhered mortar in RFA because this material has less internal strength and adherence as compared to fresh aggregates (Barragan-Ramos et al. 2022). With increasing curing time, the f_c' increases considerably due to the formation of calcium silicate hydrate (CSH) gel caused by the pozzolanic reaction. A comparison of f_c' determined by concrete cubes and cylinders is presented in Fig. 11, at 28 days of curing time, and the f_c' of the concrete cube is about 19% more than the concrete cylinder. Furthermore, a concrete cube made with only FFA has 25 MPa of f_c', and a concrete cube made with only RFA has 17.25 MPa of f_c', at 28 days of curing time. So, approximately 30% reduction in f_c' is estimated when the FFA is completely replaced by RFA in RAC, as illustrated

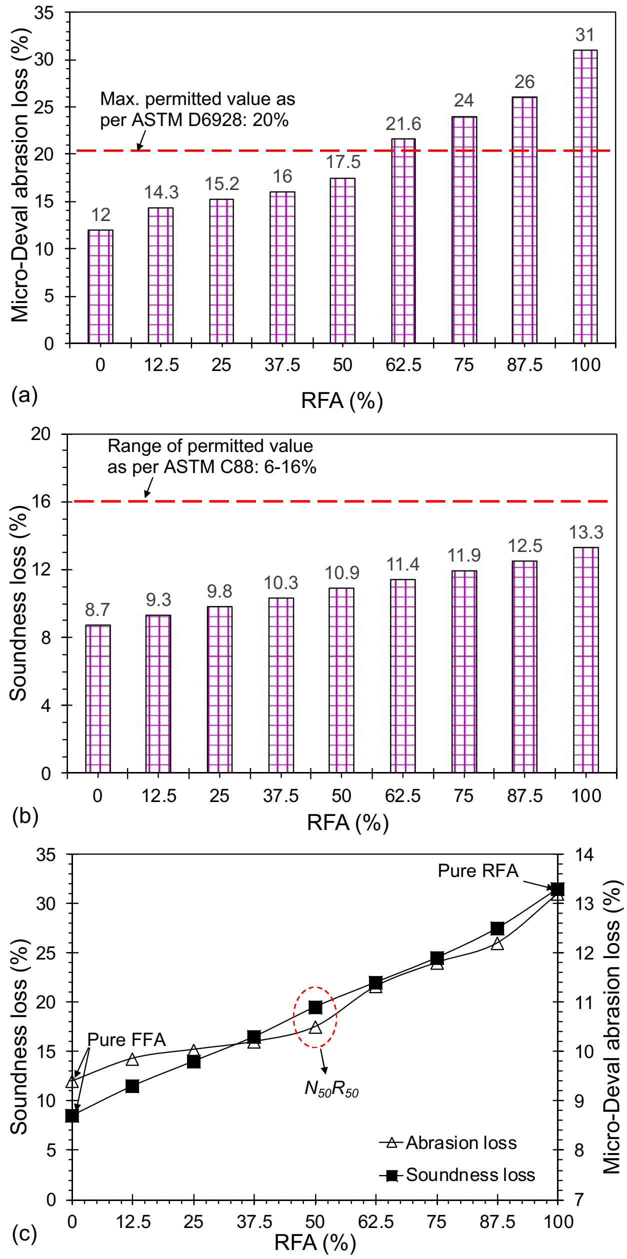

Fig. 8 Quality performance test results. **a** Micro-Deval abrasion loss; **b** soundness loss; **c** comparison of abrasion and soundness loss

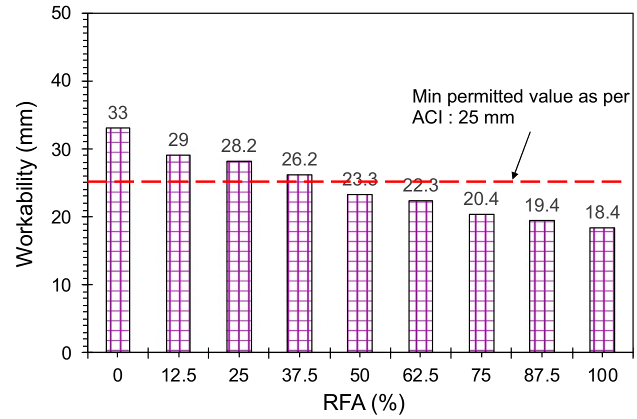

Fig. 9 Effect of RFA on workability of concrete

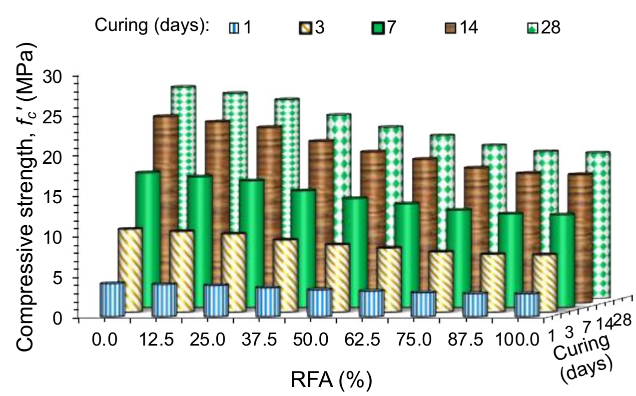

Fig. 10 Effect of curing time and RFA on f_c’ of concrete cubes

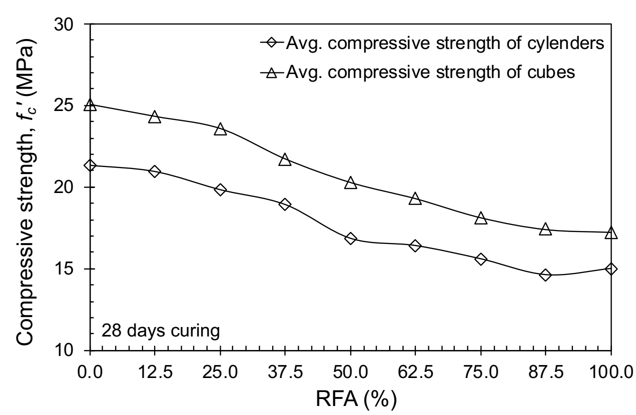

Fig. 11 Comparison of f_c’ determined by concrete cylinders and cubes

in Fig. 13; however, the reduction in f_c’ is insignificant after 87.5% RFA replacement.

Tensile strength

Tensile strength (f_{ctm}) was determined by performing a split tensile test on concrete cylinders and 1, 3, 7, 14, and 28-day curing times were considered. Figure 12 illustrates the impact of curing time and RFA of f_{ctm}. A significant reduction in f_{ctm} can be observed as the replacement of FFA with RFA increased, due to the presence of weak adhered mortar in RFA. With increasing curing time, the f_{ctm} increases noticeably caused by the generation of more CSH gel. Additionally, the f_{ctm} of a concrete cylinder made with only FFA has 2.36 MPa of f_{ctm}, and a concrete cylinder made with only RFA has 1.53 MPa of f_c’, at 28-day curing time. So, approximately

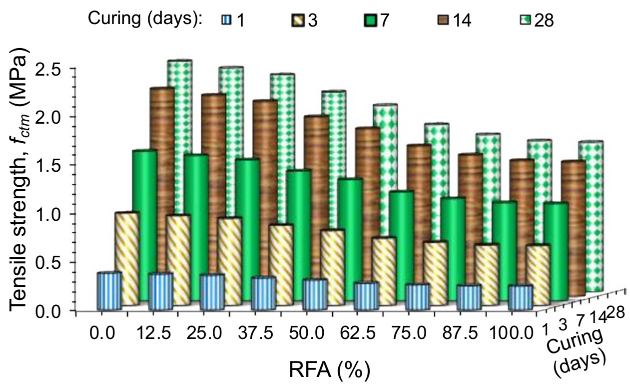

Fig. 12 Effect of curing time and RFA on f_{ctm} of concrete

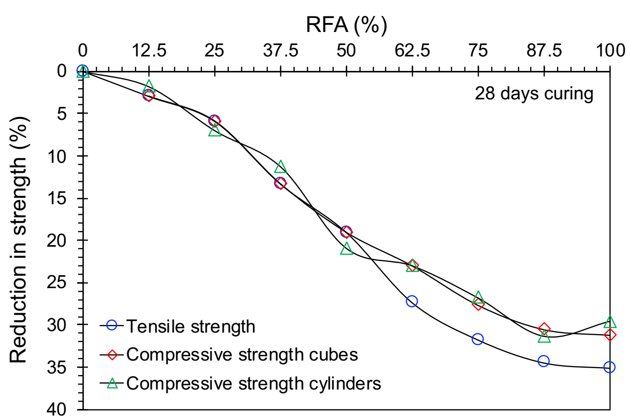

Fig. 13 Effect of RFA on reduction of strength

35% reduction in f_{ctm} is measured when the FFA is completely replaced by RFA in RAC, as illustrated in Fig. 13; though, reduction in f_{ctm} demonstrates the response similar to f_c' after 87.5% replacement of FFA with RFA. Reduction in f_{ctm} is more compared to f_c' due to increment of RFA percentage in RAC.

A linear relationship between f_c' of concrete cubes and the f_{ctm} of concrete cylinders is also developed at different curing times and RFA percentages in Fig. 14a. The correlation coefficient (R^2) value of this relationship is 0.996 which is quite good and reliable.

$$f_{ctm} = 0.0935f_c' - 0.0181 \tag{1}$$

Similar linear relationships between f_c' and RFA and f_{ctm} and RFA are established in Fig. 14b, considering the curing time of 28 days. The R^2-values of these relationships are also reliable.

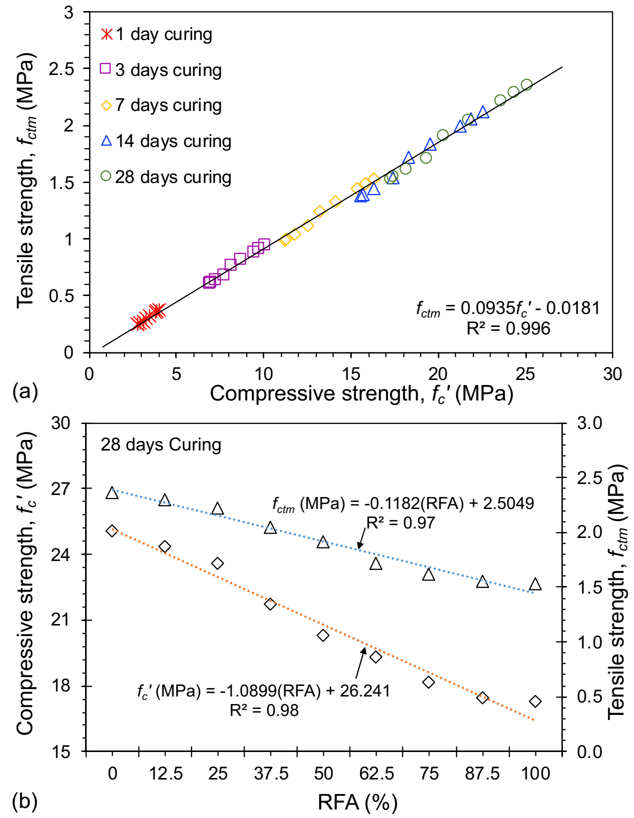

Fig. 14 Relationships of **a** f_c'-f_{ctm}; **b** RFA-f_c' and f_{ctm}

Modulus of elasticity

Modulus of elasticity (E_c) results concerning RFA replacement in RAC are illustrated in Fig. 15a at 28-day curing time. Reduction in E_c can be detected as the replacement of FFA with RFA increases, and about a 20% reduction in E_c is determined when the FFA is completely replaced by RFA in RAC. However, the reduction in E_c is also insignificant after 87.5% RFA replacement. Several studies have discussed a similar behavior of E_c of concrete due to the addition of RFA (Pedro et al. 2017). This can be clarified by the fact that the inclusion of RFA decreases the stiffness of both the mortar and the aggregates. The E_c of concrete is influenced by the E_c of its aggregates, which can be affected by the poor performance of RFA. As concrete with a lower E_c is more prone to cracking, the observed drop in E_c may have consequences regarding the durability of concrete structures. The E_c of concrete is a gauge to measure the resistance against deformation under load, so, it directly relates to the f_c' of concrete. The relationship between f_c' and E_c of RAC having different percentages of RFA is given in Fig. 15b, with an R^2-value of 0.99, which indicates that it will give about 99% accurate predictions.

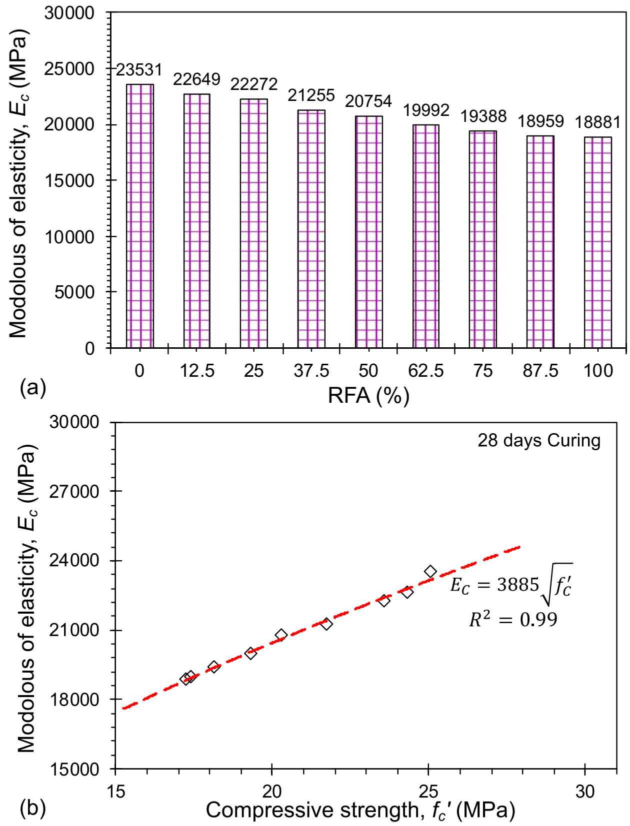

Fig. 15 Effect of RFA on **a** E_c; **b** f_c'-E_c

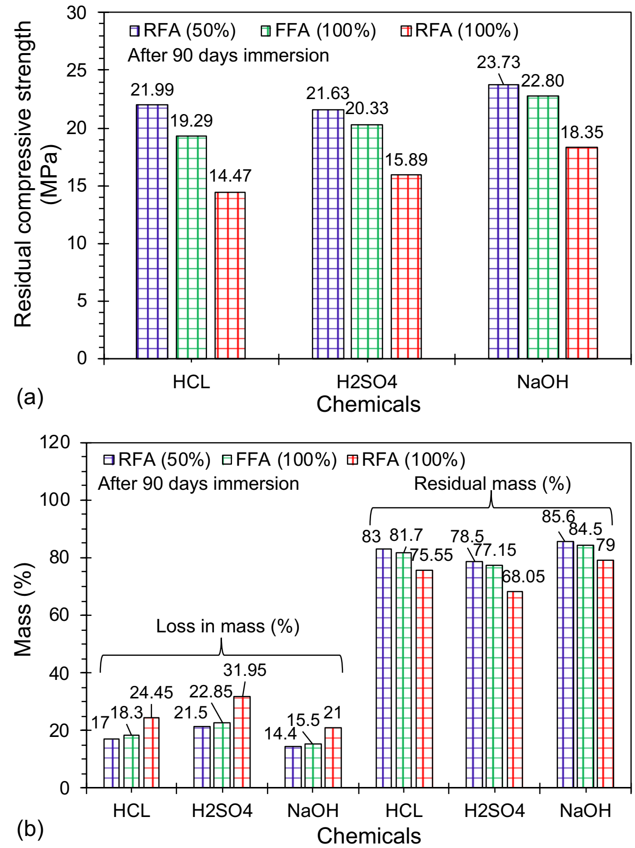

Fig. 16 Effect of 90 days of chemical exposures on **a** residual compression strength; **b** mass loss, after 28 days of curing

Resistance to chemical exposure

Resistance against chemical exposure of concrete samples was also evaluated in terms of mass loss and residual compressive strength in the current study. For this purpose, two acids, i.e., hydrogen chloride (HCL) and sulfuric acid (H_2SO_4), and one alkali, i.e., sodium hydroxide (NaOH), were used. Concrete samples of three batches ($N_{100}R_0$, $N_{50}R_{50}$, and N_0R_{100}) were immersed for 90 days in concentrated H_2SO_4, HCL, and NaOH, after 28 days of curing. The normality of all solutions was kept at 1N. The concentration of 1N HCL and NaOH solutions is 1 mol/L, and the concentration of 1N H_2SO_4 solutions is 0.5 mol/L. It is observed that residual compressive strength decreases with increment of RFA replacement in all three cases (Fig. 16a) but the effect of acids on residual compressive strength is more as compared to alkali. However, concrete samples from the $N_{100}R_0$ batch have about 22%, 25%, and 19.5% more residual compressive strength than concrete samples from the N_0R_{100} batch after 90 days of immersion in concentrated H_2SO_4, concentrated HCL, and NaOH, respectively. Concrete samples from $N_{50}R_{50}$ have higher residual compressive strength than the other two batches in all three cases, and concrete samples from the $N_{50}R_{50}$ batch have approximately 6%, 12.3%, and 4% higher strength than concrete samples from the $N_{100}R_0$ batch after immersion in concentrated H_2SO_4, concentrated HCL, and NaOH at 90 days, respectively. The primary cause of the deterioration of all batches was the collapse of hydration bonds when they came in contact with chemicals, and the presence of adhered mortar in batches having RFA considerably contributed to the samples' disintegration (Guo et al. 2018). That is the reason for the mass loss of concrete samples when those immersed in chemicals. Loss in mass and residual mass after 90 days of immersion in chemicals is illustrated in Fig. 16b. Mass loss and residual compressive strength are directly related to each other because concrete samples with higher mass loss have less residual compression strength, especially in samples immersed in acids. Concrete samples immersed in H_2SO_4 have the highest mass loss and samples immersed in NaOH have the lowest mass loss.

Resistance to chloride ion penetration

Rapid chloride penetration tests (RCPT) were performed on all batches to estimate the chloride ion penetration at 28, 56, and 90 days of curing (Fig. 17). With increasing RFA

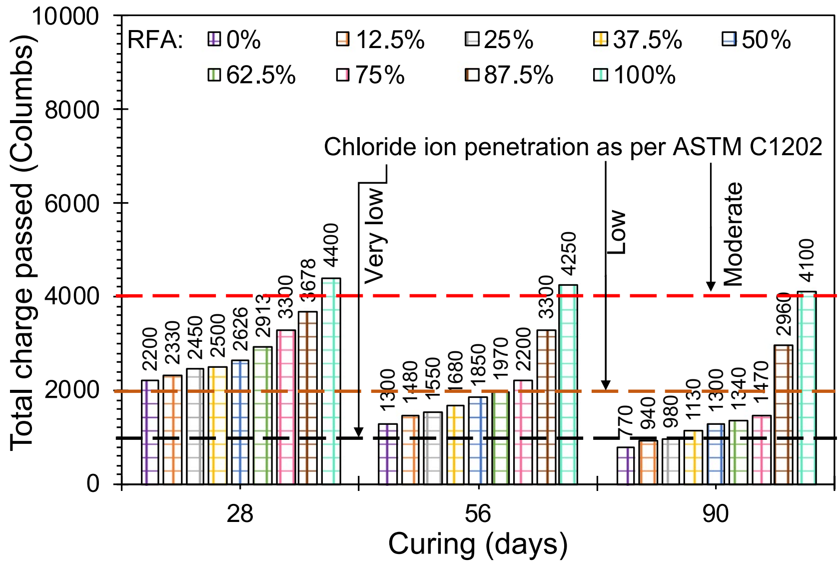

Fig. 17 Effect of curing and RFA on RCPT results

percentage in RAC, the charge passed increases rapidly but the impact of curing on charge passed is positive. Here, the charge passed represents the resistance to chloride ion penetration. If the value of charge passed of a sample is high, it means the sample will offer less resistance to chloride ion penetration. The aforementioned response of charge passed against RFA percentage and curing time is consistent with some studies (Silva et al. 2015; Kim et al. 2018). The soil structure of RFA is more porous than FFA which reduces the resistance against chloride ion penetration (Bravo et al. 2018). So, with increasing the percentage of FFA, the liquid absorption capacity of RAC increases.

It can be observed at 28, 56, and 90 days of curing, most of the samples achieved "Low" and "Moderate" classifications with values varied from 1000 to 2000 and 2000 to 4000 Coulombs, respectively, and the samples up to 25% RFA replacement also achieved a "Very Low" classification among 0 and 1000 Coulombs at 90-day curing. Concrete samples from the N_0R_{100} batch are placed outside the "Moderate" classifications at all curing. With increasing curing, resistance to chlorine ion penetration increases regardless of the RFA content. This is because the formation of CSH gel fills the void and densifies the samples with time, which enhances chloride ions' resistance to penetrate (Kirthika and Singh 2020).

Statistical analysis of the experimental data

In the current study, a statistical analysis was conducted to assess the impact of the partial replacement of FFA with RFA on the performance of concrete. The analysis focused on evaluating the effects on various properties of the concrete, including strength, workability, modulus of elasticity, resistance to chemical exposure, and resistance to chloride ion penetration. The same analysis was done for abrasion resistance and soundness of FFA and RFA. For each property, *P*-values were calculated based on comparable data sets. *P*-values below 0.05 were considered statistically significant, indicating a notable difference between the data sets at a 95% confidence level or a significance level of 0.05. Table 4 presents the *P*-values obtained for the different concrete properties, comparing the controlled samples with the RFA-modified samples. The statistically significant differences observed at a 95% confidence level demonstrate that the use of RFA does not have any significant negative effects on the performance of the concrete. These findings suggest that replacing FFA with RFA up to 50% can result in satisfactory concrete performance and emphasize the importance of selecting appropriate materials for construction purposes.

Table 4 Statistical analysis of experimental data of FFA based concrete and RFA based RAC

Property	*P*-values <0.05 (95% confidence level)	
	$N_{100}R_0$	$N_{50}R_{50}$
Compressive strength	0.0076	0.0035
Tensile strength	0.041	0.018
Workability	4.45E−05	1.91E−03
Modulus of elasticity	0.056	0.043
Residual compressive strength	0.0041	0.0037
Mass loss	0.0056	0.0049
Resistance to Cl^- penetration	3.75E−05	1.41E−03
	FFA	RFA
Abrasion resistance	0.0032	0.0011
Soundness	0.0067	0.0051

By employing statistical analysis techniques, it is possible to determine and quantify the influence of RFA on concrete performance, thereby enhancing the efficiency of building design and construction practices.

Environmental implications

Environmental impact assessment

In the current study, to evaluate the impact of replacing FFA with RFA in concrete on the environment, Hossain et al. (2016) proposed mid-point environment impacts of RFA and FFA. These impacts are mineral extraction, non-renewable energy, global warming potential, aquatic eutrophication, land occupation, aquatic acidification, terrestrial acid, carcinogens, non-carcinogens, respiratory in-organics, ionizing radiation, terrestrial ecotoxicity, respiratory organics, and ozone layer depletion. To estimate these impacts for FFA obtained from crushed stones, the processes and system boundary considered were material extraction, scalping screening, crushing and sieving, vessel loading, transport to site, and on-site handling, and during all these processes, energy is required in form of electricity or fuel. For RFA, the processes and system boundaries considered were on-site sorting, transport to the crushing plant, crushing and sieving, on-site transport and handling, and transport to the site. The environmental impacts of generating 1 ton of fine aggregates (FFA and RFA) are illustrated in Table 5.

Sustainable environmental impacts of replacing FFA with RFA in concrete are estimated considering the quantity of concrete required for a five-story residential building having a cover area of 2455 m^2. In the literature, the approximate volume of concrete with respect to the area is 0.038 m^3/ft^2 and the approximate density of concrete is 2.54 tons/m^3. So, considering these values and the mix design of concrete, the weight of FFA and RFA are determined for $N_{100}R_0$, $N_{50}R_{50}$, and N_0R_{100} samples, and then the aforementioned environmental impacts are estimated for these samples having different compositions of FFA and RFA, as presented in Fig. 18. It can be observed that sample having 100% RFA have low values of environmental impact indicators than the sample having 100% FFA. Even the 50% RFA sample has significantly low values of impact indicators as compared to the 100% FFA sample. In addition, considering some crucial environmental impacts such as global warming potential, aquatic eutrophication, and aquatic acidification, replacing 50% FFA with RFA in concrete reduces these impacts by about 47%, 40%, and 18%, respectively, as compared to concrete having 100% FFA. This implies that the substitution of RFA for FFA in concrete can result in a considerable constructive impact on the environment, and the consequent decrease in demand for FFA generation also leads to a reduced depletion of natural resources. By utilizing RFA instead of FFA, construction projects can meaningfully contribute to a more sustainable built environment, thereby aligning with the principles of sustainable development.

Table 5 Environmental impacts of fine aggregates for life cycles assessment (modified after Hossain et al. 2016)

Impact category	Units	FFA (CS)	RFA (CDW)
Mineral extraction	MJ surplus	0.1	0.11
Non-renewable energy	MJ primary	518	235
Global warming potential	kg CO_2 eq	33	12
Aquatic eutrophication	kg PO_4 P-lim	0.0007	0.0003
Aquatic acidification	kg SO_2 eq	0.19	0.13
Land occupation	m^2org.arable	0.01	0.008
Terrestrial acid	kg SO_2 eq	1.29	0.98
Carcinogens	kg C_2H_3Cl eq	0.05	0.05
Non-carcinogens	kg C_2H_3Cl eq	0.03	0.02
Respiratory in-organics	kg PM 2.5 eq	0.05	0.03
Ionizing radiation	Bq C-14 eq	40	51
Terrestrial ecotoxicity	kg TEG soil	44	25
Aquatic ecotoxicity	kg TEG water	879	282
Respiratory organics	kg C_2H_4 eq	0.02	0.006
Ozone layer depletion	kg CFC-11 eq	9.91E − 07	4.43E − 07

CDW management in developing countries

Usually, a major portion of CDW is generated as a result of the renovation, new construction, and demolition activities in developed countries, but in developing countries, the key reason for CDW generation is natural disasters as compared to the reasons above. Only in Pakistan, houses destroyed and damaged in the last two decades 1.88 million and 3.19 million, respectively, due to floods and earthquakes (ADB and WB 2005; ADB 2010; OCHA 2022). More details regarding other structures are presented in Fig. 19. According to the initial report of UNDP, 273000 buildings in Turkiya and 9100 buildings in Syria collapsed due to a recent earthquake. Ample resources are required for sustainable waste management of CDW generated due to natural disasters and it is a worrisome issue in developing countries. Several environmental and social issues are linked with CDW generation such as (a) health risks for workers and handlers; (b) wastage of resources including materials, labor, and energy; (c) esthetic impacts in case of mismanagement; (d) disposal cost of CDW; (e) need of landfill space for safe disposal of CDW; (f) pollution caused by hazardous materials; (g) consumption of energy requires for manufacture, transport, and dispose of CDW; (g) habitats destruction due to extraction of raw materials for new construction; and (h) climate change due to greenhouse gas emissions. Developed countries are doing a lot of research to tackle these issues sustainably.

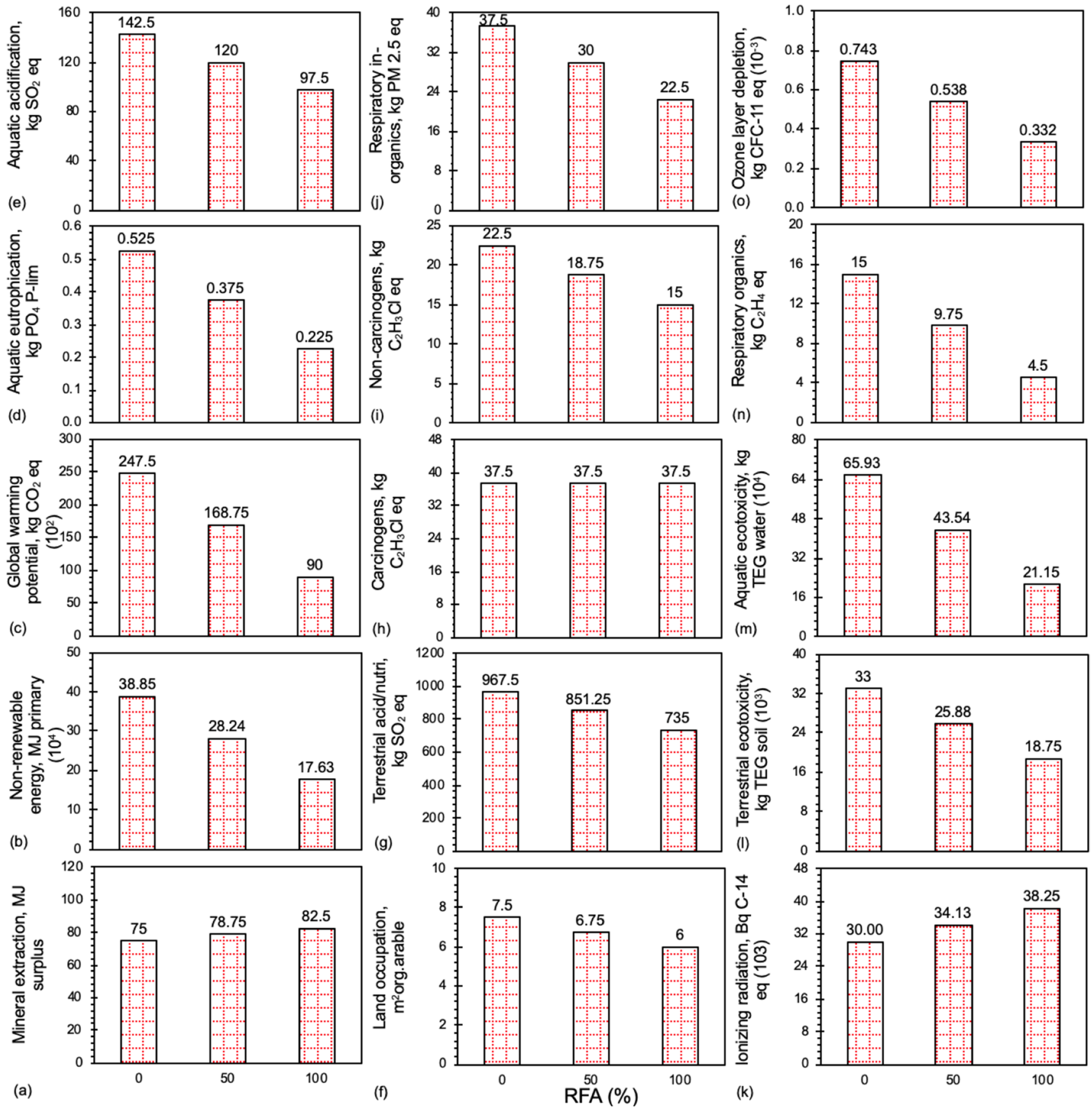

Fig. 18 Environmental impacts assessment of RFA and FFA usage in concrete

Annual CDW generation in different countries of Europe is illustrated in Fig. 20, and recovery of CDW in most of the countries is more than 70% except Cyprus, Romania, and Slovak Republic, as shown in Fig. 21 (EEA 2020). Even the recovery of CDW of several developed countries is more than 90%. However, in some developed countries like China, the recycling and reuse rate of CDW is less than 5% (Huang et al. 2018). So, the CDW recovery rate of developing countries is substandard and mismanagement of CDW is a common practice.

Mismanagement of CDW has serious negative impacts on the environment, economy, and society, as discussed in Table 6. CDW management in developing countries can be a challenging task due to the lack of proper infrastructure and regulations in place. However, some steps can be taken to manage CDW in these countries effectively:

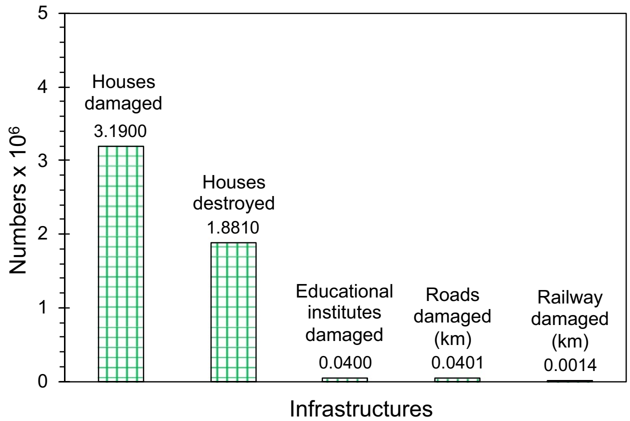

Fig. 19 Infrastructure damages during floods in 2010 and 2022 and earthquake in 2005 in Pakistan (ADB and WB 2005; ADB 2010; OCHA 2022)

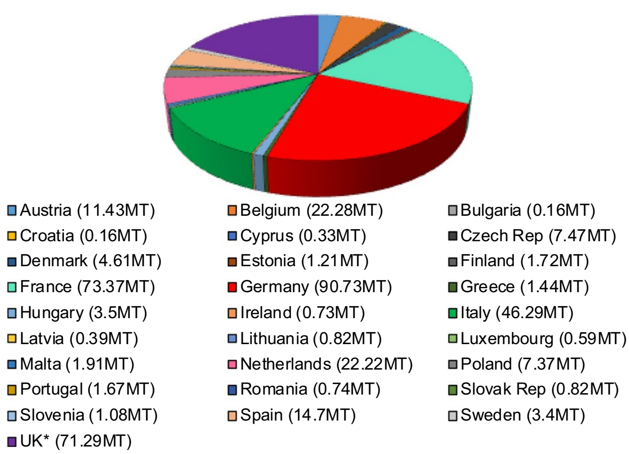

Fig. 20 Annual CDW generation in EU (modified after EEA 2020)

1. Plan: Standard operating procedures (SOPs) and guidelines must be developed according to local conditions to sort and manage CDW. This may include the separation of recyclable materials and the identification of disposal locations for non-recyclable waste.
2. Need for professional demolition company: Professional demolition companies must be hired to demolish the infrastructures and these companies must have the expertise and equipment needed to manage CDW safely and efficiently.
3. Recycle and reuse: It is important to recycle the CDW as much as possible to reduce the amount of material that ends up in landfills. Many materials, such as metal, concrete, and wood, can be recycled or reused easily in the current scenario.
4. Follow proper disposal procedures: It is important to develop appropriate SOPs to dispose of non-recyclable waste including hazardous materials, according to available resources.
5. Implement proper training: Proper training for workers can help to ensure that CDW is properly sorted and managed. This training must include proper handling and disposal of hazardous materials.

Recycling and reusing CDW in the construction of new infrastructures is the most common approach these days and a lot of research has been conducted on this issue. CDW can be effectively reused in different infrastructures as fill material, subbase, and base material, replacement of aggregates in both concrete and asphalt concrete, etc. The use of recycled CDW in construction projects will also contribute to the UN's 2030 Sustainable Development Goals (SDGs) and the circular economy, as shown in Fig. 22. Four SDGs are covered when recycled CDW is used in civil engineering projects; moreover, recycling flow chart of eco-friendly utilization of RFA is illustrated in Fig. 23.

Considering the preceding discussion, the current study is closely linked to achieving the goals of sustainable infrastructure development, waste management practices, responsible consumption and production, and reduction in global warming. Promoting sustainable practices in the

Fig. 21 Recovery of CDW in EU (modified after EEA 2020)

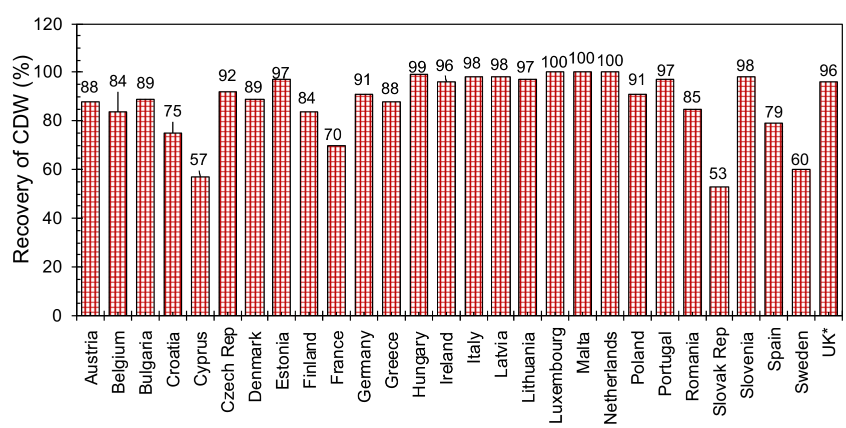

Table 6 Devastating impacts of construction waste (modified after Tafesse et al. 2022)

Sr. no	Impact of construction waste	References
1	Contamination of the environment by releasing chemicals	Coelho and Brito (2012), Hossain and Ng (2019)
2	Reduce the GDP contribution of construction companies	Jawad and Omar (2016)
3	Project cost exceeds the estimated costs	Eze et al. (2016), Olusanjo et al. (2014)
4	Drop in profit and failure of construction companies	Enshassi et al. (2010)
5	Sickness linked with extreme levels of air pollutants	Nguimalet (2007)
6	The drop-in sustainability in the construction industry	Castellano et al. (2016)
7	Delay of the project timeline	Memon et al. (2020)
8	Dumping of CDW near water body caused water pollution	Olusanjo et al. (2014)
9	Land possession or land usage for dumping wastes	Yeheyis et al. (2013)
10	The overconsumption of natural resources leads to depletion	Ignacio et al. (2011)
11	Contamination of soil by chemicals and other materials	Edwards (2014)
12	Traffic overcrowding or traffic jam	ELARD and GAA (2009)
13	The impact on biodiversity and the destruction of the natural habitat	ELARD and GAA (2009)
14	Hazards to public health and safety	Tafesse (2021)
15	The blockage due to CDW debris caused flooding	ELARD and GAA (2009)
16	The release of CO_2 into the atmosphere leads to changes in the climate	Baek et al. (2013)
17	Increase disposal of prohibited waste	Tafesse et al. (2022)
18	Rise price of natural materials, increase in landfill costs, costs for the transportation of waste	Tafesse et al. (2022)

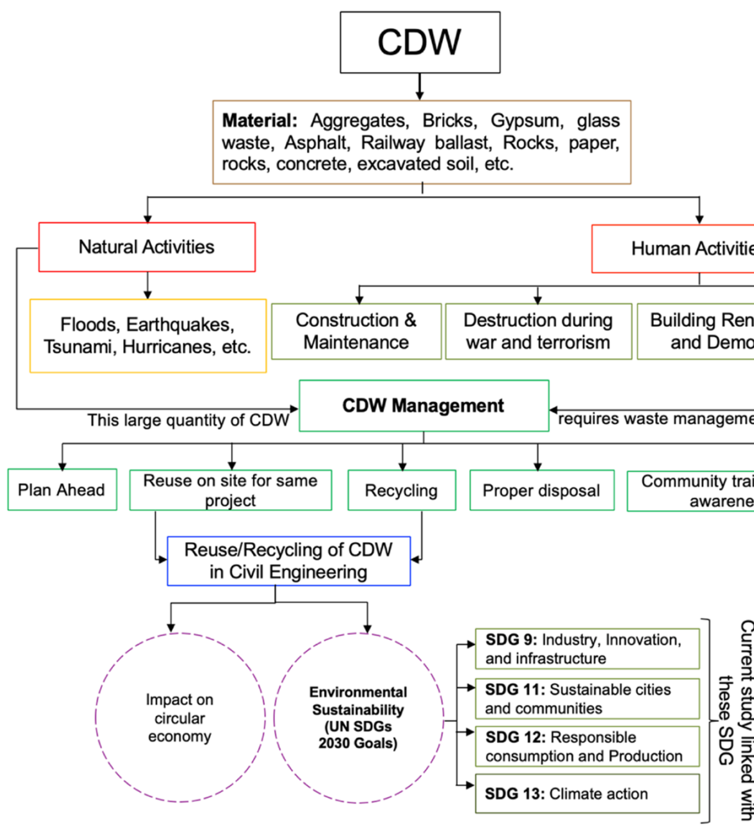

Fig. 22 Utilization of recycled CDW in construction projects to achieve SDGs and circular economy

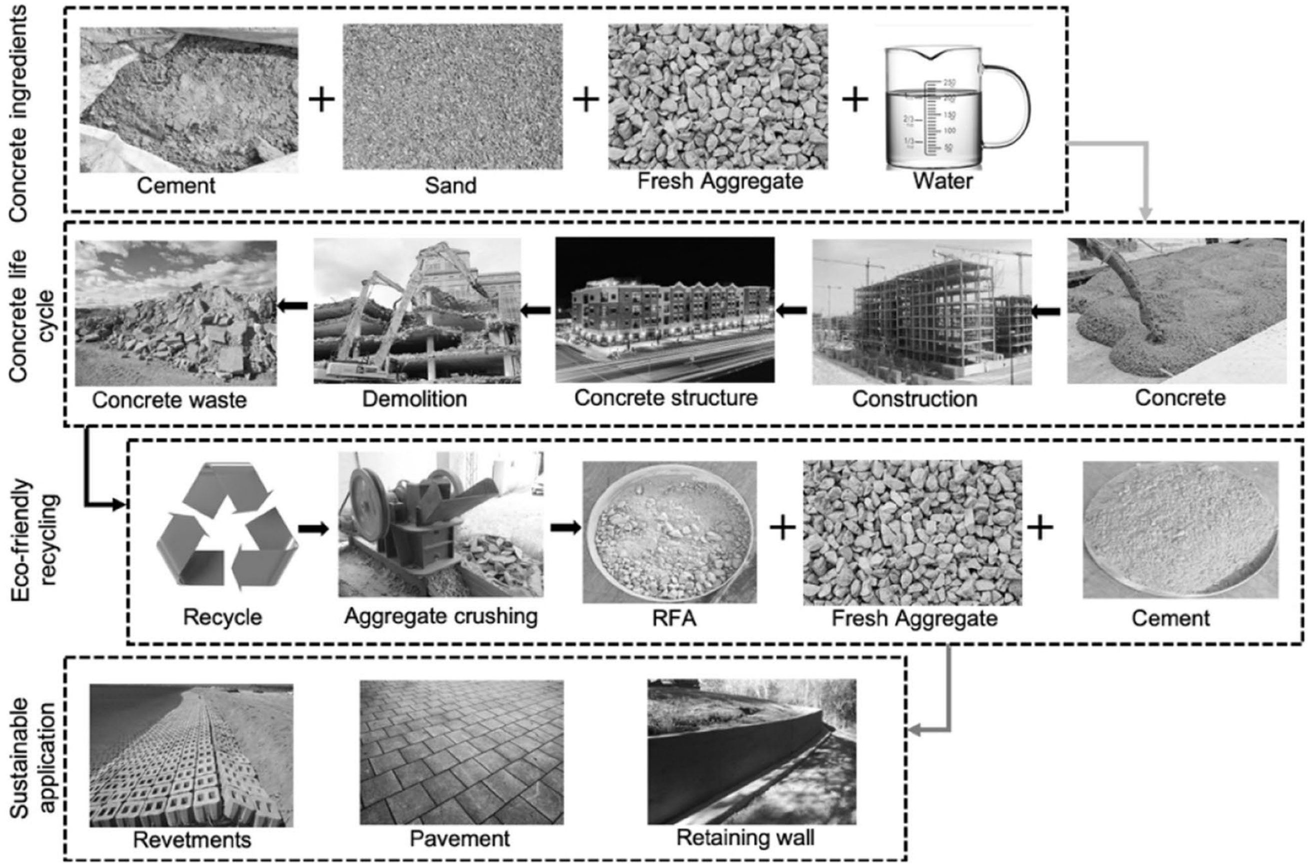

Fig. 23 Flow chart of RFA for eco-friendly civil engineering projects

construction industry also encouragingly contributes to achieving the SDGs and enhances the circular economy by keeping the resources in use for as long as possible.

Conclusions

The key objective of the current study was to reutilize the RFA in RAC as a replacement for FFA in a practical approach to analyze its strength and durability characteristics. For this purpose, an extensive laboratory testing plan was developed and executed sensibly and drew the following key conclusions.

- The influence of RFA on soundness loss and micro-Deval abrasion loss is significant. With increasing RFA percentage, a substantial increment in the values of these parameters is noted. Soundness loss and micro-Deval abrasion loss increased by approximately 53% and 158%, respectively, when RFA was replaced with FFA in RAC. Hence, RFA undergoes more soundness and abrasion losses than FFA due to the breakdown of adhered mortar under tough conditions. From the analysis of these two test results, it is determined that up to 50% of RFA replacement is beneficial for RAC in the proposed scenario because micro-Deval abrasion loss remained within the maximum permitted limit up to the mentioned replacement.
- The workability of fresh concrete decreased by about 79% when FFA was replaced with RFA because the water absorption ability of RFA is greater and has a rough surface. The value of workability is more than the minimum permitted value of up to 40% RFA replacement.
- The deleterious impact of RFA replacement in RAC with FFA is observed on strength characteristics, i.e., f_c', f_{ctm}, and E_c. About 30%, 35%, and 20% reduction are estimated in these parameters, respectively, when FFA is completely replaced with RFA in RAC. However, the reduction in these parameters is insignificant after 87.5% RFA replacement. The less internal strength of adhered mortar in RFA is the reason for the decline of strength characteristics. Furthermore, the impact of curing on f_c' and f_{ctm} is constructive due to the formation of CSH gel with time which binds the concrete aggregates tightly.
- Residual compressive strength significantly decreased than the compressive strength after 90 days of exposure

to chemicals like HCL, H_2SO_4, and NaOH. Mass loss and residual compressive strength are directly related to each other. Overall, the impact of acids on strength and mass loss is more than that of alkali. Concrete samples from the $N_{100}R_0$ batch have more residual compressive strength and less mass loss than concrete samples from the N_0R_{100} batch after 90 days of immersion in chemicals. It means the addition of RFA decreases the resistance of concrete against chemical exposure.

- Resistance against chloride ion penetration considerably decreased with increment of RFA percentage in RAC due to the porous nature of RFA. However, curing increased the resistance of RAC against chloride ion penetration substantially as pores are filled with CSH gel. Most of the samples at different curing and RFA percentages were placed within the "Moderate" classification except samples from the N_0R_{100} batch.
- Significant reduction in environmental impact indicators noted due to replacement of FFA with RFA in concrete. Major environmental impacts such as global warming potential, aquatic eutrophication, and aquatic acidification were reduced by 47%, 40%, and 18%, respectively, for concrete having 50% RFA as compared to concrete having 100% FFA. Additionally, it's found from statistical analysis of experimental data that replacing FFA with RFA up to 50% has satisfactory concrete performance in terms of strength and durability.

Implementation of CDW management in true spirit can save the substantial resources of developing countries, which can be utilized in other development schemes and for the well-being of the people. The approach proposed in the current study to utilize the CDW like RFA in concrete as a replacement for FFA is thoroughly associated with accomplishing the goals of waste management practices, sustainable infrastructure development, reduction in CO_2 emission, and responsible consumption and production.

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Author contribution MMS: conceptualization, methodology, validation, investigation, writing original draft, formal analysis, and visualization.

UK: conceptualization; data curation; resources; validation; writing—review and editing; and visualization.

HM: resources and writing—review and editing.

SAZN: visualization and data curation.

SM: resources and formal analysis.

Data availability The datasets used during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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