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Reference

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ABSTRACT

This research aims to examine the effects of multistage processing on reducing the old cement fractions and enhancing the quality of concrete recycled aggregate (CRA). The investigation involves the use of demolished concrete debris and subsequent treatments in both single and multistage processes. The recycled aggregates (RAs) were obtained using a multistage jaw crushing process followed by utilizing natural aggregate, untreated RA, RA treated with hydrochloric acid (HCl) and sodium silicate (SS) immersion (single-stage treatment), and RA treated with mechanical scrubbing and SS immersion in two separate stages (multistage treatment). The subsequent phase of the experimental inquiry involves assessing the physical attributes of both treated and untreated RA. This is followed by conducting microstructural examinations utilizing techniques such as scanning electron microscopy, energy-dispersive X-ray spectroscopy, X-ray diffraction, Fourier transform infrared spectroscopy (FTIR), and thermogravimetry-differential thermal analysis. The findings indicate that employing a two-step process, involving mechanical abrasion followed by immersion in SS, yields high-quality CRA. This conclusion is reinforced by the favorable physical performance observed. The water absorption values of CRA were lowered by 78 % through single-stage treatments such as immersion in HCl. The similar treatment is found to show densest concrete with calcium/silicon ratio reduced to around 81 % to that of untreated CRA. Additionally, for single-stage treated CRA samples, microstructural study using FTIR verified the creation of additional hydration products, whereas for two-stage treated CRA specimens, thermogravimetric analysis demonstrated the formation of stable CSH. According to the findings, it is advised to use a multistage process of jaw crushing, then treating it with mechanical abrasion and SS. This has the ability to improve the physical, chemical, and microstructural properties of CRA.

Keywords

concrete recycled aggregates, multicycle processing, hydrochloric acid, mechanical scrubbing, sodium silicate treatment, microstructure, sustainability

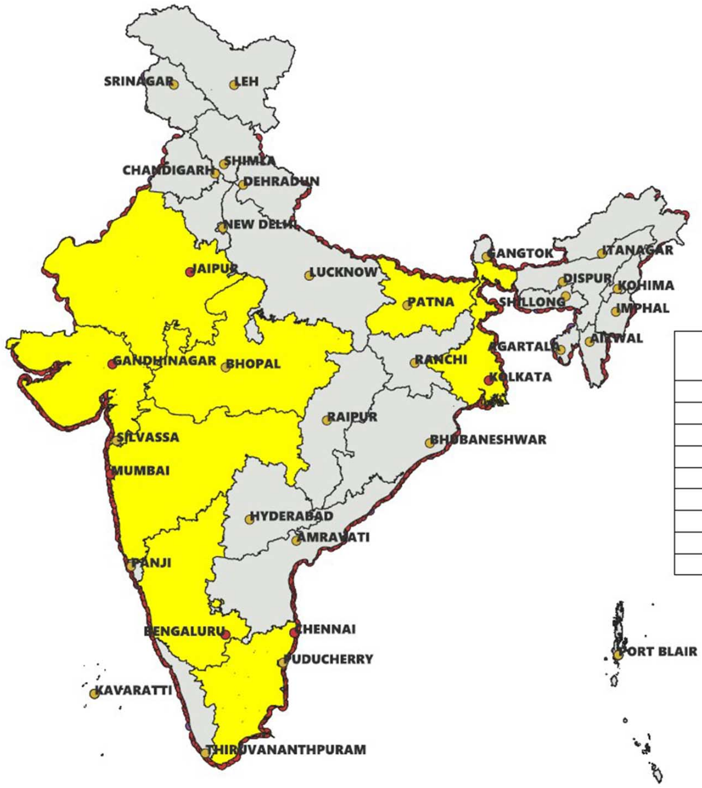
Introduction

The availability of crushed concrete has significantly increased because of the demolition of outdated buildings and the surplus concrete generated from current construction projects.[1] The primary factors contributing to the accumulation of this debris can be attributed to the deteriorating state of the buildings and the fact that they have exceeded their lifespan, along with other solid structures.[2] Furthermore, both developing and developed nations are generating substantial quantities of construction and demolition waste (CDW) as a result of rapid urbanization, industrial growth, and increasing populations.[3] China and Russia, the United States, and India account for the majority of the world's CDW production, with rates of 1,020 million metric tonnes, 600 million metric tonnes, and 400 million metric tonnes per year, respectively.[4] Additionally, numerous studies claim that the ongoing buildup of CDW results in potential risks to safety such as landslides, contamination to groundwater, and other problems,[5] and expanding landfill prices owing to the land space crunch.[6–8] On the other hand, governing entities are gravely concerned about the ongoing diminution of natural aggregates and the lack of accessible terrestrial positions.[9] From this point forward, the use of recycled aggregates (RAs) can both maintain ecological balance and offer a sustainable solution to the depletion of natural resources. **Figure 1** illustrates the CDW statistics across different Indian states as reported in a study.[10]

It has been reported that a few of the countries have already started incorporating RA.[11] It is found, nonetheless, that the RA has inferior engineering performance.[12] Old cementitious mortar on RA, which renders it porous and vulnerable to increasing water absorption and rising strain rates, is the main reason of the substandard performances.[11–18] This is further explained by the fact that the old interfacial transition zone (ITZ) created by the old mortar fractions is more vulnerable than the new ITZ created by the new cement paste and aggregates. The new ITZ is seen to exhibit additional CSH that makes it robust and leads to superior strength properties in recycled aggregate concrete (RAC), in contrast to the old ITZ, that is claimed to consist of many microcracks and ettringite.[16,18–20] Adopting appropriate processing and treatment techniques is therefore crucial for the sustainable absorption of RA.[4] Crushing, screening, and contaminant exclusion, if any, are among the processing methods reported by different authors.[12,21,22] Specifically, a jaw crusher, impact crusher, cone crusher, roll crusher, etc. can be used to crush RA.[23–27] Jaw and impact crushing are two of the most frequently utilized crushing mechanisms among these crushers.[28] It should be mentioned that the choice of crushers becomes a crucial factor in the invention of RA because it significantly influences the aggregate's shape, size, and corresponding dispersion properties.[28] Additionally, a two-stage crushing method, consisting of jaw crushing and then hammer milling, produces excellent RA, especially for improved mechanical properties in RAC.[29] An experimental study[30] examined the impact of multicycle jaw crushing (10 crushing cycles) on RA, and it was discovered that recovering supplementary mortar required a greater number of processing sequences. The excess cycles, however, required supplementary energy than the standard crushing procedure produced. In addition, the contamination removal through manual cleaning brushing is suitable for small-scale production of RA, whereas in cases of large-scale production, mechanical preseparation is recommended that can scrape off bulky waste such as wood pieces, plastics, or papers.[31] Consequently, it is essential to investigate the ideal numeral of crushing cycles for procurement of RA.

Research has shown that treatments for RA include removing related mortar or its surface coating, improving the binder, consolidating adherent mortar, and improving the microstructure between fresh mortar and RA.[4]

FIG. 1 Construction and demolition (C&D) waste statistics across Indian states (yellow: states with major waste, grey: states with minor waste).



Cities	C&D waste generation (Tonnes/day)
Kolkata	1,600
Bhopal	50
Jaipur	200
Patna	250
Ahmedabad	700
Mumbai	2,500
Bengaluru	875
Coimbatore	292
Chennai	2,500

A detailed review and respective quantified data on several treatment methods adopted by various experimental studies is presented in **Table 1**. Additionally, carbon dioxide curing and nanoparticles help to reinforce remaining mortar by significantly lowering the water absorption and porosity of the RA.[32–34] Numerous methods, including grinding of RA,[35,36] heat grinding of RA,[37] and presoaking solutions,[38,39] could be used to eliminate any residual RA mortar. However, integrating the aforementioned approaches was shown to have several drawbacks, such as poor durability characteristics,[37] development in chloride and sulphate ions,[40] immense energy costs and cumulative levels of carbon dioxide ejections,[32] etc. In particular, the chemical treatments are found to depend on various aggregate parameters such as its composition, source of origin, etc. For instance, aggregates with origin from a higher-grade parent concrete, presaturated with mineral admixtures and have fewer fractions of residual mortar shows lesser requirements of chemical treatments.[17,41,42] The use of acid treatments, chemical immersions through sodium silicate (SS), and mechanical abrasion would offer a practical and successful eradication method for the leftover cementitious remains in light of the drawbacks connected with the aforementioned techniques. For instance, it has been found that immersion in SS lowers water absorption, limits the penetration of chloride ions, and creates a denser ITZ at the microstructure level.[43] Henceforth, in order to produce RAC in a sustainable manner, it is now necessary to investigate the impact of single- and two-stage treatment techniques.

In the ongoing study, the possibility of concrete recycled aggregate (CRA) processed from demolished concrete waste is investigated. The demolished concrete debris was first processed in multiple crushing cycles using jaw crusher to attain the necessary CRA, which is then treated by means of single- and two-stage treatment approaches. The single-stage treatment involved the immersion of CRA in hydrochloric acid (HCl) and SS

TABLE 1
Assessment of several RA treatment approaches

	Variables and Impacts				
Treatment Technique	Chloride Penetration in RAC	Water Captivation in RAC	Corrosion Resilience	References
Integrating SCMs (GGBS+SF)	Decreases chloride penetration up to 53 %	Decreases water absorption up to 8 %	Minimal effect	44,52,53
Integrating ground rice husk ash (GRHA)	Offer resilience against chloride penetration	…	Better resilience against corrosion	44,52,54
Integrating GGBS	Decreases chloride penetration up to 67 %	Decreases water absorption	Comparative corrosion resilience to NAC	44,52,55
Integrating FA	Decreases chloride penetration	Decreases water permeability	Corrosion density comparable to NAC at later age	44,52,56
Mechanical abrasion	Decreases chloride penetration	Decreases water absorption	…	44,48,52
Cooperative treatment of sodium silicate + SF	Decreases chloride penetration up to 80 %	…	…	43,44,52
Cooperative treatment of carbonation + NS spray	Decreases chloride penetration by 24 %	Decreases water absorption significantly	…	44,52,57
Cement + NS slurry	Decreases chloride penetration by 15 %	Decreases water absorption	…	44,52,58
Nano surface treatment	Lessens chloride ingress	…	…	44,52,58

Note: GGBS = ground granulated blast furnace slag; NS = nano silica; SCMs = supplementary cementitious materials; SF = silica fume.

solution, whereas two-stage treatment consists of mechanical abrasion of processed CRA followed by SS immersion. Five different aggregate forms have been used in this experimental study. This study investigates the best approach to treatment in terms of the physical and microstructural performance of treated CRA samples, compared to control and untreated samples. Along with analyzing treatment approaches' shortcomings, this manuscript makes recommendations for improving the sustainability measures of treatment strategies that have been implemented.

Experimental Program

MATERIALS USED

Preparation of CRA

The demolished waste concrete cubes from the NITK structural and materials laboratory in Surathkal, India, were the source for the procurement of CRA. The discarded materials from the demolished concrete were cleaned first, then manually hammered to reduce size. In **figure 2**, a thorough multicycle processing methodology is summarized.[44] It should be emphasized that repeated crushing cycles were used to reduce the quantity of attached cementitious remnants and simultaneously provide coarse CRA. After that, the crushed material was again sieved through an appropriate size fraction to produce coarse RA fractions that were relevant to the treatment methodology's sustainability metrics.

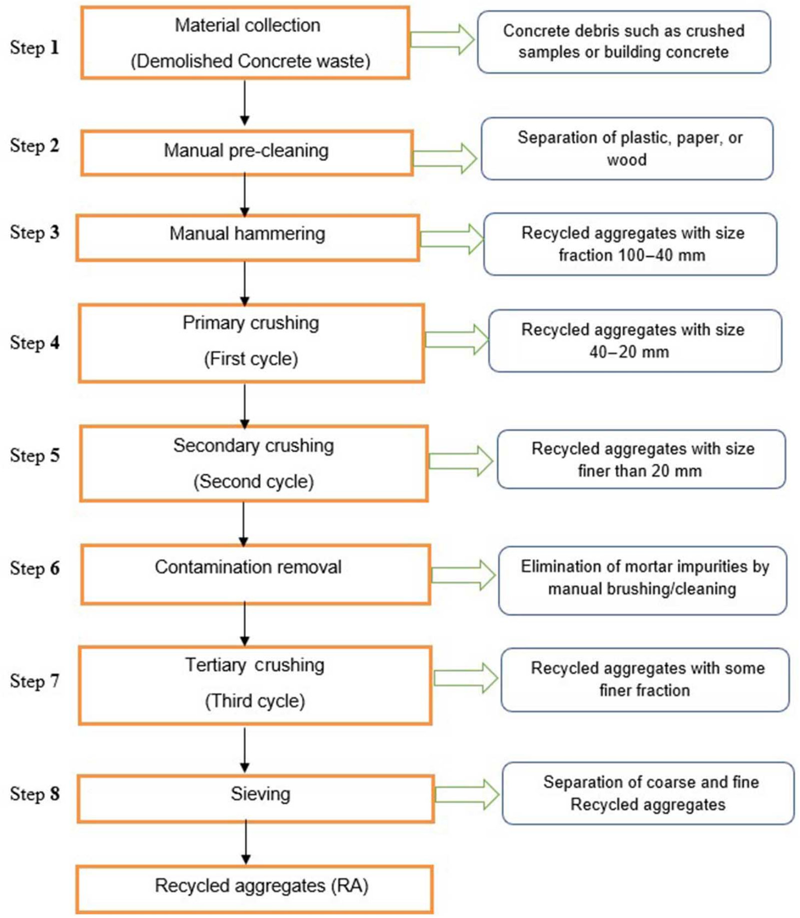
TREATMENT PROCEDURES

HCl Immersion

The single-stage treatments comprise CRA immersions in HCl_CRA and SS solution (SS_CRA). The procedure uses HCl as an acidic solvent in a decomposition process to eliminate remnant mortar fractions from the original CRA. The percentage of the HCl solution for the treatment of CRA is kept at 15 %. The concentration is optimized to ensure that the impurities are effectively removed without causing significant damage to the CRA. The adopted

FIG. 2

Multicycle processing technology for procuring CRA.



acidic solution was diluted, and the CRAs were immersed in the prepared acidic environment at 20°C for 48 h.[45] Then aggregates were removed from the acidic solution. Afterward, the aggregates were cleaned with clear water to eradicate the acidic solvents along with remnant adhered cement paste followed by oven-drying at 100°C–110°C for 24 h.

SS Immersion

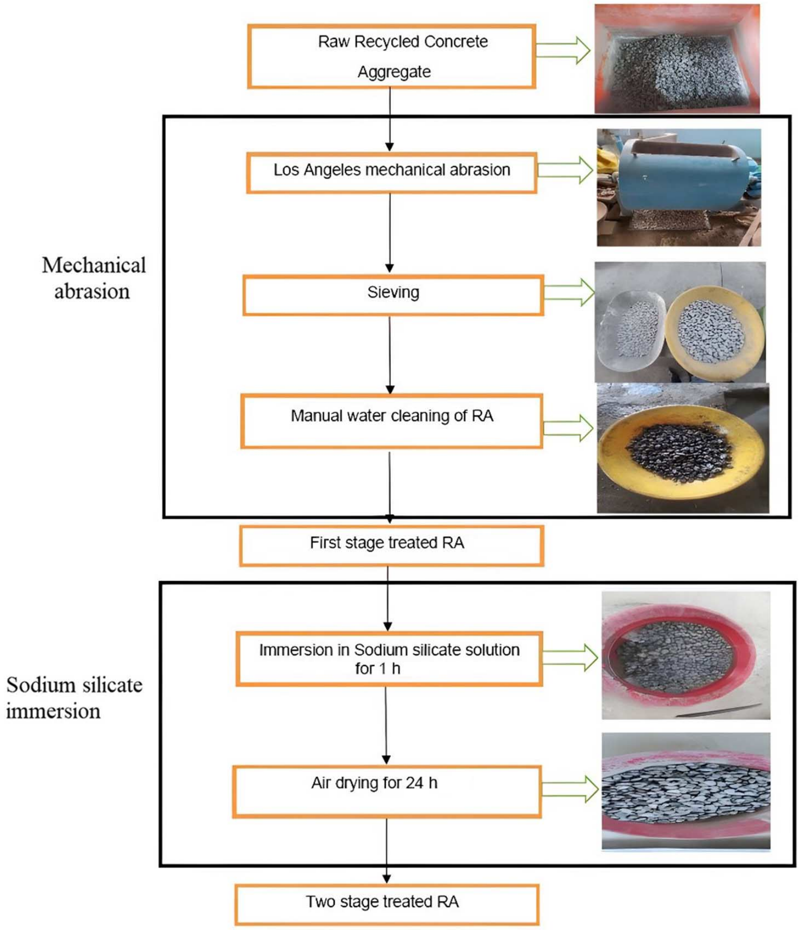
The CRA were engrossed in 20 % Na_2SiO_3 solution (waterglass) then assorted and kept for an hour. Following their removal from the solution, the aggregates were allowed to air dry for a full day. When SS and old cementitious mortar are applied on RA, a chemical reaction develops. This reaction produces CSH, which is useful for fortifying the mortar remnants and obstructing the capillary pores in concrete, as illustrated in equation (1).

$$2Na_2SiO_3 + 3Ca(OH)_2 \rightarrow 3CaO.2SiO_2.3H_2O + 4NaO \tag{1}$$

Mechanical Scrubbing and SS Immersion

A two-stage treatment procedure for CRA was incorporated as indicated in figure 3.[44] Ten kilograms of processed RA are placed inside the Los Angeles testing equipment, which is then charged and rotated at 33 rpm for 17 min. With absence of MS balls, rotation was allowed to take place. The impact resulted in the loosening of

FIG. 3
Two-stage treatment process for CRA.



detached mortar that was sticking to the aggregate surface. When the spinning period ended, the aggregates were sieved, and the 12.5-mm retained aggregates were gathered. The selected mechanical treatment ensures that the treated CRA has homogeneous characteristics and removes any remaining cementitious mortar. The second stage of treatment comprises immersion of CRA in SS solution that initiates with manual water cleaning of CRA followed by engrossed in 20 % Na_2SiO_3 solution then assorted for 1 h. The aggregates were then air dried for 24 h.

PHYSICAL PERFORMANCE OF CRA

All treated CRAs were assessed for their specific gravity, water absorption, bulk density in accordance with IS 2386, *Methods of Test for Aggregates for Concrete—Part 3 Specific Gravity, Density, Voids, Adsorption, and Bulking*, aggregate crushing value, aggregate impact value in accordance with IS 2386, *Methods of Test for Aggregates for Concrete—Part 4 Mechanical Properties*, and aggregate abrasion value. Additionally, IS 383, *Coarse and Fine Aggregate for Concrete*, specifications for coarse aggregate were contrasted with the physical properties of CRA. To compare the effectiveness of single-stage and two-stage treatment on CRA, comparative analysis is performed. **Figure 4** reveals the grading curve of natural aggregate and CRA, and it can be detected that CRA follows the IS provisions for particle size ranging from 10 to 16 mm, whereas some deviation is noticed for other size fractions.

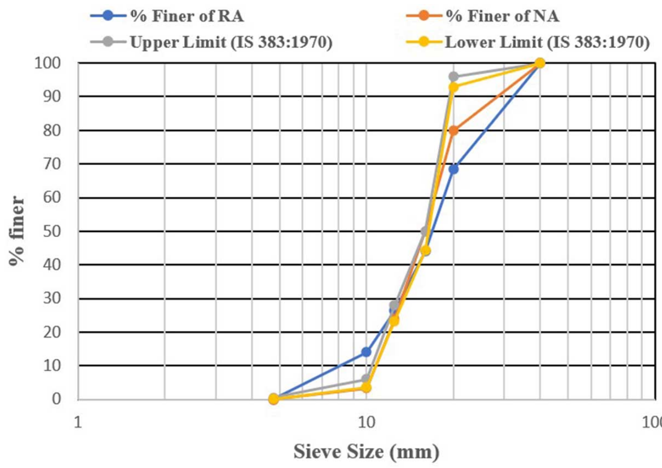


FIG. 4
Grading curve of NA and CRA.

MICROSTRUCTURE STUDIES

Scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDAX), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and thermogravimetry-differential thermal analysis (TG-DTA) were used to study the microstructure of various aggregate samples. To prepare samples for the examination of the aforementioned investigations, natural aggregate, untreated CRA, and treated CRA were all collected, crushed, and sieved. To determine the change in chemical composition inside the picture border, elemental analysis was carried out using an EDAX analyzer. Images were taken using a scanning electron microscope (GEMINI 300, Carl Zeiss, Resolution: 0.7 nm at 15 kV, 1.2 nm at 1 kV). Malvern PANalytical, with a deflection angle range of 4 to 80 and a scanning speed of 2/min, is used to do the XRD analysis at Central Research Facility, NITK. After that, the patterns were examined using the X'Pert High Score Plus software. A Bruker (Alpha II) instrument with a 2 cm^{-1} resolution and a 4,000–500 cm^{-1} wavenumber range was used for the FTIR analysis. Thermogravimetric analysis (TGA) was done using a Rigaku TG-DTA 8122 TG/DTA analyzer. Samples were put into the analyzer and heated at a frequency of 10°C/min in a nitrogen purge atmosphere (purge rate: 10 mL/min) between 25°C and 900°C.

Results and Discussions

PHYSICAL PROPERTIES OF TREATED RA

Specific Gravity and Bulk Density

Figure 5 illustrates the specific gravity of treated and untreated CRA (UCRA), along with natural aggregates. It is apparent that HCl_CRA and MS+SS_CRA has slightly higher specific gravity than UCRA, whereas SS_CRA shows slightly lower values to that of UCRA. Further, figure 6 represents the bulk density measurements of single- and two-stage treated CRA and it can be observed that treated CRA has higher bulk density as compared to UCRA but shorter value than natural aggregate.

The increase in specific gravity may be ascribed to the omission of adhering mortar from the HCl and the subsequent mechanical scrubbing (MS) treatment, that is characterized by its weak and porous nature. Moreover, by changing adherent mortar to CSH, SS solution improves the recycled aggregates. The foregoing finding is further supported by the increase in bulk density, as specific gravity indicates how dense an aggregate is. The thicker layer of SS that makes the aggregate denser is most likely the cause of the treated CRA's increased bulk density. Additionally, the development of CSH fractions leads to the development of a dense microstructure,

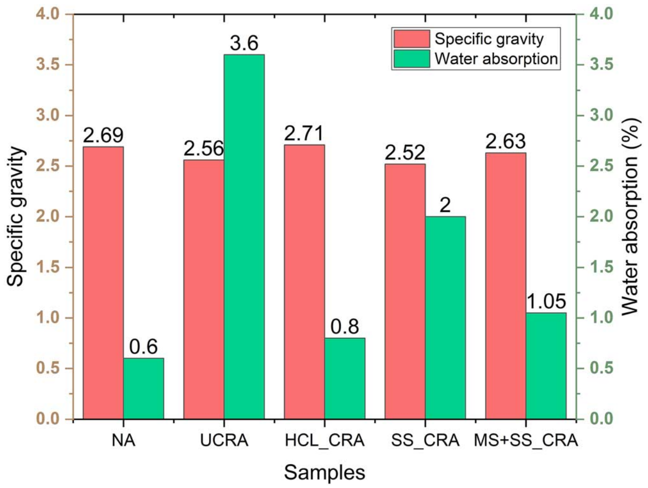


FIG. 5
Specific gravity and water absorption of CRA samples.

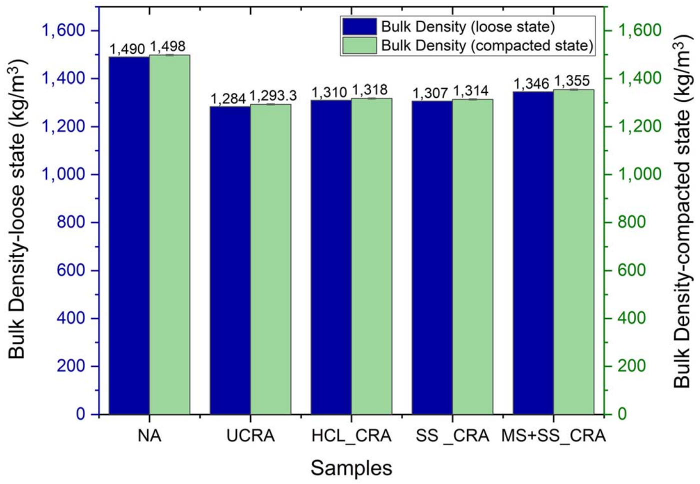


FIG. 6
Bulk density of single- and two-stage treated CRA.

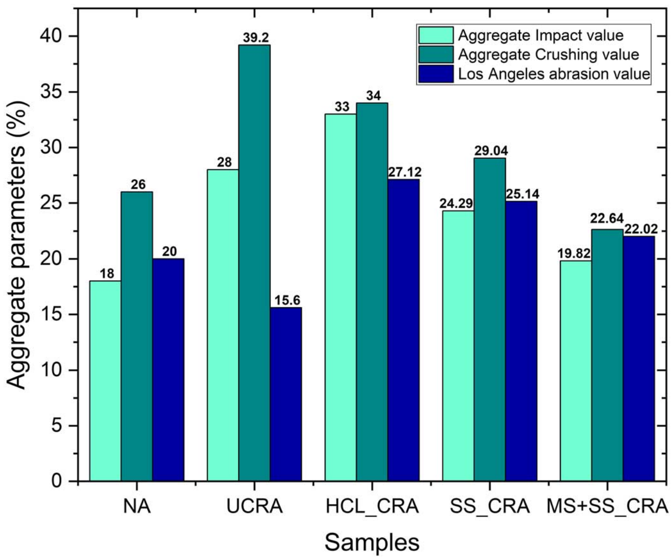
which is confirmed by the SEM findings in this study. This inference agrees with one of research,[38] which examined the impact of SS as a surface treatment approach for the creation of RA-infused self-compacting concrete. Since specific gravity and bulk density data show that single- and two-stage treated CRAs are of higher quality than UCRA, IS 383[46] advises using dense aggregates in construction projects.

Water Absorption

Figure 5 illustrates the water absorption of natural aggregate, UCRA, and treated aggregate. After treatment, a noteworthy fall is observed in the water absorption values of CRA. Furthermore, the difference of water absorption values between treated CRA and natural aggregate is minimal. This outcome may be attributed to the elimination of remnant mortar because of HCl immersion as the water absorption is lowest in case of HCl_CRA. Moreover, the formation of dense coating of SS solution have clogged the pores on the surface of CRA. Calcium hydroxide and SS solution react to generate the water-based silicate gel (CSH gel), which is a solid matrix.

FIG. 7

Various aggregate parameters for different CRA specimens.



This inference is consistent with research findings from a study,[47] which showed that the RA treated with HCl solution saw a decrease in water absorption levels, especially when compared to the UCRA. Prewetting is not necessary when RA has water absorption values less than 5 %, according to IS 383;[46] henceforth, prewetting is no longer necessary when using single- or two-stage treated CRA in concrete applications.

Aggregate Crushing Value, Impact Value, and Abrasion Value

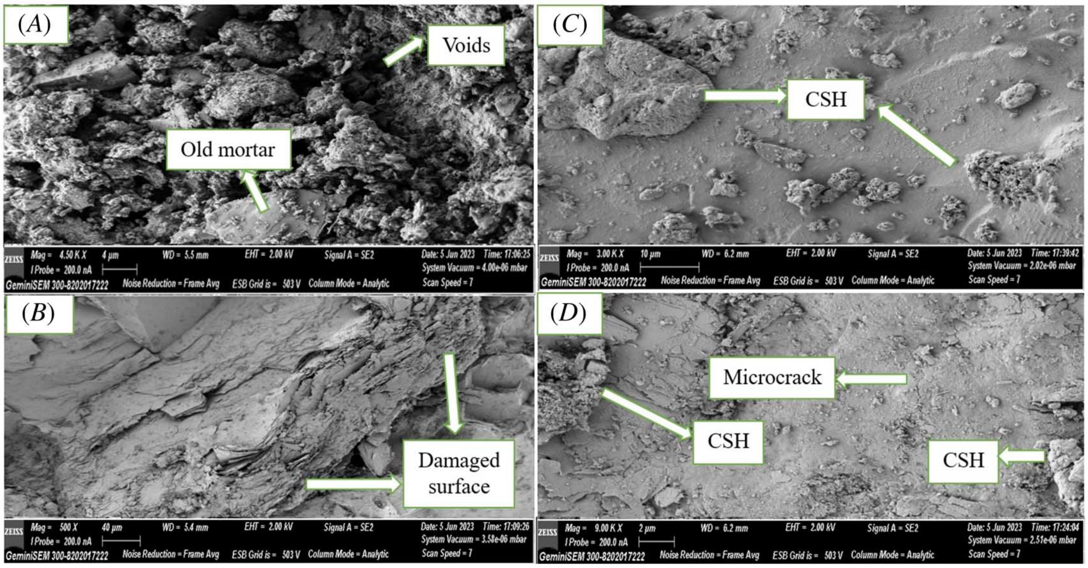
Abrasion, crushing, and impact resistance tests are typically used to determine the excellence of the aggregate and its ability to withstand failure because of handling and mixing.[36] Figure 7 displays the aggregate parameters for different CRA specimens in addition to the control aggregate. It is detected that two-stage treated CRA has somewhat better values than NA for crushing, impact, and abrasion than UCRA. It is clear from this observation that two stages of treatment are preferable to one stage for CRA. The observed pattern could be attributed to the deterioration and removal of older cementitious residue following mechanical cleaning. The Los Angeles abrasion of recycled aggregate (RA) had a significant positive impact in terms of the elimination of the aged cementitious remains from the surface of the RA particles as a consequence of abrasive motion. The aged mortar present on the surface of RA exhibits microcracks and pores, which result in a porous and weak ITZ between the surface of RA and the new mortar. By extracting the aged mortar from the surface of RA, the quality of the ITZ is improved.[48] Applying SS also improves the performance of the aggregates in terms of crushing, impact, and abrasion value by closing the holes and microcracks inside the aggregate. This study is consistent with observation,[49] which shows that adding SS treatment reduces the aggregate crushing value.

MICROSTRUCTURAL STUDIES

SEM

The SEM descriptions with relative magnifications for UCRA, HCl_CRA, SS_CRA, and MS+SS_CRA are shown in figure 8*A*–*D*, respectively. It can be detected that URAC specimen shows irregular and nonuniform surface with a large number of voids and minimum to nil occurrence of favorable hydration products. The occurrence of remnant cementitious fractions on the CRA surface, which resulted to the development of a porous and delicate microstructure, is responsible for this discovery. When it comes to treated CRA specimens like HCl_CRA, SS_CRA, and MS+SS_CRA, CSH is more common and there are rare cracks that are the result of mechanical

FIG. 8 SEM images of (*A*) UCRA (4.5K X), (*B*) HCl_CRA (500X), (*C*) SS_CRA (3K X), and (*D*) MS+SS_CRA (9K X).



abrasion cycles. A supplementary CSH is created as a consequence of the reaction between adhering mortar and SS, especially for SS_CRA and MS+SS_CRA specimens, which results in a dense and uniform surface coating. However, for HCl_CRA, an uneven surface morphology is illustrated because of the strong acidic nature of HCl. Furthermore, the surface is found to show substantial damage as a consequence of adverse acid attack owing to HCl treatment.

EDAX

The EDAX investigation of UCRA, HCl_CRA, SS_CRA, and MS+SS_CRA are shown in figure 9*A*–*D*, respectively. To quantify the elemental composition, area to point analysis is performed for each treated CRA and UCRA sample. Based on results from the EDAX analysis, figure 10 shows the calculated atomic weight ratios of calcium to silicate as well as a comprehensive elemental configuration. It is commonly known that for dense microstructure, the calcium/silicon ratio usually goes below 2.[4] Further, the aluminum/calcium atomic ratio is computed from EDAX data using comparable computations to the calcium/silicon atomic ratio for various treatment strategies. This variation is shown in figure 11. According to a study, the aluminum/calcium ratio has an influence on the amount of CH crystals and with increasing aluminum/calcium ratio, the CH crystals decreases and results in dense microstructure.[4] It can be observed that the calcium/silicon atomic ratios of all the samples are below 2, indicating a dense microstructure. This could be related to the right processing and treatment strategy that promoted increased CSH production. This is probably a good reason to use a multicycle method that can convert CH crystals into CSH, which reinforces the microstructure even more. It is to be noted that for UCRA, calcium/silicon ratio is lower than two-stage treatment but higher than single-stage treatment, whereas aluminum/calcium ratio is higher than two-stage treatment and lower than single-stage treatment. This may be accredited to the fact that multicycle processing approach has removed a substantial volume of adhered old mortar that has further densified the microstructure. However, with two-stage treatment that initiates with MS, the CRA specimen is again subjected to repeated abrasion cycles and that has created some microcracks that can be observed in SEM image of the sample (fig. 8*D*). These microcracks created rare void spaces and the same is reflected in the form of slightly higher calcium/silicon ratio and lower aluminum/calcium ratio.

FIG. 9

EDAX images of (*A*) UCRA, (*B*) HCl_CRA, (*C*) SS_CRA, and (*D*) MS +SS_CRA.

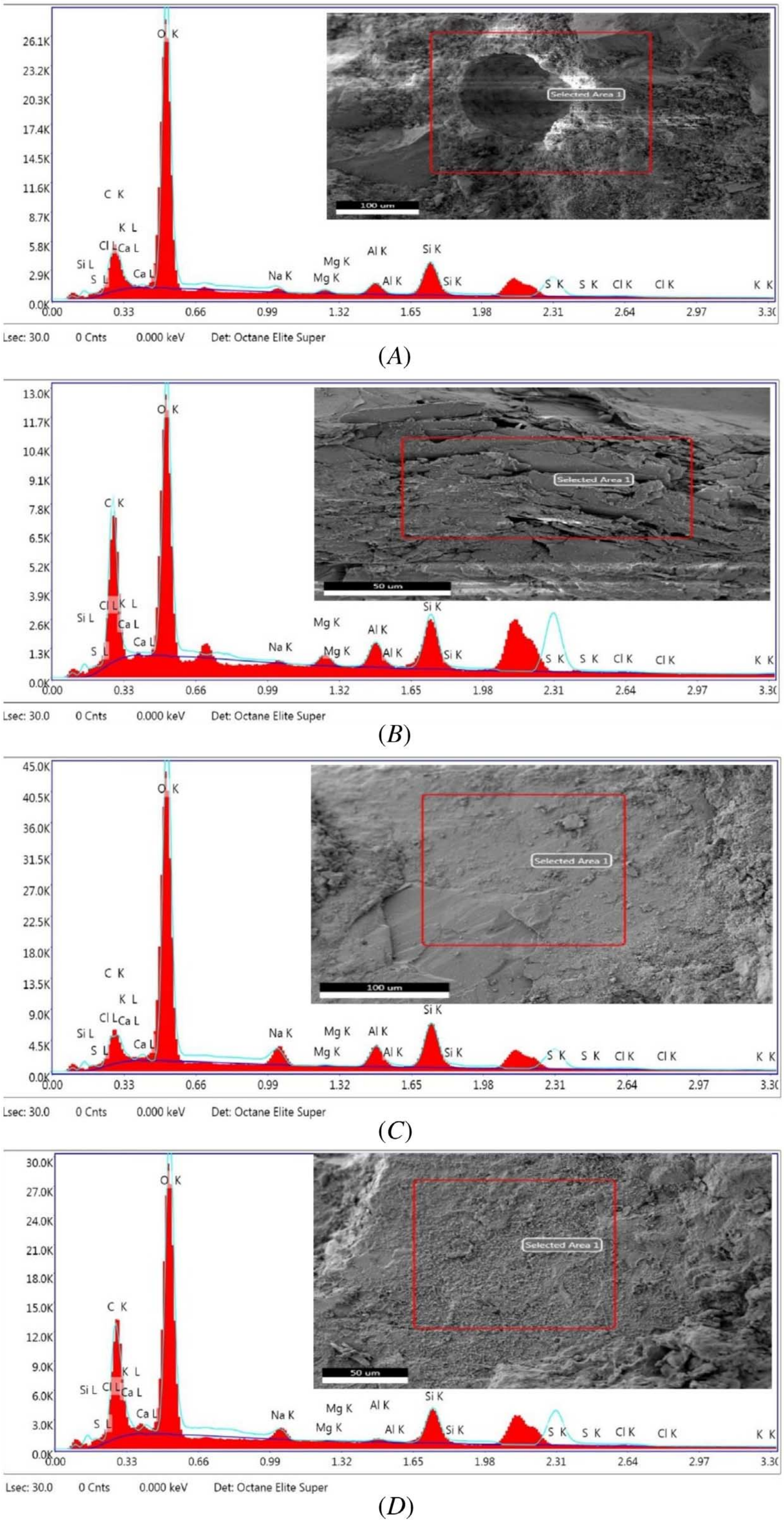
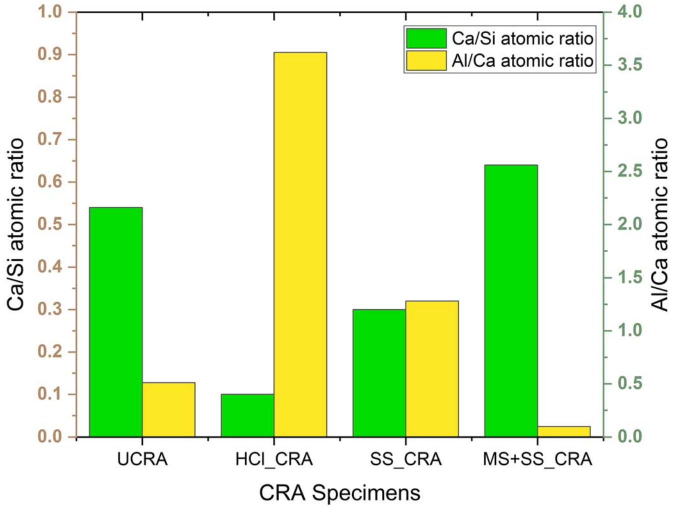


FIG. 10

Calcium/silicon and aluminum/calcium atomic ratio of CRA specimens.



XRD

The XRD peaks of UCRA, HCl_CRA, SS_CRA, and MS+SS_CRA are shown in **figure 11**. It can be detected that calcium silicate hydroxide were visible in the XRD pattern for the treated CRA samples. The highest intensity in the CSH peaks is detected for two-stage treated CRA (MS+SS_CRA) with respect to single-stage treated CRA (HCl_CRA, SS_CRA). The strong peaks in the URCA are detected at an angle of 26.46°, 20.71° (Quartz, SiO_2), 27.76°, 49.99° (Calcite, $CaCO_3$), 29.425° (unhydrated CSH). XRD peaks of HCl_CRA and MS+SS_CRA established an exaggerated peak of Calcium silicate hydroxide (27.78°) as compared to UCRA. However, SS_CRA showed a comparatively less intense CSH peak (27.78°) with respect to other treated CRA specimens but still the CSH peak intensity is 1.55 times the CSH peak intensity of UCRA. This conclusion agrees with the findings of SEM analysis for SS-based treatment about the formation of auxiliary CSH. Henceforth, the XRD findings are giving clear evidence that two-stage treatment is superior to single-stage treatment approaches.

FIG. 11

XRD peaks of various treated and untreated CRA specimens.

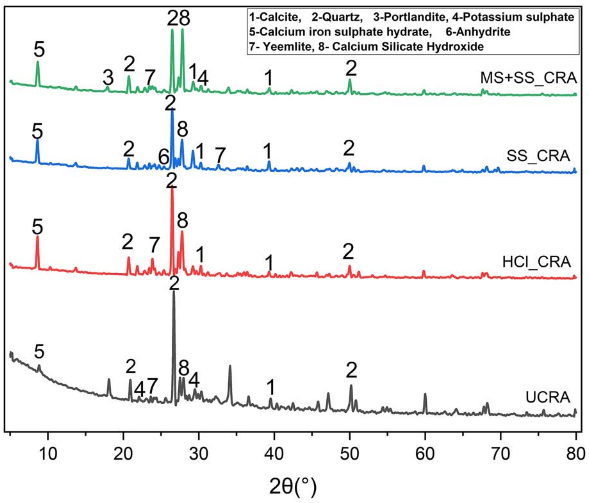
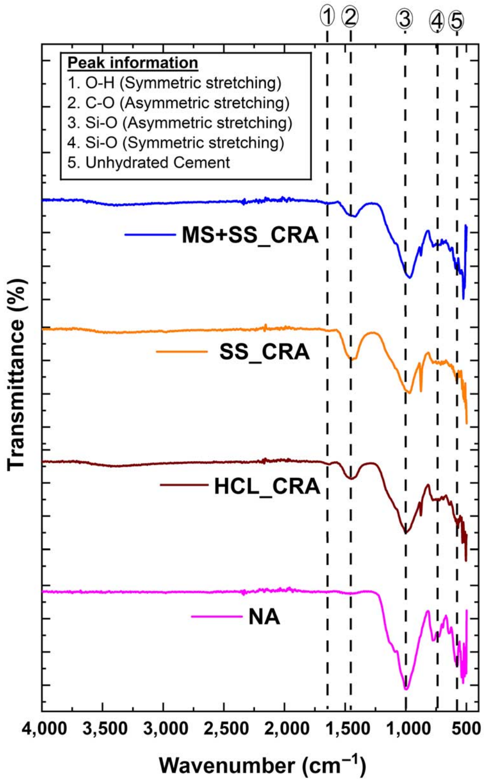


FIG. 12
Different peaks corresponding to FTIR analysis of CRA specimens.



FTIR

The FTIR spectra of NA, HCl_CRA, SS_CRA, and MS+SS_CRA specimens is illustrated in **figure 12**. In treated CRA samples, it was discovered that the main peak at a wavelength of 3,640 cm^{-1}, which conforms to the O-H stretching bond of portlandite, was absent. According to a study[50] based on FTIR analysis on RA, this observation was made. This has been accredited to the phases of calcium carbonate that were created when portlandite and ambient carbon dioxide reacted. The additional water molecules in the specimens instigated the stretching vibration of O-H amid 1,600 and 1,660 cm^{-1}.[50,51] In addition, the peak interval between 1,450–1,470 cm^{-1}, 1,000–950 cm^{-1}, 780–770 cm^{-1}, and 595–570 cm^{-1} resembles the asymmetric stretching vibration of C-O bond, Si-O bond, symmetric stretching vibration of Si-O bond, and unhydrated cement, respectively. The inclusion of SS_CRA and HCl_CRA progressively weakens the distinctive peaks at 975 cm^{-1}, 773 cm^{-1}, and 585 cm^{-1}, indicating that the calcite and CH were absorbed in the interaction between the CRA, SS, and HCl. The calcium-HCl and calcium-SS complex can be produced by the CRA's calcite and CH reacting with SS and HCl, according to the findings of the FTIR study.

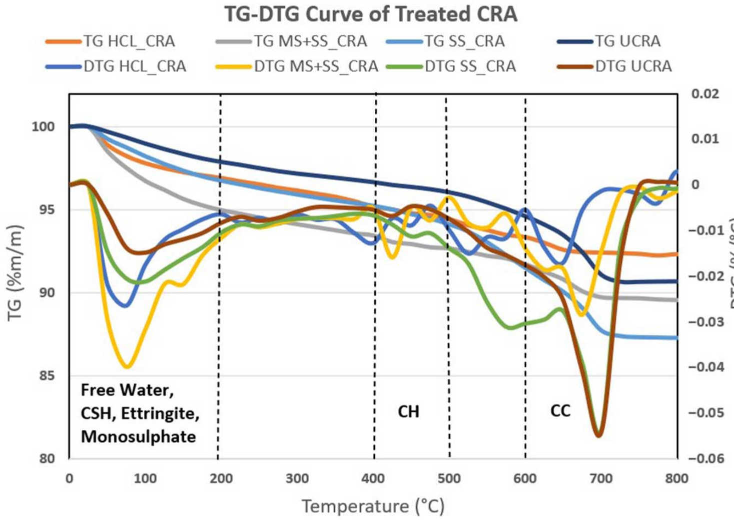
TGA

The thermogravimetry (TG) curvature demonstrates the presence of thermogravimetric mass loss during the heating evolution from 25°C to 900°C, whereas the derived of thermogravimetry (DTG) curve displays the temperature borders for the breakdown of certain compounds.

Figure 13 shows several endothermic peaks in the specified temperature range. The temperature limits that correspond to the loss of free water molecules, ettringites, and gypsum are 25°C–50°C, 50°C–120°C, and 120°C–150°C, respectively. These ranges can be additionally divided from the main endothermic peak up to 200°C.

FIG. 13

TG analysis of CRA samples.

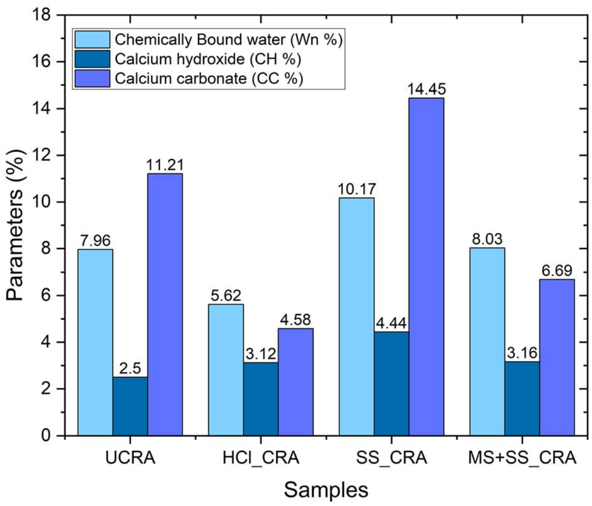


Between 400°C and 500°C is the temperature range at which calcium hydroxide (CH) is dehydroxylated; at this point, a second notable endothermic peak was seen. The third notable peak results from the decarbonization of $CaCO_3$ (CC) at temperatures between 600°C and 800°C.[4]

It should be noted that the following equations—equations (2–4) at specific temperature boundaries—are considered in this inquiry in order to control the reduction in mass proportion from TG-DTG. **Figure 14** illustrates computed results for various chemical elements from TGA analysis. The percentage of decomposed calcium hydroxide (CH%) is represented by the symbols in the following equation, whereas the percentages of bound water and calcium carbonate that have formed. M_{CH}, M_{H2O}, M_{CC}, and M_{CO2} represents the molecular weight of calcium hydroxide, water, calcium carbonate, and carbon dioxide, respectively. The remaining symbols, $\%W_{CH}$ and $\%\ W_{CC}$, represent the weight loss of calcium hydroxide and calcium carbonate, respectively.

FIG. 14

Quantification of chemical parameters for CRA samples.



$$CH\% = \left(\%W_{CH}\right) \times \left(\frac{M_{CH}}{M_{H_2O}}\right) = \left(\%W_{CH} \times \frac{74}{18}\right) \tag{2}$$

$$W_n\% = W_T - W_{CH} \tag{3}$$

$$CC\% = (\%W_{CC}) \times \left(\frac{Mcc}{M_{CO2}}\right) = \left(\%W_{CC} \times \frac{100}{44}\right) \tag{4}$$

It should be noted that the formation of stable CSH crystals as a result of triggered chemical reaction between CH phase with SS and HCl is indicated by the minor occurrence of the CH crystals for the HCl and MS tracked by SS-based treatment approaches for CRA specimens. However, the CH crystals are slightly higher in the case of the single-stage SS treatment method that further indicates an incomplete utilization of the CH crystals and lower volumes of CSH segments at microstructure stages. This might be owing to the reduction in the old cementitious remains in CRA samples because of multicycle processing technology. As a whole, the TG-DTA analysis indicates that treatment techniques adopted for this experimental investigation forms favorable hydration products at microstructure level.

Cost Estimation

In order to calculate the cost of generating the various processed and treated CRA specimens (UCRA, HCl_CRA, SS_CRA, and MS+SS_CRA) taken into consideration in the present investigation, the elemental prices of all the materials were acquired from national and intercontinental marketplaces. The expenditure on the energy used by the corresponding machinery was calculated in order to account for the expenses associated with the multicycle jaw crushing and Los Angeles test machine. Table 2 displays the cost per metric tonne of SS and HCl, given in Indian Rupees (Rs). In addition, the cost involved for producing various treated and processed CRA samples with respect to processed samples is also evaluated for distinguishing the induced cost among various single and multi-stage treatment methodologies.

As shown by the data in Table 2 particularly for treated CRA, the total cost induced is found out to be least for HCl_CRA followed by SS_CRA and MS+SS_CRA. In comparison to untreated CRA, MS+SS_CRA is observed to be the most expensive treatment method. Even though it is estimated that two-stage treatment is costly, the microstructure studies revealed that the same treatment method is found to show additional CSH alongside uniform surface characteristics with negligible void percentage. The supplementary formation of CSH is an encouraging feature for potential utilization of MS+SS_CRA in concrete applications for satisfactory mechanical and durability performance, which will reduce the overall cost.

TABLE 2
Cost estimation for various treated CRA samples (expressed in INR)

Particulars	Unit Cost, INR/ton	UCRA	HCl_CRA	SS_CRA	MS+SS_CRA
Processing cycles	1,550	155	155	155	155
HCl acid	1,750	…	582	…	…
Sodium silicate	13,500	…	…	1,125	…
Mechanical scrubbing (INR/kWh)	240	…	…	…	1,365
Total cost (INR)	…	155	737	1280	1,520
Changes in cost / UCRA sample	…	…	3.75 times higher cost	7.25 times higher cost	8.80 times higher cost
Remarks	…	…	Economical treatment	Moderate economic treatment	Expensive treatment

Note: INR = Indian rupees.

Conclusion

For the multicycle processed CRA, the current investigation examines the viability of single- and two-stage treatment approaches. The initial processing of demolished concrete debris involved multiple crushing cycles using a jaw crusher. This was tracked by single- and two-stage treatment approaches, such as immersion in a solution of SS and HCl. Los Angeles abrasion and SS immersion were the two stages of the treatment for the processed CRA. Along with microstructural analyses using techniques including SEM, EDAX, XRD, FTIR, and TG-DTA, the practicality of processing and treatment methods was evaluated in terms of the physical attributes of the CRA. The research work's findings allow for the following interpretations to be made.

1. The multicycle processing of CDW yields superior quality CRA that can be further used in the concrete mix.
2. The removal of the mortar component or surface coating methods to strengthen the adhering mortar are two ways to treat CRA, and it can be suggested that the latter method results in CRA of higher quality.
3. HCl treated CRA lowered the water absorption values by 78 % and enhanced its specific gravity by 6 % to that of UCRA.
4. MS+SS_CRA specimens are found to show 6 % additional bulk density, 30 % higher impact resistance, 42 % higher crushing resistance as compared to that of UCRA specimen.
5. FTIR results demonstrated that the treated CRA with SS and HCl produces additional amount of hydration products.
6. TGA analysis proved that mechanical scrubbed followed by SS treated CRA induced the formation of stable CSH gel at microstructure level.
7. XRD study found highly intensified CSH peaks for mechanical scrubbed followed by SS treated CRA with respect to UCRA.
8. SEM images illustrated that treatment through SS provides uniform and compact surface characteristics by eliminating significant volume of pores, whereas MS followed by SS treatment results in the formation of CSH gel with partial cracking.
9. EDAX analysis revealed that the SS_CRA samples and HCl_CRA specimens had the lowest calcium/silicon atomic ratios, which further suggests a dense microstructure by 81 %.

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