



OPEN Optimizing recycled aggregate concrete performance with chemically and mechanically activated fly ash in combination with coconut fiber

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As a matter of fact, although RCA is inferior to that of NA (natural aggregate) in terms of performance, RCA is currently being used extensively in concrete production as a sustainable solution due to global increasing construction waste. To overcome these limitations, several mechanisms and supplementary cementitious materials (SCMs) have been investigated in the recent past. This study investigates the combined effect of natural fiber coconut (0%, 0.5%, 1%, 1.5% and 2%) and activated fly ash (mechanically and chemically) on performance of recycled concrete aggregate (RCA). Four concrete compositions were studied: a control group with varying RCA percentages and no fly ash, second group with 30% inactive fly ash, third group with 30% mechanically activated fly ash, and a fourth group with 30% chemically activated fly ash. The findings revealed that the addition of 30% chemically activated fly ash with 1.5% CF increased compressive strength by 25%, tensile strength by 17% for 100% RCA mix, While strength losses for the same mix are 7.18% after one month and 22.14% after three months of acid exposure. Scanning electron microscopy further validates the enhanced packing density and effective crack filling in the optimized mixes, highlighting their superior performance. This approach holds significant potential for advancing sustainable development pathways in high-performance structural concrete, particularly in regions prioritizing green building solutions.

Keywords Fly ash, Coconut fiber, Mechanical and durability properties, SEM

In emerging economies such as Pakistan, there is a growing need for housing and infrastructure development because of fast growth and population expansion. As a prominent construction material, the demand for concrete has recently experienced a significant surge, driven mainly by the need to meet infrastructure requirements. Therefore, it is needed to develop sustainable concrete^{1–4}.

NCA (Natural coarse aggregate) contributes over half (50%) of concrete. However, although having a low carbon footprint relative to OPC, its production considerably affects the aesthetic of the natural environment^{5,6}. Consequently, the application of RCA in our built environment is being prioritized to conserve natural resources^{7,8}. The viability of recycled concrete aggregate (RCA) sourced from demolished buildings has been examined as a substitute for natural coarse aggregate (NCA)^{9,10}. Research indicates that substituting up to 50% of natural coarse aggregate (NCA) with recycled coarse aggregate (RCA) in concrete results in slight decreases in concrete performance¹¹. However, the total replacement of NCA by RCA results in a significant deterioration

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in concrete quality. RAC has 15–30% lower mechanical strength in comparison with NAC¹². The presence of attached materials in RCA facilitates the infiltration of harmful fluids such as chloride ions, sulfate ions and carbon dioxide^{13,14} resulting in a linear decline in durability as the percentage of RCA increases. Nowadays, investigations are focused on enhancing the quality of RAC by various methodologies and using different SCM (supplementary cementitious materials)^{15–17}.

The utilization of multiple industrial by-products and recycled materials provides numerous environmental benefits by potentially diverting valuable materials from waste streams, conserving natural resources, decreasing the energy required for analyzing virgin materials and mitigating pollution. A comprehensive study has been conducted on the utilization of fly ash (FA) and other supplemental cementitious materials to improve the durability and sustainability of concrete^{18–22}. The incorporation of FA (fly ash) in concrete helps to reduce waste disposal issues, decrease manufacturing costs, and decrease the environmental impact of concrete. Due to its pozzolanic properties, fly ash can serve as a substitute for cement²³. Fly ash enhances mechanical and durability properties^{24,25}, however fly ash lower early strength impacts its applicability in rapid construction conditions. Improving the reactivity of fly ash, primarily attributed to its glassy particles of silica, to achieve elevated initial strength is a significant objective for researchers aiming to enhance the reputation of concrete made from fly ash within the construction industry. The reactivity of fly ash can be enhanced by thermal activation, mechanical activation (by increasing the fineness of FA particles through intensive grinding and the surface area) and chemical activation through dissolving the non-amorphous constituents of fly ash particles using sulphates and alkalis. Gaining fly ash into fine ground particles enhances its surface area, improving its reactivity with the portlandite (CH). However, the grinding procedure may elevate the price of fly ash. The thermal activation is also known as the calcination of fly ash, at high temperatures that ignites its CO₂ content and enhances the carbon footprint linked to fly ash. Consequently, chemical activation by incorporating minimal quantities of chemical compounds, such as Na₂SO₄, during concrete mixing may significantly lower the concrete cost-to-strength ratio²⁶.

The researcher explores the prevalent proportions of FA utilized are 20–30% as a partial substitute for cement^{27–30} higher quantities of fly ash decrease the OPC percentage in concrete. Despite increasing demands from the environment to enhance fly ash utilization in concrete, other factors, such as durability performance and strength development rate, become affected when FA content exceeds 60–80%³¹. Previous Researchers have explored the feasibility of substituting OPC with fly ash utilizing chemical activators^{32,33}. The necessity to cure concrete having 50–100% FA at greater temperatures to achieve the necessary strength. As previously explained, various methods can be employed to activate FA, including mechanical grinding, thermal activation, and chemical activation. The chemical activation method has demonstrated the ultimate cost-to-strength ratio compared to alternative approaches²⁶.

The glass particles in fly ash have been dissolved using a variety of chemicals, including both salt and alkaline. According to the findings of Qian et al.¹¹, mechanically ground fly ash had lower early age strength than Na₂SO₄-activated fly ash. Sodium silicate and sodium hydroxide 4% and 2.5% by mass of binder were found to be less efficient activators than lime-silicate and sodium hydroxide in enhancing the early and later age strength qualities of 40% fly ash concrete. Poon et al.³⁴, revealed that blended cement mortars cured at 60 °C for 6 h instead of the usual 24 h increased their strength by over 70% when compared to conventional concrete. The workability was not negatively impacted by Na₂SO₄ when compared to other activators³⁵, 50% FA concrete containing 1% Na₂SO₄ improved durability over longer durations¹⁰. Previously, studies has been focused on improving the strength of FA concretes by using various chemical activators^{11,34,36}, although less evidence³⁷ exists regarding the durability characteristics of chemically activated FA concretes. There has been a lack of thorough research on the durability characteristics of activated FA concretes.

The incorporation of artificial fiber reinforcements is an expensive and environmentally harmful approach to enhancing the characteristics of recycled aggregate concrete (RAC). Utilizing waste natural fibers may serve as a viable alternative for producing RAC with enhanced tensile strength. Coconuts represent a significant agricultural product, utilized to manufacture a variety of items, such as carpets, brooms, insulation and furniture^{38,39}. Coconut fiber (CF) has been found appropriate for civil engineering applications. It serves as fiber reinforcement for concrete, enhancing its strength characteristics and durability characteristics⁴⁰. Ali et al.⁴¹ observed that incorporating 2% carbon fiber by weight increased tensile and shear strength by 15% and 40%, respectively. The concrete's strength and hardness were enhanced as CF effectively filled both small and large cracks. Through its energy-absorbing properties, CF enhanced concrete's compressive strength⁴². The investigation indicated that CF effectively bridged concrete microcracks, enhancing tensile strength and enhancing friction among concrete particles, hence improving shear strength. CF has been beneficial in enhancing the tensile strength as well as the shear strength of RAC⁴¹.

This research seeks to determine how CF, activated fly ash (AFA), and inactivated fly ash (IAFA) influence the efficiency of NAC and RAC.

Research novelty

This research presents a novel approach to enhance the strength and durability of recycled aggregate concrete, RAC through the synergistic effect of activated fly ash (chemically and mechanically) and sustainable natural fibers, particularly coconut fibers (CF). In the context of rapidly developing economies like Pakistan, where there is a critical need for sustainable construction materials due to increased infrastructure demands, this study addresses a gap by evaluating alternative activation methods of fly ash to optimize concrete performance with recycled aggregates. While prior research has examined fly ash as a supplementary cementitious material, this study delves into the comparative effectiveness of chemical and mechanical activation techniques on fly ash to enhance reactivity and early strength gains, especially in high-RCA mixes. This research is distinctive in its incorporation of coconut fibers as an economical, environmentally sustainable reinforcement that enhances the

Parameters	Values	ASTM standard (C-150) limits
Soundness (mm)	6	–
Fineness	7.5	–
Insoluble residue (%)	0.29	0.75, max
SO ₃ (%)	2.7	3.5, max
LOI (%)	2.1	3, max
MgO (%)	1.6	6, max

Table 1. Properties of ordinary Portland cement.

Parameters	Aggregate		ASTM standard
	Coarse	Fine	
Specific gravity (bulk)	2.72	2.61	C-127, C-128
M.C (%)	0.62	1.11	C-566
Water absorption (%)	1.38	1.07	C-127, C-128
Unit weight (kg/m ³)	1620.96	1682.52	C-29
Fineness modulus	7.31	2.57	C-136
Max nominal size (mm)	25.2	–	–

Table 2. Physical characteristics of coarse aggregate and fine aggregate.

Properties	Value
45 micron sieve retention (%)	Less than 34
Dry shrinkage	0.05
Reactivity with lime (N/mm ²)	5.8
Autoclave expansion soundness (%)	0.04
Compressive strength (exhibited by plain cement mortar cubes) %	81

Table 3. Physical characteristics of Fly ash.

strength and durability properties of RAC while supporting ecological objectives using agricultural waste. The study also explores the combined effects of activated fly ash and natural fiber reinforcement, aiming to develop a durable concrete mix that balances strength, sustainability, and economic feasibility.

Materials and method

Type I Ordinary Portland Cement (Fauji) which is readily available in the local area and meets the ASTM C150 specifications was used in this study. Table 1 shows the chemical and physical properties of OPC. Both the fine aggregate and coarse aggregates were collected from the local area. Fine aggregate, (Lawrencepur sand) and coarse aggregate (Margalla crush) were used in this investigation in accordance with ASTM C136 and ASTM C127, Table 2 describes the physical properties of fine and coarse aggregates. The study utilized Class F fly ash that was locally obtained from Islamabad, Pakistan. Table 3 displays the manufacturer-provided physical parameters of fly ash. Coconut fibers, or coir, were extracted from the waste shells, and pieces of husk were removed from the fibers. Ultimately, fiber was separated into sections measuring 50 mm to produce refined carbon fiber. The length of coconut fiber is determined based on the suggestions of significant research^{40,43} which proposes a 50 mm length to enhance the mechanical characteristics of concrete. The materials utilized, their preparation, casting, grinding, curing, and testing in this study were displayed in Fig. 1. The chemical properties are shown in Table 4 while the physical properties of coconut fiber are shown in Table 5.

Activation of fly ash

Mechanical activation

The mechanical activation of fly ash involves grinding to increase its surface area and enhance its reactivity. The raw material is collected from a natural source and dried at 100 °C for 24 h to ensure the removal of moisture. After drying, the material is ground using a Los Angeles abrasion machine, with 4000 revolutions performed per 5 kg batch to achieve uniform particle size. The ground material is then passed through a #200sieve with a nominal opening size of 0.075 mm to ensure consistency. Once sieved, the processed material is stored in moisture-resistant packaging, such as polythene bags, to preserve its reactivity for applications like concrete production.



Fig. 1. The materials used, preparation, casting, grinding, curing and testing of this study.

Compounds	Fly ash (%)
SiO ₂	63.9
Al ₂ O ₃	22.9
Fe ₂ O ₃	4.25
MgO	1.52
CaO	3.32
K ₂ O	1.5
Na ₂ O	0.12
LOI	2.4

Table 4. Chemical characteristics of fly ash.

Properties	Values
Length	1.97 inch
Density	1.35 g/cm ³
Modulus of elasticity	681.4 MPa
Diameter	0.4–0.8 mm

Table 5. Physical characteristics of coconut fiber.

Chemical activation

Chemical activation of fly ash for concrete involves enhancing its reactivity through a controlled laboratory process. Fly ash was sourced and oven-dried at 100 °C for 24 h to remove moisture content, then stored in airtight containers to prevent contamination or moisture absorption. Sodium sulfate (Na_2SO_4) was chosen as the chemical activator, and a solution was prepared by dissolving 2% of Na_2SO_4 by weight of the total binder (cement and fly ash) in water, ensuring complete dissolution through stirring.

Execution of research

This research is structured into two key phases to systematically optimize and test materials for concrete performance enhancement:

Optimization of different material casting mortar-Phase I

The first phase identifies the most effective material combinations using mortar casting trials. Various proportions of fly ash and different percentages of coconut fiber reinforcements are tested in this stage to determine an optimal mix design. This study focuses on the interaction between fly ash (FA) and coconut fiber (CF) in the compressive strength of concrete and the results obtained at three periods: 7, 28, and 90 days. The mixes are grouped into five sets, each associated with the variation in fly ash content (0%, 10%, 20%, 30% and 40%); and Coconut fiber (CF) dosages range from 0% and 2.0% (CF 05-CF 20, where CF 05=0.5% fiber content). Each group has 5 different mixes based on coconut fiber percentages. In this stage, a total of 20 mixes of 5 groups were evaluated to find out the best possible combination of fly ash and coconut fiber.

Use of optimized material in concrete-Phase II

Since the combination of 1.5% coconut fiber (CF) with 30% fly ash yielded the best results in the first phase as evaluated in Fig. 2 the compressive strength recorded is 38.7 Mpa after 28 days of curing, it is consistently used in the second phase to evaluate the performance of concrete mixes using different activation methods and varying RCA content (0–100%). This phase examines the combined impact on the overall performance of chemically and mechanically activated fly ash, alongside different levels of RCA (0%, 50%, 75% and 100%), while maintaining optimized fiber and fly ash proportions. The selection of 1.5% CF with 30% fly ash is crucial, leveraging the synergy between the pozzolanic activity of fly ash and the reinforcing effect of fibers to balance strength and durability.

Phase II aims to validate the efficacy of this optimized mix at the concrete casting level, focusing on assessing how the FA30-CF15 combination performs at this optimized content in structural applications. This phase will examine the impact on the strength and durability of RCA concrete, emphasizing the benefits of activated fly ash for a sustainable concrete composition suitable for real-world applications.

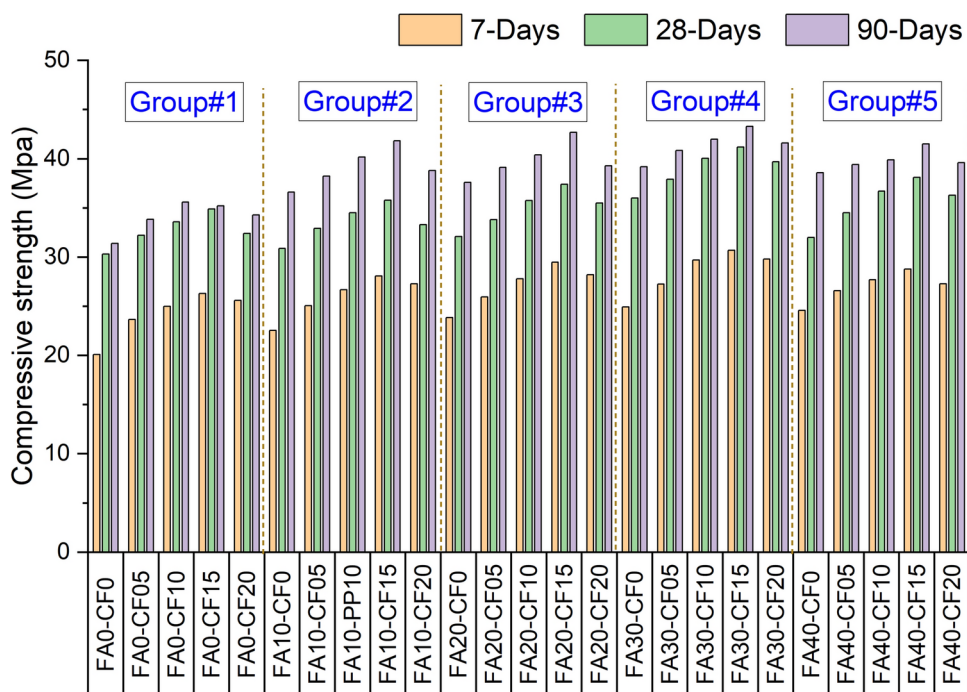


Fig. 2. Mortar Compressive strength after 7,28 and 90 days.

Composition of mixes
Phase-I

In phase I, 5 groups with 20 mixes were prepared for mortar cubes (50 × 50 mm) were cast and tested. Fly ash has been utilized as a substitute for ordinary Portland cement (OPC) in different proportions, including 10%, 15%, 20%, 25%, and 30%. Various proportions of CF (0%, 0.5%, 1%, 1.5% and 2%) were included with fly ash. FA0-CF0 describe (fly ash 0% and coconut fiber 0%). Table 6 presents the composition of the specimens.

Phase-II

In this phase, a total of four groups having concrete 16 mixes were prepared. The first group had no fly ash (control mix). The second group comprised 30% inactivated fly ash, while the third group incorporated 30% mechanically activated fly ash. The fourth and the last group contained 30% fly ash which had been chemically activated. Each group was further subdivided into four mixes based on the proportion of recycled concrete aggregate (RCA) used: 0%, 50%, 75%, and 100% RCA. The water-to-cement (W/C) ratio that was adopted was 0.55 in the mixes, and a superplasticizer that was added was 3% of the cement’s weight to help the mixes get the desired characteristics. Mix2-RCA100-IAF mix describes 100% recycled concrete aggregate with inactivated fly ash, MAF and CAF describe mechanically and chemically activated fly ash respectively. The composition of blends for phase II are shown in Table 7.

Results and discussion
Phase-I results

Phase-I compressive strength

The results of compressive strength using mortar are presented in Fig. 2. After 7 days of curing, all groups indicate increased strength with the use of Coconut fiber up to 1.5% signifying the role of bridging for strengthening of interfacial bonding between the matrix phase of the mortar. The FA30-CF15 mix reported the highest compressive strength with 30.7 MPa; the finding indicates that 30% of fly ash and 1.5% of CF form the best Mix. The strength of the control group FA0-CF0, which has no fly ash and CF fibers, showed a much lower strength of between 20.1 and 26.3MPa, this fact confirming that the inclusion of CF fibers has a positive impact on the strength enhancement of the concrete mix with and without the addition of fly ash. It is also evident that the earlier gain in strength for the higher fly ash levels was not significantly higher could be due to the slower rate of the fly ash pozzolanic reaction, which may become apparent at a later stage. At 7 days, the FA30-CF 15 mix performs 28.7 Mpa strength while the 28-day strength attains its best 38.7 MPa. These results imply that an addition of 30% fly ash and 1.5% CF produces the most adequate chemistry for producing the best possible strength. The gain in strength from 7 to 28 days varies from 20 to 30%, which over again emphasizes

Mixtures	OPC	FA	CF	SP	Aggregate (fine)	W/C**	W/C*
FA0-CF0	400	0	0	3	1200	0.5	0.5
FA0-CF05			0.5				0.53
FA0-CF10			1				0.55
FA0-CF15			1.5				0.57
FA0-CF20			2				0.59
FA10-CF0		10	0				0.5
FA10-CF05			0.5				0.53
FA10-CF10			1				0.55
FA10-CF15			1.5				0.57
FA10-CF20			2				0.59
FA20-CF0		20	0				0.5
FA20-CF05			0.5				0.53
FA20-CF10			1				0.55
FA20-CF15			1.5				0.57
FA20-CF20			2				0.59
FA30-CF0		30	0				0.5
FA30-CF05			0.5				0.53
FA30-CF10			1				0.55
FA30-CF15			1.5				0.57
FA30-CF20			2				0.59
FA40-CF0		40	0				0.5
FA40-CF05			0.5				0.53
FA40-CF10			1				0.55
FA40-CF15			1.5				0.57
FA40-CF20			2				0.59

Table 6. Composition of mixtures for phase-I (kg/m³).

Mixtures	OPC	Fly ash content	Fly ash (%)	Super plasticizer (%)	CF (%)	RCA content	Aggregate (fine)	Aggregate (coarse)	W/C
Mix1-RCA0	450	0	0	3	1.5	0	615	1230	0.55
Mix1-RCA50						615		615	
Mix1-RCA75						922.5		307.5	
Mix1-RCA100						1230		0	
Mix2-RCA0-IAF	315	135	30			0		1230	
Mix2-RCA50-IAF						615		615	
Mix2-RCA75-IAF						922.5		307.5	
Mix2-RCA100-IAF						1230		0	
Mix3-RCA0-MAF						0		1230	
Mix3-RCA50-MAF						615		615	
Mix3-RCA75-MAF						922.5		307.5	
Mix3-RCA100-MAF						1230		0	
Mix4-RCA0-CAF						0		1230	
Mix4-RCA50-CAF						615		615	
Mix4-RCA75-CAF						922.5		307.5	
Mix4-RCA100-CAF						1230		0	

Table 7. Composition of mixtures for phase-II (kg/m³).

the contribution of fly ash to highest strength gain in the case of mortar. It is also seen that 2.0% of CF dosage (namely CF20) exhibits slightly lower 28-day compressive strength than that of 1.5% dosage (CF15) confirming that there is an optimal level of CF beyond which incorporation may in fact be detrimental, this can be due to issues with fiber dispersion and problems related to matrix saturation resulting in reduced workability and packing efficiency. The 90 days result shows a similar trend of the increase of the compressive strength of all groups, and it re-establishes the pozzolanic activity of fly ash for further CSH formation which leads to strength enhancement. The 90-day maximum, 43.3 MPa, stays with the FA30-CF15 mix to show its capability on any given day. For all fly ash groups, the % higher strength between 28 and 90 days varies from 8 to 15%. This indicates that fly ash is constantly contributing to the gain in strength. There is a significant improvement of strength with higher volume, especially in mixes containing 20–30% fly ash cement thus validating this optima range. As with the 28-day results, sometimes, a higher CF content of 2.0% leads to lower 90-day strength, which remains to prove that 1.5% CF is the most effective dosage for achieving maximum strength gain throughout the period. These are evident from the results and show positive interaction between fly ash as a pozzolanic material and polypropylene fibers, particularly in the mix having 20–30% fly ash content where maximum effect from both pozzolanic activities and fiber reinforcement is obtained. The constant behavior of the FA30-CF15 mix confirms that this proportion is ideal for improving the synergy between fly ash as the pozzolan and CF as the reinforcing agent.

Phase-II results

Workability

The finding of workability is displayed in Fig. 3. The control samples exhibit a slump value of 65 mm, with the gradual substitution of NCA while using RCA (50%, 75%, and 100%) the values of slump are 68 mm, 71 mm, and 73 mm, respectively. Group-2 (having 30% inactive fly ash), the slump value is 70mm and gradual increase in the replacement of NCA with RCA (50%, 75 and 100%), the slump value is raised to 74 mm,76 mm and 79 mm respectively. In a similar way for Group -3 (having 30% Mechanically activated fly ash), the slump value is 73 mm and with the replacement of NCA with 50%, 75% and 100% RCA, the corresponding slump values are found to be 76 mm, 77 mm and 82 mm respectively. For Group-4 (having 30% Chemically activated fly ash), the Slump value is 77 mm and with the progressive substitution of NCA by 50%, 75% and 100% RCA, the slump value is 78 mm, 81 mm and 87 mm respectively. The increase in this workability can be attributed to the higher initial free water in the mixture which is needed to countercheck the high-water absorption demand of RCA's. The mix design considers aggregates to be in a saturated surface-dry (SSD) state to minimize variations between the samples. However, it is noted that during mixing, the aggregates are usually in an air-dried condition. To obtain SSD, more water is added to the mixture, based on the free surface and 24-h absorption of each aggregate because RCA has a relatively large and porous grain it would take a larger quantity of water to fully saturate but cannot accommodate all this additional water within the working time (10–15 min). Therefore, the surplus water raises the initial slump, improving the workability, and then is immobilized by RCA without affecting the cement hydration process. These findings, indicating enhanced workability with more RCA content, align with prior academic research, which found that more water within RCA mixes enables workable concrete^{44–49}. In addition, fly ash with a spherical shape produces less intergranular friction and thus improves the workability of the mix even at higher RCA doses⁴⁵. The FA is lighter than cement and is added in smaller quantities hence the density of the concrete is not significantly affected. FA also requires a relatively slightly lesser amount of plasticizer to attain the correct workability of the concrete^{49–51}. In other words, using FA enables the reduction of plasticizers and makes fresh concrete less problematic in terms of workability. The interaction effect between fly ash and coconut fiber on the slump of the concrete shows an increase in workability because of its mixture where both

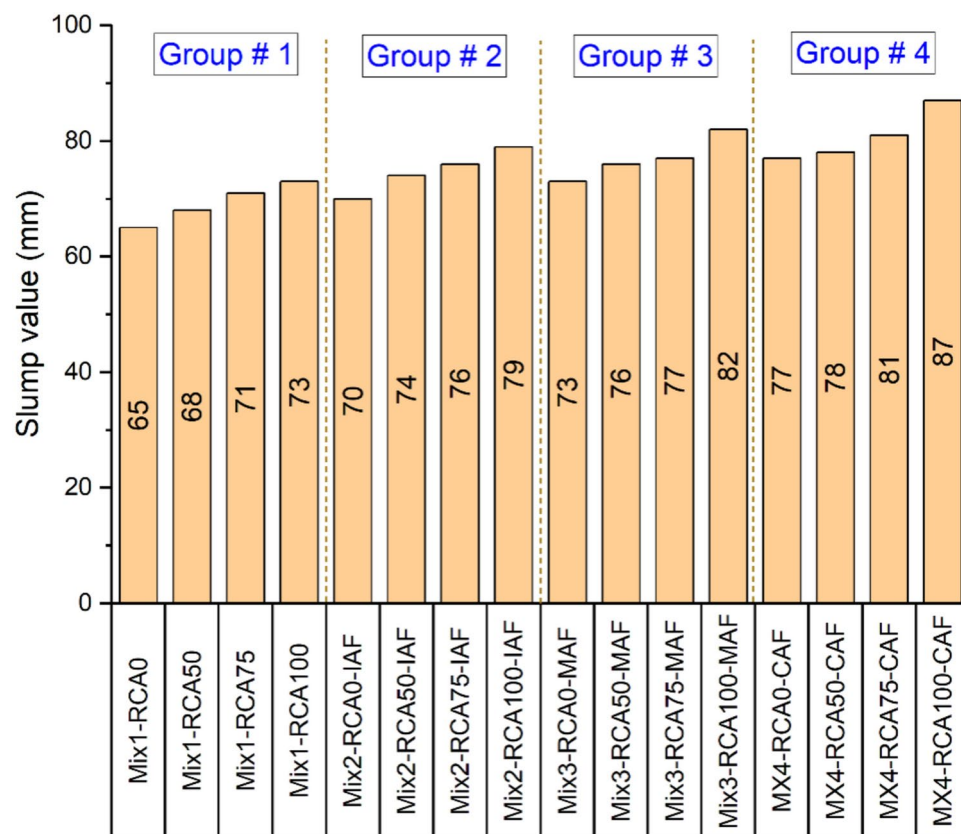


Fig. 3. Results of workability.

the materials have individual properties to influence this concrete characteristic⁵². On the other hand, coconut fiber as it contains fibers and has absorptive characteristics reduces the slump of the mixture because it makes the mixture stiffer and soaks up some of the mixed water thus providing a denser mass with less fluidity⁵³. Accordingly, both fly ash and coconut fiber could provide a slump of moderate level so that the workability in conveying concrete could be improved but the structural contribution of the fiber could also be preserved.

Compressive strength

The findings in Fig. 4 show the effect of variation of RCA and different activation method effect on compressive strength (CS), suggesting that when RCA is increased from 0 to 100% in all the mixes under consideration there is a corresponding decrease in compressive strength in the various states. Different activation methods effect on the CS with RCA shows that fly ash improves strength, furthermore, activation enhances the pozzolanic behavior and results in greater RCA strength. Ahmad et al.⁵⁴ found that 50 mm long Coconut fiber at 1.5% of binder content enhances the mechanical properties of the concrete.

The analysis of different activation methods and their respective groups' investigation in this study reveal that mechanical activation of FA is better than inactive fly ash. However, among the activation methods, chemical activation was found to be the best as far as the results obtained in the present investigation are concerned. The impact of varying activation methods for fly ash is compared, the blend Mix 1 with no-fly ash addition records the lowest compressive strength at all the RCA percentages. Mix 2 containing 30% inactive fly ash has demonstrated greater strength than Mix 1. Even without activation, fly ash enhances strength, which must be because of the siliceous and aluminous phases of fly ash that undergo partial pozzolanic reaction in the cement matrix when used in the inactive form⁵⁵. However, this is noted that the inactive state of the fly ash produces lower gains in strength as compared with its active forms.

The enhanced 28-day compressive strength seen in Mix 3 relative to Mix 2 is attributed to the superior reactivity of the mechanically activated 30% fly ash, resulting in greater bonding and matrix density. Chemically activated fly ash in Mix 4 records the highest compressive strength for all RCA levels, indicating that chemical activation better promotes the pozzolanic activity of fly ash as compared to mechanical activation, which leads to a denser and enhanced compressive strength matrix. This mix also performs the best with the higher strength as compared to the other mixes at all the available RCA replacement levels.

As in all other replacement levels of RCA, the computed compressive strength shows an overall reduction. This reduction is significantly more in Mix 1 because other enhancement methods such as additives and better mix design besides fly ash are required to boost the RCA's weaker characteristic. The improvement of fly ash by chemical activation has better resistance of strength reduction against the increase of RCA content in Mix 4. This indicates that chemical activation not only increases the initial strength but also reduces the impact of the RCA

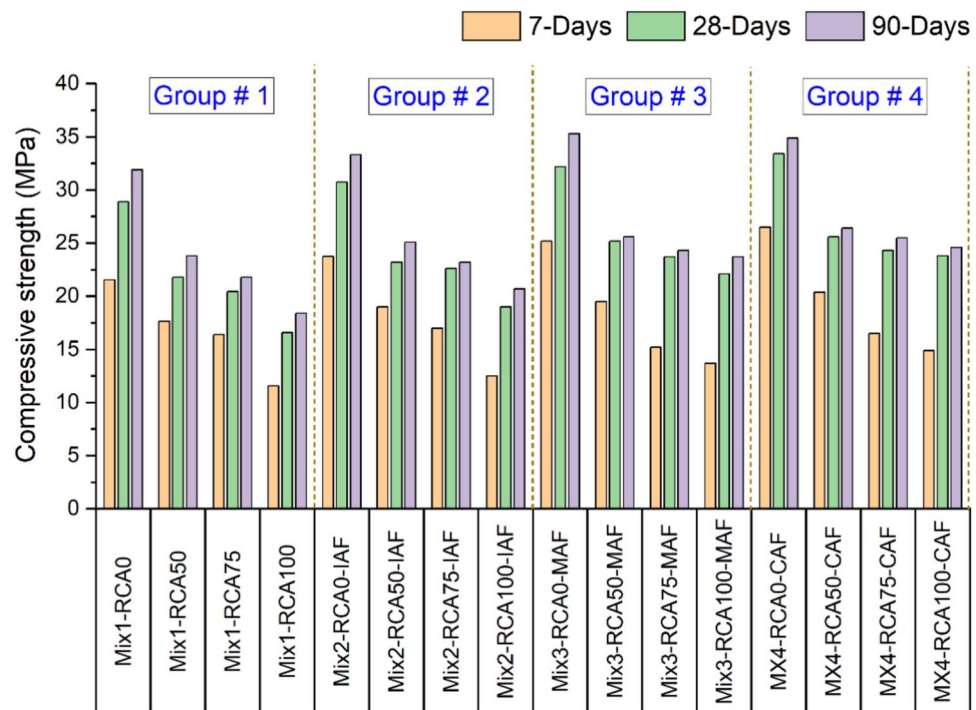


Fig. 4. Results of compressive strength.

effect of a decrease in lower mechanical strength⁵⁶. In conclusion, the findings validate that methods of fly ash activation are effective in increasing the strength of RCA. It was also noted that chemical activation on average yielded the greatest strength increases followed by mechanical activation and fly ash that was inactive⁵⁷. In general, RCA has lesser compressive strength, but the incorporation of activated fly ash particularly chemically activated illustrated the possible use of the material in sustainable concrete applications.

Effect of activation of fly ash on RCA strength Mechanical activation of fly ash increases its ability to increase compressive strength in RCA concrete. According to studies it was found that after curing for 7 days, the strength of concrete mixed with activated fly ash (AFA) increased from 5 to 25% compared to that of concrete containing only cement paste⁵⁸. Early strength gain (2–7 days after curing) is more marked for AFA than for untreated fly ash (UFA). Early strength gains and acceleration are attributed to the greater surface area and the increased reactivity of amorphous fly ash (AFA), which contribute to higher pozzolanic reactions and denser microstructures, allowing better strength in the composite⁵⁸. The improvement in the mechanical milling process mainly affects fly ash's fineness by refining the fly ash particle size. More surface area for reaction leads to improved interaction between fly ash and cementitious materials. A stronger and more compact matrix is formed because of more calcium silicate hydrate (C–S–H), and other hydration products, forming⁵⁹. The enhancement of the bond between RA and the surrounding paste via this increased densification is of paramount importance in improving the overall strength of RCA concrete. Also, the milling process generates a higher concentration of reactive alumina and silica in fly ash, which highly accelerates the hydration process. One of the most important factors influencing the pozzolanic reactivity of fly ash is particle size, and its reactivity is particularly high when the particle size is below 7 μm , resulting in an increased rate of formation of hydration products leading to both early and later strength in RCA concrete. The use of 5–10% milled fly ash leads to an increase in the compressive strength of up to 8–12% when compared to that of untreated fly ash. Fly ash is further milled with cement to reduce agglomeration and provide better dispersion of fine particles in the concrete mix. Improved particle distribution combined with increased silica and alumina content gives a more uniform and stronger cement matrix. Therefore, the use of AFA in RCA concrete results in better compressive strength and durability, which is better suited for structural applications that require higher early strength. Strength improvement due to activated fly ash (AFA) is a result of AFA content and reaction with calcium hydroxide ($\text{Ca}(\text{OH})_2$) to form more C–S–H in concrete, improving concrete properties. Furthermore, spherical AFA particles also function as micro reinforcements, spreading out internal stresses and preventing micro-cracks, which further improves the overall strength of concrete.

Similarly, research also confirms that two mechanisms contribute to concrete strength after the initial drop in strength due to fly ash. Mixes with fly ash content around 20% or less are dominated by the pozzolanic reaction between fly ash and CH. Second, fly ash filler effect becomes more important in compressive stiffness when the fly ash content increases to 40% and 60%, which is good because fly ash particles efficiently fill the void in between cement particles and fine aggregates. However, pozzolanic activity is reduced with high volume FA mixes where the calcium oxide content is lowered, and strength improvements rely more on the filler effect. The early compressive strength is improved by chemical activated of FA with 2% Na_2SO_4 to address the early

strength reduction. This activation generates a highly alkaline environment that speeds up the pozzolanic reaction and breaks the alumina and silica chains of fly ash into smaller units, thus reducing the time required to form the calcium silicate hydrate (C–S–H) gel and the ettringite. Inactive fly ash leads to a significant decrease in strength in 3 days, 15, 35 and 53% for 20, 40 and 60% fly ash mixes, respectively. Compared to their inactivated counterparts, Na_2SO_4 activated mixes have achieved 34% and 64% higher strength in 3 days. Na_2SO_4 activated mixes with 60%, found to have 61% more strength than its comparison to that of inactive. Chemically activated fly ash concrete exhibits early strength improvement due to higher alkalinity and ettringite formation which increase the reaction rate between calcium hydroxide (CH) and fly ash. Alkalinity of the higher order helps in faster reaction due to break down of fly ash particles more efficiently. By enhancing ettringite production, the increased sulfate levels also enhance early strength.

Chemical activation does reduce the difference in compressive strength between 28 and 90 days, demonstration to early consumption of CH through activation. At 28 days, 60% of fly ash concrete does not achieve the full strength of conventional concrete, but attains strength of 28 MPa, making this normal concrete, at economic cost of high-volume fly ash use when combined with chemical activation. Conversely, mixes without activation develop strength faster between 28 and 90 days, indicating the advantages of activation to achieve early strength development.

Tensile strength

The splitting tensile strength (STS) test results of all concrete mixes at 7, 28 and 90 days are shown in Fig. 5. The figure depicted how concrete strength influenced by RCA effect in combination with the impact of fly ash incorporation with coconut fiber when RCA was replaced with RCA across the mixes. The figure proves that regardless of the curing days the addition of RCA leads to a reduction in the compressive strength across all mixes.

In Group 1 (without fly ash), the control mix RCA0 exhibits splitting tensile strength (STS) values of 2.05 MPa, 3.20 MPa, and 3.58 MPa at 7, 28, and 90 days, respectively. For RCA50 (containing 50% RCA), this strength decreases to 1.54, 2.46, and 2.72 MPa at the same curing intervals. Similarly, for RCA75 (containing 75% RCA), STS decreases to 1.40, 2.40, and 2.51 MPa. Furthermore, in RCA100 (containing 100% RCA), STS further declines to 0.93, 1.94, and 2.1 MPa at 7, 28, and 90 days, respectively. The reduction in STS using RCA-based mixes is due to poor quality of RCA, poor bonding at interface between paste and aggregates, and due to less dense and weaker interfacial transition zone (ITZ) in RCA than that of NCA^{60,61}. Similar trends of reduction in STS with increase in RCA content are seen in prior works^{62,63} even though this research witnessed better performance, which might be attributed to superior quality RCA used in this work. Processed by grinding, mechanically activated fly ash proves to be a best alternative to inactive fly ash in improving the properties of cement-based materials. Grinding process improves fineness and surface area of fly ash particles and thus enhances their reactivity for pozzolanic reactions. The increased reactivity encourages more C–S–H to form,

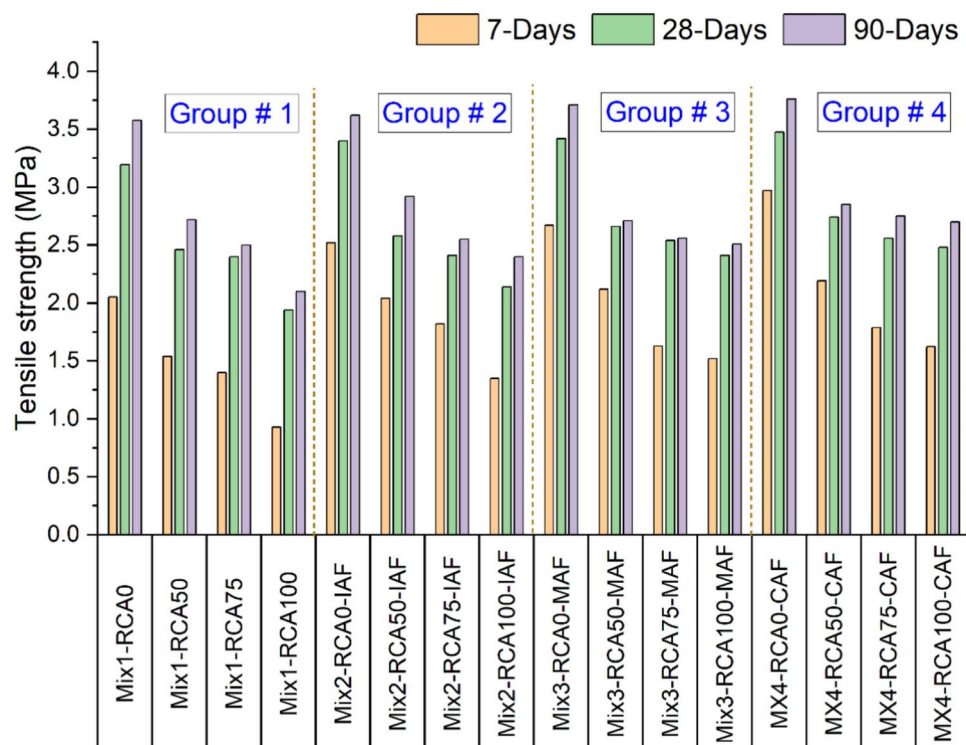


Fig. 5. Results of tensile strength.

thus strengthening the material, densifying the microstructure. While fly ash reacts more quickly in a pozzolanic reaction, its smaller particle size and greater surface area make fly ash denser⁵⁸.

Furthermore, In Group 4 (with 30% chemically activated fly ash), the control mix RCA0 shows splitting tensile strength (STS) values of 2.97, 3.47, and 3.76 MPa at 7, 28, and 90 days, respectively. For RCA50 (with 50% RCA), these strengths reduce to 2.19, 2.74, and 2.85 at the same curing intervals. Similarly, in RCA75 (with 75% RCA), STS values decreased to 1.79 MPa, 2.56, and 2.75 MPa. Furthermore, RCA100 (with 100% RCA) shows further reductions in STS to 1.62, 2.48, and 2.70 MPa at 7, 28, and 90 days, respectively.

It was found that chemical activation is more efficient and effective than mechanical activation in improving the strength and durability of fly ash based cementitious materials. The use of chemical activators like Na_2SO_4 and other sulfate compounds increases early and long-term strength⁶⁴. Calcium sulfate anhydrite and gypsum have improved the strength of high fly ash mortars utilizing nonstandard curing methods (for example, air drying). Curing at 60 °C for 6 h increased strength by more than 70% compared to normal curing, with gypsum producing strength gaining more than cement at later ages⁶⁵. Previous Research indicated that while fine grinding enhances fly ash surface area, reactivity, and improved early strength, chemical activation with Na_2SO_4 offered superior early strength. This shows the chemical activators' potential to induce more effective pozzolanic reactions and thus make the material denser and stronger³⁵. Likewise, fly ash concrete that was activated with 2.5% Na_2SO_4 and 4% sodium silicate showed both early and late strength increments those significantly outperformed mechanical methods as well as other chemical activators such as sodium hydroxide⁶⁶.

Density

The finding of density for different mixes is shown in Fig. 6. RCA0 (0% RCA), mix1, with no-fly ash, has a density of 2388 kg/m³. The density reduces as the amount of RCA increases, with a value of 2173 kg/m³ at RCA50 (50% RCA), 2080 at RCA75 (75% RCA), and less than 2003 kg/m³ for RCA100 (100% RCA). This trend implies that less density is achieved with increasing RCA content, particularly when fly ash is not added.

Group-2, incorporating inactive fly ash, exhibits a slightly reduced density of 2346 kg/m³ for RCA0 and shows enhanced density retention as RCA grows, in contrast to the active fly ash 'normal' RA Mix1. Density for RCA50 is 2195 kg/m³, RCA75 is 2103 kg/m³ and RCA100 has a density of 2090 kg/m³. Although the presence of inactive fly ash maintains a higher density than Mix1, the reduction pattern is like Mix1 even with increased RCA content. The initial density for RCA0 in Mix3 (Group-3) is 2334 kg/m³ and consists of 30% mechanically activated fly ash. The density retention of it is increased over Mix1 and Mix2 for RCA content and show improved density retention in this mix showing 2293 kg/m³ for RCA50, 2223 kg/m³ for RCA75, and 2134 kg/m³ for RCA100. Mechanically activated fly ash promotes efficient density retention, suggesting a structural benefit when even higher RCA levels are used. Group-4, with utilizing 30% chemically activated fly ash, have initial densities of 2337 kg/m³ in the case of Mix3, and 2333 kg/m³ for Mix4, which is similar to Mix3. Nevertheless, RCA content increases lead to greatest density reduction from Mix4, including 2295 kg/m³ for RCA50, 2280 kg/m³ for RCA75, and 2190 kg/m³ for RCA100. The density retention by chemically activated fly ash was the highest among all RCA levels, suggesting that it is the most effective in preventing density loss resulting from greater RCA content.

The results show that overall, density decreases with increasing RCA content across all groups, but variability in the type of ash activation has a large effect on how well density is maintained. The greatest density reduction is found when mix1 is mixed without fly ash which indicates limitations of using RCA in its pure form. Results from

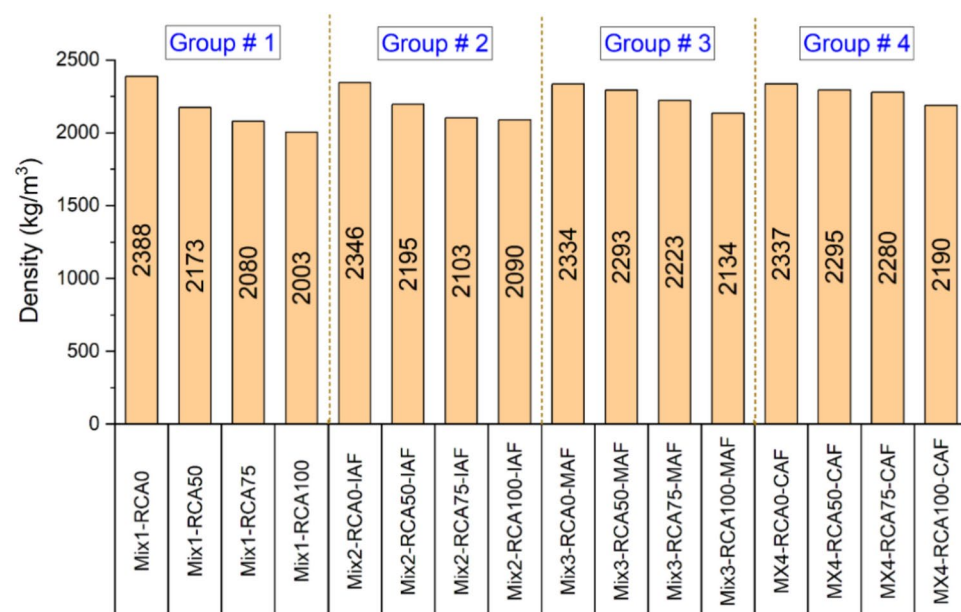


Fig. 6. Results of density.

mechanical activation of RCA in Mix3 show slightly better density retention compared to that of inactive fly ash, while Mix4 with chemically activated fly ash always shows highest density over all RCA levels, demonstrating that chemical activation is most efficient for maintaining density in recycled aggregate concrete.

The density of RCA concrete is affected both negatively and positively depending on the type of addition, that is coconut fiber and FA. It has been revealed that fly ash decreases the concrete density due to its lower specific gravity in combination with cement, but it contributes effectively to particle packing and void reduction⁶⁷. It will also help to improve compaction as well as filling the spaces that are available in RCA concrete and thus cause an improvement in its density. However, the addition of coconut fiber usually decreases bulk density because the fibers increase air voids and decrease the degree of compaction of the mix⁶⁷.

Consequently, it is found that the combined use of fly ash and coconut fiber can address these effects on density at optimal level. Besides, fly ash mitigates decreasing density resulting from coconut fibers application due to enhanced particle packing and occupying fewer void areas. This is beneficial in achieving a more uniform, slightly lighter concrete where fly ash is used to gain density and structural strength from the reinforcement while also getting the added enhancement from the reinforcement⁶⁸.

Water absorption

Water absorption is evaluated and presented in Fig. 7 for all four groups with different percentages of RCA over a period ranging from 7 days, 28 days, and 90 days with different percentages of FA content. Results confirmed that the water absorption in all four groups is found to increase with an increase in the RCA content irrespective of the fly ash content. The generic pattern reveals that the absorption is found to decrease with age among all four groups.

Incorporation of fly ash (FA) reduces the water absorption (WA) capacity in both RAC and NAC significantly. FA helps to occupy spaces between the cement particles and reduce the size of pores to decrease the concrete permeability⁶⁹. The most prominent reduction in WA is seen at 91 days. On 91 days, Group 1 (Mix1-RCA0, Mix1-RCA50, Mix1-RCA75 and Mix1-RCA100) exhibited higher water absorption (5.5%, 6.6%, 7.2% and 8.1% respectively) in comparison to Group 2 (Mix2-RCA0, Mix2-RCA50, Mix2-RCA75, and Mix2-RCA100) which exhibited relatively less water absorption of 4.8%, 5.2%, 6.4%, and 7.5%, respectively. Similarly, Group 3 (Mix3-RCA0, Mix3-RCA50, Mix3-RCA75, and Mix3-RCA100) showed water absorption of 4.1%, 4.8%, 5.4%, and 6.2%, respectively. The most lost water absorption at 90 days is observed for Group 4 (Mix4-RCA0, Mix4-RCA50, Mix4-RCA75, and Mix4-RCA100) which is 4.1%, 4.8%, 5.4%, and 6.2%, respectively. FA largely infiltrated the porous RCA mortar to seal the internal cracks and formed extra C-S-H gel, thereby further decreasing the overall absorption⁶⁷.

The water absorption in concrete increased with RA replacement levels of 50%, 75%, and 100%, attributed to the residual old mortar on the surface of RCA, which is porous and retains moisture, hence increasing the overall porosity of the concrete mix³⁷. The combination of fly ash and recycled concrete aggregate (RCA) slightly decreases the water absorption of mixtures in comparison to those containing only RCA; however, this effect is dependent upon the inclusion of fine particles and their optimal quantity, which can effectively occupy the

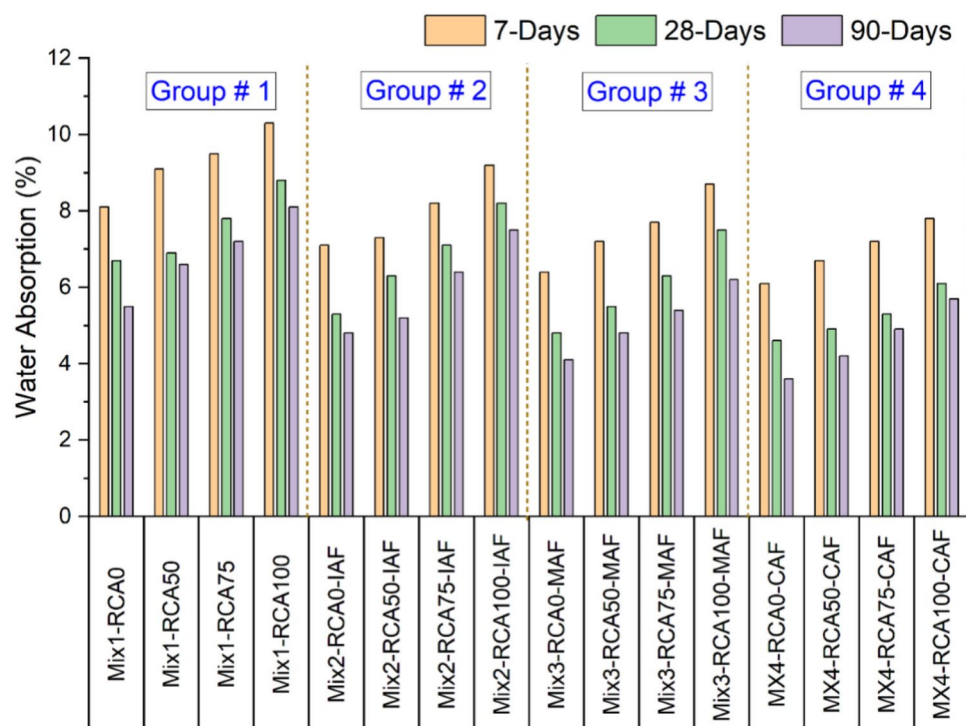


Fig. 7. Results of water absorption after 7, 28 and 90 days.

maximum pores and spaces in concrete, resulting in increased permeability of the composite⁶⁷. Coconut fibers have a strong attraction to water, depending on their distribution in the mixture, can clump together to create tiny air pockets, which is crucial for water absorption and porosity⁷⁰. However, the FA improves the workability of the mix by allowing more RCA, FA, and fibers to be distributed more uniformly and pack more uniformly. In conclusion, the composite of the combined presence FA and coconut fiber has a positive impact on the concrete absorption characteristics, its optimum addition to the mixture reduces the pores in internal microstructure and leads to more impermeability⁷⁰.

Acid resistance

Figure 8 illustrates that recycled concrete aggregate (RCA) is more susceptible to acid degradation than natural concrete aggregate (NCA), due to the higher permeability of RCA and the enhanced calcium hydroxide (CH) content in recycled aggregates, which combines with sulfate ions to produce gypsum and ettringite, resulting in expansion and diminished strength⁷¹. Mixtures containing no fly ash (group-1) and inactivated fly ash (group-2) had higher acid penetration compared to activated fly ash containing groups. As per the findings, group-4 and group-5 showed higher durability conformed by comparative less strength loss as compared to the control concrete and those without an activator. It indicates that the activation of fly ash in RCA concretes is beneficial in terms of both strength and higher durability.

The findings indicate variations in durability across groups assessing the acid resistance of concrete mixtures using different types of fly ash and RCA content. The 1-month decline in compressive strength was 6.48% for Mix1-RCA0, escalating to a 10.54% loss for Mix1-RCA100, indicating that elevated RCA concentrations make it more susceptible to acid attack. The enhanced porosity and weakened interfacial zones often present in RCA facilitate accelerated acid penetration and expedite system degradation, explaining the observed pattern. This trend continues over time, with a three-month compressive strength loss of 24% for Mix1-RCA0, which escalated to 27% for Mix1-RCA100.

Similarly, the group-2 showed the 1-month reduction after acid attack in compressive strength of 5.46% for Mix2-RCA0, which then increased to 9.66% for Mix2-RCA100 while for the same group with three-month acid exposure the loss is 21% for Mix1-RCA0, which increased to 25.5% loss for Mix1-RCA100. This improvement in group-2 mixes in comparison to group-1 is due to the presence of a partial pozzolanic effect of the fly ash which consumes some of the CH in the mix and therefore reduces the amount of CH ready to react with sulfate ions. But because the fly ash is not active, the acid resistance can provide some resistance. The inactive fly ash contributes some filler effect which improves packing and microstructure and contributes to better performance in the case of RCA concrete.

The addition of mechanically activated fly ash enhances the acid resistance of Group 3 (having 30% mechanically activated fly ash). The 1-month reduction after acid attack in compressive strength of 4.88% for Mix3-RCA0, which then increased to 8.21% for Mix3-RCA100 while for the same group with three-month acid exposure the loss is 20% for Mix3-RCA0, which increased to 23% loss for Mix3-RCA100. The enhancement in group-3 mixtures relative to group-1 is attributed to the inclusion of fly ash particles. Their reactivity is enhanced by mechanical activation, thereby augmenting the pozzolanic reactivity with calcium hydroxide. The reaction

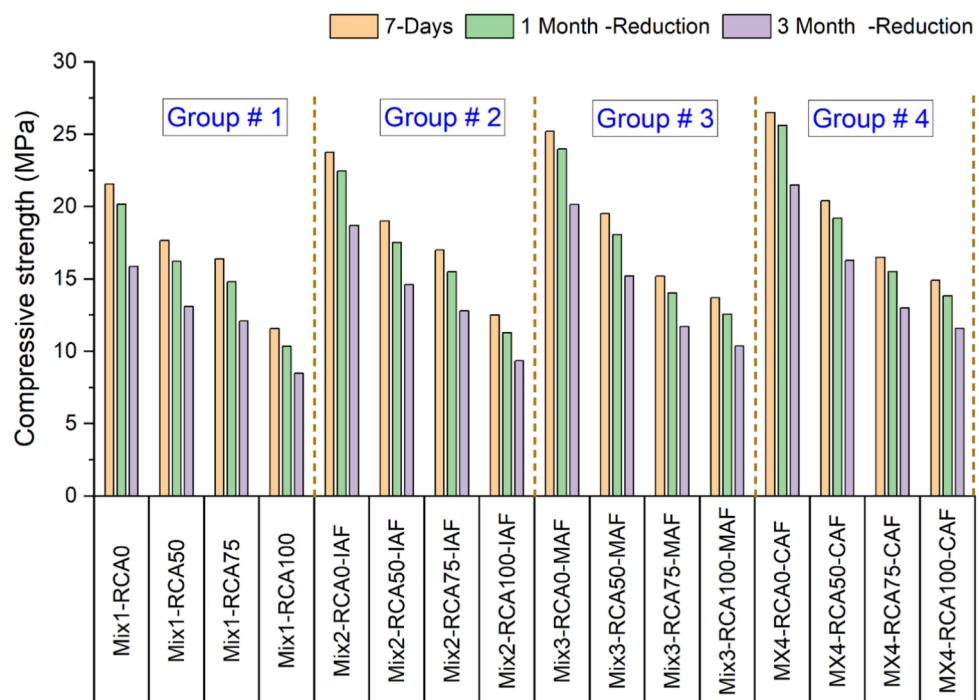


Fig. 8. Reduction of compressive strength after 1 and 3 months.

advances, resulting in the generation of more calcium silicate hydrate (C–S–H), which enhances concrete density and reduces permeability. In this case lower reduction rates are obtained over time than in Groups 1 and 2, Mix3-RCA100 reporting a reduction of 24.24% after three months, outperformed by the comparable mixes in Groups 1 and 2. This proves that in addition to filling voids, mechanically activated fly ash has the ability to increase interfacial zone strength in the concrete matrix, providing better protection against acid attack.

Group 4, which includes 30% chemically activated fly ash, delivers the greatest improvement in acid resistance, continually surpassing all other groups. The initial compressive strength loss seen in Mix4-RCA0 after one month of exposure is the lowest across all samples, with a reduction of 3.3%, demonstrating the minimal decline rates over one and three months. Similarly, Mix4-RCA100 reports a one-month reduction of 7.18% and a three-month reduction of 22.14%, among the lowest of all groups with 100% RCA. The reactivity of chemically activated fly ash approaches that of the parent inactivated fly ash, owing to the chemical treatment's capacity to dissolve the glassy phases and facilitate rapid pozzolanic reactions. The activation of this enhances the matrix and decreases pore connectivity, preventing acid entrance. The chemical activators also lead to the formation of extra C–S–H, which fills capillary pores and reinforces the interfacial transition zone, yielding concrete with improved chemical degradation resistance.

Rebound number

The findings of RN (rebound number) are shown in Fig. 9. The RN for control concrete in group-1 is 28 against the actual strength of 28.9 Mpa, while RCA content of 50%, 75% and 100% is found to be 20, 19 and 14 against the strength 21.8 Mpa, 20.4 Mpa and 16.5 Mpa respectively. Similarly the rebound number (RN) for control concrete in group-2 is 30 against the actual strength of 30.7 Mpa, while for RCA content of 50%, 75% and 100% is found to be 22, 20 and 17 against the actual strength 23.2 Mpa, 22.6 Mpa and 19 Mpa respectively. Additionally the rebound number (RN) for control concrete in group-3 is 31 against the actual strength of 32.2 Mpa, while for RCA content of 50%, 75% and 100% is found to be 24, 22 and 20 against the actual strength 25.2 Mpa, 23.7 Mpa and 22.1 Mpa respectively. Furthermore, the rebound number (RN) for control concrete in group-4 is 32 against the actual strength of 33.4 Mpa, while for RCA content of 50%, 75% and 100% is found to be 24, 23 and 21 against the actual strength 25.6 Mpa, 24.3 Mpa and 23.8 Mpa respectively.

This decline in RN is attributed to density of concrete, surface hardness, and strength of the material which forms the rebound number. Because RCA is lighter and less dense than the conventional aggregates, it helps to reduce these properties and hence has a lower rebound number⁷². Fly ash also contributes to the RCA concrete rebound number by improving the particle packing and the density by the pozzolanic activity and the formation of more C–S–H over time⁶⁷. This densification effect also fills voids, reduces porosity and improves the interfacial bonding between RCA particles and the matrix and all these collectively helped in enhancing the surface hardness and thereby indirectly supported a stable rebound number⁶⁷. Therefore, the durability and long-term rebound values of RCA concrete are increased, indicating that fly ash can counteract the reduction in concrete strength generally observed when using high levels of RCA.

Ultrasonic pulse velocity

The findings of Ultrasonic Pulse Velocity (UPV) at 90 days of curing to determine their deteriorating status, impacted by variables such as fly ash and RCA are shown in Fig. 10. The UPV of NAC is higher than that of RAC because of the higher porosity of RCA and its non-uniform nature. In all the mixtures, UPV decreases were

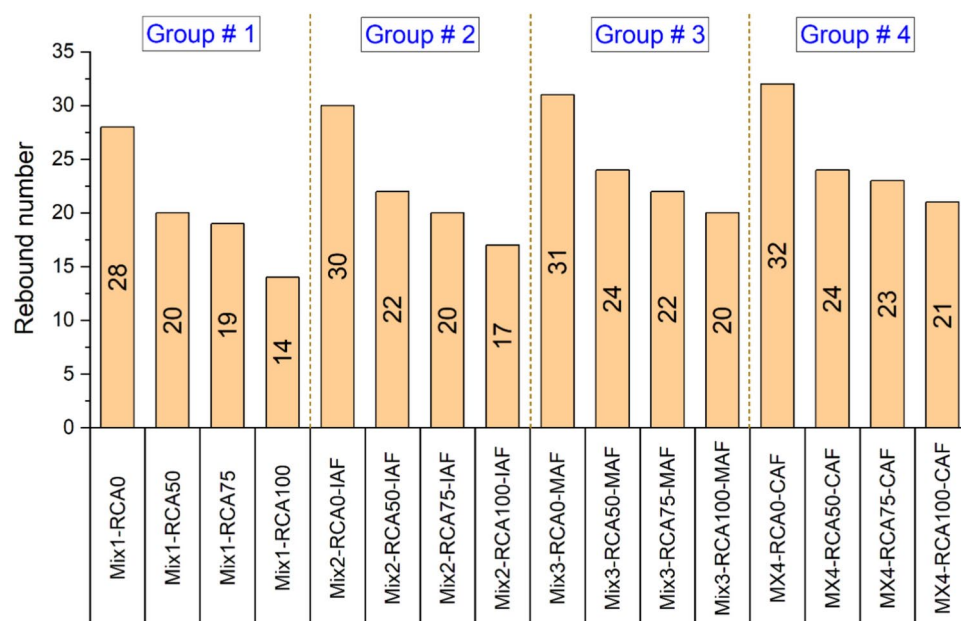


Fig. 9. Results of Rebound number.

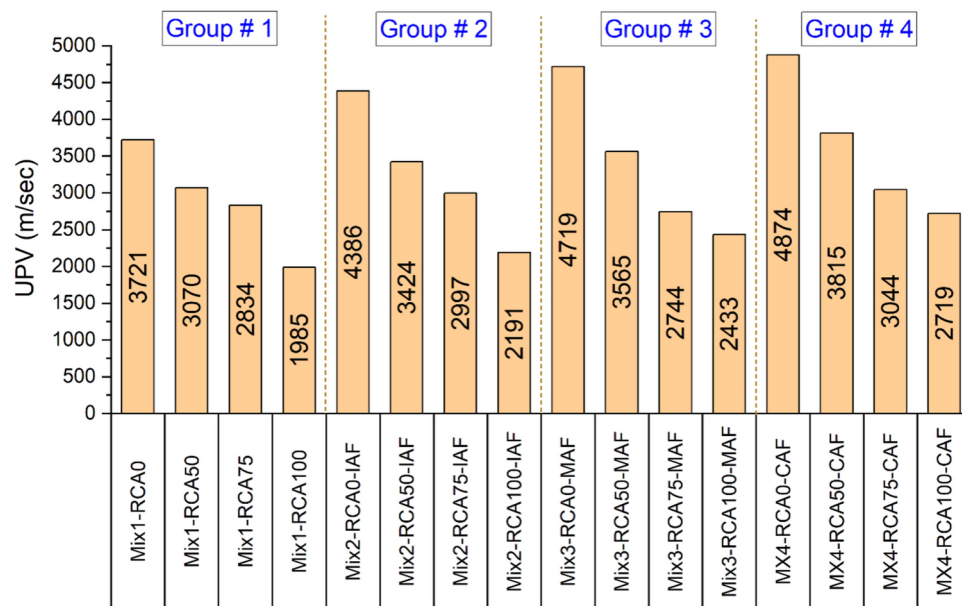


Fig. 10. Results of UPV.

seen with gradual changes due to the presence of RCA. Mixtures with both FA and RCA showed comparatively better result of UPV compared to group-1(having no fly ash). Mix1-RCA100, the mixture containing 100% RCA, showed the largest loss in UPV, indicating structural weakening. The UPV for Mix1-RCA0, Mix1-RCA50, Mix1-RCA75 and Mix1-RCA100 in Group-1is recorded as 3721 mm/s, 3070 mm/s, 2834 mm/s and 1985 mm/s. similarly the UPV for Mix2-RCA0, Mix2-RCA50, Mix2-RCA75 and Mix2-RCA100 in Group-2 is recorded as 4386 mm/s, 3424 mm/s, 2997 mm/s and 2191 mm/s. while the UPV for Mix3-RCA0, Mix3-RCA50, Mix3-RCA75 and Mix3-RCA100 in Group-3is recorded as 4719 mm/s, 3565 mm/s, 2744 mm/s and 2433 mm/s. Furthermore, the UPV for Mix4- RCA0, Mix4- RCA50, Mix4- RCA75 and Mix4- RCA100 in Group-4 is recorded as 4874 mm/s, 3815 mm/s, 3044 mm/s and 2719 mm/s. RCA particles are usually less dense, more porous and often contain lime rich acid mortar remnants that produce leaks through internal cracks in the concrete matrix, reducing UPV^{73,74}. FA is beneficial to long term pozzolanic reaction but can cause the UPV to be reduced in early stages due to the filler effect modifying the concrete microstructure which increases the concrete density, however, does not increase UPV immediately. But FA's pozzolanic reaction gradually supplies extra C–S–H gel, that might lessen UPV reduction over longer curing time⁷⁵. In the present study, as the UPV is performed at 90 day after casting to know how the pozzolanic contribution of fly ash addition to RCA concrete and comparative good results of UPV were observed in mixtures containing FA, it can be concluded that although FA enhances durability, density differences during the early stage in RCA concrete can affect the UPV values and this might be attributed to the density fluctuations when FA is first mixed with RCA concrete, but in later on UPV results at 90 days proves that FA's pozzolanic reaction gradually supplies extra C–S–H gel and improve micro structure.

Microstructure of RCA and Fly ash concrete

The SEM analysis of the concrete sample, depicted in Fig. 11. The structural voids certainly diminish the overall strength of the concrete. Secondly, pores in the surface microstructure formed by the amorphous layers of C–S–H and C–H weaken the mechanical properties of concrete. Conversely, SEM analysis of concrete modified with FA and Coconut fibers reveals that the surface of the C–S–H hydrates is more uniform and densely packed. The strength gain is attributed to the additional hydrated C–S–H compounds generated by the interaction between C–H and fly ash. The modified concrete also further strengthens itself by providing void filling as well as increased structural integrity from the ettringite crystals that grow through the concrete matrix.

Fly ash produced a compact packing effect that diminished porosity and occupied spaces within the matrix, resulting in a denser microstructure. This densification enhances mechanical characteristics and elevates sulfate content, leading to ettringite production that fills substantial cavities. The use of FA and CF fibers also provides enhanced bonding and interlocking between fibers and concrete which intermediates the stress distribution and inhibits the propagation of microcracks. The overall durability and strength of the modified concrete mixture is greatly reinforced by this bonding mechanism. The SEM analysis revealed that in the case of concrete without fly ash, the interfacial transition zone (ITZ) exhibited visible cracks and a lack of cohesive structure, indicating weak bonding areas. When inactive fly ash was introduced, there was noticeable improvement in the ITZ composition; however, some openings and voids remained evident, showing partial enhancement. The use of mechanically activated fly ash showed significant progress, as it was well-dispersed throughout the concrete matrix, effectively covering weak zones and providing a stronger, more cohesive ITZ. Among all cases, the addition of chemically activated fly ash demonstrated the most substantial improvement, completely covering and reinforcing the ITZ. The formation of additional C–S–H gels due to the chemical activation process led to enhanced densification of

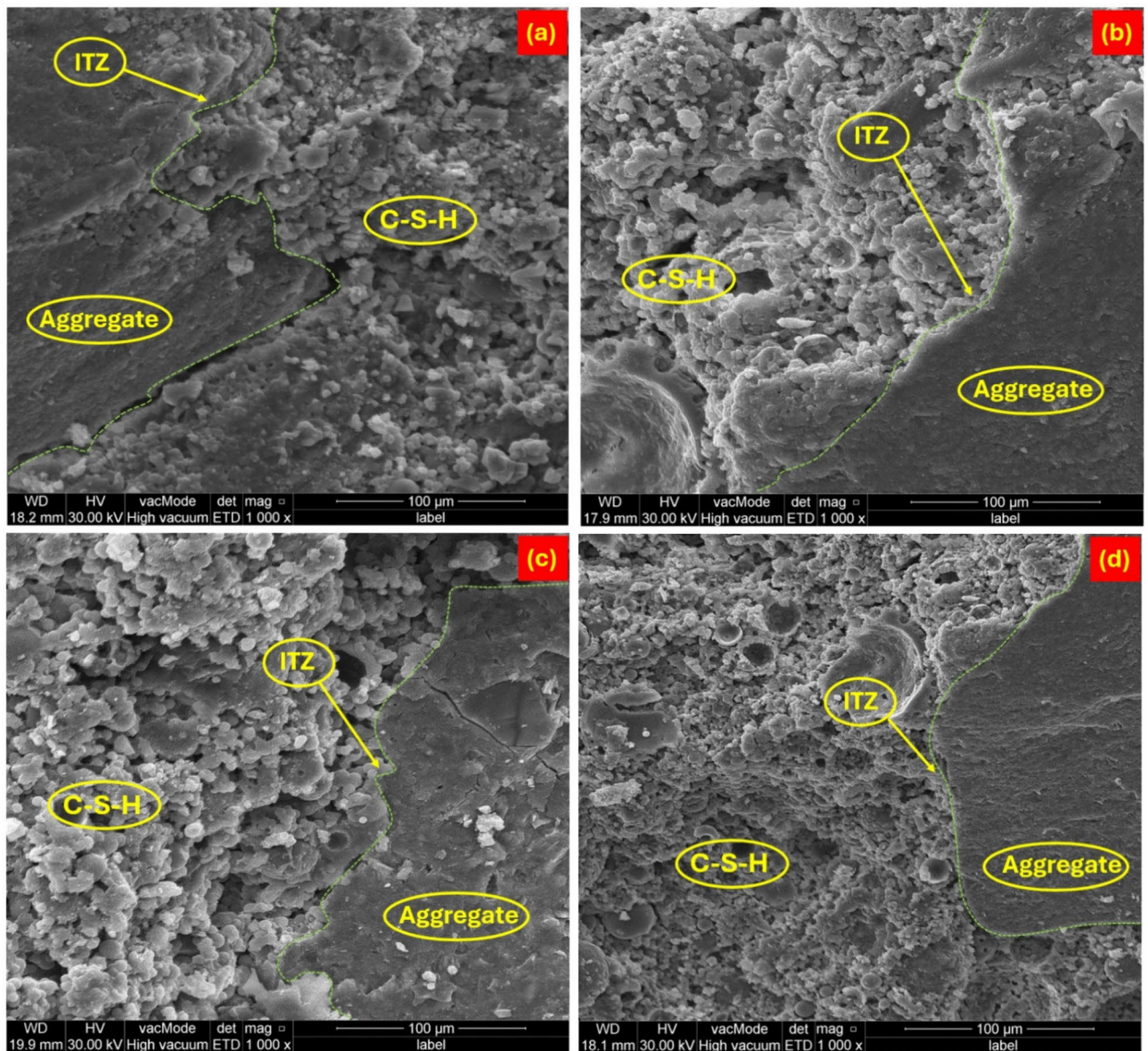


Fig. 11. SEM analysis (a) 100%RCA + no fly ash, (b) 100%RCA + inactive fly ash, (c) 100%RCA + Mechanically activated fly ash, (d) 100%RCA + Chemically activated fly ash.

the matrix and the sealing of minor cracks, greatly improving the structural integrity and overall performance of the concrete.

Conclusion

- The incorporation of 30% chemically activated fly ash along with 1.5% CF enhances compressive strength of the specimen by 25% and percentage of tensile strength by 17% in comparison to control. Furthermore, the density increase was observed at 5%, signifying enhancement in packing density and microstructure.
- The optimized mix had lower water absorption ability (6.2%) and better acid resisting capability: 7.18% strength loss after one month and 22.14% after three months of exposure to acid. This is a much better quality when compared to mixes containing no or inactivated fly ash or fibers.
- Chemically activated fly ash also led to enhanced workability since its particle plan formed spheres that reduced intergranular friction. The slump increased by 19%, which enables enhanced concrete compaction while at the same time maintaining structural characteristics.
- The incorporation of coconut fiber, which is an agricultural waste and the use of activated fly ash in the construction minimized the use of cement, emissions of greenhouse gases and the disposal of waste in the landfills hence the promotion of environment friendly construction.

Overall, the integration of sustainable materials, especially chemically activated fly ash, improved durability and strength of recycled aggregate concrete (RAC), and provided significant environmental benefits, including waste reduction, reduced emissions of carbon, and conservation of natural resources. Activated fly ash added to RCA concrete significantly improves strength and durability of resulting concrete. Both mechanically activated fly ash mix (Mix3-RCA50-MAF) and the chemically activated fly ash mix (MIX4-RCA50-CAF) satisfy structural concrete criteria with resultant strengths of over 25 MPa, proving the feasibility of these blends in structural applications. Results showed that activated fly ash and coconut fibers combination worked well in improving the mechanical properties and durability performance of RAC concrete to be a viable option for sustainable construction.

Data availability

Data will be made available on request to the corresponding author.

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T.A.: data curation conceptualization methodology. M.Z.Q.: Writing an original paper methodology testing. K.C.O.: Project administration funding analysis. E.A.: Funding analysis resources supervision. A.D.: Supervision investigation review paper. H.A.: Resources proof reading validation. A.A.: Review paper editing writing.

Declarations

Ethical approval

All authors approve that the research was performed under all the ethical norms.

Competing interests

The authors declare no competing interests.

Consent to publish

All authors consent to publishing this paper.

Additional information

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