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Strength improvement of M20 concrete using acid treated recycled coarse aggregate with fly ash

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Abstract:
Concrete, recognized for its strength and durability, poses significant environmental challenges due to natural aggregate depletion and emissions from cement production. This study investigates the potential of Recycled Coarse Aggregate (RCA) as a sustainable alternative to Natural Coarse Aggregate (NCA) and examines the synergistic effects of hydrochloric acid (HCl) treatment and fly ash incorporation on the performance of M20 grade concrete. Findings reveal that RCA can effectively replace NCA without compromising mechanical properties; however, acid treatment enhances RCA's bond with the cement matrix, leading to improved strength and durability. Furthermore, optimal mixes achieve a 25,7 % reduction in cement content when incorporating HCl with 25 % fly ash, alongside minor reductions in coarse and fine aggregates. Experimental results show that NCA achieves the highest compressive strength of 30,7 MPa, while untreated RCA shows a strength of 25,4 MPa. With HCl treatment, RCA reaches 30,0 MPa, and the optimal mix of 1,25 M HCl and 25 % fly ash yields the best performance at 32,6 MPa due to enhanced pozzolanic effects. This research emphasizes the importance of optimizing concrete mix designs through innovative treatments and sustainable materials, contributing to environmentally friendly construction practices.

Keywords:
acid treatment; compressive strength; concrete durability; fly ash; recycled coarse aggregate; strength improvement; sustainable construction

1 Introduction

Concrete is one of the most widely used building materials worldwide owing to its strength, durability, and versatility. However, the extraction of natural aggregates and the considerable energy required for cement manufacturing have a major negative influence on the environment. The building industry is moving toward environmentally friendly and sustainable options as knowledge of these problems has risen. Among these substitutes, the utilisation of recycled aggregates and additional cementitious materials has drawn much interest as a way to reduce the environmental impact of concrete without sacrificing its structural soundness. Natural coarse aggregate (NCA) traditionally used in concrete comes from quarries, which depletes natural resources and causes environmental problems such as habitat destruction and rising carbon emissions. The viability of employing recycled coarse aggregate (RCA) from building and demolition waste has been investigated in previous studies. RCA provides an eco-friendly alternative by removing waste from landfills and lowering the demand for new materials. The use of RCA could successfully replace NCA without compromising the mechanical qualities of concrete [1]. The comparison of different concrete mix designs showed that concrete built with RCA had compressive strengths comparable to those of concrete made with NCA, which confirms the potential of RCA as a sustainable alternative.

Expanding this framework, recycled aggregates affect the mechanical properties and longevity of concrete [2]. Studies showed that RCA-concrete exhibited satisfactory performance, emphasising the need for further exploration into optimising mix designs for improved structural characteristics. The performance of self-curing compounds in M25 self-compacting concrete, highlights the importance of innovation in concrete formulations [3]. Recycled concrete aggregates (RCA) produced from crushed concrete debris are a sustainable substitute for natural aggregates [4]. Residual mortar attached to the aggregate surface causes RCA to have worse quality than natural aggregates [5]. Several treatment methods, including acid treatment, have been used to improve performance of RCAs and overcome this restriction [6]. Acid treatment, which strengthens the bond between the aggregate and cement paste, is a promising technique for removing mortar and exposing the aggregate surface. The mechanical properties of concrete may benefit from this enhancement. The treatment of RCA with other chemicals, including hydrochloric acid (HCl), to improve its characteristics has been a topic of interest. According to previous research, acid treatment can strengthen the link between RCA and the cement matrix, thereby increasing the overall strength and longevity of concrete. The foundation for investigating acid-treated RCA is to examine the effects of various treatment techniques on the characteristics of the mixture [7].

A strong relationship between the treatment techniques and concrete performance demonstrated that RCA treatment could significantly enhance the mechanical properties of concrete. Furthermore, using fly ash, a by-product of burning coal, as an additional cementitious ingredient has been successful in enhancing the quality of concrete and promoting sustainability initiatives [8]. The addition of fly ash to recycled aggregate concrete may significantly enhance its technical properties, resulting in improved durability and mechanical performance [9]. The use of large amounts of fly ash along with recycled aggregates increases the strength of concrete and decreases its global warming potential [10]. The findings on how fly ash can absorb carbon dioxide emissions supports its use as an eco-friendly ingredient in concrete [11; 12]. Another study explored how incorporating both fly ash and nano-silica into recycled aggregates can result in significant enhancements in concrete properties, highlighting the potential of advanced materials in modern concrete technology [13]. Concrete is widely recognised for its strength and durability; however, its production has significant environmental impacts, particularly through the depletion of natural aggregates. Studies have demonstrated that recycled coarse aggregate (RCA) can be utilised as a sustainable substitute for natural coarse aggregate (NCA) without compromising the mechanical quality [14]. RCA minimises the waste and environmental effects, and conserves natural resources during construction and demolition, thereby substantially contributing to sustainability in structural engineering. Life-cycle design concepts that emphasise the goal of long-term, economical, and ecological benefits in building development are consistent with the addition of RCA [15]. Revolutionary concrete materials provide environmental advantages that extend beyond RCA applications, such as decreased CO_2 emissions and optimised material consumption [16]. However, high porosity and surface contaminants may impact the performance of RCA in concrete. Acid treatment increases the quality of RCA by strengthening its bonding properties and strengthens the concrete. Fly ash further improves the mechanical qualities by improving the microstructure and lowering the permeability. More studies are required to incorporate sustainability principles into structural design [17] and provide practical strategies for material selection and construction techniques that increase resilience and reduce the ecological footprint. In addition to improving the strength, the use of fly ash and acid-treated RCA in M20 concrete addresses resource depletion, environmental issues, and economic efficiency [18]. However, explicit research on the combined effects of acid treatment on RCA and the addition of supplemental elements, such as fly ash, to concrete is lacking [19]. RCA enhances the sustainability of concrete while maintaining its structural integrity. Treatment with hydrochloric acid has shown promise for improving RCA bonds with the cement matrix and enhancing the strength and durability [20]. The purpose of this study was to close the current gap by examining the effects of hydrochloric acid treatment on RCA and its interactions with fly ash to improve M20 grade concrete [21]. Workability, water absorption, compressive strength, tensile strength, and flexural strength are examined in this study to offer insights to the use of recycled materials into common concrete applications [12]. The novelty of this research is its focus on optimising concrete mix design through innovative treatments, thereby contributing to sustainable construction practices [13].

Despite the wealth of prior research on RCA and fly ash, the combined impact of acid-treated RCA and fly ash on the strength and durability of concrete, particularly, M20 grade concrete, has not been investigated. The primary focus of this study is to determine the manner in which fly ash and acid-treated RCA affect the compressive strength and other characteristics of M20 grade concrete. The following are the objectives of the study: (1) determining how various proportions of acid-treated RCA affect the compressive strength of M20 grade concrete; (2) determining how fly ash affects the compressive strength and other characteristics of concrete when it contains acid-treated RCA; (3) obtaining the required strength and durability characteristics of M20 grade concrete, the mix proportions of acid-treated RCA and fly ash should be optimised; and (4) comparing the performance of concrete containing these materials to that of ordinary concrete. This study aimed to use recycled resources to create high-performance sustainable concrete by fulfilling these goals. The uniqueness of this research is its emphasis on strengthening M20 concrete by utilising fly ash and acid-treated RCA in combination, which may pave the way for improved mechanical qualities and lower environmental impact in concrete applications. Based on these findings, this study aims to close the gap in prior research and encourage industries to embrace sustainable construction techniques.

2 Methodology

2.1 Materials

2.1.1 Ordinary Portland Cement (OPC)

In this study, M20 concrete mixtures containing natural coarse aggregate (NCA), recycled coarse aggregate (RCA), acid-treated RCA, and acid-treated RCA with fly ash were prepared using ordinary Portland cement (OPC). The OPC used to make slurries for RCA treatment was 53-grade, which has a normal density of 3,15 g/cm³ and was purchased locally. The great strength and durability of OPC are attributed to its chemical composition, which comprises important elements, including iron oxide, silica, alumina, and lime, as per IS 12269:2013. Furthermore, the effectiveness of cement in construction applications is significantly influenced by its physical characteristics such as density and specific surface area. The physical characteristics and chemical compositions of the OPC employed in this study are listed in Tables 1 and 2.

Table 1. Chemical composition of OPC

S. No	Compounds	Percentage observed in the experiment	Percentage as per IS 12269:2013
1	Calcium oxide (CaO)	66,30	60-67
2	Silicon-di-oxide (SiO_2)	23,80	17-25
3	Aluminium oxide (Al_2O_3)	6,40	3-8
4	Ferric oxide (Fe_2O_3)	5,60	0,5-6,0
5	Magnesium oxide (MgO)	3,70	0,1-4,0
6	Sulphur trioxide (SO_3)	2,60	1,3-3,0
7	Alkali in terms of Sodium Oxide (Na_2O) and Potassium oxide (K_2O)	1,15	0,4-1,3

Table 2. Physical properties of OPC

Properties	Attained values	Specified values with IS Code
Fineness (specific surface area)	314 m²/kg	≥ 225 m²/kg (IS 4031 Part 2)
Consistency	29,6 %	26-33 % (IS 1199)
Initial setting time	54 min	Minimum 30 min (IS 4031 Part 5)
Final setting time	564 min	Maximum 600 min (IS 4031 Part 5)
Soundness	3 mm	Maximum 10 mm (Le Chatelier) (IS 4031 Part 3)
Compressive strength	55,4 MPa	28 days: ≥ 53 MPa (IS 516)
Specific gravity	3,18	Typically, 3,15 (IS 4031 Part 11)

2.1.2 Fly ash

According to IS 3812 (Part 1), fly ash is a fine-grey powder with a specific gravity of 2,2; which falls between 2,0 and 2,6. Its Blaine surface area (fineness) is 350 m²/kg, which exceeds the minimum requirement of 225 m²/kg, indicating good reactivity. The loss on ignition is 3 %, which is below the maximum limit of 5 %, which ensures minimal unburned material. Fly ash requires 25 % more water than cement, which affects the water–cement ratio in concrete mixtures. Its setting time acts as a retarder and varies depending on the dosage, which enables flexibility in workability and curing times. A pH value of 8,5 indicates moderate alkalinity, which contributes to the overall stability and performance of concrete. These characteristics make fly ash an excellent means of increasing the strength of M20 concrete, particularly when mixed with acid-treated RCA. Table 3 lists the chemical composition of the fly ash used in this study.

Table 3. Chemical composition of fly ash

Component	Typical value (% by weight)	Typical range (% by weight) as per IS 3812 (Part 1)
Silicon Dioxide (SiO_2)	50,8	30-60
Aluminum Oxide (Al_2O_3)	25,3	15-30
Iron Oxide (Fe_2O_3)	8,6	5-15
Calcium Oxide (CaO)	5,2	1-10
Magnesium Oxide (MgO)	2,8	0-5
Sodium Oxide (Na_2O)	1,9	0-5
Potassium Oxide (K_2O)	1,7	0-5
Sulphur Trioxide (SO_3)	2,3	0-5

The primary ingredient influencing the pozzolanic qualities of the fly ash is silicon dioxide, which accounts for 50,8 % of the mixture. Aluminum oxide, which constitutes 25,3 %, also contributes to these qualities. Iron Oxide (8,6 %) affects the colour and strength, and calcium oxide (5,2 %) contributes to early strength. Oxides of magnesium (2,8 %), sodium (1,9 %), and potassium (1,7 %) influences the workability and reactivity, whereas sulphur trioxide (2,3 %) is important for controlling the setting times. Class F fly ash was presumably used in this investigation. The chemical composition of Class F fly ash matches that of the fly ash used in this study and often has a high percentage of SiO_2 and Al_2O_3. The high concentrations of SiO_2 (50,8 %) and Al_2O_3 (25,3 %) appear to be within the normal range for Class F fly ash, which is distinguished by its pozzolanic qualities. The use of fly ash in conjunction with acid-treated RCA to increase the strength of M20 concrete is supported by its comprehensive chemical composition, which improves the mechanical performance and sustainability of concrete applications.

2.1.3 Natural Coarse Aggregate (NCA)

Table 4 lists the mechanical characteristics of NCA, which demonstrates its suitability for concrete applications requiring high strength and durability. NCA had an average particle size of 21 mm, which is ideal for maintaining good workability in M20 concrete. NCA has a moderately dense specific gravity of 2,7; which adds to the overall strength and compactness of the concrete. The water absorption of the NCA is low at 1.05 %, which supports moisture stability in the concrete mix and helps to avoid unwanted shrinkage or expansion over time. The mechanical characteristics of NCA, such as its aggregate crushing value (ACV) of 23,8 % and aggregate impact value (AIV) of 20,4 %, indicate that it is suitable for load-bearing applications because of its strong resistance to crushing and impact forces. The Los Angeles abrasion value of 25,2 % for the NCA reflects its excellent resistance to wear, which is critical for concrete structures exposed to abrasive forces. With a porosity of only 1,7 %, NCA has a minimal void content, which reduces the risk of moisture ingress and improves freeze–thaw durability. The bulk density of NCA, measured at 1550 kg/m³, further emphasizes its compactness and ability to contribute to denser concrete. Furthermore, NCA is contaminant-free, which ensures optimal bonding with the cement matrix and results in consistent concrete quality.

Table 4. Mechanical properties of natural coarse aggregate

Property	Typical value for NCA
Size (average)	21 mm
Specific gravity	2,7
Water absorption	1,05 %
Aggregate crushing value (ACV)	23,80 %
Aggregate impact value (AIV)	20,40 %
Los Angeles abrasion value	25,20 %
Porosity	1,70 %
Bulk density	1550 kg/m³
Cleanliness (contaminants)	None

2.1.4 Natural Fine Aggregate (NFA)

The appropriateness of natural fine aggregate (NFA) is demonstrated by its mechanical qualities for use in concrete applications, thereby ensuring optimal performance and durability (Table 5). With an average particle size of 4,75 mm, NFA effectively fills voids in the concrete mix and contributes to enhanced workability and stability. A specific gravity of 2,6 demonstrates a moderate density, which supports the overall strength of the concrete. A controlled water-to-cement ratio is maintained during mixing, and the possibility of excessive moisture absorption is reduced because of the comparatively low water absorption rate of 1,2 %. According to sieve analysis, 90-100 % of the NFA passes through the 4,75 mm sieve, guaranteeing appropriate gradation that promotes effective packing and lowers segregation. A fineness modulus of 2,5 indicates a well-balanced particle size distribution, which aids in achieving a cohesive and workable mix. The bulk density of NFA is 1465 kg/m³, which provides adequate mass and stability to the concrete structure. Furthermore, the lack of impurities guarantees a strong link between the cement paste and aggregates, which eventually improves the strength and longevity of the concrete. Collectively, these properties make NFA essential components for obtaining high-quality concrete for various construction applications.

Table 5. Mechanical properties of natural fine aggregate (NFA)

Property	Typical value for NFA
Size (average)	4,75 mm
Specific gravity	2,6
Water absorption	1,2 %
Sieve analysis (passing 4.75 mm)	90-100 %
Fineness modulus	2,5
Bulk density	1465 kg/m³
Cleanliness (contaminants)	None

2.1.5 Recycled coarse aggregate

Table 6 depicts the difference between RCA and NCA in terms of mechanical strength, density, and water absorption. RCA has an average particle size of 22 mm, which is comparable to NCA, however, it may vary slightly owing to the presence of residual mortar and aggregate fragments from its previous use. Owing to its higher porosity and attached mortar, RCA has a specific gravity of 2,4; which renders it lighter than NCA. The water absorption of RCA is significantly higher, at 4,8 %, indicating that it retains more water because of its porous structure. This increased absorption necessitates adjustments to the water–cement ratio when RCA is used in concrete to maintain workability and strength. Compared to NCA, RCA has higher ACV (33,7 %) and AIV (35,6 %). This reflects the comparatively lower resistance of RCA to crushing and impact forces, which should be considered when used in structural applications. The Los Angeles abrasion value for RCA is 40,4 %, suggesting it has moderate resistance to abrasion. Although it may not perform as well as NCA in heavy-wear conditions, RCA remains suitable for non-structural or low-load applications. The porosity of RCA is 4,8 %, significantly higher than that of NCA, which can cause increased moisture ingress and potentially affect durability. The bulk density of RCA is lower, at 1370 kg/m³, indicating a less compact material that contributes to a lighter, albeit less dense, concrete matrix. RCA may contain trace contaminants (up to 1 %), which reinforces the need for quality control during its processing and suitability primarily for applications where high strength and durability are not critical.

Table 6. Mechanical properties of recycled coarse aggregate

Property	Typical value for RCA
Size (average)	22 mm
Specific gravity	2,4
Water absorption	4,8 %
Aggregate crushing value (ACV)	33,7 %
Aggregate impact value (AIV)	35,6 %
Los Angeles abrasion value	40,4 %
Porosity	4,8 %
Bulk density	1370 kg/m³
Cleanliness (contaminants)	Trace (up to 1 %)

2.1.6 Acid-treated RCA

A possible technique for improving the quality of recycled coarse aggregate (RCA) and increasing its suitability for use in concrete construction is treatment with hydrochloric acid (HCl). This treatment enhances the durability and mechanical quality of the concrete by efficiently eliminating impurities and residual cement paste. It also encourages the reuse of waste materials, which helps in sustainability initiatives in the construction sector. However, the acid concentration and treatment duration must be analysed comprehensively to maximise the benefits while minimising the potential adverse effects on the aggregates. Previous studies have established that treating RCA with hydrochloric acid concentrations between 0,3-1,6 M can significantly enhance the quality of the aggregate. The typical treatment duration ranges from 30-60 min; however, extended exposure may result in over-dissolution, thereby compromising aggregate integrity. Therefore, a concentration range of 0,75-1,50 M with increments of 0,25 M was selected for this study and the RCA was treated for 45 min.

2.1.7 Integration of fly ash in acid treated RCA

Studies and instructions in IS codes, particularly IS 456:2000, indicate that the effective percentage of fly ash required to boost the strength of acid-treated RCA using OPC 53 grade in M20 concrete typically varies from 20-30 % by cement weight. A control mix without fly ash served as the baseline, whereas incorporating 20 % fly ash causes moderate improvements in strength and workability. A 25 % replacement is optimal for significant strength gain, particularly for the acid-treated RCA. Although using 30 % fly ash may offer additional benefits, excessive fly ash can cause increased water demand and reduced strength. Conversely, a low fly ash content (below 20 %) may not fully harness its benefits, thereby limiting the improvements in durability and workability. Therefore, this study incorporated a range of 20-30 % fly ash content with increments of 5 %, in conjunction with acid-treated RCA to optimise the performance and structural integrity of M20 concrete.

2.1.8 Superplasticizers

The analysis on the strength improvement of M20 concrete using acid-treated RCA and fly ash did not use superplasticisers to evaluate the natural workability and performance of the concrete mix without chemical admixtures. This decision aimed to assess the intrinsic properties of recycled aggregates and fly ash while minimising the costs associated with additives. Furthermore, this study aimed to understand how acid-treated aggregates influence water absorption and surface texture, which could affect their workability. By relying solely on fly ash to enhance workability and strength, researchers can isolate the impact of these materials and ultimately focus on the sustainability and effectiveness of the concrete mix in promoting eco-friendly construction practices.

2.1.9 Water quality

In this study, concrete was mixed and cured using locally acquired potable water. The water conformed to the standards outlined in IS 456:2000, ensuring that it was free from harmful impurities, such as oils, acids, bases, salts, sugars, and organic substances. Achieving the required strength and durability of concrete crucially depends on the quality of the mixed water. The strength and durability of the finished product may be diminished by the negative effects of contaminants on the hydration and cement paste–aggregate bond. The investigation maximised the strength and durability of M20 concrete by using clean, drinkable water to guarantee ideal hydration conditions.

2.1.10 Specimen preparation

The type of coarse aggregate used has a significant impact on the concrete performance. NCA is preferred owing to its low porosity and consistent quality, which positively contribute to the properties of concrete. However, RCA presents challenges such as irregular shapes and residual mortar, which can negatively affect the performance of concrete. During specimen preparation, the selected coarse aggregate was mixed with other ingredients, such as cement, fine aggregates, and water, to form a concrete mixture. After mixing, the concrete was poured into moulds, compacted to remove air voids, and cured under controlled conditions. After curing, compressive strength tests using a hydraulic compression testing machine, flexural strength tests on the beams, and tensile strength tests on the cylindrical specimens were performed to evaluate the mechanical properties of the concrete. Figure 1 illustrates the concrete mix preparation, curing, and testing processes.

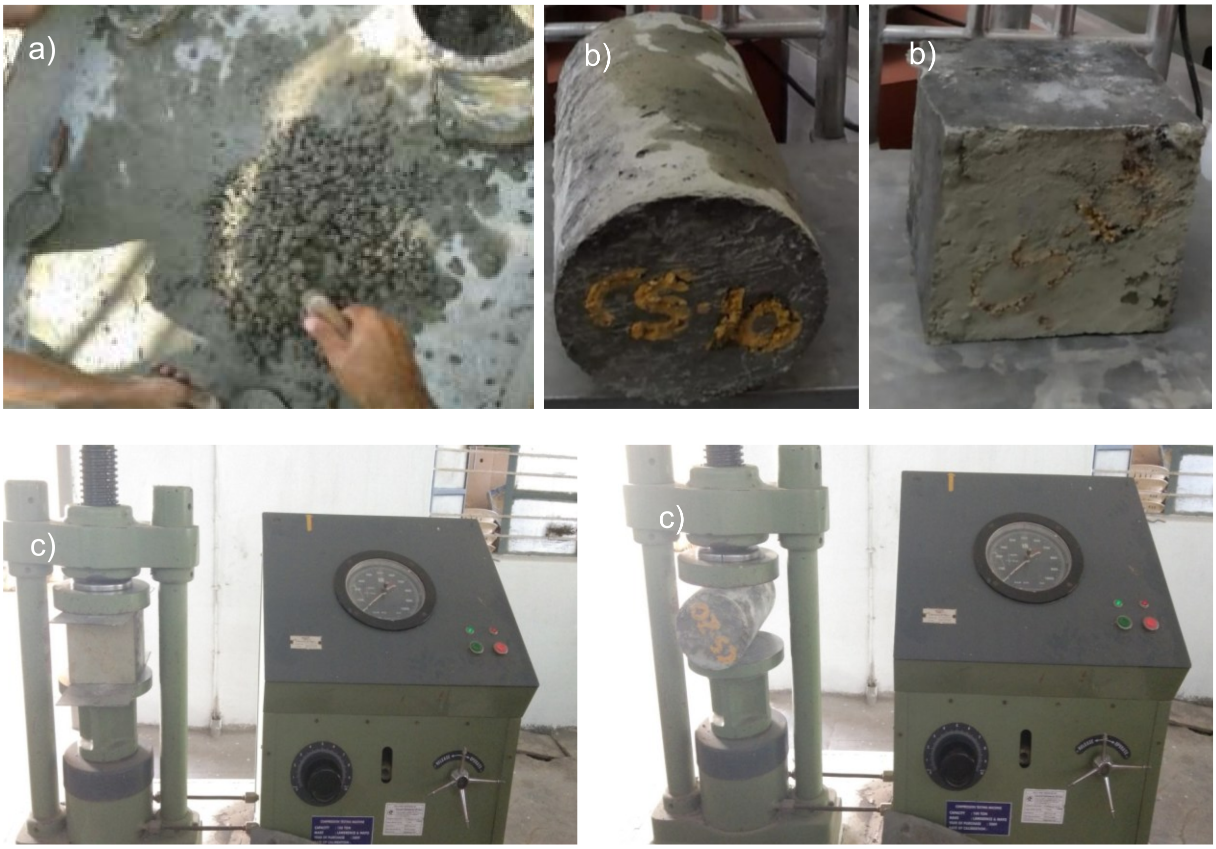

Figure 1. Concrete mix preparation, curing, and testing processes: a) mixing of raw materials; b) specimen preparation; c) laboratory testing

2.1.11 Performance of M20 concrete under different mix compositions

The type of coarse aggregate used has a significant impact on the concrete performance. NCA has a better quality because of its low porosity and constant quality. In contrast, RCA exhibits challenges such as irregular shapes and residual mortar, which can negatively affect concrete performance. However, the application of HCl treatments at varying concentrations (0,75 M, 1,00 M, 1,25 M, and 1,50 M) has shown promise in enhancing the characteristics of RCA by improving its workability and structural integrity. Furthermore, the incorporation of fly ash (20 %, 25 %, and 30 %) combined with optimal HCl treatment (1,25 M) further contributed to the performance enhancement of RCA, thereby rendering it a viable alternative to NCA while promoting sustainability in concrete production. The aggregate mix types and treatment variations are presented in Table 7.

Table 7. Description of aggregate mix types and treatment variations

Mix design ID	Mix type	Description
MD 1	NCA	Natural coarse aggregate
MD 2	RCA	Recycled coarse aggregate
MD 3	RCA + 0,75 M HCl	RCA treated with 0,75 M hydrochloric acid
MD 4	RCA + 1,00 M HCl	RCA treated with 1,00 M hydrochloric acid
MD 5	RCA + 1,25 M HCl	RCA treated with 1,25 M hydrochloric acid
MD 6	RCA + 1,50 M HCl	RCA treated with 1,50 M hydrochloric acid
MD 7	RCA + 1,25 M HCl + 20 % Fly Ash	RCA with 1,25 M HCl and 20 % fly ash
MD 8	RCA + 1,25 M HCl + 25 % Fly Ash	RCA with 1,25 M HCl and 25 % fly ash
MD 9	RCA + 1,25 M HCl + 30 % Fly Ash	RCA with 1,25 M HCl and 30 % fly ash

2.2 Methods

Evaluating the quality of building materials is essential to guarantee the performance and quality of concrete. Important components such as fly ash, NCA, NFA, RCA, and OPC were measured according to standard procedures and rules. The chemical composition and physical properties of the OPC were analysed per IS 12269:2013. Fly Ash was evaluated for specific gravity, fineness, water requirement, pH, and chemical composition according to IS 3812 (Part 1). The specific gravity, water absorption, sieve analysis, fineness modulus, and cleanliness of NCA and NFA were assessed according to IS 2386 (Parts 1, 3, and 4). RCA was tested similarly, whereas the acid-treated RCA focused on treatment effectiveness and the optimal acid concentration per IS 383:2016. This systematic approach ensures compliance with quality standards and enhances the sustainability and performance of the concrete. The properties, method of determination, and corresponding IS codes for M20 concrete with RCA are listed in Table 8.

Table 8. The properties, method of determination, and corresponding is codes for making M20 concrete using RCA

Property	Method of determination	IS Code
Ordinary Portland Cement (OPC)	1. Chemical Composition: Analyzed using X-ray fluorescence (XRF) to quantify major oxides (CaO, SiO_2, Al_2O_3, Fe_2O_3, MgO, SO_3, Na_2O, K_2O). 2. Physical Properties: Determined by standard tests per IS codes, including fineness (Blaine test), consistency (flow table test), setting times (vicat apparatus), soundness (Le Chatelier test), compressive strength (cube test), and specific gravity (density bottle method).	IS 12269:2013
Fly Ash	1. Specific Gravity: Measured using a pycnometer. 2. Fineness: Assessed using the Blaine permeability test. 3. Loss on Ignition: Conducted by heating a sample in a furnace and measuring the weight loss. 4. Water Requirement: Determined by trial mixes to establish the required water-to-cement ratio. 5. pH Value: Measured using a pH meter. 6. Chemical Composition: Analyzed using XRF for major oxides.	IS 3812 (Part 1)
Natural Coarse Aggregate (NCA)	1. Specific Gravity: Determined using a density bottle or pycnometer. 2. Water Absorption: Measured by soaking aggregates in water and calculating the increase in weight. 3. Mechanical Properties: Evaluated through standard tests for Aggregate Crushing Value (ACV), Aggregate Impact Value (AIV), and Los Angeles Abrasion Value. 4. Porosity and Bulk Density: Calculated from specific gravity and	IS 2386 (Part 3 and Part 4)

	water absorption data. 5. Cleanliness: Visually assessed for contaminants.	
Natural Fine Aggregate (NFA)	1. Specific Gravity: Similar to NCA, using a density bottle or pycnometer. 2. Water Absorption: Measured similarly to NCA. 3. Sieve Analysis: Conducted using a set of standard sieves to determine gradation. 4. Fineness Modulus: Calculated from sieve analysis data. 5. Bulk Density: Measured using a calibrated container to assess the mass of aggregates. 6. Cleanliness: Visually inspected for contaminants.	IS 2386 (Part 1)
Recycled Coarse Aggregate (RCA)	1. Specific Gravity: Determined using a density bottle or pycnometer. 2. Water Absorption: Evaluated by soaking and weighing as with NCA. 3. Mechanical Properties: Tested for Aggregate Crushing Value, Aggregate Impact Value, and Los Angeles Abrasion Value according to IS standards. 4. Porosity and Bulk Density: Similar methods as NCA. 5. Cleanliness: Assessed for contaminants through visual inspection.	IS 2386 (Part 3 and Part 4)
Acid-Treated RCA	1. Treatment Effectiveness: Evaluated by measuring changes in specific gravity, water absorption, and mechanical properties before and after acid treatment. 2. Optimal Acid Concentration: Determined based on trial tests with varying concentrations and treatment durations to achieve desired enhancements.	IS 383:2016

3 Results and discussion

The type of aggregate, chemical treatment, and other components affect the workability of concrete, which is a critical aspect that influences its placement, compactness, and durability. NCA are known for their high workability owing to their smooth texture and low water absorption, which renders them suitable for various applications. In contrast, RCA often face workability challenges owing to their irregular shapes and residual mortar. The workability of RCA can be considerably improved through HCl acid treatment, and its quality can be further enhanced by the inclusion of other ingredients, such as fly ash. Optimising RCA mixes through these treatments and additions facilitates workability levels comparable to NCA, promoting more sustainable concrete solutions.

3.1 Workability

Concrete workability varies with aggregate type, chemical treatments, and supplementary materials, which influence the ease of placement, compactness, and durability. Figure 2 shows the workability of M20 concrete using NCA, RCA, acid-treated RCA, and acid-treated RCA with fly ash for curing times of 3, 7, and 28 d. The consistency and workability of concrete were evaluated using slump and flow values, expressed in millimetres (mm). A stiff mix is indicated by low slump values (0-25 mm), whereas normal concrete is indicated by medium slump values (25-75 mm). Very high slump values (over 150 mm) indicate a highly fluid mix, whereas high slump values (75-150 mm) indicate more workable mixes. Medium flow values (300-500 mm) are typical for ordinary concrete applications, whereas low flow values (< 300 mm) imply lower workability and are appropriate for stiffer concrete. High flow values (> 500 mm) indicate highly workable and fluid self-compacting concrete. From Figure 2, it can be observed that NCA demonstrated high workability, with a slump of 75 mm and flow of 600 mm, owing to its smooth texture and low water absorption, rendering it ideal for general use. Workability is crucial for ensuring that concrete can be mixed, poured, and finished without segregation or undue effort. The addition of PEG 400 improved workability, and obtained a slump of approximately 75 mm in the M25 mixes, which is sufficient for most applications [3]. In contrast, RCA, with a lower slump (60 mm) and flow (550 mm), faces challenges owing to its irregular shape and residual mortar, which limit cohesion. The use of RCA can negatively affect workability, particularly at higher incorporation levels, although specific slump values were not provided [22].

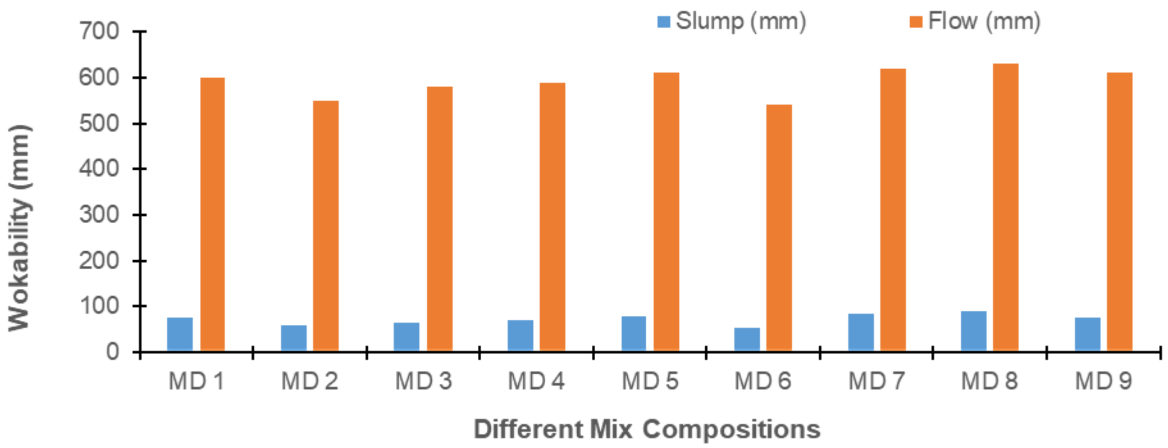

Figure 2. Workability of M20 concrete with various aggregates and curing periods (3, 7, and 28 d)

HCl treatment can increase the workability of concrete by reducing the surface roughness of RCA, which makes it simpler to mix and manage. However, if improperly managed, this improved workability can result in uneven consistency under exposed conditions. However, HCl treatment at 1.25 M significantly improved RCA workability, with an increase in slump and flow to 80 and 610 mm, respectively, as this treatment removed weak mortar particles and strengthened the particle bonds. Treated RCA generally requires a higher water content to achieve workability levels comparable to those of conventional aggregates, even though the specific slump values are unspecified. Adding fly ash further improves the workability, with RCA + 1,25 M HCl + 25 % fly Ash achieving a peak slump of 90 mm and a flow of 630 mm, which also enhances the durability and reduces the environmental impact [19]. High amounts of fly ash and metakaolin enhanced the workability in self-compacting concrete, although the slump values were not specified [23]. Overall, these results indicate that a carefully optimised RCA mix using HCl treatment and fly ash can attain a workability comparable to or better than NCA, thereby overcoming the limitations of RCA and offering a sustainable alternative. This approach holds particular value in eco-conscious projects or regions with limited natural aggregates, balancing high performance with environmental benefits despite the added costs and handling considerations associated with HCl.

3.2 Density

Density measurements of the M20 concrete using various sample types provided significant insights into the effectiveness of different treatments and materials. Figure 3 shows the densities of M20 concrete using NCA, RCA, acid-treated RCA and acid-treated RCA with fly ash for curing times of 3, 7, and 28 d. From Figure 3, it may be noted that the highest density values were observed in NCA, which demonstrated excellent structural integrity for concrete applications with values of 2400 kg/m³ at 3 d, 2450 kg/m³ at 7 d, and 2500 kg/m³ at 28 d.

The total performance of concrete materials was significantly influenced by density. For instance, the density of M20 grade concrete was approximately 2400 kg/m³, which is typical for ordinary combinations [1]. In contrast, RCA exhibited lower densities, starting at 2250 kg/m³ at 3 d and increasing to 2350 kg/m³ at 28 d, which indicates its porous nature and presence of residual cement paste that can negatively affect the strength and durability. A density of approximately 2400 kg/m³ were reported for concrete containing recycled aggregates, reflecting typical values for conventional mixtures although slightly lower owing to the presence of recycled materials [22]. A minor decrease in density was observed when recycled aggregates were used, with values of approximately 2350 kg/m³, owing to the lower specific gravity of recycled aggregates compared to natural aggregates [24].

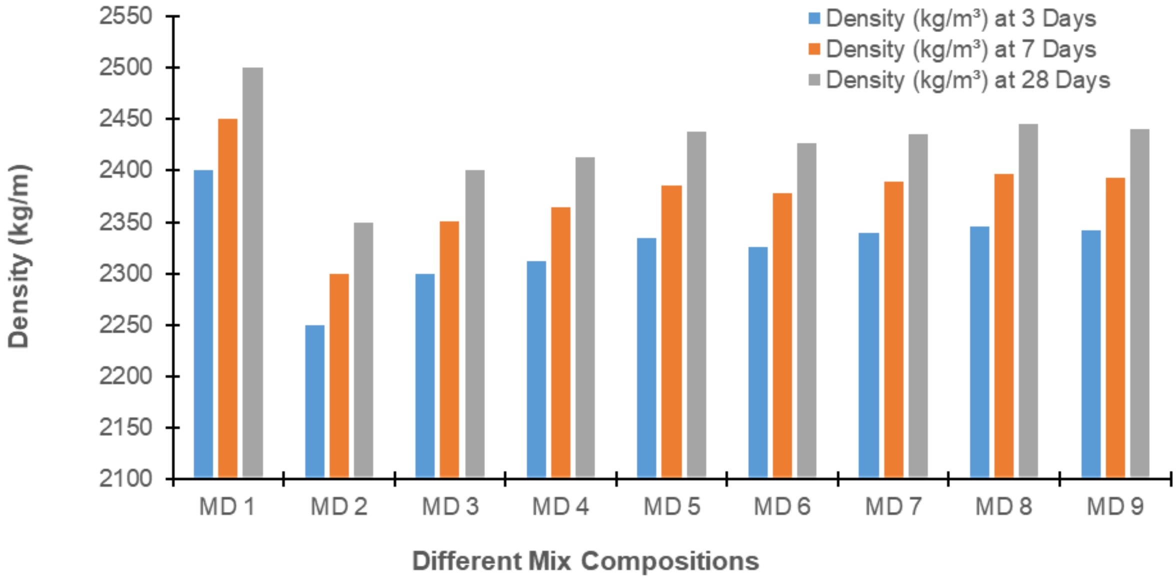

Figure 3. Density of M20 concrete with various aggregates and curing periods (3, 7, and 28 d)

Densities ranging from 2300-2400 kg/m³ were observed, depending on the amount of recycled material used in the mix [10]. Because HCl dissolves some of the mineral components in recycled aggregate, it can make concrete less compact and reduce its density when used in exposed building settings. This decrease in density can affect the long-term resilience of concrete under environmental stress. By efficiently eliminating impurities and enhancing the aggregate quality, HCl treatment significantly increased the density of RCA. 1,25 M HCl treatment exhibited densities of 2335, 2386, and 2438 kg/m³ at 3, 7, and 28 d, respectively, which represents a 2.4% increase in density at 28 d compared to untreated RCA. Compared to the 1,25 M HCl-treated RCA samples, 1,25 M HCl with 25 % fly ash combination exhibited the best density values, reaching 2346, 2397, and 2446 kg/m³ at 3, 7, and 28 d, respectively. This 4,1 % improvement is attributed to the synergistic effects of the acid treatment and the pozzolanic properties of fly ash, which resulted in the formation of additional cementitious compounds that enhanced the overall density and structural integrity. However, the densities decreased slightly in the 30 % fly ash mix, indicating that excessive fly ash content may cause workability issues and reduced density owing to increased voids and lower effective binder content. Optimal performance was observed when 25 % fly ash was used in conjunction with 1,25 M HCl treatment, which effectively balanced contaminant removal and enhanced the mechanical properties while maintaining good workability and durability in M20 concrete.

3.3 Compressive strength

In addition to other studies, the compressive strength data from this study provide information on the performance of M20 concrete when different aggregate types, treatments, and additional materials are used. Figure 4 shows the compressive strength of M20 concrete after 3, 7, and 28 d of curing with NCA, RCA, acid-treated RCA, and acid-treated RCA with fly ash. As shown in Figure 4, the structural integrity of NCA was demonstrated as the baseline when it reached a compressive strength of 30,7 MPa at 28 d. Ordinary M20 concrete has a compressive strength of 20,5 MPa, indicating an adequate performance for moderate applications [1]. Owing to its porous nature and presence of residual cement paste, RCA exhibits low strength. Untreated RCA demonstrated a compressive strength of 15,2 MPa at 3 d and 25,4 MPa at 28 d, which is consistent with the findings that strength declined as the replacement level of RCA increased [22].

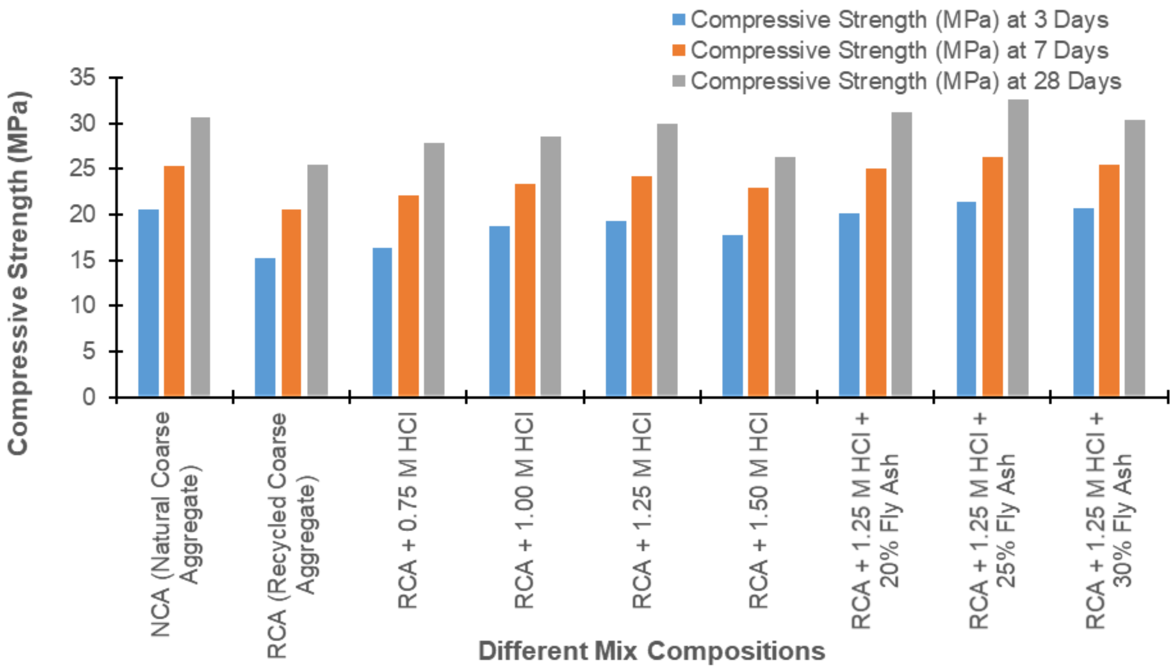

Figure 4. Compressive strength of M20 concrete with various aggregates and curing periods (3, 7, and 28 d)

By strengthening the bond between the recycled aggregate and cement paste, RCA treated with hydrochloric acid (HCl) can increase the compressive strength of concrete. External factors, such as moisture and temperature changes, may cause this bond to deteriorate over time under exposed conditions, which could lower the overall strength of the concrete. According to this study, HCl treatment increased the compressive strength of RCA; at 28 d, RCA treated with 1,25 M HCl exhibited a compressive strength of 30,0 MPa, which is an 18,1 % increase over that of untreated RCA. This finding is consistent with the observation that RCA treated with slag exhibits a compressive strength of approximately 30 MPa [19]. This study demonstrates that M20 concrete with RCA can achieve high compressive strength through a combination of HCl treatment and 25 % fly ash supplementation, achieving 32,6 MPa at 28 d. The optimised combination of 1,25 M HCl-treated RCA with 25 % fly ash yielded a 27,4 % improvement over untreated RCA and an 8,5 % increase compared to RCA treated with only 1,25 M HCl. This improvement is consistent with the findings that adding 10 % fly ash and 15 % metakaolin increases the strength [9]. In this study, the addition of 25 % fly ash to 1,25 M HCl-treated RCA provided optimal strength, as exceeding this replacement level (e.g., 30 % fly ash) caused a slight reduction owing to potential workability challenges. This dual approach surpassed the typical strengths of RCA concrete, optimising both strength and workability, which marks a novel advancement compared to previous studies that employed either individual treatments or pozzolanic materials. By integrating HCl-treated RCA with a carefully selected fly ash content, this study established an effective method for enhancing the strength and durability of RCA concrete, thereby offering a promising solution for sustainable, high-performance concrete.

3.4 Tensile strength

The results of this study, when combined with other investigations, provides novel key information on the performance of M20 concrete under various treatments and with additional materials. The tensile strengths of the M20 concrete after 3, 7, and 28 d of curing with NCA, RCA, acid-treated RCA, and acid-treated RCA with fly ash are displayed in Figure 5. Because HCl roughens the RCA surface and improves the connection with the binder, the tensile strength of the concrete should increase after its treatment. Nevertheless, the longevity of this bond may deteriorate at severe weather conditions, which would eventually impair the tensile performance. The HCl treatment significantly improved the tensile strength of RCA, as illustrated in Figure 5. At 28 d, a 1,25 M HCl treatment achieved a tensile strength of 3,87 MPa, which is a 25,9 % improvement over untreated RCA. This aligns with previous studies, as a tensile strength of approximately 2,5 MPa was measured, which is typical for concrete, however, they indicated limitations under tensile loading, while similar split tensile strengths of approximately 2,5 MPa were reported for concrete with recycled aggregates, highlighting comparable limitations in tensile performance [25; 26]. Tensile strengths of approximately 2.8 MPa were observed for recycled aggregate mixes, suggesting adequate performance, however, the need for reinforcement were indicated for applications subject to tensile stresses [27; 28]. The present study further revealed that the combination of 1,25 M HCl with 25 % fly ash yielded the highest tensile strength, reaching 4.19 MPa at 28 d, which represents a 36,3 % improvement over untreated RCA and an 8,3 % increase compared to 1,25 M HCl-treated RCA.

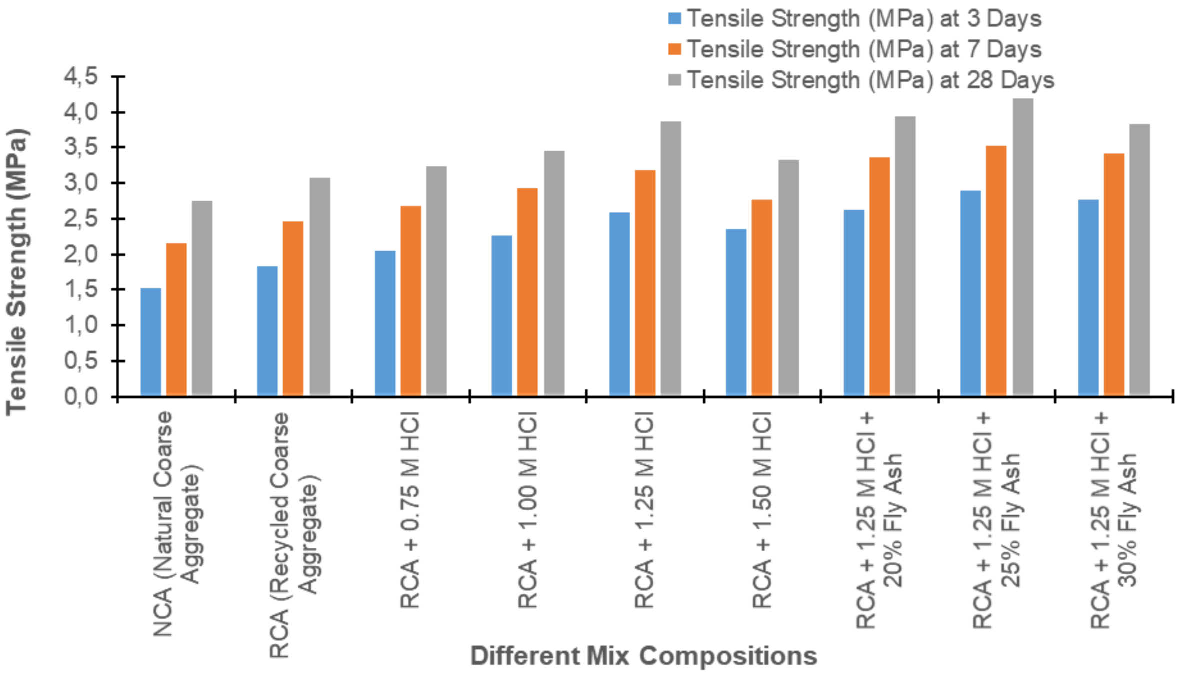

Figure 5. Tensile strength of M20 concrete with various aggregates and curing periods (3, 7, and 28 d)

This enhancement was attributed to the synergistic effects of the acid treatment, which effectively removed impurities and residual cement paste, along with the pozzolanic properties of fly ash, which fostered additional cementitious compounds. However, it is essential to note that while fly ash generally contributes to increased tensile strength, excessive fly ash content can result in diminished performance in certain mixes. Specifically, the tensile strength of a mixture with 30 % fly ash was somewhat lower than that of a mixture with 25 % fly ash, which suggests potential workability challenges and an increase in voids owing to the lower effective binder content.

This study demonstrates that optimal tensile strength is obtained with 1,25 M HCl treatment combined with a 25 % fly ash replacement level, effectively balancing the enhanced mechanical properties with good workability and durability in M20 concrete. This dual approach surpasses the typical tensile strength of RCA concrete, which marks a significant advancement compared to previous studies that utilised either individual treatments or pozzolanic materials. By integrating HCl-treated RCA with a carefully selected fly ash content, this study provides a viable alternative for high-performance sustainable concrete by establishing an efficient technique for improving the tensile strength and durability of RCA concrete.

3.5 Flexural strength

In addition to earlier studies, the flexural strength results of this study offer important new information on the performance of M20 concrete when treated and incorporated with various ingredients. The flexural strengths of the M20 concrete after 3, 7, and 28 d of curing with NCA, RCA, acid-treated RCA, and acid-treated RCA with fly ash are shown in Figure 6. It can be observed that NCA exhibited the highest flexural strength, achieving 5,32 MPa at 28 d, whereas RCA exhibited significantly lower flexural strength; its porous character is demonstrated by the fact that it increased from 2,26 MPa after 3 d to 4,13 MPa at 28 d.

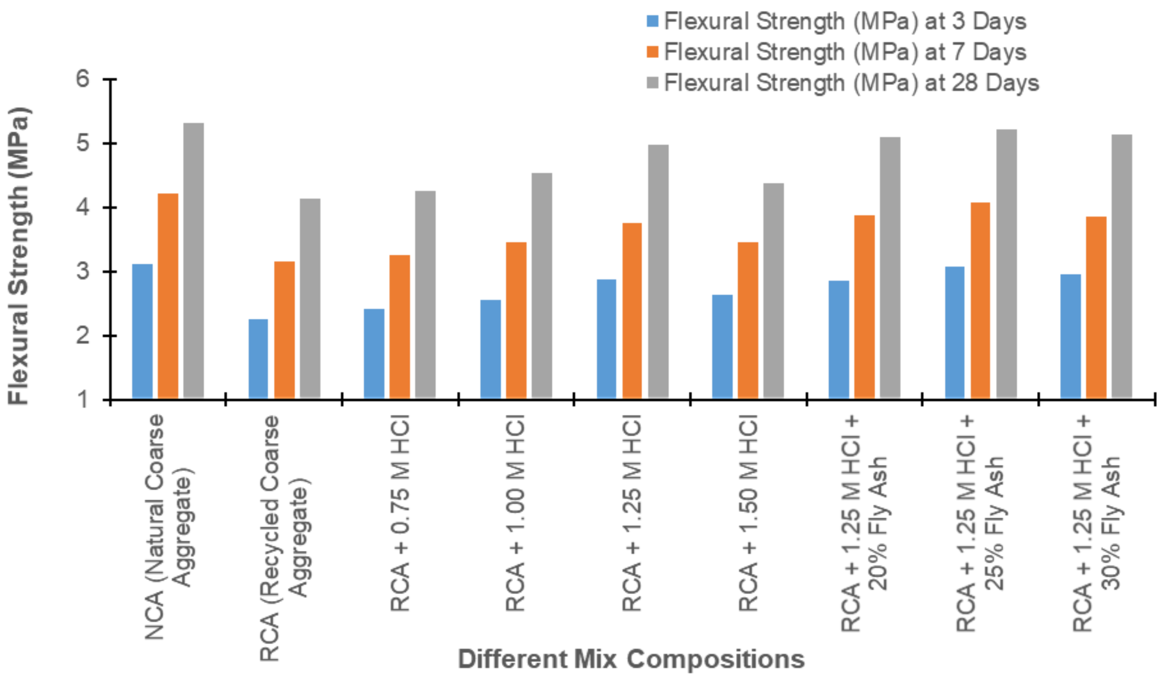

Figure 6. Flexural strength of M20 concrete with various aggregates and curing periods (3, 7, and 28 d)

Flexural strengths for conventional concrete were reported between 4,0 and 5,0 MPa, emphasizing robust performance under bending loads, which is critical for structural elements such as beams and slabs [29], while flexural strengths of approximately 5 MPa were observed for RCA, highlighting the importance of aggregate quality in resisting bending stresses [30]. By strengthening the bond between the treated RCA and the cement matrix, HCl treatment can increase the flexural strength of concrete. The ability of concrete to tolerate bending loads may be hampered by this improvement if it is subjected to extreme weather conditions, such as high humidity or freeze–thaw cycles. The results of this investigation showed that HCl treatment greatly increased the flexural strength of RCA; at 28 d, 1,25 M HCl treatment yielded a flexural strength of 4,98 MPa, which was 20,6 % higher than that of untreated RCA. Furthermore, a highest flexural strength of 5.22 MPa was attained by combining 1,25 M HCl with 25 % fly ash, which was 26,5 % higher than that of untreated RCA. Adding large amounts of fly ash to recovered aggregates resulted in flexural strengths in the range of 4-6 MPa, which is consistent with previous findings [31], whereas excessive amounts of fly ash diminished the performance, with pozzolan slurry achieving approximately 4,5 MPa, however, it showed limitations at higher percentages [32]. The 30 % fly ash blend in the current investigation showed a modest decrease in flexural strength compared with the 25 % fly ash mix, suggesting possible workability issues. Therefore, the optimal flexural strength was obtained with a 25 % fly ash replacement level combined with the 1,25 M HCl treatment, which effectively balances the enhanced strength with good workability and durability in M20 concrete. This integrated approach surpassed the typical flexural strength of RCA concrete, marking a significant advancement over previous studies that utilised either individual treatments or pozzolanic materials.

The bonding between the aggregates and cementitious matrix, as well as the overall microstructural integrity, are the main factors influencing the flexural strength of concrete. The flexural strength values observed in this investigation were quite high and nearly matched the tensile strength values even though fibres were not used. The combined benefits of the fly ash, acid treatment, and RCA were responsible for this improvement. Owing to its rough texture, RCA offers improved mechanical interlocking and stress transfer under flexural loading, even if its adhering mortar is weaker than that of NCA. The interfacial transition zone (ITZ) is weakened by residual mortar, which may still be present in the untreated RCA. A stronger link between RCA and the cement matrix was caused by the acid treatment (HCl at different concentrations), which successfully removed the weak and porous adhering mortar. The flexural performance was improved by enhancing the load distribution and decreasing the crack start time.

Furthermore, fly ash is an essential component for increasing flexural strength. Through void filling and ITZ refinement, fly ash increased the packing density of the matrix, resulting in decreased porosity and improved microstructural integrity. By creating more calcium silicate hydrate (C–S-–H) gel, the pozzolanic reaction strengthened the concrete over time. The highest measured flexural strength (5,22 MPa) was attained by the best-performing combination of RCA + 1,25 M HCl + 25 % fly Ash, which surpassed the expected value (4,00 MPa). This implies that the resistance of concrete to bending stresses is significantly increased when the acid-treated RCA and optimal fly ash content are combined. These findings demonstrate that properly planned material alterations, particularly by improving the aggregate characteristics and cementitious matrix optimisation, can result in the observed increases in flexural strength, which are not exclusively dependent on fibre reinforcement.

3.6 Water absorption

The water absorption (%) values for M20 concrete with different sample types provide important information on material permeability and porosity, which have a direct impact on performance and durability. Figure 7 shows the water absorption of M20 concrete using NCA, RCA, acid-treated RCA, and acid-treated RCA with fly ash after 3, 7, and 28 d of curing. It can be observed that NCA exhibited the lowest water absorption, decreasing from 2,0 % at 3 d to 1,5 % at 28 d, indicating good density and low porosity, which are essential for maintaining the structural integrity and minimising moisture ingress. In contrast, RCA exhibited significantly higher water absorption rates, starting at 4,5 % at 3 d and decreasing to 3,8 % by 28 d, which reflects the porous nature of RCA and residual cement paste, which increases the susceptibility to moisture ingress and durability issues over time. Water absorption increased with the percentage of recycled aggregates, reaching up to 6 % for mixes containing 50 % RCA compared with conventional mixes at approximately 4 % [33], whereas significant increases in water absorption rates were reported with higher percentages of recycled aggregates, reaching up to 7 % for mixes containing 100 % RCA compared with conventional mixes at approximately 4 % [34].

HCl treatment positively affected the reduction of water absorption in RCA; 1,25 M HCl treatment reduced the absorption to 3,0 % at 28 d, signifying the efficacy of the acid treatment in enhancing the quality of recycled aggregates by removing impurities and reducing porosity, which is crucial for better concrete performance. HCl treatment can reduce the water absorption of RCA by removing impurities and creating a smoother surface, resulting in a denser concrete mix. However, under exposed conditions, factors, such as prolonged wetting and drying cycles, can reverse the reduction in water adsorption, thereby affecting the long-term durability of concrete.

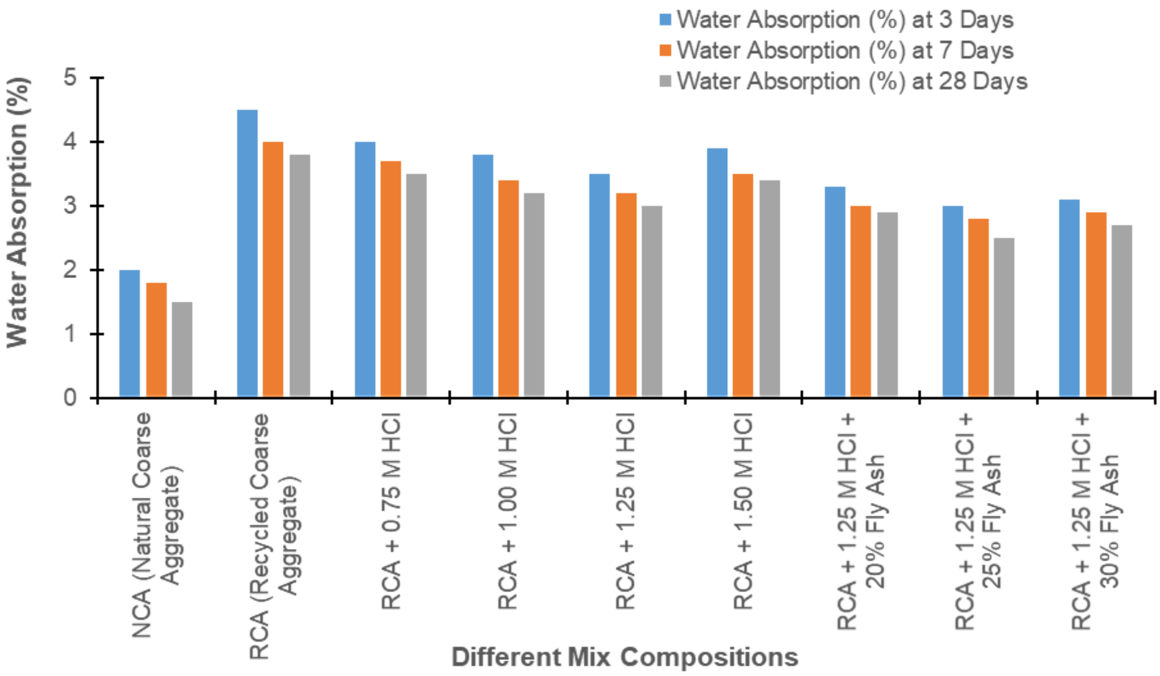

Figure 7. Water absorption of M20 concrete with various aggregates and curing periods (3, 7, and 28 d)

The combination of 1,25 M HCl and 25 % fly ash resulted in the lowest water absorption of 2,5 % after 28 d because the pozzolanic qualities of fly ash create a denser microstructure, which reduces the permeability and increases the durability of concrete. While an increased fly ash content generally improves water absorption, excessive amounts can result in marginal increases, as observed with the 30 % fly ash mix, suggesting an optimal percentage for fly ash inclusion that balances enhanced strength and reduced water absorption with good workability. Water absorption increased significantly with higher percentages of recycled aggregates, with a mix containing 75 % recycled aggregate exhibiting maximum water absorption rates of 6,3 %, whereas lower percentages demonstrated better performance owing to reduced porosity from supplementary materials, such as fly ash and metakaolin [9]. Furthermore, water absorption rates increased significantly with treated recycled aggregates, obtaining values as high as 7 %, which could affect the durability over time [35]. These findings reinforce the understanding that while recycled aggregates can compromise both the strength and durability, the qualities of M20 concrete can be greatly enhanced by acid treatment and conservative use of fly ash, optimising formulations for better performance in construction applications.

3.7 Comparison between the tensile and flexural strengths with compressive strength

To demonstrate that the materials used in this study have beneficial properties that increase the strength of M20 concrete, an empirical comparison of the tensile and flexural strengths with the compressive strength was performed. According to IS 456:2000, an empirical formula can be used to approximate the expected tensile and flexural strengths obtained from compressive strength.

$$f_t = 0{,}47 \cdot f_c^{0{,}5} \quad (1)$$

$$f_f = 0{,}7 \cdot f_c^{0{,}5} \quad (2)$$

where, f_t is the predicted tensile strength, f_f is the predicted flexural strength, and f_c is the experimentally obtained compressive strength. The following table presents the predicted tensile and flexural strengths for M20 concrete across all the mix combinations.

Table 9. Comparison of observed and predicted tensile and flexural strengths for M20 concrete with different mix variations

Mix design ID	**Observed compressive strength** (MPa)	**Observed tensile strength** (MPa)	**Observed flexural strength** (MPa)	**Predicted tensile strength** (MPa)	**Predicted flexural strength** (MPa)
MD 1	30,70	2,75	5,32	2,60	3,88
MD 2	25,40	3,08	4,13	2,37	3,53
MD 3	27,80	3,24	4,26	2,48	3,69
MD 4	28,50	3,46	4,54	2,51	3,74
MD 5	30,00	3,87	4,98	2,57	3,83
MD 6	26,30	3,33	4,37	2,41	3,59
MD 7	31,20	3,94	5,09	2,63	3,91
MD 8	32,60	4,19	5,22	2,68	4,00
MD 9	30,40	3,84	5,14	2,59	3,86

From Table 9, it can be observed that the empirical formulas for predicting tensile and flexural strengths based on compressive strength assume a proportional relationship following the square root function; however, the observed values often exceed the predictions owing to factors such as aggregate properties, mix design, and curing conditions. For NCA concrete with f_c = 30,70 MPa (28 d, M20 concrete), the predicted tensile and flexural strengths were 2,60 and 3,88 MPa, respectively, whereas the observed values were significantly higher at 2,75 and 5,32 MPa, indicating better-than-expected material performance. Similarly, RCA concrete with f_c = 25,4 MPa exhibited an observed tensile and flexural strengths of 3,08 and 4,13 MPa, respectively, compared to predicted values of 2,37 and 3,53 MPa, respectively, suggesting that the rougher texture of RCA improves the mechanical interlock. Acid treatment further enhances these properties, as observed in RCA + 1,25 M HCl (f_c = 30,00 MPa), where the observed tensile strength (3,87 MPa) was significantly higher than the predicted 2,57 MPa, and the observed flexural strength (4,98 MPa) exceeded the predicted 3,83 MPa, demonstrating the benefits of weak mortar removal. The best-performing mix, RCA + 1,25 M HCl + 25 % fly Ash (f_c = 32,60 MPa), achieved the highest observed tensile strength (4,19 MPa) and flexural strength (5,22 MPa), both of which are considerably higher than the predicted 2,68 of 4,00 MPa, respectively. Based on these results, RCA with 1,25 M HCl treatment and 25 % fly ash was the optimal mix for M20 concrete at 28 d, providing the best combination of compressive, tensile, and flexural strengths while enhancing sustainability.

3.8 Mix design analysis

Important information on the sustainability and performance of concrete mixtures can be obtained by examining the mixed components. The M20 concrete mix design with NCA, RCA, acid-treated RCA, and acid-treated RCA with fly ash for 28 d curing periods is shown in Figure 8. The first mixes, which use NCA and RCA, have a cement content of 350 kg/m³, which guarantees strong compressive strength, as observed in Figure 8. However, when fly ash is added, the cement content drops to 280, 260, and 240 kg/m³, encouraging environmentally friendly methods without sacrificing functionality. Water content remains constant at 175 kg/m³ for initial mixes and increases to accommodate moisture absorption in fly ash mixes, ranging from 185 kg/m³ for 20 % fly ash to 195 kg/m³ for 30 % fly ash. Adjustments in coarse and fine aggregate quantities were minimal, ensuring workability while enhancing the sustainability of the mix through the addition of up to 100 kg/m³ of fly ash, which provides pozzolanic benefits. An analysis of the material savings between the optimal HCl treatment and HCl combined with 25 % fly ash revealed notable reductions in the specific material quantities. In the optimal HCl mix (RCA + 1,25 M HCl), the cement content was 350 kg/m³, while the optimal mix incorporating HCl with 25 % fly ash reduced the cement requirement to 260 kg/m³, achieving a saving of 90 kg/m³, which translates to a 25,7 % reduction in cement usage. The water content, however, increased from 175 kg/m³ to 190 kg/m³, resulting in a necessary adjustment of 15 kg/m³ (an 8,6 % increase) owing to the moisture absorption characteristics of fly ash. Both the coarse and fine aggregate exhibit slight reductions as well: from 900 kg/m³ to 890 kg/m³ for coarse aggregate (saving 10 kg/m³, or 1,1 %); from 620 kg/m³ to 610 kg/m³ for fine aggregate (saving 10 kg/m³, or 1,6 %). Adding fly ash requires more water, even though it results in considerable cement savings and minor decreases in coarse and fine aggregates. These blend designs have a noticeable effect on the durability and compressive strength. NCA exhibited the highest compressive strength and durability of 90,5 % at 28 d.

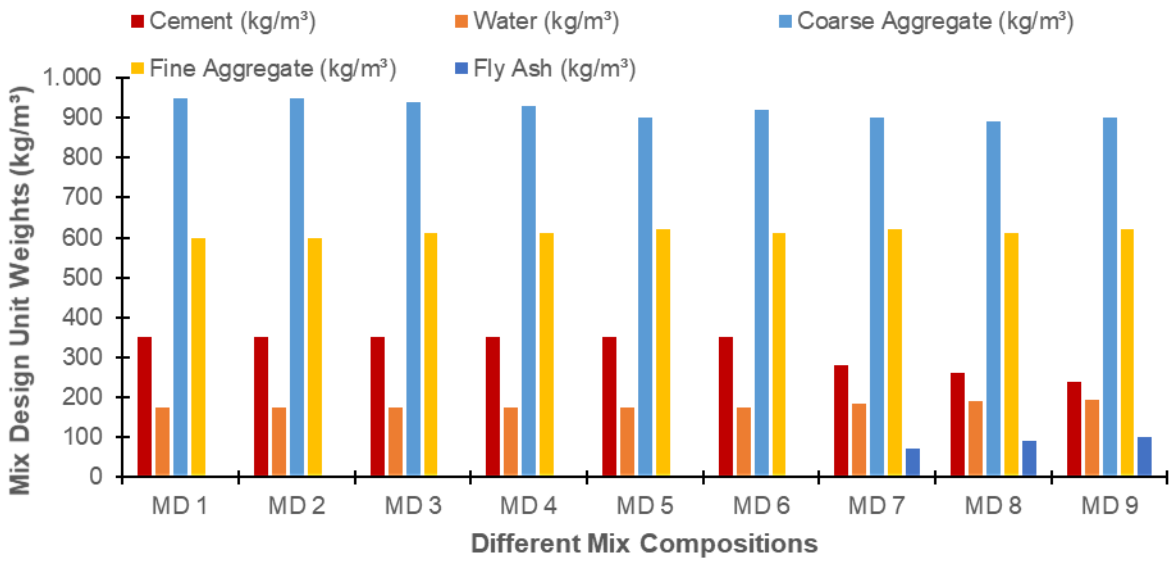

Figure 8. Mix design of M20 concrete using NCA, RCA, acid treated RCA and acid treated RCA with fly ash for 28 days curing periods

RCA demonstrated reduced compressive strength (25,4 MPa) and improved significantly with HCl treatment, particularly for 1,25 M HCl mix, which enhanced both strength and durability [36]. Notably, mixes with 25 % fly ash demonstrate optimal performance, achieving a compressive strength of 32,6 MPa and durability of 85,3 %, whereas the performance slightly declined with higher fly ash proportions. The incorporation of RCA and fly ash promotes environmental sustainability by recycling materials and reducing carbon emissions, and enhances the workability and durability of concrete, which could result in construction cost reductions [37]. This study underscores the importance of tailoring concrete mix designs to balance mechanical performance and sustainability. Future research is needed to explore the long-term performance and additional supplementary materials required to further improve concrete properties.

3.9 Recommendations

The following suggestions can be made based on the results and understanding gained from the investigation of RCA, the impact of hydrochloric acid treatment, and the integration of fly ash:

- Optimize Mix Design with RCA and Fly Ash: Incorporate a higher percentage of fly ash (approximately 25 %) in conjunction with hydrochloric acid-treated RCA to maximise the mechanical properties of M20 concrete. This combination yielded significant improvements in the compressive strength (32,6 MPa) and durability (85,3 %) while reducing the cement content by 25,7 %, contributing to environmental sustainability.
- Implement Hydrochloric Acid Treatment: hydrochloric acid treatment (1,25 M concentration) was used for RCA prior to mixing, as it significantly enhances the bond between aggregates and cement, improving the compressive strength by 18,1 % compared to untreated RCA. This treatment effectively cleaned aggregates and enhanced their overall quality and durability.
- Monitor Long-term Performance: The durability and long-term performance of concrete mixtures containing fly ash and RCA should be assessed further. Evaluating factors, such as shrinkage, creep, and resistance to environmental conditions, will ensure that these sustainable mixes maintain their integrity over time.
- Educate Stakeholders on Sustainability: Raise awareness among construction industry stakeholders on the benefits of using RCA and fly ash. Highlighting environmental advantages, such as reduced carbon emissions and resource conservation, alongside economic incentives, will encourage the adoption of these sustainable practices in mainstream construction.

3.10 Future scope

The long-term performance and durability of concrete mixtures containing fly ash and acid-treated RCA should be the focus of future research to confirm the preliminary results of this study. A deeper understanding of the best mix designs can be obtained by examining the impact of different fly ash amounts and acid concentrations on concrete characteristics [38]. The mechanical qualities of RCA-based concrete can also be improved by investigating the incorporation of other elements, such as metakaolin or silica fume. Promoting the use of these novel combinations in the building sector requires field research to evaluate their effectiveness in practical settings [39]. Life cycle assessments might be conducted to measure the environmental advantages of employing fly ash and RCA, assisting in the shift to sustainable building practices [40].

4 Conclusion

This study closes the gap in the literature by investigating the combined effects of fly ash addition and hydrochloric acid (HCl) treatment on recycled coarse aggregate (RCA) to improve the mechanical properties of M20 grade concrete, this study closes a gap in the literature. When compared to untreated RCA, the HCl treatment greatly enhanced the connection between RCA and the cement matrix, resulting in an 18,1 % increase in the compressive strength to 30.0 MPa. With a compressive strength of 32,6 MPa and a durability of 85.3% at 28 days, a 9,4 % increase in durability over untreated RCA, the greatest results were obtained with 1,25 M HCl-treated RCA mixed with 25 % fly ash. The pozzolanic quality of fly ash can be improved by creating new cementitious compounds.

Cement usage and carbon emissions were reduced by optimising the mix and lowering the cement composition from 350 kg/m³ to 260 kg/m³ (a 25,7 % reduction). The effective application of fly ash and acid-treated RCA demonstrates the potential of recycled materials in concrete, providing long-term solutions with increased material efficiency and environmental advantages.

By demonstrating the viability of high-performance concrete through creative mix designs, this study advances sustainable construction methods and opens the door to further research on long-term performance and other supplemental materials. To further improve the quality of the concrete, future research should assess its long-term performance and investigate other supplementary materials.

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