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Research Article

Comparing mechanical properties of concrete with recycled aggregates using different mixing methods

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Abstract

This study addresses the growing use of recycled coarse aggregate (RA) from construction and demolition waste (CDW) as a sustainable alternative in concrete production. It evaluates the influence of varying RA by 0%, 25%, 50%, 75% and 100% by natural coarse aggregate (NA) on the mechanical properties of M20 grade concrete. Additionally, the study compares four mixing methods: Normal Mixing Approach (NMA), Treated Aggregate Mixing Approach (TAMA), Two-Stage Mixing Approach (TSMA), and Mortar Mixing Approach (MMA). Results reveal that increasing RA content reduces the workability and strength of recycled aggregate concrete (RAC). The performance in workability, compressive strength, splitting tensile strength, and flexural strength of RAC by four mixing methods was compared. Among them, TSMA showed significant improvement of 27.27, 15.55, 9.3, and 12.22% compared to NMA for a 100% RA mix. TSMA enhances these properties by promoting better mortar coverage around aggregate particles, reducing pores and strengthening the interfacial transition zone. This study highlights that optimizing mixing techniques can improve RAC's performance, making it an environmentally responsible option for the construction industry.

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1. Introduction

India's rapid urbanization and infrastructure development, including construction, renovation, reconstruction, and highway expansion projects, significantly added to construction and demolition waste (CDW). As per the Centre for Science and Environment analysis, India produces approximately 150 million tons of CDW annually, yet only 1.3% of this waste is recycled [1, 2]. Most CDW is indiscriminately dumped in landfills, along roadsides, or in vacant plots, leading to environmental, ecological, and logistical challenges. These non-biodegradable materials occupy considerable space, pollute land, and cause long-term environmental degradation.

The construction sector's high demand for coarse aggregates, combined with the exhaustion of resources from natural and increased carbon dioxide emissions from producing virgin aggregates, underscores the need for sustainable alternatives. Recycled aggregates (RA), derived from CDW, offer a worthwhile solution by meeting the demand for coarse aggregates, preserving natural resources, reducing waste, and mitigating environmental pollution. Moreover, utilizing RA in construction promotes circular economy principles, which aim to reduce waste and encourage the continual use of resources, thereby aiding in achieving sustainability goals [3].

Despite these advantages, the adoption of RA in India faces several barriers, including insufficient CDW recycling facilities, high labour costs associated with segregation and processing, the absence

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of standardized guidelines for recycled aggregates, and limited awareness among stakeholders [2]. Recycling CDW for use as aggregates in the construction sector presents a practical approach to reducing waste volumes and environmental impacts. The production of raw construction materials accounts for 80–90% of CO_2 emissions. In comparison, alternative materials like RA can reduce these emissions by up to 90%, offering a hopeful prospect for the environmental benefits of sustainable construction [4]. However, compared to regular concrete created from natural aggregates (NA), recycled aggregate concrete (RAC) is typically of lower quality, which increases the vulnerability of such structures [5]. The adhered hydrated cement on the surface of RA reduces its specific gravity, decreases its modulus of elasticity, and increases its porosity compared to NA, as demonstrated in various studies [6–8]. The heterogeneous nature of RA, adhered cement content, exposure conditions, crushing operations, and rheology further contribute to RAC's variability [3, 7–9]. Improving the quality of RA is vital for widespread applications of RAC [10, 11]. Among these quality enhancement methods, proper mixing techniques play a critical role in improving RAC properties and often offer an efficient option by reducing cost, time and energy consumption. This study specifically examines the impact of different mixing methods on optimizing the performance of RAC.

2. Literature Review

The use of RA in construction is a sustainable alternative and cost-effective than NA [4, 6, 12–14]. However, challenges such as reduced workability, mechanical performance and variability in the properties of RAC necessitate quality improvement measures [15]. Researchers have used several strategies to enhance RA quality and to optimize RAC performance. One widely adopted method for improving RA quality involves mechanical treatment, such as removing adhered cement content through abrasion techniques comparable to the Los Angeles abrasion method [16, 17]. Though effective, this process is energy-intensive and often results in surface cracks on the RA. Chemical treatment methods have also been investigated in previous research by presoaking RA in various acids, lime water, and sodium silicate to remove porous hydrated cement layers [18–22]. However, the disposal of used presoaking materials also causes environmental issues. Other innovative techniques utilized for enhancing RA include accelerated carbonation [23], incorporation of fine supplementary cementitious materials [6, 16, 24–27], and the use of admixtures or superplasticizers to reduce the water-cement ratio [10, 23]. Surface treatments, such as coating RA with cement slurry, have demonstrated improved micro-crack sealing and interfacial transition zone (ITZ) strength [22]. Additionally, using discrete fibres in RAC has been shown to improve ductility, toughness, and impact resistance while mitigating shrinkage cracking [28–31].

Experimental studies have focused on various aspects of RAC performance, including mechanical and durability properties [12, 14, 16, 32–34], shear strength [35, 36], leaching behavior [13], precast applications [37], and long-term deflection behavior [37]. These investigations underscore the potential of RA to meet construction standards when its quality is sufficiently improved. Among the quality enhancement methods, appropriate mixing techniques play a pivotal role in enhancing RAC properties [38–42]. These techniques not only improve the quality of RAC but also reduce costs, time, and energy consumption, making them an efficient choice for construction. Premixing techniques coat micro-cracks and pores on RA surfaces, stiffen aggregates, and improve ITZ, enhancing RAC performance [4, 38, 43, 44]. Although many methods to strengthen RA quality have been investigated in the literature, there are limited studies on the comprehensive and comparative effects of different mixing techniques on various mechanical properties (workability, compressive, splitting tensile and flexural strength) of RAC, especially evaluating these four methods (NMA, TAMA, MMA, and TSMA) together. This study aims to fill this gap and investigate the efficacy of different mixing processes as a quality enhancement method for concrete. Specifically, the effects of four distinct mixing techniques, Normal Mixing Approach (NMA), Treated Aggregate Mixing Approach (TAMA), Mortar Mixing Approach (MMA), and Two-Stage Mixing Approach (TSMA), on RAC's workability, compressive, splitting tensile, and flexural strength were analyzed. The goal was to identify an economical and sustainable approach to utilizing recycled aggregates derived from CDW.

3. Experimental Program

3.1. Materials and Their Properties

Portland Pozzolana Cement (PPC), which is fly ash-based and adheres to the Indian Standard IS: 1489-1 (1991) [45], was used as the binder for all mixes. The PPC has a specific gravity of 3.09, a normal consistency of 34%, and setting times of 42 minutes (initial) and 370 minutes (final) as shown in Table 1. Locally manufactured sand (M-Sand) served as the fine aggregate. It possesses a specific gravity of 2.46, a fineness modulus of 3.37, and falls within Zone II according to IS: 383-2016 [46]. Crushed granite rock with a nominal size of 20mm was sourced from local markets to function as the NA. This material exhibits a specific gravity of 2.68, water absorption of 0.75 % and a fineness modulus of 7.11. We collected CDW from nearby construction sites and landfills. The CDW was manually broken down, sieved, and segregated into coarse aggregates before use. The RA has a nominal size of 20mm, a specific gravity of 2.63, a water absorption of 4.44 %, and a fineness modulus of 7.01. IS: 2386-1963[47] guidelines were followed in conducting physical tests on aggregates. Table 1 enumerates the properties of the aggregates used.

Table 1. Physical properties of the constituents

Constituents	Materials Used	Specific Gravity	Consistency (%)	Water Absorption (%)	Setting Time (minutes)		Fineness Modulus
					Initial	Final	
Binder	PPC Cement	3.09	34	-	42	370	-
Fine Aggregate	M-Sand	2.46	-	0.93	-	-	3.37
Natural Aggregate	Crushed Gravel	2.68	-	0.75	-	-	7.11
Recycled Aggregate	Constructio n and demolition waste	2.63	-	4.44	-	-	7.01

3.2 Concrete Mix Proportion, Sample Preparation and Testing

Mix proportioning for the control concrete using NA for M20 grade concrete was prepared according to IS: 10262 (2019) [48], with a water-cement ratio of 0.5, and designated as NAC. The target compressive strength for this mix was 26.60 MPa. For the RAC, the natural coarse aggregate in the control mix was volumetrically replaced by 25, 50, 75, and 100% with RA. These mixes were designated 25RAC, 50RAC, 75RAC, and 100RAC, respectively. The mix proportion is given in Table 2.

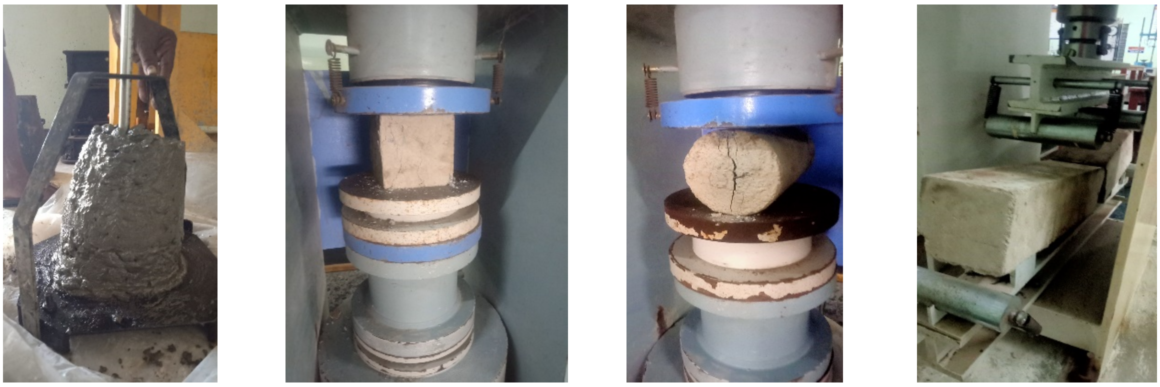
Table 2. Mix proportions for M20 grade concrete

Mix Designation	Cement [kg/m³]	M-Sand [kg/m³]	RA Replacement [%]	NA [kg/m³]	RA [kg/m³]	Water [litres/m³]
NAC	396	621	0	1169	0	198
25RAC	396	621	25	876.75	270.50	198
50RAC	396	621	50	584.50	541.00	198
75RAC	396	621	75	292.25	811.50	198
100RAC	396	621	100	0	1082	198

Workability of fresh concrete was assessed using slump cone tests, following IS: 456 (2000) [49] as in Fig. 1(a). The mixed concrete was arranged in roughly three layers within oiled cast iron moulds and compacted on a vibrating table. Three 150 mm cubes were fabricated for each mix type to test compressive strength using a 2000 kN compression testing machine (CTM) in Fig.1(b) of the model number AIM 317-E-DG-1. Furthermore, three cylinders with a diameter of 100 mm and a height of 200 mm for each mix type were cast to assess splitting tensile strength, as outlined in IS: 516 (2021) [50] using CTM as illustrated in Fig.2(c). Additionally, three prisms measuring 100 x 100 x 500 mm for each mix type were cast to assess flexural strength, utilizing a flexure testing machine with 3-point loading of model number AIM331, following the guidelines of IS: 516 (2021) as in Fig. 2(d). Casted samples as in Fig. 1(a) were kept undisturbed for 24 hours, then demoulded, labelled, and immersed in a water-filled curing tank shown in Fig.1(b), at a nominal temperature of 30 °C and 60% relative humidity for 28 days.

(a) (b)

Fig. 1. (a)Casted samples and (b) Curing of samples in the curing tank



(a) (b) (c) (d)

Fig. 2. (a) Slump Cone Test (b) Compression Test (c) Splitting Tensile Test (d)Flexure Test

3.3 Mixing Methods

This study investigated four mixing techniques, namely: Normal Mixing Approach (NMA), Treated Aggregate Mixing Approach (TAMA), Mortar Mixing Approach (MMA), and Two-Stage Mixing Approach (TSMA), and their impact on the mechanical properties of RAC was evaluated [38–40, 42–44]. Five mixes of RAC were prepared for each mixing approach by substituting NA with RA at replacement levels of 0, 25, 50, 75, and 100% by volume. The mechanical strength of these samples was assessed after curing for 28 days. Schematic illustrations of each mixing method are presented in Figs. 3, 5, 6.

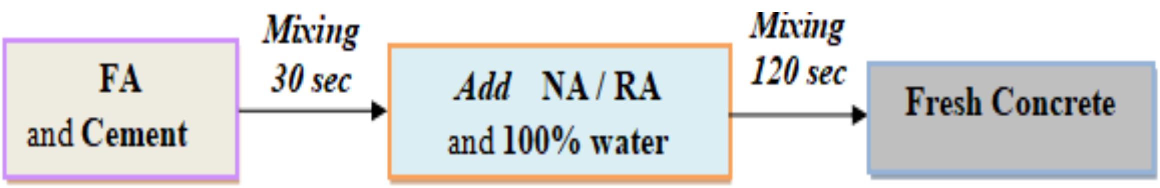


Fig. 3. Schematic illustration of NMA - Normal Mixing Approach [40]

In the NMA, fine aggregate (FA) and cement were added to the pan mixer and rotated for 30 seconds in a dry state. Subsequently, measured quantities of coarse aggregates NA and RA were added along with the total amount of water, and the mixture was rotated for 120 seconds [38–40, 43], as illustrated in Figs. 3. In TAMA, treated aggregate (TA) is used instead of RA. The required quantity of RA was soaked for 24 hours in the cement slurry prepared by mixing 50% of the calculated cement content with water, as in Fig. 4(a). The soaked RA with cement coating was dried until a surface-dried aggregate coated with a cement layer was formed. TA, the surface-dried recycled aggregate, shown in Fig. 4(b), was used in casting concrete samples in the TAMA method following the mixing process similar to NMA as given in Fig. 3.

(a) (a)

Fig.4. (a) RA soaked in cement slurry and (b) Surface-dried RA (Treated Aggregates)

In MMA, cement and FA were dry mixed, and 75% of the total water was mixed thoroughly for 90 seconds. Subsequently, RA and NA were added with the remaining 25% water and mixed for 90 seconds [39]. This method is shown in Fig. 5. The TSMA, introduced by Tam et al. [40], splits the mixing process into two phases. In the first phase, only half the water is added; the remaining water is incorporated during the second phase. This method has significantly improved RAC strength, particularly at replacement ratios of up to 25% RA after 28 days of curing. Further enhancements have been achieved by incorporating silica fume or a cement-silica fume blend within the TSMA process [42]. The TSMA process is illustrated in Fig. 6.

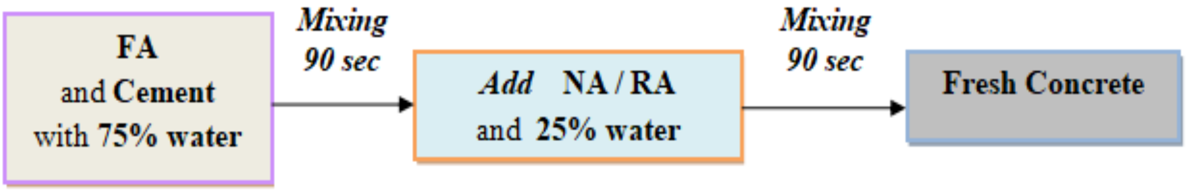
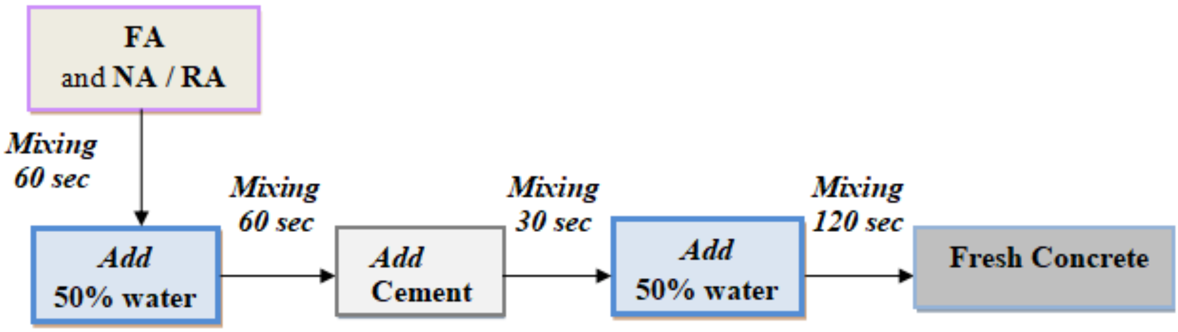


Fig. 5. Schematic illustration of MMA



- Mortar Mixing Approach [39]

Fig. 6. Schematic illustration of TSMA - Two Stage Mixing Approach [40]

In NMA and TAMA, the total water required for mixing is added in a single stage along with all other ingredients in the mixer pan before rotation, as in Fig. 3. In contrast, in MMA and TSMA mixing processes, the required quantity of water is split proportionally into two parts and is added at different timings, as illustrated in Fig 5, 6.

4. Results and Discussions

4.1 Workability

A graphical plot of the average value of three trials in each mixture composition for slump results with different replacement levels of RA using NMA, TAMA, MMA, and TSMA is presented in Fig. 7. The concrete mix was designed to achieve a slump of 100 mm for M20-grade concrete as specified in IS 10262 (2019)[48]. For the control mix, NAC, mean slump values were 87mm, 93mm, 94mm, and 99 mm for NMA, TAMA, MMA, and TSMA, respectively. At a 25% RA replacement level, the average values of the slump test were 84mm, 87mm, 88mm, and 94mm for NMA, TAMA, MMA, and TSMA, respectively. The average slump values of 44mm, 49mm, 51mm, and 56mm for NMA, TAMA, MMA, and TSMA were observed for a 100% RA replacement level, and it was the lowest among all the mix types. These findings align with similar research reports [39, 51–53]. The decrease in workability is attributed to the presence of hydrated mortar adhered to the surface of RA, which exhibits a higher water absorption of 4.44% compared to 0.75% in NA, as shown in Table 1. This study's increasing order of mean slump values is NMA< TAMA<MMA< TSMA. Thus, it is evident that TSMA is more suitable than all other mixing methods for enhancing fresh concrete's workability.

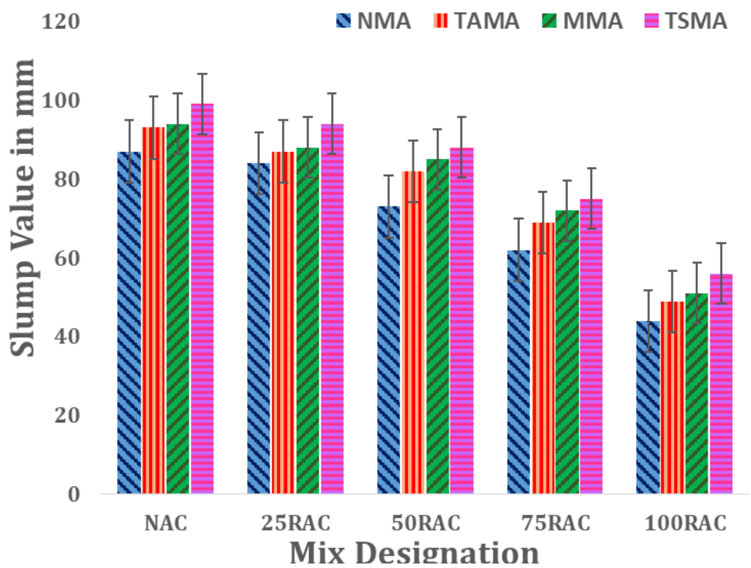


Fig. 7. Slump values in mm for four mixing approaches

4.2 Compressive Strength

This investigation involved conducting a compressive strength test on three 150mm concrete cubes for each mix after 28 days of curing as per IS: 516-2021[50]. The concrete compressive strength consistently diminished as the percentage of RA increased at replacement levels of NA. Previous researchers noted the same pattern in the results [40, 41, 43, 54–56]. The relationship between RA and ITZ significantly influences the compressive strength of RAC. The compressive strength primarily relies on the interconnections between cement paste and aggregate [39, 40].

The average compressive strength values of three samples tested after 28 days of curing ranged from 26.47 MPa to 17.17 MPa for NMA, 27.43 MPa to 17.62 MPa for TAMA, 27.86 MPa to 18.43 MPa for MMA, and 28.55 MPa to 19.84 MPa for TSMA, across varying RA replacement levels from 0% to 100%. Average values of 28-day compressive strength for various mixing approaches is represented in Fig. 8. Failure pattern of 100% RA cube samples for various mixing approaches is shown in Fig. 9. A 15.55 % improvement in compressive strength was observed for 100% RAC using TSMA compared to increments of 2.62% and 7.34% observed in TAMA and MMA, respectively, relative to NMA. These findings align with similar trends described by other investigators [54, 55]. This study found TSMA to be more effective than other methods. The observed average compressive strength of 25% RA was 25.45 MPa (NMA), 26.58 MPa (TAMA), 26.95 MPa (MMA), and 27.25 MPa (TSMA). Among these, TAMA (26.58 MPa), MMA (26.95 MPa), and TSMA (27.25 MPa) values were agreeable with the M20 grade concrete target strength of 26.60 MPa.

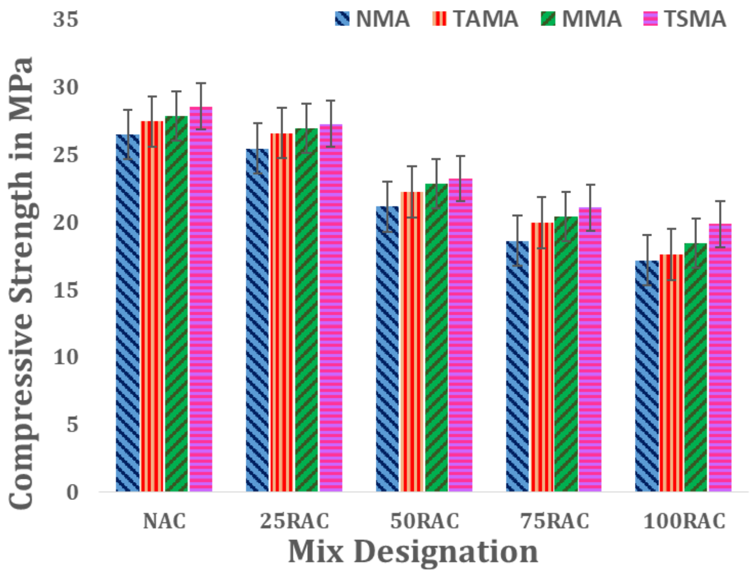


Fig. 8. Compressive strength of concrete for various mixing approaches

(a) (b) (c) (d)

Fig. 9. Damaged cube samples of 100 % RA mix for various mixing approaches(a) NMA 100%RA, (b) TAMA 100%RA, (c) MMA 100%RA and (d) TSMA 100%RA

4.3 Splitting Tensile Strength

The splitting tensile strength of concrete outlined in IS: 516-2021[50] was conducted on a cylinder sample with a diameter of 100 mm and height of 200 mm. Fig. 10 shows the graph of 28-day average splitting tensile strength of three cylinders for each concrete mix, where NA was replaced with RA by 0%, 25%, 50%, 75%, and 100% and by using four different mixing procedures, namely NMA, TAMA, MMA and TSMA. The average splitting tensile strength values ranged from 3.13 MPa to 2.15 MPa for NMA, 3.24MPa to 2.23 MPa for TAMA, 3.29MPa to 2.28 MPa for MMA, and 3.32 MPa to 2.35 MPa for TSMA. Fig.12 shows the damaged cylinder sample of 100% RA mix using the TSMA method. Among the four mixing approaches, TSMA showed the maximum improvement, ranging from 6.07% to 12.35%, followed by MMA with an increase of 4.97% to 9.56% and TAMA with a rise of 2.32% to 4.38%, compared to the NMA mixing approach. Based on the experimental results, TSMA and MMA were more effective than TAMA and NMA. The splitting tensile strength values diminished as the replacement level of RA increased across all mixing procedures, as noted by several previous researchers [41, 43, 54, 55].

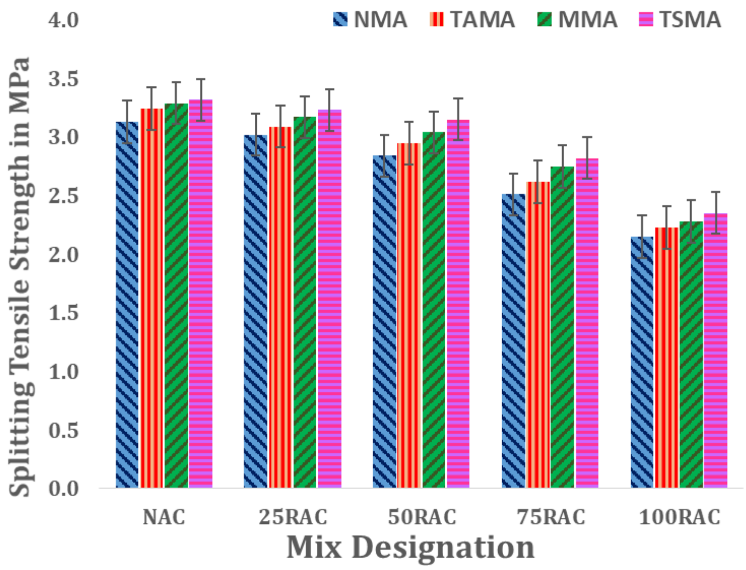


Fig. 10. Splitting tensile strength of concrete for various mixing approaches

4.4 Flexural Strength

The current study tested flexural strength on concrete beams measuring 100 mm x 100 mm x 500 mm, adhering to the guidelines outlined in IS: 516- 2021 [50]. Fig. 11 shows the variation in average flexural strength of three prism samples for 28 days of curing, with varying contents of RA and different mixing methods. Failure pattern of 100RAC beam samples using various mixing methods is shown in Fig.13. The flexural strength of RAC was observed to be lower than that of the control mix. This reduction is because of the poor quality of the adhering cement paste and the feeble interfacial bond between the old and new cement paste, as documented by prior researchers [53, 55, 56]. The mean flexural strength values ranged from 3.34 to 2.21 MPa for NMA, 3.47 to 2.25 MPa for TAMA, 3.52 to 2.32 MPa for MMA, and 3.75 to 2.48 MPa for TSMA. A 12.22 % improvement in flexural strength was observed for 100% RAC using TSMA compared to increments of 1.81% and 4.98% observed in TAMA and MMA, respectively, relative to NMA. Among all the mixing methods, the highest flexural strength was observed with the TSMA method, while the lowest was with the NMA method.

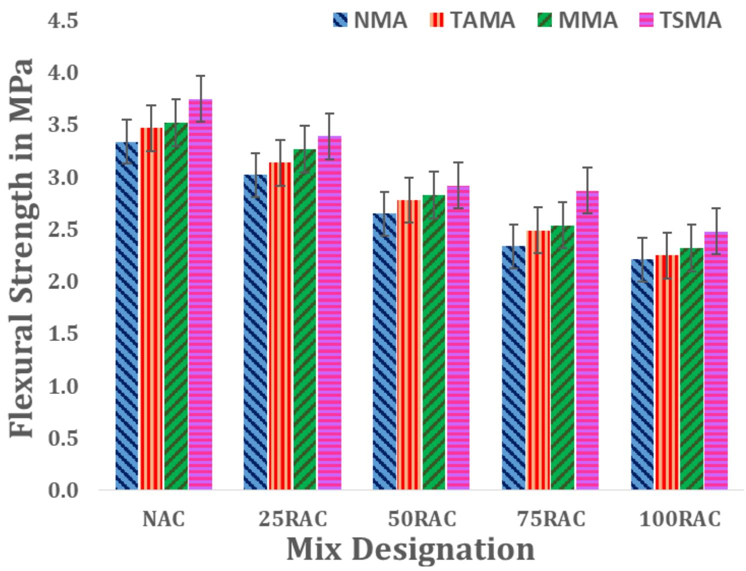


Fig. 11. Flexural strength of concrete for various mixing approaches

Fig. 12. Damaged NMA 100% RA cylinder

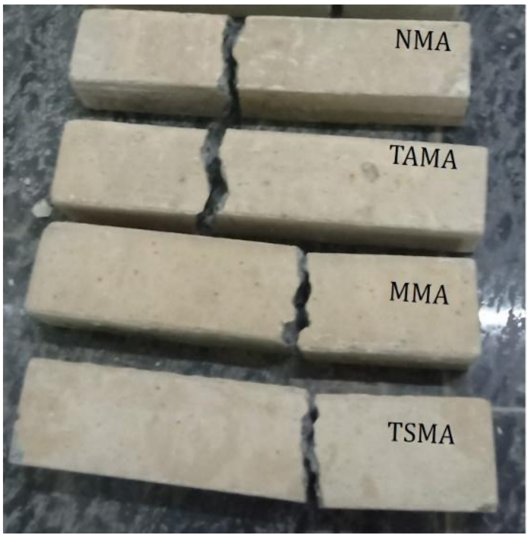
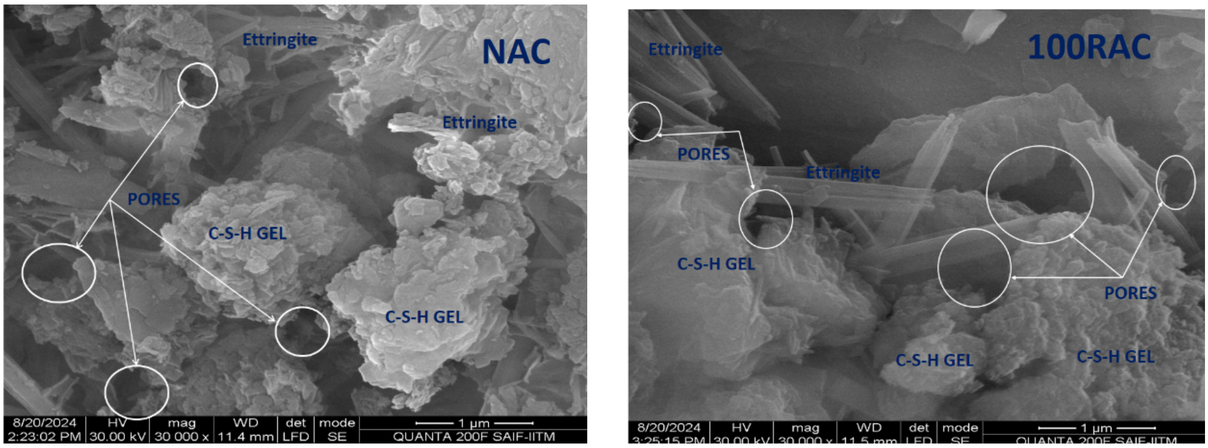


Fig. 13. Damaged 100% RA beam samples

4.5 Microscopic Analysis

Scanning Electron Microscopy (SEM) analysis was carried out for the control concrete, NAC with natural aggregate and 100RAC with recycled aggregate prepared by using TSMA mixing method at The Sophisticated Analytical Instruments Facility (SAIF) in IIT Madras, India, using FEI-Quanta FEG 200F, a versatile high resolution Scanning Electron Microscope to get a precise and accurate details. SEM analysis of Fig.14 (a, b) reveals that concrete with 100% RA exhibits a more porous, less dense and disconnected microstructure than NAC. The loose C-S-H gel, larger ettringite crystals and increased pore density of 100RAC indicate a weaker microstructure responsible for the reduced workability and mechanical strength. Despite this, both NAC and 100RAC still show active hydration, suggesting that performance has improved due to excess water for hydration in the TSMA mixing method as indicated by Tam et.al [40, 42].



(a) (b)

Fig. 14. SEM image of (a) NAC and (b) 100% RA samples using TSMA

The adhered cement mortar at the ITZ of RA forms the weak portion in RAC. It is composed of many minute pores and cracks, which affect the ultimate strength of the RAC. These pores and cracks consume more water, reducing the water required for hydration at the ITZ of RAC. In TSMA, half the water added in the first stage creates a thin cement slurry that coats the recycled aggregates. This slurry penetrates the pores and cracks of the old mortar on the aggregates, filling them up. The remaining water is added in the second stage, which helps to complete the concrete mixing process. This process improves the bond between the recycled aggregate and the new cement paste, resulting in a stronger and more durable interfacial transition zone (ITZ) [40, 54, 55].

5. Conclusions

This investigation involved the preparation of five concrete mixtures by replacing NA with RA at volumetric substitution levels of 0, 25, 50, 75, and 100%. Four distinct mixing methodologies, specifically Normal Mixing Approach (NMA), Treated Aggregate Mixing Approach (TAMA), Mortar Mixing Approach (MMA), and Two-Stage Mixing Approach (TSMA), were utilised to ascertain the optimal replacement ratio of RA and the most appropriate mixing technique.

- The specific gravity and fineness modulus of RA were lower than those of NA; however, the water absorption of RA was higher. The presence of adhering cement on the surface of RA led to increased porosity and a compromised ITZ, reducing workability and mechanical properties in RA relative to NA.
- Workability, measured in terms of slump value, decreased with increasing levels of RA substitution across all concrete mixes. Maximum reduction was observed for 100% RA substitution. The higher water absorption property of RA is likely responsible for this decrease. Among the mixing methods, TSMA yielded the highest slump values, ranging from 99 mm to 56 mm for different RA mixes, followed by MMA, TAMA and NMA. The observed slump of 94 mm in TSMA for 25% RA substitution is closer to the designed slump value of 100mm.
- Compressive strength of the mixes reduced with an increment in the replacement levels of RA. For 25% RA substitution, compressive strengths were 25.45, 26.58, 26.95, and 27.25 MPa for NMA, TAMA, MMA and TSMA, respectively. The TAMA, MMA, and TSMA values were consistent with the target strength of 26.60 MPa for M20 grade concrete. TSMA and MMA showed improvements of 7.07% and 5.89% over NMA.
- Splitting tensile strength ranged from 2.15 MPa to 3.32 MPa and decreased with increasing RA replacement levels across all the mix types. For 25% RA substitution, splitting tensile strengths were 3.02 MPa (NMA), 3.09 MPa (TAMA), 3.17 MPa (MMA), and 3.23 MPa (TSMA).
- Flexural strength also decreased with increasing levels of RA substitution across all mix types using various mixing methods. Values ranged from 2.21 MPa to 3.75 MPa. Flexural strength values for 25% RA substitution were 3.02 MPa, 3.14 MPa, 3.27 MPa, and 3.39 MPa for NMA, TAMA, MMA and TSMA, respectively. Among these methods, TSMA yielded the highest flexural strength value (12.25%), followed by MMA (8.28%), concerning NMA.

Based on the above observations, it can be concluded that NA can be replaced by up to 25% of RA without affecting the workability and mechanical properties of normal-strength concrete. Among the four mixing approaches studied, TSMA gives the best result, followed by MMA. The two-stage mixing method is significant because it specifically targets and mitigates the main limitation of recycled aggregate concrete—the weak ITZ—by ensuring better mortar coverage around aggregate particles, pore reduction, better hydration and bonding at the aggregate-cement interface. This not only improves the strength and durability of RAC but also broadens its practical applications in construction.

The economic and environmental evaluation of the four mixing methods—Normal Mixing Approach (NMA), Treated Aggregate Mixing Approach (TAMA), Mortar Mixing Approach (MMA), and Two-Stage Mixing Approach (TSMA)—reveals significant differences in sustainability, cost-effectiveness, and practical application. NMA, the most conventional method, and TAMA involve mixing all components with full water content simultaneously. While operationally simple and cost-efficient in the short term, it often results in poor bonding with recycled aggregates, reducing strength and durability, and may require higher cement content, thus increasing environmental impact through elevated CO_2 emissions. MMA improves upon this by pre-mixing cement and fine aggregate with 75% water, enhancing hydration and particle distribution. This staged mixing moderately improves workability and strength, better balancing performance and resource efficiency. TSMA, the most advanced method, divides water and introduces materials in stages, significantly enhancing the coating of recycled aggregates and the overall microstructure of the concrete. This leads to superior compressive strength, durability, and water efficiency, reducing cement usage and reducing carbon emissions. Although TSMA requires more time and energy due to multiple mixing steps, its long-term benefits in sustainability and structural performance outweigh the initial operational costs. Therefore, TSMA stands out as the most sustainable and cost-effective approach for projects prioritising durability and environmental responsibility. At the same time, MMA serves as a practical alternative when simplicity and moderate improvements are desired over traditional NMA.

This research underscores the potential of RA as a sustainable material in concrete production while emphasising the importance of optimising mixing techniques to enhance RAC performance. The findings highlight the role of mixing approaches like TSMA in promoting sustainable construction practices and advancing the use of recycled materials in industry. Future studies should investigate long-term durability, economic feasibility, and environmental impact to further validate the practical applications of RAC with RA in different construction scenarios.

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