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Strengthening the Quality and Quantity of Optimum RCA in Structural Concrete

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Abstract

Construction sector generate abundance of waste which pose a significant challenge in developing countries like India due to improper disposal methods and environmental impact. With India's vision of becoming a developed country with a $30 trillion economy by 2047, demand of construction of new residential, commercial, and public structures has risen. Hence, it becomes a national interest to develop abiding laws and regulate the considerable amount of Construction and Demolition (C&D) waste getting generated to mitigate the adverse effects of waste accumulation. This study explores the potential of Recycled Concrete Aggregates (RCA) as a sustainable solution to mitigate C&D waste and promote a circular economy in the construction sector. RCA utilization offers environmental benefits by reducing reliance on Natural Aggregate (NA) and lowering CO_2 emissions from transportation [1]. However, current practices in India are limited by a lack of awareness and undefined policies [2]. This study reviews existing methods to improve RCA quality, considering both environmental impact and construction efficacy. Encouragingly, the Indian Standards IS 383:2016 [3] acknowledges RCA as an alternative aggregate to NA and has stipulated a maximum replacement limit of 20% for grades up to M25. This research aims to increase the maximum replacement of NA with RCA using thermo-mechanical treatment and explore alternative mixing approaches to further modify the surface. The goal is to develop a "fit for purpose" mix design for fresh Recycled Aggregate Concrete (RAC) that incorporates recent advancements and paves the way for RCA as a viable structural material. This approach aligns with India's vision for sustainable construction practices and responsible waste management. The findings of this study can contribute to increased R*CA* utilization as a solution for a more sustainable construction practice in India.

KEYWORDS: *Construction and Demolition (C&D) waste, Recycled Concrete Aggregates, Circular economy, Sustainable, Treatment techniques, Thermo-mechanical.*

1. Introduction

Concrete is a widely utilized material in construction due to its versatility, durability, and ease of use. It serves as a key indicator of a country's technological and technical progress, often influencing the pace of infrastructural development and contributing to advancements in sustainability.Key elements of the construction industry, such as cement and aggregate production and transportation, contribute significantly to its carbon footprint. Cement

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production alone accounts for approximately 7% of global CO2 emissions, with China being the largest producer, followed by India, which produces around 2350 million metric tons. To achieve sustainability, the construction industry must not only reduce its carbon footprint but also conserve natural resources essential for on-going development [1]. The growth in the construction industry has results in increased C&D waste, leading to environmental degradation and pollution.

Consequently, promoting the use of secondary materials is essential to supplement primary materials [2]. Aggregates are critical components of concrete, comprising about 60%-75% of its total volume. The rapid industrialization and urbanization, driven by economic and population growth, have made concrete a major consumer of natural resources. Annually, concrete production uses approximately 20 billion tons of raw materials, primarily coarse aggregates.

According to the C&D waste management rule 2016, C&D waste includes building materials, debris, and rubble from construction, remodelling, repair, and demolition of civil structures [4]. Upon segregation, it can be categorized into concrete, soil, steel, wood, bricks, mortar, and other salvaged components as shown in Figure 1.

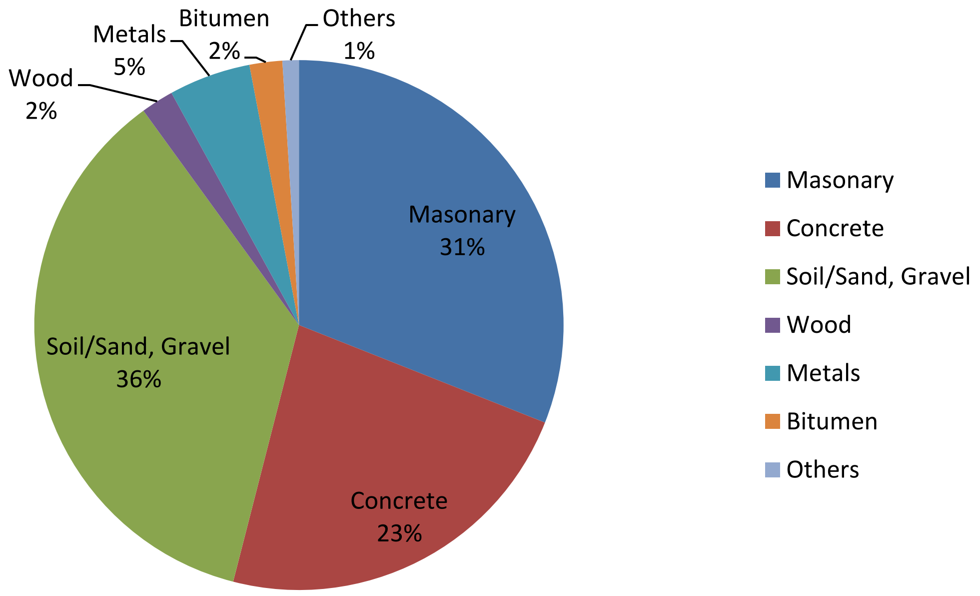

Figure 1: Composition of C&D Waste in India [6].

In India, C&D waste generation is estimated at 12 million tonnes annually, varying by city due to differing construction practices. Approximately 95% of this waste can be reused or recycled if processed scientifically. However, due to inadequate processing infrastructure, most C&D waste ends up in landfills or mixed with municipal solid waste. Globally, the recycling rates for C&D waste are 50% in the EU, with the UK at 90%, the US at 70%, and France at 48% [6]. Hence, Effective waste management and recycling policies are crucial to address these challenges [7].

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RCA derived from C&D waste treatment plants [Table 1.1] offers potential solutions but faces limitations due to perceived inferior quality compared to NA. Concerns about Adhered Mortar (AM) in RCA affect its structural integrity, but surface modification and beneficiation techniques can enhance its properties [8]- [9].

Table 1.1: C&D waste recycling plants in India

City	Place	Capacity (TPD)
Delhi	Burari	1000
	Mundka	150
	Shastri Park	1000
	Industrial Area	1000
Noida	Sector 80	150
Gurugram	Basai	300
Ghaziabad	Ghaziabad	150
Thane	Daighar	300
Indore	Devguradia	100
Hyderabad	Jeetimedla	300
Bengaluru	Chikkajala*	1000
	Kannur	750
Ahemdabad	GyaspurPirana	1000
Tirupati	Tukivakam Village	150
Vijayawada	Vijayawada	200
Chandigarh	Industrial Area Phase	1150
Prayagraj	Sangam City, Baswar	100
Chhattisgarh	HirapurJarwai, Raipur	500^
Total	**18**	**8800**

*Note: *Privately owned and operated, ^approx. Source: [11],[6],[12],[13],[14]. TPD: Tonnes Per Day.*

Additionally, products like kerb stones, paver blocks, and concrete blocks from recycled C&D waste serve as excellent substitutes for conventional products. Major applications of processed C&D waste include [5]:

- Granular Sub-Base (GSB): Crushed C&D waste can serve as a base layer for roads offering support, drainage, and frost protection.
- RCA: Pure concrete debris can be transformed into aggregates of varying sizes,substituting NA.
- RA: Mixed C&D waste can be processed into standard-sized aggregates suitable for non-load-bearing structures.
- Manufactured Sand (M-Sand): Fine particles from crushed C&D waste can replace natural sand in non-load-bearing applications.
- Metal Recovery: Scrap metal extracted from C&D waste can be melted down and recycled to produce new metal products.

2. Recycled Concrete Aggregate

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RCA utilization can mitigate environmental impacts by reducing the extraction of Natural Aggregates (NA), decreasing landfill waste, promoting circular economy principles, and generating employment through C&D waste management plants [3].

The strength of RAC is influenced by various factors. These include the physical properties of the RCA, such as AM content, density, abrasion resistance, crushing characteristics, and surface texture. Additionally, the concrete mixing process, Interfacial Transition Zone (ITZ), and aggregate size play significant roles in determining the overall strength of the RAC. [15]. Since aggregate makes up 60-80% of the concrete volume, using discarded concrete waste (Figure 1.2) as RCA is essential for conserving non-renewable NA resources.

Overall, the future of RCA is likely to be characterized by greater adoption, driven by environmental, economic, and regulatory factors, as well as advancements in technology and ongoing research efforts. The global market for C&D waste recycling was valued at $126,897.2 million in 2019 and is expected to reach $149,190.9 million by 2027, with a Compound Annual Growth Rate (CAGR) of 2.7%.

The utilization of RCA in the production of new concrete offers advantages for addressing social and environmental challenges by:

- Diminishing the necessity for extracting Natural Aggregates (NA) essential for concrete manufacturing .
- Decreasing the volume of C&D waste getting disposed in land-fills to mitigate environmental harms, including urban flooding, water body destruction, groundwater pollution, landfill clogging, mixed Municipal Solid Waste (MSW), open space degradation, mobility obstruction, and dust pollution [5].
- Advocating for a circular economy approach where products reaching the end of their lifecycle are not discarded as waste but recognized as potentially valuable resources capable of being repurposed and recycled for fresh applications. This approach not only diminishes the environmental ramifications of disposal but also contributes to economic advancement.

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Figure 1.2: C&D waste generated in Durg Chhattisgarh, India due to demolition of a) - d) residential buildings, e) laying new pipelines near Water Treatment Plant and f) Water tank Columns

The primary objectives of this research includes - Enhancing the quality of RCA in Structural Concrete, Enhancing the quantity of RCA in Concrete Production and Performance Evaluation of Treated RCA Concrete.

2.1 Previous Studies on RCA & its Inferences

The microstructure of Recycled Aggregate Concrete (RAC) differs from normal concrete due to Adhered Mortar (AM), forming complex ITZs which includes: ITZ_1 between NA and old mortar, ITZ_2 between old and new mortar, and ITZ_3 between NA and new mortar as shown in Figure 2.1(a, b). [12]. To differentiate between the microstructure of Natural Aggregate Concrete (NAC) and RAC techniques such as nano-indentation, scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy are used by S. Erdem et al. [23]. SEM helps in assessing hydration, pore characteristics, and the content of calcium hydroxide ($Ca(OH)_2$) and Calcium Silicate Hydrate (C-S-H) in concrete. In NAC, micro-cracks typically propagate through the ITZ near aggregates, leading to concrete failure. This occurs due to the "wall effect," where small cement particles near large aggregates cannot pack densely. ITZ characteristics significantly impact RAC's performance [22]. There are four stages in ITZs: porosity, $Ca(OH)_2$, other hydration products (primarily C-S-H gel and ettringite), and unhydrated cement particles. C-S-H, smaller than $Ca(OH)_2$, contributes to densification. New ITZs contain a higher volume fraction of C-S-H compared to old ITZs Figure 2.2(c,d).

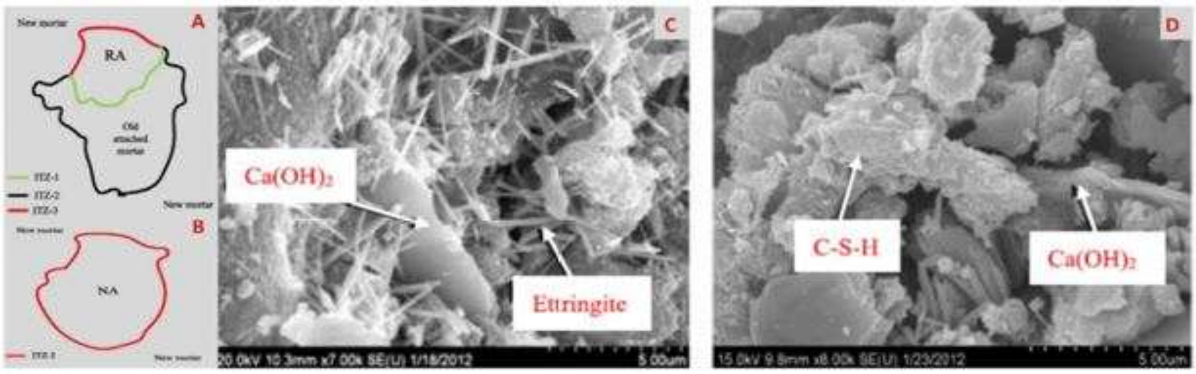

Figure 2.1 Schematic of Different types of ITZ in concrete (a) ITZ s of RAC, (b) ITZ of NAC [30]. SEM images of ITZs in RAC (c) Old ITZ (d) New ITZ [28].

Over time, hydration products reduce unhydrated cement in the ITZs, filling pores and improving mechanical properties. Although the bond between coarse RCA and cement paste is initially weak due to water absorption and large $Ca(OH)_2$ crystals, extended hydration can fill these pores and enhance RAC properties [22].

Recycled concrete aggregates (RCA) are 10-20 times more porous than natural aggregates due to the AM [25]. In hardened concrete, AM leads to additional ITZs, which affects the mechanical and durability performance of RAC. RAC performance degradation is linked to

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the quantity and quality of adhered mortar (AM) and the ITZ. Careful selection and proportioning of RCA are essential for high-performance RAC. Improving RCA defects and ITZs can enhance RAC's microstructure and performance. To enhance RCA properties, various improvement methods are used as shown in flowchart Figure 2.2, which either removes AM, modify RCA surfaces or combination of different methods.

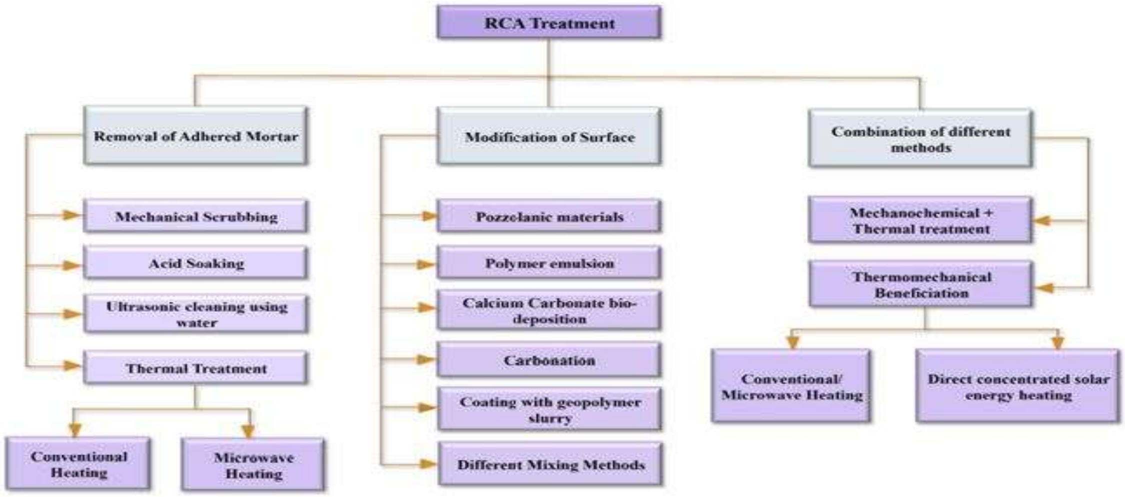

Figure 2.2: Different methods for enhancing quality of RCA [15],[28],[19]

Various AM removal techniques, such as acid soaking and ultrasonic cleaning, are water-intensive and problematic due to water disposal and chemical handling issues. Mechanical scrubbing and heating are more efficient but energy-intensive. Surface modification with pozzolanic slurries, like fly ash, offers a cost-effective and environmentally beneficial solution, promoting circular economy principles. Techniques like microwave heating, high voltage electric pulse, and CO_2 curing require specialized equipment, limiting their accessibility. Despite these challenges, enhancing RCA through effective beneficiation can improve its performance and support sustainable construction practices.

On reviewing current advancements in techniques for improving the evaluating them based on adopted methodology with its environmental impact and technical criteria [22],[26]. Techniques such as adding fibres, pozzolana, and coating RCAs with geopolymer slurry are particularly effective. RCAs can be enhanced by reinforcing, cleaning, or improving concrete without modifying RCAs.

Strengthening AM through polymer impregnation, pozzolanic slurry, accelerated carbonation curing, bio-deposition, coating RCA with geopolymer slurry and using different mixing approaches can also improve RCA by enhancing weak areas [14]. However, combining different treatment methods results in RCA of better quality like thermo-mechanical treated Coarse RCA properties surpassed those of jaw-crushed and industrially-produced RCA, with slightly higher dry density than pristine granite aggregates. This enhancement is attributed to the removal of porous surface regions through heating and mechanical rubbing resulting insimilar morphologies between pristine granite aggregates and beneficiated RCA, showcasing the absence of adhered mortar in the latter. These findings underscore the

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efficacy of thermo-mechanical beneficiation in enhancing RCA properties, positioning it as a viable sustainable alternative in construction applications [24].

The study by *Rohit Prajapati et al [21]* also revealed that concrete waste subjected to thermal treatment at 500 °C (932°F) for 60 minutes and milling with a charge produced the most favorable outcomes compared to other temperature and residing time combinations. Photographs in Figure 2.3 illustrate significantly reduced AM after thermo-mechanical treatment. Fine RCA exhibited improved dry density by about 15% and reduced water absorption by about 40% compared to conventionally crushed and commercially produced fine RCA. Similarly, properties of beneficiated coarse RCA surpassed those of conventionally crushed and commercially produced RCA. Beneficiated coarse RCA even showed slightly higher dry density than NA, likely due to the removal of porous surface regions through heating and mechanical rubbing. Original aggregates extracted from waste concrete through acid washing were marginally better in terms of strength compared to thermo-mechanically beneficiated RCA, though the associated safety and environmental risks outweigh the benefits significantly.

Figure 2.3: Comparison of physical appearance of treated RA with NA [21].

3. Adopted Treatment Methods

To determine optimal mix proportions and assess quality control parameters, trial mixtures were prepared using varying amounts of coarse TMRCA (Thermo-mechanical Recycled Concrete Aggregate) & fine NA (Natural Aggegates). RCA is employed in concrete with compressive strengths ranging from 30 to 60 MPa, flexural strengths exceeding 4 MPa, splitting tensile strengths surpassing 2 MPa, and elastic moduli between 20 and 40 GPa. Based upon the literature review, the mix design for M40 concrete is opted by substituting

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TMRCA at varying proportions from 0 to 100% at an interval of 25% for NCA. The experimental procedure is depicted in a flowchart presented in Figure 3.1. The trial concrete mixtures were prepared incorporating treated RCA using SEMA will conduct laboratory experiments to examine how RCA influences the mechanical properties of RAC under controlled conditions.

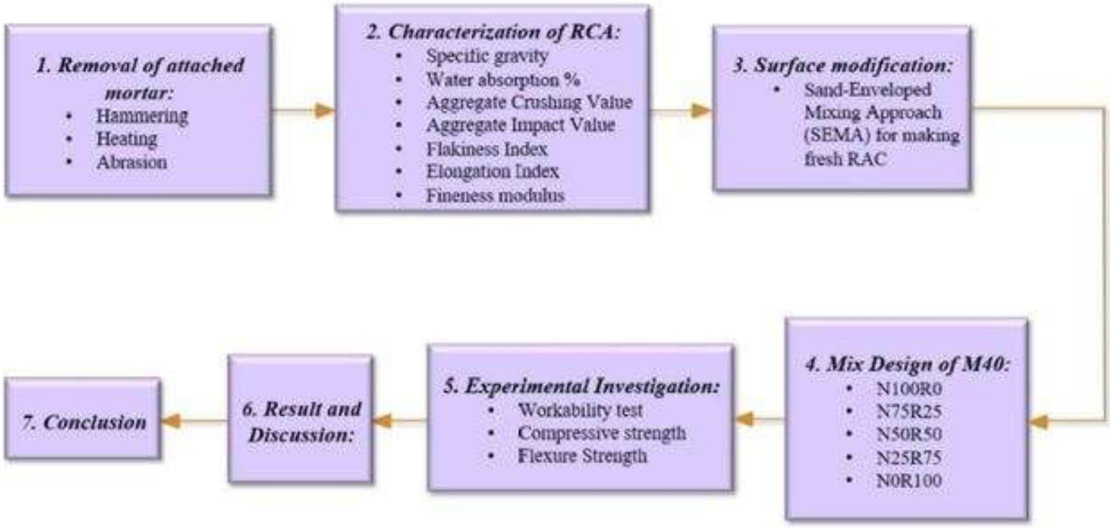

Figure 3.1 Schematic of experimental procedure

3.1. Removal of Attached mortar

Firstly, demolition of residential or commercial buildings, aged between 25 to 50 years, is identified as suitable sources of C&D waste. To ensure uniformity, chunks ranging from 50 to 500mm are selected, while excluding steel reinforcement, finishing materials, and bricks. Upon collection, larger chunks undergo a hammering process to reduce their size to a minimum of 50mm, facilitating subsequent processing. These chunks are then subjected to controlledheating in a crucible which could accommodate 5Kg of waste chunks at a time within a pit furnace (as shown in Figure 3.2). The Pit Furnace temperature was set to 500°C for 90 minutes, with temperatures ranging from 29°C to 500°C. Following the heating process, the aggregates undergo natural cooling at room temperature for 24 hours, ensuring stability and preventing structural damage of aggregate.

Figure 3.2: (a) A crucible weighing 5 kg was used in the pit furnace. (b) The crucible was filled with 5 kg of concrete waste. (c) The pit furnace heated the concrete waste to 500°C.

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After cooling, 10 kg of the treated aggregate is carefully placed in a Los Angeles abrasion machine. This machine, fitted with 10 steel balls as an abrasive charge, subjects the aggregate to 400 revolutions at a constant speed of 33 rpm. This rigorous abrasion process effectively removes adhered materials from the aggregate post heating. The result of this abrasion process is the generation of both coarse and fine RCA, which is subsequently sieved using a coarse sieve to obtain TMRCA with properties comparable to those of pristine NA.

The RCA produced through this method is then analysed for its physical and mechanical characteristics, which are essential for its use in high-strength concrete applications. A detailed schematic of the methodology adopted for extracting TMRCA from waste chunks is illustrated in Figure 3.3. This process ensures that the TMRCA meets the necessary standards and specifications for use in construction, providing a sustainable and efficient alternative to natural aggregates. The method demonstrates a practical approach to recycling concrete waste, contributing to sustainable construction practices and the reduction of hazardous solid waste.

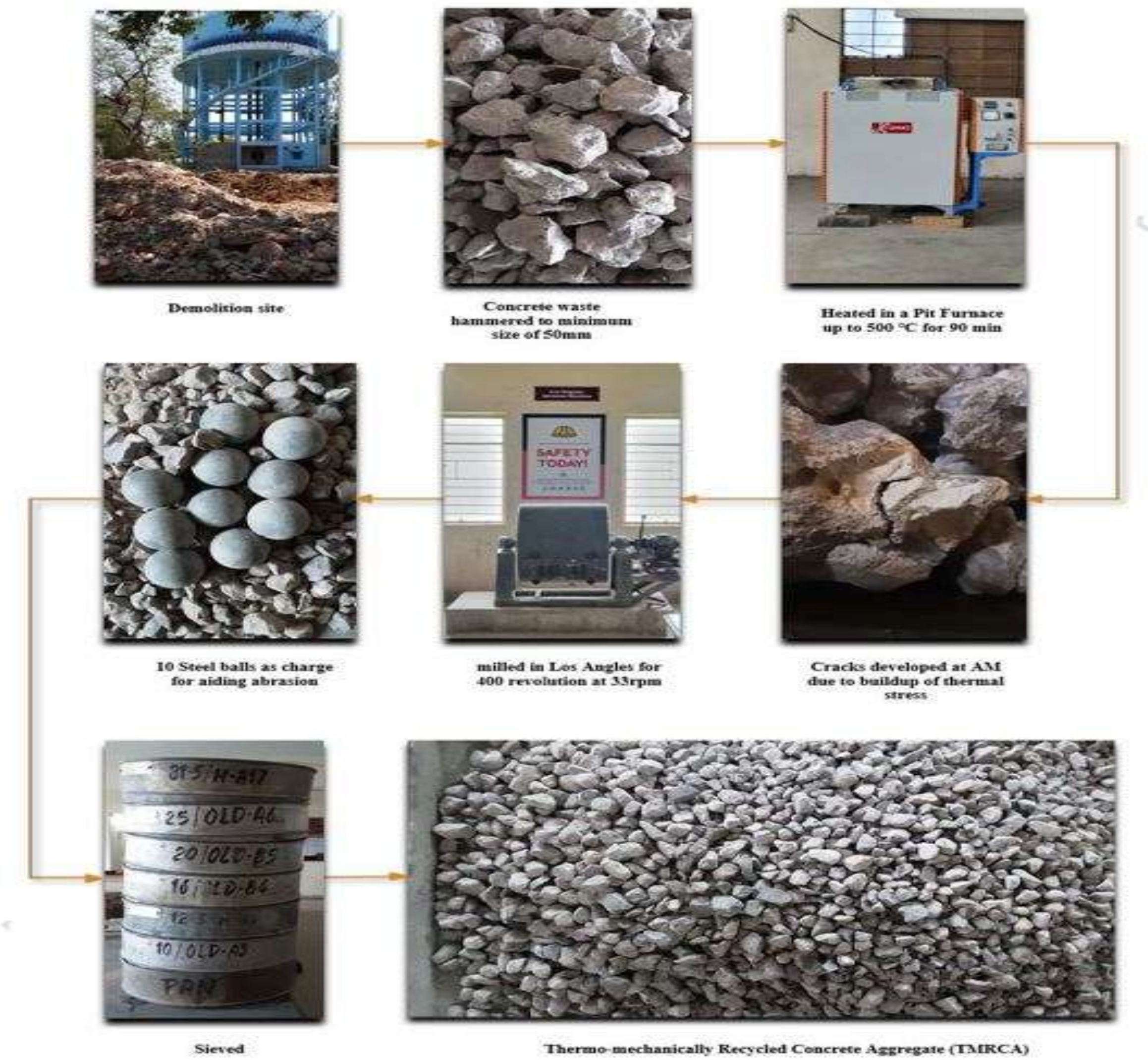

Figure 3.3 Schematic of the methodology adopted for extracting TMRCA from waste chunks

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3.2. Surface modification

Mixing methodologies play a crucial role in enhancing RCA-based concrete. As highlighted by Verian et al. [8], different approaches to mixing can significantly impact the properties of the final concrete product. One such method is the two-stage mixing approach (TSMA), which has been shown to increase compressive strength by approximately 20% compared to the normal mixing approach (NMA). In TSMA, RCA is initially coated with a thin layer of cement slurry, which is then allowed to dry before water is added again. This process helps to seal the pores and cracks in the RCA, thereby improving the compressive strength.

Other innovative mixing techniques include the mortar mixing approach (MMA) and the sand-enveloped mixing approach (SEMA). In both MMA and SEMA, fine aggregates, cement, and water are first mixed to form a mortar or cement slurry, which then fills the pores and cracks in the RCA. Among these methods, SEMA has been found to produce concrete with compressive strength 20% higher than that of MMA and 30% higher than TSMA . The comparisons of all methods are shown in Figure 3.4. The SEMA mixing process involved combining fine aggregate with 75% of the total water for 30 seconds. Cement was then introduced and mixed for an additional 45 seconds. Finally, the remaining water, along with the NA and TMRCA, was added and mixed for 90 seconds to prepare the fresh mix.

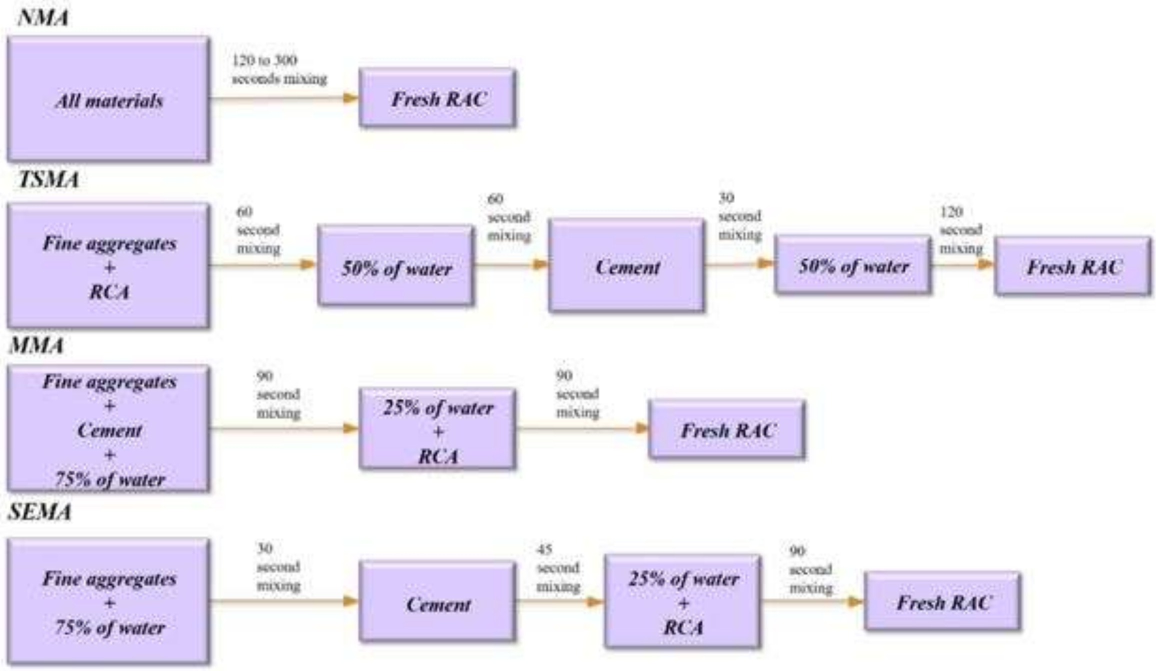

Figure 3.4: Mixing methods for preparing fresh RAC by using RCA

3.3. Material

Pozzolanic Portland Cement (PPC) having specific gravity of 2.9 is used as cementitious material in accordance with IS 1489 Part 1 specifications. Basalt rock served as the natural coarse aggregate (NCA), while river sand was utilized as the fine aggregate. RCA was

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obtained from a building that had been demolished in Durg, Chhattisgarh, India. The samples were taken from 2 sites primarily from a water tank site and from a residential building, both approximately 40 years old, where in the prior columns of water tanks were demolished and new steel column are installed to clear space to construct new room and later was demolished to repurpose the land for recreational activities. Physical testing of the original coarse aggregate in the RAC indicated that basalt rock had been used in the building's construction.

The demolition debris predominantly consisted of concrete rubble, broken bricks, masonry, metals, wood, and some plastic waste. The waste was sorted to extract only the concrete blocks, separating out metal, wood, plastic, and other materials. These concrete blocks were then broken into smaller pieces by hammering. As suggested by Prajapati et al. [21], the segregated concrete waste is heated.

In this research, concrete waste chunks were subjected to a thermal treatment process by heating them in a pit furnace for duration of 90 minutes. The temperature within the furnace ranged from 29°C to 500 °C. Following the thermal treatment, the waste materials underwent mechanical abrasion using a Los Angeles machine to facilitate the removal of AM. A sample weighing 10 kg, along with 10 steel balls, was placed in the machine and subjected to 400 revolutions at a speed of 33 rpm.

After the abrasion process, the treated material was sieved using a set of coarse sieves with sizes ranging from 25 mm to 4.75 mm. This sieving process resulted in the production of two distinct fractions: approximately 40% coarse TMRCA and 60% fine TMRCA which can be depicted from the bar graph shown in Figure 3.5. It was observed that the fine fraction predominantly consisted of cement particles, stone powder, sand, and very fine crushed aggregates. This indicates that the fines generated during the mechanical abrasion process are primarily composed of smaller particles, which include residual cement and other fine materials separated from the original concrete waste. The process effectively enhances the quality and usability of the recycled concrete aggregates for further applications in construction.

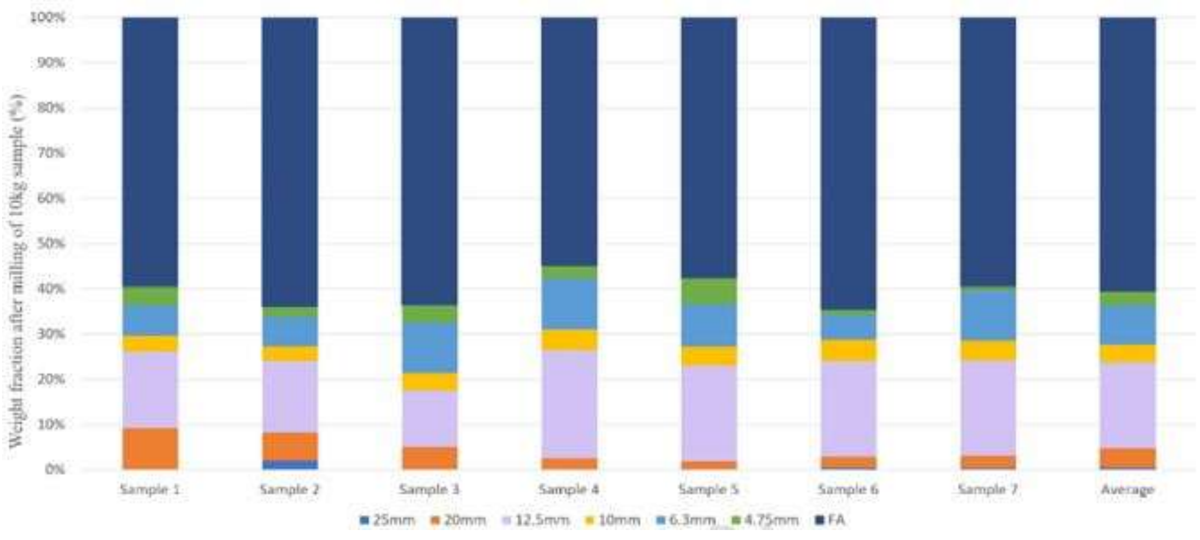

Figure 3.5: Fractions of weight of random samples obtained after milling

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After sieving, the coarse TMRCA is combined with coarse NA in varying proportions. These mixtures also include sand and a polycarboxylate ether (PCE) based superplasticizer. The purpose of incorporating the superplasticizer is to enhance the workability and performance characteristics of the concrete mix, specifically designed to achieve an M40 grade RAC.

The detailed procedures and specific proportions used in these mixtures, along with the rationale behind selecting each component, are extensively explained in the latter part of this paper. This includes discussions on the effects of varying TMRCA content on the mechanical properties of the concrete, the role of the superplasticizer in enhancing workability, and the overall performance of the M40 RCA in different testing scenarios. The comprehensive analysis provided at the end of the chapter offers valuable insights into the optimization of recycled concrete aggregate mixtures for structural applications.

3.4. Characterization of TMRCA in comparison with NA and MRCA

To decide suitability of aggregate for road construction test in accordance with IS 2386-1967 Part (IV) [27], IS 2386-1967 Part (III) [28], IS 2386-1967 Part (I) [29] and IS 383-2016 [30] certain tests were carried out to determine the mechanical properties and shape test for TMRCA, NA and Mechanically Recycled Concrete Aggregate (MRCA) is done to drawn a conclusion on efficacy of utilization of RA. The tests includes Water Absorption and Specific gravity test, Crushing test, Impact test, Abrasion test, shape test and sieve analysis whose results have been represented in the Table 3.1 to 3.5 and Figure 3.6 respectively.

Table 3.1: Water absorption and specific gravity of TMRCA, NA and MRCA

	TMRCA	**NA**	**MRCA**
Weight of saturated aggregate and basket in water = W_1 (kg)	2.8	2.8	2.7
Weight of basket in water = W_2 (kg)	1.5	1.5	1.5
Weight of saturated surface dry aggregates in air = W_3 (kg)	2.003	2.004	2.022
Weight of open dried aggregates in air = W_4 (kg)	1.998	1.996	1.962
Specific Gravity	2.81	2.835	2.387
Apparent Specific gravity	2.862	2.867	2.575
Water Absorption %	0.651%	0.4%	3.058%

Table 3.2: Crushing value of TMRCA, NA and MRCA

	TMRCA	**NA**	**MRCA**
Total weight of dry sample = W_1 (kg)	2.846	2.710	2.72
Weight of fines passing through 2.36 mm sieve = W_2 (kg)	0.558	0.718	0.822
ACV	19.606%	26.494%	36.179%

Table 3.3: Impact value of TMRCA, NA and MRCA

	TMRCA	**NA**	**MRCA**
Total weight of dry sample = W_1 (kg)	0.338	0.320	0.282
Weight of fines passing through 2.36 mm sieve = W_2 (kg)	0.050	0.054	0.092
AIV	14.79%	16.875%	32.622%

Table 3.4: Abrasion test on TMRCA, NA and MRCA

	TMRCA	**NA**	**MRCA**
Total weight of dry sample = W_1 (kg)	5	5	5

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Weight of fines passing through 1.70 mm sieve = W_2 (kg)	0.549	0.523	0.983
Percentage Wear	10.98%	10.46%	19.66%

Table 3.5: Shape test of TMRCA, NA and MRCA

	TMRCA	**NA**	**MRCA**
Flakiness Index %	12.6	14.3	19.36
Elongation Index %	9.1	9.4	24.96
Combined %	21.7	23.7	51.2

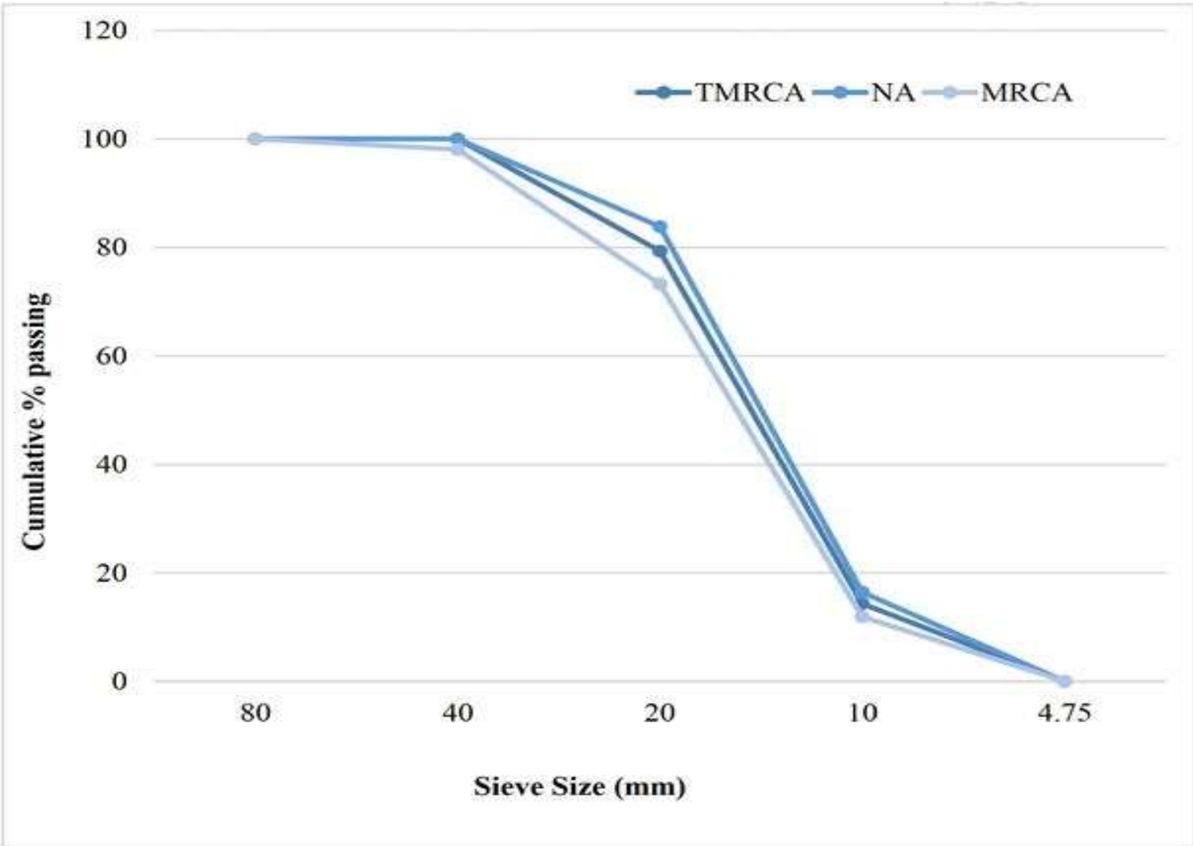

Figure 3.6 Gradation of coarse TMRCA, NA and MRCA

3.5 Mix Design

In this study, the quantity of materials for the concrete mixture was prepared for 0.38 w/c ratios to achieve target strength of 44.25 MPa at 28 days for M40 grade of concrete in accordance with IS 10262:2009 [34]. A total of 5 concrete mixes were designed wherein 4 concrete mixes were intended to optimize the TMRCA and 1 concrete mix was designed using NA to have a comparative study of RAC which were prepared by replacing coarse NA by 0%, 25%, 75% and 100% of Coarse RCA.The SEMA is adopted as the Mixing approach instead of NMA to further of TMRCA. This systematic study provides a comprehensive understanding of the performance of recycled concrete with varying RCA proportions.

The Mix Design Calculation for M40 Concrete (IS 10262:2019) was performed in two trials. In Trial 1, water-cement ratio of 0.38 and polycarboxylate ether (PCE) superplasticizer at 1% was used. However, the desired slump was not achieved. Consequently, in Trial 2, the water-

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cement ratio was increased to 0.4 while maintaining the PCE rate at 1%. This adjustment resulted in a desirable slump of 108 mm. Therefore, the mix design with a 0.4 water-cement ratio was adopted for all subsequent mixes incorporating TMRCA which is shown in Table 3.6 where the TMRCA as discussed in Table 3.1 has water absorption of 0.651% and hence all the mixes incorporating RA are adjusted for dry aggregate as well.

Table 3.6: Different Mixes after adjustment for wet and dry aggregates

Mix	**N100R0**	**N75R25**	**N50R50**	**N25R75**	**N0R100**
Cement Content (kg/m^3)	400	400	400	400	400
Water Content (kg/m^3)	118.5	121.851	125.096	129.47	131.602
Fine Aggregate Content (kg/m^3)	681.37	681.37	681.37	681.37	681.37
NA (kg/m^3)	1247.5	935.602	623.735	310.75	0
TMRCA (kg/m^3)	0	308.42	616.85	925.277	1233.702
Chemical Admixture (kg/m^3)	4.00	4.00	4.00	4.00	4.00
Free w/c materials ratio	0.4	0.4	0.4	0.4	0.4

3.6 Test of Fresh properties of concrete

The fresh properties of the concrete were evaluated using three standard tests: the slump test, the compaction factor test, and the Vee-Bee test. The results of these evaluations are detailed in Table 3.7. These assessments were conducted on five different concrete mixtures, all designed to achieve a target compressive strength of 40 MPa.

The reference mix, labelled N100R0, utilized only natural aggregates. In addition to this reference mix, four other mixtures incorporated recycled concrete aggregate (RCA) at varying substitution levels. These mixtures included N75R25, with 25% RCA and 75% natural aggregates; N50R50, with a 50% substitution of RCA; N25R75, containing 75% RCA; and containing N0R100, which used RCA exclusively without any natural aggregates.

Table 3.7: Workability Test of Different Mix

Mix Type	**Slump (mm)**	**Compaction Factor**	**Vee-Bee Time (s)**
N100R0	108	0.92	10
N75R25	105	0.9	11
N50R50	103	0.89	12
N25R75	100	0.87	13
N0R100	98	0.85	16

3.7Test of mechanical properties of RAC in comparison with NCA

3.7.1 Compressive Strength Test

The compressive strength test is essential for evaluating the performance and quality of various concrete mixes, measuring the concrete's ability to withstand axial loads and ensuring it meets structural and durability standards. Standard cubic specimens of size 150 mm x 150

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mm x 150 mm are prepared for each mix, with six cubes for each mix, resulting in a 30 cubes cast.

The mixes include: Mix 1 (N100R0) with 100% NA; Mix 2 (N75R25) with 75% NA and 25% RCA; Mix 3 (N50R50) with equal parts NA and RCA; Mix 4 (N25R75) with 25% NA and 75% RCA; and Mix 5 (N0R100) with 100% RCA. The specimens are cured in water for periods of 7, 14, and 28 days, according to the testing schedule.

3.7.2 Flexural Strength Test

To conduct this test, various concrete mixes with different proportions of natural aggregates (NA) and recycled concrete aggregates (RCA) were prepared. For each concrete mix, standard beam specimens were cast, each measuring 150 mm x 150 mm x 700 mm. Three beams were prepared for each concrete mix to ensure accurate and reliable results. The specimens were then subjected to a curing process in water for durations of 28 days. This curing period allows the concrete to achieve the necessary hydration and strength development before testing.

The flexural strength test involves placing the cured beam specimens on a loading frame and applying a two-point loading method. The loading was conducted at a controlled rate of 400 kg/min. This method ensures uniform distribution of stress along the beam's length, providing an accurate measure of its flexural strength.

4. Results

The TMRCA used in concrete mixes, replacing NA at 25% intervals up to 100%, has demonstrated comparable and, in many cases, superior performance relative to NA. A comparative analysis of the three types of aggregates TMRCA, NA, and MRCA is presented previously in the paper. The study summarizes key mechanical properties, providing a clear and concise comparison. The analysis reveals that combining different treatment methods, specifically thermal and mechanical treatments, enhances the quality of recycled aggregates, making TMRCA closely comparable to NA. This finding supports the potential of TMRCA as a viable alternative to NA, promoting sustainable construction practices by utilizing recycled materials without compromising on quality and performance.

4.1 Compressive strength of different concrete mix

The compressive strength of the concrete mixtures was evaluated in the laboratory following IS 516:2021 [36]. When replaced with TMRCA up to 100% at 25% intervals, the 7-day compressive strength of the mixes (N100R0, N75R25, N50R50, N25R75, N0R100) decreased from 31.45 MPa to 26.40 MPa as shown in Figure 4.1. The reduction in compressive strength when comparing the N100R0 mix to the NOR100 mix was 16.06%. After 28 days of curing, the compressive strength exhibited a decrease from 48.50 MPa to 43.69 MPa, as shown in Figure 4.1.

This reduction in strength with the incorporation of TMRCA can be attributed to some mortar adhering to the TMRCA during mixing. Additionally, TMRCA are more rounded than NA

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due to the mechanical scrubbing action in the ball mill, which results in less crack deflection and toughening. Despite this, the overall observed decrease in strength was 9.92% at 100% TMRCA after 28 days, compared to conventional concrete (N100R0).

However, the achieved strength still met the required target strength specified by IS code provisions. The compressive strength tests for various concrete mixes at 28 days revealed that concrete with TMRCA replacement achieved strengths comparable to the control mix with 100% NA. However, mixes with higher TMRCA content exhibited slight reductions in compressive strength, yet remained within acceptable limits for structural applications.

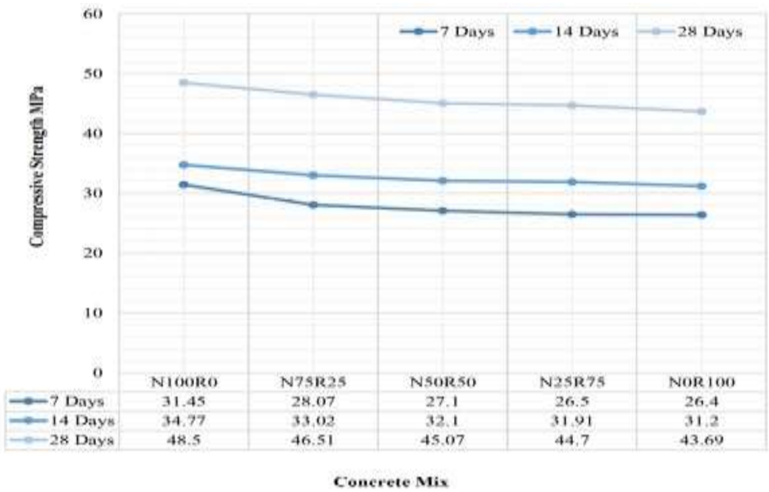

Figure 4.1: Graph of compressive strength test of various concrete mixes in 7, 14 and 28 Days

4.2 Flexural strength of different concrete mix

Similar to the compressive strength results, the graph (Figure 4.2) shows a consistent pattern in concrete's flexural strength relative to the degree of TMRCA replacement. Notably, flexural strength decreases as the amount of TMRCA increases, indicating a negative impact on the concrete's bending resistance. After 28 days, the "N75R25" mix exhibited the highest flexural strength among the mix incorporating TMRCA of 4.56 MPa, while the "N0R100" mix demonstrated the lowest flexural strength of 3.36 MPa.

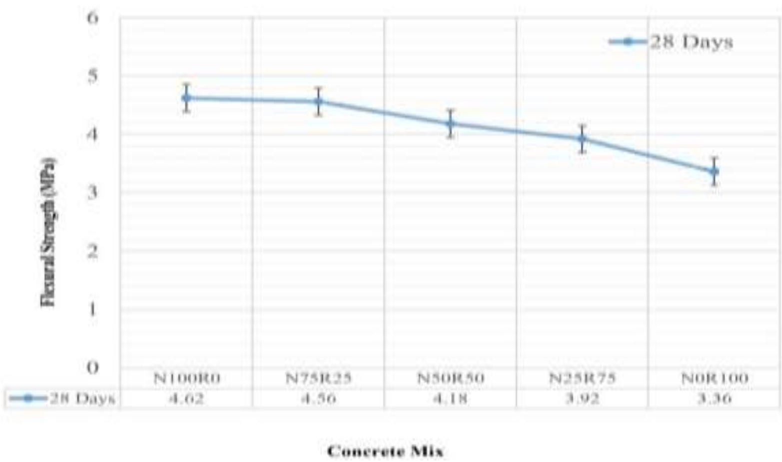

Figure 4.2: Flexural strength test of various concrete mixes at 28 Days

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5. Conclusion

This research reviews current advancements in techniques for improving the quality of RCA, evaluating them based on adopted methodology with its environmental impact and technical criteria [22]. The combination of treatments results in RCA of better quality like TMRCA with a significantly reduced water absorption of 0.651% and enhanced mechanical properties compared to the MRCA or jaw-crushed and industrially-produced RCA, as summarized in Table 3.1. Proper selection and proportioning of RCA are crucial for high-performance RAC. Enhancing RAC involves addressing RCA defects and ITZs. However, TMRCA properties surpassed those of NA with slightly higher impact and crushing value which can be attributed to fewer amounts of flaky particles due to abrasion. The study examines key parameters such as workability, compressive strength and flexural strength. A notable aspect of this research is the replacement of NA with TMRCA in varying proportions: 0%, 25%, 50%, 75%, and 100%. The comprehensive analysis highlights significant improvements in the fresh and hardened properties of concrete such as:

- The TMRCA exhibit ACV and AIV of 19.606% and 14.79% respectively which is better than the NA having ACV and AIV of 26.494% and 16.875% respectively. This increase in strength in crushing and impact of TMRCA is due to a lower Fl and El compared to the NA.
- The Concrete made with 100% TMRCA (NOR100) displays 9.25% lower slump compared to that of conventional concrete (N100R0) using the same additives and NA which is due to the slight presence of AM in TMRCA.
- The compressive and flexural strength results show an optimal mixture at 25% RCA replacement (N75R25), notably comparable with controlled mix (N100R0) where the grade of concrete (M40) is higher than the recommended limit (M25) provided in IS 383:2016 which demonstrates higher grade must also be explored.
- The compressive and flexural strength of mixes incorporating TMRCA shows a slight decrease in graph with increase in amount of TMRCA which can be attributed to circularity of aggregates due to undergoing abrasion which also aligns with. However, the compressive strength curve is moreover flatter showing almost similar strength. Hence, higher replacement for higher grades can also be recommended.
- Incorporating RA greatly reduces environmental impact by lowering the demand for natural resources, conserving existing materials, and promoting circular economy. Using RA in construction supports sustainable practices, reduces landfill waste, and encourages the reuse of resources.

These findings underscore the efficacy of TMRCA with SEMA for making concrete incorporating TMRCA positioning it as a viable sustainable alternative in construction applications. However, knowledge gaps remain especially regarding the implementation of different treatment methods in industries. Future studies should provide solid statement for actual implementation of such treatment methods in C&D plants in developing countries like India for maximum utilization of RCA in construction industry.

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