# The continuous and rapid rise in global population has significantly intensified

*by* Lakshay Raj Badgujjar

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# CHAPTER 1
# INTRODUCTION

## 1.1 General

The increasing accumulation of debris from construction and demolition activities, along with the dwindling availability of natural resources, has emerged as a critical concern worldwide. Concrete, widely regarded as the most versatile construction material, plays a crucial role in the growth of infrastructure and industry. However, its heavy consumption of resources and long-term environmental impact have raised concerns regarding its sustainability. Despite these drawbacks, concrete remains the most extensively used material in the global construction industry[1].

The continuous and rapid rise in global population has significantly intensified the demand for infrastructure development. To meet these growing requirements, the construction industry is expected to expand swiftly and efficiently. Among the various construction materials, concrete remains the most widely used due to its adaptability and ease of moulding into desired shapes. Projections suggest that the global consumption of concrete may double by the year 2050. In addition to concrete, mortar is also extensively required for masonry works, especially for binding and plastering applications[2].

Traditionally, the production of concrete and mortar relies heavily on non-renewable natural resources such as river sand (for fine aggregates), gravels and crushed stones (for coarse aggregates), and limestone (for cement clinker). This excessive dependence on natural resources raises significant environmental concerns, including ecosystem disturbance, depletion of resources, and increased carbon emissions[2].

In this context, Construction and Demolition (C&D) waste has emerged as a promising and sustainable alternative. If processed properly, C&D waste can serve as a substitute for both fine and coarse aggregates, thereby reducing the pressure on natural resources and contributing to circular construction practices[3]. This study aims to investigate the feasibility of using recycled aggregates sourced from C&D

waste as a complete replacement (up to 100%) for conventional aggregates in concrete production.

This chapter outlines the background and motivation for adopting alternative materials in concrete, highlights the challenges associated with C&D waste management, defines the core problem addressed in this research, states the objectives of the study, and provides an overview of the dissertation structure.

## 1.2 Significance of Construction and Demolition Waste in Sustainable Infrastructure

Construction and demolition (C&D) activities are integral to the growth and modernization of urban infrastructure. However, these activities generate a considerable volume of waste, commonly referred to as C&D waste. This category of waste includes a wide variety of materials such as concrete, wood, metals, bricks, plastics, and other by-products produced during construction, renovation, or demolition operations. The improper handling of this waste can lead to severe environmental consequences such as soil and water pollution, ecosystem disruption, and increased greenhouse gas emissions. These challenges emphasize the urgent need for sustainable waste management strategies[4].

Economically, mismanagement of C&D waste contributes to elevated costs due to transportation, disposal, and the underutilization of potentially reusable materials. From a social perspective, unmanaged waste negatively affects public health and urban aesthetics. On the contrary, effective recycling and reuse of C&D waste can generate employment, support circular economy models, and enhance local economic development. This highlights the growing relevance of research and innovation in optimizing the reuse of C&D materials for construction[5].

In the Indian context, the rapid pace of infrastructure development has led to an exponential increase in waste generation. With the construction sector playing a vital role in the national GDP, this also results in extensive use of raw materials and subsequent waste. According to the Central Pollution Control Board (CPCB), an estimated 500 kg of C&D waste is generated per capita annually, amounting to around 23.75 million tons nationwide of which only 5% is currently being processed.

This underlines the immense potential for improving resource recovery and reducing dependence on natural aggregates[6].

The situation has been further exacerbated by the 2012 ban on river sand mining, which has driven up the cost of construction materials and highlighted the need for sustainable alternatives such as recycled aggregates. Adopting C&D waste recycling can address multiple issues: reduce landfill pressure, conserve non-renewable resources, lower construction costs, and promote greener construction practices[6].

The present study focuses on utilizing C&D waste more effectively by analysing its composition, environmental and economic impacts, social relevance, and associated policy frameworks. By evaluating these dimensions, the study aims to contribute toward the development of environmentally responsible and economically viable construction practices[7].

### 1.3 Significance of Sustainable Management of Construction and Demolition Waste

The sustainable management of construction and demolition (C&D) waste is increasingly vital due to its significant environmental, economic, and societal implications. Generated from activities such as building construction, renovation, and demolition, this waste typically comprises materials like concrete, wood, metals, bricks, and asphalt. Proper handling and reuse of these materials help in conserving natural resources, reduce the environmental burden of mining and manufacturing, and minimize landfill usage[8]. Recycling C&D waste also significantly cuts energy consumption compared to producing new construction materials from raw sources, thereby reducing carbon emissions. Economically, it lowers material procurement and disposal costs and stimulates employment through the recycling industry, contributing to overall project feasibility. Environmentally responsible waste practices also mitigate hazards such as dust, noise, and water pollution, thereby protecting air and water quality and reducing health risks for both workers and surrounding communities. Moreover, effective C&D waste management aligns with sustainable construction initiatives and certification systems like Leadership in Energy and Environmental Design (LEED), promoting responsible material use and eco-conscious building methods. Legal compliance is another critical benefit,

ensuring adherence to environmental regulations and minimizing the risk of penalties. These practices not only enhance workplace safety, but also bolster the public image of construction companies through community engagement and transparent operations. Additionally, growing sustainability demands have led to innovation in material recovery, modular construction, and waste reduction technologies. In essence, the efficient management of C&D waste supports environmental protection, economic growth, and social responsibility, forming a cornerstone of sustainable urban development[9].

### 1.4 Research Gap

While extensive research has been conducted on the incorporation of recycled aggregates (RA) in concrete, several gaps continue to hinder their widespread acceptance—especially the impact of residual cement mortar adhered to RA surfaces. This adhered mortar alters essential characteristics of RA such as increased water absorption, decreased density, and compromised mechanical strength. Despite these known drawbacks, limited research has focused on quantitatively evaluating the influence of adhered mortar on the interfacial transition zone (ITZ), microstructure, and long-term performance parameters of recycled aggregate concrete (RAC). Additionally, the variation in mortar content across different RA sources derived from diverse concrete grades has not been thoroughly explored[10].

The effectiveness of surface treatment techniques for improving RA quality is another area with insufficient empirical data. Although several approaches like chemical treatments, cement coatings, carbonation, and mechanical abrasion have been proposed, comparative studies analyzing their performance under long-term durability exposure have also been done. Furthermore, the combined or sequential application of such techniques and their influence on ITZ enhancement and bond strength development remains under-researched. There is also a critical need for modern characterization techniques to study at micro-level interactions between treated RA and the surrounding cement matrix[10].

Durability issues remain a concern in RAC, with specific problems such as high drying shrinkage, reduced corrosion resistance in aggressive environments (like

chloride- and sulphate-rich media), and inconsistencies in carbonation resistance. The absence of standardized durability assessment protocols leads to conflicting results, which further complicates reliable performance prediction of RAC structures[11].

**The Interfacial Transition Zone (ITZ)** is the thin region between aggregate particles and the surrounding cement paste in concrete. It is typically more porous and weaker than the bulk matrix. A **denser and stronger ITZ** is desirable because a weak or porous ITZ can act as a path for cracks and reduce the overall mechanical strength and durability of the concrete. Therefore, minimizing the porosity and improving the quality of the ITZ is crucial for high-performance concrete.[12]

### 1.5 Objective of the Study

This research investigates the enhancement of recycled aggregate concrete (RAC) by addressing the adverse effects of adhered mortar on recycled aggregates (RA), which typically leads to inferior performance compared to natural aggregates. The study purpose a practical surface treatment techniques to improve RA quality and assesses its performance in structural concrete. The objectives are as follows:

- **To reduce the presence of adhered mortar on recycled aggregates** using thermal treatment (heating at 100°C and 200°C for 24 Hrs. and 48 Hrs. at 500 revolution and 1000 revolution) followed by mechanical abrasion through the Los Angeles machine, thereby improving the quality of RA.
- **To evaluate the feasibility of using treated recycled aggregates in concrete** by replacing natural aggregates at 50% and 100% levels, reflecting partial and full substitution scenarios.
- **To assess the impact of treated RA on the physical and mechanical properties of RAC**, with specific focus on compressive strength and drying shrinkage, in accordance with IS:516 (Part 1/Sec 1)-2021 and IS:516 (Part 6)-2020 standards.

### 1.6 Scope of the Study

This study focuses on the effective utilization of recycled aggregates obtained from

construction and demolition (C&D) waste by improving their properties through practical surface treatment methods. The scope is defined by experimental investigation, sustainability assessment, and practical applicability in structural concrete. Key elements include:

- **Material Treatment:** Recycled aggregates were subjected to thermal treatment at 100°C and 200°C for 24 Hrs. and 48 Hrs. to weaken adhered old mortar, followed by 500 revolution and 1000 revolution in abrasion using the Los Angeles abrasion machine to enhance aggregate quality.
- **Replacement Levels:** Concrete was prepared by replacing natural coarse aggregates with treated recycled aggregates at 50% and 100% replacement levels, allowing for a comparative study of partial and complete substitution.
- **Concrete Performance Evaluation:** The research evaluates compressive strength [as per IS:516 (Part 1/Sec1)-2021] and drying shrinkage [as per IS:516(Part 6)-2020], which are critical parameters for assessing structural and long-term performance.
- **Environmental Impact:** In view of the reuse of C&D waste, the study contributes to reduction in landfill burden, conservation of natural resources, and reduction in greenhouse gas emissions associated with extraction and transportation of virgin materials[4].
- **Economic and Sustainable Viability:** The project highlights the cost-effectiveness of using recycled aggregates and explores their role in promoting circular economy principles in the construction sector[4].
- **Policy and Practical Relevance:** The outcomes may support the broader objective of integrating recycled materials into mainstream construction, aligning with national and international sustainability goals[13].

### 1.7 Significance of the Study

This study holds significant importance in the context of sustainable construction and responsible resource management. By incorporating recycled aggregates (RAs) sourced from construction and demolition (C&D) waste into concrete production, it directly addresses the urgent need for eco-friendly alternatives to natural aggregates, thereby contributing to environmental conservation and

sustainable development[14].

The core significance of this research lies in:

- Reducing the environmental footprint of the construction industry by minimizing the use of virgin aggregates and promoting the reuse of C&D waste[15].
- Developing and applying practical surface treatment techniques i.e. heating at 100°C and 200°C for 24 Hrs. and 48 Hrs. followed by mechanical abrasion at 500 revolution and 1000 revolution to improve the quality of recycled aggregates by removing adhered old mortar.
- Experimentally validating the performance of recycled aggregate concrete (RAC) at 50% and 100% replacement levels through tests such as compressive strength and drying shrinkage, which ensures practical applicability in real-world conditions.
- Addressing long-term durability concerns, especially shrinkage behavior, which is critical for the structural performance and service life of RAC[16].
- Supporting economic sustainability by demonstrating potential cost savings from reduced virgin material and disposal costs of C & D waste, alongside promoting local recycling industries and job creation[16].
- Promoting energy savings by avoiding energy-intensive extraction and processing of virgin materials, thus contributing to lower greenhouse gas emissions and climate change mitigation efforts[16].
- Advancing construction industry practices through the promotion of circular economy principles, resource efficiency, and environmentally responsible engineering solutions[17].
- Encouraging innovation and laying the foundation for future research in improving the quality and performance of recycled aggregates in structural applications[18].
- Enhancing public perception and community trust, as the adoption of sustainable practices strengthens the social image of construction projects and organizations[18].

This study is not just a technical investigation but a step forward in aligning construction practices with global sustainability goals, offering a pathway to reduce environmental degradation while maintaining structural performance and economic feasibility.

### 1.8 Thesis Layout

This thesis is structured into the following comprehensive chapters to systematically present the study:

- **Chapter 1 :– Introduction**

  This chapter introduces the critical need for sustainable construction solutions in light of growing urbanization and resource scarcity. The chapter outlines the background, research motivation, key objectives, scope, significance, and overall organization of the thesis.

- **Chapter 2 :– Literature Review**

  This chapter reviews national and international research worked carried out on the use of recycled aggregates (RA) in concrete, covering both untreated and surface-treated aggregates. It discusses the challenges related to adhered mortar, interfacial transition zones (ITZ), durability, and mechanical properties, while identifying research gaps. The review sets a foundation for this study, particularly in the areas of aggregate treatment, performance analysis, and sustainability outcomes.

- **Chapter 3 :– Experimental Programme**

  This chapter details the materials used, including natural aggregates and recycled aggregates obtained from a recycling plant. It describes the treatment methods applied i.e. heating at 100°C and 200°C for 24 Hrs. and 48 Hrs. followed by abrasion using the Los Angeles abrasion machine at 500 revolution and 1000 revolution. The chapter outlines the mix design and use of two replacement levels (50% and 100%), the casting of concrete specimens.

- **Chapter 4 :– Test Results and Discussion**

  This chapter presents and interprets the experimental test results obtained from the concrete samples. It compares the performance of control mixes and RAC with treated RAs. Key parameters discussed include compressive strength and drying shrinkage.

- **Chapter 5 :– Conclusions and Future Scope**

  This chapter summarizes the key findings of the study, confirming that surface-treated recycled aggregates can significantly improve concrete performance at 50% and 100% replacement levels. It also identifies practical benefits and limitations, and outlines potential future research directions, including microstructural analysis, durability under aggressive environments, and long-term performance studies.

- **References**

  This section includes all academic and technical references cited throughout the thesis, following a standardized citation format.

# CHAPTER 2
# LITERATURE REVIEW

## 2.1 General

The increasing emphasis on sustainable construction practices has led to growing interest in utilizing construction and demolition (C&D) waste as a substitute for natural aggregates in concrete. This literature review aims to present a comprehensive evaluation of previous studies conducted on recycled aggregate concrete (RAC), with a particular focus on the mechanical and durability characteristics of concrete incorporating treated and untreated recycled aggregates[19].

Multiple studies have confirmed that the presence of adhered mortar on recycled coarse aggregates (RCA) negatively affects concrete performance, primarily due to increased porosity, reduced density, and weak interfacial bonding. These deficiencies result in a drop in compressive strength, durability, and workability of concrete. To overcome these limitations, researchers have proposed various surface treatment methods such as acid or chemical treatments, cement slurry coating, and mechanical abrasion[19].

Some studies have focused on heat treatment to reduce the presence of old mortar, aiming to alter the microstructure and remove loosely bonded fines. Others have emphasized abrasion methods (e.g., Los Angeles machine) to physically detach old mortar from RCA. Combined treatments have also shown promising results in improving aggregate properties[20].

However, the effectiveness of such treatments varies widely depending on the source of RCA, treatment parameters, and the extent of replacement. Literature also highlights that complete replacement (100%) often leads to significant performance reductions, while partial replacement (up to 50%) can sometimes match or closely approach the performance of conventional concrete, especially when effective pre-treatment is used.

Studies also suggest that drying shrinkage in RAC is generally higher compared to conventional concrete due to the porous nature of adhered mortar. Nonetheless, effective treatment of RCA has been shown to reduce shrinkage and improve dimensional stability.

Although a wide range of surface treatments and replacement ratios have been studied, limited literature exists on the combined effect of heating and mechanical abrasion, particularly at higher replacement levels (50% and 100%). Furthermore, while compressive strength and workability are commonly tested, fewer studies have addressed long-term deformation characteristics like drying shrinkage in treated recycled aggregate concrete.

This gap underscores the significance of the present study, which focuses on:

- Evaluating the effectiveness of heat and abrasion treatment on recycled aggregates.
- Analysing the compressive strength and drying shrinkage at 50% and 100% replacement levels.
- Assessing the practicality of using such treated aggregates in structural concrete applications.

## 2.2 Utilization of Construction and Demolition Waste in Concrete

The construction industry grapples with a critical environmental challenge, namely the management of construction and demolition (C&D) waste, which encompasses materials such as concrete, wood, metal, glass, and plastics. Emerging from construction, renovation, and demolition activities, ineffective waste management leads to severe environmental consequences. The rapid depletion of essential resources like sand, gravel, and wood results in habitat loss, soil erosion, and the exhaustion of non-renewable resources. Additionally, the energy-intensive production of materials like concrete and steel significantly contributes to greenhouse gas emissions and climate change. Disposal methods such as land filling and incineration pose risks, causing soil and groundwater contamination and emitting hazardous chemicals. The transportation of C&D debris to disposal sites further amplifies the industry's carbon footprint. Hence, sustainable practices, waste reduction, recycling, and innovative solutions are imperative to foster a resilient and eco-friendly construction industry, addressing environmental concerns and promoting sustainable development.

**Sonawane and Pimplikar (2020)** confirmed that up to 30% RCA replacement (fine and coarse) does not significantly affect functionality in M30 and M40 mixes,

although higher grades showed more noticeable strength reduction[21].

**Dhapekar and Mishra (2018)** replaced up to 90% of natural coarse aggregates with RCA in M20 mixes and found that these mixes still achieved desirable strength, suggesting potential for large-scale application[22].

**Kalpavalli and Naik (2015)** found that replacing natural coarse aggregates with demolition waste aggregates at 30% improved compressive strength in high-strength concrete mixes, validating the performance potential of such waste materials[23].

**Hussain and Assas (2013)** evaluated various RCA replacement percentages (0% to 100%) and noted a 40% increase in compressive strength at 75% RCA replacement, though accompanied by reduced slump, highlighting the importance of balancing mechanical performance and workability[24].

**Ahmed (2013)** investigated the influence of replacing natural coarse aggregates with RCA at varying proportions (ie.25%, 50%, 75%, and 100%.) He reported that 25% replacement yielded optimal mechanical performance (compressive, tensile, and flexural strengths) and reduced water absorption, supporting the feasibility of sustainable concrete with lower environmental impact[25].

**Reddy, Bhavani and Ajitha (2012)** evaluated concrete made entirely with 100% recycled concrete aggregates (RCA) conditioned to a saturated surface-dry (SSD) state. They reported that after 28 days, the compressive strength of the RCA concrete reached approximately 87% of that of conventional natural aggregate concrete (NAC) under the same mix design (M20, w/c 0.5), confirming the feasibility of using demolition waste as a sustainable alternative without major strength reduction [26].

**Mohd. Monish (2013)** demonstrated that replacing up to 30% of natural coarse aggregates with demolished waste retained strength in the range of 86.84% to 94.74% compared to control concrete, showcasing its potential as a sustainable substitute[5].

**Vyas and Bhatt (2013)** studied RCA at multiple replacement levels and determined that 40% RCA offered the best balance of workability and strength, supporting its suitability for practical applications in sustainable construction[27].

**Patel and Patel (2016)** revealed that 50% RCA replacement in M20 concrete delivered the highest compressive strength, encouraging its use in mid-grade structural applications[28].

**Zhang et al. (2018)** assessed RCA replacement from 0% to 100% and found 25% to be the most efficient level for improving compressive strength while reducing environmental impact[29].

**Koondhar et al. (2020)** observed that 20% replacement of natural fine aggregates with RCA gave the most favorable compressive strength, showing that fine recycled materials also hold significant promise[30].

**Raihen et al. (2017)** demonstrated increased strength by partially replacing cement with demolished waste cement powder (DWCP), particularly at 20% replacement, reinforcing the utility of cementitious C&D waste[31].

## 2.3 Long-term Performance of Concrete with Recycled Aggregate.

### 2.3.1 Drying Shrinkage of Concrete

Drying shrinkage is one of the most critical factors affecting the long-term dimensional stability of concrete, especially in structural elements exposed to atmospheric conditions. It primarily results from the gradual evaporation of free water through the capillary pores and interconnected microchannels within the concrete matrix. This loss of moisture leads to volume reduction, which may cause surface cracking and eventually compromise the durability and serviceability of the concrete structure.

Early foundational work by **Tremper and Spellman in 1962** highlighted the importance of laboratory-based shrinkage tests to replicate and understand field conditions effectively. Their findings established the groundwork for future studies focused on controlling shrinkage in concrete design[32].

Subsequent research over the decades has emphasized the influence of various factors such as aggregate type, gradation, cementitious materials, and admixtures on drying shrinkage behaviour. Several researchers have shown that **recycled aggregate concrete (RAC)** often exhibits greater shrinkage than conventional mixes due to the porous nature and adhered mortar of recycled aggregates.

Recent studies continue to explore the effect of material combinations and aggregate modifications on shrinkage. For instance, **Sosa and Zega in 2023** highlighted that the mineral composition of fine recycled aggregates significantly affects shrinkage behaviour and that pre-saturated aggregates may not negatively impact performance[33]. Similarly, **Hameed in 2024** demonstrated that using a hybrid mix of recycled coarse and brick aggregates, along with 20% fly ash, can provide both strength and dimensional stability in concrete suitable for paver block applications[34].

These studies collectively highlight that drying shrinkage in recycled aggregate concrete is highly dependent on material selection, mix design, and curing. Innovative approaches such as internal curing, optimized aggregate gradation, and admixture use are key to minimizing shrinkage and enhancing long-term performance.

### 2.4 Research Gap from the Literature Review

The increasing emphasis on sustainable concrete solutions has led to extensive research on the incorporation of recycled aggregates (RCA) in concrete. However, certain critical issues remain inadequately addressed, especially in the context of **high-level RCA replacement (50% and 100%)** and **combined surface treatment methods**, which are central to the present study.

**a) Lack of Focused Studies on Combined Thermal and Abrasion Treatment**

Although individual surface treatment methods like chemical soaking, abrasion, or carbonation have been widely studied, limited research exists on the combined effect of thermal and mechanical (abrasion) treatment on RCA properties. The influence of heating RCA to 100°C or 200°C followed by mechanical abrasion as conducted in the present study has not been extensively evaluated in available literature. There is a clear need to understand how such combined treatments affect adhered mortar removal, water absorption, and microstructural integrity.

**b) Performance at Higher Replacement Levels (50% & 100%) Remains Underexplored**

Most prior studies recommend RCA replacement levels up to 25–30% to maintain

acceptable concrete performance. However, systematic studies evaluating the mechanical and shrinkage behaviour of RAC at 50% and 100% RCA replacement using treated aggregates are scarce. There is insufficient data on how such high replacement levels perform in terms of compressive strength and dimensional stability when pre-treatment is applied..

**C) Insufficient Data on Drying Shrinkage in Treated RAC**

Drying shrinkage is a critical concern in RAC due to the porous nature of adhered mortar. While this has been acknowledged in literature, limited experimental data is available on the drying shrinkage behaviour of thermally and mechanically treated RCA. The combined influence of **heat treatment and brasion** on **shrinkage strain, cracking tendency, and long-term dimensional stability** needs focused exploration.

**d) Limited Use of Microstructural Techniques to Validate ITZ and Treatment Efficiency**

Few studies have used advanced characterization techniques like **SEM and EDAX** to analyze the interfacial transition zone (ITZ) and material densification after treatment. There is a gap in the **microstructural validation of treated RCA concrete**, especially when using combined treatment methods, which this study aims to bridge.

**Need for the Present Study**

The current research is designed to address these gaps by:

- To assure effectiveness of **heat and abrasion based surface treatments** on RCA
- Evaluating **compressive strength and drying shrinkage at 50% and 100% RCA replacement**
- Demonstrating the **practical feasibility** of using treated RCA in structural concrete

This study is expected to provide valuable insights into improving the performance of high-replacement RAC using affordable and scalable treatment techniques.

# CHAPTER 3
# EXPERIMENTAL PROGRAMME

## 3.1 General

This experimental program was developed to evaluate the feasibility of using Construction and Demolition (C&D) waste as recycled coarse aggregates (RCA) in concrete. The study investigates the effect of heat and abrasion treatment on RCA at 50% and 100% replacement levels. This chapter outlines the materials used, surface treatment methods, mix design, and testing procedures adopted to assess the mechanical strength, drying shrinkage, and microstructural properties of treated RAC.

## 3.2 Material

The materials used in this study, include Ordinary Portland Cement (OPC), natural fine aggregates, natural coarse aggregates, and recycled coarse aggregates (RCA). Surface-treated RCA was prepared using heat and abrasion techniques. Potable water and superplasticizer were also used to maintain desired workability. Each material was tested for its physical properties as per relevant IS codes to ensure accuracy in mix design and performance evaluation.

### 3.2.1 Cement

Ordinary Portland Cement (OPC) of 43 grade was used as the primary binding material in this study, complying with IS: 269–2015[35]. The cement was tested for its physical properties to ensure suitability for concrete production. The results are summarized in Table 3.1.

**Table 3.1 Physical properties of cement**

| Property | Value Measured | Requirements of IS 269: 2015 |
|---|---|---|
| Consistency | 29% | - |
| Initial Setting Time | 52 min | > 30 min |
| Final Setting Time | 410 min | < 10 Hrs. |
| Specific Gravity | 3.10 | 3.0-3.15 |

### 3.2.2 Natural Fine Aggregates (NFA)

Crushed stone aggregates ranging from 4.75 mm to 20 mm were used as natural fine aggregates (NCA) in accordance with IS:383–2016[36]. These aggregates were tested for particle size distribution and physical properties to ensure suitability for structural concrete. The grading details are shown in Table 3.2.

**Table 3.2 Particle size distribution of natural fine aggregates**

| IS Sieve | Weight Retained (gm) | Weight Retained (%) | Cumulative Weight Retained (%) | Cumulative Weight Passing (%) | Values as per IS: 383-2016 |
|---|---|---|---|---|---|
| 10 mm | 0 | 0 | 0 | 100 | 100 |
| 4.75 mm | 36 | 3.6 | 3.6 | 96.4 | 90-100 |
| 2.36 mm | 118 | 11.8 | 15.4 | 84.6 | 75-100 |
| 1.18 mm | 161 | 16.1 | 31.5 | 68.5 | 55-90 |
| 600 µ | 230 | 23.0 | 54.5 | 45.5 | 35-59 |
| 300 µ | 190 | 19.0 | 73.5 | 26.5 | 8-30 |
| 150 µ | 103 | 10.3 | 83.8 | 16.2 | 0-20 |

**Table 3.3 Properties of fine aggregates**

| Properties | NFA | Standard Limits |
|---|---|---|
| Specific Gravity | 2.56 | 2.30-2.90 IS: 2386 (Part 3) |
| Water Absorption (%) | 0.93 | ≤ 2.0 IS: 2386 (Part 3) [137] |

### 3.2.3 Natural Coarse Aggregates (NCA)

The crushed stone aggregates employed in this research exhibit a size range from 4.75mm to 20mm, adhering to the specifications as outlined in IS: 383-2016[36], serving as natural coarse aggregates (NCA). The particle size distribution of these natural coarse aggregates is visually depicted in Table 3.4 and Table 3.5 provides a comprehensive overview of their properties.

**Table 3.4 Particle size distribution of natural coarse aggregates**

| IS Sieve | Weight Retained (gm) | Weight Retained (%) | Cumulative Weight Retained (%) | Cumulative Weight Passing (%) | Values as per IS: 383-2016 |
|---|---|---|---|---|---|
| 40 mm | 0 | 0 | 0 | 100 | 100 |
| 20 mm | 655 | 13.1 | 13.1 | 86.9 | 85-100 |
| 10 mm | 4218 | 84.36 | 97.46 | 2.54 | 0-20 |
| 4.75 mm | 95.5 | 1.91 | 99.37 | 0.63 | 0-5 |
| Pan | 31.5 | 0.63 | 100 | 0.00 | - |

**Table 3.5 Properties of coarse aggregates**

| Properties | NCA | Standard Limits |
|---|---|---|
| Specific Gravity | 2.71 | 2.30-2.90 IS: 2386 (Part 3) |
| Water Absorption (%) | 0.46 | ≤ 2.0 IS: 2386 (Part 3) |
| Crushing Value (%) | 20.23 | < 30 IS: 2386 (Part 4) |
| Impact Value (%) | 18.20 | < 30 IS: 2386 (Part 4) |
| | | |

### 3.2.4 Recycled Coarse Aggregates (RCA)

The recycled coarse aggregates (RCA) used in this study were sourced from crushed concrete debris processed at the IL&FS C&D Waste Recycling Plant, Delhi. These aggregates conform to IS: 383–2016[36] and range in size from 4.75 mm to 20 mm. The physical properties of RCA are listed in Table 3.7, while the particle size distribution is shown in Table 3.6.

**Table 3.6 Particle size distribution of Recycled coarse aggregates**

| IS Sieve | Weight Retained (gm) | Weight Retained (%) | Cumulative Weight Retained (%) | Cumulative Weight Passing (%) | Values as per IS: 383-2016 |
|---|---|---|---|---|---|
| 40 mm | 0 | 0 | 0 | 100 | 100 |
| 20 mm | 480 | 9.6 | 9.6 | 90.4 | 85-100 |
| 10 mm | 4415 | 88.3 | 97.9 | 2.1 | 0-20 |
| 4.75 mm | 95 | 1.9 | 99.8 | 0.2 | 0-5 |
| Pan | 10 | 0.20 | 100 | 0.0 | - |

**Table 3.7 Properties of recycled coarse aggregates**

| Properties | RCA | Standard Limits |
|---|---|---|
| Specific Gravity | 2.29 | 2.30-2.90 IS: 2386 (Part 3) |
| Water Absorption (%) | 6.15** | ≤ 2.0 IS: 2386 (Part 3) |
| Crushing Value (%) | 20.23 | < 30 IS: 2386 (Part 4) |
| Impact Value (%) | 18.20 | < 30 IS: 2386 (Part 4) |

### 3.2.5 Chemical Admixture

A high-range water-reducing admixture (superplasticizer –SUNANDA) was used in all concrete mixes at a dosage of 1% by weight of cement to enhance workability. The admixture complied with the specifications laid out in IS: 9103–1999[37], ensuring improved flowability without affecting the strength characteristics of the concrete.

### 3.2.6 Water

Water is essential in the concrete mix as it initiates the hydration process, which is critical for strength development. In this study, ordinary potable tap water available in the laboratory was used for both mixing and curing, in accordance with standard practice.

### 3.3 Surface Modification of Recycled Coarse Aggregate

In this research, a two-stage surface treatment approach was adopted to improve the quality of Recycled Coarse Aggregates (RCA). The flowchart in Figure 3.1 shown the process of Treatment, the process was finalized after performing and comparing two sequential treatment schemes:




**Figure 3.1 Flowchart of the Process**

#### 3.3.1 Initial Attempt:

- RCA samples were heated at 100°C and 200°C separately for 24 hours in a hot air oven.
- The purpose of heating was to weaken the bond between the adhered old mortar and the parent aggregate.
- After heating, the aggregates were subjected to abrasion in the Los Angeles abrasion machine at 500 revolution.
- However, concrete prepared with these treated aggregates showed limited improvement in strength and durability properties.

#### 3.3.2 Final Optimized Treatment:

- Based on the limited improvement in initial trials, the surface treatment process was modified.
- The heating duration was extended to **48 hours** for the same temperatures (i.e.100°C and 200°C).
- Abrasion speed in the Los Angeles machine was increased to 1000 revolution to ensure better removal of new loose adhered mortar.

- This optimized process yielded noticeably improved surface texture, reduced porosity, and better bonding potential with fresh cement paste.

The final treated aggregates were then used in concrete mixes at 50% and 100% replacement levels, and their performance was evaluated through strength, shrinkage, and durability tests. Figure 3.2 shown the process of Abrasion.

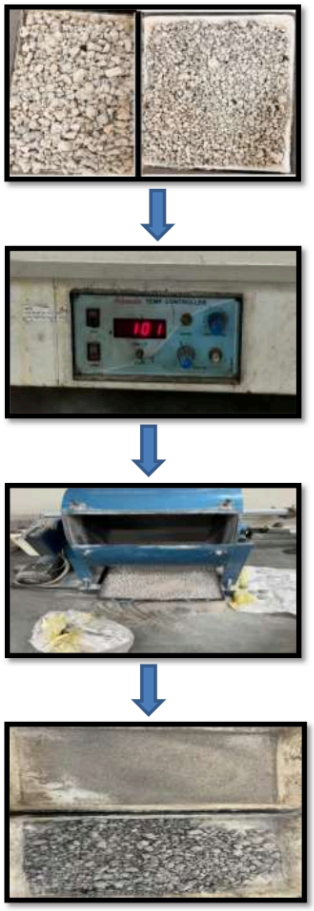

**Figure 3.2 Abrasion process**

### 3.4 Testing Methodology

To evaluate the effectiveness of treated recycled coarse aggregates (RCA) on the performance of concrete, a systematic testing programme was carried out. Both **mechanical** and **durability-related** properties were assessed for mixes incorporating **50% and 100% replacement levels** using **heat and abrasion-treated RCA**.

Initially, the **workability** of fresh concrete was tested using the slump cone method to ensure ease of placement and compaction. For mechanical evaluation, **compressive strength**, were determined at standard curing ages.

To assess long-term performance, **drying shrinkage** tests were conducted as per Indian standards, considering the higher shrinkage risk in recycled aggregate concrete.

For a deeper understanding of the internal structure and the effect of surface treatment on aggregate–paste bonding, advanced microstructural tests such as **Scanning Electron Microscopy (SEM)**, and **Energy Dispersive X-ray Spectroscopy (EDAX)** were conducted.

This combined approach provided a holistic view of how surface-modified RCA influences the **strength, dimensional stability, and durability** of concrete, helping to establish its **suitability for structural grade applications**.

#### 3.4.1 Materials Characterization

Before incorporating the constituent materials into concrete, microstructural analysis was conducted to evaluate their internal structure and chemical composition. Techniques such **Scanning Electron Microscopy (SEM)** provided high-resolution images to observe surface texture, porosity, and bonding characteristics, especially for natural and recycled aggregates. Additionally, **Energy-Dispersive X-ray Spectroscopy (EDAX)** was employed for **elemental analysis**, enabling a detailed understanding of the chemical constituents of the materials.

This combination of techniques ensured a comprehensive evaluation of the materials prior to mix design, which helped in interpreting the effect of recycled aggregate treatments on the final concrete performance.

### 3.4.1.1 Scanning Electron Microscopy (SEM) analysis of different constituent materials

**Scanning Electron Microscopy (SEM)** is a high-resolution imaging technique used to study the **surface morphology** and **microstructural features** of materials. It works on the principle of the interaction between a **focused electron beam** and the sample surface. When the high-energy electron beam strikes the specimen, it generates various signals including **secondary electrons (SE)** and **backscattered electrons (BSE)**, which are used to form detailed images of the surface.

In this study, SEM analysis was carried out using a **Sigma 300 SEM system** at the Indian Institute of Technology, Roorkee and figure-3.3 shown the SEM instrument picture used in the test. The samples were prepared by oven-drying and gold-coating (if applicable) to ensure conductivity.

**SEM was performed on the following samples:**

- Natural aggregate
- Untreated Recycled Coarse Aggregates (RCA)
- Heat-treated RCA (heat at 100°C / 200°C and abrasion at 500 revolution)
- Final treated RCA (heat at 100°C / 200°C and abrasion at 1000 revolution)

The SEM images of untreated RCA revealed a rough, porous surface with large quantities of adhered mortar and visible microcracks. In contrast, the treated RCA exhibited a cleaner and more compact surface texture, with significantly reduced porosity and improved particle definition. The removal of loose mortar through heat and abrasion led to a denser and more stable interface, indicating enhanced bonding potential with the cement matrix. These microstructural

differences are clearly illustrated in **Figures 3.4 to 3.11**, which compare the untreated and treated RCA surfaces. These observations confirm the effectiveness of the adopted treatment technique in improving the microstructural quality of RCA, thereby making it more suitable for structural concrete applications.

To ensure high-quality imaging, all samples were placed inside a vacuum chamber to eliminate air molecules that could interfere with electron movement. A finely focused electron beam was scanned over the sample surface, and the resulting signals were captured to produce high-magnification SEM images.

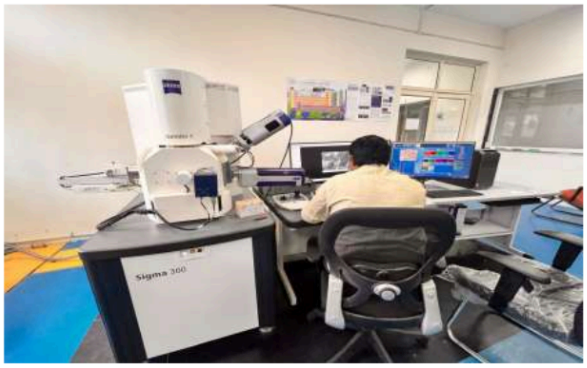


**Figure 3.3 High resolution sigma 300 scanning electron microscope**

Microstructural features were observed at various magnifications to examine **surface texture, particle size, porosity**, and **adhered mortar removal**.

These improvements reflect better **interfacial transition zone (ITZ)** potential and stronger bonding capability when incorporated into concrete. The SEM findings played a key role in validating the effectiveness of the adopted surface treatment technique for enhancing RCA performance in structural concrete.

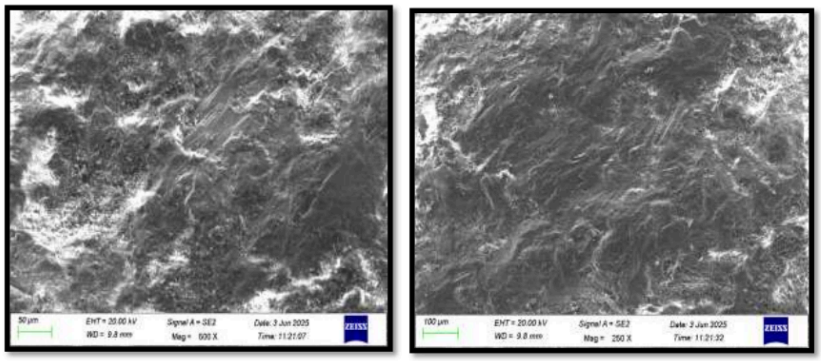

**Figure 3.4 SEM for Natural Aggregate**

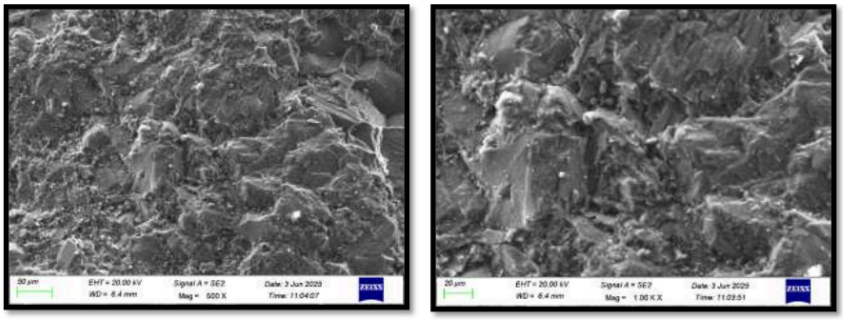

**Figure 3.5 SEM for Untreated RCA**

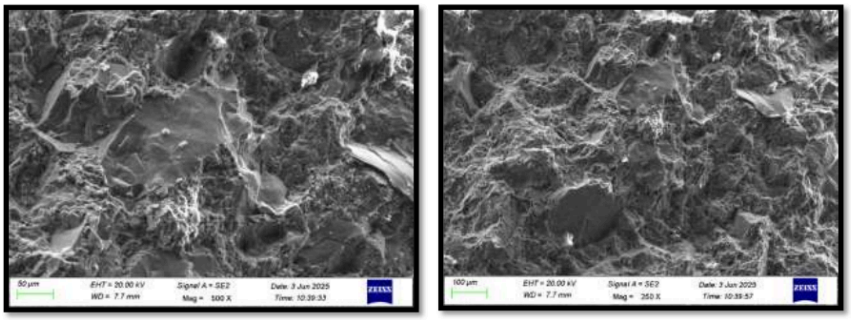

**Figure 3.6 SEM for Treated RCA for 24 Hrs. at $100^0$ C**

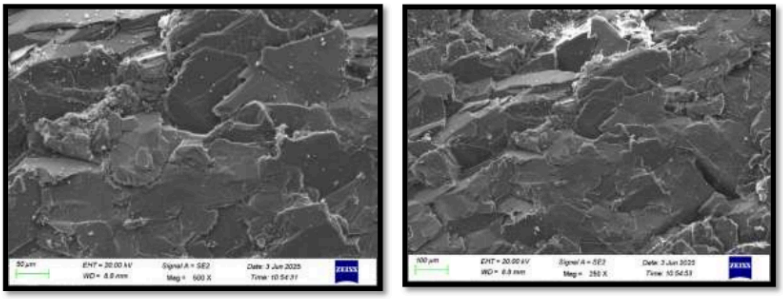

**Figure 3.7 SEM for Treated RCA for 24 Hrs. at $200^0$ C**

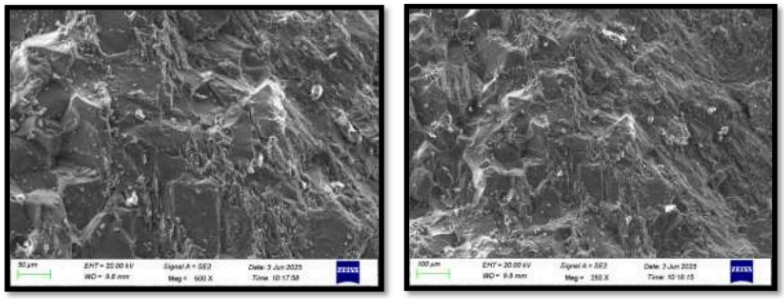

**Figure 3.8 SEM for 100% Natural Aggregate after 28 Days**

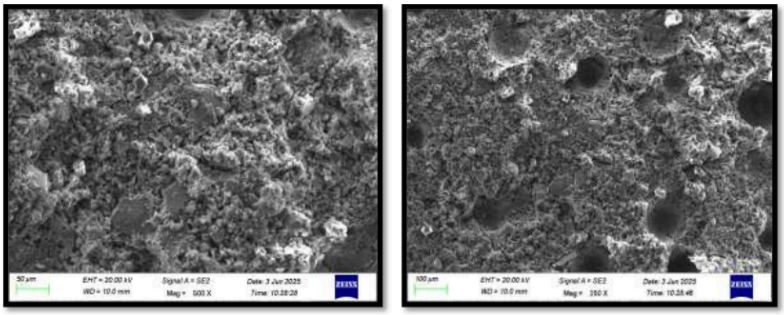

**Figure 3.9 SEM for 100% Recycled Aggregate after 28 Days**

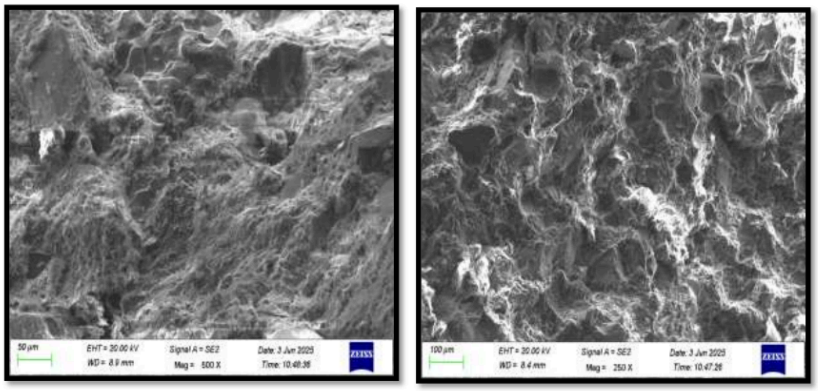

**Figure 3.10 SEM for Treated RCA for 48 Hrs. at $100^0$ C**

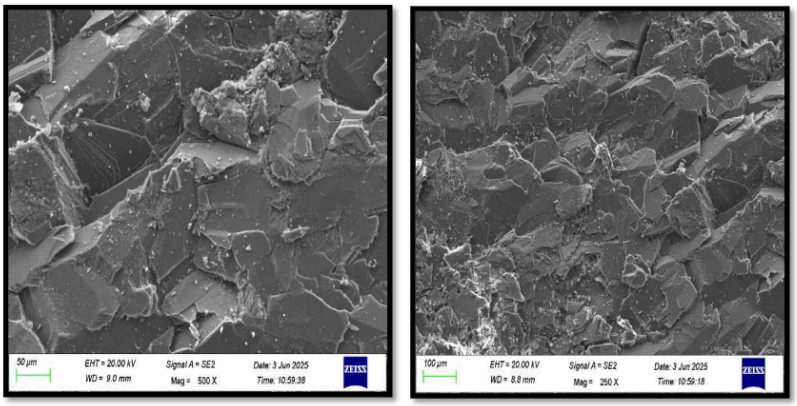

**Figure 3.11 SEM for Treated RCA for 48 Hrs. at $200^0$ C**

### 3.4.1.2 Energy Dispersive X-ray Spectroscopy (EDAX)analysis of different constituent materials

Energy Dispersive X-ray Spectroscopy (EDAX) is an elemental analysis technique integrated with Scanning Electron Microscopy (SEM), used to determine the chemical composition of materials. When a high-energy electron beam strikes the sample surface, it excites inner-shell electrons of the atoms, causing them to be

ejected. As electrons from higher energy levels fill these vacancies, characteristic X-rays are emitted. These X-rays are unique to each element, allowing for precise elemental identification and quantification.

In this study, EDAX analysis was performed using the sigma 300 SEM equipped with an EDAX detector at the Indian Institute of Technology, Roorkee. The analysis was conducted under vacuum conditions to eliminate interference from air particles and ensure accurate detection. Emitted X-rays were captured and processed using dedicated EDAX software to generate spectra representing the elemental composition of the materials.

**The analysis was conducted on:**

- Natural aggregate
- Untreated Recycled Coarse Aggregates (RCA)
- Heat-treated RCA (heat at 100°C / 200°C and abrasion at 500 revolution)
- Final treated RCA (heat at 100°C / 200°C and abrasion at 1000 revolution)

The results showed that untreated RCA contained higher amounts of impurities and residual hydrated products in the form of loosely bound mortar phases. In contrast, the treated RCA samples exhibited cleaner chemical profiles with a reduced presence of calcium hydroxide and other weakly bound phases. These improvements highlight the effectiveness of the combined heat and abrasion treatment in enhancing the chemical purity of RCA and preparing it for improved bonding with the cement matrix.

Figures 3.12 to 3.18 present the EDAX analysis results, which were crucial in confirming that the applied treatment significantly improved the material quality. This enhancement directly contributes to the suitability of RCA for use in durable and sustainable concrete applications.

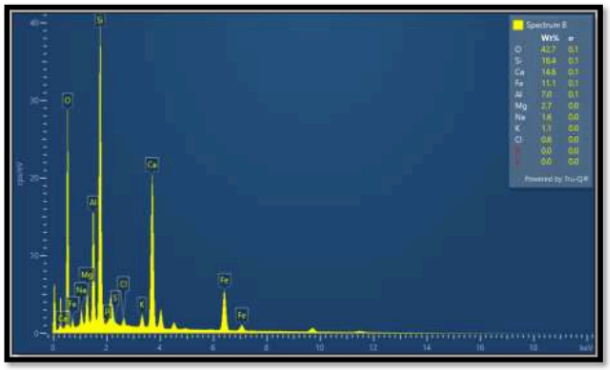

**Figure 3.12 EDAX for Natural Aggregate (EDAX)**

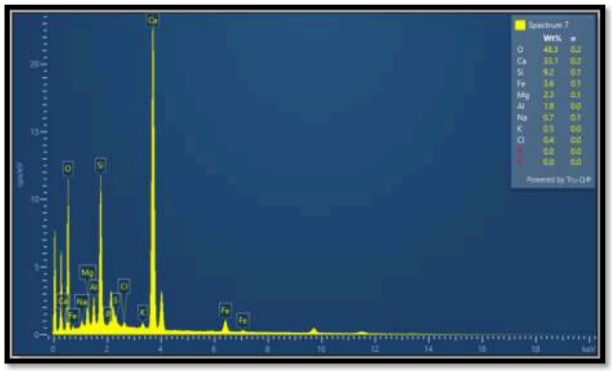

**Figure 3.13 EDAX Test for Untreated RCA**



**Figure 4.14 Treated RCA at $100^0$C for 24 Hrs.**

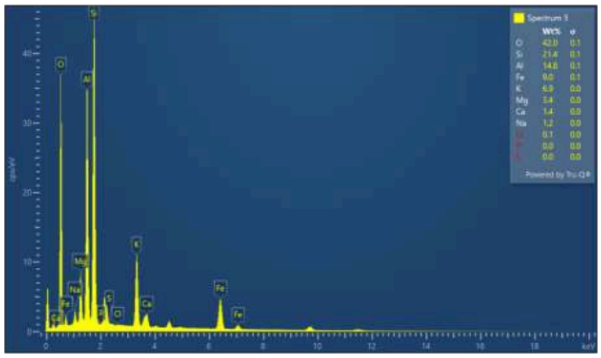

**Figure 3.15 EDAX for Treated RCA at 200$^0$C for 24 Hrs.**

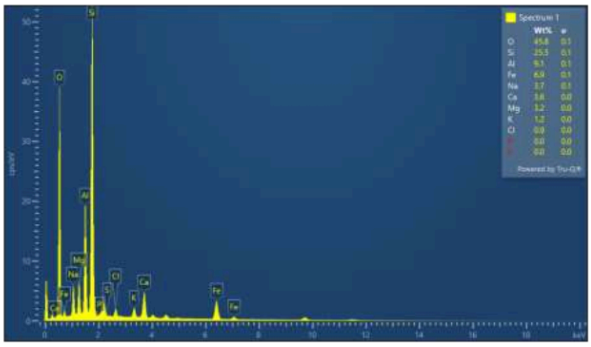

**Figure 3.16 EDAX for Casted 100% Natural Aggregate Cube after 28 Days.**

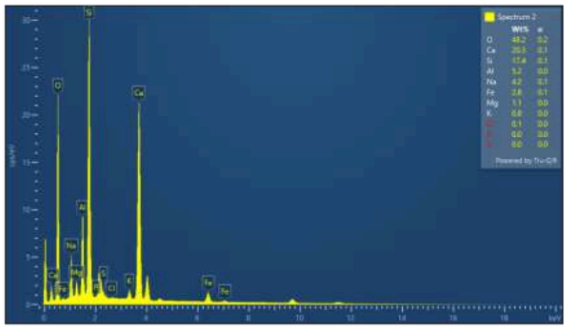

**Figure 3.17 EDAX for Casted 100% Untreated RCA Cube after 28 Days.**

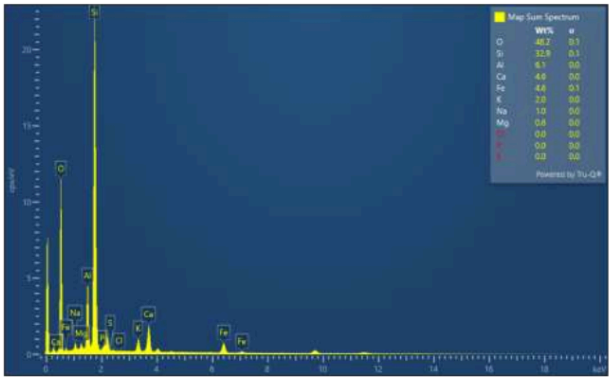


**Figure 3.18 EDAX for Treated RCA at 100$^0$C for 48 Hrs.**

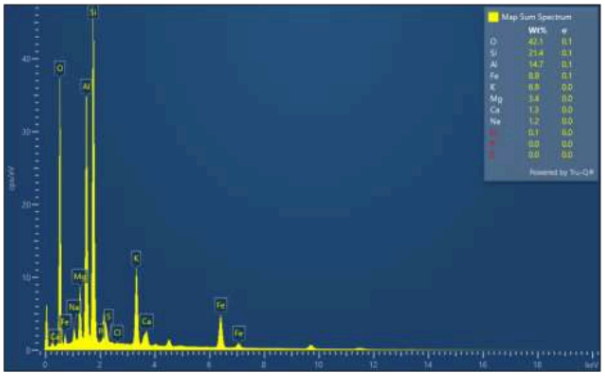


**Figure 3.19 EDAX Test for Treated RCA at 200$^0$C for 48 Hrs.**

### 3.4.2 Compressive Strength test on Hardened Concrete

To evaluate the structural applicability of recycled coarse aggregates (RCA), compressive strength tests were performed on concrete specimens with varying RCA replacement levels and treatment methods. The tests aimed to assess the mechanical performance of untreated and heat + abrasion treated RCA, used as a substitute for natural aggregates in concrete.

**A total of eleven mix variations were prepared:**

- **M0**: Control mix with 100% Natural Coarse Aggregates (NCA)
- **M1**: 50% Untreated RCA
- **M2**: 100% Untreated RCA
- **M3**: 50% RCA treated at 100°C for 24 Hrs. + abrasion at 500 revolution
- **M4**: 100% RCA treated at 100°C for 24 Hrs. + abrasion at 500 revolution
- **M5**: 50% RCA treated at 200°C for 24 Hrs. + abrasion at 500 revolution
- **M6**: 100% RCA treated at 200°C for 24 Hrs. + abrasion at 500 revolution
- **M7**: 50% RCA treated at 100°C for 48 Hrs. + abrasion at 1000 revolution
- **M8**: 100% RCA treated at 100°C for 48 Hrs. + abrasion at 1000 revolution
- **M9**: 50% RCA treated at 200°C for 48 Hrs. + abrasion at 1000 revolution
- **M10**: 100% RCA treated at 200°C for 48 Hrs. + abrasion at 1000 revolution

### 3.4.3 Mix Design Identification and Details

The concrete mix design is a vital step in ensuring that concrete achieves the desired strength, durability, and workability. In this study, the mix proportions were developed using the weight batching method as per IS: 10262-2019 for M25 grade concrete, targeting a mean strength of 31.6 MPa. The water-cement ratio was fixed based on workability and durability requirements.

Three distinct concrete mixes were designed and shows in Table 3.8.

**Mix 1:** (Control Mix): Made with 100% natural coarse aggregates (NCA) and served as the reference.

**Mix 2:** Included a 50% replacement of natural coarse aggregates with recycled coarse aggregates (RCA).

**Mix 3:** Used 100% RCA in place of NCA.

**Table 3.8 Mix Design for 1m³ concrete**

| Component | Mix 1 (100% Fresh Aggregate) | Mix 2 (50% Fresh + 50% RAC) | `Mix 3 (100% RAC Aggregates) |
|---|---|---|---|
| Cement (kg/m³) | 350 | 350 | 350 |
| Water (kg/m³) | 175 | 175 | 175 |
| 20 mm Aggregate (kg/m³) | 683 | 629 | 575 |
| 10 mm Aggregate (kg/m³) | 455 | 420 | 384 |
| Fine Aggregate (kg/m³) | 718 | 653 | 589 |
| Admixture (kg/m³) | 2.45 | 2.98 | 2.80 |
| **Total (kg/m³)** | **2384** | **2230** | **2076** |

Each mix was cast in standard **150 mm × 150 mm × 150 mm cubes**. The specimens were demoulded after 24 hours and water-cured until testing. Compressive strength tests were conducted at **7 days and 28 days**, following the procedure prescribed in **IS:516 (Part1/Sec1): 2021**[39], using a **2000 kN capacity compression testing machine**.

### 3.4.4 Drying Shrinkage

Drying shrinkage refers to the time-dependent reduction in the volume of hardened concrete as moisture gradually evaporates from the cement paste matrix. It is a critical factor influencing the long-term dimensional stability and crack resistance of concrete. Recycled coarse aggregates (RCA), due to the presence of adhered old mortar and higher porosity, tend to absorb and release more moisture, often leading to greater drying shrinkage compared to natural aggregates.

In this study, the drying shrinkage behaviour of various concrete mixes containing **treated and untreated RCA at 50% and 100% replacement levels** was assessed according to **IS: 516 (Part 6): 2020**[40].

Prismatic specimens of size **75 mm × 75 mm × 300 mm** were cast and **water cured for 28 days**. After curing, the specimens were air-dried under controlled laboratory conditions. Length measurements were taken initially (at the time of exposure) and then at **28 and 56 days** using a **length comparator** with a precision of **0.005 mm** and figure 3.19 shows the drying shrinkage apparatus and specimen under testing.

The drying shrinkage strain was computed as the change in length relative to the original length. For each mix, three specimens were tested, and the **average value** was considered as the representative of drying shrinkage. This test was essential to assess the impact of **RCA treatment temperature (100°C and 200°C)** on the **dimensional stability** of concrete.




**Figure 3.20 Drying shrinkage apparatus and specimen under testing**

### 3.5 Summary

This chapter outlines the experimental program designed to evaluate the performance of concrete using treated and untreated recycled coarse aggregates (RCA) as partial and full replacements for natural aggregates. The key highlights are:

**a) Material Characterization:**

Physical and microstructural properties of cement, natural aggregates, and recycled aggregates were studied. RCA exhibited higher water absorption and lower density due to the presence of adhered mortar, confirmed through SEM, and EDAX analyses.

**b) Surface Modification of RCA:**

The RCA was initially heated at 100°C and 200°C for 24 hours, followed by abrasion at 500 rpm. Based on test results, the process was modified by increasing the heating duration to 48 hours and abrasion speed to 1000 revolution.

**c) Mix Design and Proportions:**

Concrete was prepared as conventional with 50%, and 100% replacement of natural coarse aggregates by both untreated and treated RCA. Mixes were proportioned for M25 grade concrete using a constant water-cement ratio of 0.50 and superplasticizer dosage of 1% by weight of cement.

**d) Testing Methodology:**

Standard tests were conducted to evaluate fresh and hardened properties of concrete, including slump, compressive strength, drying shrinkage, SEM. Specimens were tested at intervals of 7, 28 days.

This chapter provides the foundation for study to consider effects of heat and abrasion-treatment on RCA influence concrete performance. The next chapter presents and discusses the results obtained from these tests.

# CHAPTER 4
# TEST RESULTS AND DISCUSSIONS

## 4.1 General

This chapter presents a comprehensive analysis of the experimental that results obtained from concrete specimens incorporating both untreated and surface-treated recycled coarse aggregates (RCA). The study evaluates the influence of two-stage surface modification techniques first treatment involving 24-hour heating at 100°C and 200°C followed by abrasion at 500 revolution, and other treatment involving extended 48-hour heating and abrasion at 1000 revolution on the mechanical strength performance of recycled aggregate concrete (RAC). Key concrete properties such as compressive strength, drying shrinkage, and microstructural behavior have been examined and compared with conventional concrete made using natural aggregates. Additionally, the performance of concrete mixes containing RCA at 50% and 100% replacement levels is discussed in detail, with the objective of identifying the optimal treatment method for improving strength and dimensional stability of concrete.

## 4.2 Workability

The workability of fresh concrete was assessed using the slump test as per IS:1199 (Part 1)–2018. The slump values provide an indication of the ease of compaction and placement of concrete. In this study, the workability of mixes incorporating untreated and treated recycled coarse aggregates (RCA) at 50% and 100% replacement levels was compared with that of conventional concrete made using natural aggregates.

It was observed that concrete with untreated RCA exhibited lower slump values compared to natural aggregate concrete, primarily due to the higher water absorption and porous nature of the adhered mortar. Among the treated RCA mixes, the samples subjected to **24-hour heating followed by 500 revolution abrasion** showed marginal improvement in slump, but still fell short of the control mix. However, the mixes prepared with **48-hour heating and 1000 revolution abrasion** demonstrated better workability, indicating a reduction in surface porosity and improved packing density of the aggregates.

Despite of surface treatments, RCA mixes consistently showed slightly reduced slump compared to the control mix, requiring adjustments through the use of superplasticizers. The incorporation of 1% Sunanda superplasticizer by weight of cement across all mixes helped in maintaining acceptable workability without compromising the water–cement ratio.

The trend (**Table 4.1 Slump values for different concrete mixtures and Figure 4.1 Slump value bar graph**) clearly shows that advanced surface treatment of RCA not only enhances mechanical performance but also positively influences the fresh concrete behaviour, making treated RCA more compatible for practical use in structural concrete.

**Table 4.1 Slump values for different concrete mixtures**

| Mix ID | Types of Aggregate | Replacement Level | Treatment Method | Slump (mm) |
|---|---|---|---|---|
| CC | Natural Coarse Aggregate (NCA) | 0% | None | 120 |
| RCA-50% | Recycled Coarse Aggregate (Untreated) | 50% | None | 105 |
| RCA-100% | Recycled Coarse Aggregate (Untreated) | 100% | None | 95 |
| RCA-50%-100°C | RCA (Heated 24h @ 100°C + 500 rpm) | 50% | First Treatment | 110 |
| RCA-100%-100°C | RCA (Heated 24h @ 100°C + 500 rpm) | 100% | First Treatment | 100 |
| RCA-50%-200°C | RCA (Heated 24h @ 200°C + 500 rpm) | 50% | First Treatment | 102 |
| RCA-100%-200°C | RCA (Heated 24h @ 200°C + 500 rpm) | 100% | First Treatment | 100 |
| RCA-50%-100°C | RCA (Heated 48h @ 100°C + 1000 rpm) | 50% | Final Treatment | 115 |
| RCA-100%-100°C | RCA (Heated 48h @ 100°C + 1000 rpm) | 100% | Final Treatment | 110 |
| RCA-50%-200°C | RCA (Heated 48h @ 200°C + 1000 rpm) | 50% | Final Treatment | 120 |
| RCA-100%-200°C | RCA (Heated 48h @ 200°C + 1000 rpm) | 100% | Final Treatment | 115 |

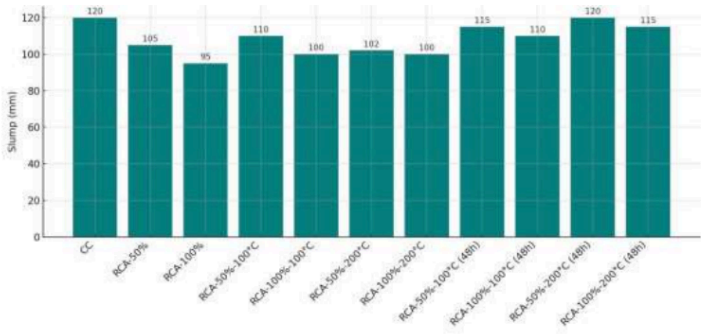


**Figure 4.1 Slump value bar graph**

### 4.3 Compressive Strength

To assess the mechanical performance of concrete incorporating recycled coarse aggregates (RCA), compressive strength tests were carried out in accordance with **IS: 516 (Part 1/Sec 1): 2021**. A total of **56 cube specimens** (150 mm × 150mm × 150mm) were cast using various concrete mixes comprising natural, untreated, and treated RCA. The tests were conducted at **7 days and 28 days** of curing using a **2000 kN capacity compression testing machine**. Table 4.2 shows the test result of compressive strength and figure 4.2 shows the variation for different concrete mixtures.

**Mix Categories:**

- **Control Mix** using 100% Natural Coarse Aggregate (NCA)
- **Untreated RCA** at 50% and 100% replacement levels
- **RCA Treated with 24h Heat (100°C/200°C) + 500 revolution abrasion**
- **RCA Treated with 48h Heat (100°C/200°C) + 1000 revolution abrasion**

**Key Observations:**

- The **control mix (CC)** achieved the highest strength and was used as a benchmark.
- Concrete with **untreated RCA** exhibited lower compressive strength due to the presence of adhered surface mortar, which increases porosity and weakens the interfacial transition zone (ITZ).

- **24-hour heat + 500 revolution abrasion** treated RCA showed moderate improvement in strength compared to untreated RCA, but still lagged behind the control mix.
- The **48-hour heat + 1000 revolution abrasion** treated RCA produced **the best results**, significantly improving RCA quality by effectively removing adhered mortar and refining surface texture. These mixes showed strength values close to the control concrete and **outperformed both untreated and 24-hour treated RCA mixes**.
- **Untreated RCA** mixes showed a reduction in compressive strength, especially at 100% replacement.
- **Treated RCA (100°C & 200°C)** showed a significant improvement in compressive strength over untreated RCA.
- **200°C treatment** showed better performance at both 50% and 100% replacement levels compared to 100°C treatment.
- At 50% replacement with treated RCA, compressive strength values approached or exceeded those of the control mix.

29 The compressive strength results are detailed in **Table 4.2**, while **Figure 4.2** illustrates the strength development trends. These findings highlight the effectiveness of the combined **heat + abrasion treatment** in improving RCA quality for sustainable structural concrete applications.



**Figure 4.2 Compressive strength determinations**

**Table 4.2 Test results of compressive strength**

| Mix Identification | Replacement | 7 Days compressive strength ($N/mm^2$) | | | Average value ($N/mm^2$) | 28 Days Compressive strength ($N/mm^2$) | | | Average value ($N/mm^2$) |
|---|---|---|---|---|---|---|---|---|---|
| - | Virgin Aggregate | 20.26 | 21.40 | 22.30 | **21.32** | 34.40 | 35.40 | 34.50 | **34.70** |
| **Without Treated** | Untreated Recycled Aggregate 50% RCA | 18.62 | 17.69 | 19.20 | **18.50** | 28.60 | 29.40 | 28.70 | **28.90** |
| **Without Treated** | Untreated Recycled Aggregate 100% RCA | 16.80 | 15.90 | 17.20 | **16.63** | 25.60 | 27.40 | 26.80 | **26.60** |
| **24h @100°C + 500 rpm Abrasion** | 50% | 18.26 | 20.13 | 21.10 | **19.83** | 29.52 | 30.10 | 28.60 | **29.41** |
| | 100% | 18.24 | 17.62 | 16.92 | **17.59** | 26.42 | 27.82 | 27.69 | **27.31** |
| **24h @200°C + 500 rpm Abrasion** | 50% | 18.92 | 19.75 | 20.30 | **19.66** | 30.15 | 29.86 | 29.48 | **29.48** |
| | 100% | 17.10 | 16.20 | 16.80 | **16.70** | 28.10 | 26.96 | 28.40 | **27.82** |
| **48h @100°C + 1000 rpm Abrasion** | 50% | 20.60 | 21.10 | 21.00 | **20.90** | 30.20 | 30.00 | 30.30 | **30.17** |
| | 100% | 18.90 | 19.10 | 19.00 | **19.00** | 28.50 | 28.80 | 28.60 | **28.63** |
| **48h @200°C + 1000 rpm Abrasion** | 50% | 22.00 | 22.20 | 22.10 | **22.10** | 34.10 | 34.50 | 34.60 | **34.40** |
| | 100% | 20.5 | 20.60 | 20.70 | **20.60** | 32.00 | 32.40 | 32.20 | **32.20** |

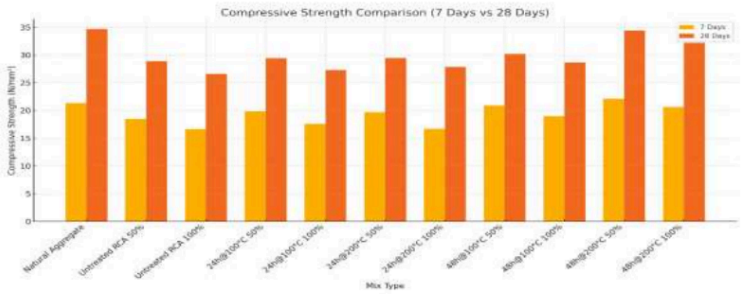


**Figure 4.3 Compressive strength variations for different concrete mixtures**

### 4.3.1 Conclusion:

The results clearly demonstrate that **RCA treated for 48 hours at elevated temperatures followed by abrasion at 1000 revolution** delivers the most effective improvement in compressive strength. This treatment method enables the use of RCA at **50% replacement levels** without compromising the structural performance of the concrete, supporting its viability as a substitute for natural aggregates in structural applications.

### 4.4 Drying Shrinkage

Drying shrinkage is a critical parameter that affects the dimensional stability and long-term durability of concrete. In this study, the drying shrinkage behavior of concrete specimens incorporating surface-treated recycled coarse aggregates (RCA) was evaluated at 28 days. The tests were conducted as per IS 516 (Part 6) – 2020, and the change in length was recorded over a period using a length comparator with a precision of 0.005 mm.

Concrete mixes prepared with untreated RCA showed a notable increase in drying shrinkage compared to the control mix with natural coarse aggregates (NCA). This is primarily due to the presence of adhered old mortar on RCA, which increases water absorption and creates a more porous microstructure, thereby promoting higher shrinkage.

**Table 4.3. Drying Shrinkage Test (As per IS 516(Part-6):2020 [Natural Concrete Aggregate]**

| S. No. | Initial Length, mm | Length after 1st cycle | Length after 2nd cycles | Length after 3rd cycles | Length after 4th cycles | Effective Gauge Length, mm | Drying Shrinkage, % |
|---|---|---|---|---|---|---|---|
| 1 | 6.523 | 6.420 | 6.385 | 6.351 | 6.356 | 250 | 0.067 |
| 2 | 6.823 | 6.732 | 6.702 | 6.672 | 6.676 | 250 | 0.059 |
| 3 | 6.859 | 6.749 | 6.713 | 6.676 | 6.682 | 250 | 0.071 |
| | | | | | | Average | 0.066 |

**Table 4.4. Drying Shrinkage Test (As per IS 516(Part-6):2020 [50% RAC Material] (Untreated)**

| S. No. | Initial Length, mm | Length after 1st cycle | Length after 2nd cycles | Length after 3rd cycles | Length after 4th cycles | Effective Gauge Length, mm | Drying Shrinkage, % |
|---|---|---|---|---|---|---|---|
| 1 | 6.953 | 6.851 | 6.817 | 6.783 | 6.773 | 250 | 0.072 |
| 2 | 7.026 | 6.934 | 6.903 | 6.872 | 6.824 | 250 | 0.081 |
| 3 | 5.963 | 5.854 | 5.817 | 5.781 | 5.791 | 250 | 0.069 |
| | | | | | | Average | 0.074 |

**Table 4.5. Drying Shrinkage Test (As per IS 516(Part-6):2020 [100% RAC Material] (Untreated)**

| S. No. | Initial Length, mm | Length after 1st cycle | Length after 2nd cycles | Length after 3rd cycles | Length after 4th cycles | Effective Gauge Length, mm | Drying Shrinkage, % |
|---|---|---|---|---|---|---|---|
| 1 | 7.215 | 7.112 | 7.078 | 7.044 | 6.975 | 250 | 0.096 |
| 2 | 6.992 | 6.901 | 6.870 | 6.840 | 6.750 | 250 | 0.097 |
| 3 | 6.836 | 6.726 | 6.690 | 6.653 | 6.621 | 250 | 0.086 |
| | | | | | | Average | 0.093 |

**Table 4.6 Drying Shrinkage Test (As per IS 516(Part-6):2020 [50% RAC Material] (100˚c and 500 revolution)**

| S. No. | Initial Length, mm | Length after 1st cycle | Length after 2nd cycles | Length after 3rd cycles | Length after 4th cycles | Effective Gauge Length, mm | Drying Shrinkage, % |
|---|---|---|---|---|---|---|---|
| 1 | 6.559 | 6.456 | 6.421 | 6.387 | 6.379 | 250 | 0.072 |
| 2 | 7.059 | 6.967 | 6.937 | 6.906 | 6.889 | 250 | 0.068 |
| 3 | 7.215 | 7.105 | 7.068 | 7.031 | 7.043 | 250 | 0.069 |
| | | | | | | Average | 0.070 |

**Table 4.7. Drying Shrinkage Test (As per IS 516(Part-6):2020[100% RAC Material] (100˚c and 500 revolution)**

| S. No. | Initial Length, mm | Length after 1st cycle | Length after 2nd cycles | Length after 3rd cycles | Length after 4th cycles | Effective Gauge Length, mm | Drying Shrinkage, % |
|---|---|---|---|---|---|---|---|
| 1 | 6.992 | 6.889 | 6.855 | 6.821 | 6.777 | 250 | 0.086 |
| 2 | 7.158 | 7.067 | 7.036 | 7.006 | 6.931 | 250 | 0.091 |
| 3 | 7.023 | 6.914 | 6.878 | 6.842 | 6.801 | 250 | 0.089 |
| | | | | | | Average | 0.089 |

**Table 4.8. Drying Shrinkage Test (As per IS 516(Part-6):2020 [50% RAC Material] (200°c and 500 revolution)**

| S. No. | Initial Length, mm | Length after 1st cycle | Length after 2nd cycles | Length after 3rd cycles | Length after 4th cycles | Effective Gauge Length, mm | Drying Shrinkage, % |
|---|---|---|---|---|---|---|---|
| 1 | 6.882 | 6.777 | 6.742 | 6.707 | 6.702 | 250 | 0.072 |
| 2 | 6.289 | 6.198 | 6.168 | 6.138 | 6.117 | 250 | 0.069 |
| 3 | 5.638 | 5.528 | 5.492 | 5.455 | 5.473 | 250 | 0.066 |
| | | | | | | Average | 0.069 |

**Table 4.9. Drying Shrinkage Test (As per IS 516(Part-6):2020[100% RAC Material] (200°c and 500 revolution)**

| S. No. | Initial Length, mm | Length after 1st cycle | Length after 2nd cycles | Length after 3rd cycles | Length after 4th cycles | Effective Gauge Length, mm | Drying Shrinkage, % |
|---|---|---|---|---|---|---|---|
| 1 | 6.339 | 6.236 | 6.202 | 6.168 | 6.137 | 250 | 0.081 |
| 2 | 6.924 | 6.832 | 6.802 | 6.771 | 6.734 | 250 | 0.076 |
| 3 | 7.021 | 6.911 | 6.875 | 6.838 | 6.839 | 250 | 0.073 |
| | | | | | | Average | 0.077 |

**Table 4.10. Drying Shrinkage Test (As per IS 516 (Part-6):2020[50% RAC Material] (100°c Treated for 48 hours and 1000 revolution)**

| S. No. | Initial Length, mm | Length after 1st cycle | Length after 2nd cycles | Length after 3rd cycles | Length after 4th cycles | Effective Gauge Length, mm | Drying Shrinkage, % |
|---|---|---|---|---|---|---|---|
| 1 | 6.789 | 6.690 | 6.657 | 6.624 | 6.619 | 250 | 0.066 |
| 2 | 7.013 | 6.908 | 6.872 | 6.840 | 6.832 | 250 | 0.067 |
| 3 | 6.587 | 6.487 | 6.455 | 6.420 | 6.418 | 250 | 0.071 |
| | | | | | | Average | 0.068 |

**Table 4.11. Drying Shrinkage Test (As per IS 516(Part-6):2020[100% RAC Material] (100°c Treated for 48 hours and 1000 revolution )**

| S. No. | Initial Length, mm | Length after 1st cycle | Length after 2nd cycles | Length after 3rd cycles | Length after 4th cycles | Effective Gauge Length, mm | Drying Shrinkage, % |
|---|---|---|---|---|---|---|---|
| 1 | **6.789** | **6.690** | **6.657** | **6.624** | **6.619** | **250** | **0.066** |
| 2 | **7.013** | **6.908** | **6.872** | **6.840** | **6.832** | **250** | **0.067** |
| 3 | **6.587** | **6.487** | **6.455** | **6.420** | **6.418** | **250** | **0.071** |
| | | | | | | Average | 0.074 |

**Table 4.12. Drying Shrinkage Test (As per IS 516(Part-6):2020[50% RAC Material] (200°c Treated for 48 hours and 1000 revolution)**

| S. No. | Initial Length, mm | Length after 1st cycle | Length after 2nd cycles | Length after 3rd cycles | Length after 4th cycles | Effective Gauge Length, mm | Drying Shrinkage, % |
|---|---|---|---|---|---|---|---|
| 1 | 6.982 | 6.878 | 6.841 | 6.803 | 6.789 | 250 | 0.061 |
| 2 | 7.125 | 7.020 | 6.982 | 6.944 | 6.926 | 250 | 0.066 |
| 3 | 6.702 | 6.603 | 6.567 | 6.532 | 6.524 | 250 | 0.065 |
| | | | | | | Average | 0.064 |

**Table 4.13. Drying Shrinkage Test (As per IS 516(Part-6):2020[100% RAC Material] (200°c Treated for 48 hours and 1000 revolution )**

| S. No. | Initial Length, mm | Length after 1st cycle | Length after 2nd cycles | Length after 3rd cycles | Length after 4th cycles | Effective Gauge Length, mm | Drying Shrinkage, % |
|---|---|---|---|---|---|---|---|
| 1 | 6.852 | 6.747 | 6.708 | 6.671 | 6.660 | 250 | 0.069 |
| 2 | 7.062 | 6.952 | 6.916 | 6.879 | 6.865 | 250 | 0.073 |
| 3 | 6.620 | 6.515 | 6.479 | 6.442 | 6.431 | 250 | 0.071 |
| | | | | | | Average | 0.071 |

To mitigate this, various thermal and mechanical surface treatments were applied. The results revealed the following key trends:

- Mixes treated at 100°C and 200°C for 24 hours followed by abrasion at 500 rpm showed moderate reduction in shrinkage compared to untreated RCA, but the values were still higher than natural aggregates.
- However, when the RCA was treated for 48 hours at 100°C and 200°C followed by abrasion at 1000 rpm, there was a significant reduction in shrinkage strain, especially for 200°C treatment. This improvement can be attributed to:
    - Effective removal of loose adhered mortar
    - Reduction in water absorption
    - Improved aggregate texture and surface bonding
- Among all, the RCA 50% @ 200°C for 48h + 1000 rpm mix showed the lowest shrinkage value (0.064%), nearly matching the shrinkage performance of the control mix (NCA – 0.066%).

- Table 4.3 to Table 4.13 shown the values of variation in dry shrinkage.

## 4.5 Scanning Electron Microscopy (SEM) Analysis

Scanning Electron Microscopy (SEM) was employed to analyze the surface morphology and microstructural characteristics of various coarse aggregates used in this study. These included Natural Coarse Aggregates (NCA), untreated Recycled Coarse Aggregates (RCA), and RCA subjected to heat and abrasion-treated surface modifications—specifically at 100°C and 200°C for 24 and 48 hours.

The SEM micrograph of the NCA sample displays a compact and uniform surface texture with minimal impurities, aside from slight surface roughness due to crushing. This morphology is typical of high-quality crushed stone aggregates and contributes to better bond formation with the cement matrix.

In contrast, the untreated RCA sample reveals a relatively rough and porous surface, with visible remnants of old mortar attached from previous usage. These adhered particles create weak zones and increase the overall porosity of the concrete, which can compromise strength and durability.

The SEM analysis of RCA samples treated at 100°C and 200°C for 24 hours followed by abrasion at 500 revolution shows partial removal of the adhered mortar. However, traces of loose particles and surface irregularities remain, indicating incomplete refinement. The porosity is reduced compared to untreated RCA but still higher than natural aggregates.

Further microstructural refinement is evident in RCA samples treated at 100°C and 200°C for 48 hours followed by high-intensity abrasion at 1000 revolution. These samples exhibit significantly cleaner surfaces, minimal residual mortar, and the formation of micro-pores due to heat-induced detachment of old paste. The resulting texture is denser and smoother, promoting stronger interfacial bonding with the cement paste.

This progression from untreated to treated RCA demonstrates the effectiveness of prolonged heating and intensified abrasion in enhancing aggregate quality. The 48-hour treatment not only removed weak attached mortar but also improved surface uniformity and reduced porosity, leading to better concrete performance.

These microstructural improvements directly correlate with enhanced bond with cement mortar resulting in better compressive strength and reduced drying shrinkage observed in treated RCA-based concrete mixes. The SEM results validate that the two-step surface treatment—thermal activation followed by mechanical abrasion—is a viable strategy to improve the performance of recycled aggregates for structural concrete applications.

### 4.6 Energy Dispersive X-ray Spectroscopy (EDAX) Analysis

Energy Dispersive X-ray Spectroscopy (EDAX) was utilized to determine the elemental composition of key constituent materials used in this study, including Natural Coarse Aggregates (NCA), untreated Recycled Coarse Aggregates (RCA), and RCA treated under varying conditions of heat and abrasion.

The EDAX spectra revealed the elemental constituents of each material, providing insight into the chemical changes induced by the surface treatments. Cement exhibited dominant peaks for calcium (Ca), silicon (Si), oxygen (O), and minor quantities of aluminum (Al) and iron (Fe), as expected. NCA primarily displayed silicate mineral peaks, consistent with natural stone aggregates.

Untreated RCA showed a higher presence of calcium and silicon due to the adhered cement paste from its previous use in concrete. Upon treatment, especially with prolonged heating and increased abrasion, a reduction in calcium content was observed. This is attributed to the partial or complete removal of aged mortar from the RCA surface, particularly evident in the 48-hour, 1000 rpm-treated samples.

The most notable finding from the EDAX analysis was a relative increase in silicon content across all treated RCA samples. This suggests an improvement in surface cleanliness and exposure of the siliceous base material beneath the adhered

mortar. Such a change enhances the chemical compatibility of RCA with the cement matrix may improve bonding at the interfacial transition zone (ITZ).

In samples treated at 100°C and 200°C for 48 hours followed by abrasion at 1000 rpm, the EDAX results indicated a cleaner surface profile with a decrease in calcium and a rise in silicon content compared to untreated RCA. This trend may supports the conclusion that thermal treatment combined with mechanical abrasion is effective in reducing old mortar content and refining surface chemistry, thereby improving the performance of RCA in structural concrete.

### 4.7 Cost Analysis

A comprehensive cost analysis was carried out to assess the feasibility of using recycled coarse aggregates (RCA) as a substitute for natural coarse aggregates in concrete production. The material cost calculations were based on prevailing market rates for cement, water, natural aggregates, recycled aggregates, sand, and admixtures. The RCA used in this study was obtained from the IL&FS Construction and Demolition (C&D) Waste Recycling Plant at Rani Khera, Mundaka, operated by the Delhi Metro Rail Corporation (DMRC). These aggregates were produced by processing discarded concrete through an impact crusher.

**Table 4.14 Cost Analysis with 1 m³ Material Quantity**

| Mix ID | Cement (₹) | Water (₹) | Sand (₹) | Admixture (₹) | Coarse Agg. (₹) | Total Cost (₹/m³) |
|---|---|---|---|---|---|---|
| CC | 2800.00 | 0.00 | 538.50 | 227.85 | 830.74 | **4397.09** |
| RCA-50% | 2800.00 | 0.00 | 489.75 | 277.14 | 419.60 | **3986.49** |
| RCA-100% | 2800.00 | 0.00 | 441.75 | 260.40 | 383.60 | **3885.75** |
| RCA-50%-100°C | 2800.00 | 0.00 | 489.75 | 277.14 | 419.60 | **3986.49** |
| RCA-100%-100°C | 2800.00 | 0.00 | 441.75 | 260.40 | 383.60 | **3885.75** |
| RCA-50%-200°C | 2800.00 | 0.00 | 489.75 | 277.14 | 419.60 | **3986.49** |
| RCA-100%-200°C | 2800.00 | 0.00 | 441.75 | 260.40 | 383.60 | **3885.75** |
| RCA-50%-100°C-Final | 2800.00 | 0.00 | 489.75 | 277.14 | 419.60 | **3986.49** |
| RCA-100%-100° C-Final | 2800.00 | 0.00 | 441.75 | 260.40 | 383.60 | **3885.75** |
| RCA-50%-200°C-Final | 2800.00 | 0.00 | 489.75 | 277.14 | 419.60 | **3986.49** |
| RCA-100%-200°C-Final | 2800.00 | 0.00 | 441.75 | 260.40 | 383.60 | **3885.75** |

Notes:

Cement = ₹8/kg

Sand = ₹0.75/kg

NCA = ₹0.73/kg (for CC mix)

RCA = ₹0.40/kg (for all others)

Admixture = ₹93/kg

Concrete mixes were prepared using varying replacement levels of natural aggregates with both untreated and surface-treated RCA. The cost analysis shown in Table 4.14 included all material components and additional treatment expenses, such as energy required for heating and abrasion. It was observed that mixes incorporating untreated RCA required comparatively lower expenditure than those using natural aggregates alone. Additionally, although treated RCA involved extra processing costs, the enhancement in concrete performance offered a practical justification for its use.

This cost assessment highlights the practical applicability of RCA in concrete, offering a balance between material cost and performance. It also reinforces the potential of recycled aggregates in sustainable construction practices by reducing the demand for virgin materials and promoting effective use of C&D waste.

# CHAPTER 5
# CONCLUSIONS, FUTURE SCOPE AND SOCIAL IMPACT

## 5.1 General

The construction sector today faces major challenges related to the depletion of natural resources and the growing need for sustainable development. With rapid urban growth and rising infrastructure demands, there has been excessive consumption of natural aggregates and a simultaneous surge in construction and demolition (C&D) waste. Reusing this waste as recycled coarse aggregate (RCA) offers a promising approach toward sustainability and supports circular economy practices.

In this research, a practical and low-cost method was adopted to improve the quality of RCA by addressing the problem of adhered mortar, which adversely affects its strength, density, and durability. Recycled aggregates were first subjected to thermal treatment at two different temperatures—100°C and 200°C—to weaken the old mortar. This was followed by mechanical abrasion using a Los Angeles Abrasion machine, which helped remove the loosened mortar from the RCA surface. Concrete mixes were then prepared using both 50% and 100% replacement levels of natural coarse aggregates with treated RCA. The performance was evaluated through compressive strength and drying shrinkage tests. Results indicated that the aggregates treated at 200°C delivered better strength and reduced shrinkage compared to untreated RCA, highlighting the effectiveness of the adopted treatment method.

Although microstructural analysis tools such as SEM were not employed in this study, the mechanical test outcomes provide strong evidence of improved interfacial bonding and concrete performance. Furthermore, this method contributes positively to environmental conservation and cost efficiency, demonstrating its potential for adoption in sustainable concrete applications. This chapter summarizes the key findings and encourages future exploration to further optimize RCA usage in structural concrete.

## 5.2 Present Outcomes Practical Significance of the Study

This research explores the use of recycled coarse aggregates (RCA), derived from construction and demolition (C&D) waste, as a sustainable replacement for natural aggregates in concrete. Emphasis was placed on enhancing the properties of RCA through thermal and mechanical modification, and assessing its influence on the mechanical behaviour and dimensional stability of recycled aggregate concrete (RAC).

A major outcome of the study was the development of an economical and straightforward treatment method for RCA. This involved heating the aggregates at 100°C and 200°C to weaken the old adhered mortar, followed by abrasion using the Los Angeles abrasion machine. This process significantly improved the physical quality of RCA, eliminating the need for chemical or slurry-based techniques.
Concrete mixes were prepared with 50% and 100% RCA replacement levels to evaluate the performance of treated aggregates. The results demonstrated that concrete made with RCA treated at 200°C, especially at 50% replacement, achieved strength values comparable to natural aggregate concrete, confirming its practical viability. Even at full replacement, the treated aggregates maintained acceptable strength levels, showcasing the effectiveness of the adopted method.

In terms of volumetric stability, drying shrinkage tests were conducted as per IS 516 (Part 6): 2020. The results proved that shrinkage increased with higher RCA content, but the treatment process—especially at 200°C significantly reduced this effect. The removal of adhered mortar improved the interfacial bond and reduced internal porosity, leading to better dimensional stability.

The findings validate that the combination of heat and abrasion treatment enhances RCA's structural performance. Treated aggregates showed superior workability, improved compressive strength, and lower shrinkage than untreated RCA. These enhancements affirm the practicality of the proposed method for real-world applications.

Furthermore, this study contributes to eco-friendly construction by encouraging the reuse of C&D waste. The low-energy treatment approach is scalable and suitable for on-site implementation, supporting the transition toward greener infrastructure solutions. Lastly, microstructural analyses via SEM have been scheduled for further evaluation of treated RCA's surface structure. These upcoming results will offer deeper insights and serve as a basis for future investigations into material behavior at the microscopic level.

### 5.3 Conclusions and Recommendations

This study aimed to enhance the performance of recycled aggregate concrete (RAC) by improving the properties of recycled coarse aggregates (RCA) using a two-step surface treatment technique. The treatment involved controlled thermal exposure at 100°C and 200°C, followed by mechanical abrasion to reduce the adhered mortar and improve aggregate texture. The outcomes highlight that this method positively influenced the mechanical properties and shrinkage behavior of RAC, offering a viable pathway for sustainable concrete applications.

**(a) Compressive Strength**

Concrete mixes prepared with **50% RCA treated at 200°C** showed compressive strength close to that of the control mix. The **100% replacement mix**, while showing a strength reduction, still exhibited acceptable performance, particularly when the RCA was heated at 200°C. The treatment significantly improved the bond between RCA and the cement matrix by reducing the adhered mortar.

**(b) Drying Shrinkage**

Drying shrinkage increased with higher RCA content. However, mixes containing RCA treated at **200°C for 48 Hrs.** showed lower shrinkage than untreated mixes, indicating better dimensional stability due to improved ITZ and reduced porosity.

**Recommendations**

- **50% replacement using RCA treated at 200°C** for 48 Hrs. with abrasion of 1000 revolution is recommended for structural-grade concrete.
- **100% replacement** may be considered in non-critical or moderately loaded elements with better quality control.
- Heat treatment at 200°C is preferable over 100°C due to improved performance.

### 5.4 Scope for Future Development

Although the present work effectively demonstrated improvements in compressive strength and drying shrinkage behavior through surface-treated recycled coarse aggregates (RCA), several potential research directions are suggested to broaden its practical relevance:

**1. Microstructural Validation**

Microstructural evaluation RAC through Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Analysis (EDAX), will help in visualizing changes in the interfacial transition zone (ITZ) and verify the densification of the paste-aggregate interface achieved through 48-hour thermal and abrasion treatment.

**2. Comprehensive Durability Performance**

Future research should focus on evaluating long-term durability indicators such as chloride ion penetration, resistance to sulphate attack, carbonation behavior, and freeze–thaw cycles to assess the concrete's behavior in harsh environmental conditions.

**3. Integration with Supplementary Cementitious Materials**

Future studies can explore the combined effect of treated recycled aggregates with mineral admixtures like fly ash, silica fume, or GGBFS. These combinations may offer added benefits in reducing shrinkage, enhancing strength, and improving durability.

**4. Standardization and Design Guidelines**

There is a need to develop standardized methodologies and design codes for using treated recycled aggregates in structural concrete. These guidelines will be critical for ensuring consistency and widespread acceptance in the construction industry.

**5. Environmental and Economic Assessment**

A detailed sustainability analysis, such as a Life Cycle Assessment (LCA), need to carried out to evaluate the environmental and economic impact of using treated recycled aggregates in concrete. This includes assessing carbon footprint reduction, energy savings, and overall cost-effectiveness compared to conventional concrete.

The continuous and rapid rise in global population has significantly intensified

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