INVESTIGATION OF BANANA FIBER-REINFORCED DIATOMACEOUS EARTH SLURRY TREATMENT OF RECYCLED AGGREGATE FOR STRUCTURAL CONCRETE APPLICATIONS

M.Tech. Thesis

By

MOMIN NOMAN HUSAIN MOHAMMAD HUMAYU
(2302104005)

DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

MAY 2025

INVESTIGATION OF BANANA FIBER-REINFORCED DIATOMACEOUS EARTH SLURRY TREATMENT OF RECYCLED AGGREGATE FOR STRUCTURAL CONCRETE APPLICATIONS

A THESIS

Submitted in partial fulfillment of the requirements for the award of the degree

of

Master of Technology

by

MOMIN NOMAN HUSAIN MOHAMMAD HUMAYU

(2302104005)

DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

MAY 2025

INDIAN INSTITUTE OF TECHNOLOGY INDORE

I hereby certify that the work which is being presented in the thesis entitled **INVESTIGATION OF BANANA FIBER-REINFORCED DIATOMACEOUS EARTH SLURRY TREATMENT OF RECYCLED AGGREGATE FOR STRUCTURAL CONCRETE APPLICATIONS** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DEPARTMENT OF CIVIL ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from July 2023 to May 2025 under the supervision of **Prof. SANDEEP CHAUDHARY**, Professor, Department of Civil Engineering.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

28/05/2025

Signature of the student with date

MOMIN NOMAN HUSAIN MOHAMMAD HUMAYU

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

28/05/2025

Signature of the Supervisor with date

Prof. SANDEEP CHAUDHARY

MOMIN NOMAN HUSAIN MOHAMMAD HUMAYU has successfully given his M.Tech. Oral Examination held on **May 2025**.

28/05/2025

Signature of Supervisor with date — Convener, DPGC

Prof. SANDEEP CHAUDHARY — **Dr. PRIYANSH SINGH**

“My work is dedicated to my family, who have always supported and encouraged my passion for research.”

ACKNOWLEDGEMENT

I would like to express my heartfelt gratitude to **Prof. Sandeep Chaudhary** and **Mr. Habtamu Melesse Dicha** for their unwavering support, invaluable expertise, and insightful guidance throughout this project.

I am also thankful to the Head of Department, Prof. Abhishek Rajput, for his guidance and the resources provided during my journey. Additionally, I would like to thank Dr. Kaustav Bakshi, Dr. Ravinder Bhattoo, Dr. Guru Prakash, and Dr. Priyansh Singh for their periodic assessments and valuable feedback, which helped me maintain the quality and direction of my thesis.

I want to thank my father, Mr. Mohammad Humayu, my mother, Ms. Salma Bano, my uncle, Mr. Anees Ahmed, my aunty Dr. Naziya, and my brother, Mr. Farogh Islam, for their faith in me and for teaching me so much to help me grow.

I would like to specially thank **Ms. Astha Sharma**, and I am also thankful to Mr. Suresh Waskle, Mr. Gaurav Sharma, Dr. Sanchit Gupta, Dr. Harish Panghal, Mr. Kameshwar Singh Nim, Dr. Ashita Singh, Mr. Akash Paradkar, Mr. Jitendra Mathankar, Mr. Krishna Singh Rajput, Mr. Maneesh Chaudhary, Mr. Ehtesham, Mr. Ghanshyam, as well as all my lab mates and classmates.

It is through the combined efforts and support of these individuals that I was able to fully grasp the project and successfully complete the experimental work. This thesis would not have been possible without their invaluable contributions.

Date:23/05/2025 ***Signature and name of the student***

Momin Noman Husain

Mohammad Humayu

DECLARATION

We declare that the Project Work titled **"INVESTIGATION OF BANANA FIBER-REINFORCED DIATOMACEOUS EARTH SLURRY TREATMENT OF RECYCLED AGGREGATE FOR STRUCTURAL CONCRETE APPLICATIONS"** is Bonafide work carried out by me, under the supervision of **Prof. Sandeep Chaudhary**.

Further we declare that this has not previously formed the basis of award of any degree, diploma, associate-ship or other similar degrees or diplomas, and has not been submitted anywhere else.

Date:23/05/2025 ***Signature and name of the student***

Momin Noman Husain

Mohammad Humayu

ABSTRACT

This study proposes a sustainable method for improving the performance of RAC through the surface treatment of RCA using a DE and BF reinforced slurry. RCA was treated with a mix containing 5% DE, ordinary Portland cement, and banana fiber ranging from 0–7% to improve its physical and mechanical properties. The optimal mix, containing 5% fiber (5/5-RAC), significantly enhanced aggregate quality by increasing specific gravity and reducing crushing, impact, and abrasion values.

Concrete made with treated RCA showed notable mechanical improvements, with compressive strength increased by 25.14%, tensile strength increased by 36.58%, and flexural strength increased by 72% compared to untreated RAC. Durability was also enhanced, evidenced by reduced water absorption, lower porosity, and less mass loss after exposure to elevated temperatures (200°C–800°C). Microstructural analysis (SEM and XRD) confirmed better bonding, fiber bridging, and C–S–H formation, contributing to long-term stability.

From a structural application, the 5/5-RAC mix exhibited significant improvements in shear performance. Beams without stirrups showed a 16.12% strength increase at 1.6% reinforcement and 22.22% at 2.5%, while a 13.33% improvement was also noted in beams with stirrups. These findings highlight the method's effectiveness for practical structural use. Overall, this treatment method offers a cost-effective, eco-friendly, and practical applicable to enhance the quality and durability of RAC, supporting sustainable construction practices.

LIST OF PUBLICATIONS

Outcomes from M.Tech thesis work:

1. Habtamu Melesse Dicha, Sandeep Chaudhary, **Momin Noman Husain**, and Ramaswamy Krishnaraj, "Banana fibre-reinforced diatomaceous earth slurry treatment of recycled aggregate for enhanced structural concrete performance," Scientific Reports, vol. 15, no. 1, Feb. 2025, doi: 10.1038/s41598-024-84762-w. (**Published** in Scientific Reports Nature Q1 Journal). https://www.nature.com/articles/s41598-024-84762-w.
2. Habtamu Melesse Dicha, Sandeep Chaudhary, **Momin Noman Husain**, and Ramaswamy Krishnaraj, "Performance of banana fiber-reinforced diatomaceous earth slurry treated recycled aggregate concrete after exposure to elevated temperatures". (**Under Review** in Scientific Reports Nature Q1 Journal).
3. Habtamu Melesse Dicha, **Momin Noman Husain**, Sandeep Chaudhary and Ramaswamy Krishnaraj, "Innovative Abrasion and Banana Fibre-Reinforced Diatomaceous Earth Slurry Treatment for Enhanced Recycled Aggregate in Structural Concrete Applications". (**Under Review** in Heliyon Q1 Journal).
4. Astha Sharma, Sanchit Gupta, **Momin Noman Husain**, and Sandeep Chaudhary, "Factors affecting the rheology of cement-based composites: A review," Journal of the American Ceramic Society, published Feb. 21, 2025, doi: 10.1111/jace.20429. (**Published** in Journal of the American Ceramic Society Q1 Journal). https://doi.org/10.1111/jace.20429.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

C&D: Construction and Demolition

RA: Recycled Aggregate

NA: Natural Aggregate

RCA: Recycled Concrete Aggregate

NAC: Natural Aggregate Concrete

RAC: Recycled Aggregate Concrete

DE: Diatomaceous Earth

BF: Banana Fiber

SSD: Saturated Surface Dry

XRD: X-Ray Diffraction

XRF: X-ray Fluorescence

SEM: Scanning Electron Microscopy

EDX: Energy Dispersive X-ray

BET: Brunauer-Emmett-Teller

WA: Water Absorption

SG: Specific Gravity

ACV: Aggregate Crushing Value

AIV: Aggregate Impact Value

AAV: Aggregate Abrasion Value

RA-UT: Untreated RCA

RA-CT: Cement slurry treated RCA

RA-DE/BF: Banana Fiber-reinforced DE Slurry treated RCA

RAC-UT: Untreated RAC

RAC-CT: Cement slurry treated RAC

RAC-DE/BF: Banana Fiber-reinforced DE Slurry treated RAC

RRAC Beam: Reinforced Recycled Aggregate Concrete Beam

OPC: Ordinary Portland Cement

BIS: Bureau of Indian Standards

ITZ: Interfacial Transition Zone

SFD: Shear Force Diagram

BMD: Bending Moment Diagram

LCA: Life Cycle Assessment

RC: Reinforced Concrete

CA: Coarse Aggregate

NFA: Natural Fine Aggregate

w/c: Water to Cement ratio

w/b: Water to Binder ratio

^{o}C: Degrees Celsius

MPa: Mega Pascal

(a/d): Shear Span to Depth Ratio

ρ: Percentage of Longitudinal Reinforcement

S: Spacing

C/S: Cross-Section

w/out: Without

@: At

V_{test}: Experimental Shear Force

$V_{pred.}$: Predicted Shear Force

P_u: Ultimate Load

F_c: Compressive Strength

C-S-H: Calcium Silicate Hydrate

Ca: Calcium

SiO_2: Silicon Dioxide

$Ca(OH)_2$: calcium Hydroxide

NaOH: Sodium Hydroxide

CO_2: Carbon Dioxide

CHAPTER – 1
INTRODUCTION

1.1 Background:

The construction sector plays a vital role in driving urban growth and industrial development [1]. In India, it is expanding rapidly, fueled by population increase and the demand for improved living standards [2]. However, the production of C&D waste [3] and natural resource depletion [4] provide global concerns for industry. India's construction industry generates substantial waste during the construction, demolition, and destruction of concrete structures, exacerbated by inefficient practices and disasters [5]. Although this waste is less than that of developed nations, it presents significant disposal and environmental challenges [6]. The widespread use of cement-based materials in the construction industry has significantly increased aggregate demand and aggravated resource depletion. Concurrently, the upgrading of old buildings and the construction of new infrastructure projects lead to an increase in the production of C&D waste.

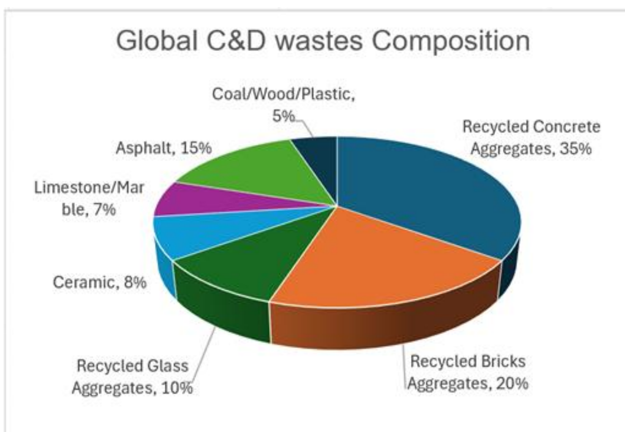

Figure 1 Global C&D waste composition

According to Hassan et al. (2023), the global composition of C&D waste, as shown in Figure 1 [7], primarily consists of recycled concrete aggregates

(35%), followed by recycled brick aggregates (20%), asphalt (15%), recycled glass aggregates (10%), ceramic (8%), limestone/marble (7%), and coal/wood/plastic (5%). Similarly, Trivedi and Snehal et al. (2023) [8] reported the C&D waste composition for India, as shown in Figure 2, where limestone/marble accounts for the largest share (34%), followed by recycled glass aggregates (24%), recycled concrete aggregates (14%), recycled brick aggregates (12%), asphalt (6%), ceramic (5%), and coal/wood/plastic (5%). Based on these previous studies, recycled concrete aggregate (RCA) forms a significant portion of C&D waste composition, highlighting its potential for sustainable reuse in construction applications.

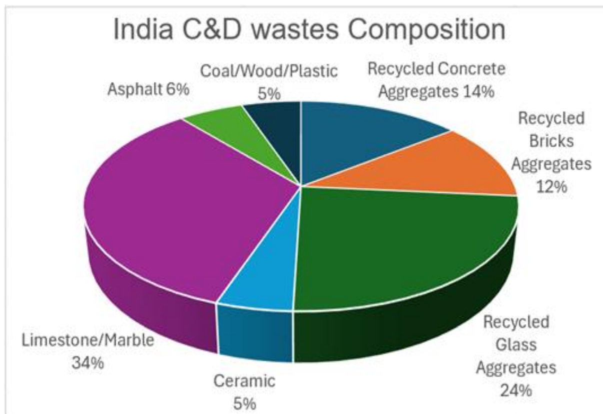

Figure 2 India C&D waste composition

The growing demand for aggregates and the increasing production of C&D waste worldwide have been highlighted by several studies, as summarized below:

- Yehia et al. (2015) reported that the Asia Pacific region accounts for the largest share (67%) of global aggregate consumption, followed by Others (19%), North America (8%), and Western Europe (6%), as shown in Figure 3 [9] .
- Global demand for aggregates has grown steadily, from 30 billion metric tons in 2010 to 43 billion in 2019, reaching 62.9 billion today and projected at 74 billion metric tons by 2030 (United Nations Environment Programme. 2019) [10] as shown in Figure 4.

➢ The UK C&D industry generates approximately 60 million tons of waste annually, accounting for 62% of the nation's total waste (Market Research Future, 2021) [11].

➢ In comparison, almost 35% of the global C&D waste is produced in India [12], which generates 150 million tons annually (Jain, 2021; Kolaventi et al., 2019).

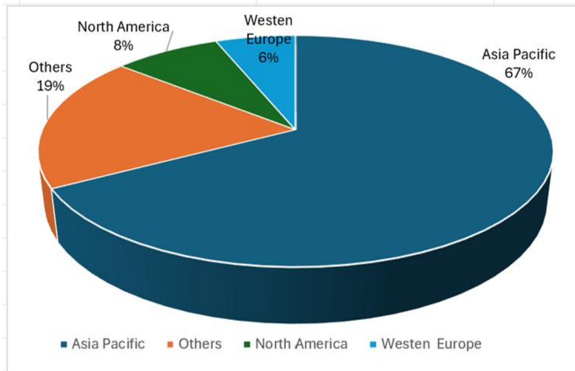

Figure 3 Global aggregate consumption

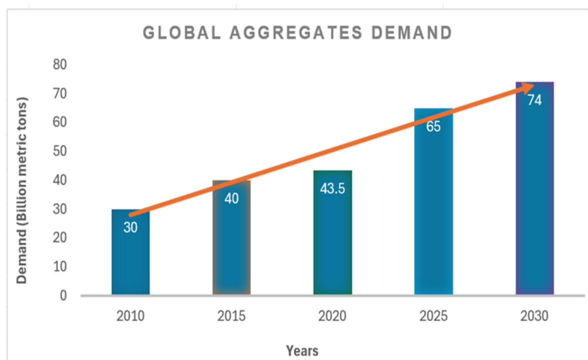

Figure 4 Global aggregate demand

Additionally, the excessive consumption of natural aggregates for concrete production is expected to raise serious concerns about resource depletion by 2030 [13]. In response to these issues, recycling C&D waste to produce RA has gained interest [14]. RA can be used in concrete production for structural applications, offering environmental and economic benefits [15]. Traditional disposal of these wastes not only takes up significant space in landfills but also poses serious environmental issues. These situations have highlighted the need for sustainable practices, such as the use of RCA, comes from C&D waste, as an alternative to NA for the production of concrete. RCA utilization addresses resource depletion, reduces waste, and promotes circular economy in construction. The deriving forces for RCA utilization include environmental sustainability goals, regulatory pressures, and the increasing costs associated with natural resource extraction and waste disposal. Environmentally, it reduces the need for natural resource quarrying and minimizes the corresponding environmental impact [16]. It also lowers CO_2 emissions since recycling consumes less energy than producing new aggregates [17] and addresses landfill overuse [18]. Economically, using RCA can reduce transport and energy costs due to local sourcing [19].

1.2 Objective:

The important goal of this study is enhancement of the RCA quality for structural concrete applications by treating the adhered mortar, as illustrated in Figure 5. This is accomplished either by mechanically or chemically removing the adhered mortar (such as thermal and ultrasonic treatments) or by strengthening it using polymer impregnation, bio-deposition, carbonation treatment, or pozzolanic slurry immersion. These treatment approaches aim to improve the mechanical performance and durability of RCA, promoting its effective use as a sustainable replacement for natural aggregates.

Enhancing RAC's mechanical and durability properties depends significantly on improving RCA quality [20]. Strategies include improving the ITZ and strengthening or removal of attached mortar on the surface of RCA. Methods for enhancing RCA quality include mechanical, thermal, chemical, and ultrasonic treatments for removing attached mortar in RCA; and polymer impregnation, mixing approaches, bio-deposition, pozzolanic slurry immersion and carbonation treatment for strengthening the adhered mortar [21].

To address the limitations of current techniques, a novel approach is introduced that uses BF reinforced DE slurry for treating RCA. This method aims to enhance RCA quality by addressing ITZ and improving the adhered mortar. DE is a silica-rich material recognized for its significant pozzolanic activity, capable of filling voids and enhancing RCA surface texture. Banana fibers have high tensile strength, biodegradable, and renewable nature, can strengthen both the aggregate and cement mortar. This innovative slurry is applied to RCA to reduce cracks in the ITZ, improve bonding with the new cement paste, and provide a sustainable alternative to conventional treatments. The primary goal is to optimize the BF content in the DE slurry with fiber reinforced to achieve maximum RCA and RAC performance.

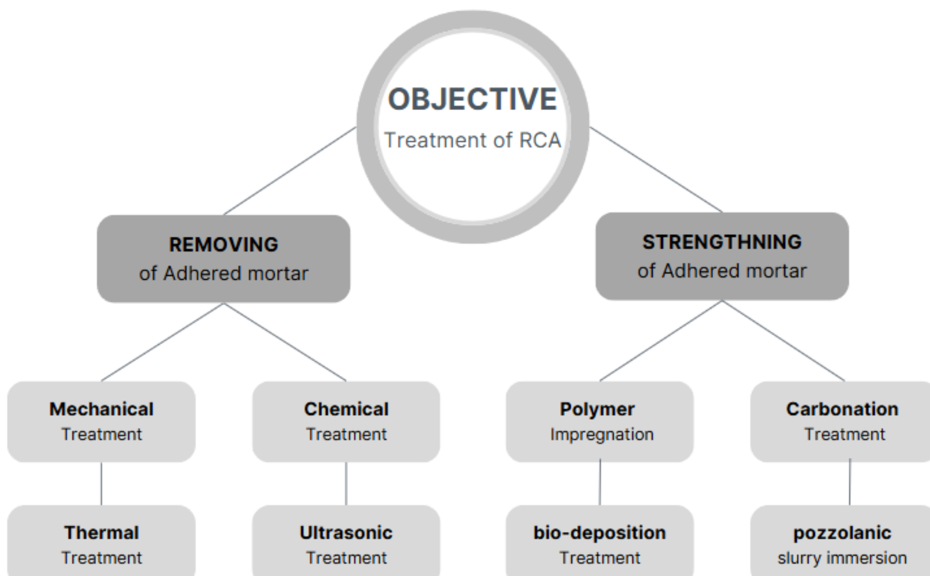

Figure 5 Different treatment methods of RCA

This study aims to optimize BF content in DE slurry with fiber reinforced to enhance the performance of RCA and RAC. It starts by using C&D waste to produce RCA, which is treated to improve its properties. Banana fibers are then added to the slurry to enhance the bond strength and overall performance of the RCA. The treated RCA is incorporated into RAC, which is tested for strength and durability. Finally, the optimized fiber-enhanced RAC is applied in structural beams, focusing on load-bearing capacity and long-term performance, creating a sustainable and high-performance concrete solution. These steps are shown in Figure 6.

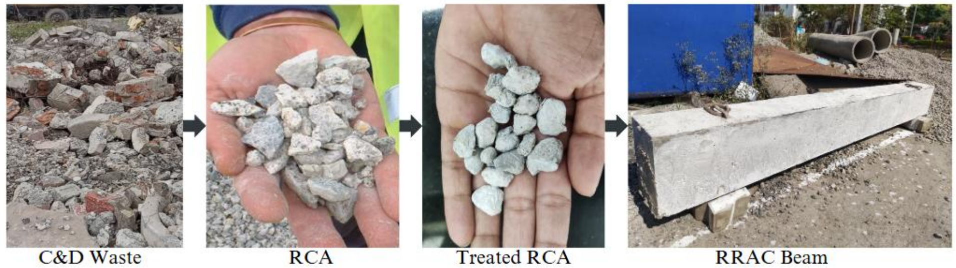

Figure 6 Application of treated RCA

1.3 Problem Definition:

Despite these advantages, RCA’s use in structural concrete faces technical challenges as follows, shown in Figure 7 [22].

- Adhered mortar
- High water absorption
- High porosity
- Heterogeneous composition
- Reduce specific gravity

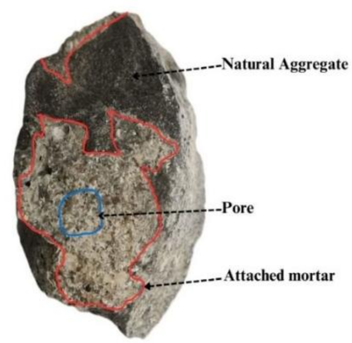

Figure 7 RCA

In general RCA has worse mechanical properties compared to NA [23] due to the presence of attached mortar [24] and a weak ITZ [25]. This adhered mortar increases porosity and reduces RCA density, resulting in higher water absorption and lower fragmentation resistance [3]. The ITZ in recycled aggregate concrete is more porous and contains microcracks, which weaken the bond between cement paste and aggregates, and compromise the strength [26]. Consequently, RAC’s characteristics, such as workability [27], compressive strength [28], split tensile strength [29], flexural strength [30], and others [31-37] are typically inferior to those of NAC. This inferiority extends to structural performance such as bond behavior [38], load-carrying capacity [39], seismic capacity [40], flexural capacity [41] and shear capacity [42].

But using RCA directly in structural concrete is challenging because it has variable quality, less density, and more porosity than NA. This means that RAC is inferior to NAC in strength and durability.

1.4 Methodology:

- Physical and chemical Characterization of ingredients of concrete (cement, DE, sand, NA and RCA)

  To assess the fundamental properties of raw materials.

  - X-ray diffraction (XRD) for mineralogical analysis.
  - Specific gravity for density.
  - Water absorption for porosity evaluation.

- Treatment of Banana fiber

  To prepare banana fibers to reinforce the slurry.

  - Treating with alkaline solution to enhance bonding properties.
  - Cleaning and drying the fibers.
  - Cutting into desired length.

- Pre-wetting of RCA

  To minimize the water absorption of RA and increase their workability in concrete.

  - Soaking RCA in water for a specified time.
  - Surface drying to achieve saturated surface-dry (SSD) conditions.

- BF reinforced DE Slurry preparation

  To create a uniform slurry for RCA treatment.

  - Diatomaceous earth as the base material.
  - Banana fibers for reinforcement.
  - Water and any cement for desired consistency

- Immersion of RCA in slurry

  Coating of RCA with the prepared slurry.

  - Submerging RCA in the slurry for specified duration.
  - Ensuring uniform coating on the aggregate surface.

- Drying of treated RCA

  To allow the slurry coating to adhere firmly to the RCA.

  - Air drying at a controlled temperature.

- Mechanical properties of Aggregate

  To evaluate the performance of treated RCA.

  - Aggregate crushing, impact, abrasion value tests.
  - Sive size analysis of aggregate.

- Concrete mixing

  To prepare concrete mixtures with treated RCA.

  - Batching materials (cement, DE, sand, NA, RCA, and water).
  - Uniform mixing in a concrete mixer.

- Fresh properties of concrete

  To assess workability and consistency.

  - Slump test.

- Casting and Demolding

  To prepare specimens for mechanical, microstructural, and durability testing.

  - Casting concrete into molds of specified dimension.
  - Demolding specimens after setting.

- Curing

  To ensure proper hydration and development of strength in concrete.

  - Immersion in water for a specific curing period.

- Mechanical Testing

  To assess the concrete strength characteristics.

  - Compressive strength.
  - Split tensile strength.
  - Flexural strength.

- Microstructural properties of concrete

  To analyze the internal structure and bonding.

  - Scanning Electron Microscopy (SEM).
  - X-ray Diffraction (XRD).
  - Energy Dispersive X-ray Spectroscopy (EDX).

- Durability of concrete

  To analyze long term performance of concrete.

  - Water absorption.
  - Resistance at elevated temperatures.

- Structural application

  To demonstrate practical use cases of the developed concrete.

  - Casting structural elements (e.g. Beam).
  - Load testing under simulated conditions.

1.5 Limitations:

This study is done under a controlled lab environment. The high-water absorption of banana fiber requires pre-wetting of treated RCA, adding complexity to the process. The DE slurry and banana fiber optimization is unique to this study. Additionally, higher contents of banana fiber can cause balling effects during mixing, which limits its effective use.

1.6 Chapterisation Scheme:

- Chapter 1 Introduction:

  This chapter introduces the background, objective, problem definition, scope of work and the need to study the treatment of recycled concrete aggregate (RCA) using banana fiber-reinforced diatomaceous earth slurry. It also outlines the methodology, limitations, and Chapterisation Scheme.

- Chapter 2 Review of Literature:

  This chapter reviews existing research on recycled aggregates, different treatment methods of RCA, banana fiber applications in concrete, diatomaceous earth as a treatment material, and the mechanical and durability properties of treated concrete.

- Chapter 3 Materials and Methods:

  This chapter describes the physical and chemical characterization of materials, the alkaline treatment process of banana fiber, the treatment process for RCA using banana fiber-reinforced DE slurry, and the preparation and testing methods for concrete. It includes details on mix design, curing, and experimental setups for mechanical, microstructural, and durability studies.

- Chapter 4 Results and Discussion:

  The results presented and interpreted in this chapter are mechanical property tests, microstructural analysis, and durability assessments. It discusses the effects of RCA treatment, banana fiber, and diatomaceous earth on concrete performance. Furthermore, this chapter includes the performance of RCA at elevated temperatures and its structural application particularly the shear performance of RC beam.

- Chapter 5 Conclusion, Limitations and Recommendations:

  This chapter summarizes the key findings of the study, highlights its contributions to the field of sustainable concrete, and makes recommendations for further study and practical uses.

- Chapter 6 References:

  This chapter provides a list of all sources and literature cited for this study.

1.7 Scope of Work:

The goal of this study is to improve the characteristics of RCA through a novel treatment using DE slurry reinforced with banana fiber. Evaluation of the treated RCA concrete mechanical, microstructural, and durability properties, including properties at elevated temperatures, is the focus of the study. Additionally, the research explores the application of the treated RCA concrete in structural elements and simulates its behavior under different types of loading conditions to evaluate its performance for practical use.

CHAPTER – 2
REVIEW OF LITERATURE

Researchers have explored various treatment methods to address the limitations of direct use of the RCA. They commonly use mechanical methods, thermal methods, chemical methods, ultrasonic cleaning methods, polymer impregnation, mixing approaches, incorporation of additives, bio-deposition methods, carbonation, and pozzolanic slurry treatment methods to mitigate the poor performance of RCA and RAC.

Figure 8 illustrates various treatment approaches that have been developed and studied to remove the mortar adhered to the aggregate. Mechanical treatment, which involves scrubbing, reduces adhered mortar using a rotating drum, ball mill, impact crusher, or similar equipment [43]. This technique can remove up to 62% of adhered mortar [44], improving RAC workability up to 0.84-8.95% and compressive strength up to 21- 29% [45]. However, it consumes significant energy and causes equipment wear [46], generating substantial dust and fine particles [47]. Thermal treatment, such as heating up to 500^{o}c for 2 hours, removes up to 90% of the adhered mortar, increasing specific gravity by 2.4% and reducing water absorption by 17% [48]. This method enhances compressive strength up to 25-34% [44] but requires considerable energy input and contributes to greenhouse gas emissions. Chemical methods using acids like hydrochloric or sulfuric acid effectively clean RCA but pose handling and disposal challenges due to hazardous chemicals [49,50]. High frequency sound waves are used in ultrasonic cleaning to eliminate the adhered mortar and improve bonding, but it requires substantial energy and specialized equipment, limiting its widespread application [51]. Combining techniques, including heating and mechanical treatment, can improve outcomes but increase complexity and have an adverse effect on the environment [52,53].

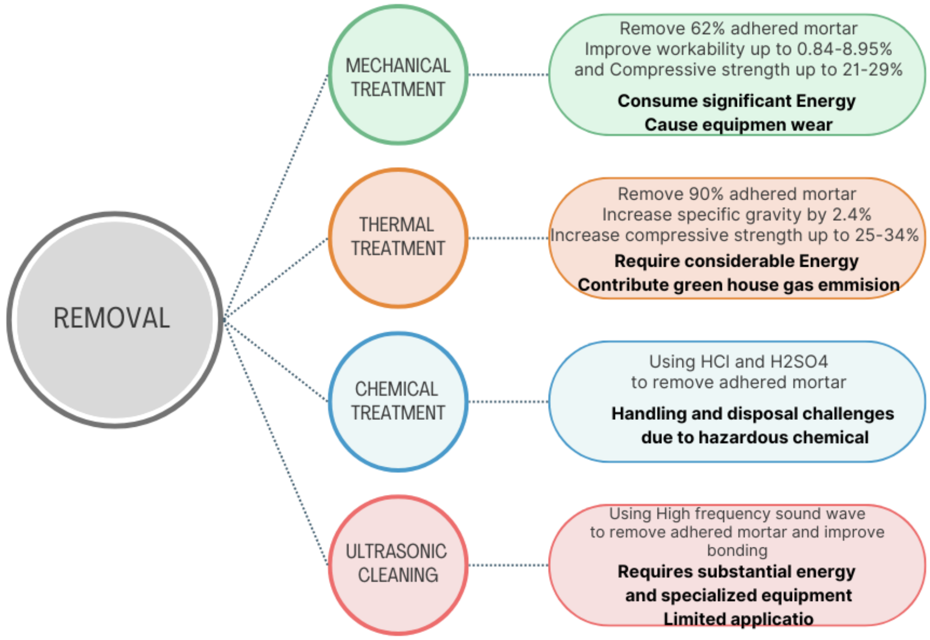

Figure 8 Removal of adhered mortar

Strengthening the attached mortar to the aggregate can also enhance the quality of RCA and RAC, as shown in Figure 9. Polymer impregnation uses materials such as silane polymers [54], polyvinyl alcohol [55], epoxy resin [56], or aerogel and paraffin [57] to fill voids and cracks, enhancing the concrete's mechanical properties. However, it is expensive and might potentially weaken the bond between the new cement paste and RCA. Optimized mixing approaches involve carefully proportioning the concrete mixes, including RCA, and incorporating pozzolanic powders such as silica fume or fly ash to improve RAC properties [58-63]. However, improvements are often limited, and effectiveness depends heavily on the precise control of the mixing process. Bio-deposition uses microorganisms to precipitate calcium carbonate, filling pores and cracks to enhance strength but involves costs related to microorganism cultivation and inconsistent quality [64-66]. Carbonation treatment converts calcium hydroxide in RCA to calcium carbonate, enhancing various concrete properties while contributing to carbon sequestration, though a stable CO_2 source is needed [67]. Pozzolanic slurry immersion, using materials like silica fume, water glass, nano-silica, pozzolanic powder, or zeolite powder, improves workability and strength by forming additional calcium-silicate-hydrate [68-70] but the high demand for pozzolanic materials in the cement industry has increased costs [71].

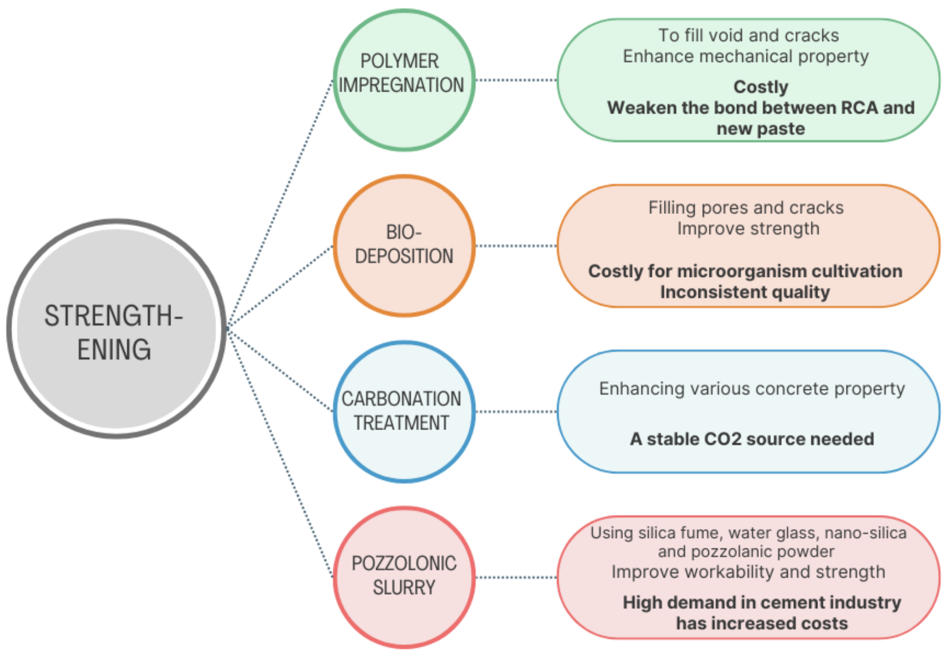

Figure 9 Strengthening of adhered mortar

The performance of RAC when exposed to high temperatures is affected by numerous factors, including the origin and quantity of RCA, the characteristics of the mix constituents, the water to cement ratio (w/c), the inclusion of supplementary cementitious materials, the use of mineral admixtures and fibers, and the adopted testing methods [72-77]. Studies report varying outcomes regarding RAC's behavior compared to NAC. Some findings suggest that RAC exhibits performance like NAC, with no distinct link to the replacement ratio, whereas others observe a more rapid decline in RAC's properties under thermal loading [72,73].

Additionally, research indicates that RAC generally shows reduced residual strength at lower RCA replacement levels (up to 30%) but better retains mechanical properties when the replacement rate exceeds 50% [74-77]. These contrasting results emphasize the need for more standardized investigations on the effects of replacement rates from diverse RCA sources.

Regarding the water-cement ratio, a lower w/c has been found to result in a denser, less porous microstructure, thereby improving fire resistance [78].

Moreover, the incorporation of supplementary cementitious materials, such as silica flour and silica fume, has been shown to enhance the thermal resilience of RAC [79,80]. These materials contribute to a denser microstructure through pozzolanic reactions, leading to a refinement of pores and enhanced strength under temperatures reaching up to 400°C. Similarly, the addition of mineral admixtures has been reported to mitigate mechanical deterioration at elevated temperatures (500°C and 800°C) more effectively in RAC than in NAC [81].

The use of fiber has also been widely recognized for improving RAC's behavior under heat. Steel fibers have been found to boost residual compressive strength and fracture toughness [82], while combinations of steel fibers with materials like crumb rubber and silica fume further strengthen thermal resistance and compressive performance. Polypropylene fibers help control explosive spalling by generating pathways for pressure release. However, they can weaken the mechanical strength when exposed to high temperatures. Basalt fibers, on the other hand, improve thermal performance by restricting crack propagation [81].

CHAPTER – 3
MATERIALS AND METHODS

3.1 Characterisation of Ingredients:

This study used a mix of materials, including RCA, BF, DE, cement, and both CA and NFA. The RCA was collected from a recycling plant of C&D waste in Indore, India. NA, with a nominal size of 20 mm, was used as reference material to compare with the recycled aggregate. Based on gradation analysis, the sand met the Zone II classification as per IS 383-2016 [91]. The specific gravity and water absorption rates were evaluated to be 2.91 and 1.51% for NCA, 2.39 and 5.67% for RCA, and 2.71 and 0.4% for sand. Standardized tests were conducted to evaluate the properties of the cement, sand, and aggregates, with the corresponding results shown in Tables 1&2. The equipment used for material characterization is illustrated in Figure 10.

Table 1 Properties of fine aggregate

Properties	Fine aggregate
Classification	Natural Sand
Gradation	Zone II
Specific gravity	2.71
Water absorption (%)	0.4

Table 2 Properties of coarse aggregate

Properties	Coarse aggregate	
	NA	RCA
Specific gravity	2.91	2.39
Water absorption (%)	1.51	5.67

The strength of grade 43 Ordinary Portland cement (OPC), which is commercially available and complies with Bureau of Indian Standards (BIS) requirements, was utilized. Table 3 displays the cement's consistency, specific gravity, specific surface area, initial setting time, and final setting time data. Table 4 displays the compositions of cement and DE (chemically) as determined by the XRF study.

Figure 10 Equipment for testing of cement, sand, and aggregate

Table 3 Properties of cement

Properties	Cement
Consistency	32%
Initial setting time	56 min
Final setting time	430 min
Specific gravity	3.125
Specific surface area	0.352 m^2/g

Table 4 Mineral composition of cement and DE

Materials	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	SO_3	TiO_2	MnO
Cement	17.07	4.95	4.78	0.91	67.6	0.25	1.73	1.67	0.56	0.17
DE	86.17	7.39	1.69	0.43	0.81	0.78	0.23	0.17	0.4	0.03

Commercially available DE powder was used in this study to assess its suitability as a treatment material. DE is categorized as Class N natural pozzolan according to ASTM C618-19 [83]. The DE exhibited a specific gravity of 0.52 g/cm^3 and a specific surface area of 68.08 m^2/g, as determined using the BET method. The high surface area of DE is confirmed by BET test results, and its porous microstructure is highlighted by SEM analysis. Furthermore, XRF analysis indicated a high silica content (Table 4), supporting its effectiveness as a filler in concrete applications.

3.2 Extraction Process of Banana Fiber:

The extraction of banana fibers is a sustainable process that utilizes agricultural waste from banana plants, typically discarded after fruit harvesting.

Figure 11 Mechanical extraction process of banana fiber

As shown in Figure 11, the process begins with the collection of banana stalks from mature plants. These stalks are rich in fibrous material and undergo a series of steps to isolate the useful fibers. Initially, the outer layers are manually or mechanically separated to expose the fibrous core. The fibrous portion is then subjected to mechanical extraction using a decorticator machine, which scrapes and isolates the long natural fibers. Following extraction, the fibers are thoroughly dried under sunlight to eliminate excess moisture and improve storage stability. The resulting banana fibers are light, strong, and biodegradable, making them an ideal natural reinforcement material for composite applications in construction.

3.3 Alkaline Treatment of Banana Fiber:

The "Fiber Region" in Chennai, India, provided the BF used in this study. These fibers were mechanically extracted from the banana stem using fiber extraction equipment. The fibers were treated with 6% alkali to eliminate hemicellulose, lignin, wax, and oil coating while also increasing surface roughness. For this treatment includes, raw BF is cut into 10mm lengths, submerged for three hours in a 6% NaOH and distilled water solution, washed BF in distilled water until PH reaches to 7, dried in an oven, and then separated into single fibers, as shown in Figure 12. The fiber measured 0.21 mm in diameter, with a density of 900 kg/m^3, moisture content of 12.5%, and a tensile strength of 58.4 MPa, after treatment of BF.

Figure 12 Treatment process of banana fiber

3.4 Slurry Treatment of RCA:

The study suggests improving RCA characteristics using DE slurry with BF reinforced treatment. The slurry was made from proposed treated BF, DE, and cement. The treatment of surface of RCA with slurries differ depending on the DE and BF proportions, with 0%, 1%, 3%, 5%, and 7% fiber dosages. Each slurry included 5% DE, as reported in related previous studies. The effects of DE with cement as filler materials were compared with control, only cement slurry treated RCA. The slurry had a water to binder ratio of 0.5. Table 5 provides the banana fiber, DE, and OPC dosages for making 100g of the BF reinforced DE slurry. The slurry type was defined by RCA and treated with the slurry as RA-DE/BF, as shown in Table 5.

Table 5 Slurry composition

Slurry type	RA-CT	RA-5/0	RA-5/1	RA-5/3	RA-5/5	RA-5/7
DE dosage (%)	-	5	5	5	5	5
OPC Cement (%)	100	95	94	92	90	88
Banana fiber (%)	-	0	1	3	5	7
Water (%)	50	50	50	50	50	50

To evaluate the effectiveness of surface treatment, NA and RCA were utilized as controls for comparison with untreated. Figure 13 shows the process described in this study for BF reinforced DE slurry treatment of RCA. It involves steps like putting of RCA in a container and adding the required water to obtain to the saturated aggregate.

Figure 13 Treatment process of RCA

The RCA was left to be in soaked condition for 24 hours to ensure complete saturation and absorption. After 24 hours, RA was taken out and dried the surface of it for SSD condition. Its purpose is to guarantee that the water-to-binder ratio is consistent and effective before casting concrete. Similarly, BF reinforced DE slurry preparation involves mixing the necessary amount of BF, DE, and cement at the dry stage for 2 minutes before pouring it into a container containing the required amount of water. After proper mixing of ingredients for 2 minutes, the SSD RCA was dipped or immersed and stirred in this well-prepared slurry at 0.5-hour intervals to ensure uniform that each RCA particle is uniformly coated.

Following a predetermined coating duration, the aggregates are removed and enabled to cure for 3 days and to dry in a well-ventilated, sunny location. Figure 14 depicts RCA phases covered by a BF reinforced DE slurry pre-coated layer in treated RCA.

Figure 14 Treated RCA

3.5 Mix Design and Concrete Preparation:

The control concrete mixes as a reference were designed to achieve a 30 MPa targeted strength using a water to cement (w/c) ratio of 0.45, following IS 10262 [84] guidelines. The mix included 413.3 kg/m^3 of cement and 186 kg/m^3 of water, along with 1246 kg/m^3 of natural coarse aggregate and 683.8 kg/m^3 of fine aggregate. The RAC mixes were proportioned by substituting the volume of natural CA with corresponding volume of RCA, which equals 42.8%.

Table 6 Mix design of concrete

Concrete	**NAC**	**RA-UT**	**RA-CT**	**RA-5/0**	**RA-5/1**	**RA-5/3**	**RA-5/5**	**RA-5/7**
Cement	413.3	413.3	413.3	413.3	413.	413.3	413.3	413.3
NA	1246.0	-	-	-	-	-	-	-
RCA	-	1061.9	1023.4	1049.0	1027.6	1023.4	1057.6	1053.3
FA	683.8	683.8	683.8	683.8	683.8	683.8	683.8	683.8
Water	186.0	186.0	186.0	186.0	186.0	186.0	186.0	186.0

Table 6 displays the proportion of mix design for the 8 various types of concrete. All coarse aggregates were in SSD condition. Furthermore, because slurry treatment increases in cement content, the cement utilized for RCA treatment was reduced in comparison to the total cement content needed for the mix.

As illustrated in Figure 15, all specimens were fabricated and cured in accordance with the standards of IS 516 (Part 1/Sec 1):2021 [85]. Concrete mixes, as detailed in Table 6, were used to cast vibration compacted specimens of various sizes for mechanical strength testing. The specimen types included 150 mm size cubes for compressive strength tests, 150 mm × 300 mm (cylinders) for splitting tensile strength tests, and 100 mm × 100 mm × 500 mm (beams) for flexural strength tests. For each test, three specimens were prepared, resulting in a total of 96 cubes, 72 cylinders, and 72 beams, bringing the total to 240 specimens. After 24 hours of setting of concrete at room temperature, the specimens were demolded and placed in water tank for curing for 7, 14, and 28 days.

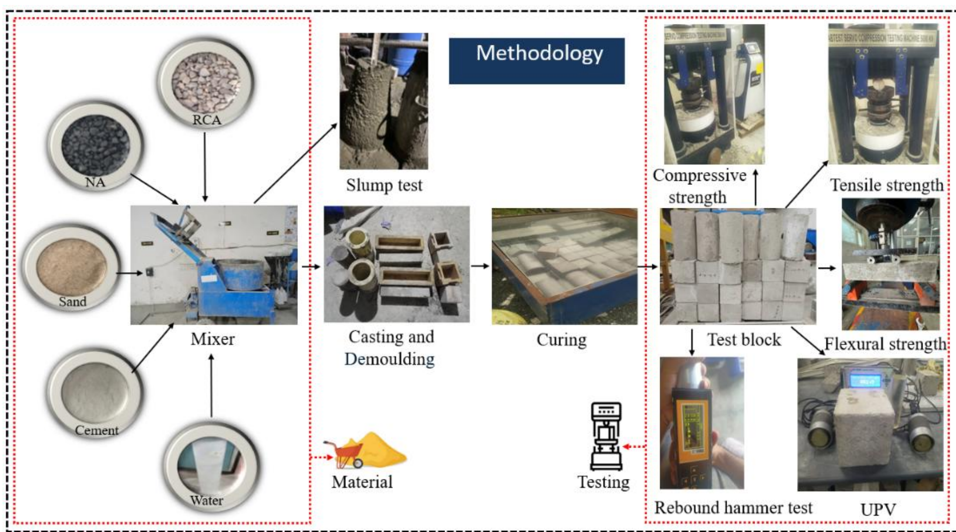

Figure 15 Methodology

3.6 Microstructural Characterization:

The microstructure of the materials was characterized by using XRD and SEM techniques. Prior to analysis, the concrete specimen was cut into a 10 mm × 10 mm × 10 mm cube to facilitate handling. The sample surface was then polished with progressively finer grits of sandpaper to achieve a smooth finish, followed by vacuum drying to eliminate moisture. The dried specimen was stored in a desiccator to maintain a moisture-free environment before testing. For XRD analysis, a portion of the concrete was ground into a fine powder using a ball mill and sieved to pass through a 75-micron mesh to ensure homogeneity. The entire equipment and process used for microstructure characterization, including sample preparation and analytical techniques, are illustrated in Figure 16. This systematic approach ensured accurate phase identification via XRD and detailed microstructural examination using SEM.

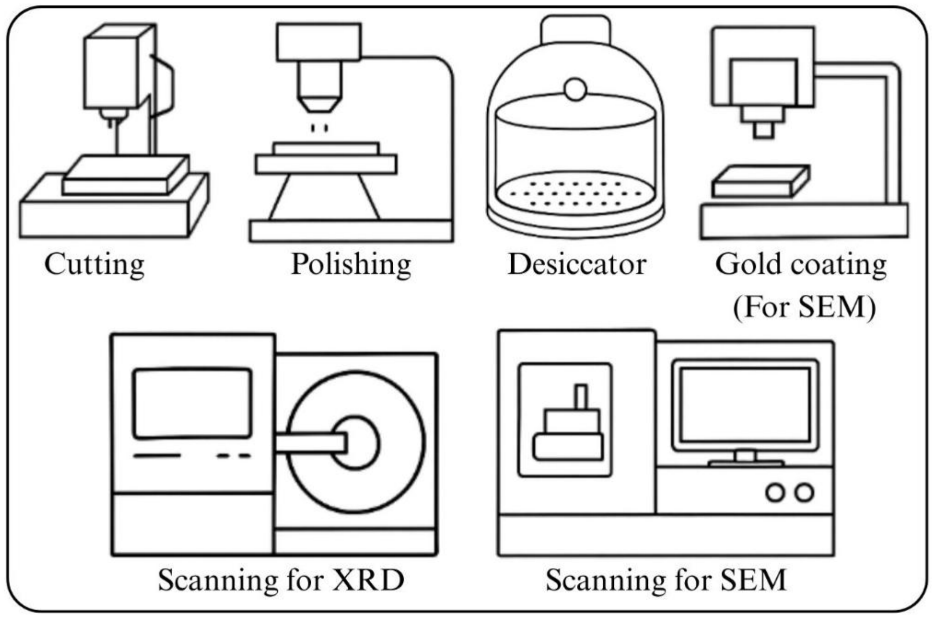

Figure 16 Methodology for microstructure characterization

3.7 Heating and Cooling Methodology:

To study the effects of high temperatures on treated and untreated RAC, the cylinder specimens heated at a controlled temperature increment rate and allowing them to cool to room temperatures. The specimens were placed in an electric furnace (measuring 47 cm × 47 cm × 43 cm) and heated from room temperature (25°C) to targeted temperatures; 200°C, 400°C, 600°C, and 800°C—following the rate of heating similar to the ISO 834 [86] standard. The temperature-time curve shown in Figure 17 indicates the heating rate of specimens.

Two cylinders were heated at a time, kept at the target temperature for one hour to ensure even heat distribution. For confirmation of uniform distribution of temperature Testo 868 thermal imager used, shown in Figure18.

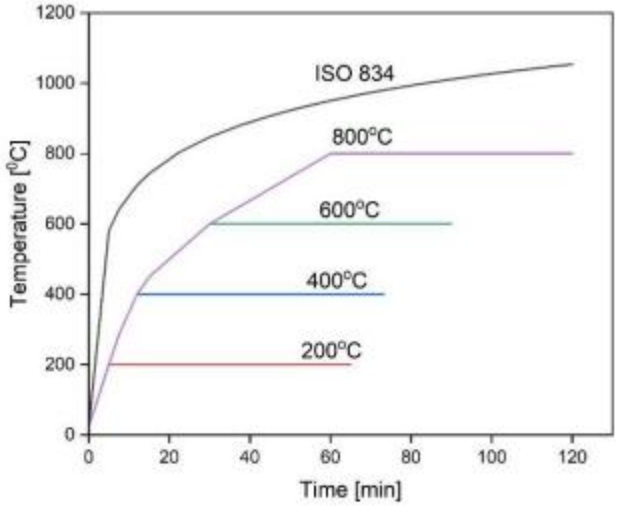

Figure 17 Temperature vs time curve

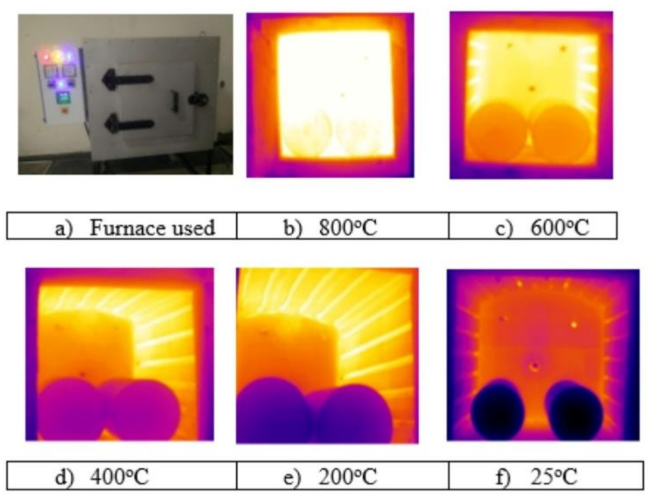

Figure 18 Thermal imaging

After heating, the furnace was turned off, but the door remained closed for an additional hour to allow gradual cooling. Once opened, the specimens continued cooling naturally to room temperature before being stored in a dry environment for 24 hours prior to testing. This method ensured consistent thermal exposure while simulating real-world fire conditions.

3.8 Physical and Transport Properties:

The methodology used to evaluate the physical and transport characteristics of concrete after exposure to elevated temperatures is illustrated in Figure 19. To evaluate the effect of high temperatures on concrete, several physical and microstructural properties were assessed. Mass loss was determined by calculating the percentage reduction in weight before and after thermal exposure. Changes in surface appearance, including color and cracking, were monitored through microscopic imaging at identical magnifications taken both before and after heating. A crack gauge meter was employed to measure the maximum crack widths, providing accurate readings up to 0.01 mm. Additionally, high-resolution microscopy enabled a detailed visual assessment of how cracks initiated and spread across the surface.

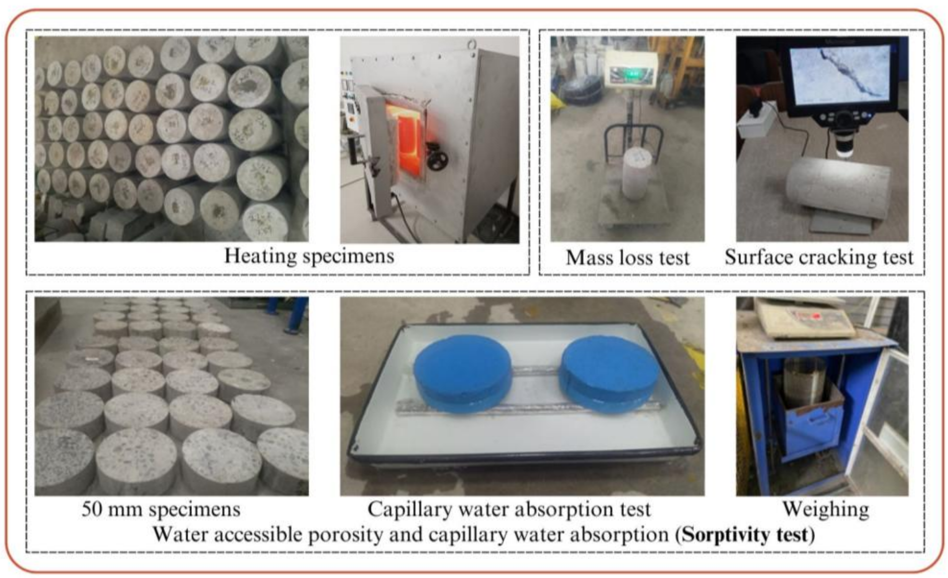

Figure 19 Methodology of temperature study

The capillary water absorption test (sorptivity test) was carried out as per EN 480-5 [87]. From each concrete cylinder (150 mm diameter of cylinder and 300 mm height of cylinder), a 50 mm thick disc was extracted. These discs were oven-dried at 105°C until a constant mass was obtained. To ensure controlled testing conditions, all surfaces except the base were sealed with epoxy resin, leaving only the bottom face exposed to water. The samples were then placed in shallow water, with the level maintained at 5 mm above the exposed surface. Weights were recorded at time intervals of 0, 0.25, 0.5, 1, 2, 4, 8, and 24 hours, using a precision scale (±0.1 g).

For water-accessible porosity, the ASTM C642-97 [88] was followed. Concrete samples were oven dried at 105°C–115°C for at least 24 hours until reaching a constant dry mass (M_A). After cooling, they were immersed in water at ~21°C for 48 hours to obtain the saturated mass (M_B). Subsequently, the specimens were boiled for 5 hours, then allowed to cool in water for no less than 14 hours, maintaining a final temperature between 20°C and 25°C. The mass in air after boiling (M_C) and the saturated submerged mass (M_D) were then measured. These values were used to calculate water absorption and porosity, representing the volume of permeable pore spaces within the concrete.

3.9 Casting of RRAC Beam for Shear Performance:

The step-by-step fabrication process of Reinforced Recycled Aggregate Concrete (RRAC) beams. The process begins with the preparation of reinforcement cages, as shown in Figure 20, which are placed inside the molds.

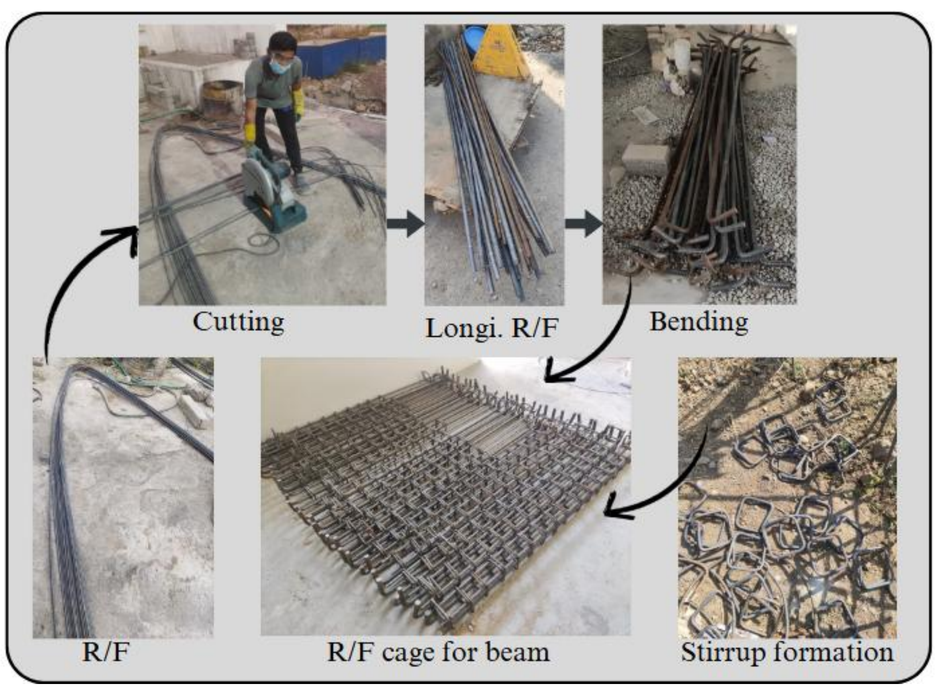

Figure 20 Reinforcement cage preparation

The entire process of beam casting is shown in Figure 21, starting with concrete filling, followed by compaction to ensure proper consolidation. After compaction, the beams undergo drying, and then demoulding and curing to facilitate strength development. The final RRAC beams are shown, ready for structural testing or application.

Figure 21 Casting of beam

3.10 Details of Beam and Test Setup:

The rectangular beams had a cross section of 150 × 200 mm and a total length of 1800 mm, as illustrated in Figure 22. The effective depth was maintained at 170 mm, resulting in a shear span to depth ratio (a/d) of 3.3. A uniform 25 mm cover of concrete was provided. To ensure under-reinforced behavior, the beams were designed with two different longitudinal reinforcement ratios: five beams were reinforced with two 16 mm bars (ρ = 1.6%), and ten beams with two 20 mm bars (ρ = 2.5%), as summarized in Table 7.

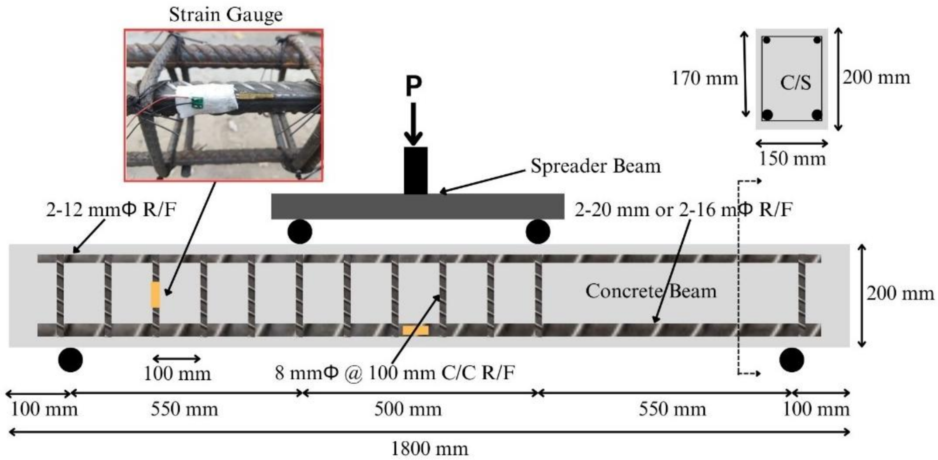

Figure 22 Cross-section of beam

Table 7 Details of beam

ID	Beam Specimen	Beam parameters		
		ρ (%)	S @ 1/3 zone	(a/d)
B1	NAC	1.6	w/out stirrups	3.3
B2	UT-RAC	1.6	w/out stirrups	3.3
B3	5/3-RAC	1.6	w/out stirrups	3.3
B4	5/5-RAC	1.6	w/out stirrups	3.3
B5	5/7-RAC	1.6	w/out stirrups	3.3
B6	NAC	2.5	w/out stirrups	3.3
B7	UT-RAC	2.5	w/out stirrups	3.3
B8	5/3-RAC	2.5	w/out stirrups	3.3
B9	5/5-RAC	2.5	w/out stirrups	3.3
B10	5/7-RAC	2.5	w/out stirrups	3.3
B11	NAC	2.5	Ø8@100	3.3
B12	UT-RAC	2.5	Ø8@100	3.3
B13	5/3-RAC	2.5	Ø8@100	3.3
B14	5/5-RAC	2.5	Ø8@100	3.3
B15	5/7-RAC	2.5	Ø8@100	3.3

In total, fifteen beams were cast and grouped into two series. The first series consisted of ten beams without stirrups—five with 16 mm bars and five with 20 mm bars. The second series comprised five beams with stirrups and 20 mm longitudinal reinforcement. In all beams, two 12 mm steel bars were provided as longitudinal reinforcement in top. For the stirrup-reinforced beams, 8 mm diameter round steel bars were used as shear reinforcement, placed along two-thirds of the beam span at 100 mm intervals.

Figure 23 Four bending test setup

To monitor the strain in the longitudinal reinforcement, strain gauges were attached at critical shear zones, as shown in Figure 22. A four point bending test setup was employed to evaluate the shear behavior of the RC beams, with the complete experimental arrangement illustrated in Figure 23.

CHAPTER – 4
RESULTS AND DISCUSSION

4.1 Effect on Physical and Mechanical Properties of Aggregate:

Table 8 presents the result of SG, WA, ACV, AIV, and AAV, of NA, untreated RCA, and treated RCA with their standard limit as per IS 2386 (Part 3&4) [89], [90].

Table 8 Physical and mechanical properties of aggregate

Mix Type	SG	WA (%)	ACV (%)	AIV (%)	ABV (%)
NA	2.91	1.51	15.63	6.57	11.54
RA-UT	2.39	5.67	28.66	23.76	27.45
RA-CT	2.4	4.21	27.21	25.15	25.03
RA-5/0	2.48	4.25	26.87	21.05	24.89
RA-5/1	2.52	5.69	26.3	21.37	23.95
RA-5/3	2.53	6.59	27.6	21.11	23.83
RA-5/5	2.6	7.69	23.49	15.9	22.95
RA-5/7	2.42	10.24	26.07	24.93	29.56
Standard Limit	2.3–2.9	≤2 IS 2386 (P-3)	≤30 IS 2386 (P-4)	≤30 IS 2386 (P-4)	≤30 IS 2386 (P-4)

NA: Natural Aggregate, RA-UT: Untreated RCA, RA-CT: Cement slurry Treated RCA, RA-5/0: DE slurry without BF reinforced treatment of RCA, RA-5/1: DE slurry with 1% BF reinforced treatment of RCA, RA-5/3: DE slurry with 3% BF reinforced treatment of RCA, RA-5/5: DE slurry with 5% BF reinforced treatment of RCA, RA-5/7: DE slurry with 7% BF reinforced treatment of RCA

4.2 Effect on Gradation:

Gradation analysis showed that all aggregate samples, including NA, untreated RCA, cement slurry treated RCA, and RCA treated with DE slurry reinforced with varying BF contents (0%, 1%, 3%, 5%, and 7%), fell within the acceptable range of maximum and minimum passing limits as specified by IS 383: 2016 [91] (Figure 24). This is attributed to the effective crushing and manufacturing processes of the local concrete waste recycling plant. The gradation curve meets the grading requirements for coarse aggregate so that the resulting concrete can be effectively utilized for structural elements. The gradation analysis indicates that treated RCA with DE slurry and BF reinforcement does not affect significantly to the particle size distribution of RCA.

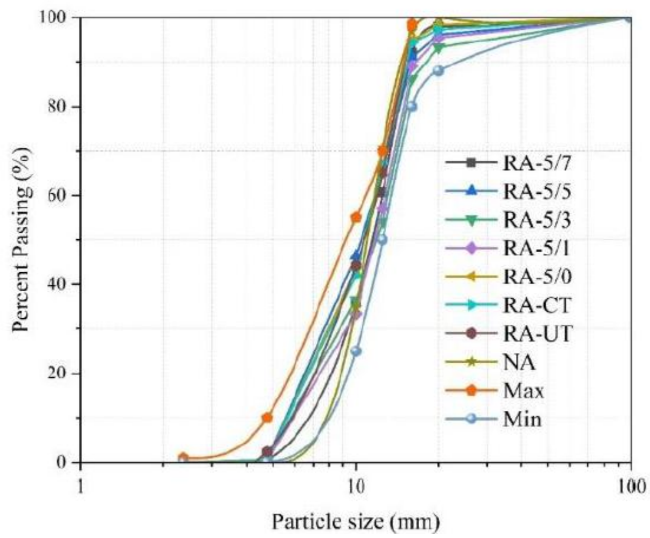

Figure 24 Gradation of aggregate

4.3 Effect on Workability:

Table 9 summarizes the slump values of various concrete mixes, indicating their workability. The NAC has the highest slump of 102 mm, demonstrating superior workability. Among RAC mixes, the control treated RAC (RAC-CT) and RAC-5/0 showed relatively higher slump values of 72 mm and 75 mm, respectively. However, the addition of fibers from 1% to 7% (RAC-5/1 to RAC-5/7) led to a gradual reduction in slump, reflecting decreased workability due to increased fiber content.

Table 9 Slump of fresh concrete

Property	**NA**	**RA-UT**	**RA-CT**	**RA-5/0**	**RA-5/1**	**RA-5/3**	**RA-5/5**	**RA-5/7**
Slump	101	61	72	75	50	55	54	50

4.4 Effect on Compressive Strength:

Figure 25 shows the results of 28 days compressive strength of concrete prepared using BF reinforced DE slurry treated RCA. The results suggest that treating the RCA surface with BF reinforced DE slurry improves its compressive strength significantly.

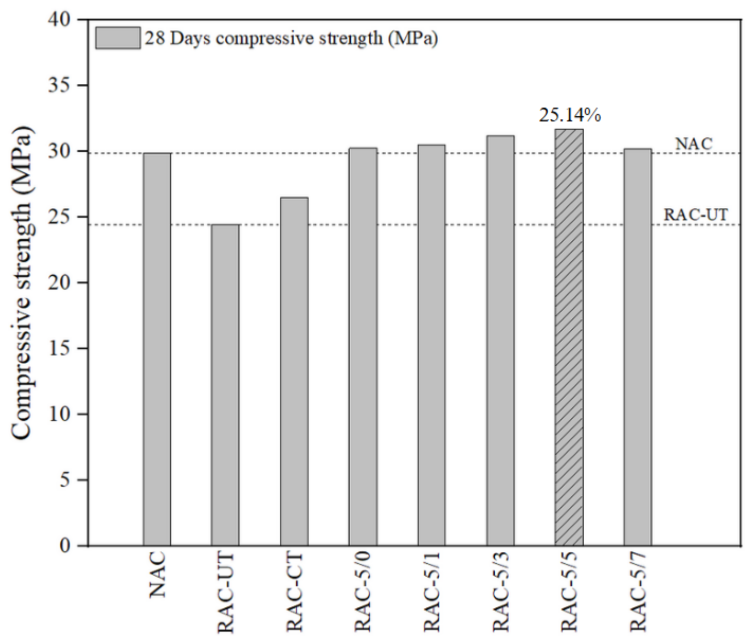

Figure 25 Compressive strength

At 28 days, the compressive strength showed improvements of 18.12% with no fiber addition, 19.15% with 1% fiber, 21.86% with 3% fiber, 25.14% with 5% fiber, and 16.55% with 7% fiber, relative to the untreated recycled aggregate concrete (RAC-UT). The use of DE slurry alone led to an 18.12% increase, while cement slurry on its own resulted in a more improvement of 3.56%. The optimal performance was observed at 5% banana fiber content, where compressive strength nearly matched that of concrete made with NA.

4.5 Effect on Tensile Strength:

Figure 26 presents the splitting tensile strength results for concrete made with BF reinforced DE slurry treated RCA. The treatment effectively enhanced the tensile strength of the RAC. When compared to the untreated RAC, which had a tensile strength of 1.91 MPa, the strength increased by

19.82% with 0% fiber, 21.61% with 1%, 27.14% with 3%, 36.58% with 5%, and 20.00% with 7% fiber content. These results highlight the effectiveness of the treatment, particularly at 5% fiber levels.

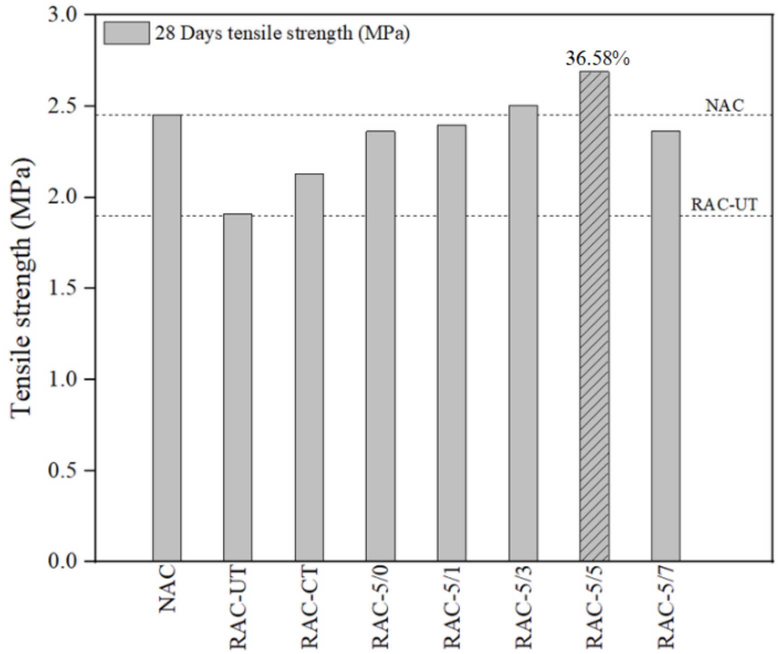

Figure 26 Tensile strength

4.6 Effect on Flexural Strength:

Figure 27 shows the flexural strength test results of treated RAC, untreated RAC, and NAC. The addition of banana fiber to the DE slurry had a notable impact on the flexural strength of the concrete. At fiber contents of 0%, 1%, 3%, 5%, and 7%, the flexural strength increased by 28.22%, 43.73%, 50.21%, 72%, and 43.76%, respectively, compared to the untreated RAC, which had a baseline flexural strength of 3.02 MPa. Among the mixes, the 5% fiber content delivered the highest improvement, indicating it as the optimal dosage for enhancing flexural performance.

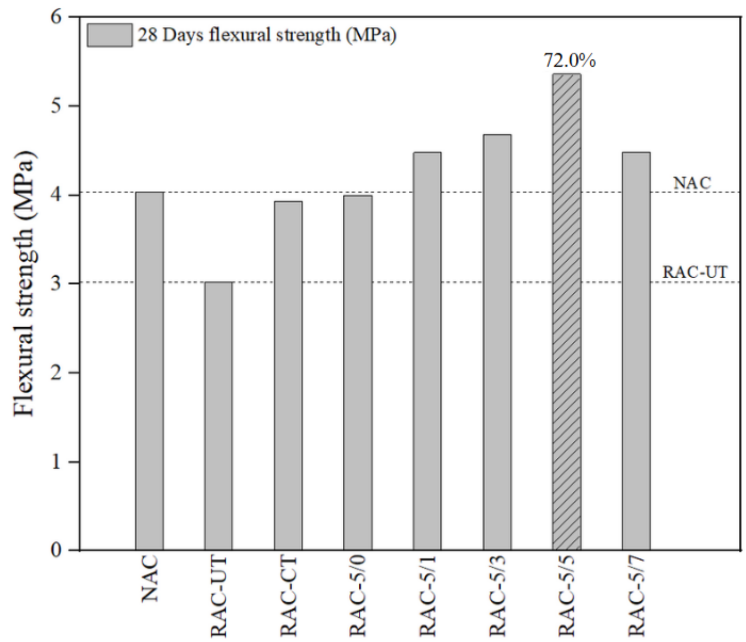

Figure 27 Flexural strength

4.7 Effect on Microstructural Properties:

X-ray Diffraction analysis is conducted to evaluate the mineralogical composition and to identify the crystalline phases present in a material. The XRD patterns of all ingredients—cement, sand, aggregates, and treated banana fiber—are presented in Figure 28. These patterns provide valuable insights into the internal structure. Notably, the sharp peaks found in the alkali treated BF show high crystallinity, which is caused by the efficient removal of contaminants such as hemicellulose, lignin surface oil, and wax during the alkali treatment process. Furthermore, the presence of amorphous silica (SiO_2), especially in supplementary materials is crucial in pozzolanic reaction. Within 7 days, it reacts with $Ca(OH)_2$ to generate additional C-S-H gels (given in Equation 1), which significantly improve the strength and durability in the composite material.

$$\mathrm{SiO_2\ (from\ DE) + Ca(OH)_2 + H_2O \rightarrow C - S - H} \qquad \text{....... (1)}$$

The schematic presentation of RCA in recycled aggregate concrete is shown in Figure 29. It illustrates the presence of all three Interfacial Transition Zones (ITZs): between new mortar and old mortar, old mortar and natural aggregate (NA), and NA and new mortar.

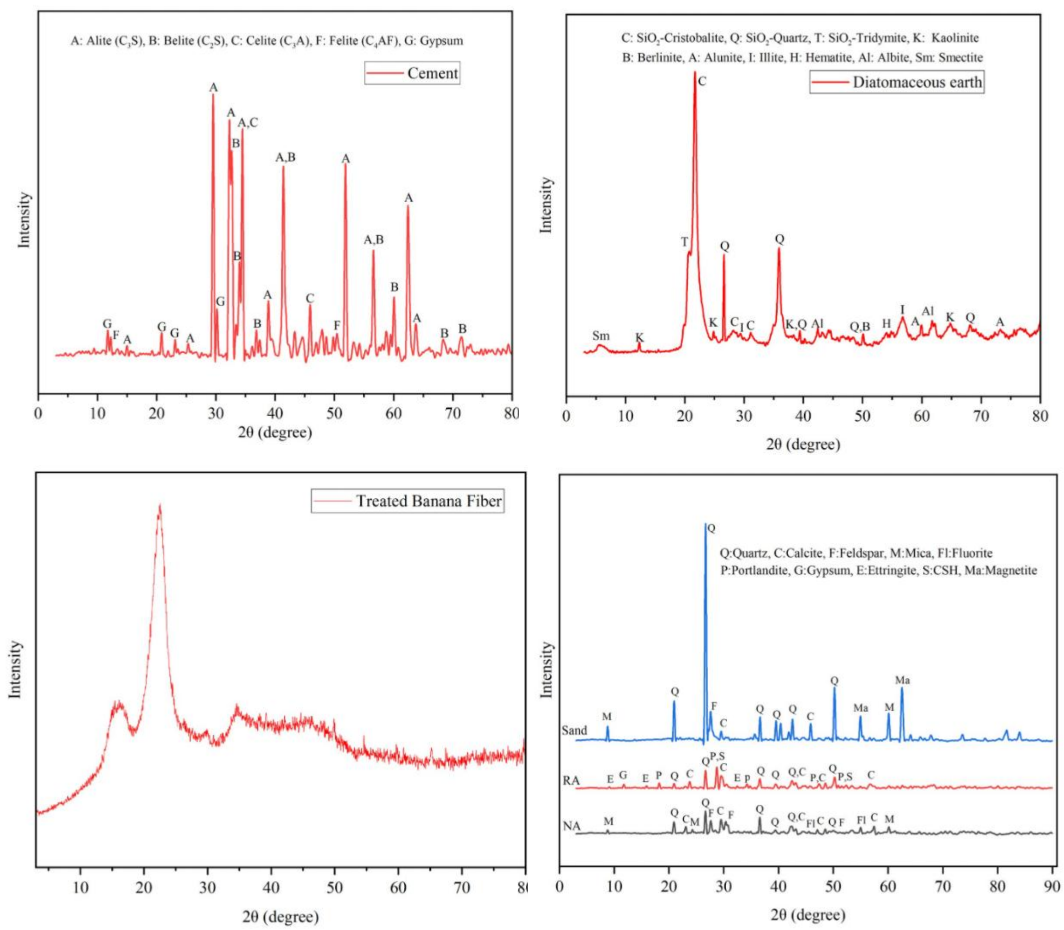

Figure 28 XRD of cement, DE, banana fiber, and aggregate

The diagram also highlights the presence of microcracks on the surface of the adhered mortar, which are characteristic of RCA due to the previous loading history and mechanical processing. These weak ITZs and surface flaws significantly influence the overall performance and durability of recycled aggregate concrete.

Scanning Electron Microscopy (SEM) analysis is used to investigate the surface of RCA has microstructural changes after different types of treatments. The SEM images in Figure 30 demonstrate a clear distinction between untreated and treated RCA.

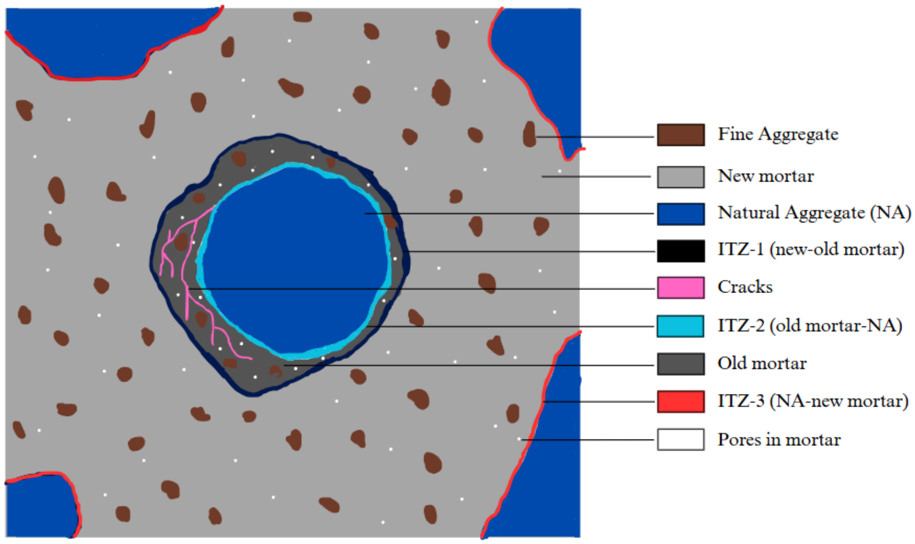

Figure 29 Schematic diagram of RCA

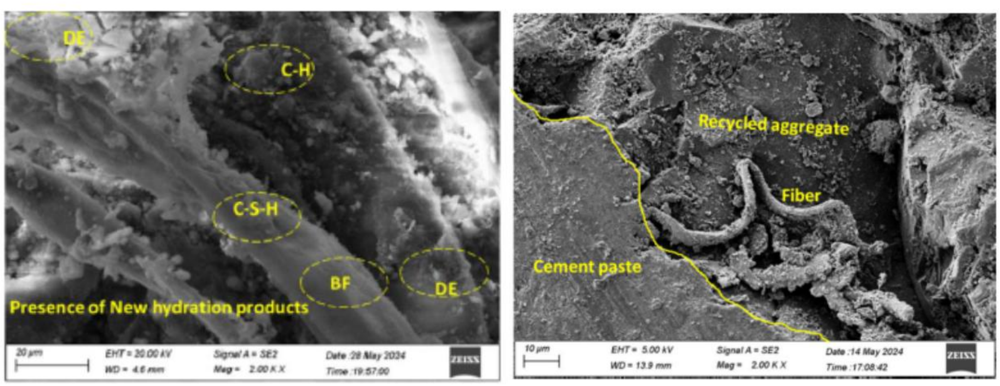

Figure 30 SEM of RA+DE+BF and 5/5-RAC

In the untreated RCA, the surface appears rough, porous, and loosely bound, with visible microcracks and attached old mortar, indicating weak interfacial zones. In contrast, the treated RCA, especially when modified with DE slurry as a filler, shows improved surface densification and crack filling, resulting in a more compact and homogeneous texture. Furthermore, the incorporation of natural fibers, such as treated banana fibers, was analyzed to evaluate their positive and negative effects on the matrix. The SEM images demonstrate better fiber dispersion and bonding in treated mixes, contributing to enhanced interfacial transition zones (ITZ). Overall, the treatment leads to improved microstructure, reduced porosity, and enhanced bond characteristics, which are crucial for the mechanical performance and durability of recycled aggregate concrete.

4.8 Effect on Mass Loss After Subjected to Elevated Temperatures:

The concrete behavior at elevated temperatures reveals a series of physical and chemical changes shown in Figure 31&32.

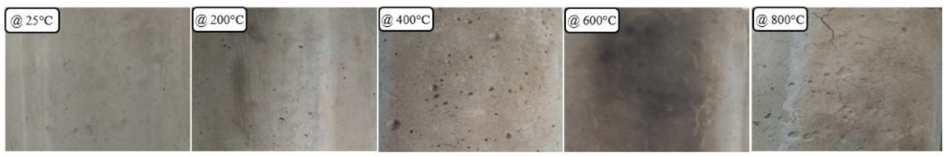

Figure 31 Color change

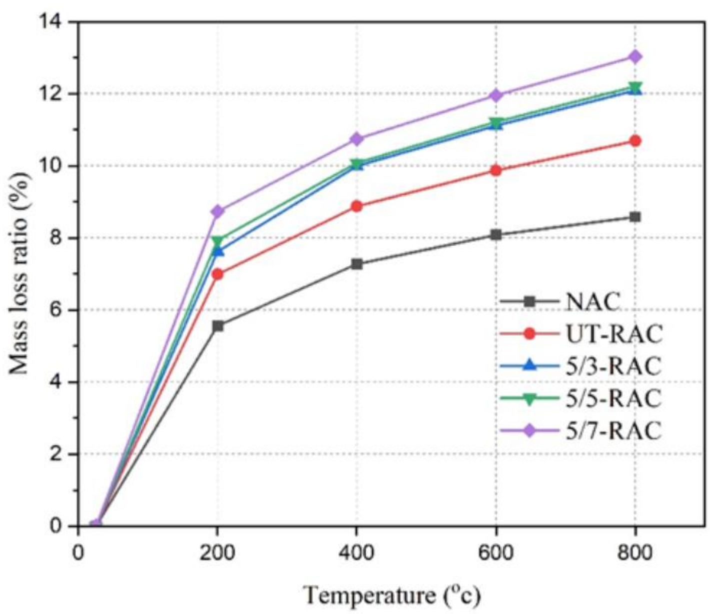

Figure 32 Mass loss

At room temperature (≈ 25°C), the surface remains gray, indicating chemical stability. At 200°C, there is no significant color change, but minor microstructural changes occur due to water evaporation. At 400°C, the concrete turns pink/reddish because of the oxidation of iron compounds, typically from riverbed sand and siliceous aggregate. At 600°C, the color changes to yellow/buff, reflecting the decomposition of calcium hydroxide ($Ca(OH)_2$). At 800°C, the concrete becomes whitish gray because of C-S-H dehydration and the breakdown of calcareous materials. In the case of banana fiber incorporation, black discoloration appears due to carbon release from fiber combustion, indicating thermal degradation of organic fibers.

4.9 Effect on Transport Properties at Elevated Temperatures:

Transport properties, including water-accessible porosity and capillary water absorption (sorptivity), are essential for assessing the durability of concrete. Sorptivity is a function of the square root of time, representing the rate at which water is absorbed by capillary action. In treated Recycled Aggregate Concrete (RAC), both porosity and sorptivity values are significantly lower compared to untreated RAC, indicating better resistance to water ingress. Sorptivity typically increases steadily up to 8 hours, after which it becomes nearly constant across all temperature ranges. However, under elevated temperatures, factors such as thermal expansion, moisture loss, and microcrack formation degrade the cement matrix and increase void interconnectivity, negatively impacting transport properties.

4.10 Effect on Shear Performance of RRAC Beam:

The Shear Force Diagram (SFD) and Bending Moment Diagram (BMD) for the four point bending test are shown in Figure 33. The ratio of experimental to predicted shear force is consistently higher than one, indicating that the IS 456 [92] design code underestimates the actual shear capacity of treated RRAC beams. This suggests a higher inherent factor of safety in IS 456 [92] based calculations when applied to these types of modified concrete. The empirical equation used for calculating the predicted shear force as per IS 456 [92] is presented in Equation 2.

$$v_c = \frac{0.85\sqrt{f_c}\,(\sqrt{1+5\beta}-1)}{6\beta} \quad \text{where} \quad \beta = \frac{0.8 f_c}{6.89\rho_s} > 1 \qquad \ldots\ldots (2)$$

The shear performance of treated Recycled Aggregate Concrete (RRAC) beams shows a clear improvement over untreated RAC (UT-RAC), validating the effectiveness of the treatment strategy.

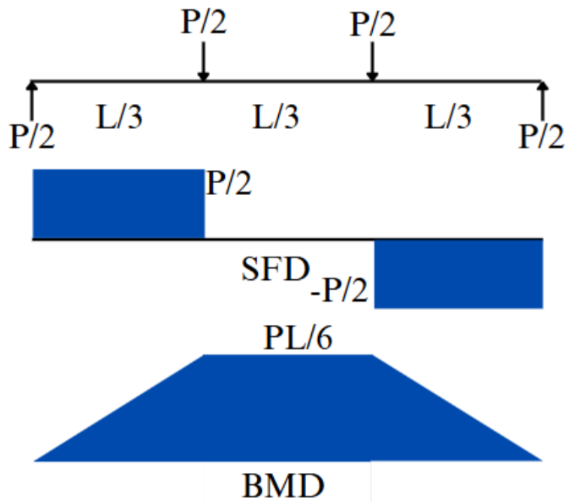

Figure 33 SFD and BMD

Table 10 presents the experimentally tested shear force, predicted shear force using IS 456 [92], and the ratio of experimental to predicted shear force for all fifteen beams.

In beams without stirrups, the 5/5-RAC mix exhibited a 16.12% increase in shear strength at a 1.6% reinforcement ratio and a 22.22% increase at a 2.5% reinforcement ratio compared to UT-RAC. Even with stirrups, the 5/5-RAC mix achieved a 13.33% enhancement. These improvements are due to the combined action of DE, which improves the ITZ, and banana fibers, which help in crack bridging and shear failure resistance. In contrast, higher fiber content (e.g., 7%) led to fiber agglomeration and increased void formation, ultimately reducing strength.

Table 10 Shear performance of RRAC beam

ID	Mix	F_c MPa	ρ (%)	P_u (kN)	V_{test} (kN)	$V_{pred.}$ (kN)	$V_{test}/V_{pred.}$
B1	NAC	29.18	1.6	165	82.5	26.1	3.2
B2	UT-RAC	24.72	1.6	155	77.5	25.4	3
B3	5/3-RAC	29.05	1.6	170	85	26	3.3
B4	5/5-RAC	30.89	1.6	180	90	26.3	3.4
B5	5/7-RAC	28.18	1.6	160	80	25.9	3.1
B6	NAC	29.18	2.5	215	107.5	30.3	3.5
B7	UT-RAC	24.72	2.5	180	90	29.4	3.1
B8	5/3-RAC	29.05	2.5	205	102.5	30.3	3.4
B9	5/5-RAC	30.89	2.5	220	110	30.6	3.6
B10	5/7-RAC	28.18	2.5	190	95	30.1	3.2
B11	NAC	29.18	2.5	265	132.5	30.3	4.4
B12	UT-RAC	24.72	2.5	225	112.5	29.4	3.8
B13	5/3-RAC	29.05	2.5	235	117.5	30.3	3.9
B14	5/5-RAC	30.89	2.5	255	127.5	30.6	4.2
B15	5/7-RAC	28.18	2.5	240	120	30.1	4

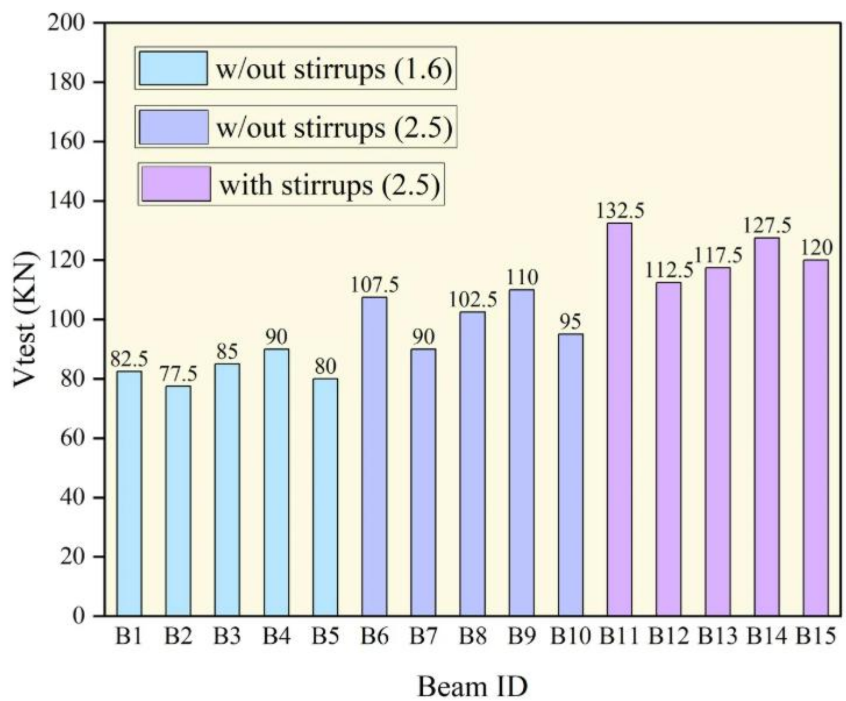

Figure 34 Shear strength of RRAC beam

Figure 34 shows the shear behavior of all tested beams, highlighting the performance trends. Therefore, 5% fiber content is identified as the optimum dosage, offering the best balance between mechanical performance, structural reliability, and workability in treated RRAC for structural applications.

4.11 Effect on Failure Pattern of Shear Behaviour of RRAC Beam:

The failure pattern of RRAC beams under shear, as illustrated in Figure 35, predominantly exhibited diagonal shear cracking originating near the support and propagating toward the loading point. This is characteristic of typical shear failure, where inclined cracks develop due to high shear stress in the web region.

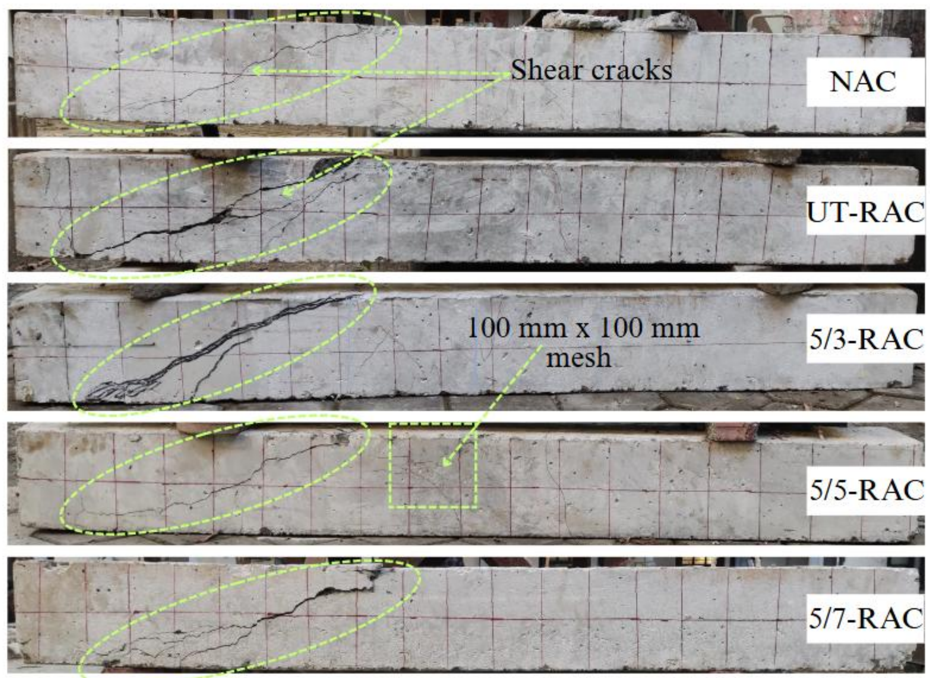

Figure 35 Failure patterns of RRAC beam

In beams without stirrups, cracking occurred more abruptly and extended rapidly, indicating brittle failure. Conversely, beams with fiber reinforcement showed improved crack distribution and reduced crack widths, highlighting the role of fibers in bridging microcracks and enhancing post-cracking behavior. The presence of banana fibers contributed to better energy absorption and delayed crack propagation, particularly at the optimum 5% fiber dosage.

CHAPTER – 5
CONCLUSION

- BF reinforced DE slurry treatment improves aggregate characteristics by increasing specific gravity through dense coating, reducing porosity. It lowers crushing, impact, and abrasion values, indicating improved strength. However, water absorption rises due to the fibrous nature of the fibers. Particle size distribution remains consistent. A 5% fiber content provides optimal performance.

- The treatment of RCA using BF reinforced DE slurry significantly enhances the compressive strength of concrete at the optimal 5% fiber content. Compared to untreated recycled aggregate concrete, compressive strength increases by 25.14%, tensile strength by 36.58%, and flexural strength by 72% at 28 days. These enhancements are attributed to improved bonding, reduced porosity, and the fiber's bridging action. However, excessive fiber content beyond the optimal level reduces the strength.

- This approach offers a sustainable, economical, and practical solution. By utilizing waste banana fibers and naturally occurring diatomaceous earth, it reduces reliance on natural aggregates and promotes sustainable construction. The treatment process is relatively simple and can be easily integrated into existing recycling workflows, making it a viable solution for enhancing the quality of recycled aggregates.

- Concrete made with BF reinforced DE slurry treated RCA shows reduced water absorption and porosity compared to untreated RAC. The concrete remains effective up to 400 °C, due to the filler effect of DE and the reinforcing role of BF, which together enhance their durability under high temperatures.

- From an application perspective, the optimal mix (5/5-RAC) demonstrated notable improvements in shear strength. In beams without stirrups, it achieved a 16.12% increase at a 1.6% reinforcement ratio and a 22.22% increase at 2.5% compared to untreated RAC. Even in the presence of stirrups, the 5/5-RAC mix showed a 13.33% enhancement, highlighting its effectiveness in structural applications.

CHAPTER – 6
FUTURE SCOPE

- **Long-Term Durability Studies:**

  Future research should concentrate on evaluating the long-term durability of treated RAC under actual circumstances, such as freeze-thaw cycles, chloride ingress, carbonation, and sulfate attack.

- **Optimization of DE Treatment:**

  Optimization of DE slurry to maximize pozzolanic reactivity and bond enhancing properties, especially in the ITZ, more investigation is required to refine its composition, concentration, and application technique.

- **Life cycle assessment (LCA) and sustainability:**

  A thorough LCA should be carried out to determine the suggested approach's environmental benefits. In comparison to traditional concrete, this would measure decreases in waste production, resource consumption, and carbon footprint.

- **Structural Applicability:**

  Examining how treated RAC behaves in full-scale structural components like slabs, columns will help determine whether it is feasible for use in more extensive structural applications. To support practical implementation, field-level research on workability, mix design adjustment, and construction techniques are also required.

CHAPTER – 7
REFERENCES

[1] J. Qiu, J. Wang, Z. Feng, Z. Xiao, and L. Li, "Study on the modification mechanism of recycled brick-concrete aggregate concrete based on water glass solution immersion method," *Journal of Building Engineering*, vol. 82, Apr. 2024, doi: 10.1016/j.jobe.2023.108303.

[2] S. Tafesse, Y. E. Girma, and E. Dessalegn, "Analysis of the socio-economic and environmental impacts of construction waste and management practices," *Heliyon*, vol. 8, no. 3, Mar. 2022, doi: 10.1016/j.heliyon.2022.e09169.

[3] H. Panghal and A. Kumar, "Enhancing concrete performance: Surface modification of recycled coarse aggregates for sustainable construction," *Construction Building Materials*, vol. 411, Jan. 2024, doi: 10.1016/j.conbuildmat.2023.134432.

[4] F. Amin, M. F. Javed, I. Ahmad, O. Asad, N. Khan, A. B. Khan, S. Ali, S. Abdullaev, F. A. Awwad, and E. A. A. Ismail, "Utilization of discarded face masks in combination with recycled concrete aggregate and silica fume for sustainable civil construction projects," *Scientific Reports*, vol. 14, no. 1, Dec. 2024, doi: 10.1038/s41598-023-50946-z.

[5] W. Z. Taffese, "Suitability Investigation of Recycled Concrete Aggregates for Concrete Production: An Experimental Case Study," *Advances in Civil Engineering*, vol. 2018, 2018, doi: 10.1155/2018/8368351.

[6] L. F. Nigussie, M. M. Darwish, and T. Ghebrab, "Recycling Fine Aggregate from Demolished Hollow Concrete Block for Green Concrete in Ethiopia," *Global Journal of Engineering Sciences*, vol. 3, no. 2, Sep. 2019, doi: 10.33552/gjes.2019.03.000559.

[7] H. S. Joseph, T. Pachiappan, S. Avudaiappan, N. Maureira-Carsalade, Á. Roco-Videla, P. Guindos, and P. F. Parra, “A Comprehensive Review on Recycling of Construction Demolition Waste in Concrete,” Mar. 01, 2023, *MDPI*. doi: 10.3390/su15064932.

[8] S. Sai Trivedi, K. Snehal, B. B. Das, and S. Barbhuiya, “A comprehensive review towards sustainable approaches on the processing and treatment of construction and demolition waste,”Aug. 22, 2023, *Elsevier Ltd*. doi: 10.1016/j.conbuildmat.2023.132125.

[9] S. Yehia, K. Helal, A. Abusharkh, A. Zaher, and H. Istaitiyeh, “Strength and Durability Evaluation of Recycled Aggregate Concrete,” *Int J Construction Structural Materials*, vol. 9, no. 2, pp. 219–239, Jun. 2015, doi: 10.1007/s40069-015-0100-0.

[10] “Sand and sustainability: Finding new solutions for environmental governance of global sand resources,” 2019. [Online]. Available: http://www.unepgrid.ch/

[11] N. Lawson, I. Douglas, S. Garvin, C. Mcgrath, D. Manning, and J. Vetterlein, “EMH 12,2 Recycling construction and demolition wastes ± a UK perspective,” # MCB University Press, 2001. [Online]. Available: http://www.emerald-library.com/ft

[12] S. S. Kolaventi, H. Momand, T. Tadepalli, and M. V. N. Siva Kumar, “Construction waste in India: A structural equation model for identification of causes,” *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, vol. 173, no. 6, pp. 303–314, Mar. 2020, doi: 10.1680/jensu.19.00047.

[13] AggBusiness, "Growing Global Aggregates Sustainably," AggBusiness.com. https://www.aggbusiness.com/growing-global-aggregates-sustainably.

[14] J. Yin, A. Kang, P. Xiao, C. Kou, Y. Gong, and C. Xiao, “Influences of spraying sodium silicate-based solution/slurry on recycled coarse aggregate,” *Construction Building Materials*, vol. 377, May 2023, doi: 10.1016/j.conbuildmat.2023.130924.

[15] J. Los Santos-Ortega, E. Fraile-García, and J. Ferreiro-Cabello, “Environmental and Economic Viability of Using Concrete Block Wastes from a Concrete Production Plant as Recycled Coarse Aggregates,” *Materials*, vol. 17, no. 7, Apr. 2024, doi: 10.3390/ma17071560.

[16] Q. Peng, C. Xi, N. Wang, and F. Ren, “Discussion on Management-and-Control Mode for Precise Disposal of Construction and Demolition Waste,” in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, Aug. 2020. doi: 10.1088/1755-1315/555/1/012061.

[17] W. Z. Taffese and K. A. Abegaz, “Embodied energy and CO2 emissions of widely used building materials: The Ethiopian context,” *Buildings*, vol. 9, no. 6, 2019, doi: 10.3390/BUILDINGS9060136.

[18] Y. Ji and H. Zhang, “Frost resistance investigation of fiber reinforced recycled brick aggregate cementitious materials,” *Scientific Reports*, vol. 12, no. 1, Dec. 2022, doi: 10.1038/s41598-022-19006-w.

[19] T. Ding, J. Xiao, and V. W. Y. Tam, “A closed-loop life cycle assessment of recycled aggregate concrete utilization in China,” *Waste Management*, vol. 56, pp. 367–375, Oct. 2016, doi: 10.1016/j.wasman.2016.05.031.

[20] J. Sivamani, N. Thurvas Renganathan, and S. Palaniraj, “Enhancing the quality of recycled coarse aggregates by different treatment techniques-a review”, doi: 10.1007/s11356-021-16428-3/.

[21] Y. Ding, J. Wu, P. Xu, X. Zhang, and Y. Fan, “Treatment Methods for the Quality Improvement of Recycled Concrete Aggregate (RCA) - A Review,” *Journal Wuhan University of Technology, Materials Science Edition*, vol. 36, no. 1, pp. 77–92, Feb. 2021, doi: 10.1007/s11595-021-2380-3.

[22] G. Sua-Iam and N. Makul, “Potential Future Direction of The Sustainable Production of Precast Concrete with Recycled Concrete Aggregate: A Critical Review,” Apr. 01, 2024, *Engineered Science Publisher*. doi: 10.30919/es1075.

[23] Bhartesh and G. J. Singh, “High-quality recycled concrete aggregates developed through an integrated thermomechanical approach,” *J Sustainable Cement Based Materials*, vol. 13, no. 8, pp. 1132–1148, 2024, doi: 10.1080/21650373.2024.2353227.

[24] F. Muhammad, M. Harun, A. Ahmed, N. Kabir, H. R. Khalid, and A. Hanif, “Influence of bonded mortar on recycled aggregate concrete properties: A review,” Jun. 21, 2024, *Elsevier Ltd*. doi: 10.1016/j.conbuildmat.2024.136564.

[25] M. Allal, L. Zeghichi, and K. Larkat, “Improvement of mechanical and interfacial properties (ITZ) of concrete based on treated recycled aggregates,” *Studies in Engineering and Exact Sciences*, vol. 5, no. 1, pp. 955–973, Apr. 2024, doi: 10.54021/seesv5n1-050.

[26] D. Sun, X. Fan, Y. Xie, X. Ren, F. Ding, R. Wu, and H. Ji, “Experimental study and multi-objective optimization of the shear mechanical properties of recycled aggregate concrete with hybrid fibers and nano SiO2,” *Construction Building Materials*, vol. 429, May 2024, doi: 10.1016/j.conbuildmat.2024.136463.

[27] C. Medina, W. Zhu, T. Howind, M. I. Sánchez De Rojas, and M. Frías, “Influence of mixed recycled aggregate on the physical-mechanical properties of recycled concrete,” *Journal of Cleaner Production*, vol. 68, pp. 216–225, Apr. 2014, doi: 10.1016/j.jclepro.2014.01.002.

[28] H. G. Gebremariam, S. Taye, and A. G. Tarekegn, “Parent Concrete Strength Effects on the Quality of Recycled Aggregate Concrete: A Review,” Feb. 29, 2024, *Elsevier Ltd*. doi: 10.1016/j.heliyon.2024.e26212.

[29] G. Bai, C. Zhu, C. Liu, and B. Liu, "An evaluation of the recycled aggregate characteristics and the recycled aggregate concrete mechanical properties," Apr. 20, 2020, *Elsevier Ltd*. doi: 10.1016/j.conbuildmat.2019.117978.

[30] H. K. Yaba, H. S. Naji, K. H. Younis, and T. K. Ibrahim, "Compressive and flexural strengths of recycled aggregate concrete: Effect of different contents of metakaolin," in *Materials Today: Proceedings*, Elsevier Ltd, 2021, pp. 4719–4723. doi: 10.1016/j.matpr.2021.01.164.

[31] P. Matar and J. Barhoun, "Effects of waterproofing admixture on the compressive strength and permeability of recycled aggregate concrete," *Journal of Building Engineering*, vol. 32, Nov. 2020, doi: 10.1016/j.jobe.2020.101521.

[32] X. Chen, X. Wu, X. Bian, Q. Wu, S. Cheng, and C. Ren, "Evaluating the physicochemical properties of pervious recycled aggregate concrete incorporating pozzolanic additives under acid rain attack," *Construction Building Materials*, vol. 411, Jan. 2024, doi: 10.1016/j.conbuildmat.2023.134507.

[33] Y. Xu, H. Chen, Y. Liang, J. Shen, and H. Yang, "Study on fracture characteristics and fracture mechanism of fully recycled aggregate concrete using AE and DIC techniques," *Construction Building Materials*, vol. 419, Mar. 2024, doi: 10.1016/j.conbuildmat.2024.135540.

[34] Z. Ma, M. Liu, Q. Tang, C. Liang, and Z. Duan, "Chloride permeability of recycled aggregate concrete under the coupling effect of freezing-thawing, elevated temperature or mechanical damage," *Construction Building Materials*, vol. 237, Mar. 2020, doi: 10.1016/j.conbuildmat.2019.117648.

[35] Y. Wang, Y. Liu, and X. Wang, "Fatigue damage evolution of modified recycled aggregate concrete," *Case Studies in Construction Materials*, vol. 20, Jul. 2024, doi: 10.1016/j.cscm.2024.e03293.

[36] J. Chen, Y. Zhou, and F. Yin, "A Practical Equation for the Elastic Modulus of Recycled Aggregate Concrete," *Buildings*, vol. 12, no. 2, Feb. 2022, doi: 10.3390/buildings12020187.

[37] Y. Zhou, J. Zhuang, W. Lin, W. Xu, and R. Hu, "Creep and Shrinkage Properties of Nano-SiO_2-Modified Recycled Aggregate Concrete," *Materials*, vol. 17, no. 8, Apr. 2024, doi: 10.3390/ma17081904.

[38] A. Basit, R. Hameed, S. Abbas, M. S. Karam, S. Shahzad, S. M. S. Kazmi, and M. J. Munir, "Impact of Recycled Concrete and Brick Aggregates on the Flexural and Bond Performance of Reinforced Concrete," *Applied Sciences (Switzerland)*, vol. 14, no. 7, Apr. 2024, doi: 10.3390/app14072719.

[39] C. Wang, J. Xiao, C. Zhang, and X. Xiao, "Structural health monitoring and performance analysis of a 12-story recycled aggregate concrete structure," *Engineering Structures*, vol. 205, Feb. 2020, doi: 10.1016/j.engstruct.2019.110102.

[40] J. Xiao, Z. Cheng, Z. Zhou, and C. Wang, "Structural engineering applications of recycled aggregate concrete: Seismic performance, guidelines, projects and demonstrations," *Case Studies in Construction Materials*, vol. 17, Dec. 2022, doi: 10.1016/j.cscm.2022.e01520.

[41] M. Ghalehnovi, A. Karimipour, A. Anvari, and J. de Brito, "Flexural strength enhancement of recycled aggregate concrete beams with steel fibre-reinforced concrete jacket," *Engineering Structures*, vol. 240, Aug. 2021, doi: 10.1016/j.engstruct.2021.112325.

[42] W. Mansour, W. Li, P. Wang, and M. Badawi, "Experimental and numerical evaluations of the shear performance of recycled aggregate RC beams strengthened using CFRP sheets," *Engineering Structures*, vol. 301, Feb. 2024, doi: 10.1016/j.engstruct.2023.117368.

[43] P. Savva, S. Ioannou, K. Oikonomopoulou, D. Nicolaides, and M. F. Petrou, "A mechanical treatment method for recycled aggregates and its effect on recycled aggregate-based concrete," *Materials*, vol. 14, no. 9, May 2021, doi: 10.3390/ma14092186.

[44] H. Wu, C. Liang, Z. Zhang, P. Yao, C. Wang, and Z. Ma, "Utilizing heat treatment for making low-quality recycled aggregate into enhanced recycled aggregate, recycled cement and their fully recycled concrete," *Construction Building Materials*, vol. 394, Aug. 2023, doi: 10.1016/j.conbuildmat.2023.132126.

[45] G. Dimitriou, P. Savva, and M. F. Petrou, "Enhancing mechanical and durability properties of recycled aggregate concrete," *Construction Building Materials*, vol. 158, pp. 228–235, Jan. 2018, doi: 10.1016/j.conbuildmat.2017.09.137.

[46] D. Prasad, A. Pandey, and B. Kumar, "Sustainable production of recycled concrete aggregates by lime treatment and mechanical abrasion for M40 grade concrete," *Construction Building Materials*, vol. 268, Jan. 2021, doi: 10.1016/j.conbuildmat.2020.121119.

[47] K. Oikonomopoulou, S. Ioannou, P. Savva, M. Spanou, D. Nicolaides, and M. F. Petrou, "Effect of Mechanically Treated Recycled Aggregates on the Long-Term Mechanical Properties and Durability of Concrete," *Buildings,* vol. 15, no. 8, Apr. 2022, doi: 10.3390/ma15082871.

[48] K. Pandurangan, A. Dayanithy, and S. Om Prakash, "Influence of treatment methods on the bond strength of recycled aggregate concrete," *Construction Building Materials*, vol. 120, pp. 212–221, Sep. 2016, doi: 10.1016/j.conbuildmat.2016.05.093.

[49] W. Thaue, M. Iwanami, K. Nakayama, and W. Yodsudjai, "Influence of acetic acid treatment on microstructure of interfacial transition zone and

performance of recycled aggregate concrete,” *Construction Building Materials*, vol. 417, Feb. 2024, doi: 10.1016/j.conbuildmat.2024.135355.

[50] V. W. Y. Tam, C. M. Tam, and K. N. Le, “Removal of cement mortar remains from recycled aggregate using pre-soaking approaches,” *Resources, Conservation and Recycling*, vol. 50, no. 1, pp. 82–101, Mar. 2007, doi: 10.1016/j.resconrec.2006.05.012.

[51] A. Katz, “Treatments for the Improvement of Recycled Aggregate,” *Journal of Materials in Civil Engineering*, vol. 16, no. 6, pp. 597–603, Dec. 2004, doi: 10.1061/(asce)0899-1561(2004)16:6(597).

[52] V. Bhasya and B. H. Bharatkumar, "Mechanical and Durability Properties of Concrete Produced with Treated Recycled Concrete Aggregate," *ACI Materials Journal*, vol. 115, no. 5, pp. 655–666, 2018. DOI: 10.14359/51701239.

[53] B. Lal Chauhan and G. Jail Singh, “Sustainable development of recycled concrete aggregate through optimized acid-mechanical treatment: A simplified approach,” *Construction Building Materials*, vol. 399, Oct. 2023, doi: 10.1016/j.conbuildmat.2023.132559.

[54] Y. G. Zhu, S. C. Kou, C. S. Poon, J. G. Dai, and Q. Y. Li, “Influence of silane-based water repellent on the durability properties of recycled aggregate concrete,” *Cement and Concrete Composites*, vol. 35, no. 1, pp. 32–38, Jan. 2013, doi: 10.1016/j.cemconcomp.2012.08.008.

[55] S. C. Kou and C. S. Poon, “Properties of concrete prepared with PVA-impregnated recycled concrete aggregates,” *Cement and Concrete Composites*, vol. 32, no. 8, pp. 649–654, Sep. 2010, doi: 10.1016/j.cemconcomp.2010.05.003.

[56] W. Geng, C. Li, D. Zeng, J. Chen, H. Wang, Z. Liu, and L. Liu., “Effect of epoxy resin surface-modified techniques on recycled coarse aggregate and

recycled aggregate concrete," *Journal of Building Engineering*, vol. 76, Oct. 2023, doi: 10.1016/j.jobe.2023.107081.

[57] J. Rostami, O. Khandel, R. Sedighardekani, A. R. Sahneh, and S. A. Ghahari, "Enhanced workability, durability, and thermal properties of cement-based composites with aerogel and paraffin coated recycled aggregates," *Journal of Cleaner Production*, vol. 297, May 2021, doi: 10.1016/j.jclepro.2021.126518.

[58] S. C. Kou, C. S. Poon, and F. Agrela, "Comparisons of natural and recycled aggregate concretes prepared with the addition of different mineral admixtures," *Cement and Concrete Composites*, vol. 33, no. 8, pp. 788–795, Sep. 2011, doi: 10.1016/j.cemconcomp.2011.05.009.

[59] V. W. Y. Tam and C. M. Tam, "Diversifying two-stage mixing approach (TSMA) for recycled aggregate concrete: TSMAs and TSMAsc," *Construction Building Materials*, vol. 22, no. 10, pp. 2068–2077, Oct. 2008, doi: 10.1016/j.conbuildmat.2007.07.024.

[60] R. M. Faysal, M. Maslehuddin, M. Shameem, S. Ahmad, and S. K. Adekunle, "Effect of mineral additives and two-stage mixing on the performance of recycled aggregate concrete," *J Mater Cycles Waste Manag*, vol. 22, no. 5, pp. 1587–1601, Sep. 2020, doi: 10.1007/s10163-020-01048-9.

[61] R. Kurad, J. D. Silvestre, J. de Brito, and H. Ahmed, "Effect of incorporation of high volume of recycled concrete aggregates and fly ash on the strength and global warming potential of concrete," *Journal of Cleaner Production*, vol. 166, pp. 485–502, Nov. 2017, doi: 10.1016/j.jclepro.2017.07.236.

[62] A. Kumar, G. Jail Singh, B. L. Chauhan, and R. Kumar, "Strength and Durability Performance of Recycled Aggregate Structural Concrete with

Silica Fume, Furnace Slag, and M-Fine," *Journal of Materials in Civil Engineering*, vol. 36, no. 7, Jul. 2024, doi: 10.1061/jmcee7.mteng-17547.

[63] A. Verma, V. Sarath Babu, and S. Arunachalam, "Influence of mixing approaches on strength and durability properties of treated recycled aggregate concrete," *Structural Concrete*, vol. 22, no. S1, pp. E121–E142, Jan. 2021, doi: 10.1002/suco.202000221.

[64] H. Sharma, S. K. Sharma, D. K. Ashish, S. K. Adhikary, and G. Singh, "Effect of various bio-deposition treatment techniques on recycled aggregate and recycled aggregate concrete," *Journal of Building Engineering*, vol. 66, May 2023, doi: 10.1016/j.jobe.2023.105868.

[65] J. Wang, B. Vandevyvere, S. Vanhessche, J. Schoon, N. Boon, and N. De Belie, "Microbial carbonate precipitation for the improvement of quality of recycled aggregates," *Journal of Cleaner Production*, vol. 156, pp. 355–366, Jul. 2017, doi: 10.1016/j.jclepro.2017.04.051.

[66] R. Wang, P. Jin, Z. Ding, and W. Zhang, "Surface modification of recycled coarse aggregate based on Microbial Induced Carbonate Precipitation," *Journal of Cleaner Production*, vol. 328, Dec. 2021, doi: 10.1016/j.jclepro.2021.129537.

[67] Y. Li, S. Zhang, R. Wang, Y. Zhao, and C. Men, "Effects of carbonation treatment on the crushing characteristics of recycled coarse aggregates," *Construction Building Materials*, vol. 201, pp. 408–420, Mar. 2019, doi: 10.1016/j.conbuildmat.2018.12.158.

[68] A. Katz, "Properties of concrete made with recycled aggregate from partially hydrated old concrete," *Cement and Concrete Research*, vol. 33, no. 5, pp. 703–711, May 2003, doi: 10.1016/S0008-8846(02)01033-5.

[69] H. Hu, Z. He, J. Shi, C. Liang, T.-g. Shibro, B. Liu, and S.-Y. Yang, "Mechanical properties, drying shrinkage, and nano-scale characteristics of concrete prepared with zeolite powder pre-coated recycled aggregate,"

Journal of Cleaner Production, vol. 319, Oct. 2021, doi: 10.1016/j.jclepro.2021.128710.

[70] W. M. Shaban, K. Elbaz, J. Yang, B. S. Thomas, X. Shen, L. Li, Y. Du, J. Xie, and L. Li., "Effect of pozzolan slurries on recycled aggregate concrete: Mechanical and durability performance," *Construction Building Materials*, vol. 276, Mar. 2021, doi: 10.1016/j.conbuildmat.2020.121940.

[71] H. Zhang, C. Zhang, B. He, S. Yi, and L. Tang, "Recycling fine powder collected from construction and demolition wastes as partial alternatives to cement: A comprehensive analysis on effects, mechanism, cost and CO_2 emission," *Journal of Building Engineering*, vol. 71, Jul. 2023, doi: 10.1016/j.jobe.2023.106507.

[72] J. Z. Xiao and C. Z. Zhang, "Fire Damage and Residual Strengths of Recycled Aggregate Concrete," *Key Engineering Materials*, vol. 348–349, pp. 937–940, Sep. 2007, doi: 10.4028/www.scientific.net/kem.348-349.937.

[73] C. J. Zega and A. A. Di Maio, "Recycled concrete exposed to high temperatures." [Online]. Available: www.concrete-research.com

[74] H. Yang, Y. Qin, Y. Liao, and W. Chen, "Shear behavior of recycled aggregate concrete after exposure to high temperatures," *Construction Building Materials*, vol. 106, pp. 374–381, Mar. 2016, doi: 10.1016/j.conbuildmat.2015.12.103.

[75] D. Cree, M. Green, and A. Noumowé, "Residual strength of concrete containing recycled materials after exposure to fire: A review," 2013. doi: 10.1016/j.conbuildmat.2013.04.005.

[76] S. R. Sarhat and Edward. G. Sherwood, "Residual Mechanical Response of Recycled Aggregate Concrete after Exposure to Elevated Temperatures," *Journal of Materials in Civil Engineering*, vol. 25, no. 11, pp. 1721–1730, Nov. 2013, doi: 10.1061/(asce)mt.1943-5533.0000719.

[77] C. Laneyrie, A. L. Beaucour, M. F. Green, R. L. Hebert, B. Ledesert, and A. Noumowe, “Influence of recycled coarse aggregates on normal and high-performance concrete subjected to elevated temperatures,” *Construction Building Materials*, vol. 111, pp. 368–378, May 2016, doi: 10.1016/j.conbuildmat.2016.02.056.

[78] C. J. Zega and A. A. Di Maio, “Recycled concrete made with different natural coarse aggregates exposed to high temperature,” *Construction Building Materials*, vol. 23, no. 5, pp. 2047–2052, May 2009, doi: 10.1016/j.conbuildmat.2008.08.017.

[79] D. Anupama Krishna, R. S. Priyadarsini, and S. Narayanan, “Effect of elevated temperatures on the mechanical properties of concrete,” *Procedia Structural Integrity*, Elsevier B.V., 2019, pp. 384–394. doi: 10.1016/j.prostr.2019.05.047.

[80] M. S. Cülfik and T. Özturan, “Mechanical properties of normal and high strength concretes subjected to high temperatures and using image analysis to detect bond deteriorations,” *Construction Building Materials*, vol. 24, no. 8, pp. 1486–1493, Aug. 2010, doi: 10.1016/j.conbuildmat.2010.01.020.

[81] D. Cree, M. Green, and A. Noumowé, “Residual strength of concrete containing recycled materials after exposure to fire: A review,” 2013. doi: 10.1016/j.conbuildmat.2013.04.005.

[82] J. P. B. Vieira, J. R. Correia, and J. De Brito, “Post-fire residual mechanical properties of concrete made with recycled concrete coarse aggregates,” *Cement and Concrete Research*, vol. 41, no. 5, pp. 533–541, May 2011, doi: 10.1016/j.cemconres.2011.02.002.

[83] “Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete,” Jan. 01, 2019, *ASTM International, West Conshohocken, PA*. doi: 10.1520/C0618-19.

[84] Bureau of Indian Standards, M. Bhavan, B. Shah, and Z. Marg, " IS 10262 (2019): Concrete Mix Proportioning-Guidelines" [Online]. Available: www.bis.org.inwww.standardsbis.in New Delhi, India.

[85] Bureau of Indian Standards, " IS 516 (2021): Hardened Concrete-Methods of Test Part 1 Testing of Strength of Hardened Concrete Section 1 Compressive, Flexural and Split Tensile Strength (First Revision),". [Online]. Available: www.standardsbis.in, New Delhi, India.

[86] "ISO 834: INTERNATIONAL STANDARD." [Online]. Available: https://standards.iteh.ai/catalog/standards/sist/9f6ee18c-6c7a-465c-b3e9-

[87] "BS EN 480-5 (2005): Admixtures for concrete, mortar and grout-Test methods,".

[88] "ASTM C642: Standard Test Method for Density, Absorption, and Voids in Hardened Concrete,".

[89] Bureau of Indian Standards, "IS 2386-3 (1963): Methods of test for aggregates for concrete, Part 3: Specific gravity, density, voids, absorption and bulking." New Delhi, India.

[90] Bureau of Indian Standards, "IS 2386-4 (1963): Methods of test for aggregates for concrete, Part 4: Mechanical properties." New Delhi, India.

[91] Bureau of Indian Standards, "IS 383 (2016): Coarse and Fine Aggregate for Concrete" – Specification, 6th Revision, New Delhi, India.

[92] Bureau of Indian Standards, "IS 456 (2000): Plain and Reinforced Concrete - Code of Practice." New Delhi, India.