EXPERIMENTAL INVESTIGATIONS ON STRUCTURAL ASPECTS OF CONCRETE MADE WITH C&D WASTE

A Thesis Submitted
in Partial Fulfillment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY
in
Civil Engineering

by
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March, 2025

ACKNOWLEDGEMENT

I express my heartfelt gratitude to the Almighty for bestowing blessings upon me, enabling the successful completion of this thesis. I extend my thanks to all those who have been pillars of support and served as the driving force behind the realization of this thesis. My appreciation for them is conveyed in the following lines.

Foremost, I extend my deepest gratitude and special thanks to my supervisor, Dr. Awadhesh Kumar, Professor in the Department of Civil Engineering, Delhi Technological University, Delhi, for his unwavering support. Your invaluable guidance throughout my Ph.D. duration, especially during challenging times, is unforgettable. Your motivation and leadership are unparalleled, and words cannot adequately express my gratitude for your support and cooperation. The knowledge and wisdom gained under your mentorship will continue to guide me in my future endeavors.

Special thanks go to Dean Academic (PG), Prof. Rinku Sharma for providing me with this opportunity. I sincerely thank the department head, Prof. K. C. Tiwari for his assistance during my Ph.D. duration. The cooperation and assistance from the faculty members of the Department of Civil Engineering, Delhi Technological University are deeply appreciated. I extend my sincere gratitude to SRC members Prof. Asif Hussain, Department of Civil Engineering, Jamia Millia Islamia, New Delhi; Dr. Rajeev Goel, Chief Scientist & Head, Engineering Services Division, Central Road Research Institute, Delhi; Prof. Alok Verma, Department of Civil Engineering, DTU; Prof. Sudarshan Kumar Babu Valluru, Department of Electrical Engineering, DTU; Prof. V. K. Minocha, DRC Chairman, Department of Civil Engineering, DTU, for generously sharing their knowledge and providing insightful comments.

I express my thanks to Mr. Parteek, Manager at ILFS, DMRC C&D Waste Plant Ranikhera Mundka, Delhi, for his unwavering support during my research. Special acknowledgment goes to Mr. Narender Goel and Mr. Radhey, Laboratory In-charge at ADCO Testing Pvt. Ltd. Ghaziabad, for their support by timely testing of samples.

My deepest gratitude goes to Mr. Harsh and Mr. Divyanshu, Lab Incharges, for their support during my SEM and XRD testing at the University Science Instrumentation Center, University of Delhi.

I extend my thanks to all my friends, including Dr. Nitin Kumar Lamba, Dr. Rahul Kumar Meena, Dr. Sombir Kundu, Dr. Sunil Kadyan, Mr. Aditya Apurva, Mr. Harish (PG Section), Mr. Nikhil, Mr. Bharamjeet, Mr. Ankit Rana, Mr. Harsh Kumar, Mr. Manoj, Mr. Shivam, and Mr. Parshant, for providing valuable suggestions and assistance, whenever needed.

I cannot adequately express my love and gratitude to my family members, who have supported and encouraged me throughout this duration. I extend special thanks to my parents, Late Shri Satyanarayan Singh and Smt. Kamla Devi, for their blessings. Words are insufficient to convey the depth of appreciation for the unwavering support of my mother, Smt. Kamla Devi. Her love, steadfast support, and role as my backbone have been immeasurable, especially in shouldering the stress during my journey. My gratitude also goes to my sisters Poonam Devi, Savita Rani, and Jyoti for their unwavering support. I am grateful to friends Mr. Gaurav Gill, Mr. Prince, Mr. Puneet, and Mr. Nitin for their efforts and support during this Ph.D. journey.

I extend my gratitude to individuals not explicitly mentioned here, with whom I have had the opportunity to engage at DTU, Delhi. Their assistance, suggestions, discussions, and friendship have been invaluable. I also appreciate the timely support and documentation work provided by all the staff members at DTU, Delhi.

Harish

CANDIDATE'S DECLARATION

I, Harish, hereby certify that the work which is being presented in the thesis entitled **"Experimental Investigations on Structural Aspects of Concrete Made with C&D Waste",** in partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy, submitted in the Department of Civil Engineering, Delhi Technological University is an authentic record of my own work carried out during the period from July, 2018 to April, 2024 under the supervision of Prof. Awadhesh Kumar, Department of Civil Engineering, Delhi Technological University, Delhi, India.

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

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This is to certify that the student has incorporated all the corrections suggested by the examiners in the thesis and the statement made by the candidate is correct to the best of my knowledge.

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CERTIFICATE BY THE SUPERVISOR

Certified that **Mr. Harish (Registration No: 2K18/PHD/CE/22)** has carried out his research work presented in this thesis entitled **"Experimental Investigations on Structural Aspects of Concrete Made with C&D Waste",** for the award of **Doctor of Philosophy** from Department of Civil Engineering, Delhi Technological University, Delhi, India, under my supervision. The thesis embodies results of original work, and studies are carried out by the student himself and the content of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University/Institution.

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ABSTRACT

The present research addresses the critical imperative for sustainable waste management in the construction industry by harnessing construction and demolition (C&D) waste as Recycled Fine Aggregate (RFA) and Recycled Coarse Aggregate (RCA) in concrete production. Acknowledging the environmental advantages of RCA, persistent concerns about potential strength and durability reductions due to residual cement mortar prompt a multifaceted exploration. The study meticulously enhances RCA through a sequence of procedures: coating, chemical treatment and abrasion treatment. In the coating process, a cement paste is applied to the RCA surface. Chemical treatment entails the use of hydrochloric acid to dissolve the material adhering to the RCA surface. Abrasion treatment employs a machine to remove attached mortar from the RCA surface. This investigation explores two innovative combined treatment strategies. The first combine strategy involves chemical treatment followed by abrasion. Here, adhered mortar is weakened by immersing RCA in a 0.5mol hydrochloric acid solution, which is then removed by abrasion. The second combine strategy commences with abrasion treatment followed by cement coating; initial abrasion effectively eliminates aged mortar from the RCA surface, while subsequent modification with cement slurry provides a fresh surface.

The first stage of the research begins with material characterization using XRD, SEM, and EDAX to evaluate their microstructural characteristics, followed by evaluating the workability of fresh concrete. Afterward, attention turns to the hardened properties of concrete, encompassing factors such as compressive strength, flexural strength, split tensile strength, modulus of elasticity and diverse durability attributes such as drying shrinkage, electrical resistivity and rapid chloride ion penetration. Additionally, in-depth exploration of the microstructural properties of various concrete mixtures has been conducted through XRD and SEM analyses. The findings underscore that replacing natural coarse aggregates with surface modified RCA at varying percentages significantly enhances the mechanical strength and durability characteristics of concrete. Essential considerations for optimal replacement ratios in sustainable concrete production are identified, with a

recommended replacement of 25% for both RFA and untreated RCA instead of natural aggregates. For treated RCA (with cement slurry, abrasion, and chemical treatments), the optimal replacement range extends to 25-50%, reaching 50-75% with combined treatments.

The study evaluates various concrete mixtures incorporating recycled coarse aggregates (RCA) and different surface treatments to amplify mechanical properties and durability. Noteworthy findings include: Mixtures RFA-25 and RCA-25, containing 25% RFA and 25% untreated RCA respectively, exhibit slight strength improvements, but lower modulus of elasticity, potentially leading to increased deflection. Mixtures RCACST-25 and RCACST-50, containing 25% and 50% replacement of NCA by RCA treated with cement slurry, exhibit superior strengths, higher moduli of elasticity and increased shrinkage strain, rendering them suitable for applications necessitating robust structural integrity. Mixtures RCACT-25 and RCACT-50, containing 25% and 50% replacements of NCA by RCA treated with chemicals, showcase notable improvements in strengths, moduli of elasticity, electrical resistance and permeability, positioning them as versatile choices for diverse construction projects.

Mixtures RCAAT-25 and RCAAT-50, treated with abrasion and containing 25% and 50% replacements of NCA by RCA treated with abrasion, display significant enhancements in mechanical properties crucial for structural integrity, making them promising for challenging conditions. Mixtures RCACAT-25, RCACAT-50, and RCACAT-75, containing 25%, 50%, and 75% replacement of NCA by RCA treated with chemical and abrasion, exhibit improvements in strengths, moduli of elasticity and higher shrinkage strain, emphasizing their suitability for various construction projects with reduced corrosion risk and enhanced long-term behavior. Mixtures RCAACST-25, RCAACST-50, and RCAACST-75, containing 25%, 50%, and 75% replacement of NCA by RCA treated with abrasion and cement slurry, excelled in strength sand moduli of elasticity, with higher shrinkage strain, offering invaluable options for applications demanding robust structural integrity and durability in construction endeavors. The incorporation of recycled aggregates leads to a rise in shrinkage strain. With a higher quantity of recycled aggregates, there is a corresponding increase in shrinkage strain, necessitating greater attention is required for concrete during its initial stages to avert the onset of shrinkage cracks.

Results indicate that replacing natural aggregates with surface-modified RCA significantly improves compressive, flexural, and split tensile strength, along with enhanced modulus of elasticity and durability characteristics. Optimal replacement levels were identified: 25% for untreated RCA, 25–50% for treated RCA and 50–75% for combined treated RCA, ensuring superior mechanical performance while maintaining workability. Cost analysis highlights RCACAT-25 and RCAACST-25 as the most economical mixtures (6.78% cost reduction), followed by RCA-25 (2.18%) and RFA-25 (0.64%). Neutral-cost alternatives include RCACST-50, RCACT-50, and RCAAT-50, while RCACT-75 and RCAACST-75 offer enhanced durability with a 1.97% cost increase. These findings emphasize the economic feasibility of treated RCA, demonstrating cost benefits while maintaining structural integrity. This research advances sustainable concrete technology by promoting C&D waste utilization, reducing reliance on natural resources, and mitigating environmental impact. It offers valuable insights into the intricate relationship between surface-modified recycled aggregates and concrete properties, facilitating their integration into structural applications and supporting the transition toward greener, more resource-efficient and economically viable construction practices.

LIST OF PUBLICATIONS

<u>Details of Publications in SCI/SCIE Journals</u>

1. Harish Panghal and Awadhesh Kumar "Enhancing Durability and Strength of Concrete through an Innovative Abrasion and Cement Slurry Treatment of Recycled Concrete Aggregates," *Minerals Engineering*, Elsevier, Vol. 220, January 2025, Article 109109. DOI: 10.1016/j.mineng.2024.109109. (Citation-1)
2. Harish Panghal and Awadhesh Kumar "Enhancing Concrete Performance with Treated Recycled Aggregates: A Comparative Study of Coating, Chemical, and Abrasion Treatments," *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, Springer, Vol. 10, No. 8, 2024, pp. 1–17, Impact Factor: 1.7. DOI: 10.1007/s40996-024-01633-0. (Citation-1)
3. Harish Panghal and Awadhesh Kumar "Eco-Friendly Concrete: A Dual Surface Modification Approach for Enhanced Mechanical Performance of Recycled Coarse Aggregates," *Journal of Materials in Civil Engineering*, ASCE, Vol. 37, No. 4, 3 Feb. 2025. DOI: https://ascelibrary.org/action/10.1061/jmcee7.mteng-19054. (Citation-0)
4. Harish Panghal and Awadhesh Kumar "Recycled Coarse Aggregates in Concrete: A Comprehensive Study of Mechanical and Microstructural Properties," *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, Vol. 10, No. 8, 2024, pp. 1–17, Impact Factor: 1.7. DOI: 10.1007/s40996-024-01539-x. (Citation-5)
5. Harish Panghal and Awadhesh Kumar "Enhancing Concrete Durability and Strength: An Innovative Approach Integrating Abrasion and Cement Slurry Treatment for Recycled Coarse Aggregates," *Structural Concrete*, Vol. 10, No. 8, 2024, pp. 1–22, Impact Factor: 3. DOI: 10.1002/suco.20240038. (Citation-6)
6. Harish Panghal and Awadhesh Kumar "Examining the Structural Viability of Recycled Fine Aggregates in Sustainable Concrete," *Journal of Mechanical Science and Technology*, Vol. 38, No. 6, 2024, pp. 1–12, Impact Factor: 1.6. DOI: http://dx.doi.org/10.1007/s12206-024-0513-2. (Citation-7)

7. Harish Panghal and Awadhesh Kumar "Enhancing Concrete Performance: Surface Modification of Recycled Coarse Aggregates for Sustainable Construction," *Construction and Building Materials*, Vol. 411, 2023, pp. 1–15, Impact Factor: 7.6. DOI: 10.1016/j.conbuildmat.2023.134432. (Citation-23)
8. Harish Panghal and Awadhesh Kumar "Effects of Surface-Modified Recycled Coarse Aggregates on Concrete's Mechanical Characteristics," *Materials Research Express*, Vol. 10, No. 9, 2023, pp. 1–20, Impact Factor: 1.8. DOI: 10.1088/2053-1591/acf915. (Citation-13)
9. Harish Panghal and Awadhesh Kumar "Sustainable Concrete: Exploring Fresh, Mechanical, Durability, and Microstructural Properties with Recycled Fine Aggregates," *Periodica Polytechnica Civil Engineering*, Vol. 68, No. 2, 2024, pp. 1–16, Impact Factor: 1.5. DOI: 10.3311/PPci.22711. (Citation-6)
10. Harish Panghal and Awadhesh Kumar "Structural Aspects of Concrete Incorporating Recycled Coarse Aggregates from Construction and Demolished Waste," *Materiales de Construcción*, Vol. 74, No. 353, 2024, pp. 1–17, Impact Factor: 1.1. DOI: 10.3989/mc.2024.360023. (Citation-4)

Details of Publications in Scopus Indexed International Conferences

1. Harish Panghal and Awadhesh Kumar "Investigation of Concrete Strength and Electrical Resistivity through Incorporation of Construction and Demolition Waste Aggregates: A Novel Approach for Assessing Corrosion Vulnerability," *Conference Proceedings*, 2nd International Conference on Advances in Sustainable Construction Materials (ICASCM 2023), Vijayawada, India, December 1–2, 2023.
2. Harish Panghal and Awadhesh Kumar "Enhancing Concrete Sustainability: Assessing the Impact of Construction and Demolition Waste Aggregates on Strength and Rapid Chloride Permeability as a Durability Indicator," *E3S Web of Conferences Proceedings*, Volume 453, Article 01009 (2023), International Conference on Sustainable Development Goals (ICSDG 2023), Phagwara, India, September 29–30, 2023. DOI: 10.1051/e3sconf/202345301009.

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LIST OF SYMBOLS AND NOTATION

Abbreviation	Meaning
C&D	Construction and Demolition
GDP	Gross Domestic Product.
CPCB	Central Pollution and Control Board
LEED	Leadership in Energy and Environmental Design
RA	Recycled Aggregates
RAC	Recycled Aggregates Concrete
XRD	X-ray Diffraction
SEM	Scanning Electron Microscopy
EDAX	Energy dispersive X-Ray Analysis
CAC	Conventional Aggregates Concrete
RCA	Recycled Coarse Aggregates
SSD	Saturated Surface Dry
NAC	Natural Aggregate Concrete
DWCP	Demolished Waste Cement Powder
RSM	Response Surface Methodology
SRA	Shrinkage Reduction Admixtures
RFA	Recycled Fine Aggregates
FRCA	Fine Recycled Concrete Aggregates
HRAC	Hybrid Recycled Aggregate Concrete
RBA	Recycled Brick Aggregates
RCPT	Rapid Chloride ion Penetration Test
ASTM	American Society of Testing and Materials
NS	Nano-silica
MK	Metakaolin
RP	Recycled Powder
NCA	Natural Coarse Aggregates
MSP	Marble Sludge Powder
CRP	Crusher Rock dust Powder
SEPP	Stone Enveloped with Pozzolanic Powder

SCC	Self Compacting Concrete
TM	Triple Mixing Method
MCP	Microbial Carbonate Precipitation
AASGM	Alkali-activated Slag and Glass Powder Mortar
SF	Silica Fume
ULFC	Ultra-lightweight Foamed Concrete
SDNs	Silicon Dioxide Nanoparticles
HCl	Hydrochloric Acid
CM	Calcium Metasilicate
OPC	Ordinary Portland Cement
RCACST	Cement Slurry Treated Recycled Coarse Aggregates
RCACT	Chemical Treated Recycled Coarse Aggregates
RCAAT	Abrasion Treated Recycled Coarse Aggregates
USIC	University Science Instrumentation Centre
SMRCA	Surface Modified Recycled Coarse Aggregates
MoE	Modulus of Elasticity
NaCl	Sodium Chloride
NaOH	Sodium Hydroxide
DMRC	Delhi Metro Rail Corporation
C_3S	Tri-calcium Silicate
C_2S	Di-calcium Silicate
C_3A	Tri-calcium Aluminate
C_4AF	Tetra-calcium Alumino Ferrite
CaO	Calcium Oxide
MgO	Periclase (Magnesium Oxide)
$CaSO_4$	Calcium Sulfate
SiO_2	Quartz (Silica)
Hbl	Hornblende
$NaAlSi_3O_8$	Albite
$CaAl_2Si_2O_8$	Anorthite
H-M	Chamosite

Fe_2O_3	Hematite
$CaMg(CO_3)_2$	Dolomite
CSH	Calcium Silicate Hydrate
CH	Calcium Hydroxide
CASH	Calcium Aluminate Silicate Hydrate
ITZs	Interfacial Transition Zones
INR	Indian Rupees

CHAPTER 1

INTRODUCTION

1.1 GENERAL

The rapid increase of population has underscored the imperative for infrastructural development. The construction industry must ascend swiftly to meet the burgeoning demands effectively. Concrete, renowned for its versatility and status as a paramount construction material owing to its easily moldable nature, is projected to witness a twofold increase in consumption by the year 2050 [1]. Similarly, there is a substantial demand for mortar in the binding and plastering of masonry structures. Traditional components of concrete and mortar heavily rely on natural resources such as river sand for fine aggregates, rocks, and gravels for coarse aggregates, and lime deposits for cement clinker. Recognizing the environmental impact of this reliance, construction and demolition (C&D) waste emerges as a promising source that can sustainably ensure a consistent supply of alternative building materials. This study delves into the exploration of fine and coarse aggregate alternatives derived from C&D waste, examining their viability for utilization in concrete with a potential replacement of up to 100% of traditional aggregates [2]. This chapter not only addresses the need for alternative aggregate substitutes, but also delves into the requirements of C&D waste management, presents the problem statement, outlines the objectives of the dissertation as a means to address the issue, and provides an organizational overview of the dissertation.

1.2 CONSTRUCTION AND DEMOLITION (C&D) WASTE SCENARIO

Construction and demolition (C&D) activities play a crucial role in the global development and modernization of urban areas, generating a substantial amount of waste known as C&D Waste. This waste encompasses a diverse range of materials, including concrete, wood, metal, bricks, plastics, and more, discarded when infrastructure and buildings are being constructed, renovated, or demolished. Proper management of C&D waste has become a pressing concern due to its multifaceted environmental, economic, and social implications [3]. C&D waste significantly contributes to environmental degradation when improperly disposed of in landfills or through illegal dumping, leading to soil and groundwater pollution, habitat destruction, and increased greenhouse gas emissions, putting additional strain on natural ecosystems. Inefficient C&D waste management results in substantial economic losses, as high costs associated with its transportation, handling, and disposal. Additionally, the untapped potential for recycled represents missed opportunities for resource recovery and economic growth. Furthermore, C&D waste management has significant social consequences, negatively impacting urban quality of life when waste is improperly managed. Conversely, recycling and repurposing C&D waste materials create job opportunities and stimulate local economies, contributing positively to community development. Recognizing these challenges and opportunities, there is a growing demand for comprehensive research to utilize C&D waste effectively [4].

In India, construction and development activities are major sources of waste generation, with the government investing significantly in the construction sector, contributing to the gross domestic product (GDP) of the country. However, these activities require large quantities of natural resources and also lead to substantial waste generation. Efforts to utilize recycled aggregates date back to 1945, with increasing research focusing on the properties of concrete prepared using recycled aggregates. The construction boom in India has resulted in a considerable amount of waste, with the Central Pollution and Control Board (CPCB) reporting as individual citizen contributing to about 500 kg of C&D waste annually. The country generates approximately 23.75 million tons of C&D waste, of which only 5% is processed [5]. The use of recycled C&D waste into concrete can address the issue of waste disposal, conserve natural resources, and contribute to economic savings. As the GDP and per capita waste generation are strongly correlated, effective waste management becomes crucial for sustaining the economy and also preventing the depletion of natural resources. With the ban on river sand extraction in 2012, the cost of construction materials has increased, necessitating the efficient use of C&D waste. Recycling of C&D waste not only solves the problem of disposal, but also saves money, creates business opportunities, and conserve energy and resources [6].

This study aims to address key objectives, including the utilization of C&D waste by understanding its composition and sources, assessing the environmental impact of C&D waste management practices, analyzing financial feasibility of recycling and repurposing C&D waste materials, examining the social implications of C&D waste management, and analyzing existing policies and regulations to propose recommendations for more effective and sustainable practices. The overarching goal is to provide valuable insights into C&D waste management, promoting sustainable practices that minimize environmental harm, generate economic value, and enhance the well-being of urban communities. In conclusion, addressing the challenges and opportunities presented by C&D waste requires comprehensive research and sustainable practices. Recycling and repurposing C&D waste materials not only mitigate environmental impact, but also contribute to economic growth and community development. The responsible utilization of natural resources and the efficient management of waste are essential for sustaining economic development and environmental well-being [7].

1.3 BENEFITS OF MANAGING C&D WASTE

The effective management of C&D waste holds paramount importance due to its profound impact on environmental, economic, and social dimensions. C&D waste, originating from construction, renovation, demolition, and deconstruction activities, encompasses materials like concrete, wood, metals, asphalt, etc. The following comprehensive elaboration highlights the benefits of managing C&D waste across various dimensions:

a) **Environmental Benefits:** Proper C&D waste management is crucial for environmental conservation. Recycling and reusing materials such as concrete, wood, and metals conserve valuable natural resources, reducing the environmental impact associated with resource extraction. This lessens the strain on ecosystems, preventing habitat destruction, soil erosion, and water pollution linked to mining activities. Recycling C&D waste consumes less energy than producing new materials, leading to a decrease in energy consumption and greenhouse gas emissions. Diverting C&D waste from landfills extends its lifespan, mitigating negative environmental consequences, including the release of harmful chemicals and greenhouse gases [8].

b) **Economic Benefits:** Efficient C&D waste management yields economic advantages. Recycling and reusing materials can lower the cost of construction projects, as recycled materials are often more cost-effective than virgin resources. Additionally, the recycling and waste management sector creates job opportunities, contributing to local and regional economies. Cost reduction through recycling enhances the feasibility of construction projects, attracting investors and reducing financial burdens on builders. Proper C&D waste management also decreases waste disposal costs, leading to reduced disposal fees and transportation expenses, ultimately improving economic viability [9].

c) **Energy Savings:** C&D waste management contributes to energy efficiency and reduced greenhouse gas emissions. Recycling of C&D waste materials require less energy than extracting and manufacturing virgin resources, resulting in a smaller carbon footprint associated with construction activities. Efficient management of C&D waste significantly reduces energy requirements by minimizing dependence on energy-intensive processes such as mining, transportation, and manufacturing of virgin materials. This leads to fewer greenhouse gas emissions, aligning with global efforts to combat climate change and reduce environmental impact [10].

d) **Reduce Environmental Impact:** Proper C&D waste management mitigates environmental impacts associated with construction activities. It includes reducing dust and emissions from heavy machinery, controlling erosion, minimizing noise pollution, and preserving natural habitats. By implementing responsible waste management practices, construction sites can enhance air and water quality, reduce noise and vibration disturbances, and promote biodiversity conservation. Beyond waste disposal, C&D waste management acts as a key enabler of environmentally sustainable construction, addressing multiple facets of responsible construction practices [11].

e) **Sustainable Building Practices:** C&D waste management is a crucial component of sustainable construction practices, especially for projects pursuing Leadership in Energy and Environmental Design (LEED) certification. Achieving LEED certification necessitates significant waste reduction and diversion through recycling and reuse. The emphasis on efficient C&D waste management aligns with broader sustainability goals, contributing to resource conservation, reduced energy demand, and responsible construction practices [12].

f) **Regulatory Compliance:** Regulatory compliance is a cornerstone of C&D waste management, ensuring adherence to environmental regulations and waste management standards. Compliance is not only a legal requirement, but also demonstrates ethical responsibility and a commitment to environmental stewardship. Proper C&D waste management practices, including the identification and safe disposal of hazardous materials, prevent legal consequences, fines, and reputational damage. Compliance contributes to transparent and accountable waste management efforts [13].

g) **Public Health and Safety:** Proper C&D waste management improves public health and safety at construction sites. Hazardous materials identification and handling, reduction of physical hazards, fire prevention, control of dust, and improvement in air quality are integral components. Responsible waste management practices contribute to a safer construction environment by minimizing accidents, injuries, and disturbances. Adequate signage, training, and community engagement further enhance safety measures and reduce potential risks [14].

h) **Community and Public Relations:** Responsible C&D waste management positively impacts reputation of a construction company and community relations. Demonstrating environmental stewardship, ensuring safety, minimizing disturbances, complying with regulations, transparent communication, and community engagement contribute to a positive public image. A construction company actively embracing responsible practices, fosters trust, community support, and a favourable reputation [15].

i) **Innovation and Research:** The management of C&D waste drives innovation in recycling and waste reduction technologies. On-going research and development contribute to advancements in sustainable construction practices, including waste reduction strategies, modular construction techniques, and design for deconstruction. Collaboration with policymakers to develop regulations that encourage sustainable practices ensures continuous innovation in C&D waste management, which is driving the industry toward a greener and more resource-efficient future [16].

In conclusion, the multifaceted benefits of managing C&D waste underscore its pivotal role in promoting responsible and sustainable construction practices. From environmental preservation and economic advantages to energy savings, reduced environmental impact, support for sustainable building practices, regulatory compliance, public health and safety, positive community relations, and fostering innovation. Effective C&D waste management is integral for a responsible construction industry and ethical development [17].

1.4 RESEARCH GAP

Numerous studies have investigated the challenges associated with incorporating recycled aggregates (RA) into concrete production. However, a notable research gap still exists, specifically regarding the adverse effects on the properties and performance of old cement mortar stuck on recycled aggregates [18]. The adhered mortar significantly affects the physical and mechanical properties of recycled aggregates, leading to increased water demand and reduced load-bearing capacity. However, systematic studies quantifying its impact on the interfacial transition zone (ITZ), microstructural integrity, and long-term durability are lacking. Additionally, the variability in mortar content across different concrete grades remains unexplored. Another significant research gap lies in the effectiveness of surface treatment techniques. Various treatments, including cement slurry coating, chemical treatments, abrasion, and carbonation, have been proposed to enhance recycled aggregates. However, their comparative effectiveness, durability performance under long-term exposure, and the combined effects of multiple treatments remain insufficiently studied. Similarly, limited research has been conducted on how different surface treatments influence ITZ characteristics and bond strength in RAC. The interaction between recycled aggregates and cementitious materials requires further experimental validation using advanced techniques to better understand the underlying mechanisms affecting bond strength and overall concrete performance.

Durability challenges also pose a major concern in RAC. Issues such as drying shrinkage, cracking susceptibility, and reduced corrosion resistance in aggressive environments, including marine and sulfate-rich conditions, need further investigation. Additionally, inconsistencies in chloride penetration and carbonation test results highlight the necessity for standardized assessment protocols to ensure reliable durability evaluations. To address these gaps, this study focuses on developing innovative and cost-effective surface treatment techniques to improve recycled aggregate quality. Investigations into ITZ enhancement strategies, long-term field studies, and performance-based mix design approaches are essential to optimizing both mechanical and durability properties. Advancing these areas will promote the seamless integration of recycled aggregates into high-performance concrete applications, thereby contributing to sustainable construction practices.

1.5 OBJECTIVES OF THE STUDY

The research on integrating recycled aggregates in concrete production addresses crucial gaps, offering innovative solutions for sustainable practices and valuable insights into the sustainability goals of the construction industry. The objectives of this investigative study include:

1. To study surface treatment methodologies (including Cement Slurry Treatment, Chemical Treatment, Abrasion Treatment, and combinations thereof), aimed at mitigating the negative impacts of stuck cement mortar on the surface of recycled aggregates.
2. Feasibility and viability of incorporating surface-treated recycled aggregates into concrete construction to assess the practicality and sustainability of such

integration.

3. Evaluation of the effectiveness of surface-treated recycled aggregates with five replacements (0%, 25%, 50%, 75%, and 100%), conducting a comprehensive examination that evaluates a range of characteristics, including physical, mechanical, and microstructural properties.
4. To assess the economic feasibility of incorporating recycled aggregates in concrete by analyzing material costs, production expenses, and long-term savings. As it gives valuable insights to construction decision-makers for the adoption of a sustainable and cost-effective alternative.

1.6 SCOPE OF THE STUDY

The present study thoroughly examines C&D waste, encompassing waste characterization, resource utilization, and environmental impact assessment. It meticulously evaluates the composition, quantity, and quality of C&D waste in a specified area, identifying both non-hazardous and hazardous materials. The study explores the technical feasibility of recycling and reusing C&D waste in construction, considering factors like material quality and structural integrity [19]. Simultaneously, it delves into the environmental implications, seeking to quantify potential greenhouse gas emission reduction by diverting waste from landfills and addressing soil and water contamination risks. The economic analysis assesses tangible benefits, including cost savings for construction companies, job creation in recycling, and potential revenue from recycled materials [20]. Energy savings by incorporating recycled materials are evaluated, contributing to a significant reduction in overall energy consumption and carbon emissions. The study emphasizes waste diversion strategies to extend life spans of landfill and reduce the demand for new sites. Addressing health and safety, accurate waste characterization ensures worker safety and prevents environmental contamination [21]. Regulatory compliance/guidance aligns waste management practices with environmental regulations. Championing sustainability and the circular economy, the study actively promotes waste reduction, material reuse, and responsible resource management [22]. Lastly, the research aims to catalyze innovation in C&D waste management, providing a foundational framework for industry-leading practices, spurring recycling technology innovation, and propelling the construction sector toward a more sustainable future.

1.7 SIGNIFICANCE OF THE STUDY

The investigation into C&D waste utilization is crucial for sustainable construction and environmental stewardship. Focused on a comprehensive assessment and effective utilization of C&D waste, the research significantly contributes to environmental conservation, improvement of resource efficiency, and economic sustainability [23]. Addressing the urgent need to reduce the environmental impact of C&D waste disposal, the study employs meticulous waste characterization and utilization strategies, mitigating concerns like greenhouse gas emissions, soil contamination, and water pollution, preserving ecosystems, biodiversity, and overall environmental health [24]. In terms of resource efficiency, the research advocates for responsible management of resources through recycling and reuse, reducing demand for virgin materials, and minimizing the ecological footprint of construction activities. Economically, the study emphasizes the positive outcomes of recycling C&D waste, stimulating economic growth, creating job opportunities, lowering waste management costs, aligning economic efficiency with sustainability, and enhancing industry competitiveness [25]. Furthermore, the research highlights potential energy savings through recycled materials, contributing to an overall reduction in energy consumption and combating climate change. Waste diversion strategies extend life spans of landfill and mitigate environmental impacts, while health and safety measures ensure workers' well-being. Aligned with broader sustainability goals, the study actively promotes waste reduction, material reuse, and responsible resource management, playing a pivotal role in creating a sustainable construction industry [26]. The emphasis on innovation serves as a foundation for future advancements, and the study positively impacts community and public relations, enhancing the reputation of construction companies and fostering positive relationships [27]. In conclusion, the multifaceted significance of this study represents a critical step toward a more sustainable and responsible construction industry, benefiting both the environment and society at large.

1.8 ORGANISATION OF THESIS

The thesis is organized into the following segments comprehensively as given below:

Chapter 1 (Introduction): Chapter 1 underscores the urgency of sustainable solutions in the face of economic growth and urbanization, emphasizing pivotal role of recycling in achieving a circular economy. The chapter stresses the imperative for extensive research to advance sustainability, offering a comprehensive overview of the study, including background, objectives, scope, significance, and organization of the work.

Chapter 2 (Literature Review): Chapter 2 extensively reviews past studies on incorporating construction and demolition waste as recycled aggregates in concrete production, whether surface modified or unmodified. The literature explores diverse research, examining methodologies, outcomes, and challenges. This chapter aims to consolidate knowledge, providing insights into the potential benefits and drawbacks of recycled aggregates, setting the stage for advancements in sustainable construction, particularly with Recycled Aggregate Concrete.

Chapter 3 (Experimental Programme): Chapter 3 highlights the diverse range of constituent materials, surface modification treatment techniques, mix proportions, and testing methodologies employed in the experimental program. This section delves into the specifics of the study, providing insight into the materials chosen by evaluation of their properties and charaterization, the methodologies applied for surface modification treatments, the proportions used in mixing, and the various testing procedures adopted to assess the outcomes of the research.

Chapter 4 (Results and Discussion): Chapter 4 assess concrete performance with treated and untreated recycled aggregates. Surface modifications include individual and combined treatments. The analysis coversthe properties of fresh concrete (workability) and properties of hardened concrete (compressive strength, flexural strength, split tensile strength, modulus of elasticity) along with durability characteristics (drying shrinkage, electrical resistance, rapid chloride penetration). X-ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) coupled with Energy Dispersive X-ray Analysis (EDAX) analyses delve into microstructural properties, ensuring a comprehensive understanding of materials and their role in concrete production.

Chapter 5 (Conclusions and Future Scope of work): Chapter 5 encapsulates the conclusions drawn from the study andfuture scope of work. This section provides a summary and insights derived from the research, offering a cohesive overview of the key findings and their implications. This section offers suggestions and explores potential avenues for further research based on outcomes of the present study.

References: At last succinctly compiles and summarizes the references utilized in the study.

1.9 SUMMARY

This chapter provides a comprehensive overview of the research by outlining the background, significance, objectives, and scope of the study. The key findings from this chapter are summarized below.

a) **Importance of Sustainable Construction and C&D Waste Management:** The rapid expansion of infrastructure development has significantly increased the demand for concrete and construction materials. However, the depletion of natural resources and the environmental challenges posed by construction and demolition (C&D) waste highlight the urgent need for sustainable alternatives. Recycling C&D waste into concrete aggregates offers a viable solution to mitigate environmental impacts, conserve natural resources, and promote circular economy practices, ultimately contributing to more sustainable construction methodologies.

b) **Challenges in Managing C&D Waste:** Construction and demolition (C&D) waste is a major contributor to environmental degradation, leading to pollution and excessive landfill use. Despite ongoing efforts to recycle construction waste, only a small fraction is effectively processed, exposing inefficiencies in existing waste management systems. Additionally, the high costs and technical complexities associated with recycling processes hinder widespread adoption in the construction industry, posing a significant challenge to sustainable waste management.

c) **Research Gaps Identified:** The presence of old adhered mortar on recycled coarse aggregates (RCA) negatively impacts their physical and mechanical properties, leading to reduced concrete strength and durability. While various surface treatment techniques, including cement slurry coating, chemical treatment, and abrasion treatment, have been explored, their effectiveness in enhancing RCA performance requires further evaluation. Additionally, the long-term durability and economic feasibility of incorporating treated RCA in concrete remain areas that necessitate deeper investigation to ensure sustainable and practical implementation in the construction industry.

d) **Research Objectives and Scope:** This study aims to investigate various surface treatment methodologies to enhance the properties of recycled coarse aggregates (RCA) and improve their performance in concrete applications. The feasibility of using treated RCA will be assessed through comprehensive mechanical and durability testing to determine its structural reliability. Additionally, the research will evaluate the economic and environmental benefits of incorporating recycled aggregates in construction, ensuring sustainability and resource efficiency. To further understand the impact of surface modifications on aggregate bonding, microstructural analysis using scanning electron microscopy (SEM), X-ray diffraction (XRD), and energy-dispersive X-ray spectroscopy (EDAX) will be conducted.

e) **Thesis Structure:** The thesis is organized into five chapters, each addressing key aspects of the research. **Chapter 1** provides an introduction, outlining the research significance, objectives, and overall structure of the thesis. **Chapter 2** presents a comprehensive literature review, summarizing previous studies on recycled aggregates and their impact on concrete performance. **Chapter 3** details the experimental program, including materials, surface treatment methods, mix proportions, and testing methodologies. **Chapter 4** discusses the research findings, analyzing the performance of both treated and untreated recycled coarse aggregates (RCA) in concrete. Finally, **Chapter 5** concludes the study by summarizing key insights, discussing practical implications, and providing recommendations for future research.

This chapter establishes the foundation for the study by highlighting the need for sustainable concrete solutions and defining the research approach to address the identified gaps. The subsequent chapters build upon this framework by analyzing previous research, conducting experiments, and evaluating results to advance the use of recycled aggregates in concrete production.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

The use of construction and demolition (C&D) waste as aggregates in concrete production has gained significant attention in recent years due to its potential to address environmental concerns and resource scarcity. This section presents a comprehensive review of the existing literature on the structural aspects of concrete produced with C&D waste as recycled aggregates. The exploration of C&D waste in concrete production aligns with the broader sustainability goals within the construction industry. Researchers have extensively investigated the mechanical properties and durability performance of concrete incorporating C&D waste as recycled aggregates [28]. The literature reveals a range of findings by shedding light on the opportunities and challenges associated with this innovative approach. Studies focusing on treated coarse aggregates underscore the potential benefits of various treatment methods to enhance the quality and performance of concrete with recycled aggregates. The effectiveness of these treatments in mitigating deleterious effects and improving the overall structural integrity of concrete has been a subject of investigation. In contrast, investigations into the utilization of non-treated aggregates provide insights into the inherent challenges and limitations associated with incorporation of untreated recycled materials in concrete mixes. Issues related to variability in quality, potential contaminants, and their impact on the structural properties of concrete are thoroughly examined in the literature. Moreover, the literature review delves into the diverse applications and performance criteria of concrete produced with C&D waste as recycled aggregates in different structural elements. Researchers have explored its use in pavements, structural elements, and precast components, among others, highlighting the adaptability and versatility of this sustainable construction material. Scholars have assessed the overall environmental impact, comparing it with conventional concrete, and identified areas for improvement and optimization. As the literature unfolds, it becomes evident that while the use of C&D waste as recycled aggregates presents a promising avenue for sustainable construction practices, a nuanced understanding of the structural aspects, treatment methodologies, and environmental implications is essential for effective implementation [29]. This chapter sets the stage for a deeper exploration of these facets in subsequent sections, laying the groundwork for an informed discussion on the integration of C&D waste aggregates in concrete construction.

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.

Khater (2011) delved into the chemical composition and properties of concrete by incorporating ceramic waste, grog, and hydrated lime. While the study highlighted the utilization of waste materials, it did not specifically focus on the potential of demolition waste as an aggregate replacement. Nonetheless, it contributed valuable insights into the broader realm of sustainable materials in concrete construction [30].

Lokeshwari and Swamy (2011) meticulously examined the use of demolished brick and mosaic tiles in concrete. Their findings concluded that recycled aggregate concrete (RAC) is economically and environmentally feasible compared to conventional aggregate concrete (CAC), shedding light on the viability of incorporating demolition waste into concrete mixes for sustainable construction practices [31].

Kamala and Rao (2012) undertook a comprehensive study on the impact of ceramic waste as a replacement for concrete. Their research revealed an increase in split tensile strength with 40% coarse aggregate replacement, indicating the potential for enhancing concrete properties through the integration of waste materials. This underscores the importance of exploring innovative solutions for sustainable concrete production [32].

Reddy and Bhavani (2012) delved into the use of 100% recycled concrete aggregates (RCA) in saturated surface-dry (SSD) conditions. Their investigation found that the compressive strength of RCA was 87% of natural aggregate concrete (NAC) at 28 days, indicating the feasibility of incorporating recycled aggregates into concrete mixes without compromising structural integrity. This highlights the potential of utilizing demolition waste to mitigate the environmental impact of construction activities [33].

Ahmed (2013) meticulously investigated the effect of replacing natural coarse aggregates (NCA) with varying percentages (25%, 50%, 75%, and 100%) of RCA. The study revealed decreased water absorption and optimal compressive, tensile, and flexural strengths with 25% RCA replacement, signaling the potential for utilizing demolition waste to enhance concrete performance while reducing environmental footprint [34].

Hussain and Assas (2013) delved into the compressive strength of concrete using different replacement percentages (0%, 25%, 50%, 75%, and 100%) of natural aggregates with recycled aggregates. Their findings highlighted a 40% increase in compressive strength with 75% replacement, but a significant decrease in slump, emphasizing the need for a balanced approach when incorporating recycled materials into concrete mixes [35].

Monish et al. (2013) conducted a thorough investigation into the use of demolished waste as a replacement for up to 30% coarse aggregates. Their results indicated remarkable strength retention 86.84-94.74% compared to conventional concrete, underlining the potential of integrating demolition waste into concrete production to reduce reliance on natural resources [36].

Vyasand Bhatt (2013) conducted a comprehensive investigation into the workability and strength of concrete with different percentages (0%, 20%, 40%, 60%, 80%, and 100%) of RCA. Their research showcased the use of 40% RCA for yielding of strong and workable concrete, highlighting the potential of integrating recycled materials into concrete production for sustainable construction practices [37].

Kalpavalli and Naik (2015) delved into the compressive strength of concrete by replacing NCA with demolition waste aggregates (DWA) at varying percentages (0%, 10%, 20%, 30%, and 40%). Their study concluded that the optimum replacement for high-strength concrete was at 30% demolished waste aggregate, shedding light on the potential of integrating demolition waste into concrete mixes for enhancement of compressive strength [38].

Devi (2015) meticulously investigated the use of crushed C&D waste as a replacement for conventional sand in concrete. Their findings suggested that C&D waste can be effectively utilized as a fine aggregate replacement, highlighting the need for further research on different replacement percentages to optimize concrete properties [39].

Srivastava et al. (2015) explored the effects of replacing cement, fine aggregate, and coarse aggregate with varying percentages (0%, 10%, 20%, and 30%) of RCA. Their research concluded that 10% replacement of cement, 20% replacement of fine aggregate, and 30% replacement of coarse aggregate yielded better results, offering insights into optimizing concrete mix designs to promote sustainability in construction practices [40].

Katam and Dumpa (2016) conducted a meticulous investigation into the compressive strength of concrete with different percentages (0%, 10%, 20%, 30%, 40%, and 50%) of demolished concrete as a replacement for natural coarse aggregates. The findings revealed a decrease in compressive strength with an increasing percentage of demolished material, highlighting the importance of exploring different concrete grades for optimal performance [41].

Patel and Patel (2016) studied the impact of replacing natural coarse aggregates with RCA at varying percentages (0%, 25%, 50%, 75%, and 100%). Their research identified the maximum compressive strength of M20 grade with 50% RCA replacement, offering valuable insights into optimizing concrete mix designs for sustainable construction practices [42].

Aiyewalehimnmi and Adeoye (2016) explored the compressive, flexural, and split tensile strengths of concrete with different percentages (0%, 15%, and 25%) of RCA. Their findings underscored the significance of the water-cement ratio (0.60 to 0.65) in producing better compressive strength, offering practical guidance for enhancing concrete performance while promoting sustainability [43].

Raihen et al.(2017) investigated the effect of replacing a portion of cement with demolished waste cement powder (DWCP) on compressive strength. Their research demonstrated an increase in compressive strength with 20% replacement, indicating the potential of utilizing waste materials to enhance compressive strength of concrete [44].

Kamal et al. (2017) delved into the use of RCA at varying percentages (8.6% to 86.4%) in concrete mixes, employing response surface methodology (RSM) to optimize compressive strength. Their research highlighted the potential of RCA in achieving desired compressive strength, offering a systematic approach to sustainable concrete production [45].

Devi et al. (2017) investigated the compressive strength of concrete with different percentages (0%, 25%, 50%, 75%, and 100%) of RCA. Their findings suggested that 25% and 50% RCA replacements yielded compressive strength comparable to standard concrete, indicating the feasibility of integrating recycled aggregates into concrete production [46].

Hagde et al. (2018) investigated the use of RCA in concrete mixes, exploring different replacement percentages. Their research concluded that up to 50% RCA replacement enhanced concrete suitability, with the highest compressive strength at 30% replacement emphasizing the potential of recycled aggregates in sustainable construction practices [47].

Gupta et al. (2018) investigated the compressive strength of concrete by replacing fine and coarse aggregates with varying percentages (0%, 10%, 20%, 30%, 40%, 50%, and 100%) of RCA. Their research suggested that 30% replacement of fine aggregate and 20% replacement of coarse aggregate produced equivalent concrete properties, highlighting the potential of recycled aggregates in sustainable construction practices [48].

Kanungo et al. (2018) explored the use of RCA in different concrete grades, examining various replacement percentages (0%, 10%, 30%, and 50%). Their findings indicated satisfactory results with 30% RA replacements, offering valuable insights into optimizing concrete mix designs for sustainable construction practices [49].

Zhang et al. (2018) investigated the impact of replacing natural coarse aggregates with RCA at varying percentages (0%, 25%, 50%, 75%, and 100%) on compressive strength of concrete. Their research identified 25% replacement percentage yielding optimal results, emphasizing the potential of recycled aggregates in enhancing concrete strength while reducing environmental impact [50].

Dhapekar and Mishra (2018) explored the impact of replacing up to 90% of NCA with RCA in concrete mixes. Their research highlighted M20 mix designs producing higher compressive strength, offering insights into optimizing concrete formulations for sustainable construction practices [51].

Manjhi et al. (2020) delved into the compressive strength of concrete with different percentages (0%, 10%, 30%, 50%, and 100%) of RCA as a replacement for natural aggregates. Their research identified 20% replacement percentages yielding optimum results, offering practical guidance for incorporating recycled aggregates into concrete production for sustainable construction practices [52].

Ankesh et al. (2020) investigated the compressive and split tensile strengths of concrete with varying percentages (0%, 3%, 6%, 9%, and 15%) of RCA. Their findings suggested that 50% RCA with 15% RFA of recycled aggregates to achieve desired compressive strength and split tensile strength, highlighting the potential of recycled materials in enhancing concrete performance while reducing environmental impact [53].

Uma and Vishala (2020) explored the compressive strength of concrete with different percentages (0%, 25%, 50%, 75%, and 100%) of RCA and 3% steel fiber. Their research identified 25% RCA replacements yielding the highest compressive strength, offering valuable insights into optimizing concrete mix designs for sustainable construction practices [54].

Koondhar et al. (2020) explored the compressive strength of concrete by replacing natural fine aggregates with RCA at different percentages (0%, 10%, 20%, 30%, 40%, 50%, and 60%). Their research identified 20% RCA replacement percentages yielding the best results, offering valuable insights into concrete mix for sustainable construction [55].

Sonawane and Pimplikar (2020) investigated the impact of replacing fine and coarse aggregates with RCA at varying percentages (0%, 10%, 20%, and 30%). Their research highlighted up to 30% RCA replacement percentages without significantly affecting the functional requirements of structures, offering practical guidance for sustainable concrete production and also observed that the strength reduction was more pronounced in M40 grade compared to M30 [56].

This comprehensive analysis underscores the significance of employing C&D waste concrete for global sustainability initiatives, vital for nurturing a more sustainable construction. Through innovative research and the utilization of recycled materials, the construction industry can mitigate environmental impact while advancing toward a more sustainable future.

2.3 DURABILITY PROPERTIES OF RECYCLED AGGREGATES CONCRETE

2.3.1 Drying Shrinkage of Concrete

The susceptibility of concrete to drying shrinkage, a phenomenon primarily induced by the migration of free water through porosity and channels near the surface, poses a significant challenge to the structural integrity of concrete constructions. A comprehensive understanding of the potential for shrinkage strain is crucial for evaluating the long-term performance of freshly produced concrete.

Tremper and Spellman (1962) ground breaking research addressed concrete shrinkage under both controlled laboratory settings and real-world conditions. Their pioneering work underscored the efficacy of meticulously designed laboratory tests in characterizing complex shrinkage behavior of concrete, laying a solid foundation for subsequent investigations [57].

Torrans et al. (1963) delved into the drying shrinkage of concrete with different admixtures, revealing intriguing insights. Their study discovered that the use of D-type admixtures led to decreased shrinkage under specific conditions, countering the observed increased shrinkage without admixtures at temperatures ranging from 75°F to 95°F [58].

Whiting et al. (2012) experimented on concrete incorporating recycled aggregates, with or without fly ash, yielded significant findings regarding drying shrinkage. Notably, their research demonstrated 25% increase in drying shrinkage in concrete without fly ash and 7% increase with fly ashdue to pore refinement in comparison to traditional concrete [59].

Maruyama and Sugie (2014) conducted an analytical study extensively investigating the correlation between aggregate size and concrete drying shrinkage.

Their meticulous analysis proposed that modification in particle size distribution holds promise in mitigating shrinkage issues, offering a potential avenue for enhancing concrete performance [60].

Taylor and Wang (2014) study underscored the influence of aggregates quality, paste content, admixtures type along with its dosage and environmental exposures on concrete drying shrinkage. Their comprehensive analysis delved into concrete for pavement design and analysis [61].

Sutthiwaree et al. (2015) investigated the influence of internal curing on expansive concrete, revealing intriguing findings. While their study suggested the capacity of internal curing to enhance effectiveness. They stressed the critical importance of striking a delicate balance between drying shrinkage and expansion [62].

Zhao et al. (2016) research delved into the intricate relationship between steel fiber volume and autogenous shrinkage versus drying shrinkage in steel fiber-reinforced lightweight concrete. Their meticulous analysis shed light on the complexities underlying concrete behavior about shrinkage and offering valuable insights for material optimization [63].

Babu and Kumar (2018) investigated drying shrinkage resulting from partial replacement of cement, uncovering intriguing findings. Their study revealed that substituting 30% of cement with china clay and 10% with fly ash mitigated drying shrinkageeffectively, providing practical solutions for concrete mix design [64].

Li et al. (2019) focused on drying shrinkage-induced stress in concrete by incorporating fly ash and slag. Their study unveiled initial heightened stress levels gradually diminishing over time, illuminating insights on the behavior of material and long-term performance [65].

Raj et al. (2020) delved into the effects of shrinkage reduction admixtures (SRA) on drying shrinkage, offering valuable insights. Their research determined an optimal SRA dosage of 2%, providing practical guidance for mitigating shrinkage-related issues and enhancing concrete durability [66].

Choi et al. (2020) explored comprehensive assessment on drying shrinkage characteristics using recycled heavy-weight glass and steel slag aggregates. Their findings indicated a reduction in modulus and drying shrinkage with increasing percentages of steel slag replacements, showcasing the potential for sustainable construction materials [67].

Zhang et al. (2020) developed a drying shrinkage model for RAC considering fine and coarse recycled aggregate (FRA and CRA). Their study showed significant influences of FRA and CRA on drying shrinkage, with a proposed model validated against RAC shrinkage test data [68].

Sakthivel et al. (2021) investigation examined the drying shrinkage behavior of concrete prepared with blended cementitious materials. Despite the addition of fly ash and slag, their findings suggested that drying shrinkage mitigation was not significant, emphasizing the need for further research into alternative approaches [69].

Mushtaq et al. (2021) highlighted a 45.18% increase in concrete drying shrinkage with proportions of waste foundry sand increased from 10 to 50%. Their study underscored the critical role of material selection and proportioning in concrete mix designs, offering insights into sustainable construction practices [70].

Nasser et al. (2021) explored into the impact of 0.06% sugar on mortar, uncovering multifaceted effects on concrete properties. Their study revealed not only an increase of 9.25% in compressive strength, but also a significant influence on drying shrinkage and carbonation, highlighting the complexities of additives in concrete formulations [71].

Mao et al. (2021) carried out a comprehensive review of factors influencing autogenous and drying shrinkage in RAC. They highlighted lower autogenous shrinkage of RAC due to internal curing by recycled concrete aggregate (RCA), but higher drying shrinkage attributed to mortar attached to original virgin aggregate

(OVA). Strategies to mitigate shrinkage, including environmentally friendly methods, are discussed alongside prediction models for RAC [72].

Sosa and Zega (2023) assessed the impact of fine recycled concrete aggregates (FRCA) on drying shrinkage in concrete production. They found that mineralogy and quality of FRCA, alongside compensation for water absorption, affect shrinkage differently. Water storage within FRCA particles does not negatively impact shrinkage, and existing models remain reliable when incorporating FRCA [73].

Hameed et al. (2024) investigated the mechanical and durability properties of hybrid recycled aggregate concrete (HRAC) [comprising of recycled brick aggregates (RBAs) and RCAs] with partial cement replacement by fly ash. Results showed compressive strength dependency on RBA and RCA proportions, while 20% fly ash replacement yielded satisfactory mechanical properties and durability performance for concrete block for paver production [74].

These collective studies offer valuable insights into the multifaceted factors influencing concrete drying shrinkage, emphasizing the ongoing need for research and innovation in this critical area of construction materials science.

2.3.2 Electrical Resistivity of Concrete

The investigation into the electrical resistivity of concrete surfaces as an indicator of corrosion risk has emerged as a focal point of extensive global research endeavors. Over time, researchers have employed diverse methodologies and advanced techniques to delve deeper into this pivotal aspect of concrete durability, aiming to unravel its complexities and implications comprehensively.

In a seminal study by **Hansson and Hansson (1983),** both alternating and direct electric fields were harnessed to scrutinize the electrical resistivity of four distinct types of cement. Their insightful analysis revealed intriguing insights, notably highlighting the markedly different age dependencies exhibited by the electrical resistivity of each cement variant [75].

Laksminarayanam et al. (1985) delved into the electrical resistivity of concrete by subjecting a steel concrete system submerged in an electrolyte to a current pulse. Their meticulous investigation unveiled a compelling trend, showcasing the resistivity of concrete as hyperbolic function of curing days, shedding light on the dynamic evolution of concrete properties over time [76].

Morris et al. (1996) employed a sophisticated four-point Wenner Array Probe to measure resistivity of concrete in test cylinders. Their meticulous experimentation unveiled a moderate variation in resistivity values, with intriguing nuances based on the size distribution of coarse particles, enriching our understanding of the factors influencing resistivity of concrete [77].

Feliu et al. (1996) embarked on a meticulous calculation of electrolyte resistance between disks and a counter electrode situated at infinity. Their findings delineated the critical boundary between active and insignificant corrosion at 100-200 kΩ-cm, providing valuable insights into the conditions conducive to corrosion initiation within concrete structures [78].

Silva et al. (2011) conducted pioneering research on electrical resistivity measurements for quality control purposes by establishing a robust correlation between electrical resistivity of concrete and various other concrete properties. Their findings underscored the utility of electrical resistivity as a reliable parameter for assessing quality of concrete and its performance [79].

In comparison to the Rapid Chloride ion Penetration Test (RCPT), the study by **Rupnow and Icenogle (2011)** elucidated the lower standard deviation of data obtained from a surface electrical resistivity meter, highlighting the potential advantages of employing this method for concrete evaluation and monitoring [80].

Osterminski et al. (2012) embarked on an extensive exploration of resistivity statisticsup to 17 years lifespan of concrete samples. Their comprehensive analysis unveiled the intricate interplay of specimen characteristics, initial climate conditions, and cover depth in shaping resistivity behavior, offering valuable insights into the long-term performance of concrete structures [81].

Laysei et al. (2015) demonstrated the remarkable potential of electrical resistivity tests as a robust tool for quality assurance and performance evaluation of concrete materials. Their findings underscored the versatility and reliability of electrical resistivity assessments in ensuring the durability and integrity of concrete structures [82].

Mishra and Tripathi (2017) utilized electrical resistivity to scrutinize the effects of curing time, binder type, and aggregate composition on concrete strength and maturity. Their comprehensive analysis highlighted the utility of electrical resistivity testing as a non-destructive method for assessing concrete durability [83].

Malakooti (2017) conducted a meticulous investigation comparing field and laboratory tests of electrical resistivity on concrete. His findings revealed no appreciable differences between the two, while suggesting potential enhancements in penetrability by incorporating chemical and mineral admixtures, thereby contributing to ongoing efforts aimed at improving concrete performance [84].

Oleiwi et al. (2018) employed the two-electrode approach to ascertain concrete resistivity, elucidating the significant influence of chloride ions and water-cement ratio on the results. Their research underscored various factors in shaping concrete resistivity, offering valuable insights for enhancing corrosion resistance in concrete structures [85].

Cosoli et al. (2020) conducted a comprehensive analysis of various methods for determining electrical resistivity, emphasizing its pivotal role in monitoring and inspecting concrete conditions Their findings highlighted the importance of incorporating electrical resistivity assessments into routine inspection protocols to ensure long-term durability and performance of concrete structures [86].

Azba and Alnuman (2021) conducted a seminal study on concrete made with recycled brick aggregates, uncovering a notable decrease in electrical resistivity with the increase in percentage of recycled brick aggregates. Their findings underscored the importance of considering material composition in assessing concrete properties, particularly concerning sustainability and environmental impact [87].

Lu et al. (2021) delved into the equivalent age method based on concrete electrical resistivity, showcasing its promising viability for promptly and continuously tracking of concrete with age. Their research offered a novel approach to assess concrete maturity, with implications of optimizing construction timelines and ensuring structural integrity [88].

Araujo and Meira (2022) conducted a groundbreaking correlation study between compressive strength, splitting tensile strength and surface electrical resistivity of concrete. Their findings elucidated a relationship between these concrete properties, offering valuable insights into the complex interplay between structural strength and electrical resistivity in concrete materials [89].

In summation, these seminal studies underscore the critical importance of electrical resistivity assessments in understanding and enhancing the durability performance, and sustainability of concrete structures. Through rigorous experimentation and analysis, researchers refine concrete behavior insights, advancing resilient and sustainable construction practices.

2.3.3 Rapid Chloride ion Penetration Test (RCPT)

The exploration into the resistance of concrete to chloride ion permeability, particularly through the lens of the Rapid Chloride ion Permeability Test (RCPT) as defined by ASTM C1202, has evolved into a central theme of extensive global research endeavors. This critical literature review aims to comprehensively analyze the findings of various studies, elucidating the nuanced results and far-reaching implications of each investigation, thereby contributing to a deeper understanding of concrete durability in chloride-rich environments.

Whiting and Mitchell (1935) pioneering work introduced a field test method aimed at directing chloride ions toward reinforcing steel at a positive potential. Their seminal findings not only shed light on the inherent constraints associated with such an approach but also laid a foundational understanding for subsequent research endeavors, igniting a trajectory of inquiry into concrete corrosion mitigation strategies [90].

Wee et al. (1999) meticulous analysis focused on evaluating the reliability of concrete mixtures under varying aggregate fractions. Their comprehensive study uncovered that plain cement mortar exhibits a diminished resistance to chloride ion penetration compared to its counterpart i.e. plain cement concrete, offering valuable insights into the intricate interplay between concrete material composition and chloride permeability dynamics [91].

Iffat et al. (2014) emphasized the precision and reliability of the RCPT method while highlighting its cost advantage over alternative testing equipment. Their insightful findings not only underscored vulnerability of concrete to marine environments, but also hinted at potential long-term durability concerns that merit further investigation, stimulating discourse on the optimization of concrete formulations for enhanced resistance to chloride ingress [92].

Vijaya and Selvan (2015) research placed a spotlight on M-sand concrete, emphasizing its lower permeability in comparison to conventional concrete. Supported by RCPT data, their study underscored the durability of M-sand concrete, offering promising implications for sustainable construction practices and signaling a paradigm shift towards environmentally conscious material choices [93].

Ozalp et al. (2016) investigation delved into the permeability of concrete prepared with construction and demolition (C&D) waste. Their comprehensive study concluded that a higher proportion of recycled aggregates contributes to increased concrete permeability, shedding light on the implications of using recycled materials in concrete production and catalyzing discussions on sustainable waste management practices in the construction industry [94].

Obla et al. (2016) research highlighted the sensitivity of concrete permeability to stress, identifying the RCPT as the most effective index test method for evaluating chloride ion penetration. Their insightful study emphasized the importance of considering external factors, such as mechanical loading, in assessing concrete durability, thereby broadening the scope of research in this critical area [95].

Dhanya and Sanathanam (2017) focused on the use of RCPT in concrete containing supplementary cement ingredients. Their meticulous study established RCPT as a reliable technique for evaluating chloride ion penetration, providing valuable insights for concrete quality assessment for best practices in concrete mix design and optimization [96].

Prakash and Nirmala (2019) exploration delved into the strength characteristics of self-compacting concrete, revealing optimal outcomes with the incorporation of a 2% dosage of super-plasticizers. Their groundbreaking findings hinted at the enhanced resistance of self-compacting concrete to chloride ion penetration, thereby paving the way for advancements in concrete technology aimed for achieving superior durability performance in aggressive environments [97].

Carmichael and Arulraj (2019) investigation explored concrete permeability with various nano-materials, concluding that replacing cement with nano-silica materials (30%) reduces permeability. Their groundbreaking findings opened avenues for innovative approaches in concrete mix design, paving the way for the integration of nano-materials to enhance concrete performance in chloride-rich environments [98].

Shafiq et al. (2019) discussion centered on concrete durability with modified metakaolin (MK) and Nano Silica (NS), revealing a significant reduction in permeability with the optimal combination of 10% MK and 1.55% NS. Their findings highlighted the potential of supplementary materials in enhancing concrete performance, inspiring further exploration into innovative admixture formulations [99].

Ma et al. (2019) investigated recycled powder (RP) as a cement substitute in concrete, revealing reduced chloride permeability and improved hydration with RP. They suggested 30% RP replacement ratio to maintain optimal properties, while minimizing freeze-thaw damage and chloride permeability [100].

Satish (2020) evaluation focused for effectiveness of corrosion inhibitors on concrete durability using RPCT, discovering increased resistance to chloride ion penetration with their use. Their seminal study contributed valuable insights into corrosion mitigation strategies in concrete structures, underscoring the importance of proactive measures to preserve concrete integrity in aggressive environments [101].

Saad et al. (2021) assessment examined durability of M30 grade concrete using RCPT, emphasizing resistance measurement over permeability via the voltage-to-current ratio. Their meticulous findings offered a nuanced understanding of concrete performance, aiding in the optimization of concrete mix designs and informing decision-making processes in concrete construction projects [102].

Yang and Lee (2021) investigated rapid chloride penetration and drying shrinkage of new concrete with recycled aggregates. Their comprehensive study revealed increased chloride ion penetration (RCPT values) at 50% RCA replacement compared to a conventional mix, highlighting the influence of recycled materials on concrete properties and stimulating further research into sustainable concrete production methods [103].

Mohammed et al. (2021) explored the impact of RCPT on lightweight concrete made with oil palm and clinker aggregates. Their insightful findings indicated higher RCPT values at early ages compared to later stages, offering valuable insights into the long-term performance of lightweight concrete and informing strategies for optimizing durability in lightweight concrete structures [104].

Hameed et al. (2021) carried out RCPT study on self-compacting high-performance concrete (SCHPC) with marble sludge powder (MSP) and crusher rock dust powder (CRP). Their groundbreaking findings revealed remarkably low permeability in concrete containing SCHPC with MSP and CRP, showcasing the potential of supplementary materials in enhancing concrete durability and inspiring further research into sustainable concrete production [105].

Ying et al. (2023) utilized a biaxial compression device to test chloride ion diffusion in recycled aggregate concrete under various stress states. Employing digital imaging correlation (DIC) and X-ray fluorescence, they developed a theoretical model accurately predicting diffusion coefficients, vital for practical engineering applications [106].

Gagg et al. (2024) examined the durability of self-compacting concrete (SCC) incorporating recycled aggregates from construction and demolition waste (CDW), with and without metakaolin (MK). Results indicated MK significantly enhanced SCC performance, reducing chloride ion diffusion, while increasing electrical resistivity. SCC with recycled sand and MK exhibited comparable strength to reference mixes, suggesting feasibility of environmentally robust construction [107].

Wang et al. (2024) comprehensively reviewed chloride penetration in recycled coarse aggregate concrete (RAC) and enhancement methods. They revealed effects of modifiers on chloride resistance, noting a 15–30% improvement with mortar treatments and variable efficacy (5–95%) of modifier materials. They also highlighted service life reduction with increased RA replacement and suggest future research directions on chloride transport in RAC [108].

Henriques et al. (2024) evaluated concrete mixes with 8% silica fume and 30% recycled fine aggregate replacements. Tests for capillarity, mechanical strength, and chloride migration showed improved properties, especially with silica fume incorporation, enhancing mechanical strength and chloride ion penetration resistance [109].

This comprehensive examination not only presents the results but also synthesizes diverse findings, contribution to a nuanced understanding of chloride ion permeability complexities in concrete and paving the way for informed decision-making in concrete materials selection, mix design, and construction practices aimed to achieve sustainable and durable infrastructure solutions for the future.

2.4 SURFACE TREATED RECYCLED AGGREGATE CONCRETE

The exploration into the advantages and limitations of integrating recycled aggregate (RA) into concrete has been an extensive endeavor, driven by the imperative to address sustainability concerns and optimize material performance. A multitude of strategies have been proposed and investigated to enhance the properties and applicability of RAC, each offering unique insights and potential solutions to the challenges posed by recycled materials in concrete production. The following elaborates on these strategies:

Tam et al. (2005) responded to the pressing issue of land scarcity in Hong Kong, where RCA utilization is on the rise. Their study introduced a novel two-stage mixing approach aimed at bolstering compressive strength and reducing variability in recycled aggregate concrete, thereby addressing concerns related to material consistency and structural performance [110].

Li et al.(2009) employed a sophisticated two-stage crushing process to extract RA from concrete debris. Their study further innovated by incorporating stone enveloped with pozzolanic powder (SEPP) into concrete mixes, resulting in improved workability and higher compressive and flexural strengths. SEM analysis confirmed a denser interfacial transition zone with SEPP, shedding light on the mechanisms behind the observed enhancements in concrete properties [111].

Juanand Gutierrez (2009) delved into the unique compositions of recycled concrete aggregates (RCA), establishing quantitative relationships between mortar content and key properties such as density, absorption, and abrasion. By elucidating these relationships, their study facilitated applications and recycling processes, laying a foundation for informed decision-making in concrete material selection and production [112].

Kong et al. (2010) introduced the innovative triple mixing method (TM) to augment RAC properties by coating aggregates with pozzolanic materials. Their groundbreaking research demonstrated that TM significantly improved the interfacial transition zone (ITZ) microstructure, compressive strength, and chloride ion resistance compared to conventional methods, thus offering a promising avenue for enhancing the durability and performance of recycled aggregate concrete [113].

Spaeth and Tegguer (2013) directed their focus towards promoting sustainability through the recycling of concrete, bricks, and masonry rubble as aggregates. Their experimental endeavors aimed at enhancing RCA performance through polymer-based treatments, resulting in lower water absorption and improved fragmentation resistance. These findings underscored the potential of innovative treatment methods in advancing the environmental and structural sustainability of concrete construction [114].

Quattrone et al. (2014) delved into recent mechanical and thermo-mechanical processing techniques aimed at reducing the volume of adhered cement paste in RCA, thereby improving their quality. Through a comprehensive investigation, they evaluated the environmental impacts of these methods and highlighted their significant potential in reducing environmental loads associated with concrete production [115].

Qiu et al. (2014) addressed the limited utilization of recycled concrete aggregates (RCA) in new structures due to high water absorption and weak bonding. Their pioneer study explored a novel microbial carbonate precipitation (MCP) treatment for RCA surfaces, revealing optimal conditions for enhanced RCA treatment and resulting in increased weight and reduced water absorption. These findings offered insights into innovative strategies for improving the properties of produced concrete and applicability of recycled aggregate concrete, thereby advancing sustainable construction practices [116].

Zhang et al. (2015) investigated the carbonation treatment of cement paste in RCAs to enhance density, reduce water absorption and crushing values, improve flow-ability and compressive strength, and mitigate drying shrinkage of recycled aggregate mortars. Their comprehensive study shed light on the potential of carbonation treatment as an effective strategy for improving the properties and performance of recycled aggregate concrete, thus contributing to the advancement of sustainable construction practices [117].

Pandurangan et al. (2016) delved into various methods, including acid, thermal, and mechanical treatments, aimed at enhancing the quality of RCA. Through a meticulous comparison using fifteen RILEM beam specimens, they evaluated reinforcement bond strength with different treatment methods, offering valuable insights into the efficacy of these treatments in improving the properties and performance of recycled aggregate concrete [118].

Shi et al. (2018) tackled the challenges associated with recycling of construction and demolition waste into new concrete, focusing on RCA porosity and water absorption. Their study explored the efficacy of pozzolanic slurry and CO_2 treatments in improving RCA properties, resulting in reduced water absorption and enhanced fluidity and mechanical strength. These findings provided valuable insights into innovative strategies for enhancing the quality and applicability of recycled aggregate concrete in sustainable construction practices [119].

Li et al. (2019) conducted study on how carbonation treatment enhances the crushing characteristics of RCAs, leading to increased crushing stresses and reduced water absorption. Their findings indicated that smaller RCAs captured CO_2 more effectively, resulting in significant improvements in stress characteristics, thus offering promising avenues for enhancing the properties and performance of recycled aggregate concrete [120].

Ahmad et al. (2019) investigated methods to enhance recycled aggregate concrete (RAC) properties by removing residual mortar from the surface of RA. Their study revealed that abrasion, combined with sodium silicate treatment, notably improved workability, strength and durability of concrete prepared with RCA, offering practical solutions for enhancing the performance of recycled aggregate concrete in construction applications [121].

Zhan et al. (2019) explored the impact of accelerated carbonation treatment on cement mortars attached to surface of RCA, resulting in improved transport properties and enhanced corrosion resistance in RAC incorporating carbonated RCA. Their findings highlighted the potential of carbonation treatment as an effective strategy for enhancing the durability and performance of recycled aggregate concrete in aggressive environments [122].

Sasanipour et al. (2020) investigated the effects of surface pretreatment of

RCAs with silica fume slurry on recycled aggregate concrete (RAC) properties. They found improved durability, particularly in chloride ion penetration and electrical resistivity. SEM analysis revealed enhanced interface transition zones responsible for reductionof permeability. A strong correlation between total charge passed and electrical resistivity was observed [123].

Wang et al. (2020) conducted study on how RCA often suffers from attached mortar, leading to poor microstructure. Their research explored various methods to improve RCA microstructure, including mortar removal, surface coating, mixing techniques, and $CaCO_3$ precipitation, considering environmental impact, RCA particle size, and application. These findings offered valuable insights into innovative strategies for enhancing the quality and performance of recycled aggregate concrete in sustainable construction practices [124].

Alqarni et al. (2021) focused on RCA to address aggregate shortages and promote environmental friendly concrete. Their study examined various parameters, revealing improvements in concrete slump by 15%-35% and enhanced compressive strength compared to untreated RCA, thus highlighting the potential of recycled aggregate concrete as a sustainable construction material [125].

Cano et al. (2023) explored enhancement on treatments for RCAs to improve RC durability by altering adhered cement paste. Their findings indicated that reduced water absorption in RCAs correlated with increased compressive strength and improved durability against carbonation and chloride ion penetration, with treatment mechanisms and particle size being crucial factors, thus providing valuable insights into optimizing the performance of recycled aggregate concrete in aggressive environments [126].

Silva et al. (2023) investigated methods to enhance RCA quality, including mechanical grinding and a two-stage mixing approach with Portland cement treatment. Their study revealed that these methods improved the mechanical properties and durability of concrete containing RCA, facilitating greater use of RCA in concrete production, and thus contributing to the advancement of sustainable construction practices [127].

Raman and Ramasamy (2023) studied about the assessment of concrete strength using both destructive and non-destructive methods. They noted the integration of demolition waste into concrete is reducing cost of coarse aggregate. Pre-treated recycled coarse aggregate (RCA with mechanical scrubbing and acid treated significantly enhanced concrete properties. Mechanical treatment boosted compressive strength by 25.79% compared to untreated aggregate concrete. Moreover, rebound numbers and ultrasonic pulse velocity improved by 12.5-26.31% and 8.17-22.82%, respectively, in concrete prepared with treated recycled aggregate. Additionally, treated recycled aggregate enhanced impact resistance, underscoring the efficacy of treatment methods in improving the performance and durability of recycled aggregate concrete [128].

Han et al. (2023) conducted a systematic review of techniques for modifying RCA and their application in RAC. Through a comprehensive analysis of pre-treatment approaches, their efficiency, and their impacts on RAC properties, the review addressed challenges and perspectives in RCA and RAC, thus offering valuable insights into optimizing the performance of recycled aggregate concrete in construction applications [129].

Murali et al. (2023) investigated the enhancement of the environmental friendliness of concrete by employing recycled construction materials as aggregates. Their study explored the impact of different replacement levels (10-40%) of RA in RAC, coupled with pre-treated RA with three concentrations of $MgSO_4$ solution (10-20%) for varying immersion periods (5, 10, and 15 days). The findings suggested that a five-day immersion in a 10% $MgSO_4$ solution enhanced impact strength of RAC, thus offering practical solutions for enhancing the sustainability and performance of recycled aggregate concrete [130].

Luan et al.(2023) investigated the impact of RFA and carbonated RFA (CRFA) on alkali-activated slag and glass powder mortar (AASGPM). Their study revealed that increasing RFA content (0-100%) led to a decreased flow value, decreased autogenous shrinkage, and initially increased compressive strength, followed by a decrease. In contrast, increasing CRFA content (0-100%) resulted in an increased flow value, delayed setting time, and reduced compressive strength, thus offering insights into optimizing the performance of recycled aggregate concrete in construction applications [131].

Kumar and Singh (2023) reviewed the importance of enhancing RCA properties to align with NCA. Through a comprehensive examination of various treatments, including mechanical, chemical, and thermal methods, they explored strategies for improving RCA properties, thus offering practical solutions for advancing the sustainability and performance of recycled aggregate concrete [132].

Chauhan and Singh (2023) focused on optimizing acid-mechanical treatment for RCA, wherein acid-soaked RCA underwent mechanical treatment to produce acid-mechanically treated recycled concrete aggregates. Through a performance-based approach, they selected three aggregates for study, achieving a compressive strength of 71.27 MPa, 16.06% higher than virgin aggregate concrete. SEM analysis revealed improved surface morphology and reduced micro-cracks, while XRD analysis showed lower CH content, hence providing insightful information about the best treated materials to improve performance of RAC in building applications [133].

Majeed et al. (2024) conducted study on the use of silicone dioxide nanoparticles (SDNs) in ultra-lightweight foamed concrete (ULFC). Their findings revealed significant enhancements in mechanical properties i.e. up to 70.49%, 76.19%, and 51.51% improvements in 28-day compressive, split tensile and flexural strengths, respectively, at 1.5% SDNs inclusion. Higher SDN percentages contributed to improvements in sorptivity, porosity, water absorption, intrinsic air permeability, and chloride diffusion, thus offering promising solutions for enhancing the sustainability and performance of recycled aggregate concrete in construction applications. Additionally, thermal conductivity increased with SDNs due to smaller pore size, with adjustments observed in pore diameter distribution, thus offering insights into optimizing the incorporation of nano-materials in recycled aggregate concrete [134].

In summary, the thorough exploration of strategies to improve RAC has uncovered valuable insights and solutions for enhancing sustainability of concrete construction. Each study adds to our understanding of using recycled materials in concrete, paving the way for innovative and sustainable practices in the construction industry.

2.5 RESEARCH GAP FROM THE LITERATURE REVIEW

Numerous studies have investigated the challenges associated with incorporating RA into concrete production. While substantial progress has been made in understanding RAC, several critical aspects remain unexplored. The following research gaps underscore the need for further investigation:

a) **Influence of Residual Cement Mortar on Recycled Aggregates Properties:** The presence of residual cement mortar has a significant impact on the physical and mechanical properties of recycled aggregates. This residual mortar is more porous than the aggregate itself, leading to increased water demand during mixing to achieve the same slump. Additionally, the mortar is loosely attached to the aggregates and tends to disintegrate under lower loads, reducing the concrete's ability to withstand heavy loads. However, systematic studies quantifying its impact on the interfacial transition zone (ITZ), microstructural integrity, and long-term durability are lacking. The variability in mortar content across different concrete grades remains unexplored.

b) **Effectiveness of Surface Treatment Techniques for Recycled Aggregates:** Various surface treatment methods; such as cement slurry coating, chemical treatments, abrasion, and carbonation have been proposed to improve recycled aggregates. However, the comparative effectiveness of these methods is not well defined. The durability performance of treated recycled aggregates, including resistance to chloride penetration, carbonation depth, and shrinkage under long-term exposure conditions, has not been comprehensively studied. Additionally, limited research has evaluated the combined effects of multiple treatment techniques, such as mechanical and chemical modifications, on the properties of recycled aggregate concrete.

c) **Bond Strength and Interfacial zone (ITZ) in Recycled Aggregate concrete:** A detailed analysis is needed to understand how various treatment techniques influence ITZ characteristics and their impact on bond strength. The interaction between recycled aggregates and cementitious materials in ITZ development remains inadequately explored. Furthermore, experimental validation of ITZ behavior using advanced methods is lacking, which hinders a deeper understanding of the underlying mechanisms that affect bond strength and overall concrete performance.

d) **Durability Challenges in Recycled Aggregates Concrete:** Recycled aggregate concrete (RAC) faces significant durability challenges, particularly in terms of drying shrinkage and cracking susceptibility. Its electrical resistivity and corrosion resistance in aggressive environments, such as marine and sulfate-rich conditions, require further study. Additionally, tests on rapid chloride penetration and carbonation depth have yielded inconsistent results, highlighting the need for standardized assessment protocols to ensure reliable evaluation of RAC's long-term durability.

Point of Departure for Further Research: To address these research gaps, present study focuses on the development of innovative and cost-effective surface treatment techniques to improve the quality of recycled aggregates. In-depth investigations into ITZ enhancement strategies are essential to improve bond strength and durability. Long-term field studies of structural RAC are critical to validate laboratory findings and assessing real-world performance. Additionally, performance-based mix design approaches for tailored RAC should be explored to optimize both mechanical and durability properties. These research directions are pivotal for advancing the integration of recycled aggregates into high-performance concrete applications.

Addressing these identified research gaps promises significant advancements in sustainable construction practices and ensures the seamless integration of recycled aggregates into concrete production.

2.6 SUMMARY

This chapter presents a comprehensive review of the literature on the use of recycled aggregates in concrete, highlighting key findings related to engineering properties and durability. The main results obtained from the literature review are as follows:

a) **Mechanical Properties of Recycled Aggregates Concrete:** RAC typically exhibits lower compressive strength compared to conventional concrete, primarily due to the presence of adhered mortar and weaker ITZ. However, strength retention can be significantly enhanced through optimized mix designs and effective surface treatment techniques. Additionally, the split tensile and flexural strengths of RAC tend to decrease with higher replacement levels of recycled aggregates, as the weaker ITZ leads to reduced load transfer efficiency. The incorporation of supplementary cementitious materials (SCMs), such as fly ash and silica fume, has been shown to improve mechanical properties by refining the ITZ, reducing porosity, and enhancing overall workability.

b) **Durability Aspects of Recycled Aggregates Concrete:** RAC exhibits significantly higher drying shrinkage compared to conventional concrete due to the increased porosity and water absorption of recycled aggregates. This issue can be mitigated through internal curing techniques and optimized mix proportioning to enhance moisture retention and reduce shrinkage-induced cracking. Additionally, RAC demonstrates lower electrical resistivity than natural aggregate concrete, making it more vulnerable to corrosion, particularly in aggressive environments. The resistance of RAC to chloride ion penetration is highly dependent on the treatment methods applied to recycled aggregates. Surface modifications such as carbonation and pozzolanic treatments have been shown to enhance durability by reducing permeability and improving the overall resistance to chloride ingress.

c) **Influence of Surface Treatments on RAC Performance:** Surface treatment techniques, including carbonation, cement slurry coating, and chemical modifications, play a crucial role in enhancing the performance of RAC. These treatments effectively reduce water absorption, refine the ITZ, and improve the overall strength of recycled aggregates. By enhancing aggregate surface characteristics, these modifications lead to stronger bond formation within the concrete matrix, thereby improving mechanical properties, durability, and long-term structural performance.

d) **Structural and Environmental Considerations:** RAC can be effectively utilized in structural applications, provided that mix design optimizations and performance enhancements are implemented. However, challenges remain in achieving the required mechanical properties for high-strength applications, necessitating further research and refinement of treatment techniques. From an environmental perspective, the incorporation of recycled aggregates significantly reduces the carbon footprint of concrete production and promotes the conservation of natural resources. This makes RAC a sustainable and eco-friendly alternative to conventional concrete, contributing to the advancement of green construction practices.

e) **Scope for Further Improvement:** Advancing the performance of RAC requires innovative strategies to enhance the bond between recycled aggregates and the cement matrix through novel surface modification techniques. Comprehensive long-term field studies are essential to evaluate the durability and structural performance of RAC under real-world conditions. Additionally, the development of standardized mix design methodologies is crucial to optimize both strength and durability, ensuring its viability for widespread application.

This review underscores the potential of RAC as a sustainable construction material while identifying critical challenges and research opportunities that must be addressed for its effective integration into modern infrastructure.

CHAPTER 3

EXPERIMENTAL PROGRAMME

3.1 GENERAL

In pursuit of the research objectives, the experimental program has been designed to explore the feasibility of incorporating Construction and Demolition (C&D) waste materials as recycled aggregates, replacing natural aggregates in concrete production. This chapter comprehensively addresses a variety of materials utilized in the study, diverse treatment techniques employed to enhance the surface of recycled aggregates, the constituents of different mixtures, and an array of testing methods to analyze various concrete properties.

3.2 MATERIALS

This research utilizes a range of materials, including ordinary Portland cement, natural fine aggregates, recycled fine aggregates, natural coarse aggregates, recycled coarse aggregates, surface-modified recycled coarse aggregates, admixtures, and water. The subsequent sections furnish an in-depth depiction and delineate diverse properties inherent of these individual materials. Furnishing a comprehensive understanding of the unique characteristics of each material guarantees a meticulous examination of their influence on the research outcomes.

3.2.1 Cement

Cement serves as the primary component in concrete production, functioning as the binding material for various concrete constituents. For this research, ordinary Portland cement (OPC) of 43 grade has been employed in accordance with the guidelines outlined in IS: 269-2015 [135]. Table 3.1 provides a comprehensive list of the physical properties determined from the tests and associated with the selected cement.

3.2.2 Natural Fine Aggregates (NFA)

Locally available natural sand has been employed as the natural fine aggregate (NFA) in this study. The fine aggregates conform to the sieve size as specified by IS

383-2016 [136], and these values found from test results, fall within grading Zone II according to IS: 2386 (Part 3) -1963 (Reaffirmed 2021) [137]. The particle size distribution of natural fine aggregates is illustrated in Table 3.2, while Table 3.3 enumerates the properties of the fine aggregates.

Table 3.1 Physical properties of cement

Property	Value Measured	Requirements of IS 269: 2015 [135]
Consistency	31%	-
Initial Setting Time	58 min	> 30 min
Final Setting Time	435 min	< 10 Hrs
Specific Gravity	3.11	3.0-3.15

Table 3.2 Particle size distribution of natural fine aggregates

IS Sieve	Weight Retained (gm)	Cumulative Weight Retained (gm)	Cumulative Weight Retained (%)	Cumulative Weight Passing (%)	Values as per IS: 383-2016 [136]
10 mm	6	6	0.6	99.4	100
4.75 mm	14	20	2.0	98	90-100
2.36 mm	22	42	4.2	95.8	75-100
1.18 mm	330	372	37.2	62.8	55-90
600 μ	224	596	59.6	40.4	35-59
300 μ	266	862	86.2	13.8	8-30
150 μ	109	971	97.1	2.9	0-10

3.2.3 Recycled Fine Aggregates (RFA)

The recycled fine aggregates (RFA) utilized in this study are derived from crushed recycled concrete processed at the IL&FS C&D Waste Recycling Plant in Delhi, India. These aggregates also adhere to the specifications outlined in IS: 383-2016 [136], passing through a sieve size of 4.75mm and falling within grading Zone II, as per IS: 2386 (Part 3) -1963 (Reaffirmed 2021) [137]. The properties of Recycled Fine Aggregates (RFA) are detailed in Table 3.3, and the gradation size distribution is depicted in Table 3.4.

Table 3.3 Properties of fine aggregates

Properties	NFA	RFA	Standard Limits
Specific Gravity	2.675	2.654	2.30-2.90 IS: 2386 (Part 3) [137]
Bulk Density (kg/m^3)	1625	1580	1200-1750 IS: 2386 (Part 3) [137]
Water Absorption (%)	0.51	1.12	≤ 2.0 IS: 2386 (Part 3) [137]
Abrasion loss (%)	15.52	18.44	< 30 IS: 2386 (Part 4) [138]
Crushing Value (%)	16.21	17.34	< 30 IS: 2386 (Part 4) [138]
Impact Value (%)	15.31	18.74	< 30 IS: 2386 (Part 4) [138]

Table 3.4 Particle size distribution of recycled fine aggregates

IS Sieve	Weight Retained (gm)	Cumulative Weight Retained (gm)	Cumulative Weight Retained (%)	Cumulative Weight Passing (%)	Values as per IS: 383-2016 [136]
10 mm	0	0	0	100	100
4.75 mm	23.02	23.02	2.30	97.70	90-100
2.36 mm	80.44	103.46	10.35	89.65	75-100
1.18 mm	153.04	256.50	25.65	74.35	55-90
600 μ	230.31	486.81	48.68	51.32	35-59
300 μ	221.93	708.74	70.87	29.13	8-30
150 μ	155.83	864.57	86.46	13.54	0-10

3.2.4 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 [136], serving as natural coarse aggregates (NCA). The particle size distribution of these natural coarse aggregates is visually depicted in Table 3.5 and Table 3.6 provides a comprehensive overview of their properties.

3.2.5 Recycled Coarse Aggregates (RCA)

The recycled coarse aggregates employed in this research originated from crushed recycled concrete processed at the IL&FS C&D Waste Recycling Plant in Delhi, India. These aggregates conform to the specifications outlined in IS: 383-2016 [136], exhibiting a size range from 4.75mm to 20mm. The properties of the Recycled

Coarse Aggregates (RCA) are meticulously detailed in Table 3.6, and the gradation size is represented in Table 3.7.

Table 3.5 Particle size distribution of natural coarse aggregates

IS Sieve	Weight Retained (gm)	Cumulative Weight Retained (gm)	Cumulative Weight Retained (%)	Cumulative Weight Passing (%)	Values as per IS: 383-2016 [136]
40 mm	0	0	0	100	100
20 mm	462	462	9.24	90.76	85-100
10 mm	4312	4774	95.48	4.52	0-20
4.75 mm	163	4937	98.74	1.26	0-5
Pan	63	5000	100	0.0	-

Table 3.6 Properties of coarse aggregates

Properties	NCA	RCA	Standard Limits
Specific Gravity	2.754	2.681	2.30-2.90 IS: 2386 (Part 3) [137]
Bulk Density (kg/m^3)	1740	1660	1200-1750 IS: 2386 (Part 3) [137]
Water Absorption (%)	0.62	4.33*	≤ 2.0 IS: 2386 (Part 3) [137]
Abrasion loss (%)	25.43	28.76	< 30 IS: 2386 (Part 4) [138]
Crushing Value (%)	26.24	27.71	< 30 IS: 2386 (Part 4) [138]
Impact Value (%)	17.31	20.68	< 30 IS: 2386 (Part 4) [138]
*Water Absorption of RCA is more			

3.2.6 Surface Modified Recycled Coarse Aggregates (SMRCA)

The primary reason for strength loss in recycled coarse aggregates (RCA) is attributed to the presence of old adhered mortar on the RCA surface, due to its presence, water absorption is also higher. Consequently, it becomes imperative to remove this adhered mortar before incorporating RCA into concrete. This emphasizes the critical significance of surface modification for RCA before its application in concrete. The RCA subjected to various treatment methods such as Cement Slurry Treatment (RCACST), Chemical Treatment (RCACT), and Abrasion Treatment (RCAAT) are referred to as surface modified RCA. Table 3.8 provides a detailed presentation of the properties of surface modified RCA using different techniques.

Table 3.7 Particle size distribution of recycled coarse aggregates

IS Sieve	Weight Retained (gm)	Cumulative Weight Retained (gm)	Cumulative Weight Retained (%)	Cumulative Weight Passing (%)	Values as per IS: 383-2016 [136]
40 mm	0	0	0	100	100
20 mm	395	395	7.90	92.1	85-100
10 mm	4586	4981	99.62	0.38	0-20
4.75 mm	8	4989	99.78	0.22	0-5
Pan	11	5000	100	0	-

Table 3.8 Properties of surface modified coarse aggregates

Properties	RCACST	RCACT	RCAAT	Standard Limits
Specific Gravity	2.708	2.731	2.718	2.30-2.90 IS: 2386 (Part 3) [137]
Bulk Density (kg/m^3)	1704	1695	1714	1200-1750 IS: 2386 (Part 3) [137]
Water Absorption (%)*	4.31	2.67	2.79	≤ 2.0 IS: 2386 (Part 3) [137]
Abrasion loss (%)	27.46	26.03	27.56	< 30 IS: 2386 (Part 4) [138]
Crushing Value (%)	26.36	24.36	27.36	< 30 IS: 2386 (Part 4) [138]
Impact Value (%)	15.26	14.23	15.26	< 30 IS: 2386 (Part 4) [138]
*Water absorption of surface treated RCA is reduced with reference to untreated RCA, but still higher.				

3.2.7 Chemical Admixture

Chemical admixture, specifically super-plasticizers (C-MAX) in accordance with IS: 9103-1999 [139], was incorporated at a rate of 1% by weight of cement in all mixes to achieve the desired workability without compromising strength.

3.2.8 Water

Water plays a crucial role in the concrete mixture as it actively participates in the formation of hydration products, when it comes into contact with cement. This interaction contributes significantly to the overall strength of the concrete. For the mixing and curing processes, ordinary potable tap water available in the laboratory has been used.

3.3 SURFACE MODIFICATION OF RECYCLED COARSE AGGREGATES

The reduction in the strength of concrete made with untreated recycled coarse aggregates (RCA) can be attributed to an insufficient bond between the cement mortar and RCA, weakened by the presence of old mortar on RCA surfaces. To enhance the compressive strength of concrete with RCA, three innovative surface modification techniques have been implemented. The first method involves creating a cement paste by dissolving it in 10% water, vigorously agitating it, and then immersing aggregates in the paste for 24 hours. The treated aggregates are subsequently dried in an oven and thereafter incorporated into concrete formulations. This was done to improve the properties of RCA. The second technique entails immersing RCA in hydrochloric acid (HCl), inspired by Tam et al.(2007) [140] research and Ismail and Ramli (2013) [141] study. The research indicates improved characteristics of RCA treated with HCl, with optimal results achieved at a concentration of 0.5 mol. The third technique involves abrasion treatment, with multiple trials conducted to determine the optimal drum rotation duration. These treatments may enhance the properties of RCA. One of the objective of this research is to enhance the suitability of RCA for concrete applications, by refining existing methods and exploring new avenues. By offering a comprehensive understanding of modifications made to recycled aggregates, the study aims to contribute to more sustainable practices in concrete production.

3.3.1 Surface Modification of RCA by Cement Slurry Treatment

Cement Slurry Treatment represents a method employed to modify the surface of RCA by facilitating the efficient penetration of cement paste into the porous structure of the aggregates. This meticulous process involves several steps, including the preparation of cement paste, agitation, homogenization, immersion of recycled aggregates, and then drying in an oven at 100°C. The intricacies of the Cement Slurry Treatment process are illustrated in Figure 3.1.

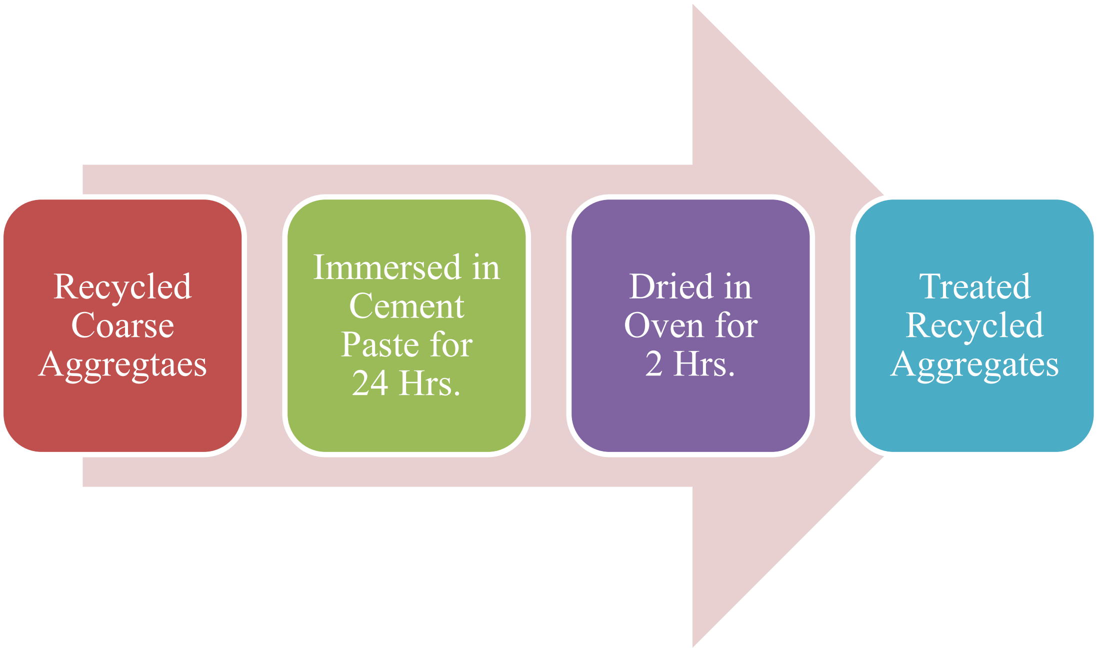


Figure 3.1 Process of cement slurry treatment of RCA

To prepare the cement paste, cement was mixed with water at a 10% cement-to-water ratio to ensure that the paste can effectively coat the aggregate surfaces. The mixture underwent vigorous agitation for 10 to 15 minutes to achieve homogeneity. Once the cement paste is ready, the RCA was immersed in the slurry for 24 hours, allowing the paste to be thoroughly absorbed by the porous surfaces of the RCA. The coated aggregates were then dried in an oven to ensure the bond between the paste and the aggregate structure. The controlled drying process eliminates excess moisture from the paste, leaving behind cement particles that have effectively permeated the porous surface. Through this meticulous Cement Slurry Treatment, the RCA undergoes a transformative process, enhancing the mechanical strength of the aggregates and also establishing a robust interfacial connection between the surrounding mortar and the treated aggregates. Due to this process, the treated aggregates became highly efficient and sustainable component for concrete production. Figure 3.2 showcases the treatment administered to RCAs.

(a) RCA immersed in cement slurry (b) Cement slurry treated RCA

Figure 3.2 Surface modification of RCA by cement slurry treatment

3.3.2 Surface Modification of RCA by Chemical Treatment

In this comprehensive investigation, an innovative technique was employed to enhance the performance of RCAs by effectively eliminating weakly adhered mortar from their surfaces. This method involves the use of a hydrochloric acid (HCl) solution, serving as a potent agent to dissolve or disintegrate the cement mortar from the RCA surface. For clarity, Figure 3.3 illustrates the intricacies of the chemical treatment process of RCA. The initial step of this technique involves immersing the RCAs in a solution prepared with a precisely controlled concentration of 0.5M hydrochloric acid. This immersion process spans for 24 hours at room temperature. It is essential to note that the cement mortar on the RCA surface consists of complex oxides of calcium oxide (CaO), silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3), all susceptible to chemical reactions with HCl. The chemical reactions, as outlined vide equations (1) to (3), illustrate the intricate processes used in this acidic environment:

$$CaO + 2HCl \rightarrow CaCl_2.H_2O \quad (1)$$

$$Fe_2O_3 + 6HCl \rightarrow 2FeCl_3.3H_2O \quad (2)$$

$$Al_2O_3 + 6HCl \rightarrow 2AlCl_3.3H_2O \quad (3)$$

The aforementioned reactions effectively weaken the mortar adhered to the RCA, thus facilitating its subsequent removal through abrasion. This process removed most of the mortar off the RCA surface successfully. When using chemical treatment to enhance the properties of recycled coarse aggregates, it is essential to prevent the introduction of chloride ions, due to the possibility that they might damage steel reinforcement used in concrete, thereby jeopardizing the integrity of the structure. A number of careful procedures were recommended to make sure of this. First and foremost, it's imperative to use non-chloride chemicals for cleaning of surface of the treated aggregates; pay close attention to their specifications and, if at all feasible, choose alternatives free of chlorides. It is also essential to store treated aggregates in a dry place away from materials that contain chlorides. It's also essential to thoroughly clean all mixing equipment to get rid of any residue from earlier mixes. The water supply needs to be controlled, and tap water should only be used if it is verified that it is free of chlorides. Distilled or deionized water should be preferred. Frequent testing of processed aggregates and raw materials is essential to allow for the early identification and prompt remediation of contamination problems. The equipments of plastic or stainless steel are chosen, since they are less likely to leak chlorides.

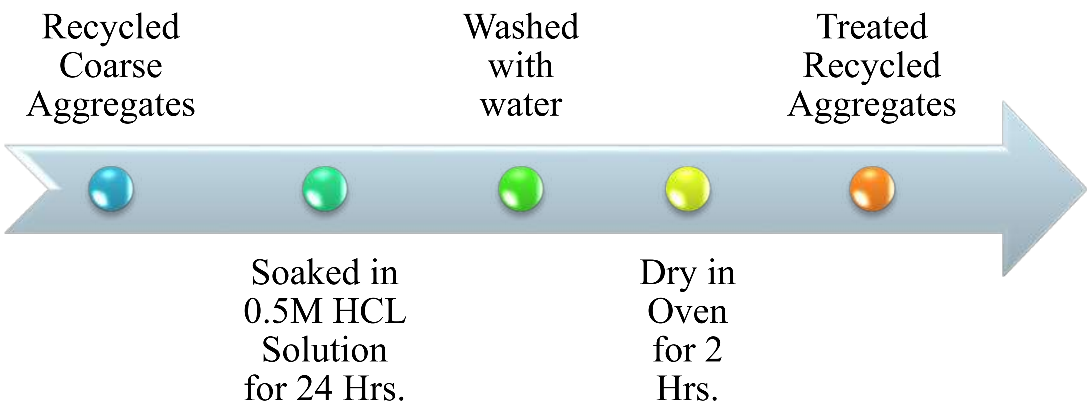


Figure 3.3 Process of chemical treatment of RCA

Diligence is required to prevent aggregates from coming into contact with contaminated surfaces during mixing and storage. Rigorous quality control measures are indispensable, covering every aspect from the selection of raw materials to the final product. This calls for routine testing and inspections. To avoid the buildup of finer particles with greater chloride content, segregation must be avoided during the handling and transportation of treated aggregates. To reduce the amount of pollutants released over time, it is crucial to have the right curing conditions after treatment. Finally, pinpointing the source of any possible contamination requires meticulous documenting of the chemical treatment procedure, including the kinds and quantities of chemicals utilized. The danger of introducing chloride ions during the chemical treatment of recycled coarse aggregates may be greatly minimized by firmly following to these measures and maintaining a strict quality control routine. This will ensure the structural integrity of the final concrete. Figure 3.4 illustrates the applied chemical treatment on RCAs.

(a) Pre-soaking of RCA in acid (b) Chemically treated RCA

Figure 3.4 Surface modification of RCA by chemical treatment

3.3.3 Surface Modification of RCA by Abrasion Treatment

The technique employed in this study focuses on a precise abrasion treatment method designed to reduce the quantity of adhered mortar on the surface of RCA. This process utilizes a specialized apparatus known as the Los Angeles Abrasion Machine (LAM), a hollow steel cylinder with a 711 mm internal diameter that is closed at both ends. The LAM is capable of rotating about its horizontal axis at a consistent speed of 25 RPM for duration of 5 minutes. This machine facilitates efficient mortar removal from the RCA surface. As the drum rotates, the individual aggregate particles come into contact with each other, resulting in mechanical interactions that effectively remove any attached mortar on them. This abrasion action, where particles rub against each other, ensures a thorough cleaning of the RCA surface, making it free from excess mortar. The entire process is represented in Figure 3.5, illustrating the surface modification achieved through the abrasion treatment of RCA.

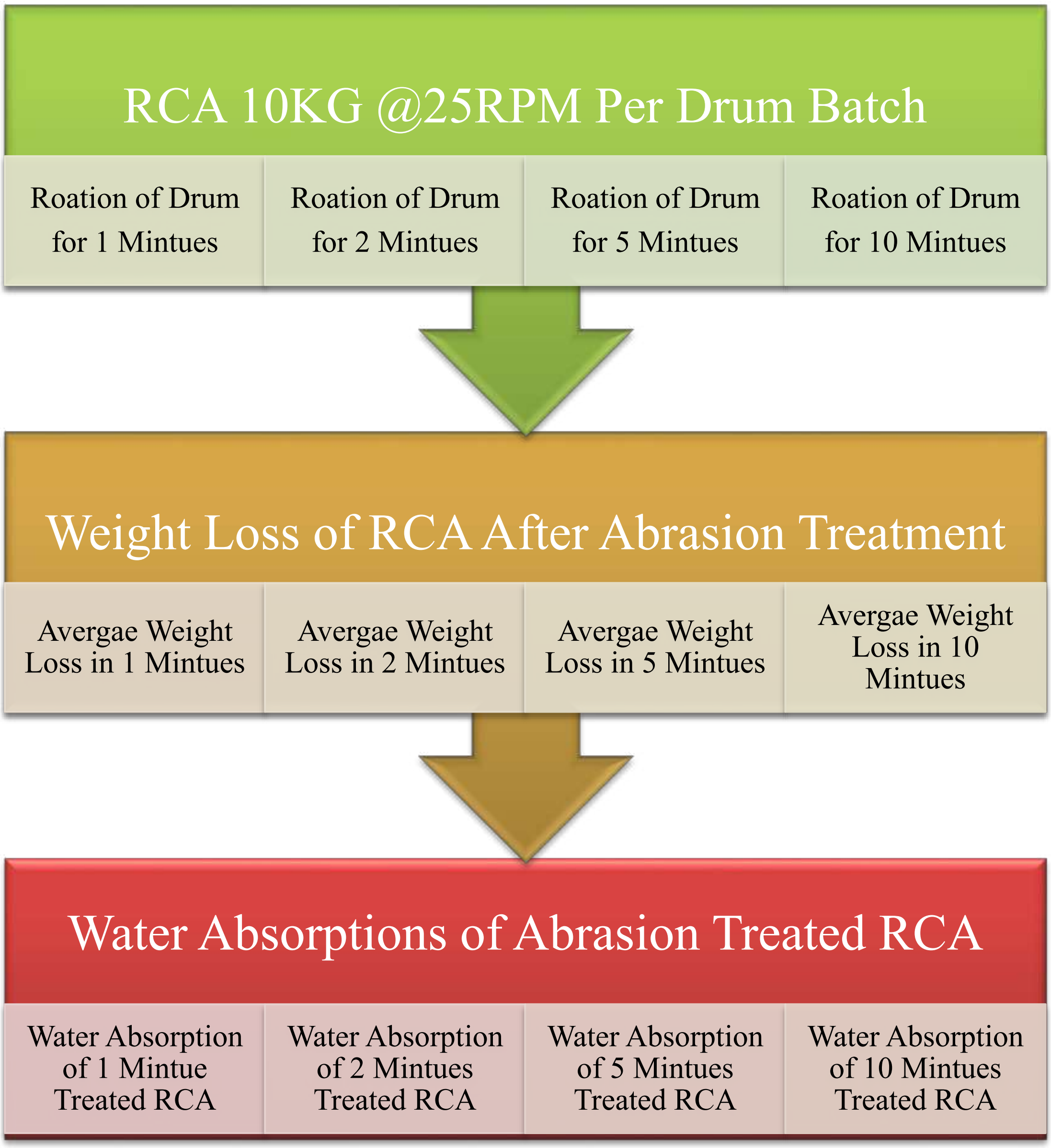


Figure 3.5 Process of RCA by abrasion treatment

To determine the optimal duration for the drum rotation, several trials were conducted, varying the revolution duration of the abrasion machine. The rotation duration was chosen based on minimum percentage of water absorption by RCA samples after treatment, indicating the level of cleanliness achieved. The results of these trials, presented in Table 3.9, revealed that after 5 minutes of continuous rotation at 25 RPM, the treated RCA sample absorbed only 1.87% water. This low water absorption indicates a successful removal of attached mortar from RCA surfaces and 5 minutes duration considered as ideal treatment duration for the recycled coarse aggregates.

Table 3.9 Test results of the drum rotation trails and water absorption

weight of RCA before the test (kg)	weight of RCA after 1 minute of test duration (kg)	Weight loss After 1 minute test duration (%)	weight of RCA after 2 minute of test duration (kg)	Weight loss after 2 minute test duration (%)	weight of RCA after 5 minutes of test duration (kg)	Weight loss after 5 minute test duration (%)	weight of RCA after 10 minute of test duration (kg)	Weight loss after 10 minute test duration (%)
10	8.36	16.40	8.70	13.00	8.75	12.50	8.60	14.00
10	9.93	0.70	9.38	6.20	8.64	13.60	9.21	7.90
10	8.83	11.70	9.18	8.20	7.84	21.60	8.75	12.50
10	8.76	12.40	9.17	8.30	8.28	17.20	7.19	28.10
10	9.75	2.50	8.07	19.30	8.18	18.20	8.71	12.90
10	8.85	11.50	8.12	18.80	8.25	17.50	8.15	18.50
10	9.23	7.70	9.18	8.20	7.25	27.50	7.74	22.60
10	8.43	15.70	9.03	9.70	8.27	17.30	9.22	7.80
10	9.26	7.40	8.42	15.80	8.75	12.50	8.68	13.20
10	8.25	17.50	9.12	8.80	7.67	23.30	7.21	27.90
Average Weight loss (%)	10.35		11.63		18.12		16.54	
Water absorption (%)	03.43		03.16		01.87		02.98*	
*Higher value may be due to sample variation.								

In its essence, this intricate abrasion treatment procedure, meticulously executed under precise conditions, guarantees a comprehensive cleansing and enhancement of the surface of RCA. Through rigorous experimentation, optimal treatment duration has been determined to ensure the making of high-quality RCA, ideal for sustainable and resilient concrete applications within the construction sector. Figure 3.6 provides a visual representation, illustrating the specific abrasion treatment applied to RCAs, showcasing the intricacies and meticulousness of the process undertaken to achieve superior results.

(a) Los Angeles abrasion machine (b) Abrasion treated RCA

Figure 3.6 Surface modification of RCA by abrasion treatment

3.3.4 Surface Modification of RCA by Chemical Treatment followed by Abrasion Treatment

To address the compromised strength of concrete arising from insufficient bonding between mortar and untreated RCA, this study employs an experimental approach. The strategy involves enhancing the surfaces of RCA through a series of treatments, including soaking in HCl and subsequent abrasion. To remove the adhered mortar from the surface of RCA, 0.5M HCl solution has been utilized. The 24-hour room temperature soaking proves effective in weakening the bond of adhered mortar for its subsequent removal through abrasion. The chemically treated RCA then undergoes abrasion in Los Angeles Abrasion machine, rotating for 5 minutes at 25 revolutions per minute (RPM). The comprehensive process depicted in

Figure 3.7, significantly enhances the quality of aggregates, minimizing attached mortar and resulting in the production of surface-modified recycled coarse aggregates (SMRCA).

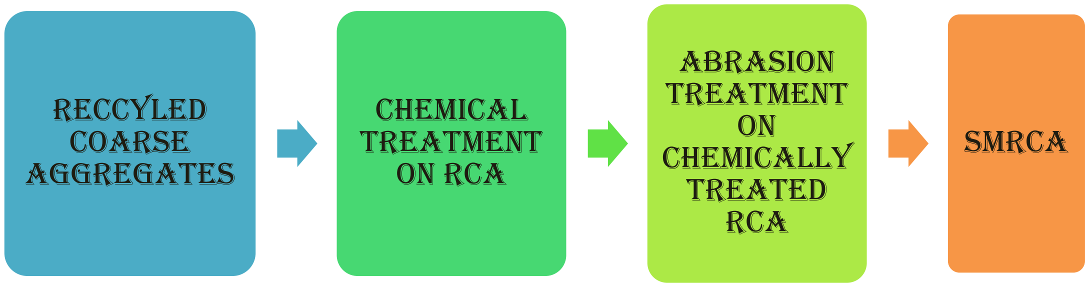


Figure 3.7 Production of SMRCA by integrating chemical and abrasion processes

3.3.5 Surface Modification of RCA by Abrasion Treatment followed by Coating Treatment

In addressing the significant strength reduction observed with untreated RAC due to inadequate bonding of untreated RCA with the cement mortar, a novel approach was implemented by incorporating abrasion and cement slurry treatments. The objective was to enhance the surfaces of RCA by challenging the bonding of RCA with aged mortar residues. For the abrasion treatment, Los Angeles Abrasion machine was utilized, rotating at 25 revolutions per minute for 5 minutes to dislodge loosely attached mortar. Through the experiments it was found that 5 minutes of revolutions was the optimal treatment time, resulting in a water absorption rate of 1.87%. Subsequently, the RCA surface underwent a cement slurry treatment, involving immersion for 24 hours in already prepared cement paste followed by drying in an oven for 2 Hours. The treated recycled aggregates, now termed as surface-treated RCA (STRCA), were then incorporated into concrete preparations. The comprehensive treatment process, illustrated in Figure 3.8, signifies a strategic approach to enhance the properties and overall performance of RAC, with specific emphasis on improving the compressive strength of concrete. This innovative surface modification technique contributes to bridging the existing gap of durability challenges for recycled aggregate concrete.

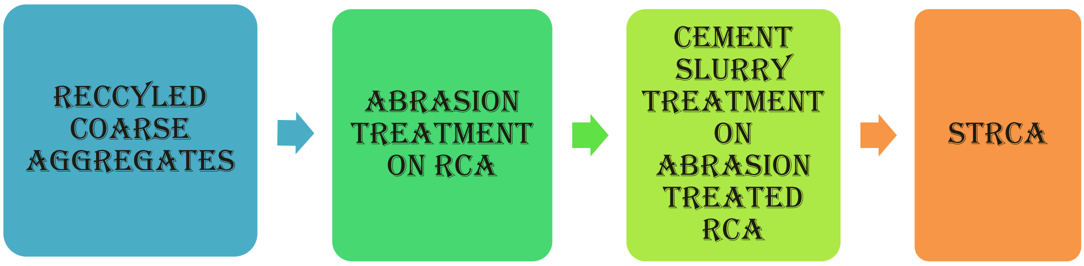


Figure 3.8 Production of STRCA by integrating abrasion and cement slurry treatments

3.4 MIX PROPORTIONS

To explore the mechanical properties of concrete prepared with surface-modified RCA, a total of 29 concrete mixtures were meticulously formulated for target strength of 27 MPa and slump of 90 ± 25 mm. The weight batching method was employed for these mixtures while maintaining a consistent water-cement ratio of 0.50 [142]. The detailed compositions of these mixes are presented in Table 3.10. The baseline mixture (CC) was composed of natural aggregates and mixtures labeled RFA 25 to RFA 100 were prepared by substituting natural fine aggregates with RFA, by varying replacement percentages of 25%, 50%, 75% and 100%. Mixtures labeled RCA 25 to RCA 100 were prepared by substituting natural coarse aggregates with RCA, by varying replacement percentages of 25%, 50%, 75% and 100%. Additionally, mixtures labeled RCACST 25 to RCACST 100 was prepared by substituting natural coarse aggregates with cement slurry-treated RCA, with varying replacement percentages of 25%, 50%, 75% and 100%. Similarly, mixtures RCACT 25 to RCACT 100 were formulated by replacing 25%, 50%, 75% and 100% natural coarse aggregates with chemically treated RCA. Furthermore, RCAAT 25 to RCAAT 100 were developed by replacing natural coarse aggregates with abrasion-treated RCA, with varying replacement percentages of 25%, 50%, 75% and 100%. Moving on to the next mixtures, RCACAT 25 to RCACAT 100 were prepared by substituting natural coarse aggregates with chemically and abrasively treated RCA, by replacement of 25%, 50%, 75% and 100%. Finally, RCAACST 25 to RCAACST 100 were prepared by substituting natural coarse aggregates with abrasively and cement slurry treated RCA, by replacement of 25%, 50%, 75% and 100%.

Table 3.10 Composition of concrete mixtures

S. No.	Mixture ID	NFA (kg/m^3)	RFA (kg/m^3)	NCA (kg/m^3)	RCA (kg/m^3)	Cement (kg/m^3)
1	CC	444.48	0	1511	0	400
2	RFA-25	333.36	111.12	1511	0	400
3	RFA-50	222.24	222.24	1511	0	400
4	RFA-75	111.12	333.36	1511	0	400
5	RFA-100	0	444.48	1511	0	400
6	RCA-25	444.48	0	1133.25	377.75	400
7	RCA-50	444.48	0	755.5	755.5	400
8	RCA-75	444.48	0	377.75	1133.25	400
9	RCA-100	444.48	0	0	1511	400
10	RCACST-25	444.48	0	1133.25	377.75	400
11	RCACST-50	444.48	0	755.5	755.5	400
12	RCACST-75	444.48	0	377.75	1133.25	400
13	RCACST-100	444.48	0	0	1511	400
14	RCACT-25	444.48	0	1133.25	377.75	400
15	RCACT-50	444.48	0	755.5	755.5	400
16	RCACT-75	444.48	0	377.75	1133.25	400
17	RCACT-100	444.48	0	0	1511	400
18	RCAAT-25	444.48	0	1133.25	377.75	400
19	RCAAT-50	444.48	0	755.5	755.5	400
20	RCAAT-75	444.48	0	377.75	1133.25	400
21	RCAAT-100	444.48	0	0	1511	400
22	RCACAT-25	444.48	0	1133.25	377.75	400
23	RCACAT-50	444.48	0	755.5	755.5	400
24	RCACAT-75	444.48	0	377.75	1133.25	400
25	RCACAT-100	444.48	0	0	1511	400
26	RCAACST-25	444.48	0	1133.25	377.75	400
27	RCAACST-50	444.48	0	755.5	755.5	400
28	RCAACST-75	444.48	0	377.75	1133.25	400
29	RCAACST-100	444.48	0	0	1511	400

CC-Conventional Concrete, NFA-Natural Fine Aggregates, RFA- Recycled Fine Aggregates, NCA-Natural Coarse Aggregates, RCA-Recycled Coarse Aggregates, RCACST- Recycled Coarse Aggregates Treated with Cement Slurry, RCACT- Recycled Coarse Aggregates Treated with Chemical, RCAAT- Recycled Coarse Aggregates Treated with Abrasion, RCACAT- Recycled Coarse Aggregates Treated with Chemical and Abrasion, RCAACST- Recycled Coarse Aggregates Treated with Abrasion and Cement Slurry.

3.5 TESTING METHODOLOGY

Several assessments were conducted to thoroughly evaluate various aspects of structural concrete. Various constituent materials employed in the study undergo analysis using X-ray diffraction (XRD), scanning electron microscopy (SEM), and Energy-Dispersive X-ray Spectroscopy (EDAX) to assess their microstructural characteristics. The workability was measured to determine the easiness of compaction of the concrete. Additionally, mechanical properties underwent comprehensive scrutiny through tests for compressive strength, flexural strength, and split tensile strength. Furthermore, a series of evaluations were carried out to assess the sustained performance of concrete. These evaluations included tests for modulus of elasticity, drying shrinkage, electrical resistivity and rapid chloride ion penetration. To delve deeply into the microstructure of the concrete samples, sophisticated techniques such as scanning electron microscopy (SEM) and X-ray diffraction (XRD) were employed. These methodologies facilitated an intricate exploration of the internal characteristics of the concrete across various combinations. By implementing these findings of thorough analyses, the study aimed to acquire profound insights into the behavior of the concrete, illuminating its mechanical properties and contributing to the advancement of concrete technology. This comprehensive approach ensured a holistic understanding about the performance of the concrete and provided valuable contributions to the field of concrete research and technology.

3.5.1 Materials Characterization

The seamless integration of constituent materials such as cement and aggregates into concrete commences with a pivotal step: microstructural analysis before incorporation. X-ray Diffraction (XRD) serves to identify crystalline phases within the materials, providing a deeper understanding of their structural composition. Simultaneously, Scanning Electron Microscopy (SEM) offers high-resolution images, enabling a detailed exploration of microstructural features. Additionally, Energy-Dispersive X-ray Spectroscopy (EDAX) comes into play by facilitating quantitative elemental analysis to comprehensively assess the elemental composition of the materials under scrutiny. This integrated approach ensures a thorough characterization, laying the foundation for a well-informed and effective utilization of these materials in concrete production.

3.5.1.1 X-ray Diffraction (XRD) analysis of different constituent materials

X-ray Diffraction (XRD) is a widely used technique for analyzing the crystalline structure of materials. The principle of XRD is based on Bragg's Law, which states that when X-rays are directed at a crystalline substance, they are scattered by the atomic planes within the material. When the scattered X-rays satisfy the condition:

$$n\lambda = 2d\sin\theta$$

$where$:

- n is an integer (order of reflection),
- λ is the wavelength of the incident $X-ray$ beam,
- d is the interplanar spacing of the crystal lattice,
- θ is the diffraction angle,

Constructive interference results in a characteristic diffraction pattern. The positions and intensities of these diffraction peaks provide crucial information about the crystalline phases present in the material. In this study, XRD analysis was conducted using a Bruker D-8 diffractometer at the University Science Instrumentation Centre (USIC) in Delhi. The high-resolution X-ray diffractometer setup is illustrated in Figure 3.9. The scanning process covered a 2θ range of 3° to 70°, with a scanning rate of 2° per minute to capture detailed diffraction patterns. The collected diffraction data were processed using Jade 7 X-ray diffraction software, where scattering angles were plotted on the x-axis and intensity on the y-axis to analyze peak positions and phase composition. Sample preparation involved pulverizing the materials into a fine powder to ensure uniform exposure to the X-ray beam and precise alignment with the instrument. XRD analysis was performed on various constituent materials used in the study, including cement, natural coarse aggregates (NCA), recycled coarse aggregates (RCA), and surface-treated RCA variants such as cement slurry-treated RCA (RCACST), chemical-treated RCA

(RCACT), and abrasion-treated RCA (RCAAT). The resulting diffraction patterns provided valuable insights into the crystalline phases, mineral composition, and structural modifications induced by different surface treatments. This information was essential in evaluating the effects of treatment methods on the phase stability and overall performance of recycled aggregates in concrete applications.

Figure 3.9 High resolution X-ray Bruker D-8 diffractometer

3.5.1.2 Scanning Electron Microscopy (SEM) analysis of different constituent materials

Scanning Electron Microscopy (SEM) is a powerful imaging technique used to analyze the surface morphology and microstructure of materials at high magnification. The working principle of SEM is based on the interaction between a focused electron beam and the surface of a sample. The fundamental process involves the following steps:

1. **Electron Beam Generation** – An electron gun (typically a thermionic or field emission source) emits a high-energy electron beam, which is accelerated and focused onto the sample using a series of electromagnetic lenses.

2. **Electron-Sample Interaction** – When the electron beam strikes the sample surface, various types of interactions occur, leading to the emission of secondary electrons, backscattered electrons, and characteristic X-rays.

3. **Image Formation** –

   a) **Secondary electrons (SE)** provide detailed topographical information about the surface.

   b) **Backscattered electrons (BSE)** give contrast based on atomic number differences in the sample.

   c) **Energy Dispersive X-ray Spectroscopy (EDAX/EDS)** (if equipped) allows for elemental composition analysis.

4. **Detection and Image Processing** – The emitted signals are captured by detectors, converted into electronic data, and processed to generate high-resolution images of the sample's surface.

In this study, scanning electron microscopy (SEM) analysis was performed using a JSM 6610V SEM **at** the University Science Instrumentation Centre (USIC) in Delhi. The high-resolution electron gun and detectors facilitated a detailed investigation of material microstructures, as illustrated in Figure 3.10.

Figure 3.10 High resolution JSM 6610V scanning electron microscope

To ensure accurate imaging, the samples were placed inside a vacuum chamber, preventing electron scattering caused by air molecules. A focused electron beam was then scanned across the sample surface, and the emitted signals were collected to generate high-magnification images. The microstructural characteristics of the samples were analyzed at various magnification levels to study particle size, texture, and surface modifications**.** SEM analysis was conducted on multiple materials used in the study, including cement, natural coarse aggregates (NCA), recycled coarse aggregates (RCA), and surface-treated RCA variants**,** such as cement slurry-treated RCA (RCACST), chemical-treated RCA (RCACT), and abrasion-treated RCA (RCAAT)**.** The SEM examination provided critical insights into surface morphology, porosity, texture, and interfacial transition zone (ITZ) characteristics of recycled aggregates before and after treatment. These findings were instrumental in assessing the effectiveness of various surface modification techniques in enhancing aggregate properties for sustainable concrete applications.

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

Energy Dispersive X-ray Spectroscopy (EDAX), also known as Energy Dispersive Spectroscopy (EDS), is an analytical technique used for elemental composition analysis of materials. It operates based on the principle that when a material is bombarded with a high-energy electron beam (as in a Scanning Electron Microscope), it excites atoms within the sample, causing them to emit characteristic X-rays unique to each element. The fundamental working mechanism of EDAX involves:

1. **X-ray Emission** – When the electron beam interacts with the sample, inner-shell electrons of atoms are ejected, creating vacancies.
2. **Energy Transition** – Electrons from higher energy levels transition to fill these vacancies, releasing energy in the form of X-rays.
3. **Detection & Spectral Analysis** – The emitted X-rays are detected and analyzed by an **EDX detector**, which measures their energy and intensity.
4. **Elemental Identification** – Since each element has a unique X-ray emission spectrum, the collected data enables the identification and quantification of elements present in the sample.

This technique provides both qualitative (elemental identification) and quantitative (elemental concentration) analysis, making it a valuable tool for material characterization. Energy Dispersive X-ray Analysis (EDAX) was conducted using the JSM 6610V SEM equipped with an EDAX detector at the University Science Instrumentation Centre (USIC) in Delhi. The setup, as shown in Figure 3.10, enabled a detailed elemental analysis of the studied materials. To ensure accurate results, the specimens were mounted inside the vacuum chamber of the SEM, preventing interference from atmospheric particles. A high-energy electron beam was directed at the samples, stimulating X-ray emission, which was then recorded to analyze the elemental composition. The collected X-ray spectra were processed using specialized EDAX software, allowing for the identification and quantification of key chemical elements present in the samples. EDAX analysis was performed on various materials, including cement, natural coarse aggregates (NCA), recycled coarse aggregates (RCA), and surface-treated RCA variants, such as cement slurry-treated RCA (RCACST), chemical-treated RCA (RCACT), and abrasion-treated RCA (RCAAT). The results provided valuable insights into the mineralogical composition, presence of impurities, and chemical modifications induced by surface treatment techniques. This information was essential in assessing the effectiveness of treatments in improving the properties of recycled aggregates for sustainable concrete applications.

3.5.2 Workability

To assess the easiness of compaction of concrete mixes incorporating different proportions of surface-treated RCA, slump test study was performed in accordance with the guidelines outlined in IS: 1199-2018 (Part 1) [143].

3.5.3 Compressive Strength

Figure 3.11 illustrates the determination of compressive strength at 7 and 28 days for various mixes, as already explained in Table 3.10. A total of 174 cube specimens, using steel cubes moulds of 15×15×15 cm, were meticulously prepared, cured, and subjected to compression testing for all concretes. A compression testing machine of 2000 KN capacity was utilized for this purpose [144].

Figure 3.11 Compressive strength determinations

3.5.4 Flexural Strength

A total of 174 specimens, prepared in steel rectangular molds of 50×10×10 cm size, underwent curing and flexural strength testing across diverse concrete mixes. A thorough evaluation of these samples was conducted using a flexural testing machine of 2000 KN capacity. The average flexural strength values, derived from three specimens for each mix, were assessed at both 7 and 28 days [144]. Figure 3.12 depicts the determination of flexural strength at 7 and 28 days for various concrete mixes as referred in Table 3.10.

Figure 3.12Flexural strength determination

3.5.5 Split Tensile Strength

A comprehensive assessment was carried out on 174 specimens cast in steel cylindrical molds with a diameter (ϕ) of 15 cm and height (H) of 30 cm. These specimens underwent curing and thereafter were subjected to split tensile strength by placing laterally during tests using a compression testing machine of capacity 2000 KN. The average split tensile strength values were calculated from average of three specimens for each mix and the tests were conducted at 7 and 28 days [144]. Figure 3.13 depicts the determination of split tensile strength for the samples.

Figure 3.13 Split tensile strength determinations

3.5.6 Modulus of Elasticity

When assessing the deformation capacity of RAC in comparison to conventional concrete, the modulus of elasticity (MoE) plays a pivotal role. This value helps in determining a change in length and deformation of the specimen in lateral direction when subjected to axial force [145]. Figure 3.14 illustrates the process of determining the modulus of elasticity for the cylindrical specimens. These specimens were also having 15 cm diameter and 30 cm height.

Figure 3.14 Modulus of elasticity determination

3.5.7 Drying Shrinkage

The assessment of drying shrinkage in concrete mixes involved monitoring of changes in their length over time, adhering to the standards outlined in IS: 516 (Part 6)-2020 [146], as illustrated in Figure 3.15. Each of the 29 unique mixtures was tested using three specimens, each measuring 75×75×300 mm, after a 28-day curing period. Initial measurements were recorded using length comparator tools with a precision of 0.005 mm. Subsequent readings were taken at 28, 56, and 90 days using dial gauges and the change in length of each specimen was calculated based on the difference between the final and initial values.The average of three specimens has been taken as drying shrinkage value.

Figure 3.15 Drying shrinkage apparatus and specimen under testing

3.5.8 Electrical Resistivity

The assessment of electrical resistivity of concrete is crucial in evaluating the susceptibility to corrosion for steel reinforcement bars embedded in the concrete structure. The employed method measures the surface electrical resistivity of hardened concrete using a four-electrode setup. Employing the Resipod Resistivity Meter, as depicted in Figure 3.16, which has a 4-point Wenner Probe and follows the RILEM TC 154-EMC [147] standard. Concrete samples were meticulously prepared in cylindrical molds with a diameter of 100 mm and height of 200 mm. Table 3.11 presents the corrosion risk levels based on electrical resistivity according to the established standard.

Table 3.11 Standard level of electrical resistivity [147]

S.N.	Electrical Resistivity (Ω M)	Corrosion Risk
1	< 100	High
2	100-500	Moderate
3	500-1000	Low
4	> 1000	Negligible

Resistivity is given by the equation:

$$\rho = K.R$$

Here, R represents the concrete resistance, and K is a geometric parameter influenced by the size of sample, shape of sample and proximity to the probe of the testing equipment. In practical applications, K is determined through actual testing,

$$K = \Upsilon . a$$

Where a stands for the length between the probes, and 2π is the value of the dimensional geometry correction factor, Υ.

Figure 3.16 Resipod meter and a specimen under testing

3.5.9 Rapid Chloride ion Penetration Test (RCPT)

The RCPT unit, as illustrated in Figure 3.17, conforms to the ASTM C1202-2012 [148] standard use and incorporates a mold with dimensions of 100 mm in diameter and 50 mm in height. For this study, 174 specimens were meticulously prepared. Table 3.12 provides valuable insights into the resistance levels of concrete by categorizing chloride ion permeability based on transmitted charges.

Figure 3.17Schematic depictions of the RCPT unit and specimens

The setup consists of two chambers containing sodium chloride (NaCl) at a concentration of 0.24M and sodium hydroxide (NaOH) at 0.3M. Both samples and test cells are tightly sealed. A 60V electrical potential difference was applied with the negative end connected to the NaCl chamber and the positive end to the NaOH chamber. Readings were taken at 30-minute intervals for a maximum of 6 hours. Tests performed at 28 and 56 days measure the amount of charge transferred, indicating the resistance to penetration of chloride ions. The quantification of chloride ion permeability adhered to the ASTM C1202 standard. The total charge transferred (Q) was determined using the given formula:

$$Q = 900\ (I_o + 2I_{30} + 2I_{60} + \dots\dots\dots + 2I_{330} + I_{360})$$

Where Q = Charge Passing in Coulombs

$I_o, I_{30}, I_{60}, \dots\dots\dots.\ I_{330}, I_{360}$, are currents in Ampere at 0, 30, 60, …, 330, 360 Minutes.

Table 3.12 RCPT values as per ASTM C1202-2012 [148]

Charge Passing in Coulomb	Permeability of Chloride ions
> 4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

3.6 COST BENEFITS ANALYSIS

The study offers a comprehensive overview of the results derived from our cost-benefit analysis focusing on a comparison between various mixtures based on Delhi Scheduled of Rates for Road and Building Department Delhi Division, Government of Delhi, and the current market rates (which are not available in Delhi Schedule of Rate) for various constituent materials. It is imperative to note that the Recycled Aggregates (RA) utilized in the analysis were obtained from the IL&FS Construction and Demolished (C&D) Waste Recycling Plant, operated by the Delhi Metro Rail Corporation (DMRC) in Delhi, India. These RA were produced from waste concrete through a crushing process employing an impact crusher. The present cost analysis showcases the potential for significant cost savings by incorporating untreated and treated RCA in concrete mixes. The selection of the most cost-effective mixture depends on the desired cost savings and is based on the specific requirements of strength and durability of the project. In summary, the analysis showcases the potential for significant cost savings by incorporating various types of RCA in concrete mixes.

3.7 SUMMARY

This chapter presents a detailed investigation of the materials used in this study, the surface modification techniques applied to recycled aggregates, the mix design methodology, and the testing procedures. The key findings from this chapter are summarized below:

a) **Characterization of Materials:** A comprehensive evaluation was conducted on the physical and mechanical properties of both natural and recycled aggregates. The results indicated that RCA exhibited significantly higher water absorption (4.33%) and lower density compared to NCA, suggesting a more porous structure that could influence concrete performance. Microstructural analysis using XRD, SEM, and EDAX confirmed the presence of adhered mortar on RCA, which contributed to its inferior mechanical properties and negatively affected its effectiveness in concrete applications. Additionally, RFA demonstrated higher water absorption and lower density than natural fine aggregates, leading to reduced workability in concrete mixtures.

b) **Surface Modification of Recycled Coarse Aggregates:** To enhance the properties of recycled coarse aggregates (RCA), three surface treatment techniques were applied: cement slurry coating, chemical treatment using HCl immersion, and abrasion treatment. Cement slurry treatment reduced water absorption and improved aggregate bonding by creating a supplementary cementitious layer; however, it also introduced additional cementitious material. Chemical treatment effectively removed adhered mortar, enhancing aggregate quality, but required careful neutralization to prevent chloride contamination. Abrasion treatment mechanically eliminated weak mortar, leading to reduced water absorption and an improved surface texture. Furthermore, combined treatments, such as chemical treatment followed by abrasion or abrasion followed by cement slurry coating, demonstrated significant enhancements in both strength and durability, making RCA more suitable for high-performance concrete applications.

c) **Concrete Mix Proportions:** A total of 29 concrete mixtures were designed, incorporating RCA at replacement levels of 25%, 50%, 75%, and 100%, each subjected to different surface treatment techniques. To maintain consistency and ensure comparability across all mixes, a fixed water-cement ratio of 0.50 was used. Additionally, a control concrete (CC) mix was prepared using only natural aggregates, serving as a benchmark to assess the impact of RCA incorporation on concrete performance.

d) **Testing Methodology:** The evaluation of fresh and hardened concrete properties was conducted through a series of standardized tests, including workability, compressive strength, flexural strength, split tensile strength, modulus of elasticity, drying shrinkage, electrical resistivity, and RCPT. To further analyze the ITZ and bonding performance of treated aggregates, microstructural investigations were carried out using SEM and XRD. Additionally, a cost-benefit analysis was planned to assess the economic viability of incorporating treated RCA in concrete production, ensuring a balance between performance enhancement and financial feasibility.

This chapter establishes a systematic experimental framework to analyze the impact of treated recycled aggregates on concrete performance, addressing the identified research gaps. The subsequent chapters will discuss the results of these experiments and their implications for sustainable construction.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 GENERAL

This chapter delves into the analysis of diverse material properties through the characterization of materials utilized in the study and the examination of properties associated with concrete produced using untreated and treated recycled aggregates. The treated aggregates undergo surface modification treatments both individually and through two combined approaches of treatment. The initial phase involves the characterization of materials, followed by an assessment of fresh concrete property i.e. workability. Subsequently, the focus shifts to properties of hardened concrete, including compressive strength, flexural strength, split tensile strength, modulus of elasticity and various durability characteristics like drying shrinkage, electrical resistivity and rapid chloride ion penetration test. Furthermore, microstructural properties of different mixtures are investigated through XRD (X-ray diffraction) and SEM (scanning electron microscopy) analyses. This comprehensive approach ensures a detailed understanding of the materials, which helps in assessing their performance in the production of concrete.

4.2 MATERIALS CHARACTERIZATION

Ensuring the harmonious integration of constituent materials, such as cement and aggregates, into concrete necessitates a critical preliminary step i.e. microstructural analysis before their incorporation. This rigorous examination aims to assess the chemical elements, mineralogical properties and microstructure of these materials. Employing advanced techniques such as X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), and Energy-dispersive X-ray Spectroscopy (EDAX), these analyses delve into the intricate details of molecular structure and composition of the materials. The use of XRD allows for the identification of crystalline phases present in the materials, while SEM provides high-resolution images, offering a closer look at the microstructural features. EDAX, on the other hand, enables the quantitative analysis of elemental composition. Together, these analytical methods yield in-depth insights and lay the groundwork for understanding of the suitability of the materials for concrete applications. The subsequent discussion will delve into the ramifications of these findings, shedding light on how they influence the overall performance and durability of the concrete mixtures. This meticulous approach ensures that the chosen materials contribute positively to the structural integrity and long-term resilience of the concrete.

4.2.1 X-Ray Diffraction (XRD)analysis of constituent materials

Table 4.1 presents XRD results for different materials including cement, Natural Coarse Aggregates (NCA), Recycled Coarse Aggregates (RCA), Cement Slurry Treated Recycled Coarse Aggregates (RCACST), Chemical Treated Recycled Coarse Aggregates (RCACT) and Abrasion Treated Recycled Coarse Aggregates (RCAAT).

Table 4.1 XRD Data for various constituent materials

Material	Peak No.	Peak Angle	Intensity	Chemical Formula	Chemical Name	Crystal System
Cement	1	32.24	30.2335	C_3S	Tri Calcium Silicate	Monoclinic & Rhombohedra
	2	29.58	20.11643	C_2S	Di Calcium Silicate	Octahedral & Hexahedron
	3	26.24	14.44964	C_3A	Tri Calcium Aluminate	Cubic & Monoclinic
	4	11.7	7.25595	C_4AF	Tetra Calcium Aluminate ferrate	Octahedral & Tetrahedral
	5	39.14	6.39467	CaO	Calcium Oxide	Cubic
	6	50.1	5.66566	MgO	Periclase	Octahedral
	7	68.04	3.75862	$CaSO_4$	Calcium Sulfate	Orthorhombic
NCA	1	12.94	17.00045	SiO_2	Quartz	Tetrahedral
	2	16.58	3.75826	Hbl	Hornblende	Double Tetrahedral
	3	26.28	3.12705	$NaAlSi_3O_8$	Albite	Tetrahedral
	4	33.16	1.82238	$CaAl_2Si_2O_8$	Anorthite	Triclinic with Prismatic
	5	41.7	2.20084	H-M	Chamosite	Prismatic

	6	45.16	2.13180	Fe_2O_3	Hematite	Hexagonal
	7	77.5	1.90557	$CaMg(CO_3)_2$	Dolomite	Trigonal
RCA	1	12.94	10.76634	SiO_2	Quartz	Tetrahedral
	2	14.34	7.14107	Hbl	Hornblende	Double Tetrahedral
	3	19.12	4.67558	$NaAlSi_3O_8$	Albite	Tetrahedral
	4	26.04	2.11790	$CaAl_2Si_2O_8$	Anorthite	Triclinic with Prismatic
	5	32.16	1.64824	H-M	Chamosite	Prismatic
	6	45.34	1.14794	Fe_2O_3	Hematite	Hexagonal
	7	57.54	1.37170	$CaMg(CO_3)_2$	Dolomite	Trigonal
RCACST	1	12.8	15.43778	SiO_2	Quartz	Tetrahedral
	2	16.72	5.05474	Hbl	Hornblende	Double Tetrahedral
	3	21.3	3.44541	$NaAlSi_3O_8$	Albite	Tetrahedral
	4	24.8	1.90456	$CaAl_2Si_2O_8$	Anorthite	Triclinic with Prismatic
	5	32.34	2.00300	H-M	Chamosite	Prismatic
	6	44.42	1.00846	Fe_2O_3	Hematite	Hexagonal
	7	67.08	0.54847	$CaMg(CO_3)_2$	Dolomite	Trigonal
RCACT	1	7.64	5.93853	SiO_2	Quartz	Tetrahedral
	2	12.56	20.9961	Hbl	Hornblende	Double Tetrahedral
	3	17.66	4.48964	$NaAlSi_3O_8$	Albite	Tetrahedral
	4	28.58	3.17974	$CaAl_2Si_2O_8$	Anorthite	Triclinic with Prismatic
	5	31.84	3.21360	H-M	Chamosite	Prismatic
	6	51.2	17.9101	Fe_2O_3	Hematite	Hexagonal
	7	60.72	9.46396	$CaMg(CO_3)_2$	Dolomite	Trigonal
RCAAT	1	12.88	9.0905	SiO_2	Quartz	Tetrahedral
	2	17.84	3.9032	Hbl	Hornblende	Double Tetrahedral
	3	27.38	2.50955	$NaAlSi_3O_8$	Albite	Tetrahedral
	4	39.62	1.48442	$CaAl_2Si_2O_8$	Anorthite	Triclinic with Prismatic
	5	49.94	1.47275	H-M	Chamosite	Prismatic
	6	55.98	0.68161	Fe_2O_3	Hematite	Hexagonal
	7	69.46	0.49838	$CaMg(CO_3)_2$	Dolomite	Trigonal

The XRD profile of cement reveals distinct peaks corresponding to calcium silicates, tri-calcium aluminate, and silica phases. The XRD analysis of NCA and

RCA with and without surface modifications are shown in Figure 4.1, unveils mineralogical properties with peaks corresponding to Quartz, Hornblende, Albite and Anorthite. Significantly, the nature of RCA appears crystalline before undergoing surface modification treatment, suggesting the presence of previous cement mortar adhered to its surface. This attachment potentially results in weak bonding with the present cement mortar. The unmodified RCA particles exhibit inadequate bonding, necessitating the removal of old cements mortar from the surface of RCA to establish robust bonding with the present cement mortar. To tackle this issue, various treatments are employed to modify the surface of RCA, either individually or through a combined treatment approach. The XRD analysis depicts the mineralogical properties of Surface Modified Recycled Coarse Aggregates (SMRCA), treated using various techniques are illustrated in Figure 4.1. A prominent peak signifies the prevalence of quartz in the majority of the treated RCA. Various treatments induce noticeable changes in the XRD patterns of recycled coarse aggregates, including discernible alterations in peak intensities, indicating the dissolution of minerals present on the surface of aggregates. The emergences of new peaks suggest the potential formation of novel compounds previously concealed by impurities. Amorphization, reflected in broader peaks, indicates a transition from crystalline to amorphous structures. Changes in crystal structures and shifts in peak positions signify alterations in specific mineral phases. Additionally, the treatment may lead to mineral depletion or completely removing certain minerals from the surface. Collectively, these variations deepen our understanding of how treatments influence the mineralogical composition of recycled coarse aggregates, as revealed through XRD analysis. These results underscore the efficacy of surface treatments in enhancing the desired features of RCA, thereby contributing to improved bonding with the cement mortar. A similar observation is also reported by Kazemian et al. (2019) [149], further validating these findings. The subsequent discussion will explore the implications of these mineralogical variations for the overall performance and durability of concrete mortar. Notably, SMRCA exhibits a rougher surface, closely resembling to the characteristics of natural coarse aggregates. This distinction suggests that SMRCA is more conducive to forming a robust bond with the cement mortar, thereby enhancing the mechanical characteristics of RAC.

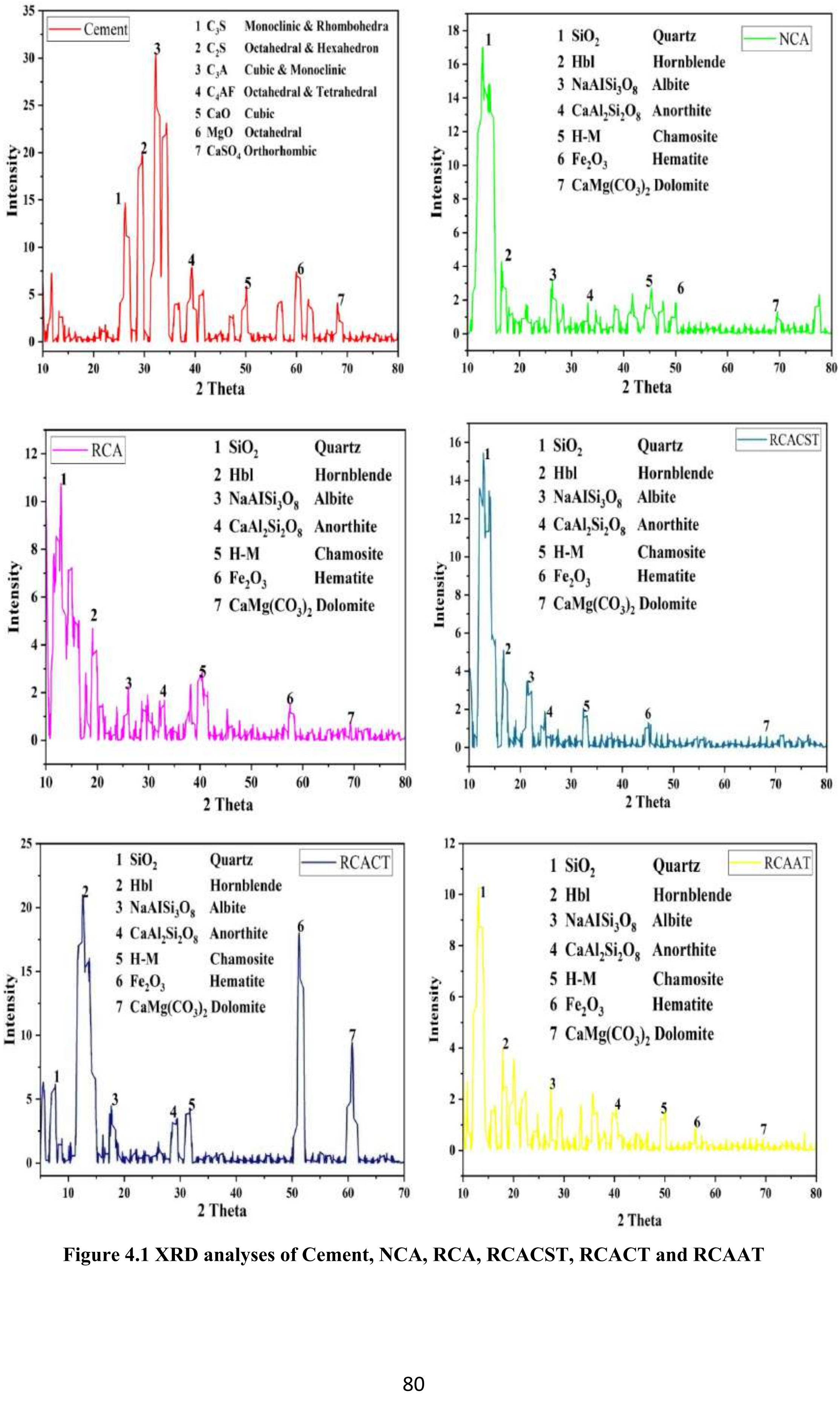
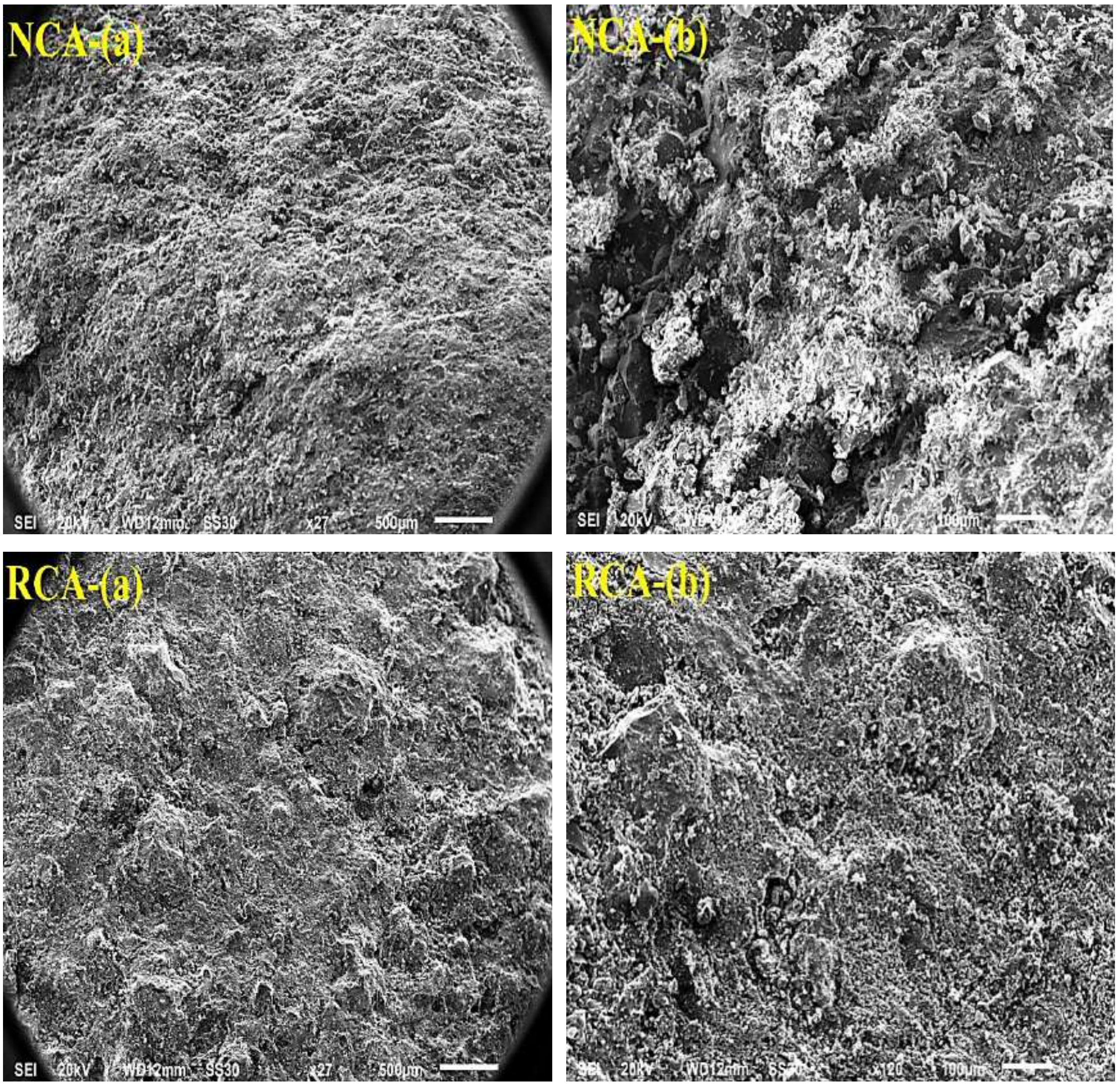


Figure 4.1 XRD analyses of Cement, NCA, RCA, RCACST, RCACT and RCAAT

4.2.2 Scanning Electron Microscopy (SEM) analysis of constituent materials

SEM played a pivotal role in characterizing a variety of materials, namely Natural Coarse Aggregates (NCA), Recycled Coarse Aggregates (RCA), Cement Slurry Treated Recycled Coarse Aggregates (RCACST), Chemical Treated Recycled Coarse Aggregates (RCACT) and Abrasion Treated Recycled Coarse Aggregates (RCAAT). The largely magnified images facilitate a detailed examination of the surface morphology and particle microstructure of these materials, as depicted in Figure 4.2.



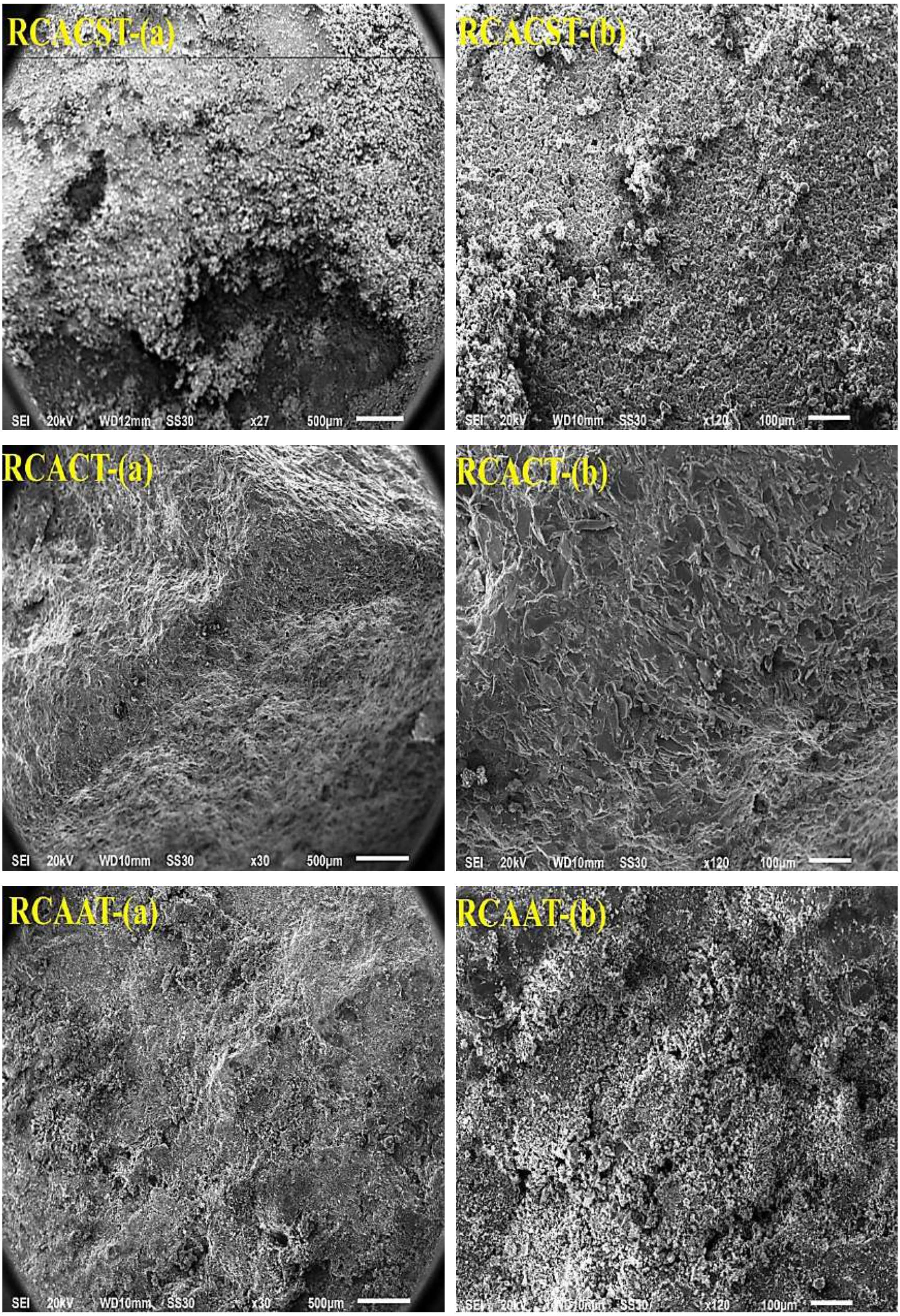
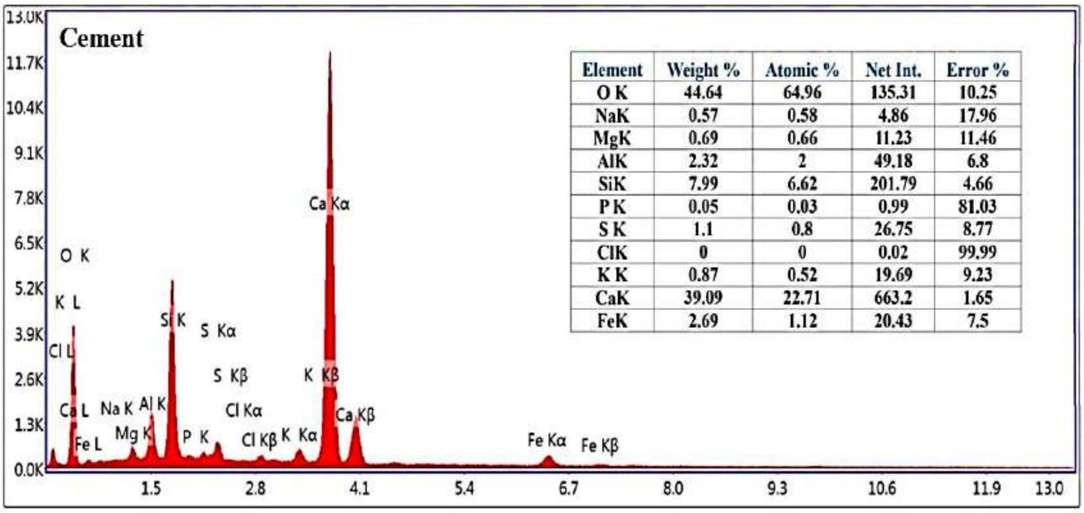


Figure 4.2 SEM analyses results for NCA, RCA, RCACST, RCACT and RCAAT

The SEM image of the NCA sample reveals a dense, uniform surface, relatively free of impurities, except for minor dust resulting from the manufacturing crushing process. Conversely, the unmodified RCA sample exhibits a more porous surface covered with fine particles and loose cement mortar, a consequence of the crushing process, as observed in the Figure 4.2. SEM images of the surface of RCACST samples illustrate the presence of cement particles covering the surface. The surface modification, attributed to the cement slurry treatment, contributes to increased bonding with cement mortar, ultimately enhancing the overall strength of the mixture. These observations align with findings by Ismail and Ramli (2013) [150]. The abrasion treatment effectively addressed the RCA surface, by removing the adhered mortar and creating new pores, as evidenced in SEM images of RCAAT. RCAAT and RCACST present a cleaner, denser, and more uniform surface compared to the unmodified RCA, visually represented in Figure 4.2. Moving on to SEM images of the surface of RCACT samples. This depicts the removal of loose particles from the unmodified RCA through acid treatment. The acidic solution effectively attacked the untreated RCA surface, dissolving the adhered mortar and creating new pores. The surface modification, attributed to the acid treatment, contributes to increased bonding with cement paste and enhances the overall strength of the mixture. RCACT displays a cleaner, denser, and more uniform surface compared to the unmodified RCA, as visually represented in Figure 4.2.

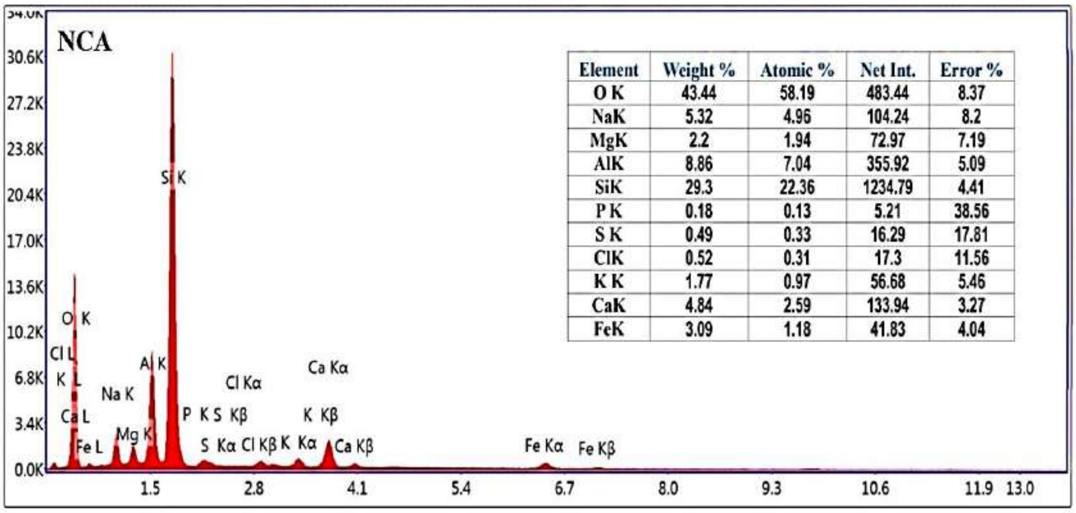
4.2.3 Energy Dispersive X-Ray Spectroscopy (EDAX)analysis of constituent materials

Thorough analysis using Energy Dispersive X-ray Spectroscopy (EDAX) was conducted to identify the crystalline constituents within both cement powder and coarse aggregates. Figure 4.3 presents the outcomes of the EDAX analyses for various constituent materials, including Cement, Natural Coarse Aggregates (NCA), Recycled Coarse Aggregates (RCA), Cement Slurry Treated Recycled Coarse Aggregates (RCACST), Chemical Treated Recycled Coarse Aggregates (RCACT), and Abrasion Treated Recycled Coarse Aggregates (RCAAT).



Element	Weight %	Atomic %	Net Int.	Error %
O K	44.64	64.96	135.31	10.25
NaK	0.57	0.58	4.86	17.96
MgK	0.69	0.66	11.23	11.46
AlK	2.32	2	49.18	6.8
SiK	7.99	6.62	201.79	4.66
P K	0.05	0.03	0.99	81.03
S K	1.1	0.8	26.75	8.77
ClK	0	0	0.02	99.99
K K	0.87	0.52	19.69	9.23
CaK	39.09	22.71	663.2	1.65
FeK	2.69	1.12	20.43	7.5

Lsec: 200.0 0 Cnts 0.000 keV Det: Octane Plus Det



Element	Weight %	Atomic %	Net Int.	Error %
O K	43.44	58.19	483.44	8.37
NaK	5.32	4.96	104.24	8.2
MgK	2.2	1.94	72.97	7.19
AlK	8.86	7.04	355.92	5.09
SiK	29.3	22.36	1234.79	4.41
P K	0.18	0.13	5.21	38.56
S K	0.49	0.33	16.29	17.81
ClK	0.52	0.31	17.3	11.56
K K	1.77	0.97	56.68	5.46
CaK	4.84	2.59	133.94	3.27
FeK	3.09	1.18	41.83	4.04

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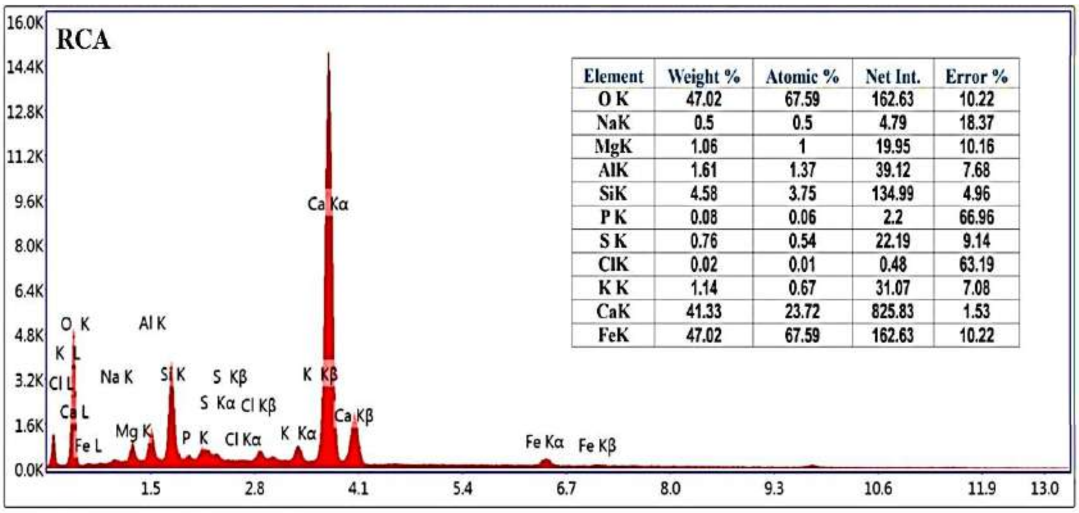
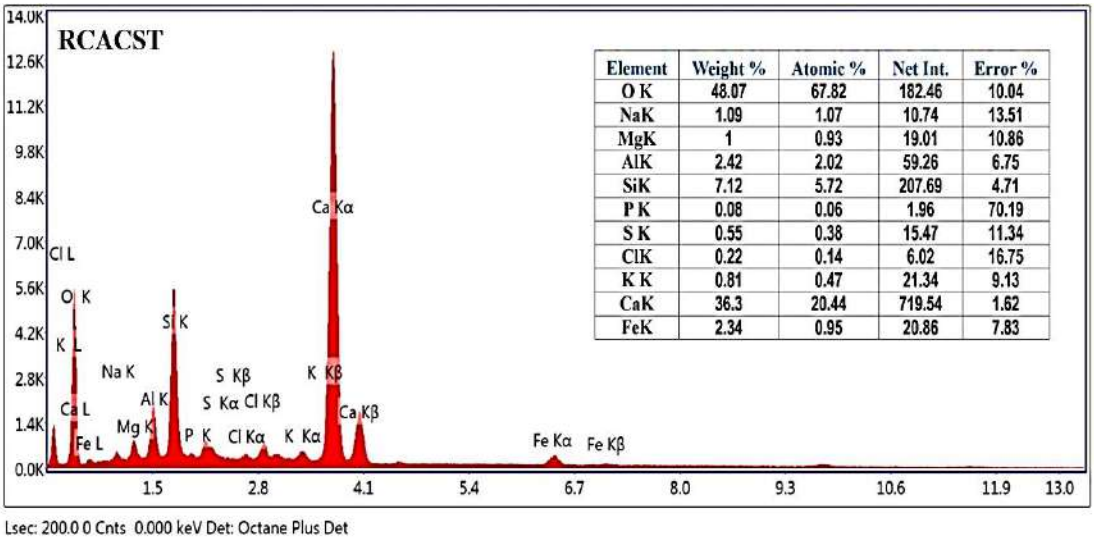
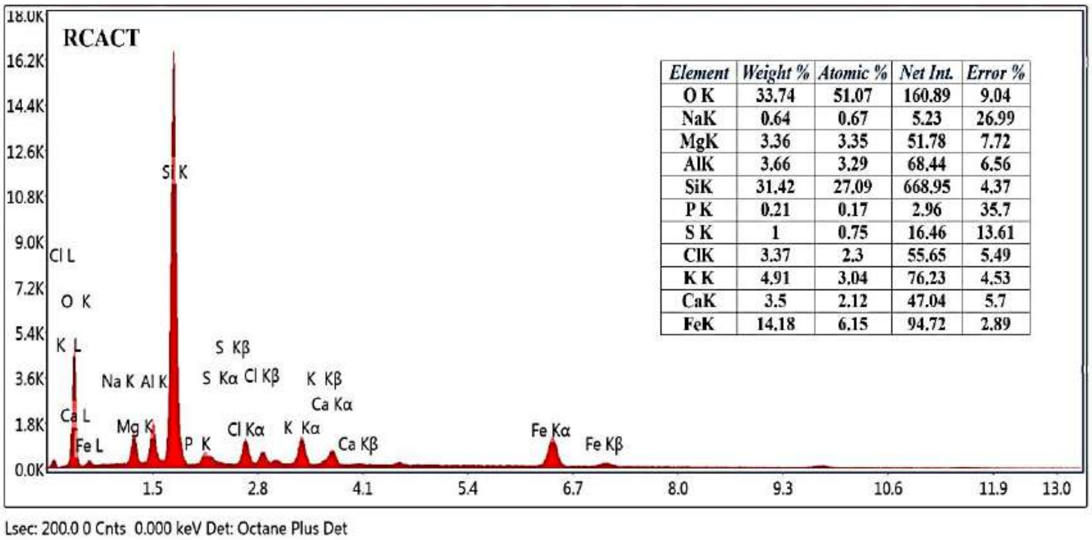


Element	Weight %	Atomic %	Net Int.	Error %
O K	47.02	67.59	162.63	10.22
NaK	0.5	0.5	4.79	18.37
MgK	1.06	1	19.95	10.16
AlK	1.61	1.37	39.12	7.68
SiK	4.58	3.75	134.99	4.96
P K	0.08	0.06	2.2	66.96
S K	0.76	0.54	22.19	9.14
ClK	0.02	0.01	0.48	63.19
K K	1.14	0.67	31.07	7.08
CaK	41.33	23.72	825.83	1.53
FeK	47.02	67.59	162.63	10.22

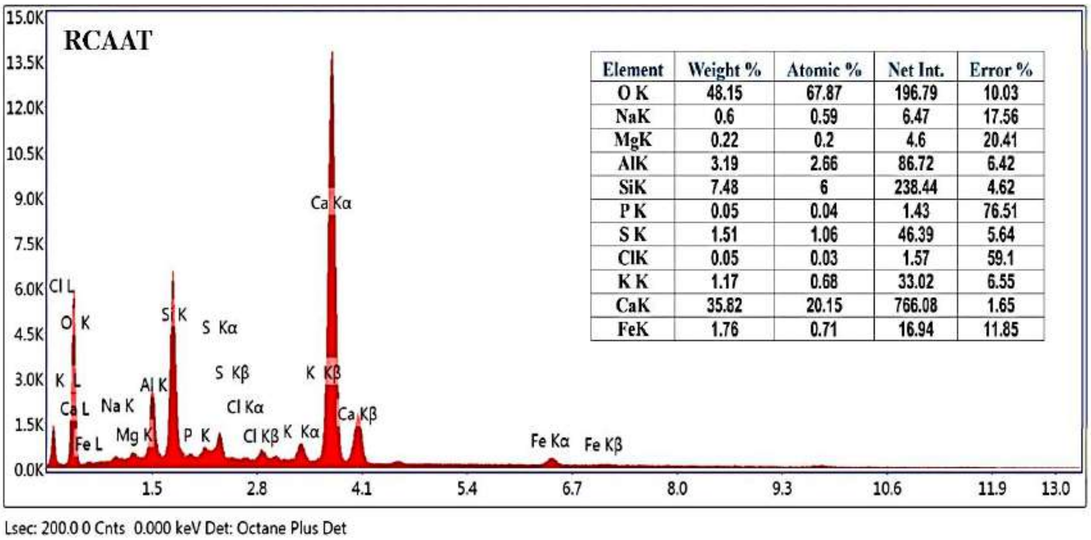
Lsec: 200.0 0 Cnts 0.000 keV Det: Octane Plus Det



Element	Weight %	Atomic %	Net Int.	Error %
O K	48.07	67.82	182.46	10.04
NaK	1.09	1.07	10.74	13.51
MgK	1	0.93	19.01	10.86
AlK	2.42	2.02	59.26	6.75
SiK	7.12	5.72	207.69	4.71
P K	0.08	0.06	1.96	70.19
S K	0.55	0.38	15.47	11.34
ClK	0.22	0.14	6.02	16.75
K K	0.81	0.47	21.34	9.13
CaK	36.3	20.44	719.54	1.62
FeK	2.34	0.95	20.86	7.83



Element	Weight %	Atomic %	Net Int.	Error %
O K	33.74	51.07	160.89	9.04
NaK	0.64	0.67	5.23	26.99
MgK	3.36	3.35	51.78	7.72
AlK	3.66	3.29	68.44	6.56
SiK	31.42	27.09	668.95	4.37
P K	0.21	0.17	2.96	35.7
S K	1	0.75	16.46	13.61
ClK	3.37	2.3	55.65	5.49
K K	4.91	3.04	76.23	4.53
CaK	3.5	2.12	47.04	5.7
FeK	14.18	6.15	94.72	2.89



Element	Weight %	Atomic %	Net Int.	Error %
O K	48.15	67.87	196.79	10.03
NaK	0.6	0.59	6.47	17.56
MgK	0.22	0.2	4.6	20.41
AlK	3.19	2.66	86.72	6.42
SiK	7.48	6	238.44	4.62
P K	0.05	0.04	1.43	76.51
S K	1.51	1.06	46.39	5.64
ClK	0.05	0.03	1.57	59.1
K K	1.17	0.68	33.02	6.55
CaK	35.82	20.15	766.08	1.65
FeK	1.76	0.71	16.94	11.85

Figure 4.3 EDAX analyses for Cement, NCA, RCA, RCACST, RCACT and RCAAT

The comprehensive EDAX analysis distinctly illustrates the presence of chemical elements in each material, forming a foundational understanding of their elemental composition. The ensuing discussion will delve into the implications of these findings for the structural and chemical properties of the concrete mixtures. The figures clearly illustrate a noticeable rise in silicon percentages following surface modification. This uptick signifies the enhanced distribution of calcium silicate minerals on the surface of RCAs, characterized by the presence of silicon (Si), oxygen (O), and calcium (Ca). The higher percentage of these elements has a major role in the enhanced cement paste-aggregate bond. The calcium (Ca) content primarily resides in cement and little in RCA, where it originates from the cement mortar adhered to the surface of RCA. When RCA subjected to abrasion treatment, a portion of this aged mortar is removed, leading to a reduction in calcium content compared to the original RCA. Conversely, in chemical treatment, the aged mortar is eliminated, resulting in the almost absence of calcium content similar to that in natural coarse NCA. Joseph et al. (2022) [151] also made a comparable observation, according to their reported findings.

4.3 WORKABILITY

In the present study, the easiness of compaction was assessed by slump test in various concrete mixes, having varying percentages of recycled aggregates (RA) in accordance with IS: 1199 (Part 1)-2018 [143] specifications. Slump, serving as an indicator of concrete consistency and workability, was measured in millimeters. Figure 4.4 visually presents the outcomes of the slump tests for various mixes, illustrating the diverse slump variations among various concrete mixtures. The detailed slump values for each mixture, showcased in Figure 4.4, expose differences and effectively demonstrate the influence of aggregate types and surface treatments on the workability of concrete. This essential information contributes to a comprehensive understanding of how these factors affect practical aspects of the construction process. The mixtures were designed for a 90 ± 25 mm slump. Test results show mixtures CC, RFA-25, RFA-50, RCA-25, RCA-50, RCACST-25, RCACST-50, RCACT-25, RCACT-50, RCACT-75, RCAAT-25, RCAAT-5-, RCAAT-75, RCAAT-25, RCAAT-50, RCAAT-75, RCACST-25, and RCACST-50 have given the slump of more than 90 mm while remaining mixtures have given slump less than 90 mm, which is also acceptable.

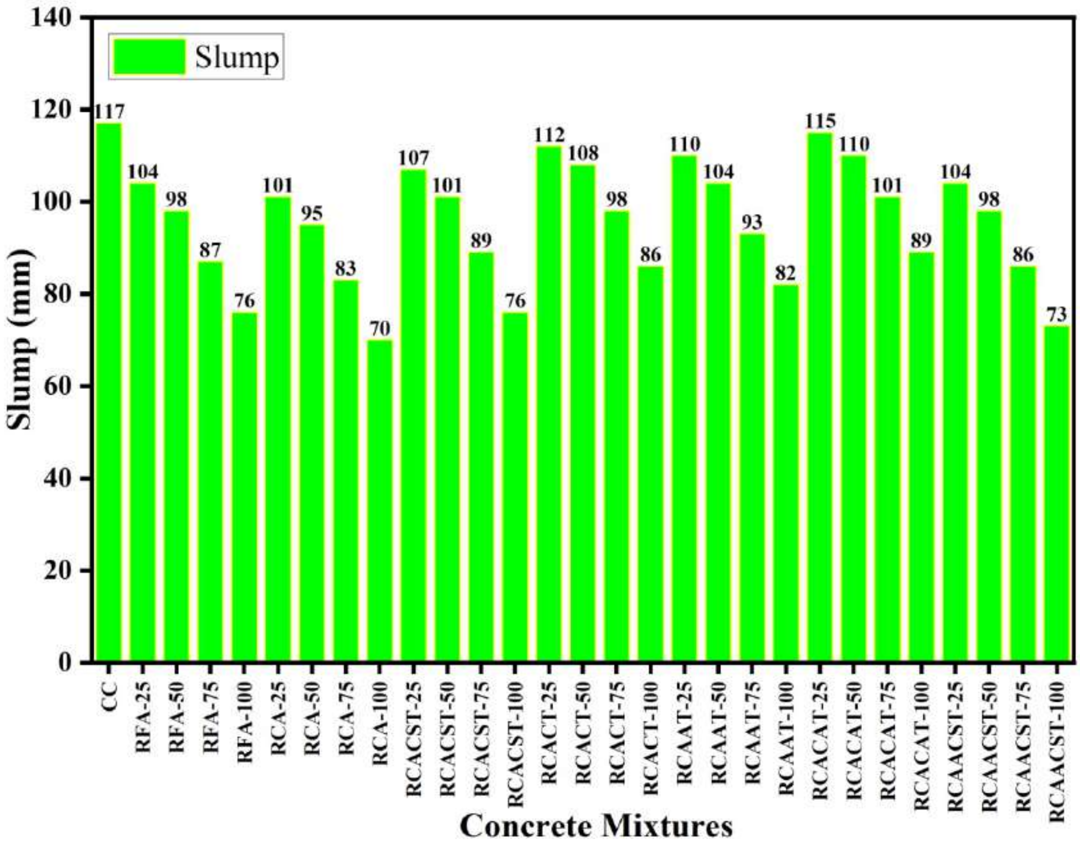


Figure 4.4Slump values for different concrete mixtures

Figure 4.4 demonstrates a consistent trend of decreasing slump in concrete as the proportion of modified or unmodified RA increases. Concretes incorporating modified or unmodified RA mostly exhibit workability in the medium range (50 to 100 mm). Due to its larger surface area and rougher texture compared to natural aggregates, RCA had a higher water absorption capacity, leading to a reduction in slump. Super plasticizer serves as an excellent plasticizing additive that efficiently decreases the water demand in concrete while preserving its uniformity. It is frequently employed to enhance the flow ability of concrete, improving its workability and facilitating easier placement and compaction. This plasticizing impact enables a reduction in the water/cement ratio of the mix, thereby enhancing strength while ensuring consistency. On comparison, it is found that concrete mixes with RCA treated by abrasion and cement slurry, abrasion treated RCA shows slightly higher slump values, indicating better workability. These results align with a previous study that observed a steady decline in a slump with an increasing percentage of RCA [152], [153]. The findings underscore the importance of considering the impact of surface modifications on workability which incorporates recycled aggregates into concrete mixes and provides valuable insights for sustainable construction practices.

4.4 COMPRESSIVE STRENGTH

Table 4.2 illustrates the percentage variation in average compressive strength for various concrete mixtures at both 7 and 28 days; relative to the conventional concrete (CC). The outcomes unveil significant differences in strength among the diverse mixtures. The compressive strength test results consistently reveal a pattern: as the replacement percentage of recycled aggregates (RA) increases, there is a corresponding decrease in compressive strength compared to the reference mixture. The 7-day compressive strength test results, as depicted in Figure 4.5, highlight those mixtures RFA-25, RCA-25, RCACST-25, RCACST-50, RCACT-25, RCACT-50, RCACT-75, RCAAT-25, RCAAT-50, RCACAT-25, RCACAT-50, RCACAT-75, RCAACST-25, and RCACAST-50 exhibit higher strength than the reference mixture. The remaining mixtures demonstrate lower strength than the reference mixture. Particularly noteworthy is the superior performance of Mixture RCACT-25 (+40.46%), followed by mixes RCAAT-25 (+36.11%), RCACAT-25 (+34.98%), RCAACST-5 (+30.64%), RCACAT-50 (+24.95%), RCACT-50 (+23.82%), RCAAT-50 (+20.60%), RCACST-25 (+20.08%), RCAACST-50 (+19.04%), RFA-25 (+16.12%), RCA-25 (+10.56%), RCACAT-75 (+3.35%), RCACST-50 (+2.17%) and RCACT-75 (+0.91%) in descending order. Similarly, the results of the 28-day compressive strength tests, also presented in Figure 4.5, indicate that mixtures RFA-25, RCA-25, RCACST-25, RCACST-50, RCACT-25, RCACT-50, RCACT-75, RCAAT-25, RCAAT-50, RCAAT-75, RCACAT-25, RCACAT-50, RCACAT-75, RCAACST-25 and RCAACST-50 surpass the strength of the reference mixture. Conversely, the remaining mixtures exhibit lower strength than the reference mixture. Notably, Mixture RCACAT-25 (+32.65%) exhibits the best performance, followed by mixes RCACT-25 (+30.17%), RCACST-25 (+29.40%), RCAAT-25 (+27.22%), RCACAT-50 (+20.88%), RCACT-50 (+20.41%), RCAAT-50

(+17.93%), RCAACST-50 (+17.16%), RCACST-25 (+15.22%), RFA-25 (+8.26%), RCA-25 (+5.25%), RCACAT-75 (+4.01%), RCACST-50 (+2.89%), RCACT-75 (+1.68%) and RCAAT-75 (+1.65%) in descending order. The most favorable replacement ratio for substituting RFA and untreated RCA in place of natural aggregates is identified as 25%. The observed increase in compressive strength at this 25% replacement level is attributed to the dense microstructure formed in the concrete mixtures. When RFA and untreated RCA were introduced at a 25% replacement level, it results in minimal voids and optimal particle packing, contributing to the higher strength as observed in Mixtures RFA-25 and RCA-25.

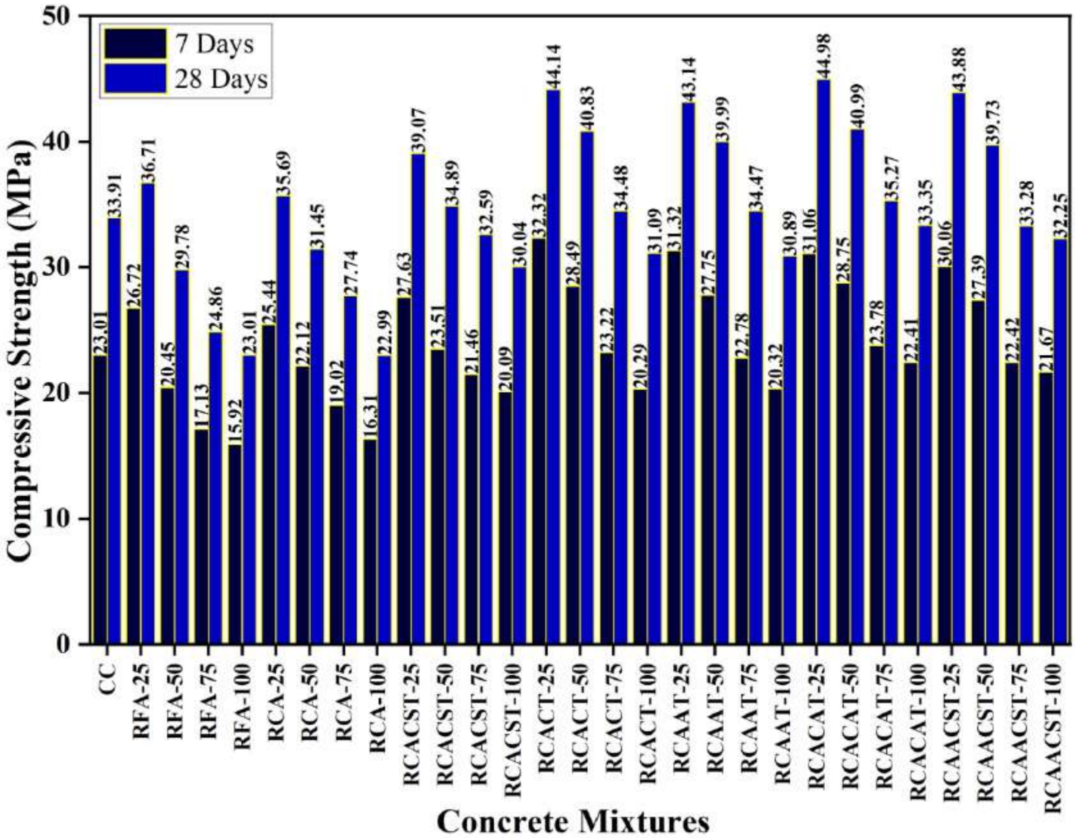


Figure 4.5 Compressive strength variations for different concrete mixtures

The particles of fine aggregates, particularly those smaller than 600 microns, play a crucial role in forming the paste. The presence of this paste in sufficient quantity is essential to fill the voids of larger particles. The strength order is closely tied to the percentage of fine aggregates passing from the 600-micron sieve. As the replacement percentages increase beyond 25%, there is a notable rise in void content and the presence of old adhered mortar further weakens the bond with aggregates, ultimately leading to reduced strength. However, when replacing natural coarse aggregates with treated RCA, which undergo cement slurry, abrasion, or chemical treatments, the optimal replacement range expands to 25-50%. Intriguingly, each surface treatment method exhibits an ideal replacement percentage. Cement slurry treatment is most successful at 25%, while chemical and abrasion treatments prove most effective at 50% replacement. Notably, chemical treatment outperforms mechanical treatment in increasing compressive strength, as evidenced by the highest strength achieved after 28 days with 50% replacement for RCA treated with chemical treatment. This treatment not only removes adhered mortar but also reduces voids and increases particle density. Pre-soaked recycled aggregates in cement slurry were found to be less effective than abrasion treatment, demonstrating slightly lower efficiency.

Moreover, the optimal replacement extends to 50-75% when utilizing treated RCA with combined treatment approaches, such as abrasion followed by cement coating treatment or chemical treatment followed by abrasion treatment. Remarkably, the combined method of surface modification proves superior in enhancing compressive strength, particularly when combining acid treatment with abrasion. This improvement arises from the effective removal of old attached mortar from the surface of recycled aggregate, resulting in maximum strength with reduced voids and higher particle packing. Concrete mixtures that entirely replace natural aggregates with RFA and untreated RCA at a 100% level exhibit a noteworthy decline in compressive strength, measuring 32.14% and 32.20% respectively, compared to the reference concrete. On the contrary, when RCA undergoes surface treatment and is utilized as a complete substitute for NCA, reductions in compressive strength are observed: 11.41% for cement slurry treatment, 08.32% for chemical treatment, and 08.91% for abrasion treatment. Concrete mixtures that incorporate treated RCA, employing a combination of treatment methods; display diminished compressive strength at 100% replacement levels. Specifically, there is a 1.65% reduction for chemical treatment followed by abrasion and 4.90% reduction with abrasion treatment followed by cement slurry coating.

Table 4.2 Percentage variation in average compressive strengths for different mixtures

Concrete Mix IDs.	Average Compressive Strength (MPa)			
	7 days	% Variation with Reference to CC	28 days	% Variation with Reference to CC
CC	23.01	–	33.91	–
RFA-25	26.72	+16.12	36.71	+8.26
RFA-50	20.45	-11.13	29.78	-12.18
RFA-75	17.13	-25.55	24.86	-26.69
RFA-100	15.92	-30.81	23.01	-32.14
RCA-25	25.44	+10.56	35.69	+5.25
RCA-50	22.12	-3.87	31.45	-7.25
RCA-75	19.02	-17.34	27.74	-18.20
RCA-100	16.31	-29.12	22.99	-32.20
RCACST-25	27.63	+20.08	39.07	+15.22
RCACST-50	23.51	+2.17	34.89	+2.89
RCACST-75	21.46	-6.74	32.59	-3.89
RCACST-100	20.09	-12.69	30.04	-11.41
RCACT-25	32.32	+40.46	44.14	+30.17
RCACT-50	28.49	+23.82	40.83	+20.41
RCACT-75	23.22	+0.91	34.48	+1.68
RCACT-100	20.29	-11.82	31.09	-8.32
RCAAT-25	31.32	+36.11	43.14	+27.22
RCAAT-50	27.75	+20.60	39.99	+17.93
RCAAT-75	22.78	-1.00	34.47	+1.65
RCAAT-100	20.32	-11.69	30.89	-8.91
RCACAT-25	31.06	+34.98	44.98	+32.65
RCACAT-50	28.75	+24.95	40.99	+20.88
RCACAT-75	23.78	+3.35	35.27	+4.01
RCACAT-100	22.41	-2.61	33.35	-1.65
RCAACST-25	30.06	+30.64	43.88	+29.40
RCAACST-50	27.39	+19.04	39.73	+17.16
RCAACST-75	22.42	-2.56	33.28	-1.86
RCAACST-100	21.67	-5.82	32.25	-4.90
+ Sign represents an increase in the strength and – sign represents a decrease in the strength.				

These findings underscore the efficacy of the applied treatment methods in mitigating the decrease in compressive strength, aligning with similar conclusions as reported by Kessal et al. (2020) [154]. Another study by Wagih et al. (2013) [155]

found that, at 7 days and 28 days, the compressive strength of concrete mixes with RCA decreased by 20–34% and 18–28%, respectively. Remarkably, even with a 100% replacement of RCA, this decrease is reduced to 3–13% at 7 days and 2–11% at 28 days with a surface modification approach. This encouraging outcome underscores the effectiveness of surface modification techniques in slowing the deterioration in the compressive strength of concrete due to recycled aggregate. Notably, surface modification of RCA through a combined approach, involving chemical treatment followed by abrasion treatment, stands out as the most practical and successful technique, yielding premium aggregates with reduced water absorption and effective removal of adhered mortar. In summary, the results emphasize the varied effects of differently treated aggregate in mixtures on compressive strength, with some formulations significantly enhancing performance while others result in substantial reductions. The analysis emphasizes the importance of aligning treatment methods, replacement percentages, and compressive strength in refining concrete mixtures. The selection of appropriate treatment approach can be done to align with the desired strength outcomes, thereby contributing to the overall optimization of concrete mixes with RCA.

4.5 FLEXURAL STRENGTH

Table 4.3 presents the variations in average flexural strength for diverse concrete mixtures at both 7 and 28 days, aligning with the observed trends in compressive strength. Intriguingly, the results distinctly indicate that, when compared to the reference mixture, concrete mixes with higher replacement percentages of RA exhibit reduced flexural strength. These findings offer valuable insights into the influence of RA on the flexural strength characteristics of concrete mixtures, shedding light on crucial considerations for optimizing the composition of sustainable concrete formulations. The 7-day flexural strength test results, as outlined in Figure 4.6, reveal that mixtures RFA-25, RCA-25, RCACST-25, RCACST-50, RCACST-75, RCACT-25, RCACT-50, RCACT-75, RCACT-100, RCAAT-25, RCAAT-50, RCAAT-75, RCAAT-100, RCACAT-25, RCACAT-50, RCACAT-75, RCACAT-100, RCAACST-25, RCAACST-50, and RCAACST-75 exhibit higher flexural strength than the reference mixture. In contrast, the remaining mixtures display lower flexural strength than the reference mixture. Notably, Mixture RCACAT-25 (+32.08%) showcases the best performance, followed by mixes RCAACST-25 (+27.67%), RCACT-25 (+24.84%), RCAAT-25 (+22.96%), RCACAT-50 (+19.50%), RCACT-50 (+17.92%), RCAACST-50 (+17.61%), RCAAT-50 (+15.72%), RCACST-25 (+15.41%), RCACAT-75 (+9.43%), RCACT-75 (+7.23%), RFA-25 (+7.23%), RCACST-50 (+6.60%), RCACAT-100 (+5.03%), RCAAT-75 (+5.03%), RCACT-100 (+4.09%), RCAACST-75 (+3.77%), RCA-25 (+3.14%), RCAAT-100 (+2.20%), and RCACST-75 (+1.89%), in descending order.

Similarly, 28-day flexural strength test results, also depicted in Figure 4.6, showcase that mixtures RFA-25, RCA-25, RCACST-25, RCACST-50, RCACST-75, RCACT-25, RCACT-50, RCACT-75, RCACT-100, RCAAT-25, RCAAT-50, RCAAT-75, RCAAT-100, RCACAT-25, RCACAT-50, RCACAT-75, RCACAT-100, RCAACST-25, RCAACST-50 and RCAACST-75 surpass the strength of the reference mixture. Conversely, the remaining mixtures exhibit lower flexural strength than the reference mixture. Mixture RCACAT-25 (+27.30%) demonstrates the best performance, followed by mixes RCAACST-25 (22.70%), RCACAT-50 (+19.39%), RCACT-25 (+18.62%), RCAAT-25 (+17.09%), RCAACST-50 (+16.33%), RCACT-50 (+14.29%), RCAAT-50 (+12.76%), RCACST-25 (+11.48%), RCACAT-75 (+9.44%), RFA-25 (+6.12%), RCACT-75 (+5.87%), RCACST-50 (+5.36%), RCAACST-75 (+4.59%), RCAAT-75 (+4.59%), RCACAT-100 (+3.06%), RCACT-100 (+3.06%), RCA-25 (+3.06%), RCACST-75 (+1.79%), and RCAAT-100 (+1.28%), are in descending order. These results provide valuable insights into the performance of different concrete mixtures, aiding in the selection and optimization of sustainable concrete compositions. Concrete mixtures, with substitute aggregates of RFA and untreated RCA at 100% replacement level, exhibit a notable decrease in flexural strength: 11.22% for RFA and 14.80% for RCA, in comparison to the reference concrete. Conversely, treated RCA at 100% replacement level displays varying flexural strengths: -0.77% with cement slurry treatment, +1.28% with abrasion treatment and +3.06% with chemical treatment. Mixtures incorporating treated RCA, employing combined approaches, exhibit variable flexural strength at 100% replacement: +3.06% with chemical treatment followed by abrasion and -0.26% with abrasion followed by cement coating.

Table 4.3 Percentage variation in average flexural strengths for different mixtures

Concrete Mix IDs.	Average Flexural Strength (MPa)			
	7 days	% Variation with Reference to CC	28 days	% Variation with Reference to CC
CC	3.18	–	3.92	–
RFA-25	3.41	+7.23	4.16	+6.12
RFA-50	3.12	-1.89	3.89	-0.77
RFA-75	2.89	-9.12	3.75	-4.34
RFA-100	2.6	-18.24	3.48	-11.22
RCA-25	3.28	+3.14	4.04	+3.06
RCA-50	3.09	-2.83	3.87	-1.28
RCA-75	2.9	-8.81	3.62	-7.65
RCA-100	2.68	-15.72	3.34	-14.80
RCACST-25	3.67	+15.41	4.37	+11.48
RCACST-50	3.39	+6.60	4.13	+5.36
RCACST-75	3.24	+1.89	3.99	+1.79
RCACST-100	3.15	-0.94	3.89	-0.77
RCACT-25	3.97	+24.84	4.65	+18.62
RCACT-50	3.75	+17.92	4.48	+14.29
RCACT-75	3.41	+7.23	4.15	+5.87
RCACT-100	3.31	+4.09	4.04	+3.06
RCAAT-25	3.91	+22.96	4.59	+17.09
RCAAT-50	3.68	+15.72	4.42	+12.76
RCAAT-75	3.34	+5.03	4.1	+4.59
RCAAT-100	3.25	+2.20	3.97	+1.28
RCACAT-25	4.2	+32.08	4.99	+27.30
RCACAT-50	3.8	+19.50	4.68	+19.39
RCACAT-75	3.48	+9.43	4.29	+9.44
RCACAT-100	3.34	+5.03	4.04	+3.06
RCAACST-25	4.06	+27.67	4.81	+22.70
RCAACST-50	3.74	+17.61	4.56	+16.33
RCAACST-75	3.3	+3.77	4.1	+4.59
RCAACST-100	3.16	-0.63	3.91	-0.26
+ Sign represents an increase in the strength and – sign represents a decrease in the strength.				

These outcomes underscore the effectiveness of treatment methods in mitigating the reduction in flexural strength. The results of the present study align with established research trends [151], [156], typically indicating a flexural strength decline of 15-20% for 100% replacement and 5-10% for 50% replacement with untreated RCA. In contrast, our study reveals a milder 0.77% decrease at a 100% surface-modified RCA replacement level. This suggests an improvement in the flexural strength of RCA due to the applied surface modification treatments, indicating a potential mitigating influence on the anticipated decrease in flexural strength. These nuanced findings significantly contribute to our understanding of the influences of surface-modified RCA on the flexural behavior of concrete mixtures. The study proposes that the selection of appropriate surface modification techniques plays a crucial role in altering the expected reduction in flexural strength, for optimizing concrete formulations with sustainable materials. This insight underscores the importance of exploring and implementing surface modification techniques as a means to enhance the mechanical properties of concrete using recycled aggregates.

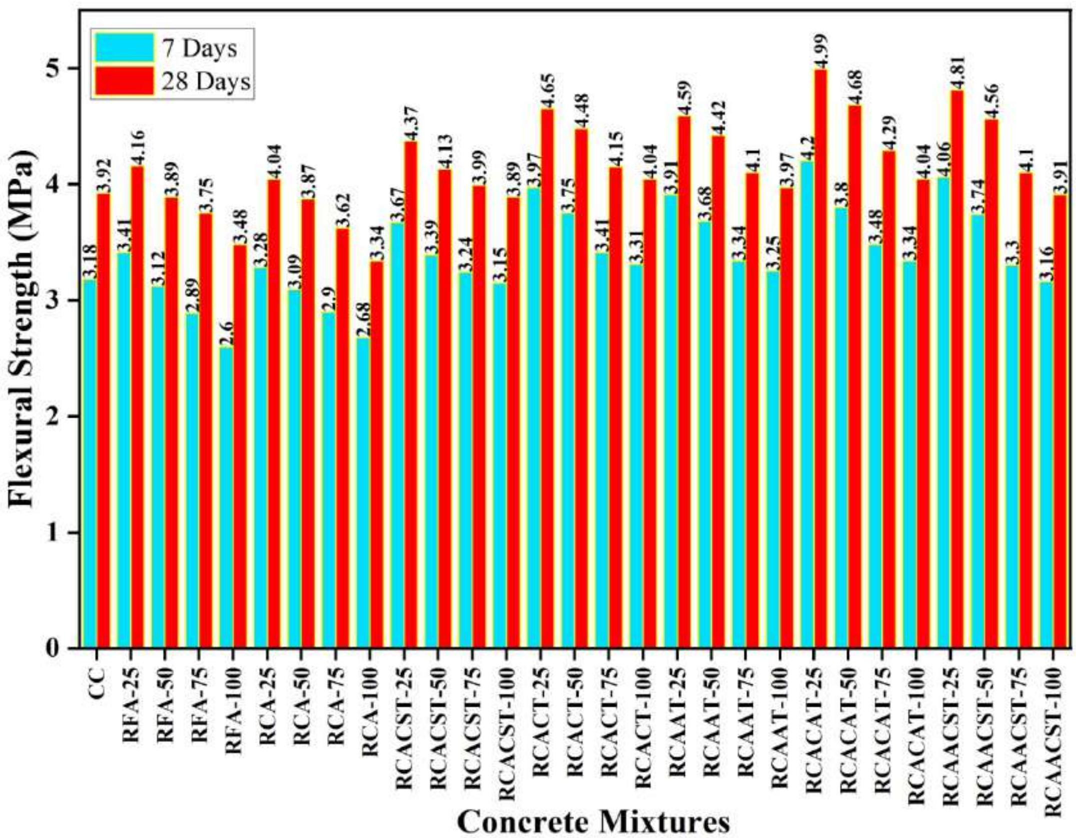


Figure 4.6 Flexural strength variations for different concrete mixtures

4.6 SPLIT TENSILE STRENGTH

Table 4.4 illustrates the variations in average split tensile strength of diverse concrete mixtures at both 7 and 28 days, aligning with the recorded trends of compressive strength. An intriguing pattern emerges, indicating a consistent decrease in the split tensile strength of concrete mixture with an increasing percentage of Recycled Aggregates (RA) substituted in place of natural aggregates. The 7-day split tensile strength test results, presented in Figure 4.7, reveal that mixture RFA-25, RCA-25, RCACST-25, RCACST-50, RCACT-25, RCACT-50, RCACT-75, RCAAT-25, RCAAT-50, RCAAT-75, RCACAT-25, RCACAT-50, RCACAT-75, RCACAT-100, RCAACST-25, RCAACST-50 and RCAACST-75 exhibits higher split tensile strengths than the split tensile strength of reference mixture. Conversely, the remaining mixtures demonstrate lower split tensile strength than the reference mix.

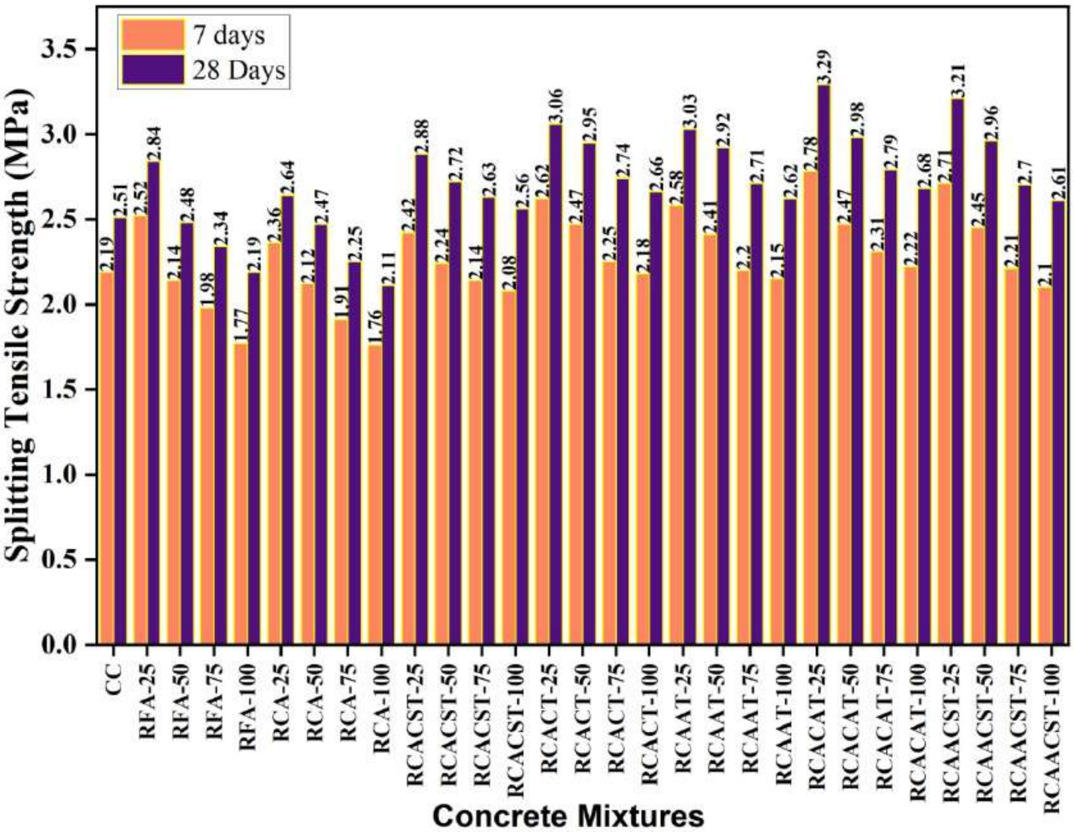


Figure 4.7 Split tensile strength variations for different concrete mixtures

Notably, Mixture RCACAT-25 (+26.94%) displays the best performance, followed by mixes RCAACST-25 (+23.74%), RCACT-25 (+19.63%), RCAAT-25 (+17.81%), RFA-25 (+15.07%), RCACAT-50 (+12.79%), RCACT-50 (+12.79%), RCAACST-50 (+11.87%), RCACST-25 (+10.50%), RCAAT-50 (+10.05%), RCA-25 (+7.76%), RCACAT-75 (+5.48%), RCACT-75 (+2.74%), RCACST-50 (+2.28%), RCACAT-100 (+1.37%), RCAACST-75 (+0.91%) and RCAAT-75 (+0.46%) in descending order. Conversely the remaining mixtures demonstrate lower split tensile strength than the reference mixture. Similarly, the results of the 28-day split tensile strength tests, also outlined in Figure 4.7, demonstrate that mixtures RFA-25, RCA-25, RCACST-25, RCACST-50, RCACST-75, RCACST-100, RCACT-25, RCACT-50, RCACT-75, RCACT-100, RCAAT-25, RCAAT-50, RCAAT-75, RCAAT-100, RCACAT-25, RCACAT-50, RCACAT-75, RCACAT-100, RCAACST-25, RCAACST-50, RCAACST-75 and RCAACST-100 surpass the strength of the reference mixture.

On Contrary, the remaining mixtures exhibit lower split tensile strength than the strength of the reference mixture. Mixture RCACAT-25 (+31.08%) demonstrates the best performance, followed by mixes RCAACST-25 (+27.89%), RCACT-25 (+21.91%), RCAAT-25 (+20.72%), RCACAT-50 (+18.73%), RCAACST-50 (+17.93%), RCACT-50 (+17.53%), RCAAT-50 (+16.33%), RCACST-25 (+14.74%), RFA-25 (+13.15%), RCACAT-75 (+11.16%), RCACT-75 (+9.16%), RCACST-50 (+8.37%), RCAAT-75 (+7.97%), RCAACST-75 (+7.57%), RCACAT-100 (+6.77%), RCAACT-100 (+5.98%), RCA-25 (+5.18%), RCACST-75 (+4.78%), RCAAT-100 (+4.38%), RCAACST-100 (+3.98%), and RCACST-100 (+1.99%), in descending order. Concrete mixtures that replace aggregates with RFA and untreated RCA at 100% level exhibit a notable reduction in split tensile strength: 12.75% for RFA and 15.94% for RCA, in comparison to the reference concrete. Conversely, treated RCA at 100% replacement level shows varying reductions in split tensile strength: +1.99% for cement slurry treatment, +4.38% for abrasion treatment, and +5.98% for chemical treatment. Concrete mixtures incorporating treated RCA, utilizing combined approaches, experience higher split tensile strength at 100% replacement: 6.77% with chemical treatment followed by abrasion and 3.98% with abrasion followed by cement coating.

Table 4.4 Percentage variation in average split tensile strengths for different mixtures

Concrete Mix IDs.	Average Split Tensile Strength (MPa)			
	7 days	% Variation with Reference to CC	28 days	% Variation with Reference to CC
CC	2.19	–	2.51	–
RFA-25	2.52	+15.07	2.84	+13.15
RFA-50	2.14	-2.28	2.48	-1.20
RFA-75	1.98	-9.59	2.34	-6.77
RFA-100	1.77	-19.18	2.19	-12.75
RCA-25	2.36	+7.76	2.64	+5.18
RCA-50	2.12	-3.20	2.47	-1.59
RCA-75	1.91	-12.79	2.25	-10.36
RCA-100	1.76	-19.63	2.11	-15.94
RCACST-25	2.42	+10.50	2.88	+14.74
RCACST-50	2.24	+2.28	2.72	+8.37
RCACST-75	2.14	-2.28	2.63	+4.78
RCACST-100	2.08	-5.02	2.56	+1.99
RCACT-25	2.62	+19.63	3.06	+21.91
RCACT-50	2.47	+12.79	2.95	+17.53
RCACT-75	2.25	+2.74	2.74	+9.16
RCACT-100	2.18	-0.46	2.66	+5.98
RCAAT-25	2.58	+17.81	3.03	+20.72
RCAAT-50	2.41	+10.05	2.92	+16.33
RCAAT-75	2.2	+0.46	2.71	+7.97
RCAAT-100	2.15	-1.83	2.62	+4.38
RCACAT-25	2.78	+26.94	3.29	+31.08
RCACAT-50	2.47	+12.79	2.98	+18.73
RCACAT-75	2.31	+5.48	2.79	+11.16
RCACAT-100	2.22	+1.37	2.68	+6.77
RCAACST-25	2.71	+23.74	3.21	+27.89
RCAACST-50	2.45	+11.87	2.96	+17.93
RCAACST-75	2.21	+0.91	2.7	+7.57
RCAACST-100	2.1	-4.11	2.61	+3.98
+ Sign represents an increase in the strength and – sign represents a decrease in the strength.				

These variations provide insights into the effectiveness of different concrete mixtures concerning split tensile strength at various curing ages. Among the tested mixtures, RCACAT-25 exhibits the highest split tensile strength of 3.29 MPa, while RCA100 demonstrates a lowest of 2.11MPa. These results align with those obtained in earlier studies [154], [156]. It's noteworthy that the present research diverges from the findings of Wagih et. al. [155], who observed a significant 24% decrease in split tensile strength. In contrast, the present study of surface-modified RCA shows a much smaller 12% decrease at the 100% replacement level. These results demonstrate a subtle impact of surface-modified RCA content on the split tensile strength of concrete mixes, providing insight information that advances understanding of the mechanical properties of these formulations.

4.7 MODULUS OF ELASTICITY

When evaluating the deformation of conventional concrete and recycled aggregate concrete (RAC), the modulus of elasticity (MoE) is a critical indication. As shown in Table 4.5, the 28-day MoE data show a noteworthy trend: a strong negative association between MoE and the addition of RA to the concrete matrix. The decrease in MoE is ascribed to innate features of RA, including brittleness and a propensity to absorb water. The data in Table 4.5 offers a comprehensive overview of MoE values for various concrete mixtures, highlighting the observed inverse relationship and shedding light on distinct characteristics influencing the deformation behavior of recycled aggregate concretes. The Moduli of Elasticity, based on the experimental test results are presented in Figure 4.8, which indicates that mixtures RCACST-25, RCACST-75, RCACT-25, RCACT-50, RCACT-75, RCAAT-5, RCAAT-50, RCAAT-75, RCACAT-5, RCACAT-50, RCACAT-75, RCAACST-5, RCAACST-50 and RCAACST-75 have exhibited a higher Elastic Moduli compared to the modulus of elasticity of reference mixture and remaining mixtures have smaller value of Moduli of Elasticity than the Modulus of Elasticity of reference mix. Notably, Mixture RCAACST-25 (+23.62%) demonstrated the highest Elastic Modulus, followed by mixes RCAAT-25 (+21.26%), RCAACST-50 (+20.81%), RCACAT-25 (+19.61%), RCAAT-50 (+18.46%), RCACT-25 (+16.93%), RCACT-

50 (+12.16%), RCACAT-50 (+11.65%), RCAAT-75 (+11.46%), RCACT-75 (+5.28%), RCACST-25 (+3.98%), RCAACST-75 (+1.30%), RCACAT-75 (+0.99%), and RCACST-75 (+0.38%) in descending order.

Table 4.5 Elasticity modulus of different concrete mixtures

Concrete Mix IDs	Modulus of Elasticity (GPa)	
	Experimental (E_c)	% Variation with reference to CC
CC	31.42	-
RFA-25	29.61	-5.76
RFA-50	24.04	-23.49
RFA-75	22.68	-27.82
RFA-100	20.31	-35.36
RCA-25	28.59	-9.01
RCA-50	25.71	-18.17
RCA-75	25.56	-18.65
RCA-100	20.28	-35.46
RCACST-25	32.67	+3.98
RCACST-50	30.14	-4.07
RCACST-75	31.54	+0.38
RCACST-100	30.86	-1.78
RCACT-25	36.74	+16.93
RCACT-50	35.24	+12.16
RCACT-75	33.08	+5.28
RCACT-100	30.06	-4.33
RCAAT-25	38.11	+21.26
RCAAT-50	37.22	+18.46
RCAAT-75	35.02	+11.46
RCAAT-100	30.63	-2.51
RCACAT-25	37.58	+19.61
RCACAT-50	35.08	+11.65
RCACAT-75	31.73	+0.99
RCACAT-100	30.82	-1.91
RCAACST-25	38.84	+23.62
RCAACST-50	37.96	+20.81
RCAACST-75	31.83	+1.30
RCAACST-100	28.42	-9.55
+ Sign represents an increase in MoE and –sign represents a decrease in MoE.		

Figure 4.8 provides a detailed exploration of the complex interplay between experimental findings. It illustrates that surface modification of RCA enhances MoE by fostering improved nucleation sites. However, a noteworthy observation emerges as the MoE consistently decreases with higher content of surface-modified RCA. A thorough investigation into compressive strength and MoE within conventional concrete, incorporating varying percentages of surface-modified RCA as a replacement for NCA, unravels this intricate pattern. Multiple factors contribute to the reduction in MoE, including the quantity and stiffness of the binder phase, the volume and rigidity of aggregates and the characteristics of the ITZ. Collectively, these factors exert a significant influence on the mechanical behavior of concrete. The observed decline in MoE aligns with trends observed in prior studies [152], [153], underscoring the crucial need to consider the incorporation of surface-modified RCA when assessing the overall mechanical performance of concrete. This nuanced understanding contributes to a comprehensive evaluation of how surface modifications carried out at the aggregate level impact structural characteristics, shedding light on the intricacies of strength enhancement along with concurrent reductions in MoE.

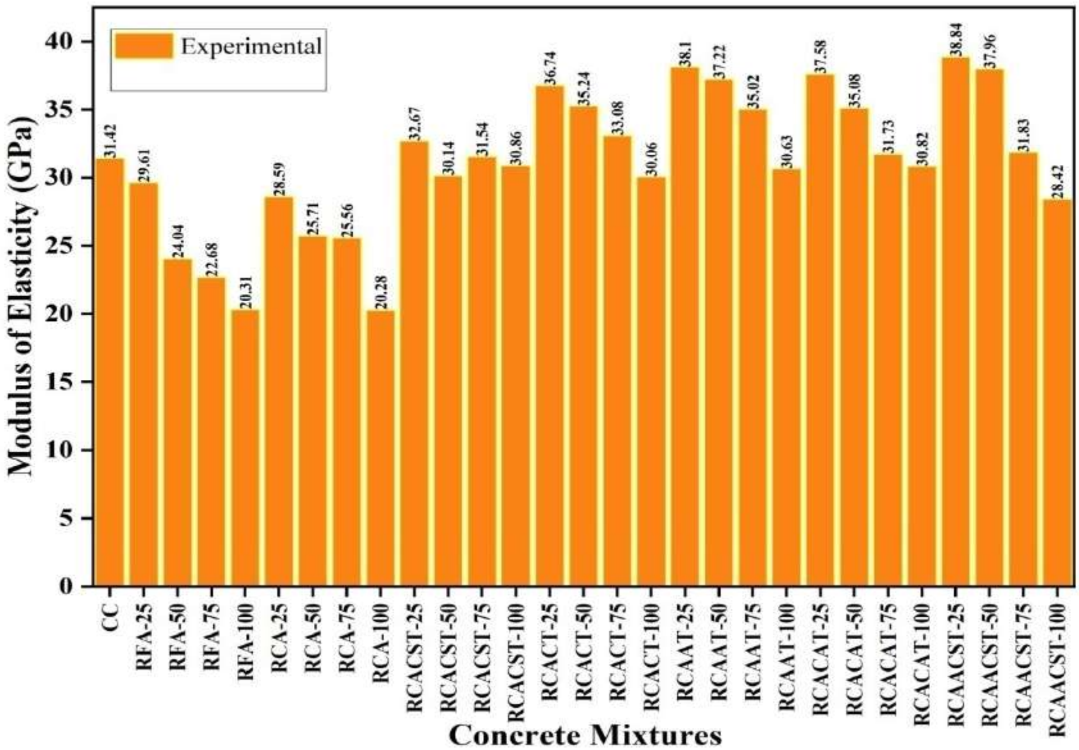


Figure 4.8 Variations in modulus of elasticity of different concrete mixtures

4.8 DRYING SHRINKAGE

The evaluation of drying shrinkage is imperative for understanding the performance of structural concrete. Table 4.6 illustrates the percentage variations in drying shrinkage for different concrete mixtures at 28, 56, and 90 days, with reference to the control mix (CC). This parameter is critical for assessing the potential for cracking during the initial stage and reduction of the pre-stress effect, if applicable. The results indicate that all mixtures adhere to Indian Standards, suggesting the feasibility of incorporating Recycled Aggregates (RA) within specified limits. The drying shrinkage curve transitions from a steep to a flat profile with prolonged drying time, signifying a diminishing rate of change of shrinkage with time. While higher replacement with RFA and RCA without surface treatment leads to increased drying shrinkage. This underscores the limited use of RFA and RCA without surface treatment to balance sustainability without compromising concrete performance. The control mix, denoted as CC, exhibited drying shrinkage values of 325 x 10^{-6} at 28 days, 401 x 10^{-6} at 56 days, and 440 x 10^{-6} at 90 days. The outcomes of the 28-day drying shrinkage strain tests, depicted in Figure 4.9, show that all mixtures displayed drying shrinkage strains higher than those of the reference mixture. Notably, Mixture RCACT-100 (+54.46%) demonstrated the highest drying shrinkage strain, followed by RCA-100 (+53.54%), RCAACST-100 (+48.62%), RCACST-100 (+47.38%), RFA-100 (+46.77%), RCAAT-100 (+45.85%), RCACAT-100 (+44.00%), RCACT-75 (+44.00%), RCA-75 (+42.77%), RCACST-75 (+37.85%), RFA-75 (+37.23%), RCAACST-75 (+34.77%), RCAAT-75 (+32.00%), RCACAT-75 (+30.15%), RCACT-50 (+28.31%), RCA-50 (+27.69%), RCACST-50 (+21.54%), RFA-50 (+20.92%), RCAACST-50 (+18.77%), RCAAT-50 (+17.85%), RCACAT-50 (+16.31%), RCACT-25 (+12.00%), RCA-25 (+11.38%), RCAACST-25 (+8.92%), RCAAT-25 (+8.92%), RCACAT-25 (+8.00%), RFA-25 (+7.73%), and RCACST-25 (+5.23%) in descending order. Similarly, the results of the 56-day drying shrinkage strain tests, also shown in Fig. 4.9, indicate that all mixtures demonstrated a higher drying shrinkage strain than the reference mixture. Mixture RCA-100 (+55.61%) displayed the highest drying shrinkage strain, followed by RCACST-100 (+52.12%), RCAACST-100 (+51.12%),

RFA-100 (+50.12%), RCAAT-100 (+49.88%), RCACAT-100 (+47.38%), RCACT-100 (+45.14%), RCACT-75 (+42.39%), RCA-75 (+40.15%), RCACST-75 (+38.40%), RFA-75 (+36.91%), RCAACST-75 (+36.16%), RCAAT-75 (+33.42%), RCACAT-75 (+32.4223), RCACAT-50 (+17.21%), RCACT-50 (+26.68%), RCA-50 (+24.94%), RCACST-50 (+22.69%), RFA-50 (+21.70%), RCAACST-50 (+19.20%), RCAAT-50 (+18.70%), RCACT-25 (+14.96%), RCA-25 (+13.97%), RCAACST-25 (+9.98%), RCAAT-25 (+9.98%), RCACAT-25 (+9.23%), RCACST-25 (+8.98%), and RFA-25 (+8.48%) in descending order.

Moreover, the results of the 90-day drying shrinkage strain tests, also depicted in Fig. 4.9, reveal that all mixtures displayed a higher drying shrinkage strain than the reference mixture. Mixture RCACT-50 (+26.68%), RCA-50 (+24.94%), RCACST-50 (+22.69%), RFA-50 (+21.70%), RCAACST-50 (+19.20%), RCAAT-50 (+18.70%), RCAAT-100 (+49.55%) demonstrated the highest drying shrinkage strain, followed by RCACT-50 (+48.18%), RCAAT-25 (+45.68%), RCA-100 (+45.68%), RCACST-75 (+43.41%), RCAACST-100 (+42.05%), RFA-100 (+40.91%), RCACAT-100 (+38.64%), RCA-75 (+35.23%), RCAACST-75 (+31.59%), RCAAT-75 (+30.23%), RFA-75 (+30.00%), RCACT-25 (+28.64%), RCACAT-75 (+28.18%), RCARCA-50 (+24.77%), RCACT-100 (+22.73%), RCACST-50 (+20.91%), RCAACST-50 (+19.55%), RFA-50 (+19.55%), RCACAT-50 (+17.73%), RCAAT-50 (+16.14%), RCACST-100 (+13.86%), RCA-25 (+12.73%), RCACT-75 (+10.91%), RCAACST-25 (+10.23%), RCACAT-25 (+9.55%), RCACST-5 (+9.32%) and RFA-25 (+7.73%) in descending order. It is important to note that a good mixture should ideally have a small drying shrinkage strain. The positive variations observed in drying shrinkage underscore the impact of incorporating SMRCA, particularly at higher replacement levels. This inclusion is found to contribute to an increased potential for cracking during the initial stage and reduction in pre-stress effect, emphasizing the need for careful consideration by structural engineers and concrete designers. This information becomes pivotal in assessing the long-term durability and performance of concrete structures.

Table 4.6 Percentage variation of drying shrinkage for different mixtures

Concrete Mix IDs.	Drying Shrinkage (10^{-6})					
	28 days	% Variation with Reference to CC	56 days	% Variation to Reference to CC	90 days	% Variation with Reference to CC
CC	325	–	401	-	440	–
RFA-25	340	+7.73	435	+8.48	474	+7.73
RFA-50	393	+20.92	488	+21.70	526	+19.55
RFA-75	446	+37.23	549	+36.91	572	+30.00
RFA-100	477	+46.77	602	+50.12	620	+40.91
RCA-25	362	+11.38	457	+13.97	496	+12.73
RCA-50	415	+27.69	501	+24.94	549	+24.77
RCA-75	464	+42.77	562	+40.15	595	+35.23
RCA-100	499	+53.54	624	+55.61	641	+45.68
RCACST-25	342	+5.23	437	+8.98	481	+9.32
RCACST-50	395	+21.54	492	+22.69	532	+20.91
RCACST-75	448	+37.85	555	+38.40	631	+43.41
RCACST-100	479	+47.38	610	+52.12	501	+13.86
RCACT-25	364	+12.00	461	+14.96	566	+28.64
RCACT-50	417	+28.31	508	+26.68	652	+48.18
RCACT-75	468	+44.00	571	+42.39	488	+10.91
RCACT-100	502	+54.46	582	+45.14	540	+22.73
RCAAT-25	354	+8.92	441	+9.98	641	+45.68
RCAAT-50	383	+17.85	476	+18.70	511	+16.14
RCAAT-75	429	+32.00	535	+33.42	573	+30.23
RCAAT-100	474	+45.85	601	+49.88	658	+49.55
RCACAT-25	351	+8.00	438	+9.23	482	+9.55
RCACAT-50	378	+16.31	470	+17.21	518	+17.73
RCACAT-75	423	+30.15	531	+32.42	564	+28.18
RCACAT-100	468	+44.00	591	+47.38	610	+38.64
RCAACST-25	354	+8.92	441	+9.98	485	+10.23
RCAACST-50	386	+18.77	478	+19.20	526	+19.55
RCAACST-75	438	+34.77	546	+36.16	579	+31.59
RCAACST-100	483	+48.62	606	+51.12	625	+42.05

+ Sign represents an increase in drying shrinkage and – sign represents a decrease in drying shrinkage.

Moreover, the advantages of SMRCA become evident in its ability to minimize drying shrinkage compared to unmodified RCA. This benefit is attributed to the effectiveness of the surface modification process applied to recycled coarse aggregates. The process plays a key role in substantially reducing the presence of mortar on the aggregate surface, a critical factor in reducing water absorption and subsequent drying shrinkage. Consequently, the removal of attached mortar through surface modification leads to a significant reduction in drying shrinkage compared to unmodified RCA. This underscores the indispensable role of surface modification in enhancing the performance of Surface Modified Recycled Concrete Aggregates (SMRCA), offering valuable insights for the improvement of concrete structures. The drying shrinkage of concrete experiences a higher value with increased replacement levels by RFA and RCA, attributed to the additional cement surrounding RCA surfaces, causing substantial shrinkage during the drying process. The incorporation of treated RCA reduces drying shrinkage by minimizing attached mortar. For example, RFA 100 exhibits a 40.91% increase in shrinkage strain at 90 days, while RCA 100 shows a 45.68% increase compared to the reference mix.

Concrete featuring treated RCA, subjected to cement slurry, abrasion and chemical treatments at a 100% replacement level, demonstrates 13.86%, 22.73% and 49.55 % respectively, increase in shrinkage strain with respect to reference mixture. A combined treatment of abrasion followed by cement coating yields 38.64% increment and chemical treatment followed by abrasion results in 42.05% increase in shrinkage strain compared to reference concrete. This highlights the effectiveness of treatment techniques in reducing shrinkage strain. These findings align with research conducted by Ismail and Ramli (2014) [150], they explored the role of treated recycled aggregates in influencing the drying shrinkage of concrete. Previous studies by Kioumarsi et al. (2020) [157] indicated higher drying shrinkage strain with unmodified recycled coarse aggregates, consistent with observations by Chen et al. (2023) [158], suggesting a systematic increase in shrinkage strain with the use of higher proportion of unmodified aggregates. In summary, the results presented in Figure 4.9 indicate that the drying shrinkage of concrete increases with higher replacement levels of SMRCA. These findings underscore the importance of carefully balancing the use of recycled materials in concrete mixtures to mitigate the risk of increased drying shrinkage and its potential consequences on the long-term performance of concrete structures.

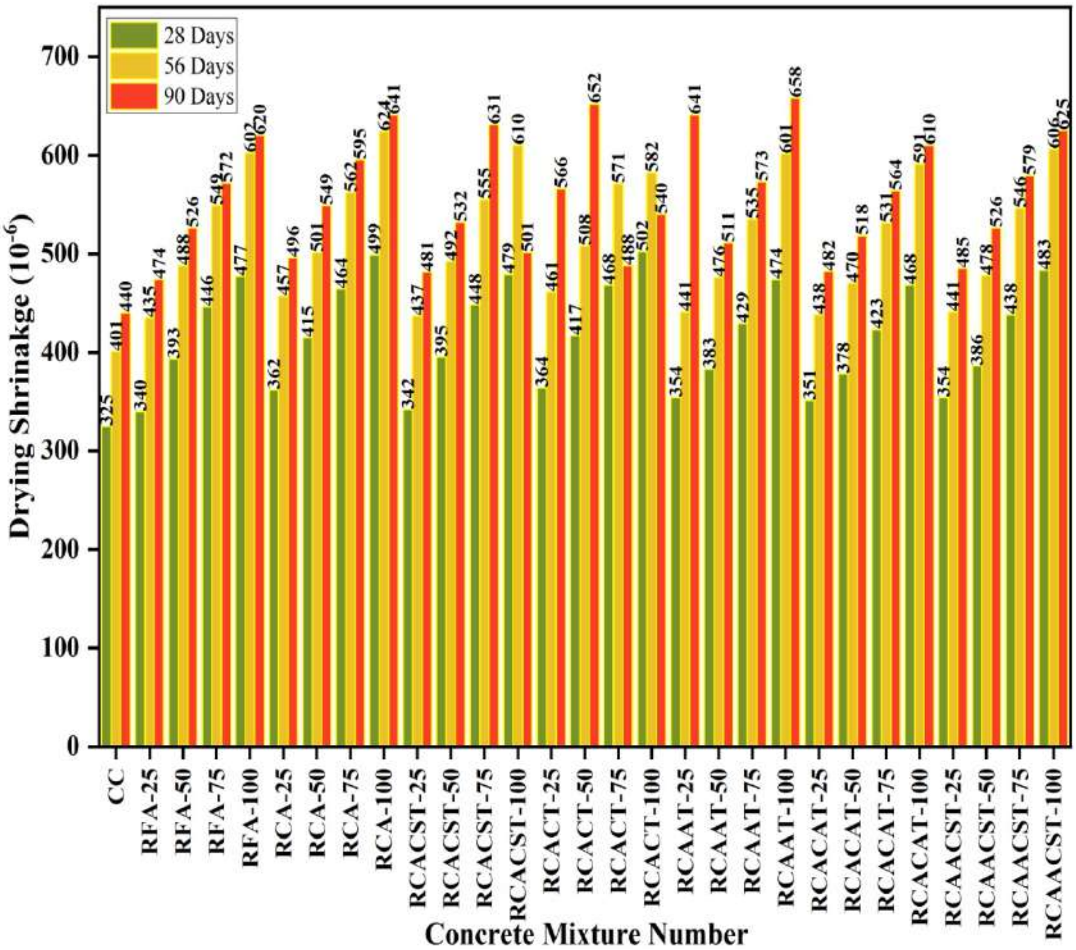


Figure 4.9 Shrinkage strain comparison among different concrete mixtures

4.9 ELECTRICAL RESISTIVITY

The interconnectivity of the porous network within cement mortar plays a pivotal role in determining electrical conductivity, offering a precise gauge of ionic transport. Consequently, electrical resistivity stands out as a critical parameter for evaluating the quality of concrete. Table 4.7 presents the percentage variations in electrical resistivity for diverse concrete mixtures at 28 and 56 days, with the control mix (CC) serving as a reference. The results showcase a significant enhancement in the electrical resistance of cement mortar following surface modification of RCA.

Table 4.7 Percentage variation of electrical resistance for different mixtures

Concrete Mix IDs.	Electrical Resistance **(kΩ)**			
	28 days	**% Variation with reference to CC**	**56 days**	**% Variation with reference to CC**
CC	22.71	–	31.99	–
RFA-25	26.72	+17.66	36.71	+14.75
RFA-50	20.45	-9.95	29.78	-6.91
RFA-75	17.13	-24.57	24.86	-22.29
RFA-100	15.92	-29.90	24.01	-24.95
RCA-25	52.81	+132.54	58.45	+82.71
RCA-50	46.69	+105.59	56.28	+75.93
RCA-75	37.33	+64.38	46.76	+46.17
RCA-100	16.01	-29.50	26.29	-17.82
RCACST-25	41.18	+81.33	51.54	+61.11
RCACST-50	38.96	+71.55	48.49	+51.58
RCACST-75	32.23	+41.92	42.17	+31.82
RCACST-100	27.11	+19.37	35.71	+11.63
RCACT-25	46.57	+105.06	58.04	+81.43
RCACT-50	42.09	+85.34	55.99	+75.02
RCACT-75	38.73	+70.54	52.83	+65.15
RCACT-100	33.6	+47.95	43.97	+37.45
RCAAT-25	45.18	+98.94	55.54	+73.62
RCAAT-50	42.96	+89.17	52.99	+65.65
RCAAT-75	36.23	+59.53	46.67	+45.89
RCAAT-100	31.11	+36.99	40.92	+27.91
RCACAT-25	50.18	+120.96	60.54	+89.25
RCACAT-50	47.96	+111.18	58.99	+84.40
RCACAT-75	41.23	+81.55	52.67	+64.65
RCACAT-100	36.1	+58.96	46.92	+46.67
RCAACST-25	49.07	+116.07	59.43	+85.78
RCAACST-50	46.85	+106.30	57.88	+80.93
RCAACST-75	40.12	+76.66	51.56	+61.18
RCAACST-100	34.99	+54.07	45.81	+43.20
+ Sign represents an increase in electrical resistance and – sign represents a decrease in electrical resistance.				

In this study, the primary factor contributing to decrease in the electrical conductivity appears to be the integrated surface modification approach applied to the cement mortar, presumed to play a pivotal role in altering the pore network and enhancing electrical resistance. At 28 days, CC exhibited an electrical resistivity of 22.71 kΩ. The results of the 28-day electrical resistance tests are depicted in Figure 4.10, indicate that mixtures RFA-25, RCA-25, RCA-50, RCA-75, RCACST-25, RCACST-50, RCACST-75, RCACST-100, RCACT-25, RCACT-50, RCACT-75, RCACT-100, RCAAT-25, RCAAT-50, RCAAT-75, RCAAT-100, RCACAT-5, RCACAT-50, RCACAT-75, RCACAT-100, RCAACST-25, RCAACST-50, RCAACST-75, and RCAACST-100 demonstrated higher electrical resistance than the electrical resistance of reference mixture. Conversely, the remaining mixtures exhibited lower electrical resistance than the reference mixture. Mixture RCA-25 (+132.54%) exhibited the highest electrical resistance, followed by RCACAT-25 (+120.96%), RCAACST-25 (+116.07%), RCACAT-50 (+111.18%), RCAACST-50 (+106.30%), RCA-50 (+105.59%), RCACT-25 (+105.06%), RCAAT-25 (+98.94%), RCAAT-50 (+89.17%), RCACT-50 (+85.34%), RCACAT-75 (+81.55%), RCACST-25 (+81.33%), RCAACST-75 (+76.66%), RCACST-50 (+71.55%), RCACT-75 (+70.54%), RCA-75 (+64.38%), RCAAT-75 (+59.53%), RCACAT-100 (+58.96%), RCAACST-100 (+54.07%), RCACT-100 (+47.95%), RCACST-75 (+41.92%), RCAAT-100 (+36.99%), RCACST-100 (+19.37%), and RFA-25 (+17.66%) in descending order.

Similarly, 56-day electrical resistance test results, depicted in Figure 4.10, reveal that mixtures RFA-25, RCA-25, RCA-50, RCA-75, RCACST-25, RCACST-50, RCACST-75, RCACST-100, RCACT-25, RCACT-50, RCACT-75, RCACT-100, RCAAT-25, RCAAT-50, RCAAT-75, RCAAT-100, RCACAT-24, RCACAT-50, RCACAT-75, RCACAT-100, RCAACST-25, RCAACST-50, RCAACST-75, and RCAACST-100 exhibited higher electrical resistance than the electrical resistance of reference mixture. The remaining mixtures demonstrated lower electrical resistance than the electrical resistance of the reference mixture. Mixture RCACAT-25 (+89.25%) displayed the highest electrical resistance, followed by RCAACST-25 (+85.78%), RCACAT-50 (+84.40%), RCA-25 (+82.71%), RCACT-

25 (+81.43%), RCAACST-50 (+80.93%), RCA-50 (+75.93%), RCACT-50 (+75.02%), RCAAT-25 (+73.62%), RCAAT-50 (+65.65%), RCACT-75 (+65.15%), RCACAT-75 (+64.65%), RCAACST-75 (+61.18%), RCACST-25 (+61.11%), RCACST-50 (+51.58%), RCACAT-100 (+46.67%), RCA-75 (+46.17%), RCAAT-75 (+45.89%), RCAACST-100 (+43.20%), RCACT-100 (+37.45%), RCACST-75 (+31.82%), RCAAT-100 (+27.91%), RFA-25 (+14.75%), and RCACST-100 (+11.63%) in descending order. Ensuring superior performance at the time of corrosion requires concrete with higher electrical resistance.

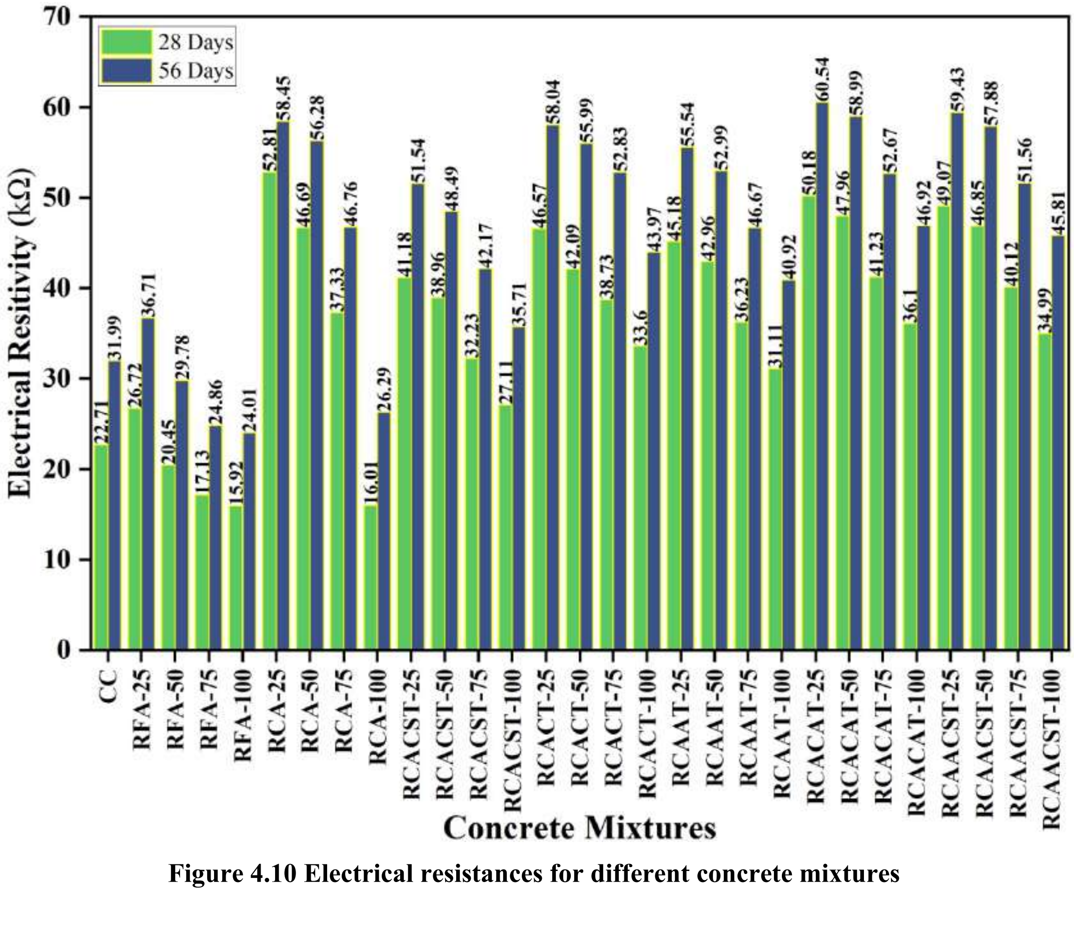


Figure 4.10 Electrical resistances for different concrete mixtures

The findings indicate that concrete mixtures with higher proportions of RFA and RCA replacements without surface treatment exhibit reduced electrical resistivity in comparison to the reference mixture, signaling a higher risk of corrosion. The higher porosity of RFA and RCA with surface treatment traps water containing dissolved ions, creating a high resistance for electric current and subsequently lowering electrical resistivity. The results highlight a significant enhancement in the electrical resistance of cement mortar following surface modification. In this investigation, the primary factor contributing to decreased electrical resistivity appears to be the integrated surface modification approach applied to the RCA, presumed to play a pivotal role in altering the pore network and enhancing electrical resistance. The inclusion of STRCA has diverse effects on electrical resistivity. Lower replacements show marginal increases, while higher replacements lead to significant decreases in electrical conductivity.

These outcomes underscore the importance of carefully evaluating electrical properties when incorporating recycled materials, as they are crucial for concrete durability and corrosion resistance. Within the context of these findings, it becomes evident that the incorporation of STRCA significantly influences the electrical resistivity of cement mortar. The observed variations suggest that STRCA surface modification effectively alters the porous network of concrete, contributing to enhanced resistance to ionic transport. These insights emphasize the need for a nuanced consideration of electrical properties when incorporating recycled materials in concrete, ultimately contributing to the improvement of durability and corrosion resistance. Concrete mixtures incorporating up to 25% and upto75% replacement by RFA and untreated RCA respectively, to natural aggregates exhibit elevated electrical resistivity, indicating a low risk of corrosion. Conversely, as replacement levels beyond 25% and 75% by RFA and untreated RCA respectively, the electrical resistivity diminishes, suggesting a moderate risk of corrosion. Similarly, concrete mixtures integrating treated RCA, subjected to cement slurry, abrasion, and chemical treatments, at replacement levels up to 75% demonstrate higher electrical resistivity, signaling no risk of corrosion. However, at 100% replacement, there is a relatively reduction in electrical resistivity, indicating a low risk of corrosion. Notably, concrete mixtures produced with treated RCA, employing combined treatment approaches, consistently exhibit higher electrical resistivity, implying a very low risk of corrosion even at 100% replacement. To ensure superior performance concerning corrosion, maintaining higher electrical resistance in the concrete is crucial.

In summary, the inclusion of STRCA yields varied effects on electrical resistivity, with lower replacements showing significant decreases in maintenance requirement, while higher replacements result in marginal decreases. These results underscore the importance of carefully evaluating electrical properties when incorporating recycled materials, a critical factor for concrete durability and corrosion resistance. In the context of these findings, the integration of STRCA significantly influences the electrical resistivity of cement mortar. The observed variations suggest that STRCA surface modification effectively alters the porous network of concrete, contributing to enhanced resistance to ionic transport. The study concludes that even at 100% replacement, STRCA exhibits 12-47% increment in electrical resistance compared to reference mixture. These findings align with studies by Sasanipour and Aslani (2021) [159], who investigated the electrical resistivity of concrete with pre-treated RCA. Similarly, research by Zhan et al. (2018) [160] explored treated recycled aggregates aligns with the present study, suggesting that concrete with STRCA poses a low risk of corrosion to steel bars. These results highlight the potential of STRCA as a beneficial component in concrete mixtures, particularly for applications requiring improved electrical resistance. Consequently, concrete up to 100% with RCA replacement carries a low risk of corrosion.

4.10 RAPID CHLORIDE ION PENETRATION TEST

The assessment of chloride resistance of concrete relies on the total charge measured by the Rapid Chloride Penetration Test (RCPT), offering insights into chloride ion transport characteristics. Table 4.8 illustrates the percentage variations in the charge passed for diverse concrete mixtures at 28 and 56 days, with reference to the control mix (CC) as a baseline. Charge passed is a crucial parameter in appraising the electrical performance of concrete, providing indications of its ability to carry electrical current. At 28 days, the control mix, CC, recorded a passed charge of 704 Coulombs. Fig. 4.11 shows the results of the 28-day rapid chloride ion penetration tests, revealing that mixtures RFA-25, RFA-50, RFA-75, RFA-100, RCA-50, RCA-75, RCA-100, RCACST-75, RCACST-100, RCACT-25, RCACT-50, RCACT-75, RCACT-100, RCAAT-25, RCAAT-50, RCAAT-75, RCAAT-100,

RCACAT-50, RCACAT-75, RCACAT-100, RCAACST-50, RCAACST-75, and RCAACST-100 have exhibited higher charges passed compared to the reference mixture. Conversely, the remaining mixtures have permitted lower charges than the reference mixture. Notably, mixture RFA-100 (+62.50) demonstrated the highest charges passed, followed by RFA-75 (+60.37), RCACST-100 (+54.97), RCA-100 (+49.57), RFA-50 (+35.51), RCA-75 (+35.37), RCACST-75 (+35.09), RCAAT-100 (+25.99), RCAACST-100 (+22.73), RFA-25 (+18.89), RCACAT-100 (+18.04), RCA-50 (+17.05), RCAAT-75 (+15.63), RCACT-100 (+13.78), RCAACST-75 (+11.79), RCACAT-75 (+8.66), RCAAT-50 (+7.95), RCACT-75 (+5.82), RCAACST-50 (+4.55), RCAAT-5 (+2.98), RCACAT-50 (+2.84), RCACT-50 (+2.27), and RCACT-25 (+0.14)) in descending order. Similarly, 56-day rapid chloride ion penetration test results, are also shown in Fig. 4.11, which indicate that mixtures RFA-25, RFA-50, RFA-75, RFA-100, RCA-50, RCA-75, RCA-100, RCACST-25, RCACST-50, RCACST-75, RCACST-100, RCACT-25, RCACT-50, RCACT-75, RCACT-100, RCAAT-25, RCAAT-50, RCAAT-75, RCAAT-100, RCACAT-50, RCACAT-75, RCACAT-100, RCAACST-50, RCAACST-75, and RCAACST-100 displayed higher charges passed compared to the reference mixture. The remaining mixtures exhibited lower charges passed than the reference mixture.

Once again, mixture RFA-100 (+63.54) demonstrated the highest charges passed, followed by RFA-75 (+60.18), RCACST-100 (+58.57), RCA-100 (+53.73), RCACST-75 (+52.42), RCA-75 (+39.09), RFA-50 (+33.38), RCAACST-100 (+28.70), RCAAT-100 (+27.38), RCACAT-100 (+23.87), RCACST-50 (+23.87), RCACT-100 (+18.01), RCAACST-75 (+16.54), RFA-25 (+16.54), RCAAT-75 (+15.37), RCA-50 (+14.49), RCACAT-75 (+13.32), RCACT-75 (+9.37), RCACT-50 (+7.03), RCAAT-50 (+6.73), RCAACST-50 (+5.86), RCACST-25 (+4.83), RCACAT-50 (+4.25), RCACT-25 (+3.66) and RCAAT-25 (+2.78)) in descending order. It's worth noting that good concrete should allow the passing of a smaller charge. Chloride permeability tests bring to light that concrete with higher replacement proportions of RFA and RCA without surface treatment exhibits an elevated level of chloride permeability in comparison to the reference mixture, indicating a decline in durability. This escalation is attributed to the higher porosity of RFA and RCA without surface treatment, which traps more water along with ions, creating a path of low resistance to electric current. The apex of chloride permeability is observed at 100% replacement by RFA and RCA without surface treatment. As the replacement of RFA and RCA without surface treatment increases, concrete durability decreases, and chloride permeability rises.

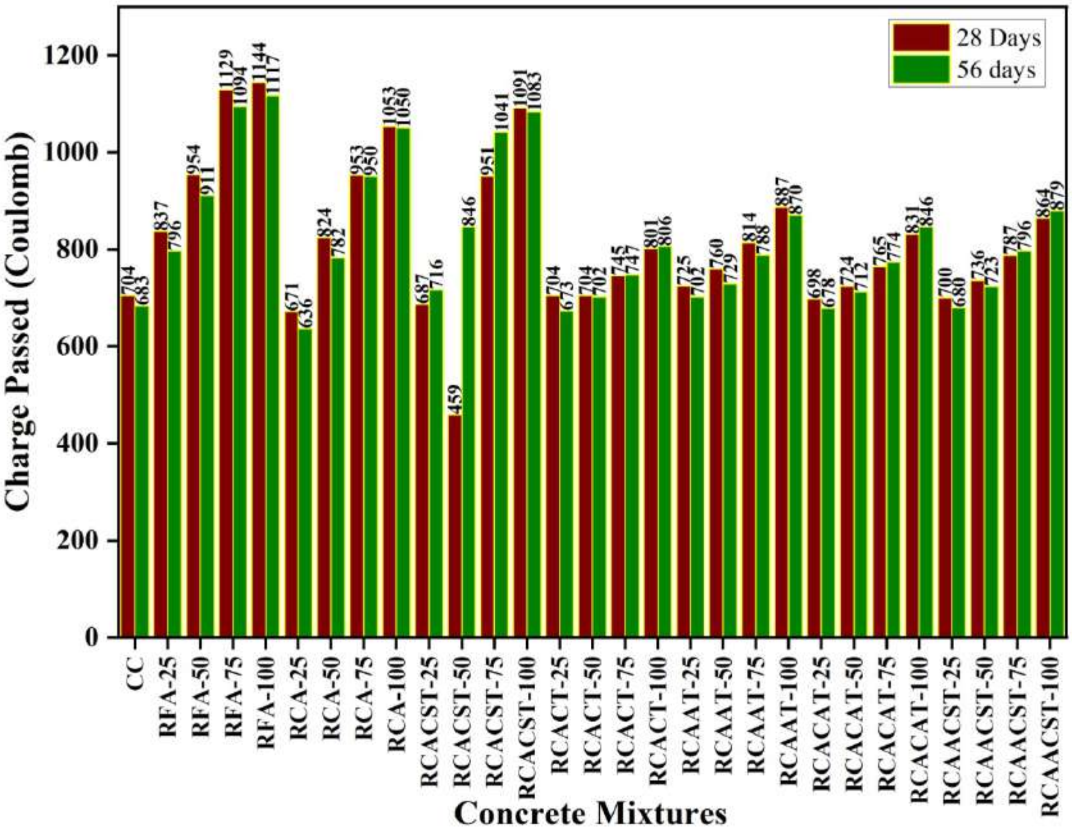


Figure 4.11Variations in the amount of charges passed through different concrete mixtures

Conversely, the results suggest that surface modification has a positive impact on chloride ion penetration resistance. The incorporation of STRCA plays a crucial role in establishing a robust bond between aggregates and cement paste, fostering the formation of strong ITZs. The enhanced ITZs act as a barrier against chloride ion ingress, owing to the cleaner, denser, and more uniformly shaped STRCA. This signifies a substantial improvement in the ability of concrete to withstand the detrimental effects of chloride exposure, highlighting the positive influence of surface modification on chloride resistance. In essence, the outcomes underscore the importance of surface modification in enhancing the durability and chloride resistance of concrete structures.

Table 4.8 Percentage variation of charge passed through different mixtures

Concrete Mix IDs.	Charge Passed (Coulomb)			
	28 days	% Variation with reference to CC	56 days	% Variation with reference to CC
CC	704	–	683	–
RFA-25	837	+18.89	796	+16.54
RFA-50	954	+35.51	911	+33.38
RFA-75	1129	+60.37	1094	+60.18
RFA-100	1144	+62.50	1117	+63.54
RCA-25	671	-4.69	636	-6.88
RCA-50	824	+17.05	782	+14.49
RCA-75	953	+35.37	950	+39.09
RCA-100	1053	+49.57	1050	+53.73
RCACST-25	687	-2.41	716	+4.83
RCACST-50	459	-34.80	846	+23.87
RCACST-75	951	+35.09	1041	+52.42
RCACST-100	1091	+54.97	1083	+58.57
RCACT-25	705	+0.14	708	+3.66
RCACT-50	720	+2.27	731	+7.03
RCACT-75	745	+5.82	747	+9.37
RCACT-100	801	+13.78	806	+18.01
RCAAT-25	725	+2.98	702	+2.78
RCAAT-50	760	+7.95	729	+6.73
RCAAT-75	814	+15.63	788	+15.37
RCAAT-100	887	+25.99	870	+27.38
RCACAT-25	698	-0.85	678	-0.73
RCACAT-50	724	+2.84	712	+4.25
RCACAT-75	765	+8.66	774	+13.32
RCACAT-100	831	+18.04	846	+23.87
RCAACST-25	700	-0.57	680	-0.44
RCAACST-50	736	+4.55	723	+5.86
RCAACST-75	787	+11.79	796	+16.54
RCAACST-100	864	+22.73	879	+28.70
+ Sign represents an increase in charge passed and – sign represents a decrease in charge passed.				

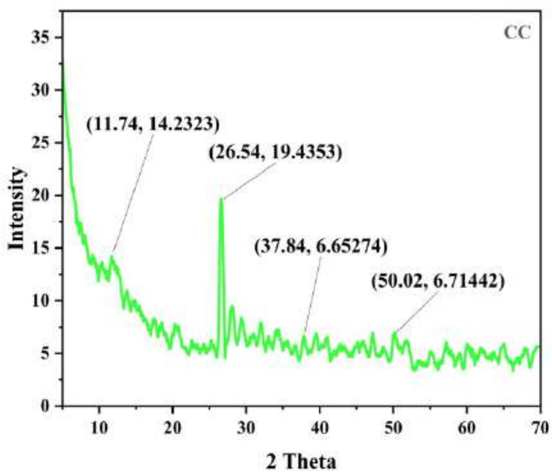
Concrete mixtures incorporating RFA and untreated RCA demonstrated low durability, showcasing smaller resistance to chloride ion penetration at replacement levels of up to 50%. However, at 75% and 100% replacement, the durability was reduced to a very low level due to a further lower resistance to chloride ion penetration. Similarly, concrete blends utilizing treated RCA, subjected to cement slurry, abrasion, and chemical treatments, display higher durability at replacement levels of up to 75%, attributed to significantly reduced penetrability to chloride ions. At 100% replacement, the durability remains moderate due to a continued but lower resistance to chloride ion penetration. Notably, concrete produced with treated RCA employing combined treatment approaches exhibits acceptable durability even at 100% replacement, showcasing low penetrability to chloride ion penetration.

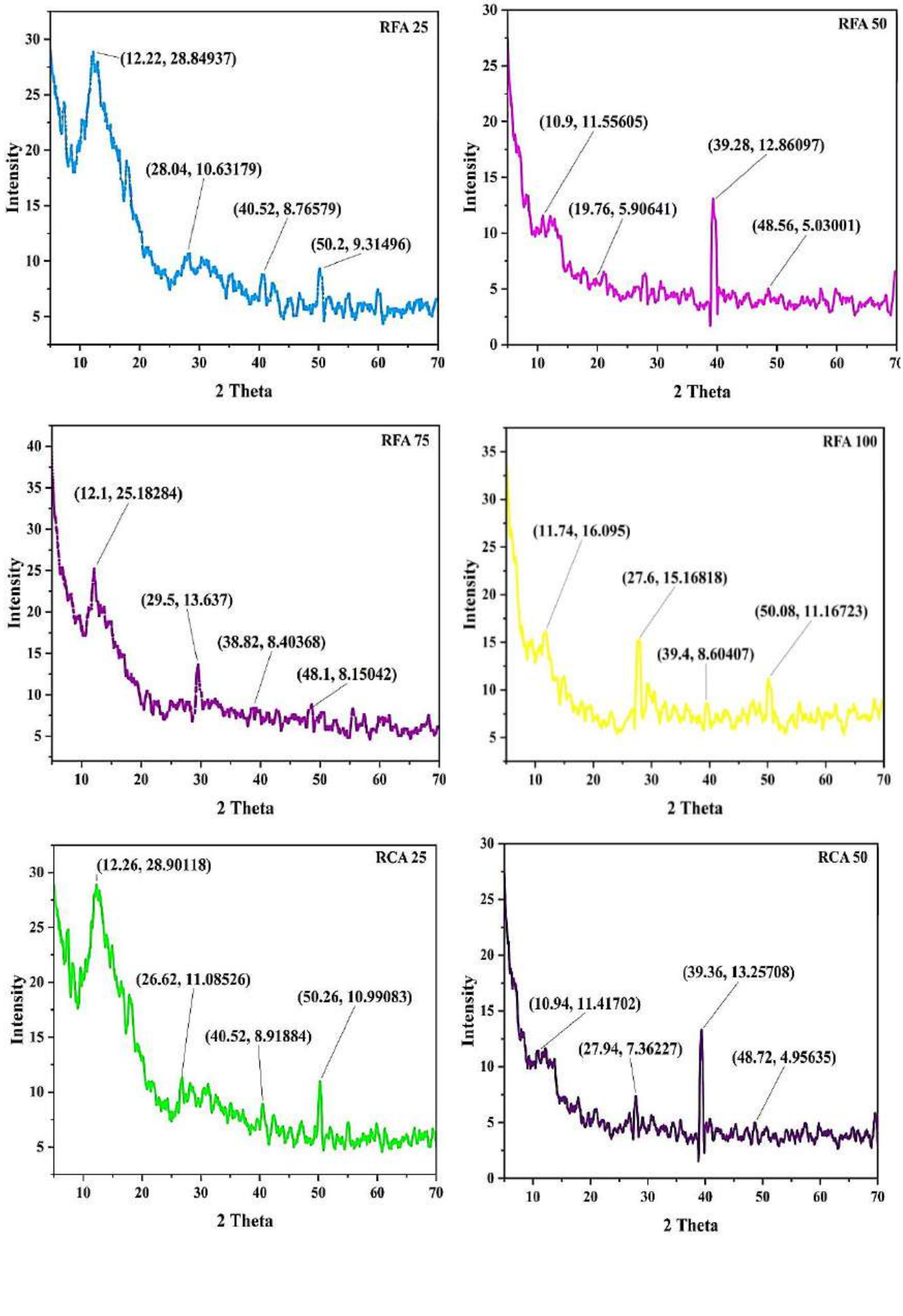
These findings suggest that surface modification crucially influences the chloride ion transport properties of concrete, with potentially positive or negative impacts depending on the percentage of STRCA incorporated. Specifically, at a 100% replacement level, STRCA demonstrates a substantial 18-59% increase in chloride ion penetration compared to reference mixture. These results correlate with Zhan et al. (2018) [160] study on the impact of treated recycled aggregates for chloride ion permeability. The observed variations underscore the complex relationship between chloride ion transport and surface-modified recycled concrete aggregate, emphasizing the necessity for meticulous consideration of STRCA proportions in concrete mixtures. Despite diverse effects, the study indicates the potential for surface modification as a valuable tool in tailoring concrete chloride resistance for specific applications. These findings underscore the importance of carefully considering the electrical properties of concrete when incorporating recycled materials, impacting the conductivity and ions passing resistance for the overall performance of concrete structures.

4.11 MICROSTRUCTURAL ANALYSIS OF CONCRETE MIXTURES

4.11.1 X-Ray Diffraction (XRD) Analysis

X-ray Diffraction (XRD) stands as a highly precise method employed for scrutinizing the crystallographic arrangement of materials. This technique involves directing X-rays onto a crystalline sample, causing them to diffract based on the crystal lattice arrangement. This, in turn, furnishes valuable insights into the crystal structure of the material under examination. The preparation of samples for XRD analysis entails finely grinding of the material into powder, meticulously loading them onto a sample holder, and aligning them accurately with the X-ray beam. Subsequently, diffracted X-rays are collected across various angles, and the resulting diffraction pattern is scrutinized to deduce the crystal structure of the material and identify its constituent phases. The XRD analysis has unveiled intriguing revelations, particularly in relation to the replacement percentage of Recycled Aggregates (RA). As the RA percentage increased, there was a noticeable reduction in the net intensity of minerals such as Calcium Silicate Hydrate (CSH), Calcium Hydroxide (CH), and Ettringite. This reduction serves as an indicative measure of the decreased density of total CSH in the concrete mixtures. The XRD analyses are shown in Figure 4.12 for various concrete mixtures effectively demonstrates the significant impact of incorporating recycled aggregates on the phase composition of minerals in concrete. Delving deeper into the analysis, it is crucial to highlight the profound influence of recycled aggregates on the diffraction peak angles of essential compounds like Calcium Silicate Hydrate (CSH), Ettringite, and Calcium Hydroxide (CH) in various concrete mixtures.

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(28.04, 10.63179)
(40.52, 8.76579)
(50.2, 9.31496)
Intensity
2 Theta
RFA 50
(10.9, 11.55605)
(39.28, 12.86097)
(19.76, 5.90641)
(48.56, 5.03001)
Intensity
2 Theta
RFA 75
(12.1, 25.18284)
(29.5, 13.637)
(38.82, 8.40368)
(48.1, 8.15042)
Intensity
2 Theta
RFA 100
(11.74, 16.095)
(27.6, 15.16818)
(50.08, 11.16723)
(39.4, 8.60407)
Intensity
2 Theta
RCA 25
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(26.62, 11.08526)
(50.26, 10.99083)
(40.52, 8.91884)
Intensity
2 Theta
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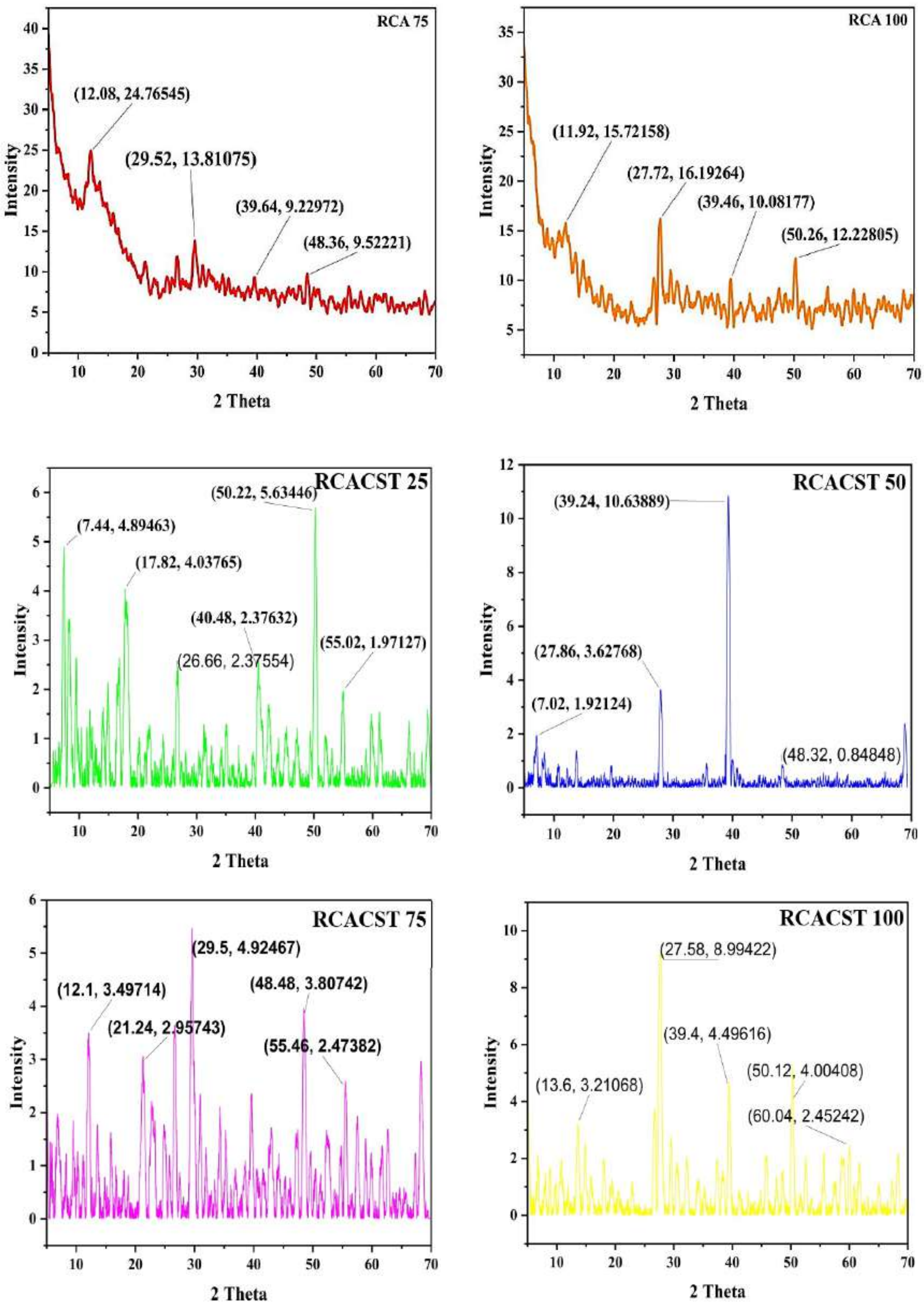
2 Theta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(48.36, 9.52221)
Intensity
2 Theta
RCA 100
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(27.72, 16.19264)
(39.46, 10.08177)
(50.26, 12.22805)
Intensity
2 Theta
RCACST 25
(50.22, 5.63446)
(7.44, 4.89463)
(17.82, 4.03765)
(40.48, 2.37632)
(26.66, 2.37554)
(55.02, 1.97127)
Intensity
2 Theta
RCACST 50
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(27.86, 3.62768)
(7.02, 1.92124)
(48.32, 0.84848)
Intensity
2 Theta
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(12.1, 3.49714)
(48.48, 3.80742)
(21.24, 2.95743)
(55.46, 2.47382)
Intensity
2 Theta
RCACST 100
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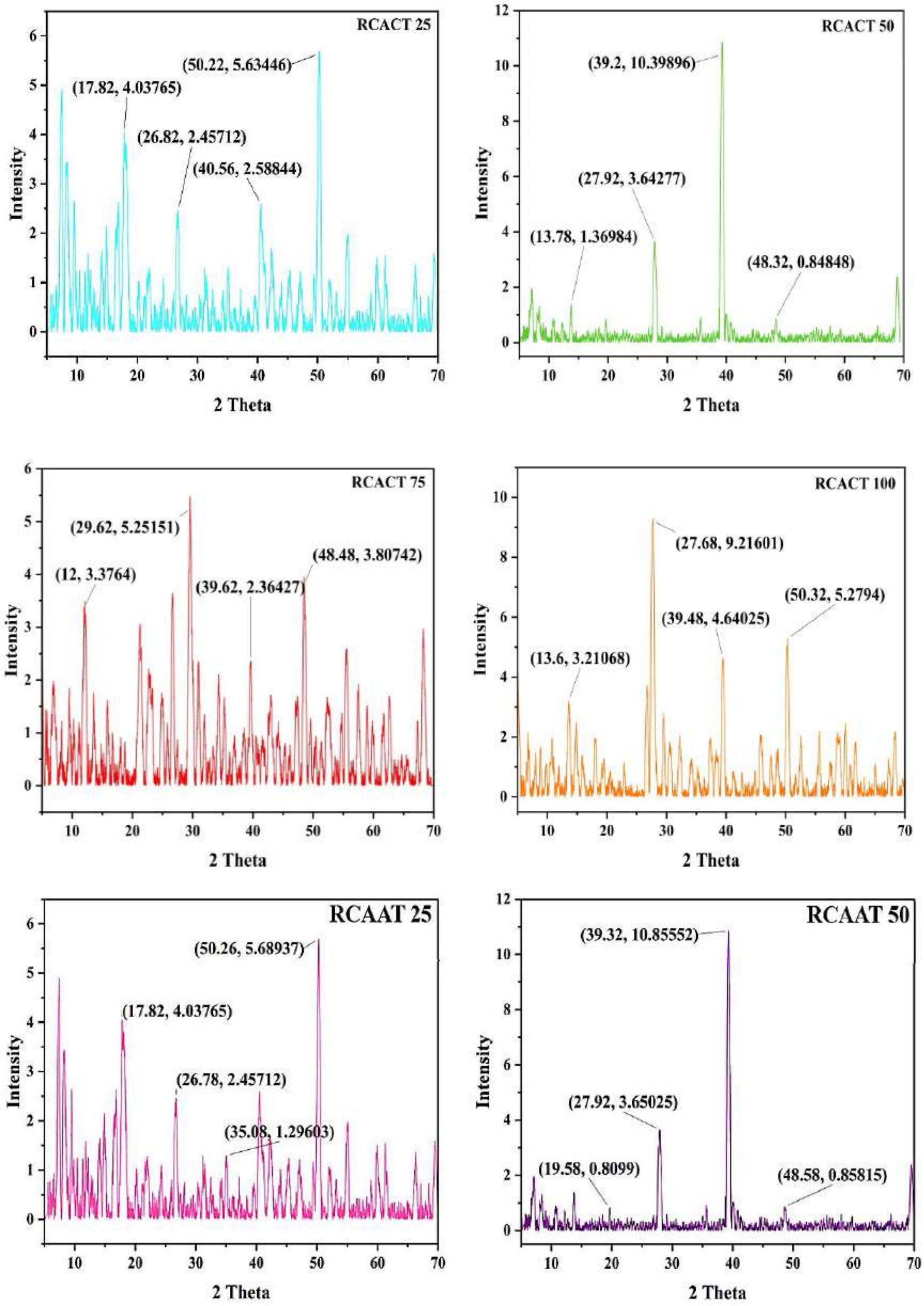
(50.12, 4.00408)
(60.04, 2.45242)
Intensity
2 Theta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(17.82, 4.03765)
(26.82, 2.45712)
(40.56, 2.58844)
Intensity
2 Theta
RCACT 50
(39.2, 10.39896)
(27.92, 3.64277)
(13.78, 1.36984)
(48.32, 0.84848)
Intensity
2 Theta
RCACT 75
(29.62, 5.25151)
(12, 3.3764)
(48.48, 3.80742)
(39.62, 2.36427)
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(27.68, 9.21601)
(50.32, 5.2794)
(39.48, 4.64025)
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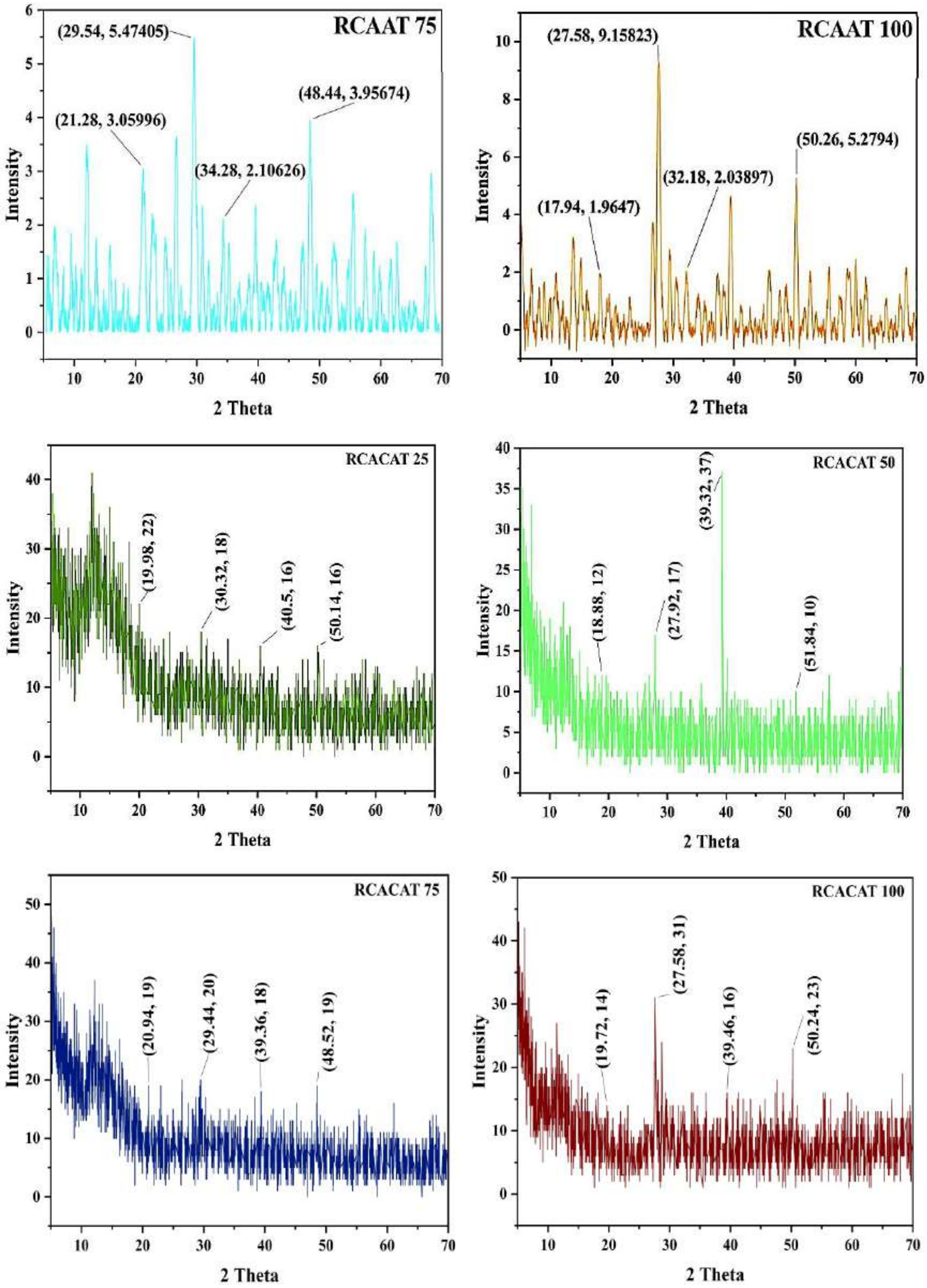
Intensity
2 Theta
RCAAT 25
(50.26, 5.68937)
(17.82, 4.03765)
(26.78, 2.45712)
(35.08, 1.29603)
Intensity
2 Theta
RCAAT 50
(39.32, 10.85552)
(27.92, 3.65025)
(19.58, 0.8099)
(48.58, 0.85815)
Intensity
2 Theta


RCAAT 75
(29.54, 5.47405)
(21.28, 3.05996)
(48.44, 3.95674)
(34.28, 2.10626)
Intensity
2 Theta
RCAAT 100
(27.58, 9.15823)
(50.26, 5.2794)
(32.18, 2.03897)
(17.94, 1.9647)
Intensity
2 Theta
RCACAT 25
(19.98, 22)
(30.32, 18)
(40.5, 16)
(50.14, 16)
Intensity
2 Theta
RCACAT 50
(39.32, 37)
(18.88, 12)
(27.92, 17)
(51.84, 10)
Intensity
2 Theta
RCACAT 75
(20.94, 19)
(29.44, 20)
(39.36, 18)
(48.52, 19)
Intensity
2 Theta
RCACAT 100
(19.72, 14)
(27.58, 31)
(39.46, 16)
(50.24, 23)
Intensity
2 Theta

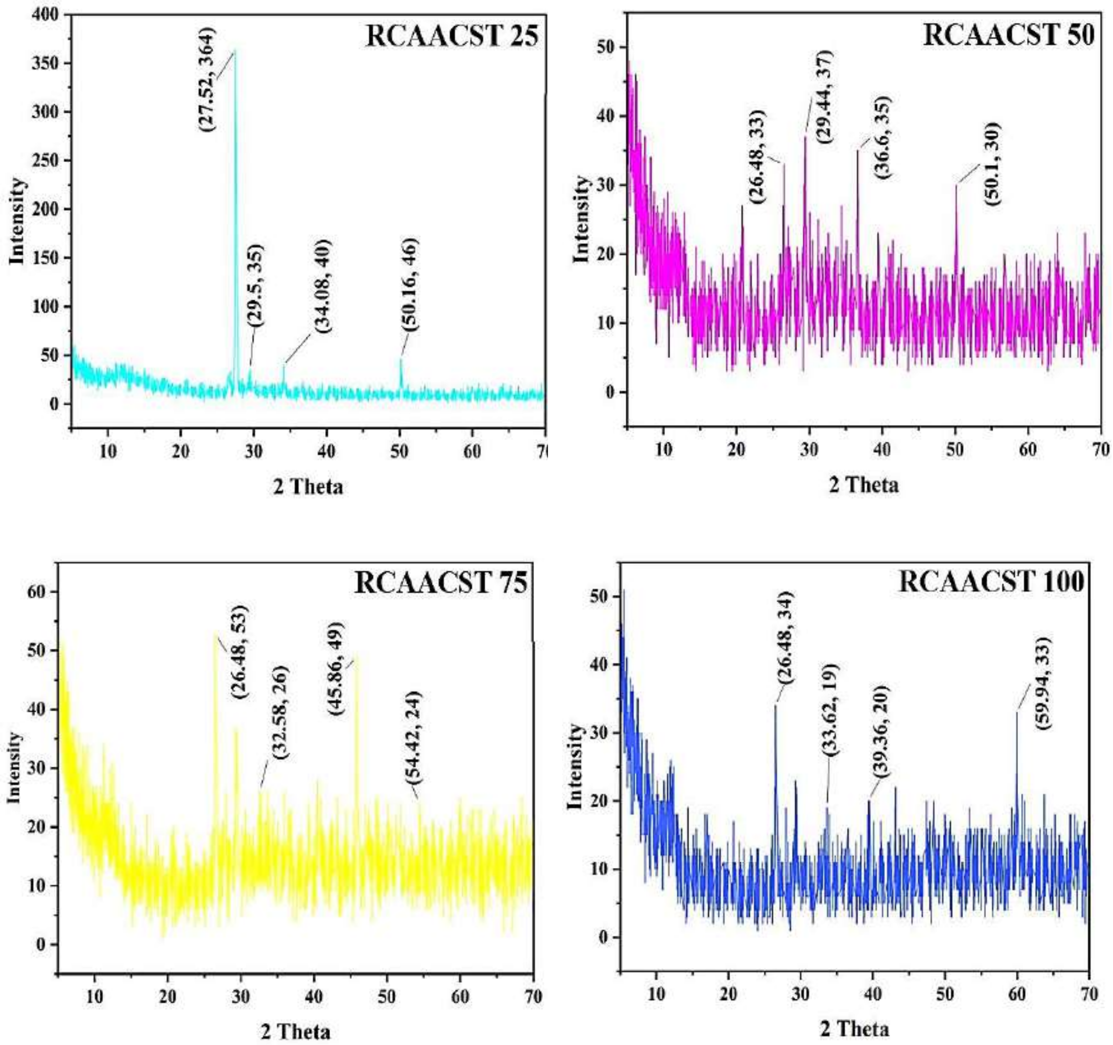


Figure 4.12 XRD analyses for different concrete mixtures

It is noteworthy that the intensity of these peaks directly correlates with the quantity of these compounds, with due consideration given to the non-homogeneity of the concrete samples at the microscopic level during the analysis.The proportional increase in recycled aggregate content is reflected in the varying diffraction peak angles for CSH, Ettringite, and CH. The comprehensive information is presented in Table 4.9, further elucidates these findings, providing details on the XRD peaks, including their locations, d-spacing, chemical names, chemical formulas, and crystal systems. Importantly, these findings align closely with earlier studies [161]–[163], reinforcing the robustness and consistency of the research outcomes.

Table 4.9 XRD data for various concrete mixtures

Mixture ID	Peak Angle	Net Intensity	Chemical Formula	Crystal System
CC	11.74	14.2323	CSH	Tobermorite
	26.54	19.4353	CASH	Tobermorite
	37.87	6.65274	ETTRINGITE	Hexagonal
	50.02	6.71442	CH	Hexagonal
RFA 25	12.22	28.84937	CSH	Tobermorite
	28.04	10.63179	CASH	Tobermorite
	40.52	8.76579	ETTRINGITE	Hexagonal
	50.2	9.31496	CH	Hexagonal
RFA 50	10.9	11.55605	CSH	Tobermorite
	19.76	5.90641	CASH	Tobermorite
	39.28	12.86097	ETTRINGITE	Hexagonal
	48.56	5.03001	CH	Hexagonal
RFA 75	12.1	25.18284	CSH	Tobermorite
	29.5	13.637	CASH	Tobermorite
	38.82	8.40368	ETTRINGITE	Hexagonal
	48.1	8.15042	CH	Hexagonal
RFA 100	11.74	16.095	CSH	Tobermorite
	27.6	15.16818	CASH	Tobermorite
	39.4	8.60407	ETTRINGITE	Hexagonal
	50.08	11.16723	CH	Hexagonal
RCA 25	12.26	28.90118	CSH	Tobermorite
	26.62	11.08526	CASH	Tobermorite
	40.52	8.91884	ETTRINGITE	Hexagonal
	50.26	10.99083	CH	Hexagonal
RCA 50	10.94	11.41702	CSH	Tobermorite
	27.94	7.36227	CASH	Tobermorite
	39.36	13.25708	ETTRINGITE	Hexagonal
	48.72	4.95635	CH	Hexagonal
RCA 75	12.08	24.76545	CSH	Tobermorite
	29.52	13.81075	CASH	Tobermorite
	39.64	9.22972	ETTRINGITE	Hexagonal
	48.36	9.52221	CH	Hexagonal
RCA 100	11.92	15.72158	CSH	Tobermorite
	27.72	16.19264	CASH	Tobermorite
	39.46	10.08177	ETTRINGITE	Hexagonal

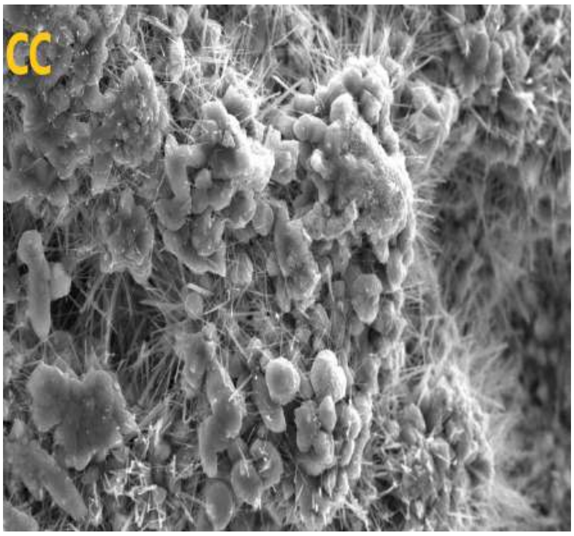
	50.26	12.22805	CH	Hexagonal
RCACST 25	26.66	2.37554	CSH	Tobermorite
	40.48	2.37632	CASH	Tobermorite
	50.22	5.63446	ETTRINGITE	Hexagonal
	55.02	1.97127	CH	Hexagonal
RCACST 50	27.86	3.62768	CSH	Tobermorite
	39.24	10.63889	CASH	Tobermorite
	48.32	0.84848	ETTRINGITE	Hexagonal
	50.12	1.04876	CH	Hexagonal
RCACST 75	21.24	2.95743	CSH	Tobermorite
	29.50	4.92467	CASH	Tobermorite
	48.48	3.80742	ETTRINGITE	Hexagonal
	55.46	2.47382	CH	Hexagonal
RCACST 100	27.58	8.99422	CSH	Tobermorite
	39.41	4.49616	CASH	Tobermorite
	50.12	4.00408	ETTRINGITE	Hexagonal
	60.04	2.45242	CH	Hexagonal
RCACT 25	17.82	4.03765	CSH	Tobermorite
	26.82	2.45712	CASH	Tobermorite
	40.56	2.58844	ETTRINGITE	Hexagonal
	50.22	5.63446	CH	Hexagonal
RCACT 50	13.78	1.36984	CSH	Tobermorite
	27.92	3.64277	CASH	Tobermorite
	39.2	10.39896	ETTRINGITE	Hexagonal
	48.32	0.84848	CH	Hexagonal
RCACT 75	12	3.3764	CSH	Tobermorite
	29.62	5.25151	CASH	Tobermorite
	39.62	2.36427	ETTRINGITE	Hexagonal
	48.48	3.80742	CH	Hexagonal
RCACT 100	19.58	0.8099	CSH	Tobermorite
	27.92	3.65025	CASH	Tobermorite
	39.32	10.85552	ETTRINGITE	Hexagonal
	48.58	0.85815	CH	Hexagonal
RCAAT 25	17.822	4.03765	CSH	Tobermorite
	26.781	2.45712	CASH	Tobermorite
	35.080	1.29603	ETTRINGITE	Hexagonal
	50.260	5.68937	CH	Hexagonal

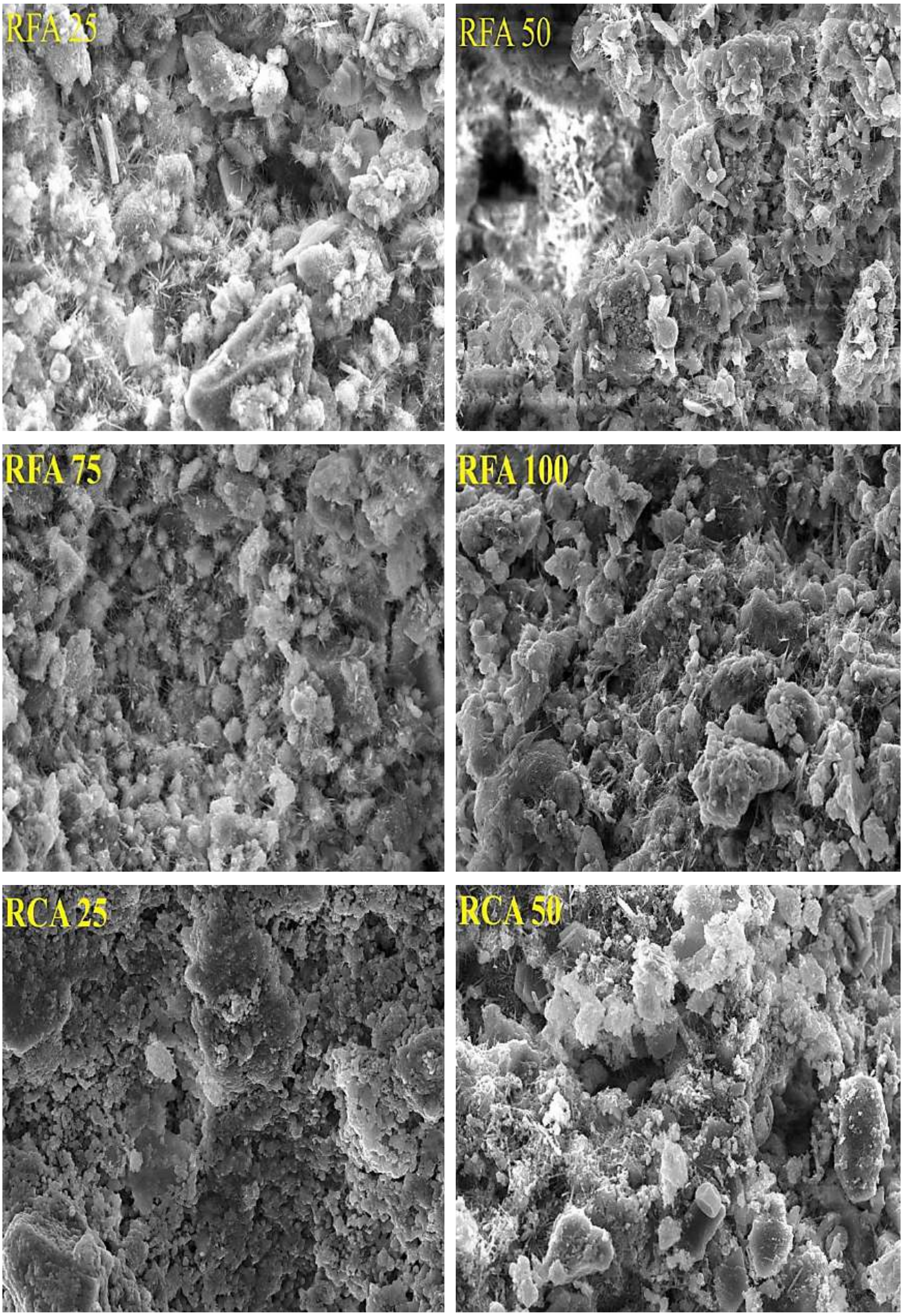
RCAAT 50	19.585	0.80991	CSH	Tobermorite
	27.924	3.65025	CASH	Tobermorite
	39.324	10.8555	ETTRINGITE	Hexagonal
	48..581	0.85815	CH	Hexagonal
RCAAT 75	21.281	3.05996	CSH	Tobermorite
	29.540	5.47405	CASH	Tobermorite
	34.284	2.10626	ETTRINGITE	Hexagonal
	48.446	3.95674	CH	Hexagonal
RCAAT 100	17.941	1.96467	CSH	Tobermorite
	27.581	9.15823	CASH	Tobermorite
	32.184	2.03897	ETTRINGITE	Hexagonal
	50.263	5.27940	CH	Hexagonal
RCACAT 25	19.98	22	CSH	Tobermorite
	30.32	18	CASH	Tobermorite
	40.5	16	ETTRINGITE	Hexagonal
	50.14	16	CH	Hexagonal
RCACAT 50	18.88	12	CSH	Tobermorite
	27.92	17	CASH	Tobermorite
	39.32	37	ETTRINGITE	Hexagonal
	51.84	10	CH	Hexagonal
RCACAT 75	20.94	19	CSH	Tobermorite
	29.44	20	CASH	Tobermorite
	39.36	18	ETTRINGITE	Hexagonal
	48.52	19	CH	Hexagonal
RCACAT 100	19.72	14	CSH	Tobermorite
	27.58	31	CASH	Tobermorite
	39.46	16	ETTRINGITE	Hexagonal
	50.24	23	CH	Hexagonal
RCAACST 25	27.52	364	CSH	Tobermorite
	29.5	35	CASH	Tobermorite
	34.08	40	ETTRINGITE	Hexagonal
	50.16	46	CH	Hexagonal
RCAACST 50	26.48	33	CSH	Tobermorite
	29.44	37	CASH	Tobermorite
	36.6	35	ETTRINGITE	Hexagonal
	50.1	30	CH	Hexagonal
RCAACST 75	26.48	53	CSH	Tobermorite

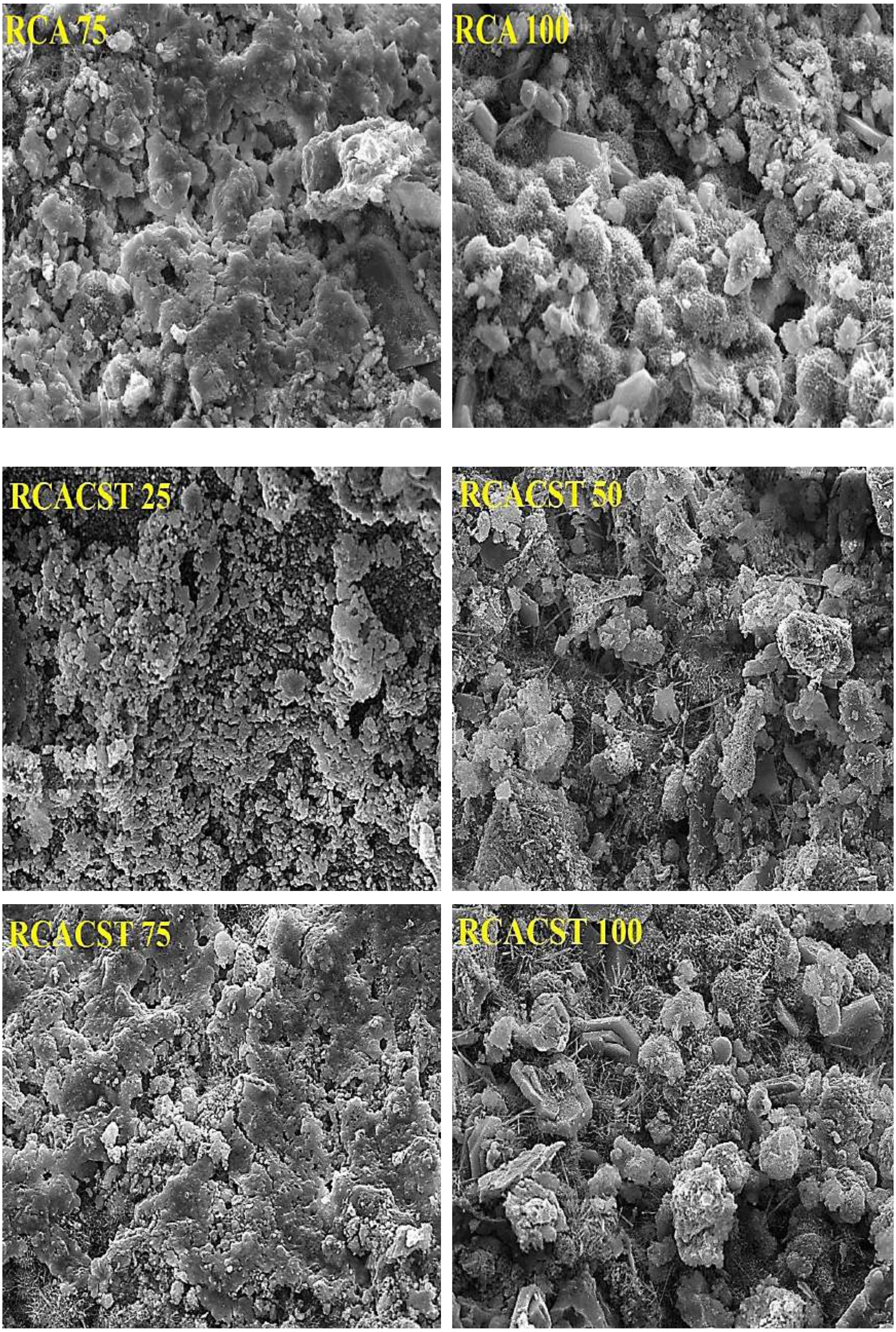
	32.58	26	CASH	Tobermorite
	45.86	49	ETTRINGITE	Hexagonal
	54.42	24	CH	Hexagonal
RCAACST 100	26.48	34	CSH	Tobermorite
	33.62	19	CASH	Tobermorite
	39.36	20	ETTRINGITE	Hexagonal
	59.94	33	CH	Hexagonal

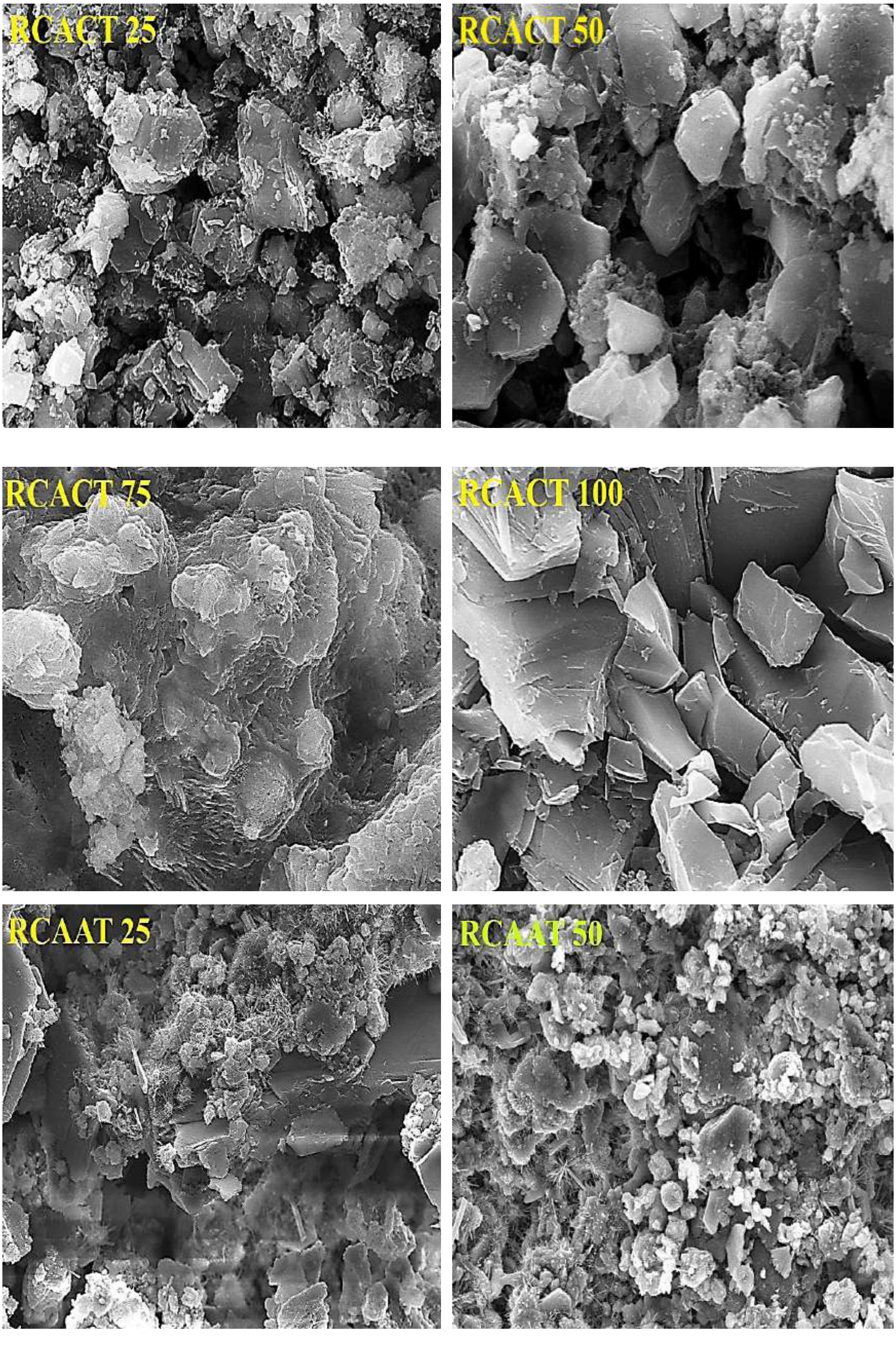
4.11.2 Scanning Electron Microscopy (SEM) Analysis

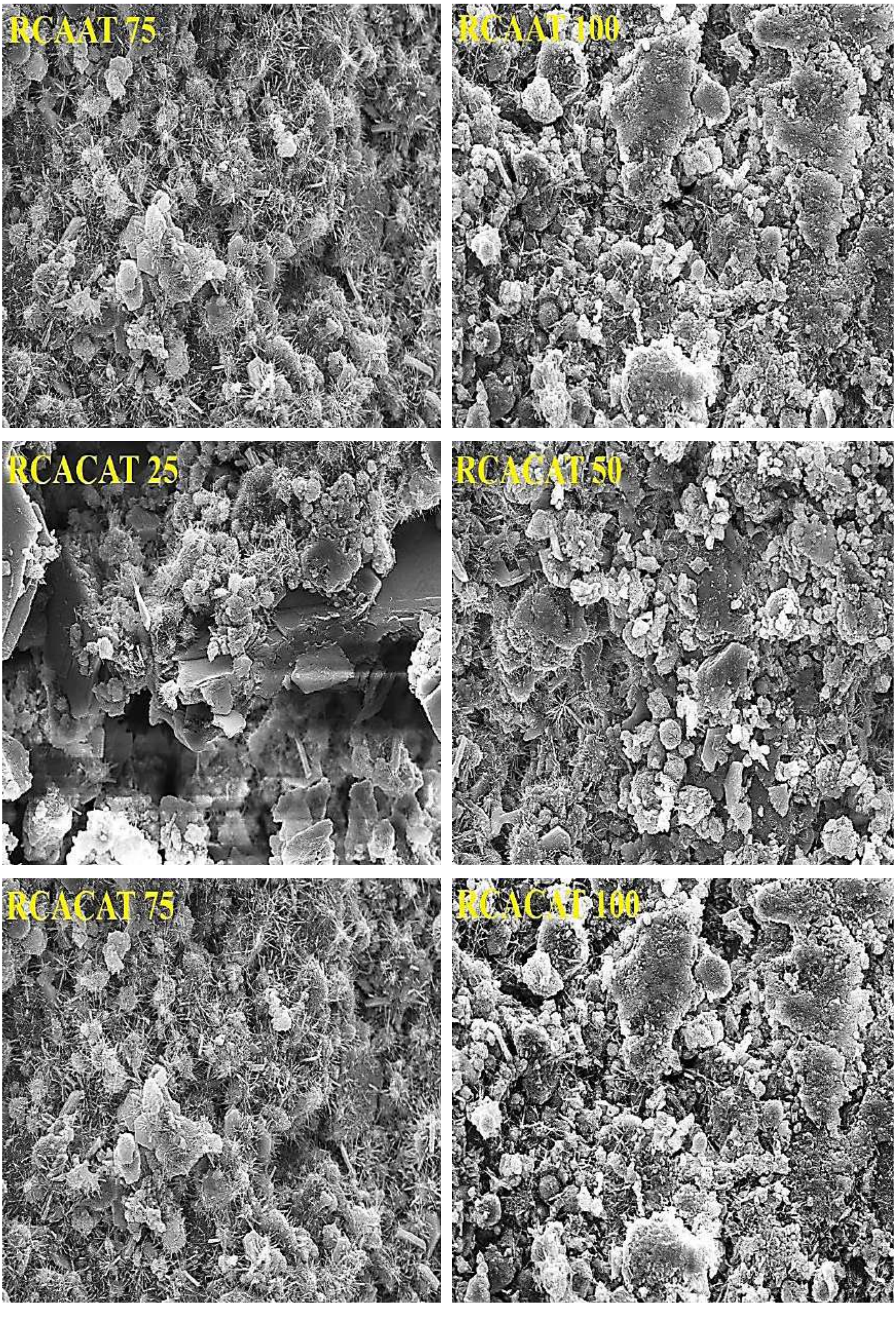
Scanning Electron Microscopy (SEM) emerges as a potent imaging technique utilizing focused electron beams to capture high-resolution surface images of materials, spanning from modest to extensive magnifications. In the context of this study, SEM serves as a crucial tool for facilitating the examination of particle microstructure and surface morphology of concrete samples. The SEM micrographs presented in Figure 4.13 showcase distinct mixtures at the 28-day, providing visual insights into the formation of hydration products at the microstructure level, a pivotal factor influencing concrete strength. During the hydration process, key compounds, namely calcium hydroxide (CH), calcium silicate hydroxide (CSH), and ettringite, play vital roles. The SEM micrographs vividly portray hexagonal crystals representing CH, flower-shaped structures indicating CSH gel, and needle-like structures representing ettringite.




RFA 25
RFA 50
RFA 75
RFA 100
RCA 25
RCA 50


RCA 75
RCA 100
RCACST 25
RCACST 50
RCACST 75
RCACST 100


RCACT 25
RCACT 50
RCACT 75
RCACT 100
RCAAT 25
RCAAT 50


RCAAT 75
RCAAT 100
RCACAT 25
RCACAT 50
RCACAT 75
RCACAT 100

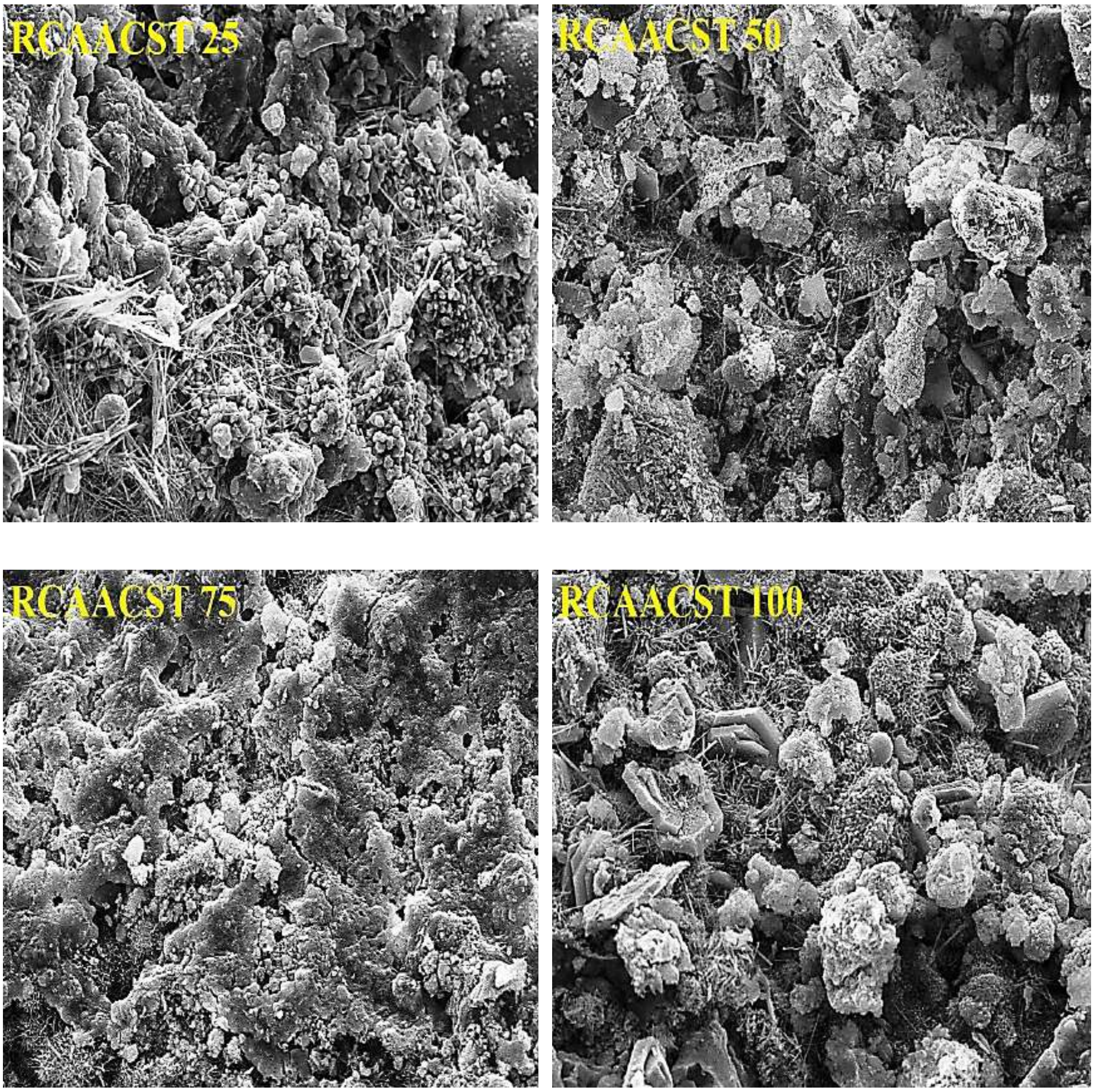


Figure 4.13 SEM micrographs for different concrete mixtures

Notably, SEM analysis reveals that lower proportions of RA result in denser CSH gel, thereby reinforcing the cement paste matrix. These compounds, integral to concrete strength and durability, contribute significantly to the overall performance. The SEM micrographs further illustrate that concrete mixtures with lower percentages of RA exhibit higher growth of CSH compared to reference concrete (CC), leading to increased strength. The extra cement encasing the recycled aggregates encourages the formation of additional hydration products, thereby improving the strength of the concrete. Conversely, increased proportions of recycled aggregates lead to fewer calcium crystals being present on recycled aggregates, suggesting the presence of voids and loose structures, ultimately leading to reduced strength. However, an excess of RA results in fragile mixtures, creating voids and loose structures that weaken the concrete, accompanied by insufficient CSH production, leading to a porous microstructure and reduced strength. The findings of the tests suggest that surface-modified Recycled Coarse Aggregate improves the microstructure of concrete by forming a dense cement paste, thus enhancing the bond between the paste and aggregates. This improvement fortifies the ITZs, making them thicker and more resilient. Based on SEM observations, the microstructure of Recycled Coarse Aggregate is enhanced; the quality and strength of recycled aggregate concrete are elevated through the elimination of attached mortar from the Recycled Coarse Aggregate surface using various treatments. These outcomes align with similar conclusions drawn from previous investigations [162], [163], confirming the favorable influence of surface alteration on both the microstructure of concrete and the overall strength of recycled aggregate concrete, as vividly captured by SEM analysis.

4.12 DISCUSSION OF RESULTS

4.12.1 Discussion on RFA and Untreated RCA Mixtures (Mixtures RFA-25 to RCA-100)

Mixtures RFA-25 and RCA-25 exhibit marginally better strengths compared to the reference concrete mixture i.e. 1. However, they possess a lower modulus of elasticity, potentially leading to increased deflection under similar load and support conditions. Additionally, these mixtures display higher shrinkage strain, which could result in a more substantial pre-stress loss, if utilized in pre-stressed concrete elements. The electrical resistance of mixture RFA-25 shows a slight increase, while mixture RCA-25 exhibits a significantly higher electrical resistance than the reference mixture. In the RCPT with RFA 25, the charge passed is slightly higher for mixture RFA-25 and slightly smaller than the reference concrete for mixture RCA-25. However, percentage replacements exceeding 25 have resulted in lower strengths compared to the reference mixture, making them not suitable to recommend.

4.12.2 Discussion on Mixtures with Cement Slurry Treated RCA (Mixtures RCACST-25 to RCACST-100)

Mixtures RCACST-25 showcase a substantial increase in strength, surpassing the reference mixtures, while Mixtures RCACST-50 exhibit a more modest yet still noteworthy improvement in strength. The moduli of elasticity for mixtures RCACST-25 and RCACST-50, although nearly equalto that of the reference mixture. Shrinkage strain in mixtures RCACST-25 and RCACST-50 is observed to be higher than the reference mixture, suggesting potential considerations for long-term structural applications. Furthermore, the electrical resistance of mixtures RCACST-25 and RCACST-50 stands out significantly, surpassing that of the reference mixture. This heightened electrical resistance is indicative of a reduced risk of corrosion, enhancing the durability of these mixtures. The charge passed from mixtures RCACST-25 and RCACST-50 is comparable to the reference mixture, emphasizing their performance similar to the reference mix. Given these noteworthy characteristics, it is strongly recommended to deploy mixtures RCACST-25 and RCACST-50 in applications where robust structural integrity and long-lasting durability are paramount. Conversely, Mixtures RCACST-75 and RCACST-100 demonstrate lower strength and inferior durability performance, rendering them unsuitable for use, in applications requiring high structural resilience and longevity.

4.12.3 Discussion on Mixtures with Chemical Treated RCA (Mixtures RCACT-25 to RCACT-100)

Mixtures RCACT-25 and RCACT-50, display notable improvements over the reference concrete by showing superior strengths, higher moduli of elasticity and increased shrinkage strain. Additionally, these mixtures exhibit significantly higher electrical resistance, suggesting a reduced susceptibility to corrosion, a critical factor for durability in various environments. Furthermore, mixtures RCACT-25 and RCACT-50 demonstrate comparable chloride ion permeability, which is indicative of their durable performance against moisture ingress and chemical exposure. This attribute enhances their longevity and performance, particularly in harsh conditions. The findings underscore the suitability of mixtures RCACT-25 and RCACT-50 for applications requiring robust structural integrity and durability. Their superior mechanical properties, combined with reduced risk of corrosion and enhanced durability, make them promising candidates for use in a wide range of construction projects. Mixture RCACT-75 exhibits a slight improvement, while Mixture RCACT-100 demonstrates strength comparable to the reference mixture. The modulus of elasticity for mixture RCACT-75 is higher, whereas mixture RCACT-100 is smaller than the reference mixture. Notably, shrinkage strain is significantly higher in both mixtures compared to the reference mixture. The electrical resistance of both mixtures is better than that of the reference mixture, with mixture RCACT-75 having higher resistance among mixtures RCACT-75 and RCACT-100. The charge passed in both mixtures is marginally to slightly higher than the reference mixture. In summary, the mixtures can be considered comparable in strength, with a marginal difference in the passing of charges. The mixtures RCACT-75 and RCACT-100 may be used with specific precautions.

4.12.4 Discussion on Mixtures with Abrasion Treated RCA (Mixtures RCAAT-25 to RCAAT-100)

Mixture RCAAT-25 exhibits significantly higher strengths than the reference mixture and mixture RCAAT-50 demonstrates higher strengths as well. Mixture RCAAT-75 provides slightly higher strengths than the reference mixture, whereas mixture RCAAT-100 shows comparable strengths to the reference mixture. The moduli of elasticity for mixture RCAAT-25 and mixture RCAAT-50 are significantly higher than that of the reference mixture. Mixture RCAAT-75 has a higher modulus of elasticity than the reference mixture, while Mixture RCAAT-100 has a slightly smaller modulus of elasticity than the modulus of elasticity of reference mixture. In terms of shrinkage strain, mixtures RCAAT-25, RCAAT-50, RCAAT-75, and RCAAT-100 follow an increasing order. The electrical resistance of mixtures RCAAT-25, RCAAT-50, RCAAT-75, and RCAAT-100 decreases in order. Notably, even mixture 21 exhibits a higher electrical resistance than the reference mixture. When it comes to charge passed, mixtures RCAAT-25, RCAAT-50, RCAAT-75, and RCAAT-100 follow an increasing order. Mixture RCAAT-25 has charge passed marginally higher than the reference mixture. Overall, mixtures RCAAT-25, RCAAT-50, RCAAT-75, and RCAAT-100 display varying strengths, moduli of elasticity, shrinkage strains, electrical resistances, and charge passed, with specific distinctions in each category. Mixtures RCAAT-75 and RCAAT-100 are not recommended due to higher shrinkage strain and higher charge passed.

4.12.5 Discussion on Mixtures of Combined Treated (Chemical Treatment followed by Abrasion Treatment) RCA (Mixtures RCACAT-25 to RCACAT-100)

Mixtures RCACAT-25, RCACAT-50, RCACAT-75 and RCACAT-100 exhibit decreasing order in strengths, with mixture RCACAT-100 has strength marginally smaller than the reference mixture. The modulus of elasticity for mixture RCACAT-100 is slightly smaller than the reference mixture, while mixtures RCACAT-25, RCACAT-50 and RCACAT-75 follow a decreasing order of modulus of elasticity. Mixture RCACAT-25 has a slightly higher shrinkage strain than the reference mixture, whereas mixtures RCACAT-50, RCACAT-75, and RCACAT-100 follow an increasing order of shrinkage strain. In terms of electrical resistance, mixtures RCACAT-25, RCACAT-50, RCACAT-75 and RCACAT-100 is decrease in order, with mixture RCACAT-100 having significantly higher electrical resistance than the reference mixture. Regarding charge passed, mixtures RCACAT-25, RCACAT-50, RCACAT-75 and RCACAT-100 increases in order, with mixture RCACAT-25 permitting a charge comparable to the reference mixture. Due to smaller strength and modulus of elasticity along with higher shrinkage strain and charge passed by mixture RCACAT-100, it is not recommended for use.

4.12.6 Discussion on Mixtures of Combined Treated (Abrasion Treatment followed by Cement Slurry Treatment) RCA (Mixtures RCAACST-25 to RCAACST-100)

In terms of strength, mixture RCAACST-75 exhibits comparable strengths to the reference mix, while mixture RCAACST-100 shows a slightly smaller. Mixture RCAACST-50 demonstrates higher strength but Mixture RCAACST-25 approaching the highest level. Moduli of elasticity align with the strengths performance. For shrinkage strain, mixture RCAACST-25 is marginally higher, and others show higher drying shrinkage in increasing order than the reference mixture. Electrical resistance decreases in order for mixtures RCAACST-25, RCAACST-50, RCAACST-75, and RCAACST-100, with mixture RCAACST-100 having significantly higher resistance than the reference mix. Regarding charges passed, mixtures RCAACST-25, RCAACST-50, RCAACST-75 and RCAACST-100 increases in order, with mixture RCAACST-25 permitting a charge comparable to the reference mixture. Due to smaller strength and modulus of elasticity along with higher shrinkage strain and higher charge passed by mixture RCAACST-100, it is not recommended for use.

4.13 COST BENEFIT ANALYSIS

The study conducts a detailed cost-benefit analysis based on Table 4.10, evaluating various concrete mixtures using cost data sourced from the Schedule of Rates (Road and Building Department, Delhi Division, Government of Delhi) and current market rates for items not included in the Delhi Schedule of Rates. The Recycled Aggregates (RA) utilized in this research were procured from the IL&FS Construction and Demolition (C&D) Waste Recycling Plant, which is operated by the Delhi Metro Rail Corporation (DMRC) in Delhi, India. These aggregates were derived from discarded concrete that was processed using an impact crusher. The primary objective of this analysis is to quantify the potential cost savings achievable by replacing natural aggregates with C&D waste-derived recycled aggregates. The cost analysis reveals significant findings regarding the economic feasibility of using recycled aggregates in concrete. Table 4.10 presents material and treatment costs across different mixtures, showing that substituting natural aggregates with untreated recycled aggregates (RA) results in cost savings ranging from 0.64% to 2.18%. Notably, RFA-25 (with 25% replacement of fine aggregate with recycled fine aggregate) demonstrates a cost reduction of 0.64%, whereas RCA-25 (with 25% replacement by RCA without surface treatment) leads to a cost reduction of 2.18% compared to control concrete (CC).

Table 4.10 Material cost comparison of various recommended mixtures (including treatment)

Mix. No.	NFA	RFA	NCA	RCA	Cement	Admixture	Materials Cost (INR)/m³	Treatment Cost of RCA (INR)/m³	Material Cost of Concrete (INR)/m³	% Variation with respect to CC
Unit Cost/kg	0.75 INR	0.5 INR	0.65 INR	0.40 INR	6.6 INR	93 INR				
CC	333.4	0.0	982.2	0	2640	372	4327.5	0.0	4327.5	0.00
RFA-25	250.0	55.6	982.2	0	2640	372	4299.7	0.0	4299.7	-0.64
RCA-25	333.4	0.0	736.6	151.1	2640	372	4233.1	0.0	4233.1	-2.18
RCACST-25	333.4	0.0	736.6	151.1	2640	372	4233.1	193.8	4426.8	2.30
RCACST-50	333.4	0.0	491.1	302.2	2640	372	4138.6	189.1	4327.7	0.00
RCACT-25	333.4	0.0	736.6	151.1	2640	372	4233.1	193.8	4426.8	2.30
RCACT-50	333.4	0.0	491.1	302.2	2640	372	4138.6	189.1	4327.7	0.00
RCACT-75	333.4	0.0	245.5	453.3	2640	372	4044.2	184.3	4228.5	-2.29
RCACT-100	333.4	0.0	982.2	0	2640	372	4327.5	198.5	4526.0	-5.46
RCAAT-25	333.4	0.0	736.6	151.1	2640	372	4233.1	193.8	4426.8	2.30
RCAAT-50	333.4	0.0	491.1	302.2	2640	372	4138.6	189.1	4327.7	0.00
RCACAT-25	333.4	0.0	736.6	151.1	2640	372	4233.1	387.6	4620.6	6.78
RCACAT-50	333.4	0.0	491.1	302.2	2640	372	4138.6	378.1	4516.7	4.37
RCACAT-75	333.4	0.0	245.5	453.3	2640	372	4044.2	368.7	4412.9	1.97
RCAACST-25	333.4	0.0	736.6	151.1	2640	372	4233.1	387.6	4620.6	6.78
RCAACST-50	333.4	0.0	491.1	302.2	2640	372	4138.6	378.1	4516.7	4.37
RCAACST-75	333.4	0.0	245.5	453.3	2640	372	4044.2	368.7	4412.9	1.97

In contrast, the use of treated recycled aggregates produces varying cost impacts, ranging from a reduction of 6.78% to an increase of 2.30%, depending on the treatment method. Among the studied mixtures, RCACAT-25 and RCAACST-25 exhibit the highest cost reduction, achieving a 6.78% decrease in costs. Meanwhile, RCACST-50, RCACT-50, and RCAAT-50 demonstrate no cost variation relative to CC, indicating economic neutrality. On the other hand, RCACT-75 and RCAACST-75 lead to a cost increase of 1.97%, suggesting a slightly higher expenditure for enhanced material properties. Based on these results, several mixtures are identified as optimal for practical applications in construction due to their cost-effectiveness and structural performance. The most cost-efficient options include RCACAT-25 and RCAACST-25, with a cost reduction of 6.78%, followed by RCA-25 and RFA-

25, which achieve cost reductions of 2.18% and 0.64%, respectively. Additionally, mixtures such as RCACST-50, RCACT-50, and RCAAT-50, which exhibit no cost variation compared to CC, are considered viable alternatives. While RCACT-75 and RCAACST-75 incur a slight cost increase of 1.97%, they remain feasible for applications where enhanced durability is a priority. The findings from this study provide valuable insights for construction industry stakeholders, enabling informed decision-making regarding material selection [164], [165]. By offering a balanced approach between cost-efficiency and sustainability, these recommendations contribute to the advancement of environmentally responsible and economically viable concrete mixtures, aligning with the principles of sustainable construction.

4.14 SUMMARY

This chapter presents a detailed discussion on the experimental results obtained from the characterization of materials, fresh concrete properties, hardened concrete properties, and durability aspects of concrete incorporating untreated and treated recycled aggregates. The main findings are summarized below:

a) Materials Characterization

I. **X-ray Diffraction (XRD) Analysis** revealed that untreated Recycled Coarse Aggregates (RCA) contained residual cementitious phases, affecting their mineralogical composition. Surface treatment methods altered the mineral phases, improving the structural integrity of RCA.

II. **Scanning Electron Microscopy (SEM) Analysis** showed that untreated RCA had a porous, irregular surface with weak bonding potential, while surface-treated RCA exhibited a more compact and rougher texture, improving bond strength with cement paste.

III. **Energy Dispersive X-ray Spectroscopy (EDAX) Analysis** indicated the presence of calcium silicates and iron oxides in treated aggregates, demonstrating improved chemical composition favorable for cementitious bonding.

b) **Fresh Concrete Properties: Workability (Slump Test)** results showed that increasing RCA content reduced workability due to higher water absorption. Surface-treated RCA improved workability, particularly in abrasion-treated and cement slurry-treated aggregates.

c) **Mechanical Properties of Hardened Concrete**

I. **Compressive Strength:** Increased RCA replacement led to a decline in compressive strength, but surface treatment methods (especially chemical treatment) improved the strength by enhancing the interfacial transition zone (ITZ).

II. **Flexural Strength:** Followed a similar trend as compressive strength, with treated RCA demonstrating better performance compared to untreated RCA. Chemical treatment and combined treatments provided the highest flexural strength improvement.

III. **Split Tensile Strength:** Increased RCA replacement weakened tensile strength; however, surface modifications helped recover strength loss, with chemically treated RCA showing the best performance.

IV. **Modulus of Elasticity:** Increased RCA content resulted in lower modulus values due to the porous nature of untreated aggregates. Surface treatment methods, particularly chemical and abrasion treatments, improved stiffness.

a) **Durability Properties**

I. **Drying Shrinkage:** Higher RCA content increased shrinkage due to higher porosity and water absorption. Treated RCA exhibited reduced shrinkage, with the best performance observed in cement slurry and chemical-treated aggregates.

II. **Electrical Resistivity:** Surface-treated RCA significantly enhanced electrical resistivity, reducing the risk of corrosion. Combined treatment approaches provided the highest resistivity values.

III. **Rapid Chloride Ion Penetration Test (RCPT):** Concrete with untreated RCA showed higher chloride permeability, while surface treatments, especially chemical and abrasion treatments, improved resistance to chloride ion penetration.

b) Microstructural Analysis of Concrete Mixtures

I. **X-ray Diffraction (XRD) Analysis of Concrete** indicated that mineral phases in concrete were influenced by the type of RCA used, with treated RCA exhibiting better crystallinity and phase stability.

II. **SEM Analysis of Concrete** showed that untreated RCA led to weak ITZ, whereas treated RCA improved ITZ densification, reducing cracks and enhancing bond strength.

The results indicate that surface treatment methods significantly enhance the mechanical and durability properties of recycled aggregate concrete (RAC). Among the treatments, chemical treatment followed by abrasion treatment emerged as the most effective in improving the performance of RCA in concrete. These findings provide valuable insights into optimizing recycled aggregates for sustainable construction applications.

CHAPTER 5

CONCLUSIONS, FUTURE SCOPE AND SOCIAL IMPACT

5.1 GENERAL

The construction industry is evolving to address the challenges of resource depletion and environmental sustainability. The rapid urbanization and increasing infrastructure demands have led to excessive consumption of natural aggregates and a surge in C&D waste. Recycled C&D waste, particularly by incorporating in the form of RFA and RCA, presents a sustainable approach to mitigate these issues while promoting circular economy principles. Despite its benefits, RCA often suffers from adhered cement mortar, leading to increased porosity, reduced strength, and compromised durability. Present study systematically evaluates the effectiveness of various surface treatment techniques—including Cement Slurry Treatment (CST), Chemical Treatment (CT), Abrasion Treatment (AT), and their combinations—in enhancing RCA properties. The combined treatment approaches further optimize RCA performance, addressing mechanical and durability deficiencies. Through a comprehensive assessment, present research identifies optimal RCA and RFA replacement levels and demonstrates how surface modifications improve structural integrity. Micro-structural analysis offers deeper insights into the behavioral changes induced by different treatments. Additionally, the study highlights the economic and environmental advantages of incorporating treated RCA and RFA, supporting the industry's transition toward sustainable concrete production. This chapter presents key research contributions, including performance enhancements achieved through individual and combined treatments, micro-structural improvements, and practical recommendations. It also outlines future research directions and discusses the broader social impact of adopting treated RFA and RCA in concrete, reinforcing their potential in sustainable and resilient construction practices.

5.2 RESEARCH CONTRIBUTIONS

The study systematically explored the utilization of C&D waste as RFA and RCA in concrete production, while evaluating various surface treatment techniques to enhance RCA performance. The major contributions are summarized as follows:

i. **Development of Surface Treatment Methodologies:** This study systematically evaluated and optimized multiple surface treatment techniques for RCA, including Cement Slurry Treatment (CST), Chemical Treatment (CT), Abrasion Treatment (AT), and Combined Treatments (CT and + AT, AT and + CST). Each technique was assessed for its impact on mechanical strength, durability, microstructural integrity, and long-term performance of concrete.

ii. **Quantification of Strength and Durability Improvements:** The experimental program established a direct correlation between surface-modified RCA and improvements in compressive strength, flexural strength, split tensile strength, and modulus of elasticity. RCA treated with cement slurry (RCACST-25, RCACST-50), chemical treatment (RCACT-25, RCACT-50), and abrasion (RCAAT-25, RCAAT-50) demonstrated superior mechanical performance compared to untreated RCA.

iii. **Microstructural Enhancements through Surface Modifications:** SEM and XRD analyses revealed that surface-modified RCA exhibited refined interfacial transition zones (ITZs), reduced micro-cracking, and improved bond strength with cement paste. Chemical and abrasion treatments led to a denser ITZ structure by reducing residual mortar content and enhancing aggregate-cement matrix interaction.

iv. **Optimization of RCA Replacement Ratios:** Through extensive experimental testing, the study established the optimal RCA replacement levels for various treatment methods. It was determined that untreated RCA should not exceed 25% replacement, whereas surface-treated RCA could be effectively used up to 50% replacement without compromising mechanical properties, durability properties and cost. Additionally, combined treatments (RCACAT, RCAACST) enabled higher RCA incorporation of up to 75% while maintaining structural integrity.

v. **Evaluation of Shrinkage and Long-Term Dimensional Stability:** The study identified the effects of RCA treatments on drying shrinkage and volumetric stability. RCA mixtures exhibited increased shrinkage strain, particularly at higher replacement levels. However, abrasion-treated and combined-treated RCA mixtures demonstrated relatively reduced shrinkage due to improved aggregate surface texture and ITZ densification, but still it was higher than the shrinkage strain of conventional concrete.

vi. **Assessment of Electrical Resistivity and Chloride Permeability:** The present research demonstrated that surface-treated RCA mixtures exhibited significantly higher electrical resistivity, thereby reducing the risk of reinforcement corrosion. Additionally, Rapid Chloride Penetration Test (RCPT) results confirmed that chemically treated RCA (RCACT-25, RCACT-50) and combined-treated RCA (RCACAT-25, RCAACST-25) exhibited superior resistance to chloride ingress, making them suitable for aggressive environmental conditions.

vii. **Economic Feasibility and Cost-Benefit Analysis:** A comparative cost analysis revealed that RCACAT-25 and RCAACST-25 provided the highest cost savings (6.78% reduction), making them the most cost-effective solutions. Other mixtures such as RCACT-50 and RCAAT-50 achieved economic neutrality, ensuring viability for large-scale structural applications.

viii. **Sustainability Contributions and Circular Economy Integration:** The study reinforced the environmental benefits of utilizing treated RCA in concrete, including the reduction in natural aggregate consumption, minimization of landfill waste, and lower carbon footprint associated with aggregate production. By promoting the reuse of C&D waste, the research aligns with global sustainability goals and circular economy principles.

5.3 CONCLUSIONS AND RECOMMENDATIONS

The insights drawn from this study lead to the following specific conclusions and recommendations based on the performance of various concrete mixtures:

5.3.1 Mechanical and Durability Performances

(a) **Strength Performance:** The study confirms that surface-modified RCA enhances the compressive, flexural, and split tensile strengths of concrete. The increase in strength is attributed to the improved ITZ, which provides better aggregate-matrix bonding. RCA mixtures treated with cement slurry (RCACST-25, RCACST-50), chemical treatment (RCACT-25, RCACT-50), and abrasion treatment (RCAAT-25, RCAAT-50) demonstrated up to a 15% increase in compressive strength compared to untreated RCA mixtures.

(b) **Modulus of Elasticity:** RCA mixtures treated with abrasion and chemical methods exhibited an increase in stiffness, with modulus of elasticity values comparable to those of conventional concrete. The combined treatment (RCACAT-25) further enhanced stiffness due to densification of the ITZ, reducing long-term deformation risks.

(c) **Shrinkage and Dimensional Stability:** The study revealed that higher RCA replacement led to increased drying shrinkage. However, abrasion-treated and combined-treated RCA exhibited reduced shrinkage due to the removal of weak residual mortar. Structural applications using high RCA content must redress shrinkage problem.

(d) **Durability and Corrosion Resistance:** The electrical resistivity results confirm that surface-treated RCA mixtures (RCACAT-25, RCACT-50, RCAACST-25) provide superior resistance against corrosion, ensuring the longevity of reinforced concrete structures. The Rapid Chloride Permeability Test (RCPT) showed that chemical and combined treatments significantly reduce chloride ingress, making these mixtures suitable for marine and chloride-exposed environments.

5.3.2 Economical and Environmental Implications

a. **Cost-Effectiveness:** The cost analysis established that RCACAT-25 and RCAACST-25 provide the highest cost savings (6.78%) while maintaining superior mechanical and durability performance. RCACT-50 and RCAAT-50 were identified as cost-neutral solutions suitable for large-scale construction applications.

b. **Sustainability Contributions:** The adoption of treated RCA reduces dependency on natural aggregates, lowering extraction rates and minimizes environmental degradation. Additionally, by diverting C&D waste from landfills, the study supports global waste management and circular economy initiatives.

c. **Structural Viability:** The results demonstrate that treated RCA mixtures can comfortably fulfill performance criteria for structural applications. The optimized RCA replacement strategies and a proper surface treatment offer a sustainable alternative without compromising strength, durability, or service life.

5.4 FUTURE SCOPE

This study offers a comprehensive evaluation of the mechanical and durability performance of treated RCA; however, several critical areas require further investigation to enhance their practical applicability and optimize sustainability:

(a) **Long-Term Durability Assessments:** Extensive field performance studies under real-world environmental conditions are essential to validate laboratory-scale findings, to ensure the long-term reliability of RCA-based concrete in diverse climatic and structural scenarios.

(b) **Optimization of Treatment Techniques:** Further refinement and advancement of chemical, mechanical, and hybrid treatment methods are necessary to maximize the mechanical properties, durability, and overall efficiency of RCA for high-performance applications.

(c) **Integration with Supplementary Cementitious Materials (SCMs):** Investigation into the combined effects of treated RCA with fly ash, silica fume, GGBFS, and other SCMs to enhance further durability may be carried out.

(d) **Development of Standardized Guidelines:** There is a need to Establish national and international codal specifications for the adoption of treated RCA in structural applications, ensuring consistency, reliability, and wider industry acceptance.

(e) **Life Cycle Assessment (LCA) and Sustainability Analysis:** Conducting comprehensive LCA studies to quantify the environmental footprint of RCA-incorporated concrete, reduction in carbon emissions, reduction in energy consumption, and long-term economic benefits in comparison to conventional concrete are also required.

Future research addressing these aspects will pave the way for the large-scale implementation of treated RCA.

5.5 SOCIAL IMPACT

The findings of this study have profound social implications, reinforcing sustainable construction practices that contribute to both environmental conservation and economic advancement. Key social impacts include:

(a) **Reduction in Construction and Demolition (C & D) Waste:** By incorporating recycled aggregates in concrete production, present study promotes efficient waste management, reducing the volume of C&D waste sent to landfills. This mitigates land pollution and minimizes the environmental burden associated with improper waste disposal.

(b) **Conservation of Natural Resources:** The replacement of natural aggregates with RCA helps in the conservation of river sand, crushed stones, and other natural resources, leading to reduction in fresh material consumption and long-term resource availability.

(c) **Improved Infrastructure Longevity:** Enhanced durability characteristics of treated RCA mixtures contribute to the longer service life of concrete structures. This reduces maintenance and repair costs, resulting in significant long-term savings for infrastructure projects.

(d) **Energy and Carbon Footprint Reduction:** The use of RCA in construction reduces the demand for virgin aggregate production, which is an energy-intensive process. This leads to lower greenhouse gas emissions and a reduced carbon footprint, aligning with global efforts to mitigate climate change.

(e) **Affordability and Economic Viability:** By utilizing locally available recycled materials, construction costs can be lowered, making infrastructure development more affordable, especially in developing regions. This supports economic growth while promoting sustainability.

(f) **Job Creation in Recycling Industries:** The widespread adoption of RCA treated aggregate encourages the growth of the recycling industry, generating employment opportunities in waste processing, material treatment/processing, and quality control sectors.

(g) **Improved Urban Development and Smart Cities Initiatives:** Sustainable concrete technologies align with modern urban planning trends, supporting smart city initiatives focused on green construction, resource efficiency, and reduced environmental impact.

Overall, the social impacts of the study are far-reaching, encompassing environmental, economic, educational and community-oriented aspects, all of which contribute to build more sustainable and resilient communities.

5.6 SUMMARY

This chapter consolidates the findings of present research, highlighting the technical advancements in sustainable concrete incorporating surface-treated recycled coarse aggregates. The study systematically assessed various treatment methods, optimizing RCA replacement ratios to balance mechanical performance, durability, and cost-effectiveness. The primary conclusions include:

i. **Significant Strength Enhancements:** The implementation of surface treatments improved RCA quality, resulting in higher compressive, flexural, and split tensile strengths compared to untreated RCA mixtures. Treated RCA exhibited superior performance due to improved ITZ densification and mechanical interlocking.

ii. **Durability Improvements:** Treated RCA mixtures demonstrated higher electrical resistivity, and lower chloride ion permeability ensuring long-term structural integrity in aggressive environments.

iii. **Economic and Environmental Viability:** The cost-benefit analysis validated that surface-treated RCA is a cost-effective alternative to natural aggregates, reducing material expenses while contributing to resource conservation and circular economy objectives.

iv. **Future Research Directions:** The study suggests further investigations into long-term field performance, integration with supplementary cementitious materials, and the development of standardized guidelines for treated RCA applications.

Overall, this research underscores the technical feasibility of utilizing treated recycled aggregates in structural concrete, providing a sustainable solution to the growing demand for eco-friendly construction materials. The findings contribute to advance green construction practices while maintaining structural performance and cost efficiency, aligning with global sustainability goals.

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LIST OF PUBLICATIONS AND THEIR PROOFS

Details of Publications in SCI/SCIE Journals

11. Harish Panghal and Awadhesh Kumar "Enhancing Durability and Strength of Concrete through an Innovative Abrasion and Cement Slurry Treatment of Recycled Concrete Aggregates," *Minerals Engineering*, Elsevier, Vol. 220, January 2025, Article 109109. DOI: 10.1016/j.mineng.2024.109109. (Citation-1)
12. Harish Panghal and Awadhesh Kumar "Enhancing Concrete Performance with Treated Recycled Aggregates: A Comparative Study of Coating, Chemical, and Abrasion Treatments," *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, Springer, Vol. 10, No. 8, 2024, pp. 1–17, Impact Factor: 1.7. DOI: 10.1007/s40996-024-01633-0. (Citation-1)
13. Harish Panghal and Awadhesh Kumar "Eco-Friendly Concrete: A Dual Surface Modification Approach for Enhanced Mechanical Performance of Recycled Coarse Aggregates," *Journal of Materials in Civil Engineering*, ASCE, Vol. 37, No. 4, 3 Feb. 2025. DOI: https://ascelibrary.org/action/10.1061/jmcee7.mteng-19054. (Citation-0)
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1. Harish Panghal and Awadhesh Kumar "Investigation of Concrete Strength and Electrical Resistivity through Incorporation of Construction and Demolition Waste Aggregates: A Novel Approach for Assessing Corrosion Vulnerability," *Conference Proceedings*, 2nd International Conference on Advances in Sustainable Construction Materials (ICASCM 2023), Vijayawada, India, December 1–2, 2023.
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Minerals Engineering 220 (2025) 109109

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Enhancing durability and strength of concrete through an innovative abrasion and cement slurry treatment of recycled concrete aggregates

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ARTICLE INFO

Keywords:
Abrasion treatment
Chloride penetration
Compressive strength
Recycled concrete aggregates
Surface treatment

ABSTRACT

The increasing demand for sustainable construction materials has driven significant interest in utilizing recycled concrete aggregates (RCA). However, the mechanical performance and durability of RCA are often compromised due to the presence of residual mortar. This study explores an innovative surface treatment approach combining abrasion and cement slurry coating to improve the properties of RCA and enhance the performance of recycled aggregate concrete (RAC). Recycled concrete aggregates were subjected to mechanical abrasion, followed by a cement slurry coating, resulting in the production of Surface-Treated Recycled Concrete Aggregates (STRCA). The study evaluates the impact of STRCA on the compressive strength, drying shrinkage, electrical resistivity, and chloride ion penetration resistance of concrete mixes with varying replacement ratios (25 %, 50 %, 75 %, and 100 %). Results revealed that the water absorption of RCA was significantly reduced from 5.35 % to 2.61 % following the treatment. STRCA 25 and STRCA 50 mixtures exhibited compressive strength increases of 30.16 % and 18.99 % at 7 days, and 29.37 % and 17.13 % at 28 days, respectively. Higher replacement levels (STRCA 75 and STRCA 100) resulted in strength reductions, with 3.91 % and 16.64 % decreases at 7 days. Drying shrinkage increased progressively with higher RCA content, showing 1.72 %, 10.91 %, 25.86 %, and 38.79 % increases at 28 days for STRCA 25, STRCA 50, STRCA 75, and STRCA 100, respectively. Electrical resistivity improved for lower replacement levels, with STRCA 25 showing a 3.41 % increase at 28 days, while STRCA 100 exhibited a 26.25 % reduction. The rapid chloride penetration test results showed that STRCA 100 had the highest resistance to chloride ion penetration, with a 22.72 % and 28.69 % increase in passed charge at 28 and 56 days, respectively, compared to the reference concrete. The findings indicate that surface-treated RCA can enhance the mechanical and durability properties of concrete, especially at lower replacement levels, making it a viable option for sustainable construction.

1. Introduction

The increasing global demand for construction materials, fuelled by rapid urbanization and economic growth (Darade and Waghmare, 2016; Panghal and Kumar, 2024; Rao et al., 2007), has significantly contributed to environmental degradation (Mnasri et al., 2017; Tamilselvan and Kumar, 2018; Reis et al., 2018). The construction industry is a major consumer of natural resources and a substantial producer of construction and demolition (C&D) waste (Paul Ntitanguranwa et al., 2018; Dhapekar et al., 2015; Kaza et al., 2050), much of which is poorly managed and disposed of in landfills (de Brito et al., 2019; Al-Mansour et al., 2019; Rizwan, 2022). Addressing these challenges necessitates more sustainable practices (Mahakud et al., 2021), including recycling C&D waste (Issa and Hilal, 2023; Masood et al., 2001; Lokeshwari and Swamy, 2011). Recycling, particularly through the reuse of concrete aggregates, offers a promising solution by reducing environmental impact, conserving resources, and lowering carbon emissions (Taffese, 2018; Asif and Assas, 2013; Panghal and Kumar, 2024). However, despite its environmental benefits, the mechanical performance and durability of recycled concrete aggregates (RCA) often fall short due to the residual mortar attached to the aggregates (Arredondo-Rea, et al., 2019; Sun et al., 2023; Zhang et al., 2019), leading to higher porosity, lower density, and increased water absorption (Shi et al., 2016; Joseph et al., 2022; Yu et al., 2022). The old mortar, which forms a weaker interfacial transition zone (ITZ), contains micro-cracks and ettringite, while the new ITZ formed between fresh cement paste and aggregates shows additional C–S–H, enhancing strength (de Juan and Gutiérrez, 2009; Wang et al., 2020; Waghmare, 2020). Effective treatment methods

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https://doi.org/10.1016/j.mineng.2024.109109
Received 9 April 2024; Received in revised form 8 November 2024; Accepted 12 November 2024

Iranian Journal of Science and Technology, Transactions of Civil Engineering
https://doi.org/10.1007/s40996-024-01633-0

METHODOLOGY

Enhancing Concrete Performance with Treated Recycled Aggregates: A Comparative Study of Coating, Chemical, and Abrasion Treatments

Harish Panghal[1] · Awadhesh Kumar[1]

Received: 5 August 2024 / Accepted: 23 September 2024

Abstract
This research focuses on optimizing the use of recycled coarse aggregates (RCA) in concrete by evaluating three advanced surface treatments: coating, chemical, and abrasion treatments. The study explores coating RCA with cement paste, using hydrochloric acid to weaken attached materials, and applying an abrasion machine to remove mortar. The main goal is to enhance the bond between recycled aggregates and the cement matrix, leading to substantial improvements in concrete properties. Chemical treatment emerged as the most effective, yielding a 32.40% increase in compressive strength at 7 days and a 22.47% increase at 28 days compared to untreated RCA. Flexural strength improved by 15.07% at 7 days and 10.71% at 28 days with chemical treatment. Abrasion treatment enhanced abrasion resistance but resulted in a 16.75% reduction in compressive strength at 7 days and a 14.28% reduction at 28 days at higher replacement levels. Cement slurry treatment showed a 28.30% increase in compressive strength at 7 days and a 19.70% increase at 28 days, and a 13.15% increase in splitting tensile strength at 25% replacement. X-ray Diffraction and Scanning Electron Microscopy analyses indicated that surface treatments improved the microstructure of RCA, leading to better concrete quality and strength. These results demonstrate the potential of surface-modified RCA for sustainable construction, offering a viable method for up to 50% replacement of conventional aggregates while minimizing environmental impact.

Keywords Abrasion treatment · Chemical treatment · Coating treatments · Mechanical characteristics · Surface treated recycled coarse aggregates

Abbreviations

RCA	Recycled coarse aggregate
NFA	Natural fine aggregates
NCA	Natural coarse aggregates
RCACT	Recycled coarse aggregates with chemical treatment
RCAAT	Recycled coarse aggregates with abrasion treatment
RCACST	Recycled coarse aggregates with cement slurry treatment
CSH	Calcium silicate hydrate
CASH	Calcium aluminate silicate hydrate
CH	Calcium hydroxide
SEM	Scanning electron microscopy
ITZ	Interfacial transition zone
Ec	Modulus of elasticity

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1 Introduction

This research explores the feasibility of incorporating recycled coarse aggregates (RCA) obtained from construction and demolition waste (CDW) in concrete production (Darade and Waghmare 2016; Mnasri et al. 2017; Gutti 2018; Tamilselvan and Kumar 2018; Barisoglu et al. 2023), aiming to reduce reliance on natural aggregates (Brito et al. 2019; Mahakud et al. 2021; K. R and krishna 2012; Issa and Hilal 2023; Taffese 2018). The RCA used in this study was sourced from the IL&FS C&D Waste Recycling Plant in Delhi, India, a facility known for its efficient processing of construction and demolition waste. The plant employs a series of mechanical operations, including primary crushing to reduce large debris, followed by screening to classify aggregate sizes. Separation techniques like air and magnetic separation are also utilized to remove impurities, ensuring

Published online: 28 September 2024

Eco-Friendly Concrete: A Dual Surface Modification Approach for Enhanced Mechanical Performance of Recycled Coarse Aggregates

Harish Panghal[1] and Awadhesh Kumar[2]

Abstract: This study aims to boost the mechanical performance of eco-friendly concrete by addressing challenges related to recycled coarse aggregates (RCA), particularly aged cement mortar adhering to aggregate surfaces. Employing a novel dual approach involving abrasion and cement slurry treatments, the research effectively removes old mortar from the RCA surface and introduces a new surface. This dual treatment minimizes strength loss and enhances the bond with the concrete matrix. Various percentages of surface-modified RCA (SMRCA) replace traditional coarse aggregates, with evaluations covering modulus of elasticity, workability, split tensile strength, flexural strength, compressive strength, porosity, and microstructural features. Results indicate that the dual modification approach significantly improves mechanical performance, particularly at a 50% SMRCA replacement rate, where compressive, flexural, and split tensile strength increase by 14.23%, 8.05%, and 4.96%, respectively. The SMRCA 75 mixture emerges as the most economically viable and aligns with eco-friendly concrete objectives. **DOI: 10.1061/JMCEE7.MTENG-19054.** © *2025 American Society of Civil Engineers.*

Author keywords: Abrasion treatment; Cement slurry treatment; Mechanical properties; Microstructural characteristics; Surface-modified recycled coarse aggregates; Sustainable concrete.

Introduction

The quantity of waste produced from construction and demolition is continuously increasing, presents significant ecological challenges, and strains disposal sites (Kaza et al. 2018). Specifically, recycling waste is done by producing recycled coarse aggregates (RCA) (Yadhu and Devi 2015), which emerges as an environmentally prudent solution (Husain and Assas 2013). This study delves into the intricacies of RCA sourced from the Recycling Plant in Delhi, India, operated by the Delhi Metro Rail Corporation (Bansal and Singh 2015). However, the abundance of cement-based mortar on aggregate substrates significantly affects the RCA's quality (De Juan and Gutiérrez 2009). Addressing this aspect during the recycling process becomes crucial, emphasizing effective techniques for eliminating or minimizing cement mortar to ensure the highest caliber RCA (Wang et al. 2020). These methods not only contribute to sustainable construction practices but also enhance the overall performance of recycled aggregates (Shi et al. 2016).

Experimental studies in this field explore various additives and methods to improve RCA concrete's sturdiness and strength (Han et al. 2023). Two-stage mixing methods enhance interfacial zones, resulting in dense concrete (Tam et al. 2005). Innovations like acid pre-soaking minimize water absorption, adhering to permissible limits for chloride and sulfate (Tam et al. 2007). Additional strategies, including pozzolanic powder coating (Li et al. 2009), fly ash incorporation (Ahmed 2013), and polymer coating (Spaeth and Djerbi Tegguer 2013), contribute to elevated strength and durability (Nanya et al. 2021). Surface modifications such as carbonation and acetic acid solution treatment further enhance compressive strength (Sun et al. 2023). Limewater-CO_2 treatment enhances cement mortar density, reducing water absorption and improving compressive and flexural strength (Zhan et al. 2018). A literature review underscores the importance of sustainable concrete solutions, advocating for recycling and the substitution of fly ash and other by-products for cement (Zaid et al. 2021). Investigations into ultra-high-performance concrete reveal innovations using superabsorbent polymers and expansive agents (Sun et al. 2023). Special issues on concrete incorporating industrial waste aim to innovate eco-friendly concrete fabrication and properties (Akyazi et al. 2020). Gypsum and NaCl effects on quicklime-activated geopolymer concrete demonstrate increased compressive strength and resistance to sulfate corrosion (Dadsetan et al. 2019). Overall, a comprehensive review highlights advancements in concrete technology, offering sustainable alternatives and innovative practices for environmentally friendly construction.

Utilizing RCA derived from construction and demolition (C&D) waste in sustainable concrete production provides advantages such as waste reduction and contributes to fostering a circular economy (Shahidan et al. 2017). Nevertheless, the existence of cement mortar on recycled aggregates presents a challenge (Vengadesh Marshall Raman and Ramasamy 2020). This study uniquely addresses the issue of strength reduction in RCA, seeking to strengthen the connection between the cement matrix and RCA. By concentrating on surface modification, our research investigates the impact of an innovative integrated approach that combines abrasion and cement slurry treatments. This groundbreaking method aims to minimize strength loss and optimize the performance of recycled aggregates in concrete applications. Building upon prior studies that identified mechanical characteristic losses with unmodified surfaces or alternative treatments, our primary objective is to comprehensively understand the influence of these techniques on RCA properties. We seek to evaluate their effective application in producing

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Note. This manuscript was submitted on March 28, 2024; approved on August 15, 2024; published online on February 3, 2025. Discussion period open until July 3, 2025; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Materials in Civil Engineering***, © ASCE, ISSN 0899-1561.

Iranian Journal of Science and Technology, Transactions of Civil Engineering
https://doi.org/10.1007/s40996-024-01539-x

METHODOLOGY

Recycled Coarse Aggregates in Concrete: A Comprehensive Study of Mechanical and Microstructural Properties

Harish Panghal[1] · Awadhesh Kumar[1]

Received: 10 April 2024 / Accepted: 7 July 2024

Abstract

Addressing the increasing demand for concrete due to advancements in the construction sector and population growth, this research explores the critical intersection of waste management and sustainable construction practices. By incorporating recycled coarse aggregate (RCA) derived from construction and demolition waste into concrete, waste reduction and natural resource conservation is achieved. An innovative standard compaction method is utilized to investigate the complex dynamics of RCA's influence on concrete properties. Key parameters examined include workability, compressive strength, flexural strength, split tensile strength, microstructural characteristics (XRD, SEM, EDAX), and modulus of elasticity. A distinctive feature of this research involves systematically replacing conventional coarse aggregates with RCA at varying proportions: 0, 25, 50, 75, and 100%. The comprehensive analysis reveals significant improvements in the fresh, hardened, and microstructural properties of concrete. Results indicate a nuanced relationship between RCA replacement levels and concrete strength, with the optimal mixture at 25% RCA replacement (RCA 25) demonstrating notably higher compressive (11.56%), flexural (3.06%), and split tensile (5.17%) strengths compared to the control concrete. Additionally, RCA 25 exhibits an 8.91% increase in modulus of elasticity. XRD, SEM, and EDAX analyses provide insights into the underlying mechanisms, indicating that pozzolanic activity enhances strength at lower RCA replacement levels by producing more hydration products, while strength may decrease at higher replacement levels. The significance of this research lies in its novel methodology, addressing a critical gap in understanding the intricate relationships between RCA content and concrete performance. The findings strongly advocate for the judicious use of recycled materials in concrete, contributing to environmental conservation and the long-term resilience of construction materials.

Keywords Concrete · Construction waste · Recycled coarse aggregate · Sustainable construction practices · Waste management · Microstructural characteristics

1 Introduction

The rapid evolution of construction methodologies in the twenty-first century has led to a surge in construction and demolition (C&D) waste, which is projected to reach an astounding 3.40 billion metric tonnes by 2050 and 2.59 billion metric tonnes by 2030 (Kaza et al. 2050; Hoornweg and Bhada-Tata 2012). Landfilling this C&D waste not only strains available landfill space but also inflicts significant ecological impacts (Amasuomo and Baird 2016; Akyazi et al. 2020). In response to these challenges, processing C&D waste into aggregate for fresh concrete, which constitutes 70–80% of the concrete's volume, emerges as a viable solution (Mahakud et al. 2021; Dardis 2012). This approach not only offers economic benefits but also aligns with environmental sustainability principles, transforming discarded waste materials into valuable resources (Gutti 2018; Marinković et al. 2023). This study specifically examines the transformation process of waste concrete from recycling plants into recycled coarse aggregate (RCABansal and Singh 2007, 2015; Bansal et al. 2014). Before considering the substitution of conventional concrete with C&D waste-derived concrete in civil engineering projects, a thorough assessment of its performance and adherence to industry standards is imperative (Han et al. 1411; Saad et al. 2021). The utilization of recycled aggregate (RA), either entirely or partially, in place of traditional aggregate, constitutes

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1 Department of Civil Engineering, Delhi Technological University, Delhi 110042, India

Published online: 17 July 2024

Received: 26 March 2024 | Revised: 3 June 2024 | Accepted: 27 June 2024
DOI: 10.1002/suco.202400387

ARTICLE

fib WILEY

Enhancing concrete durability and strength: An innovative approach integrating abrasion and cement slurry treatment for recycled coarse aggregates

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Abstract

This study introduces a novel approach to enhance the durability and strength of concrete by integrating abrasion and cement slurry treatments on surface-treated recycled coarse aggregates (STRCA). Initial abrasion treatment removes aged mortar from the recycled coarse aggregate (RCA) surface, while subsequent cement slurry modification provides a fresh surface, reinforcing the bond with the concrete matrix. Through detailed material analyses including x-ray diffraction, scanning electron microscopy, and energy-dispersive x-ray, microstructural changes are evaluated alongside compressive strength, drying shrinkage, electrical resistivity, and chloride ion penetration of STRCA-based concrete. Results indicate significant improvements in mechanical properties and durability as the treatments eliminate mortar and enhance the interfacial connection with cement paste. Notably, a substantial 29.37% strength enhancement is observed at 25% replacement (STRCA 25), demonstrating treatment efficacy. While a reduction of 11.58% occurs at 100% replacement (STRCA 100), up to 75% replacement shows minimal strength loss, with optimal enhancements at 50% replacement. Additionally, STRCA concrete exhibits lower drying shrinkage (11%–20% reduction) and increased electrical resistivity (28%–36% rise), indicating improved durability at 100% replacement. Enhanced resistance to chloride ion penetration is also evident, with a 22%–28% increase at 100% replacement compared to conventional RCA. Overall, this study highlights the effectiveness of dual treatments for enhancing concrete properties using STRCA.

KEYWORDS

abrasion treatment, cement slurry treatment, concrete durability, microstructural characteristics, surface-treated recycled coarse aggregates

1 | INTRODUCTION

The confluence of economic expansion and urbanization has emerged as a driving force behind environmental degradation,[1] posing a formidable threat to sustainability.[2] The escalating demand for natural resources, particularly within the construction sector, has given rise to a significant volume of construction waste, often inadequately managed in landfills.[3,4] This pervasive waste, spanning diverse sectors, presents complex environmental

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Springer

Journal of Mechanical Science and Technology 38 (6) 2024

Original Article
DOI 10.1007/s12206-024-04 -y

Keywords:
· Construction and demolished waste
· Mechanical properties
· Recycled coarse aggregates
· Scanning electron microscopy
· X-ray diffraction

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Citation:
Panghal, H., Kumar, A. (2024). Examining the structural viability of recycled fine aggregates in sustainable concrete. Journal of Mechanical Science and Technology 38 (6) (2024) ?~?.
http://doi.org/10.1007/s12206-024-04 -y

Received ?? th, 2023
Revised ?? th, 2023
Accepted ?? th, 2023

† Recommended by Editor ??

Examining the structural viability of recycled fine aggregates in sustainable concrete

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Abstract This study investigates the potential of incorporating recycled fine aggregates (RFA) into sustainable concrete. In this research, a conventional compaction technique is utilized to establish the order of compressive strength and, consequently, to assess particle packing density in terms of weight within a specific cylindrical volume and evaluate workability, compressive and flexural strengths, splitting tensile strength, elasticity modulus, and microstructural properties (analyzed through XRD, SEM, and EDAX). The study found that RFA can improve concrete properties, hardened characteristics, and microstructure up to an optimum 25 % RFA replacement threshold (RFA 25). Beyond this value, concrete strength and microstructure deteriorate. RFA 25 exhibits significantly higher compressive (14.75 %), flexural (6.61 %), and splitting tensile (13.14 %) strengths compared with the reference concrete, along with a 5.71 % decrease in the modulus of elasticity. Lower replacement levels promoted pozzolanic reactions, enhancing strength through additional hydration products, whereas higher replacements reduced strength.

1. Introduction

The construction industry, which is crucial for global economic growth, is simultaneously contributing to environmental degradation through the energy-intensive production of concrete, which has a substantial carbon footprint [1]. In addition, the surge in construction and demolition waste (CDW) disposal poses challenges [2], straining landfill space and causing negative ecological impacts [3]. This issue is addressed by incorporating recycled aggregate (RA) from CDW in fresh concrete, constituting 70 %–80 % of its volume, which presents economic and environmental advantages by reusing materials such as concrete, asphalt, bricks, and tiles [4–6]. This research focuses on recycled fine aggregates (RFAs) generated through an impact crusher at the IL&FS CDW Recycling Plant in collaboration with the Delhi Metro Rail Corporation [7–9]. However, a comprehensive assessment of its performance and compliance with industry standards are necessary before this substitution is considered in civil engineering projects [10–12]. RA concrete (RAC), which employs RA instead of natural aggregate (NA), has been extensively studied. RAC tends to be less workable due to its porous structure and higher water absorption capacity [13]. Various factors, including the replacement ratio of NA, water-to-cement ratio, parent aggregate type, age, exposure conditions, number of crushing stages, and physical and mechanical characteristics of RA, influence its compressive strength [15–17]. Despite flaws in RAC's microstructure compared with that of NA concrete, adding RAs significantly enhances the strength of hardened concrete, offering a viable alternative to natural sand aggregates with lower permeability [18–20]. Concrete formulations containing RFAs and demolished coarse aggregates have shown effectiveness in replacing conventional concrete [21–23]. Studies incorporating fly ash with recycled concrete aggregates reveal increased water absorption and decreased electrical resistivity [24–26]. RFA concrete, with compressive strengths and modulus of elasticity (MOE) ranging from 70 % to 90 % of NA concrete, sur-

Construction and Building Materials 411 (2024) 134432

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Enhancing concrete performance: Surface modification of recycled coarse aggregates for sustainable construction

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ARTICLE INFO

Keywords:
Recycled coarse aggregates
Scanning electron microscopy
Surface modification
Sustainable construction
X-ray diffraction

ABSTRACT

In this study, the researchers introduce an innovative method to enhance the utilization of recycled coarse aggregates (RCA) derived from construction and demolition waste (C&D) in sustainable concrete production. The presence of old cements mortar on the surface of these aggregates poses a challenge to their mechanical properties. To tackle this issue, the researchers propose a unique approach that combines chemical treatment and abrasion techniques. Firstly, RCA is immersed in a 0.5 mol hydrochloric acid (HCl) solution, weakening the adhering mortar. Subsequently, abrasion treatment removes the weakened mortar from the RCA surface. The study explores the incorporation of these surface-modified RCAs at varying levels, from 0% to 100% in 25% increments. Various concrete properties, including workability, compressive strength, flexural strength, split tensile strength, and microstructural characteristics (XRD, SEM, and EDAX), along with modulus of elasticity, are assessed. Results indicate that the combination of these modification techniques significantly enhances RCA properties. At the 100% replacement level, surface-modified RCA results in a reduction of compressive, flexural, and split tensile strength by 08.31%, 10.61%, and 07.90%, respectively, in comparison to the reference concrete. Likewise, the modulus of elasticity decreases to 30.82, and porosity decreases to 27.82% at the same replacement level. However, SEM analysis illustrates improved bonding between RCA and cement matrix due to surface modifications, leading to reduced porosity and the formation of dense Interfacial Transition Zones (ITZs). Cost analysis reveals that recycled aggregate concrete (RAC) mixtures can be more economical than those utilizing natural aggregates (NA). In summary, this novel surface modification technique presents a promising avenue for optimizing RCA utilization in sustainable concrete production, promoting environmental conservation, and efficient waste management in the construction sector.

1. Introduction

The 21st-century construction industry is expected to generate a substantial amount of construction and demolition (C&D) waste, projected to reach 2.59 billion tonnes by 2030 and 3.40 billion tonnes by 2050 [1]. This waste poses environmental challenges due to limited disposal options [2]. Recycling C&D waste into recycled aggregates, particularly recycled coarse aggregate (RCA), is identified as a promising solution offering economic and environmental benefits [3]. Recycled aggregates are obtained from processing materials like concrete, asphalt, bricks, and tiles discarded during construction and demolition activities [4], [5]. These aggregates can be transformed into both coarse and fine aggregates, opening avenues for their reuse [6]. The study focuses on RCA from the IL&FS C&D Waste Recycling Plant in Delhi, India, obtained through an impact crusher [7], [8] A key challenge is the presence of cement mortar on the aggregate surface, which can adversely affect RCA quality, leading to reduced strength and durability [9]. Effective cleaning [10], and separation techniques are crucial during recycling to ensure high-quality RCA production [11]. On-going experimental investigations aim to enhance RCA concrete properties through the incorporation of chemicals and techniques, focusing on improving strength, durability, and overall performance [12–14]. The research emphasizes the importance of addressing C&D waste challenges by implementing efficient recycling methods and continuously striving to improve the quality and usability of recycled aggregates in construction applications.

Researchers are actively working to enhance the properties of materials for sustainable construction, employing diverse strategies such as chemical admixtures, fiber reinforcement, and innovative curing processes [15]. One promising technique is the two-stage mixing process,

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https://doi.org/10.1016/j.conbuildmat.2023.134432
Received 23 August 2023; Received in revised form 22 November 2023; Accepted 2 December 2023
Available online 14 December 2023
0950-0618/

IOP Publishing Mater. Res. Express 10 (2023) 095506 https://doi.org/10.1088/2053-1591/acf915

Materials Research Express

OPEN ACCESS

RECEIVED
10 July 2023

REVISED
21 August 2023

ACCEPTED FOR PUBLICATION
12 September 2023

PUBLISHED
22 September 2023

PAPER

Effects of surface modified recycled coarse aggregates on concrete's mechanical characteristics

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Keywords: mechanical characteristics, recycled coarse aggregates, scanning electron microscopy, surface modification, x-ray diffraction

Abstract

Sustainable concrete using recycled coarse aggregates from construction and demolition waste is gaining popularity in the construction industry, but has poor mechanical characteristics due to old cement mortar adhering to aggregate surfaces. This study uses two processes (abrasion treatment and cement slurry treatment) to modify the surface of recycled coarse aggregates (RCA) to minimize the strength loss of RCA and enhance the bonding properties of the concrete matrix and RCA. Surface-modified RCA replaced coarse aggregates in varying percentages, ranging from 0 to 100% in 25% increments. To comprehend the effects of surface-modified RCA, the workability, compressive strength, flexural strength, split tensile strength, microstructural characteristics (XRD, SEM, and EDAX), and modulus of elasticity of concrete are evaluated. Surface-modified RCA improves concrete's mechanical characteristics, but abrasion-treated RCA has significantly greater strength than reference concrete up to 50% replacement level, while cement slurry treatment has slightly lower strength. Test findings reveal that among all the two processes of surface modifications of RCA, abrasion treatment is more effective and efficient. At 100% replacement level, surface-modified RCA by abrasion treatment reduces compressive, flexural, and split tensile strength by 10.89%, 10.42%, and 09.92% compared to reference concrete, while surface-modified RCA by cement slurry treatment reduces these values by 14.80%, 13.27%, and 12.76%. Surface modifications improve bonding properties of RCA and cement matrix, reducing porosity and resulting in dense and strong ITZs compared to unmodified RCA.

1. Introduction

Construction and demolition (C&D) waste generation is expected to reach 2.59 billion tonnes by 2030 and 3.40 billion tonnes by 2050 [1], causing environmental issues and a lack of disposal sites [2]. Recycling C&D waste as recycled aggregates (RA) is economically and environmentally advantageous [3]. Recycled aggregates are produced by processing construction and demolition waste materials like concrete, asphalt, bricks, and tiles [4, 5]. These aggregates can be utilized to create both coarse and fine aggregates for reuse [6]. In this study, we employ recycled coarse aggregate (RCA) produced by using an impact crusher to crush waste concrete from IL&FS C&D Waste Recycling Plant, Delhi Metro Rail Corporation (DMRC), Delhi, India [7, 8]. However, the quality of RCA is affected by cement mortar attached to the aggregate surface [9]. Proper removal or reduction of cement mortar during recycling is crucial for high-quality RCA production [10]. Efficient methods for separating and cleaning aggregates can enhance performance and contribute to sustainable construction practices [11]. Experimental studies aim to enhance RCA concrete's strength, durability, and performance by incorporating additives and techniques [12–14].

Researchers investigate factors like chemical admixtures, fiber reinforcement, and curing methods to optimize the material's characteristics for sustainable construction practices [15]. The two-stage mixing method improves recycled aggregate interfacial zones by filling pores and cracks, resulting in dense concrete [16].

Materiales de Construcción
Vol. 74, Issue 353, January-March 2024, e337
ISSN-L: 0465-2746
https://doi.org/10.3989/mc.2024.360023

Structural aspects of concrete incorporating recycled coarse aggregates from construction and demolished waste

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Received 19 July 2023
Accepted 11 November 2023
Available on line 25 March 2024

ABSTRACT: The study explores the potential of recycling construction and demolition waste into recycled coarse aggregates (RCA) to decrease waste generation and carbon footprint, using a standard compacting effort to calculate compressive strength and particle packing density in a specific cylindrical volume. This study investigates the impact of RCA on concrete's workability, compressive strength, flexural, split tensile, drying shrinkage, electrical resistivity, rapid chloride penetration, and microstructural characteristics using XRD, SEM, and EDAX. Test findings showed that increasing the replacement percentage beyond the optimum value (RCA 25) had detrimental effects on the strength and microstructure of the concrete. RCA 25 has a higher compressive, flexural, and split tensile strength in the order of 11.56%, 3.06%, and 5.17% respectively compared to reference concrete, as well as 5.23% increase in drying shrinkage, 8.79% higher electrical resistivity, and 4.68% higher resistance to chloride penetration than reference concrete.

KEY WORDS: Aggregate; Concrete; Hydration products; Ettringite formation; Portland cement.

Citation/Citar como: Panghal H, Kumar A. 2024. Structural aspects of concrete incorporating recycled coarse aggregates from construction and demolished waste. Mater. Construcc. 74(353):e337. https://doi.org/10.3989/mc.2024.360023.

RESUMEN: *Aspectos estructurales del hormigón que incorpora áridos gruesos reciclados de residuos de construcción y demolición.* Este estudio explora el potencial del reciclaje de residuos de construcción y demolición en áridos gruesos reciclados (RCA) para reducir la generación de desechos y la huella de carbono, utilizando un esfuerzo de compactación estándar para calcular la resistencia a la compresión y la densidad de empaquetado de partículas en un volumen cilíndrico específico. La investigación evalúa el impacto del RCA en la trabajabilidad, resistencia a la compresión, resistencia a flexión, tensión por flexión, retracción por secado, resistividad eléctrica, penetración rápida de cloruro y características microestructurales utilizando XRD, SEM y EDAX. Los resultados muestran que aumentar el porcentaje de reemplazo más allá del valor óptimo (RCA 25) tiene efectos perjudiciales en la resistencia y microestructura del hormigón. El RCA 25 tiene una resistencia a la compresión, a flexión y tracción superior en un 11.56%, 3.06% y 5.17%, respectivamente, en comparación con el hormigón de referencia. Además, presenta un aumento del 5.23% en la retracción por secado, una resistividad eléctrica un 8.79% mayor y una resistencia a la penetración de cloruros un 4.68% superior al hormigón.

PALABRAS CLAVE: Árido; Hormigón; Productos de hidratación; Formación de etringita; Cemento portland.

https://doi.org/10.3311/PPci.22711 | 1
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Periodica Polytechnica Civil Engineering

Sustainable Concrete: Exploring Fresh, Mechanical, Durability, and Microstructural Properties with Recycled Fine Aggregates

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Received: 03 June 2023, Accepted: 03 November 2023, Published online: 03 January 2024

Abstract

The growing construction industry and global population have led to increased demand for concrete, resulting in increased waste production. Recycling construction and demolition (C&D) waste as recycled fine aggregates (RFA) in concrete could help reduce waste and conserve natural resources. This research delves into the meticulous examination of particle packing density within specific cylindrical volumes under standard compacting efforts, elucidating an order of compressive strength. The study comprehensively explores various concrete properties, including workability, compressive strength, flexural strength, split tensile strength, drying shrinkage, electrical resistivity, rapid chloride penetration, and microstructural characteristics (analyzed through XRD, SEM, and EDAX). RFA particles, ranging from 0.15 to 4.75 mm, were employed as partial replacements for fine aggregates, with replacement percentages varying from 0% to 100% in increments of 25%. The empirical findings underscore that the incorporation of RFA significantly enhances concrete properties. However, it was observed that surpassing the optimum replacement percentage of 25% (RFA 25) adversely impacts the concrete's strength and microstructure. Specifically, RFA 25 exhibited remarkable improvements, with a 14.75% increase in compressive strength, a 6.61% boost in flexural strength, and a 13.14% enhancement in split tensile strength compared to conventional concrete (RC). Furthermore, RFA 25 demonstrated a 4.16% increment in drying shrinkage, 17.65% higher electrical resistivity, and an 18.83% superior resistance to chloride penetration compared to RC. The analysis of XRD, SEM, and EDAX results elucidated that at lower replacement percentages, the pozzolanic reaction enhances strength by forming additional hydration products. Conversely, at higher replacement levels, strength diminishes.

Keywords

construction and demolished waste, durability properties, recycled fine aggregates, mechanical properties, microstructural properties

1 Introduction

In the 21st century, rapid advancements in construction have led to the creation and demolition of structures, resulting in a significant upswing in construction and demolition (C&D) waste, projected to reach 2.59 billion tonnes by 2030 and 3.40 billion tonnes by 2050 [1]. The disposal of this waste in landfills not only depletes landfill sites but also adversely affects the land. A potential solution lies in repurposing C&D waste as aggregates in fresh concrete production, a sector where aggregates constitute 70-80% of the volume [2]. The demand for concrete is soaring, increasing annually at a rate of 7.7% [3]. To mitigate environmental impact, the global construction industry is increasingly embracing sustainable practices, requiring innovative approaches to reduce concrete's ecological footprint [4]. Recycling fine aggregates from C&D waste presents a promising solution. However, it necessitates rigorous evaluation to ensure the resulting concrete meets industry standards [5]. This study addresses this imperative need by systematically exploring various proportions of recycled fine aggregates (RFA) ranging from 0% to 100%.

Structural concrete made from C&D waste requires continuous structural health monitoring (SHM) to guarantee its long-term performance [6]. Concrete structures undergo stress due to drying-induced shrinkage, which leads to the formation of cracks. Drying shrinkage occurs as free water escapes through pores and passages near the surface of the element into the surrounding air. Consequently, analyzing shrinkage strain is essential for conducting a comprehensive study of the long-term performance of fresh concrete [7]. Surface electrical resistivity

Cite this article as: Panghal, H., Kumar, A. "Sustainable Concrete: Exploring Fresh, Mechanical, Durability, and Microstructural Properties with Recycled Fine Aggregates", Periodica Polytechnica Civil Engineering, 2024. https://doi.org/10.3311/PPci.22711

Enhancing Concrete Sustainability: Assessing the Impact of Construction and Demolished Waste Aggregates on Strength and Rapid Chloride Permeability as a Durability Indicator

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Abstract. The construction industry is adopting sustainable practices by using Construction and Demolished (C&D) waste aggregates in concrete production. This study investigates the impact of C&D waste on concrete's compressive strength and rapid chloride permeability (a vital durability Indicator), examining the relationship between aggregate replacements, strength, and chloride permeability. The goal is to guide the creation of robust and eco-friendly concrete formulations. The results show that higher levels of C&D waste aggregate replacement lead to reduced compressive strength and increased chloride ion permeability, compromising concrete's durability. Notably, a 25% replacement of C&D fine aggregates demonstrates the highest compressive strength at 36.71MPa, while a 100% replacement of C&D coarse and fine aggregates yields the lowest at 19.73MPa. RFA 25%, RCA 25%, and RFA 25% + RCA 25% mixtures experienced significant improvements in compressive strength, with gains of approximately 15.98%, 13.18%, and 12.36% at 7 days, and 15.73%, 12.33%, and 10.80% at 28 days, respectively. Concrete maintains satisfactory durability when replacing up to 50% of C&D fine aggregates, up to 75% of C&D coarse aggregates, and up to 25% of C&D fine + coarse aggregates.

Keywords: Construction and Demolished (C&D) Waste, Recycled Aggregates, Rapid Chloride Permeability Test, Sustainable Concrete

1. Introduction

The construction industry's relentless pursuit of sustainability has spurred innovative practices geared towards reducing waste generation and conserving valuable resources [1]. In this context, our research takes a deep dive into the realm of sustainable construction materials by exploring the incorporation of Construction and Demolition (C&D) waste aggregates in concrete. The primary objective is to augment both the strength and durability of concrete structures [2]. In our investigation, the spotlight is cast on two crucial parameters: the compressive strength and rapid chloride permeability of concrete [3]. By delving into these aspects, we aim to gain a comprehensive understanding of the material's performance, underpinning its significance in the construction landscape [4]. The assessment of chloride ion permeability holds particular prominence, being a pivotal factor in determining concrete durability. While this area has been extensively explored through the Rapid Chloride Permeability Test (RCPT) as outlined in ASTM C1202, existing methodologies have their limitations [5].

In the rich tapestry of research findings, intriguing discoveries have been made. Wee et al.'s work highlighted the differential resistance of plain cement mortar and plain cement concrete to chloride penetration, illuminating the complexities of this phenomenon [6]. Prakash and Nirmala's research shed light on the enhanced resistance achieved in self-compacting concrete (SCC) when specific dosages of super-plasticizers were employed [7]. An index test method, the RCPT, was identified as the best by Karthik et al. when comparing apparent chloride diffusion coefficients [8]. Additionally, innovative approaches such as the incorporation of nano-silica materials, explored by Carmichael and Arulraj, showcased a decrease in concrete permeability [9]. Rao and Kumar's investigations with fly ash cement replacements further underscored the potential of sustainable materials in mitigating permeability issues [10]. Furthermore, the research community has explored nuanced avenues, such as the modification of Metakaolin and Nano Silica by Shafiq et al., resulting in substantial reductions in permeability with specific proportions [11]. Corrosion inhibitors, as studied by Satish and Ravindra, were found to significantly enhance concrete resistance, contributing valuable insights to the field [12]. Saad et al.'s comprehensive study on M30 Grade concrete durability using RCPT emphasized the need for meticulous permeability measurements, hinting at the complexities involved [13]. Even in the realm of unconventional materials, Mohammed et al.'s examination of lightweight concrete constructed from unconventional aggregates brought forth intriguing results, indicating higher RCPT values at earlier stages[14]. Hameed et al.'s ground breaking study on Superabsorbent Polymer (SAP) incorporated High-Performance Concrete unveiled promisingly low permeability, opening new doors for exploration [15].

INVESTIGATION OF CONCRETE STRENGTH AND ELECTRICAL RESISTIVITY THROUGH INCORPORATION OF CONSTRUCTION AND DEMOLISHED WASTE AGGREGATES: A NOVEL APPROACH FOR ASSESSING CORROSION VULNERABILITY

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Abstract: The durability and performance of concrete structures are integral to sustainable infrastructure, yet the corrosion of reinforcing steel poses a significant threat. This study examines how incorporating construction and demolished waste (C&D) aggregates impacts concrete's strength and electrical resistivity. The research evaluates the potential of waste aggregates as a sustainable solution while gauging their influence on corrosion susceptibility. Through experimental analysis, this study assesses mechanical properties, electrical resistivity, and corrosion potential across varying proportions (0%, 25%, 50%, 75%, and 100%) of waste aggregates. The findings reveal that higher substitution levels of C&D waste aggregates lead to reduced compressive strength and electrical resistivity, escalating steel reinforcement corrosion rates within the concrete matrix. Notably, a 25% replacement of C&D waste fine aggregates yields the highest compressive strength (36.71 MPa), while 100% replacement of C&D waste aggregates (both coarse and fine) records the lowest (19.37 MPa). Electrical resistivity data indicate that corrosion risk remains low for up to 75% replacement of C&D waste fine aggregates, up to 50% replacement of C&D waste aggregates, and up to 25% replacement of C&D waste aggregates (both coarse and fine). Integrating waste aggregates enhances concrete performance and mitigates corrosion vulnerability, thus fostering the development of enduring and sustainable infrastructure.

Keywords: *Concrete, waste aggregates, corrosion vulnerability, mechanical strength, electrical resistivity, sustainable construction*

Drying Shrinkage Characteristics of Environmentally-Friendly Concrete Incorporating Construction and Demolition Waste Aggregates

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Abstract

The construction industry's growing demand for concrete has led to resource depletion and waste waste production associated with construction and demolition (C&D). Researchers are exploring sustainable alternatives, such as incorporating C&D aggregates into concrete mixtures, to address environmental concerns. This study investigates drying shrinkage in concrete made with C&D waste aggregates through experiments, evaluating the substitution of C&D waste at various percentages (0% to 100%) for fine, coarse, and mixed aggregates. Accurately predicting concrete shrinkage is crucial for quality and design improvements. It was discovered that adding C&D waste aggregates to natural aggregates will cause more drying shrinkage in newly mixed concrete. Interestingly, Mix2, Mix6, and Mix10 formulations showed drying shrinkage similar to the reference mixture, suggesting an optimal replacement rate of 25%. Notably, when C&D waste aggregate content in concrete rose from 25% to 100%, significant increases in drying shrinkage were observed: 4.61%, 20.92%, 37.23%, and 46.76% for Mix2, Mix6, Mix10, and Mix12, in comparison to control concrete, after 28 days of cure, respectively. Similar trends were seen for Mix25, Mix50, Mix75, and Mix100, with drying shrinkage increments of 5.23%, 20.63%, 34.88%, and 45.05%, respectively.

Keywords: Aggregates Substitution; C&D Waste Aggregates; Concrete; Drying Shrinkage; Sustainable Construction

Introduction

With the rapid pace of urbanization and industrial expansion, the demand for concrete, the primary building material, has seen an exponential surge. However, this surge has raised concerns about sustainability due to the overexploitation of natural resources like fine and coarse aggregates [1]. The construction and eventual demolition of structures, owing to age and obsolescence, contribute significantly to the mounting waste issue. Projections suggest that waste generation could reach a staggering 2.2 billion tons by 2025, a substantial increase from the anticipated 1.3 billion tons [2]. As a result, researchers all over the world are using waste from construction and demolition (C&D) in place of natural aggregates for producing concrete. This strategy effectively curbs the C&D waste being dumped in landfills while safeguarding valuable natural resources. Concrete manufacture has just begun using C&D waste as aggregates represent a proactive step towards waste reduction and environmental improvement. Nevertheless, the use of C&D waste particles into concrete raises questions about the durability and serviceability of the resulting material. The structural integrity of concrete constructions is compromised by shrinkage, primarily caused by drying processes. Free water migrates from the element's surface through channels and porosity to the surrounding air, causing drying shrinkage. Thus, assessing the potential for shrinkage strain is imperative for the long-term performance evaluation of freshly produced concrete [3].

Tremper and Spellman's seminal work in 1962 examined the shrinkage of concrete both in controlled laboratory settings and real-world conditions, concluding that well-designed laboratory tests can effectively characterize concrete's shrinkage behavior [4]. In 1964, Torrans et al. looked at how much concrete shrank while drying containing different admixtures and found that while concrete without admixtures exhibited increased shrinkage when cured at temperatures between 75°F and 95°F, the use of D-type admixtures led to a decrease in shrinkage under the same conditions [4]. McDonald and Weiss's report in 2005 outlined various factors influencing concrete shrinkage changes [5]. Whiting et al. (2012) performed experiments to assess the drying shrinkage of concrete incorporating recycled aggregates, with or without fly ash. Their findings demonstrated that concrete made from recycled aggregates can exhibit substantial drying shrinkage, comparable to traditional concrete. Drying shrinkage increased by 25% without fly ash and by 7% with fly ash [1]. Maruyama and Sugie's analytical study in 2014 delved into the relationship between aggregate size and concrete drying shrinkage, concluding that adjusting particle size distribution can mitigate shrinkage [6]. Taylor and Wang's 2014 research

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Summary

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8. **Academic Qualification:**

Standard	**Institute/ University**	**Year**	**Dissertation Title**	**Percentage**
Ph.D **(Pursuing)** (Structural Engineering)	Delhi Technological University (DTU), Delhi, India	2018-2024	Experimental Investigation on Structural Aspects of Concrete Made with C&D Waste	
M.Tech. (Structural Engineering)	Maharshi Dayanand University (MDU), Rohtak, Haryana, India	2014-2016	Study of Wind Load on High Rise Building Using Analytical Investigation	80.02%
B.Tech. (Civil Engineering)	Maharshi Dayanand University (MDU), Rohtak, Haryana, India	2009-2013	-	74.79%
Senior Secondary	Haryana Board of School Education, Bhiwani, Haryana, India	2008-2009	-	75%
Intermediate	Haryana Board of School Education, Bhiwani, Haryana, India	2006-2007	-	75%

9. Work Experience:

S. No.	Name of Institute	Designation	Duration	Stay Span	Cumulative Teaching Exp.
1	GTC, Bahadurgarh	Lecturer	02 October 2013 – 25 May 2014	7 Month 21Days	7 Month 21Days
2	GTC, Bahadurgarh	Part Time Lecturer	01 August 2014 – 02 Sep 2016	2 Years 1 Month	2 Years 8 Month 21Days
3	GTC, Bahadurgarh	Assistant Professor	03 Sep. 2016 - 30 April. 2022	5 Years 7 Months 17 Days	8 Years 3 Month 17 Days
4	GITAM, Jhajjar	Assistant Professor	02 May 2022 – 30 April 2024	1 Years 11 Months 29 Days	10 Years 4 Month 7 Days
5	GNIOT, Greater Noida	Assistant Professor	01 May 2024 – till date	Continuing	10 Years 4 Month 7 Days Continuing

10. Specific Research Experience:

S. No.	Name & Address of the Organization	Period of work	Status	Area of Research
1.	Department of Civil Engineering, Maharshi Dayanand University (MDU), Rohtak, **INDIA**	15.08.2014 To 15.05.2016	M.Tech. Scholar, Rohtak, India	Study of Wind Load on High Rise Building
2.	Department of Civil Engineering, Delhi Technological University (DTU), Delhi**, INDIA**	12.07.2018 To 19.01.2024	Research Scholar, Delhi, India	Experimental Investigation of Structural Aspects of Concrete Made with C&D Waste

11. National/ International Conferences Attended

i. National Conference on Innovative developments in Science, Technologies & Management **(IDSTM 2015),** Soldha, Bahaduragrh, Haryana, India, 1st March, 2015.
ii. International Conference on Innovative developments in Science, Technologies & Management **(IDSTM 2015),** Soldha, Bahaduragrh, Haryana, India, 22nd November, 2015.
iii. International Conference on Innovative developments in Science, Technologies & Management **(IDSTM 2017),** Soldha, Bahaduragrh, Haryana, India, 29th January, 2017.
iv. International Conference on Innovative developments in Science, Technologies & Management **(IDSTM 2018),** Soldha, Bahaduragrh, Haryana, India, 16th March, 2018.
v. International Conference on Civil, Architectural and Environmental Sciences **(ICAES 2022),** Jaipur, India, July 10, 2022. International Conference on Sustainable Development Goals **(ICSDG 2023)**, Phagwara, India, September 29-30, 2023.
vi. 4th International Conference on Futuristic and Sustainable Aspects in Engineering and Technology **(FSAET 2023),** Mathura, India, November 28-30, 2023.
vii. 2nd International Conference on Advances in Sustainable Construction Materials **(ICASCM 2023)** Vijayawada, India, December 1-2, 2023.
viii. International Conference on Advances in Sustainable Development, Innovation and Green Technology (**ICASGIGT 2024**), Gandhi Nagar Panikhati, Guwahati, Assam, India, February 19-21, 2024.

12. Publications

Details of Publications in SCI/SCIE Journals

1. Harish Panghal and Awadhesh Kumar, "Effects of surface modified recycled coarse aggregates on concrete's mechanical characteristics," *Material Reearch. Express*, Vol. 10, No. 9, 2023, https://doi.org/10.1088/2053-1591/acf915.
2. Harish Panghal and Awadhesh Kumar, "Enhancing concrete performance: Surface modification of recycled coarse aggregates for sustainable construction," *Construction and Building Materials*, Vol. 411, No. 1, 2023, https://doi.org/10.1016/j.conbuildmat.2023.134432.
3. Harish Panghal and Awadhesh Kumar, "Sustainable Concrete: Exploring Fresh, Mechanical, Durability, and Microstructural Properties with Recycled Fine Aggregates," *Periodica Polytechnica Civil Engineering,* Vol. 68, No. 2, 2024, https://doi.org/10.3311/PPci.22711.
4. Harish Panghal and Awadhesh Kumar, "Structural Aspects of Concrete Incorporating Recycled Coarse Aggregates from Construction and Demolished Waste," *Materiales de Construcción*, Vol. 74, No. 353, 2024, https://doi.org/10.3989/mc.2024.360023.
5. Harish Panghal and Awadhesh Kumar, "Examining the Structural Viability of Recycled Fine Aggregates in Sustainable Concrete," *Journal of Mechanical Science and Technology,* Vol. 38, No. 06, 2024, https://doi.org/10.1007/s12206-024-04-y.

Details of Communicated Papers in SCI/SCIE Journals

1. Harish Panghal and Awadhesh Kumar, "Eco-Friendly Concrete: A Dual Surface Modification Approach for Enhanced Mechanical Performance of Recycled Coarse Aggregates," *Cement and Concrete Composites, Elsevier* (**Under Review**).
2. Harish Panghal and Awadhesh Kumar, "Enhancing Durability and Sustainability: Innovative Surface Modification of Recycled Coarse Aggregates in Concrete," *Construction and Building Materials, Elsevier (**Under Review**).*
3. Harish Panghal and Awadhesh Kumar, "Revitalizing Concrete Durability and Strength: An Innovative Approach Integrating Abrasion and Cement Slurry Treatment for Recycled Coarse Aggregates," *Sustainable Construction and Technology, Elsevier (**Under Review**).*
4. Harish Panghal and Awadhesh Kumar, "Enhancing Concrete Performance with Treated Recycled Aggregates: A Comparative Study of Coating, Chemical, and Abrasion Treatments," *Composites Structures, Elsevier (**Under Review**).*

Details of Publications in Scopus Indexed International Conferences

1. Harish Panghal and Awadhesh Kumar, "Enhancing Concrete Sustainability: Assessing the Impact of Construction and Demolished Waste Aggregates on Strength and Rapid Chloride Permeability as a Durability Indicator," *E3S Web of Conferences Proceedings*, Volume 453, 01009(2023), International Conference on Sustainable Development Goals (ICSDG 2023), Phagwara, India, September 29-30, 2023, **https://doi.org/10.1051/e3sconf/202345301009.**
2. Harish Panghal and Awadhesh Kumar, "Investigation of Concrete Strength and Electrical Resistivity through Incorporation of Construction and Demolished Waste Aggregates: A Novel Approach for Assessing Corrosion Vulnerability," *Conferences Proceedings*, (2023), 2nd International Conference on Advances in Sustainable Construction Materials (ICASCM 2023) Vijayawada, India, December 1-2, 2023.
3. Harish Panghal and Awadhesh Kumar, "Drying Shrinkage Characteristics of Environmentally- Friendly Concrete Incorporating Construction and Demolition Waste Aggregates," *Taylor and Francis Conferences Proceedings*, 4th International Conference on Futuristic and Sustainable Aspects in Engineering and Technology (FSAET 2023), Mathura, India, November 28-30, 2023.

Details of Publications in Indexed Journals

1. Harish "Origin and development of shell structure" *International Journal of Engineering Sciences paradigm and Researches*, ISSN: 23196564. IJESPR-Issn23196564.
2. Harish "High Rise Structure development And Its Aspects" *International Journal Of Research In Civil Engineering ,Architecture & Design*, Volume -1,ISSN-4,,Oct-2015, ISSN-2347-8284.

3. Harish "Study of Wind Force on a High Rise Structure by Using Analytical Method" *Internationals Journals of Engineering Sciences and Research Technology*, ISSN-227-9655, IJESRT, ISSN-2277-9655.
4. Harish "A Study of Wind Force on A High Rise Structure", *Internationals Journals of Engineering Sciences and Research Technology*, IJESRT, ISSN-2277-9655.
5. Harish "A cost Effective Method of Slab Casting" *Internationals Journals of Engineering Sciences and Research Technology*, IJESRT, ISSN -2277-9655.

13. Computer Proficiency

Operating System Known	Software Known
Dos, Windows XP, Vista	STAAD Pro., ANSYS Microsoft Excel, PowerPoint, Word, Origin-Pro,

14. Courses Taught During The Last Two Years:

M.Tech. Materials Science and Stability of Structures

B.Tech. Design of Steel Structures (DSS)

B.Tech. Advance Steel Structures (ASS)

B.Tech. Structural Analysis (SA)

B.Tech. Introduction to Civil Engineering (ICE)

Diploma Steel Structure Design (SSD)

Major Project of Final Year

15. Number of M.Tech. Guided/Guiding

S. No.	Name of Student	Thesis Topic	Supervisor	Year
1	Parteek Gill	Construction of Post Tensioned Bridge Deck Slab	Harish Panghal	June, 2023
2	Vikas Saroha	Using A Tuned Liquid Damper for Seismic Analysis on a High Rise Building	Harish Panghal	June, 2023
3	Ravi Sharma	A critical Study of Corrosion Prevention in reinforced Concrete elements using Sacrificial Anodes	Harish Panghal	June, 2023
4	Aman Dalal	Experimental Examinations of Mechanical Characteristics of Coarse and Fine Recycled Aggregates	Harish Panghal	June, 2023

16. Peer Reviewer

1. Peer reviewer of Journal of Cleaner Production, Published by Elsevier, Science Citation Indexed Extended, Print ISSN: 0959-6526, Online ISSN: 1879-1786.
2. Peer reviewer of Journal of Emerging Materials Research, Publisher ICE, Science Citation Indexed Extended, Print ISSN: 2046-0147, Online ISSN: 2046-0155.

17. Development Works At The University/Institute/Department Level:

i. Worked as In-charge Student Cultural Activity at GTC, Soldha, Bahadurgarh, Haryana, India. 2014-2020.
ii. Coordinators of Technical Event of Department of Civil engineering in Cultural fest G- Potenzia'19 at GTC, Soldha, Bahadurgarh, Haryana, India, 2018-2019.
iii. Coordinators of Fashion show Event at Cultural fest G-Potenzia'19 at GTC, Soldha, Bahadurgarh, Haryana, India, 2018-2019.
iv. Coordinator of Cultural fest G-Potenzia'20 at GTC, Soldha, Bahadurgarh, Haryana, India, 2019-2020.
v. Coordinators of Fashion show Event at Cultural fest Achivers'23 at GITAM, Kablana Jhajjar, Haryana, 2022-2023.
vi. Coordinators of Fashion show Event at Cultural fest Achivers'24 at GITAM, Kablana Jhajjar, Haryana, 2023-2024.
vii. Coordinator of M.Tech. Program at GITAM, Kablana Jhajjar, Haryana, 2023-2024.

18. Name and Address of Persons Who Are Well Acquainted With My Academic Record and Professional Work for Reference:

1. Dr. Awadhesh Kumar, Professor, Department of Civil Engineering,
   Delhi Technological University (DTU), Delhi
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2. Dr. Asif Hussain, Professor, Department of Civil Engineering
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3. Dr. Rajeev Goel, HoD, Chief Scientist, Bridge Engineering and Structures CSIR-Central Road Research Institute, New Delhi-110025, India
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4. Dr. Rajesh Goyal, Research Dean, Department of Civil Engineering NICMAR University, Pune, India
   Phone: 07015724121: Email: rgoyal@nicmar.ac.in

19. Declaration

I hereby confirm that the information given in this bio-data is true and correct to the best of my knowledge and I hold myself responsible for the statements made herein.