Investigation of Mechanical Properties of RCA-Based Geopolymer Concrete

M. Tech. Thesis

By

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DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

MAY 2025

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A THESIS

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

by

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MAY 2025

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"Investigation of Mechanical Properties of RCA-Based Geopolymer Concrete"** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DEPARTMENT OF CIVIL ENGINEERING, IIT Indore**, is an authentic record of my own work carried out during the period from July 2024 to May 2025. Thesis submission under the supervision of Dr. Abhishek Rajput, Associate Professor, Department of Civil Engineering.

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

Mohd Ehtisham
23/05/25

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

Signature of the Supervisor of M.Tech. thesis

Dr. Abhishek Rajput

Mohd Ehtisham has successfully given his M.Tech. Oral Examination held on **9th May 2025**.

23/5/25

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Convener, DPGC
Date: May 27, 2025

ACKNOWLEDGEMENTS

I extend my heartfelt gratitude to all those who have played a significant role in my academic journey. Foremost, I express my deepest appreciation to my supervisor, Dr. Abhishek Rajput, for his unwavering support and invaluable guidance throughout my master's thesis. His mentorship, encouragement, and positive demeanor have been instrumental in shaping my research endeavors. Despite his busy schedule, Dr. Rajput consistently made time to provide guidance and address my queries, for which I am truly grateful. His patience, expertise, and constructive criticism have been invaluable in steering my research in the right direction.

I am also indebted to Prof. Suhas Joshi, Director of the Indian Institute of Technology, Indore, for providing me with the opportunity to pursue my research at this esteemed institution. I extend my sincere gratitude to the Head and DPGC Convener of the Discipline of Civil Engineering for their continuous support and encouragement. The faculty members of Civil Engineering have been instrumental in broadening my understanding of research concepts, and I am thankful for their insightful guidance.

Special thanks are due to Sumedh Limaye, Aditya Bhandakkar for their invaluable assistance and support in the laboratory. Their expertise and willingness to help have greatly facilitated the progress of my research.

I am deeply thankful to my parents, Mr. Shamshad Ahmad and Mrs. Nishat Fatima, my younger brother Asad Ahmad, Ausat Ali (maternal grandfather) Bano Begum (paternal grandmother) for their unconditional love, unwavering support, and constant encouragement. Their belief in me has been my greatest motivation. I am also grateful to my friends and classmates for their unwavering support and encouragement throughout my academic journey. Lastly, I express my gratitude to the Almighty for blessing me with the health, strength, and resilience to undertake this research journey.

Dedicated to My Parents & My Family

Abstract

Traditional concrete shows poor characteristics under various loading conditions, such as relatively low tensile and compressive strength due to its heterogeneous and brittle nature. Due to its large-scale availability, it is widely used as a construction material for civil structures; to enhance the mechanical and durability characteristics of concrete, we should incorporate innovative materials in place of ordinary Portland cement concrete. In recent years, incorporating industrial by-products in cement-based concrete has been shown to improve mechanical and durability properties of concrete, and it also decreases environmental damage. Incorporating RCA in place of NA also promotes sustainability by promoting the reuse of construction and demolition waste.

This study aims to investigate the mechanical properties of RCA-based geopolymer concrete, OPC-NA, and OPC-RCA.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

GGBS	Ground Granulated Blast Furnace Slag
SF	Silica Fume
LOI	Loss of Ignition
C&D	Construction and Demolition Waste
NA	Natural Aggregates
RA	Recycled Aggregates
GPC	Geopolymer Concrete
OPC-NA	NA-based OPC Concrete
OPC-RA	RA-based OPC Concrete
NaOH	Sodium Hydroxide
Na_2SiO_3	Sodium Silicate
H_2SO_4	Sulphuric Acid
Na_2SO_4	Sodium Sulfate
$MgSO_4$	Magnesium Sulfate
ITZ	Interfacial Transition Zone
CSH	Calcium Silicate Hydrate
CASH	Calcium Aluminate Silicate Hydrate
NASH	Sodium Aluminate Silicate Hydrate
XRD	X-ray Diffraction
SEM	Scanning electron microscopy
MIP	Mercury Intrusion Porosimetry
OPC	Ordinary Portland Cement
FA	Fly ash

Chapter 1: Introduction

1.1 Background and Motivation

Concrete, due to its availability and accessibility, is a commonly used material after water, and it is a highly versatile construction material that requires negligible maintenance throughout its lifespan (1). It is used in infrastructure development, but due to its low tensile strength, compressive strength, flexural strength, and low energy absorption capacity, conventional concrete has its limitations. This can affect the long-term durability of structures, especially under different loading conditions (2). There is a rising demand for construction materials in industry, which can enhance the mechanical properties of conventional concrete and can also reduce environmental impact. This has led to research in alternative binder systems and sustainable aggregate sources, which can meet both structural and ecological requirements (3). Geopolymer concrete significantly reduces the carbon footprint of the industry and has reduced environmental impact, and emerged as a promising substitute for OPC concrete with the use of GGBS, Fly ash, silica fume, with partial or full replacement with cement, further incorporating recycled aggregate in geopolymer concrete contributes to resource conservation and promotes sustainability (4). Incorporation of RCA in geopolymer concrete promotes sustainability and reduces environmental impact for its broader application in civil infrastructure. A comprehensive study of its mechanical and durability characteristics is important. Its strength depends on the type of mix design, quality of RCA, alkaline activator used, and curing conditions, which ultimately influence the overall behavior of geopolymer concrete (5).

1.2 **Research significance and scope**

The primary objective of this study is to assess the mechanical properties of RCA-based geopolymer concrete and compare it with OPC-NA and

OPC-RCA. This involves compressive strength measurement, flexural testing, supplemented by nondestructive techniques such as rebound hammer and ultrasonic pulse velocity assessments (6). The results of these tests will help in enhancing knowledge regarding geopolymer concrete and provide practical insights for its implementation in the construction industry.

Chapter 2: Literature Review

2.1 Development of Geopolymer concrete and use of Recycled Aggregate

2.1.1 Durability assessment of fly ash, GGBS, and silica fume-based geopolymer concrete with recycled aggregates against acid and sulphate attack

Recent advancements emphasize developing high-strength concrete formulations that require sustainable materials to increase durability and mechanical resilience (7). This research paper finds the combined effect of GGBS, Fly ash, and Silica fume on the durability performance of geopolymer concrete incorporating 100 % RCA and compares the performance of GPC mixes with OPC-NA, OPC-RCA (8). Durability evaluations were carried out by observing surface deterioration, recording weight variations, and determining the percentage loss in compressive strength at regular intervals (9). Furthermore, The evolution of the concrete’s microstructure and mineral phases were characterized using X-ray diffraction (XRD) for crystallography, (SEM) for morphology, and MIP for pore structure evaluation, concrete samples underwent submersion in 5% solutions of sulfuric acid (H_2SO_4), magnesium sulfate ($MgSO_4$), and sodium sulfate (Na_2SO_4) for an exposure duration of up to 180 days.to find out the chemical resistance of different concrete mixes (10). Microstructural investigations revealed that the internal matrix of the GPC became denser and more homogeneous, primarily resulting from the development of gel phases such as calcium silicate hydrate (C-S-H), calcium aluminosilicate hydrate (C-A-S-H), and sodium aluminosilicate hydrate (N-A-S-H) (11). The findings demonstrated that elevating the content of GGBS and silica fume led to a notable improvement in the chemical resistance of geopolymer concrete, demonstrated by reduced weight loss and minimized compressive strength degradation over time. Among the various mixes evaluated, the formulation identified as GPC-MG15, with a binder ratio of FA:GGBS: SF at 35:50:15, delivered the best mechanical strength and durability performance (12). This approach successfully resolves issues like compromised strength in OPC concrete using 100% RCA replacement. RCA from construction and demolition waste was incorporated in geopolymer concrete, and the Synergistic effect of supplementary cementitious material like GGBS, fly ash, and Silica fume on improving mechanical performance and long-term durability of geopolymer concrete (13). The conclusion drawn from experimental investigations and discussions is as follows.

1. The blended use of Fly ash, GGBS, and silica fume significantly improves the mechanical performance and durability of GPC by promoting the formation of CSH, CASH, and NASH gels, effectively mitigating the negative impacts associated with 100% RA utilization.

2. GPC-FG50 (FA: GGBS = 50:50) and GPC-MG15 (FA: GGBS: SF = 35:50:15) were identified as the optimum GPC mixes, achieving the highest compressive strengths at 180 days, which were 4.8% and 25% higher, respectively, than that of OPCC-RA

3. GPC mixes experienced mass losses ranging from 6.25% to 17.5%. When immersed for 180 days in H_2SO_4 Solution: The corresponding compressive strength losses (18.6–26.9%) were significantly lower compared to OPCC-NA (28.2%-39.7%) and OPCC-RA (31.6%-46.5 %).

4. GPC mixes give lower weight loss (0.65–6.52%), higher sulphate resistance and compressive strength reduction (3.6–21.7%) compared to OPCC-NA (11.82%, 20.6%) and OPCC-RA (13.14%, 24.9%) after 180 days of exposure. Additionally, $MgSO_4$ solution was found to be more aggressive than Na_2SO_4, causing 7.1–14.2% greater mass and strength losses (ranging from 92–275% higher deterioration rates).

5. SEM and XRD analyses of GPC mixes revealed enhanced morphological and mineralogical features, confirming that increased formation of CSH, CASH, and NASH gels resulted in a denser matrix and improved durability properties.

6. GPC-MG15 emerged as the most effective mix due to its superior strength performance. Although GPC-MG20 showed favorable durability characteristics. GPC-MG15 compressive strength surpasses that of conventional OPC concretes, making it particularly suitable for use in aggressive environments.

7. MIP analysis of the optimized GPC mixes further reveals that GPC-MG15 exhibited a greater filling of meso- and macropores compared to GPC-FG50, leading to an increase in strength and durability when exposed to an acidic environment.

2.1.2 Fly ash, GGBS, and silica fume-based geopolymer concrete with recycled aggregates: Properties and environmental impacts

The use of recycled aggregate (RA) as a green alternative to natural aggregate (NA) offers an environmentally responsible solution for construction; however, its mechanical properties often fall short compared to those of NA (14). Meanwhile, the integration of industrial byproducts as partial OPC substitutes in geopolymer concrete (GPC) has gained significant research attention. This study aims to assess the techno-environmental viability of integrating FA, GGBS, and SF into GPC to support 100% RA adaptation in concrete while maintaining environmental sustainability and circular economy principles (15). The objective is to optimize the proportions of GGBS, FA, and SF in the concrete mix design to achieve maximum mechanical performance and eco-efficiency in comparison to conventional OPC concrete (16).

The findings revealed a positive synergistic interaction among FA, GGBS, and SF, demonstrating better mechanical and microstructural integrity in RA-based GPCs compared to RA blended OPC systems. The GPC-MG15 mix, with a replacement ratio of FA:GGBS: SF at 35:50:15, showed the highest compressive strength (52.15 MPa), flexural strength (5.81 MPa), and split tensile strength (5.23 MPa). These values were 18–34% and 7–10% higher than those of OPC concretes with NA and RA, effectively mitigating the drawbacks associated with RA usage (17).

Life Cycle assessment demonstrated that optimized geopolymer concrete has a 50-60% lower environmental footprint as compared to OPC-based concrete with NA. While GPC-FG50 (50% GGBS and 50% fly ash) reduced environmental footprints, GPC-MG15 proved to be the most sustainable mix, balancing environmental benefits with robust mechanical properties (18).

2.1.2.1 Key conclusions from this study are as follows.

1. Enhancing the GGBS content (from 30% to 60%) and SF content (from 5% to 20%) strengthened mechanical performance in GPC while neutralizing the detrimental effects commonly linked to RA in concrete.
2. Increasing GGBS and silica fume content shows reduced workability of GPC mixes; workability of fresh GPC was lowered as compared to OPC concrete
3. The optimized geopolymer formulation FA: GGBS: SF(35%, 50%, and 15%) exhibited the superior compressive strength (52.15 MPa), flexural strength (5.81 MPa), and tensile strength (5.23 MPa), showing

7–10% and 18–34% gains over OPCC-NA and OPCC-RA, respectively

4. Microstructural and mineralogical assessment of GPC demonstrated the formation of

   C-S-H, C-A-S-H, and N-A-S-H gel enhanced matrix densification (improved compaction of microstructure) resulted in improved mechanical strength.

5. Results from life cycle assessment showed that the GPC mix generated 50-60% lower environmental impact than the OPC-NA mix, emphasizing the benefits of sustainable material adoption.
6. Assessing both environmental impact and technical effectiveness, GPC-MG15 emerged as the most sustainable mix, achieving 15% lower environmental impact than GPC-FG50 while maintaining excellent mechanical strength
7. Sensitivity analysis showed that environmental impacts could be reduced even more by switching to cleaner hydroelectric power and using rail instead of road transport for moving materials.
8. By using these sustainable materials in the right way, the effectiveness of recycled aggregate-based concrete can be greatly improved while also cutting down its impact on the environment
9. In future research, efforts must prioritize developing multi-scale models that address both material strength and environmental efficiency of GPCs made with different combinations and amounts of sustainable materials.

Chapter 3: Materials and Methods

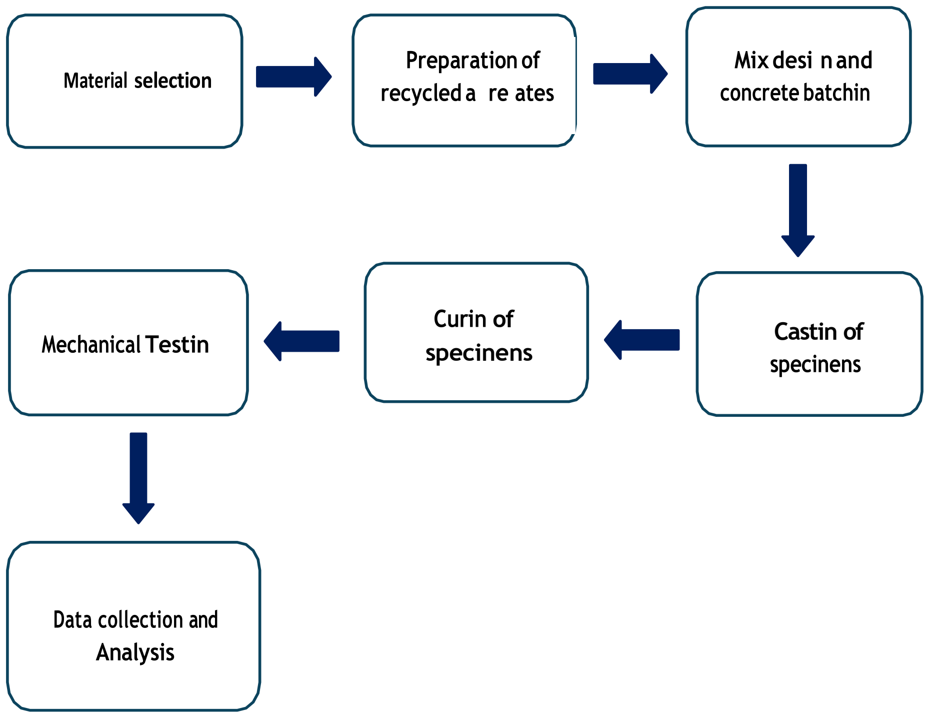

Fig. 1 Process involved in the analysis of Mechanical properties of OPC-RA and GPC-RA concrete.

3.1 Portland Cement: Development, Composition, and Challenges

3.1.1 Introduction to Portland Cement

Portland cement prevalence in the construction industry is driven by its widespread availability and accessibility, and it can be molded into various structural forms. Its extensive use in buildings, housing, and transportation has increased economic development and enhanced the standard of living (19). Although high-performance concrete has shown improved properties but limitations in the production of PC and durability of concrete still exist; thus, a shift towards sustainable materials is crucial, like geopolymers and magnesium phosphate cement (MPC) (20).

3.1.2 Historical Development of Portland Cement

The advancement of Portland cement is characterized by significant milestones.

1796: James Parker (England) obtained the patent for natural hydraulic cement.

1813: Louis Vicat (France) developed artificial hydraulic lime technology.

1824: Joseph Aspdin (England)invented Portland cement, named after Portland stone.

This innovation established the framework for modern cement manufacturing. With current rotary kilns now routinely processing 10,000 metric tons per day (21).

3.1.3 Manufacturing Process

PC production involves blending limestone and clay/shale, calcining the mixture at 1450°C in a rotary kiln, and subsequently grinding with gypsum. Critical steps include:

1. Raw Material Preparation: Homogenization and fine crushing to ensure uniform composition.
2. Kiln Processing: High-temperature reactions to form clinker minerals.
3. Grinding: Incorporation of 4–5% gypsum to regulate setting time by inhibiting rapid tricalcium aluminate (C_3A) hydration (22).

The calcined clinker is finely milled with gypsum, yielding a distinctive gray powder known as Portland cement. The principal ingredients used in the production of Portland cement include limestone, clay, and iron ore. Key chemical reactions occurring during the high-temperature calcination process are outlined as follows.

(a) Clay mainly provides silicates ($SiO_2.O_2$) together with small amounts of Al_2O_3 and Fe_2O_3. Clay undergoes thermal breakdown at a temperature near $600^{O}C$:

$$\text{Clay} \xrightarrow{600^{O}C} SiO_2 + Al_2O_3 + Fe_2O_3 + H_2O$$

(b) Limestone (CaCO3O$_3$is mainly provides calcium (CaO) and is decomposed at $1000^{0}C$

$$CaCO_3 \xrightarrow{1000^{O}C} CaO + CO_2$$

(c) Iron ore and bauxite provide additional aluminium and iron oxide (Fe_2O_3), which helps the formation of calcium silicates at low temperatures. They are incorporated into a row mix.

(d) There are different temperature zones in a rotary kiln. At various temperatures between 1000 and $1450^{0}C$, different chemical compounds are formed. The initial formation of C_2S occurs at a temperature of around $1200^{0}C$. C_3S is formed around $1400^{0}C$.

$$\left.\begin{array}{l}\text{Limestone}\\ \text{Clay}\\ \text{Iron ore, Bauxite}\end{array}\right\} \xrightarrow[\text{High temperature}]{1450^{O}C} \left\{\begin{array}{l}3Cao.SiO_2\\ 2CaO.\ SiO_2\\ 3CaO.\ Al_2O_3\\ 4CaO.\ Al_2O_3.\ Fe_2O_3\end{array}\right.$$

(e) The final product from the rotary kiln is called clinker. Pulverizing the clinker into small sizes (<75μm). With the addition of 3-5% gypsum or calcium sulphate produces Portland cement Gypsum is added to control fast setting caused by 3CaO. Al_2O_3 (23).

3.1.4 Chemical Composition and Bogue Equations

PC's properties derive from four primary compounds expressed using cement chemistry notation:

- Tricalcium Silicate (C_3S, Alite): 50% of PC; governs early strength.
- Dicalcium Silicate (C_2S, Belite): 25% of PC; contributes to long-term strength.
- Tricalcium Aluminate (C_3A): 8% of PC; influences setting kinetics.
- Tetracalcium Aluminoferrite (C_4AF, Ferrite): 12% of PC; affects color and durability.

  The oxide composition is converted into compound percentages via Bogue equations (adopted by ASTM C150):

  C_3S (%) = 4.071C - 7.600S - 6.718A - 1.450F - 2.852$\bar{S}$

  C_2S (%) = 2.867S – 0.754C_3S

  C_3A (%) = 2.650A – 1.692F

  C_4AF (%) = 3.043F

  Where C, S, A, F, and $\bar{S}$ denote weight percentages of CaO, SiO_2, Al_2O_3, Fe_2O_3, and SO_3, respectively

3.1.5 Minor Components and Their Roles

- Gypsum ($CaSO_4 \cdot 2H_2O$): Prevents flash setting by forming ettringite on C_3A surfaces. Below 3% gypsum, monosulfoaluminate may form, compromising setting control.
- Alkalis (Na_2O, K_2O): Elevate concrete pH to ~13.5, protecting steel reinforcement but risking alkali-silica reaction (ASR) and leaching.
- Magnesia (MgO): Excessive amounts may cause delayed expansion.

3.1.6 Sustainability Challenges

Two critical drawbacks hinder PC’s sustainability:

1. **Resource and Energy Intensity**:
    - 1.5 tons of raw materials and ~1 ton of CO_2 emitted per ton of PC produced (24).
    - Global production surged from 1.4 billion tons (1995) to 3 billion tons (2009), exacerbating environmental impacts (25).

2. **Durability Limitations**:
    - Susceptibility to cracking, corrosion, and chemical degradation in harsh environments, shortening service life.

3.1.7 Emerging Alternatives: Geopolymers and MPC

To address these issues, novel cementitious systems have emerged:

• Geopolymers: Alkali-activated aluminosilicates with lower CO_2 footprint.

• Magnesium Phosphate Cement (MPC): Rapid-setting, high-durability material suitable for repairs.

These alternatives align with sustainable development goals by reducing resource consumption and enhancing longevity.

While Portland cement remains integral to modern construction, its environmental and durability limitations necessitate a shift toward innovative materials like geopolymers and MPC. Future research must optimize these alternatives for scalability, cost, and performance to ensure sustainable infrastructure development (26).

3.2 Ground Granulated Blast Furnace Slag (GGBS)

Ground granulated blast furnace slag (GGBS), known as slag cement in North America, is a glass-like cementitious material generated during iron manufacturing in a blast furnace. This supplementary cementitious material is a key component in green construction; it increases durability and decreases permeability while reducing the carbon footprint of concrete by partially replacing Portland cement (27).

3.2.1 Formation in Blast Furnaces

During steelmaking, iron ore, fluxing agents (limestone/dolomite), and coke are fed into a blast furnace. At temperatures exceeding **2000°C**, iron oxide is reduced to molten pig iron, which sinks to the furnace base. Calcium, magnesium, silica, alumina, and residual coke ash form a molten slag layer. This slag is periodically tapped and processed for industrial use, while pig iron is diverted to steel production.

3.2.2 Processing for Cementitious Properties

To produce reactive slag, rapid cooling is essential to preserve its amorphous, glassy structure. Two primary methods are employed:

A. **Granulation**

- Molten slag (≈1500°C) is quenched with water, forming sand-like granules.
- Rapid cooling prevents crystallization, ensuring a vitrified (glassy) structure with hydraulic reactivity.
- The dried granules are ground into a fine powder (<4500 cm^2/g fineness), comparable to Portland cement.

B. **Pelletization**

- Slag is sprayed with water and spun into pellets via a rotating drum.
- Advantages: Reduced water usage, elimination of pre-grinding drying, and lower energy consumption.

Critical Note: Slow air cooling produces inert, crystalline slag unsuitable for cementitious applications

3.2.3 Applications of Processed Slag

A. Cementitious Material (GGBFS)

- Used as a supplementary cementitious material (SCM) in concrete, enhancing sulfate resistance, reducing heat of hydration, and lowering permeability.
- Typically replaces 20–70% of Portland cement in mixes.

B. Aggregates

Air-cooled slag: Crushed for conventional aggregate in road bases or structural fills.

Expanded slag: Lightweight aggregate produced by water quenching, ideal for insulating concrete.

3.2.4 Differentiation from Other Slags

GGBFS: Exclusively sourced from iron blast furnaces; hydraulic due to glassy structure.

Steel slag: A by-product of steelmaking (post-pig iron processing), crystalline and non-reactive, unsuitable for cementitious use.

3.2.5 Environmental and Economic Benefits

A. **Sustainability**: Diverts industrial waste from landfills, reducing CO_2 emissions by up to **40%** compared to Portland cement production.

B. **Durability**: Improves concrete resistance to chemical attack (e.g., sulfates, chlorides) and alkali-silica reaction (ASR).

GGBFS exemplifies the circular economy in construction, transforming industrial waste into high-value cementitious materials. Its successful application hinges on controlled rapid cooling (granulation/pelletization) to retain reactivity. Future research should focus on optimizing slag-concrete blends for diverse climatic and structural conditions, further advancing sustainable infrastructure.

3.3 Fly Ash

Fly ash is a fine particulate residue obtained from coal combustion. Fly ashes impart valuable applications as a cement replacement in concrete, contributing to better waste management. This finely divided material, produced from the combustion of pulverized coal captured from exhaust gases using electrostatic precipitators, when incorporated in concrete it provides dual sustainability benefits in concrete application: reducing cement consumption and enhancing durability (28).

3.3.1 Production Process

In coal-fired power stations, pulverized coal is combusted at ~1500°C, volatilizing inorganic minerals into molten droplets. Rapid cooling forms spherical, glassy particles termed **fly ash**, captured by electrostatic precipitators or baghouses. Heavier residues (**bottom ash**) settle in the furnace and are unsuitable for cementitious use, but are repurposed in masonry blocks (29).

3.3.2 Composition and Classification

Fly ash properties vary significantly based on coal type (anthracite, bituminous, subbituminous, lignite) and combustion conditions. Key compositional factors include:

1. **Calcium Content**:

   Class F (Low-Calcium): <8% CaO, derived from bituminous coal. Predominantly aluminosilicate glass (60–90%) with inert crystalline phases (quartz, mullite). Exhibits pozzolanic behavior, requiring alkalis or lime for reactivity.

Class C (High-Calcium): >20% CaO, from lignite/subbituminous coal. Contains reactive calcium-aluminosilicate glass and crystalline phases (e.g., ettringite-forming C_3A). Displays hydraulic and pozzolanic properties, hardening with water.

Intermediate (8–20% CaO): Hybrid reactivity between Class F and C.

2. **Alkalis and Sulfates**:

   Alkali content (Na_2O, K_2O) ranges from <1% to 10%, influencing pore solution pH and glass dissolution. High-alkali fly ashes accelerate reactivity but risk alkali-silica reaction (ASR). Sulfate (SO_3) content (0.1–5%) correlates with calcium; excess sulfates (>5%) may form expansive ettringite.

3. **Unburned Carbon (LOI)**:

   Measured via loss on ignition (LOI), carbon content depends on coal fineness and combustion efficiency. High LOI (>5%) increases water demand and disrupts air entrainment. Class C fly ash typically exhibits lower LOI due to more complete combustion of softer coals.

3.3.3 Physical Characteristics

1. Particle Morphology:

- Predominantly spherical (solid or hollow cenospheres) with some irregular plerospheres.
- Particle sizes range from submicron (<1 µm) to over 100 µm, with median diameters of 5–20 µm. The broad size distribution enhances packing density, reducing water demand in concrete.

Specific Surface Area and Density:

- Surface area: 300–500 m^2/kg, influenced by particle fineness.
- Bulk density: 500–1500 kg/m^3, varying with compaction.
- Specific gravity: 1.9–2.8, increasing with calcium and iron content due to denser glass formation.

Color:

3. Ranges from white to light gray; darker hues indicate higher carbon content

3.3.4 Influence on Concrete Properties

a. Reactivity and Hydration:

Class C: High calcium accelerates early strength gain but increases heat of hydration.

Class F: Slower reaction reduces thermal stress, ideal for mass concrete.

b. Durability Enhancements:

ASR Mitigation: Pozzolanic reaction consumes alkalis, reducing ASR expansion. Effectiveness depends on calcium and alkali content.

Sulfate Resistance: High-calcium fly ash may compromise resistance due to C_3A; optimal blends balance sulfate and calcium levels.

c. Equivalent Alkali Formula:

$$Na_2O_e=Na_2O_e+0.658\times K_2ONa_2O_e=Na_2O+0.658\times K_2O$$

This metric quantifies total alkali contribution, critical for ASR risk assessment.

3.3.5 Practical Considerations

Mix Design: Class F replaces 15–35% cement; Class C permits 20–40% substitution.

Quality Control:

LOI Management: Limit carbon content to ≤5% to avoid air entrainment issues.

Sulfate Limits: Adhere to specifications to prevent deleterious expansions.

Particle Fineness: Optimize gradation for workability and strength

Fly ash's role in sustainable concrete hinges on its compositional and physical variability. Class F excels in durability-focused applications, while Class C offers early strength. Future research should optimize high-volume fly ash mixes for diverse environments, balancing reactivity, sulfate resistance, and carbon content.

3.4 Silica Fume

This ultra-fine particulate material, commonly known as microsilica or condensed silica fume produced as a byproduct in electric arc furnaces during silicon/ferrosilicon manufacturing. Consisting of noncrystalline silica (SiO_2). This material is extensively employed to enhance mechanical and durability properties and increase chemical resistance.

3.4.1 Production Process

Silica fume is generated during the high-temperature reduction of high-purity quartz or quartzite (SiO_2) in electric arc furnaces at approximately **1800°C**. In this process, carbon sources (coal, wood chips) reduce SiO_2 to silicon metal (Si), which is periodically tapped. Residual SiO gas escapes with exhaust gases, oxidizes back to SiO_2, and condenses into spherical glassy particles as temperatures cool (30). These ultrafine particles are captured via filtration systems, yielding the final product.

3.4.2 Chemical Composition

Silica Content:

- Ranges from 75% to >98% SiO_2, depending on the alloy type (e.g., ferrosilicon vs. silicon metal).

- Standards (e.g., U.S., EU, Canada) mandate minimum SiO_2 levels (e.g., 85% for Canadian Type SF2).
- Impurities (iron, alumina, alkalis) increase with lower SiO_2 content, potentially affecting concrete compatibility.

Crystalline Phases:

- Predominantly amorphous, as confirmed by X-ray diffraction (XRD) patterns showing a broad hump near cristobalite peaks.
- Trace crystalline contaminants (e.g., silicon carbide, quartz) may occur.

3.4.3 Physical Characteristics

Particle Morphology:

Ultrafine spherical particles with an average diameter of 0.1–0.2 µm, approximately 100× smaller than Portland cement grains.

Surface Area and Density

Specific surface area: 15,000–25,000 m^2/kg (measured via nitrogen adsorption), far exceeding conventional SCMs like fly ash.

Specific gravity: 2.2–2.5, influenced by iron content.

Bulk density: 130–430 kg/m^3 (as-produced), often densified for practical handling.

Color and Handling: Naturally dark gray to black; processed variants may appear white. Low bulk density necessitates densification for cost-effective transport and storage.

3.4.4 Applications in Concrete Technology

3.4.4.1 Performance Benefits

Pozzolanic Reactivity: High SiO_2 content reacts with calcium hydroxide ($Ca(OH)_2$), forming dense calcium silicate hydrate (C-S-H) gels. Pore Refinement: Ultrafine particles fill interstitial voids, reducing permeability and enhancing durability against chloride ingress and sulfate attack.

3.4.4.2 Strength Development

Significant improvement in compressive and flexural strength, particularly in high-performance concrete.

3.4.4.3 Standardization and Quality Control

Compliance with regional standards (e.g., ASTM C1240, EN 13263) ensures optimal SiO_2 content and limits impurities. Ferrosilicon-derived silica fume (>75% Si alloys) is preferred for concrete applications. Silica fume exemplifies the effective repurposing of industrial by-products into high-value construction materials. Its unique combination of ultrafine particle size, high reactivity, and pozzolanic activity makes it indispensable for advanced concrete formulations. Future advancements should focus on optimizing production techniques to reduce costs and expanding applications in sustainable infrastructure

3.5 Recycled Concrete Aggregates (RCA)

Recycled aggregates are produced from crushed demolition waste and industrial byproducts, creating a sustainable alternative to natural aggregates. The use of this material promotes waste management and resource conservation, simultaneously reducing landfill burden and contributing to sustainability goals (31).

3.5.1 Recycled Coarse Aggregate

Recycled coarse aggregates (RCA) are primarily obtained by crushing and reprocessing demolished concrete, bricks, or masonry. They typically replace natural gravel or crushed stone in concrete mixes, with particle sizes ranging from **5 mm to 150 mm**.

3.5.1.1 Production Process:

Source: Derived from demolished structures, pavements, or construction waste.

Processing: Crushed, screened, and cleaned to remove contaminants (e.g., wood, metal, gypsum).

Grading: Sized to meet specifications for structural or non-structural applications.

3.5.1.2 Applications:

Non-Structural Uses: Backfill, road base, or low-grade concrete (e.g., sidewalks).

Structural Concrete: With proper quality control, RCA can replace up to **30–50%** of natural coarse aggregates in structural elements like beams and columns.

3.5.1.3 Benefits:

Sustainability: Reduces demand for virgin aggregates and lowers carbon footprint.

Cost-Efficiency: Lowers disposal costs and material expenses in regions with limited natural resources.

3.5.1.4 Challenges:

Higher Water Absorption: RCA often retains old cement paste, increasing porosity and requiring adjusted mix designs.

Contaminants: Residual mortar or impurities can weaken concrete if not rigorously processed.

3.5.1.5 Durability Concerns: Long-term performance may vary due to variability in source materials.

3.5.1.6 Quality Improvement:

Pre-Soaking: Reduces water absorption during mixing.

Carbonation Treatment: Enhances strength by reacting CO_2 with residual cement paste.

Admixtures: Use of pozzolans (e.g., fly ash) to mitigate strength loss.

3.6 Natural Aggregates (NA)

Natural aggregates are obtained from natural sources, including river plains, alluvial plains, glacial deposits, and rock quarries. Natural aggregates require minimal processing without transforming their native properties. Among the most widely used natural aggregate sand, gravel, and crushed stone, they are preferred because of their consistent gradation, long-lasting durability, resistance to degradation, and strong adhesion to cement binders.

3.6.1 River Sand: Traditionally, the most widely used fine aggregate, river sand is prized for its smooth, rounded particles, which enhance workability and finish in concrete. However, global shortages of river sand due to environmental regulations and over-extraction have prompted shifts toward alternatives.

3.6.2 Gravel and Crushed Stone

Coarse aggregates like gravel (5–150 mm) are critical for structural concrete, providing bulk and reducing shrinkage. Crushed stone, often limestone or granite, offers angular shapes that improve interlocking and mechanical strength. Natural aggregates influence both fresh and hardened concrete properties. In plastic concrete, their size, texture, and gradation affect workability and cohesion. In hardened concrete, they reduce creep and shrinkage while enhancing stiffness, thermal stability, and wear resistance.

3.7 Alkaline Activators

A 12M NaOH solution is commonly used in geopolymer systems due to its strong alkalinity, which effectively dissolves silica (SiO_2) and alumina (Al_2O_3) from precursors like fly ash or slag. Studies confirm that NaOH molarities between **8M–14M** yield optimal geopolymerization kinetics and compressive strength (32).

Potential Issues

Workability: High NaOH concentrations (≥12M) may reduce workability due to rapid gel formation.

Shrinkage Risk: Excessive alkalinity can increase autogenous shrinkage.

Safety: Requires careful handling (corrosive hazard).

Recommendation:

Use **12M NaOH** if precursors are low in reactivity (e.g., Class F fly ash) to ensure sufficient dissolution.

For reactive precursors (e.g., slag), consider lowering to **10M NaOH** to mitigate shrinkage and improve workability.

Na_2SiO_3/NaOH Ratio (2.5)

Validity: A ratio of **2.5** (by mass or volume) aligns with studies showing that **Na_2SiO_3/NaOH ratios of 2.0–3.0** enhance mechanical strength by balancing silica availability (from Na_2SiO_3) and alkalinity (from NaOH).

SiO_2/Na_2O Ratio: Sodium silicate typically has a **SiO_2/Na_2O molar ratio of 2.0–3.3**. At a 2.5 mass ratio, this ensures adequate reactive silica for polycondensation while maintaining pH stability.

Potential Issues

High Viscosity: Excess Na_2SiO_3 increases mix viscosity, requiring water reducers.

Brittleness: Over-silication (SiO_2-rich gels) may reduce fracture toughness.

Recommendation:

For structural GPC, retain the **2.5 ratio** to maximize compressive strength (40–70 MPa).

For improved ductility, reduce the ratio to **2.0** and supplement with microfibers (e.g., PP fibers).

1. **Combined Synergy and Adjustments**

Gel Formation: The 12M NaOH + 2.5 Na_2SiO_3/NaOH combination promotes:

- Rapid dissolution of precursors.
- Formation of dense N-A-S-H gel (sodium aluminosilicate hydrate).

Curing: Ambient or heat curing (60–80°C for 24h) is recommended to accelerate geopolymerization.

Mitigation Strategies:

- Add 5–10% limestone powder to reduce shrinkage.

Use superplasticizers (e.g., polycarboxylate ethers) to offset high viscosity.

3.8 Admixtures

The use of admixtures in concrete traces back to ancient civilizations. For instance, Roman engineers employed organic substances such as animal fats, milk, and blood to modify the properties of their concrete mixtures. While these additions primarily aimed to enhance workability, blood may have inadvertently acted as an early air-entraining agent, potentially improving the durability of Roman concrete (33). In modern history, calcium chloride emerged as a common accelerator to expedite cement hydration. The scientific investigation of admixtures gained momentum in the 1930s with the accidental discovery that cement processed with beef tallowinitially used as a grinding aid, exhibited superior resistance to freeze-thaw cycles compared to untreated cement. Today, admixtures are indispensable in contemporary concrete technology, enabling precise control over both fresh and hardened properties (34). Virtually all modern concrete formulations incorporate one or more admixtures, underscoring their critical role in meeting diverse structural and environmental demands.

3.8.1 Definition and Categories of Admixtures

Admixtures are materials, distinct from water, aggregates, cement, and fibers, introduced during concrete mixing to modify its characteristics. They are categorized as follows:

3.8.1.1 Air-Entraining Agents (ASTM C260)

Purpose: Introduce microscopic air bubbles to enhance frost resistance and mitigate damage from freeze-thaw cycles.

3.8.1.2 Chemical Admixtures (ASTM C494, BS 5075)

Functions

Water Reducers: Lower water content while maintaining workability, improving strength, and durability.

Set Controllers: Accelerators (e.g., calcium chloride) shorten setting time; retarders delay it for extended placement.

Specialized Additives: Include viscosity modifiers (for cohesion), shrinkage reducers, and alkali-silica reaction (ASR) inhibitors.

3.8.1.3 Mineral Admixtures

Composition: Finely ground materials such as slag, fly ash, and silica fume.

Benefits: Improve workability, long-term strength, and durability while reducing permeability and thermal cracking.

3.8.1.4 Miscellaneous Admixtures

Corrosion Inhibitors: Protect steel reinforcement in chloride-rich environments.

Expansive Agents: Counteract shrinkage to prevent cracking.

Polymer Latexes: Enhance bond strength and flexibility.

Impact of Admixtures on Concrete Properties

Workability: Enhanced by water reducers and air-entraining agents.

Setting Time: Controlled via accelerators or retarders.

Strength and Durability: Boosted by pozzolans, silica fume, and corrosion inhibitors.

Specialized Functions: Achieved through gas-forming agents (lightweight concrete), color pigments, and shrinkage reducers.

3.8.2 Modern Relevance

Admixtures enable the creation of high-performance, sustainable concrete tailored to specific structural and environmental requirements. Their strategic use optimizes cost, durability, and environmental impact, making them essential in advancing construction technology.

3.9 Experimental Methodology

3.9.1 Specific Gravity Test

Standard Reference: **IS 2386 (Part 3) – 1963** (Methods of Test for Aggregates for Concrete: Specific Gravity, Density, Voids, Absorption, and Bulking)

Objective: To determine the density of RCA relative to water.

Methodology:

1. Oven-dry the RCA sample at **110°C** for **24 hours**.
2. Immerse the sample in water for **24 hours** to achieve **saturated surface dry (SSD)** condition.
3. Weigh the sample in three states:

A: Oven-dry weight (dry mass).

B: SSD weight (surface-dry mass after soaking).

C: Submerged weight (mass in water).

Formula:

Specific Gravity= $\frac{A}{B-C}$

Result Interpretation:

RCA Result: 2.28 (lower than natural aggregates, which typically range between 2.6–2.8).

- **Code Comparison**: Lower specific gravity indicates higher porosity due to adhered mortar in RCA.

3.9.2 Water Absorption Test

Standard Reference: IS 2386 (Part 3) – 1963

Objective: To measure the porosity and moisture-retention capacity of RCA.

Methodology:

- Dry the RCA sample in an oven at 110°C until constant mass.
- Soak the sample in water for 24 hours.
- Remove the sample, blot it with a damp cloth to achieve SSD condition, and weigh**.**

Formula:

Water Absorption (%) = (SSD Weight-Oven dried weight)/(Oven dried weight) × 100

Result Interpretation:

RCA Result: 6.33% (much higher than the ≤2% limit for natural aggregates).

Code Comparison: High absorption is typical for RCA due to old cement paste, necessitating pre-wetting during concrete mixing.

3.9.3 Aggregate Impact Value (AIV) Test

Standard Reference: **IS 2386 (Part 4) – 1963** (Mechanical Properties) **Objective**: To assess resistance to sudden impact or shock loads. **Methodology**:

1. Sieve RCA to **12.5–10 mm** size.

2. Fill a cylindrical steel cup with the sample and subject it to **15 blows** from a **13.5 kg hammer** dropped from **380 mm** height.

3. Sieve the crushed material through a **2.36 mm** sieve.
   Formula:

$$AIV\ (\%) = \frac{\text{Weight of fines passing 2.36mm sieve}}{\text{Original weight of sample}} \times 100$$

Result Interpretation:

RCA Result: 16% (below the MORTH limit of ≤30%).

Code Comparison: AIV ≤ 30% is acceptable for concrete and road base layers, indicating RCA is suitable for structural use.

3.9.4 Aggregate Crushing Value (ACV) Test

Standard Reference: **IS 2386 (Part 4) – 1963**
Objective: To evaluate resistance to gradual compressive loads.
Methodology:

1. Sieve RCA to **12.5–10 mm** size.
2. Compact the sample in a cylindrical mold and apply a **400 kN load** for **10 minutes**.
3. Sieve the crushed material through a **2.36 mm** sieve.
   Formula:

$$ACV\ (\%) = \frac{\text{Weight of fines passing 2.36mm sieve}}{\text{Original weight of sample}} \times 100$$

Result Interpretation:

RCA Result: 30.76% (slightly above the ≤30% limit for surface layers).

Code Comparison: ACV ≤ 30% is preferred for pavements, but RCA can still be used in sub-base layers or low-strength concrete.

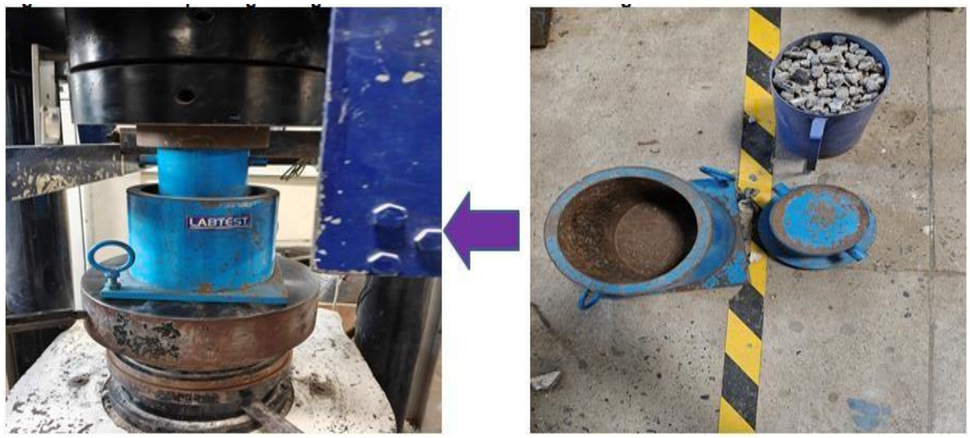

Fig. 2 Process involved in Aggregate crushing value

3.9.5 Los Angeles Abrasion Test

Standard Reference: **IS 2386 (Part 4) – 1963** (Los Angeles Abrasion Value)

Objective: To determine resistance to wear, abrasion, and degradation. **Methodology**:

1. Sieve RCA to the specified grading (e.g., **Grade A**: 12.5–10 mm).
2. Place the sample in a Los Angeles abrasion machine with steel balls (6–12 balls, depending on grading).
3. Rotate the machine for **500 revolutions** at **30–33 rpm**.
4. Sieve the abraded material through a **1.7 mm** sieve. **Formula**:

Abrasion Value (%) = $\frac{\text{Weight loss}}{\text{Original weight}} \times 100$

Result Interpretation:

RCA Result: 52.51% (exceeds the ≤35% limit for wearing surfaces).

Code Comparison: High abrasion value restricts RCA to non-wearing applications like backfill or low-traffic areas.

Fig.3 Los Angeles abrasion test

Table 1: Summary of IS 2386 Test Requirements vs. RCA Results

Test	IS 2386 Reference	RCA Result	Code Limit	Implication
Specific Gravity	Part 3	2.28	2.6–2.8 (Natural agg.)	Lower density due to adhered mortar.
Water Absorption	Part 3	6.33%	≤2% (Natural agg.)	Requires pre-wetting.
Aggregate Impact Value	Part 4	16%	≤30% (MORTH)	Suitable for structural use.
Aggregate Crushing Value	Part 4	30.76%	≤30% (Surface layers)	Marginal; use in sub-layers.
Los Angeles Abrasion	Part 4	52.51%	≤35% (Wearing surfaces)	Limited to non-abrasive uses.

Key Takeaways

IS 2386 Compliance: RCA meets requirements for impact resistance (AIV) but has limitations in abrasion resistance and water absorption.

Practical Use:

Suitable for non-structural applications (e.g., embankments, low-strength concrete).

1. Pre-treatment (e.g., removing adhered mortar) can enhance performance.

Code Alignment:

Results must be compared with IS code limits to ensure compliance for specific applications (e.g., pavements vs. backfill).

3.9.6 Mix Proportioning and Concrete Preparation

Three different types of concrete mixes were designed:

M30-NA: OPC 53-grade concrete using 100% natural aggregates.

Fig. 4 M30 NA Beams cubes and cylinders

M30-RCA: OPC 53-grade concrete using 100% recycled aggregates

Fig. 5 M30 RCA Beams cubes and cylinders

GPC-RCA: Geopolymer concrete incorporating 100% recycled aggregates

Fig. 6 GPC-RCA Beams Cubes and cylinders

All mixes were proportioned to achieve a characteristic strength of approximately 30 MPa. The geopolymer concrete mix was designed carefully, considering the activator-to-binder ratio, liquid-to-solid ratio, and binder composition.

The materials were mixed uniformly using a pan mixer. Dry components were mixed first, then gradually adding the alkaline solution for GPC mixes or water for OPC mixes.

3.9.7 Casting and Curing of Specimens

Specimens were cast in standard moulds:

Cubes:
150 mm cubes were cast for M30-NA, GPC-RCA and M30-RCA

Beams:
100 mm × 100 mm × 500 mm beams were cast for three different mixes for flexural strength testing.

The molds were filled in layers and compacted thoroughly to eliminate air voids. Demolding was done after 24 hours:

- OPC-based specimens were water-cured at room temperature.
- Geopolymer concrete specimens were cured under ambient conditions without water curing.

3.9.8 Testing of Mechanical Properties

After the designated curing periods, the following tests were conducted:

3.9.8.1 Rebound Hammer (Schmidt Hammer)

Classification: Direct-Measurement Technique (Mechanical Method)

Theoretical Foundation

The Rebound Hammer operates on the principle of elastic rebound, correlating surface hardness to compressive strength. When a springdriven mass impacts the concrete, the rebound value (0–100 scale) quantifies the material's resistance. This method aligns with **direct-measurement NDT-CE techniques**, where surface properties are directly interpreted.

Operational Workflow

1. **Surface Preparation**: Smooth, clean surfaces are critical to minimize variability from carbonation or roughness.

2. **Calibration**: Requires empirical correlation with destructive core tests to account for aggregate type (e.g., granite vs. limestone) and moisture content.

3. **Data Collection**: Multiple readings (≥10 per test location) ensure statistical reliability, addressing concrete's inherent inhomogeneity.

Applications & Limitations

Strengths:

- Rapid in situ assessment for construction quality control (e.g., uniformity in columns, slabs).
- Cost-effective screening for surface defects like spalling or weathering.

Limitations:

- Depth-restricted (~20–30 mm), ignoring subsurface flaws.
- Operator-dependent variability in impact angle and hammer maintenance.

Integration with NDT-CE Challenges

The Rebound Hammer exemplifies the trade-off between efficiency and accuracy in NDT-CE. While it meets practical requirements for speed and simplicity, its reliance on surface data underscores the need for complementary methods in heterogeneous materials.

Standards: ASTM C805, IS 13311(Part 2).

3.9.8.2 Ultrasonic Pulse Velocity (UPV) Test

Classification: Inquiring Agent Technique (Active Elastic Wave Method)

Theoretical Foundation

UPV employs high-frequency stress waves (20–150 kHz) to probe concrete's internal structure. Wave velocity ($V=\frac{L}{T}$) reflects material density, with anomalies indicating voids, cracks, or delaminations. This method falls under **active inquiring agent techniques** (35), where generated waves interact with the material to yield diagnostic data.

Operational Workflow

1. **Transducer Configuration**:

   Direct Transmission: Probes opposite faces for full-thickness assessment.

   Surface Transmission: Single-face testing for accessibility in constrained environments.

2. **Signal Processing**: Advanced DSP filters noise and isolates wave arrivals, critical in large-scale structures with acoustic interference.
3. **Data Interpretation**: Tomographic imaging reconstructs 3D defect maps, while spectral analysis identifies frequency shifts from internal discontinuities.

Applications & Limitations

Strengths:

- Non-invasive evaluation of dynamic elastic modulus and Poisson's ratio.
- Detects subsurface flaws in critical infrastructure (e.g., dams, bridge piers).

Limitations:

- Requires smooth surfaces for transducer coupling.
- Reinforcing bars parallel to wave paths artificially elevate velocities.

Integration with NDT Challenges

UPV addresses the chapter's emphasis on **quantitative evaluation** (QNDE) through wave-based metrics. Its dependency on DSP highlights modern advancements in resolving concrete variability via computational tools.

Standards: ASTM C597, IS 13311(Part 1).

Synergistic Application in Structural Diagnostics

Methodological Complementarity

1. **Surface-to-Depth Correlation:** Pair Rebound Hammer (surface hardness) with UPV (internal integrity) for holistic assessments.

2. **Calibration Framework:** Use UPV to validate rebound values in heterogeneous zones, mitigating surface-driven inaccuracies.

3. **Case Study Example:** Post-Fire Damage Assessment: UPV maps internal cracking, while rebound values quantify surface strength loss.

Bridge Deck Evaluation: UPV identifies delamination under asphalt overlays; rebound testing prioritizes areas for coring.

Fig. 7 UPV Test setup

Theoretical Implications

This synergy aligns with the chapter's discussion on **interdisciplinary collaboration**. Combining mechanical and wave-based methods bridges gaps in detection limits, exemplifying the "allowable tolerance philosophy" where no single technique satisfies all criteria.

Future Directions in NDT

- **Automation**: Integration of rebound hammers and UPV probes with robotic systems for large-scale infrastructure.
- **Machine Learning**: Predictive models trained on hybrid datasets (rebound + UPV) to infer compressive strength without destructive tests.
- **Standardization**: Harmonizing ASTM/IS protocols with emerging technologies like phased-array UPV.

3.9.8.3 Compressive Strength Test: Understanding Concrete Compressive Strength Testing: A Practical Guide

Concrete's compressive strength is the backbone of structural safety. Whether it's a skyscraper or a bridge, engineers rely on precise measurements to ensure concrete can handle the weight and stress it's designed for. Let's break down how this critical testing works in the real world (36).

Testing of Concrete Strength

Testing concrete isn't just about crushing blocks it's a science governed by strict standards. In the UK, three main tests dominate:

Squashing Cubes or Cores (Uniaxial Compression): Think of placing a concrete cube in a giant vise. Standards like BS EN 12390-3 ensure the machine applies force evenly to avoid skewed results.

Splitting Cylinders (Indirect Tension): Imagine cracking a walnut—this test uses a similar principle. A cylinder is split sideways to measure tensile strength indirectly (IS 516).

Bending Beams (Flexure): Like testing a diving board's snap, this evaluates how concrete handles bending forces (IS 516).

While squashing cubes are the gold standard, machines must be meticulously calibrated to avoid errors like a scale that's slightly off, giving you the wrong weight.

Smooth Operator: Force must be applied steadily, no jerks or shocks.

Perfectly Flat Surfaces: The plates pressing the concrete (called platens) must be flawlessly flat—think of a pancake griddle. Even a tiny warp can skew results.

Self-Aligning Design: A ball-joint mechanism lets the top plate adjust to the concrete's shape, like a self-leveling camera tripod.

Placement of Cube in Machine: If a cube isn't centered, it cracks unevenly, like a chair leg snapping under uneven weight.

Warped Platens: A dished (concave) platen might falsely boost weak concrete's strength by squeezing its sides, while a bowed (convex) one stresses the center, leading to cracks and lower readings.

Calibration: Even the best machines need checkups. Here's how engineers ensure accuracy:

The "Footemeter" Test: A steel cylinder studded with sensors (like a high-tech ruler) measures if force spreads evenly. If the machine's plates are misaligned, the sensors catch it.

Cube Comparisons: Test cubes are shared between the lab's machine and a certified reference machine. If results drift by more than 4%, it's time for repairs.

Routine Checks: Machines are recalibrated yearly or after moving, like resetting a watch after a time zone change.

Real World Example: A misaligned machine once reported a cube's strength as 15% lower than it truly was. Fixing the alignment was like tuning a guitar string suddenly, everything sounded right.

Safety First: A poorly calibrated machine might greenlight concrete that's too weak, risking collapses.

Cost Efficiency: Accurate tests prevent over-engineering. No one wants to pay for extra concrete "just in case."

Sustainability: Reusing test cubes (where possible) cuts waste good for both budgets and the planet.

The Future of Testing

Smart Machines: Imagine AI spotting cracks in real-time.

Eco-Friendly Practices: Recycling test materials or using digital simulations to reduce physical trials.

Global Standards: Harmonizing UK practices with EU or global norms to simplify international projects.

Fig. 8 Compression testing of cubes

Testing concrete isn’t just about brute strength, it’s about precision, consistency, and trust. By sticking to rigorous standards and embracing innovation, engineers ensure our buildings stand tall and safe.

3.9.8.4 Flexural Strength Test

Flexural Strength Testing Using Four-Point Loading: Methodology

1. Experimental Setup and Testing Protocol

Specimen Details:

Beam Dimensions: 100 mm (width) × 100 mm (depth) × 500 mm (span length).

Material: Concrete with a target compressive strength of 35 MPa, cured under controlled conditions (20°C, 95% humidity) for 28 days.

Four-Point Loading Configuration:

Supports: Two steel rollers positioned 400 mm apart (effective span L=400 mm) (37).

Load Application: Two additional rollers are placed symmetrically at 50 mm from each support, creating a **constant bending moment** region between the inner rollers (Figure 1).

Loading Rate: 0.1 MPa/s, compliant with **BS EN 12390-5** guidelines.

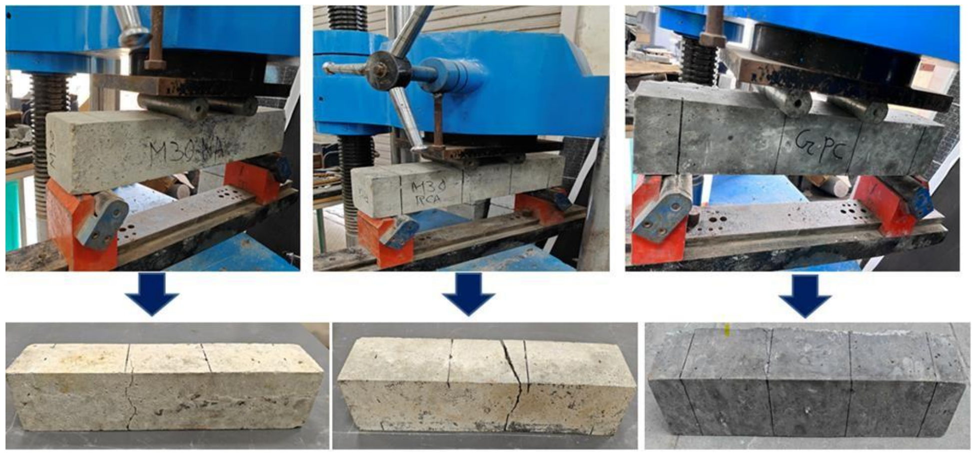

Fig.9 Flexural Testing of beam specimen

Theoretical Basis and Calculation

Stress Distribution:

- Four-point loading induces a uniform bending moment in the central third of the beam, minimizing shear effects.
- The maximum tensile stress (flexural strength) at failure is calculated as

$$f_{flex} = \frac{FL}{bd^2}$$

Where:

F = Total applied load at failure (kN)

L = Span length between supports (400 mm)

b = Beam width (100 mm)

d = Beam depth (100 mm)

Comparison with Standard Methods:

- **Two-Point Loading (Third-Point)**: Follows the same formula but applies the load at two points.
- **Center-Point Loading**: Yields 13% higher strength values due to localized stress concentration.

Four-Point Loading: Reduces shear influence and better simulates distributed loads (e.g., bridge decks under traffic).

Experimental Observations and Results

Failure Mode:

- **Typical Fracture**: Cracks initiated at the tensile face (bottom) and propagated upward, consistent with flexural failure (Figure 2).
- **Shear Influence**: Minimal shear cracking due to the constant moment region, validating the setup's efficacy in isolating bending effects.

Key Results:

- **Average Flexural Strength**: 6.8 MPa (from 3 specimens).
- **Coefficient of Variation (CoV)**: 4.2%, indicating high consistency.
- **Correlation with Compressive Strength**: $f_{flex} \approx 0.7\sqrt{f_{cu}}$ Aligning with empirical relationships for normal-strength concrete.

Advantages of Four-Point Loading

1. **Uniform Stress Field**: Ideal for studying pure bending behavior without shear interference.
2. **Real-World Relevance**: Mimics distributed loads in slabs and pavements better than center-point methods.
3. **Research Flexibility**: Enables detailed analysis of crack propagation and ductility.

Challenges and Mitigation Strategies

- **Beam Alignment**: Slight misalignment can skew results. Solution: Laser-guided positioning of rollers.
- **Load Distribution**: Uneven roller contact stresses. Solution: Use of neoprene pads to ensure uniform load transfer.
- **Data Interpretation**: Distinguishing bending failure from shear failure. Solution: High-speed cameras recorded crack initiation.

Implications for Structural Design

Pavement Applications: Results validated mix designs for highway pavements requiring $f_{flex} \geq 5.0 MPa$.

Code Compliance: Demonstrated alignment with Eurocode 2 safety factors for serviceability limit states.

Recommendations for Future Work

- **Dynamic Loading Tests**: Investigate fatigue behavior under cyclic four-point loading.
- **High-Performance Concrete**: Extend testing to fiber-reinforced or ultra-high-performance concrete (UHPC).

Digital Twins: Develop finite element models (FEM) to simulate stress distributions and validate experimental data.

The four-point flexural test on 100×100×500 mm beams provided robust insights into the tensile performance under bending. By isolating the constant moment region, this method offers precision for research and quality control, bridging theoretical models with practical applications. Future integration with advanced monitoring tools and computational methods will further enhance its utility in modern concrete engineering.

3.9.8.5 Data Analysis

The test results were analyzed statistically to evaluate the relative performance of the three different concrete types. Particular attention was given to comparing strength characteristics, surface hardness, and internal quality across OPC and geopolymer concretes using recycled aggregates.

Chapter 4: Results and Discussion

Mechanical testing and the observed behaviour of RCA-based geopolymer concrete

Table 2: Correlation Between Tests

Property	M30-NA	M30-RCA	Geopolymer-RCA
Rebound Hammer (MPa)	**21.8**	**28.0**	**12.8**
UPV (m/s)	**4237**	**4178**	**2227**
Compressive (MPa)	**37.5**	**34.0**	**20.6**
Flexural (MPa)	**2.79**	**3.07**	**2.41**

Table 3: Rebound Hammer (Surface Hardness)

Concrete Type	This Study (MPa)	Literature Values (MPa)	Key Observations
M30-NA	21.8	22–28 (IS 13311-1992 for M30)	Lower than typical possibly due to curing or surface moisture.
M30-RCA	28.0	24–30 (Kou et al., 2011 for RCA)	Matches literature RCA's rough texture increase surface hardness.
Geopolymer+RCA	12.8	15–20 (Davidovits, 1999)	Far below the literature, indicating poor geopolymer curing or weak aggregate bonding.

Key Insight: While M30-RCA aligns with literature, Geopolymer+RCA's low rebound highlights unresolved brittleness or porosity issues.

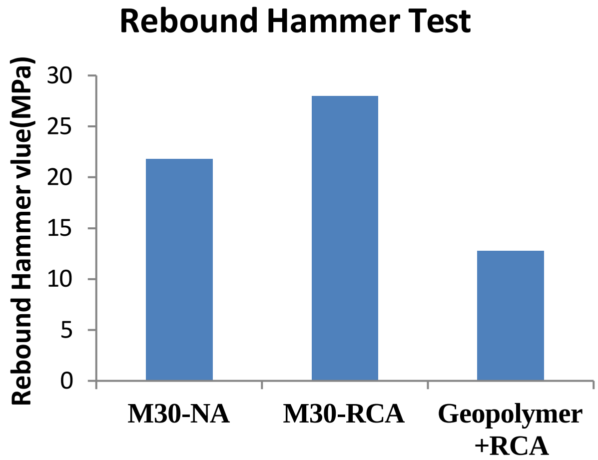

Fig. 10 Rebound hammer test

Table 4: Ultrasonic pulse velocity

Concrete Type	This Study (km/s)	Literature Values (km/s)	Key Observations
M30-NA	4237	4000–4500 (IS 13311-1992)	Within the expected range for dense concrete.
M30-RCA	4178	3800–4200 (Xiao et al., 2018)	Slightly lower than M30-NA due to RCA porosity, consistent with literature
Geopolymer + RCA	2227	3000–4000 (Lloyd & Rangan, 2010)	Extremely low, suggesting voids or incomplete geopolymerization.

Key Insight: Geopolymer + RCA's UPV is alarmingly low , indicating structural flaws not commonly reported in optimized geopolymer systems.

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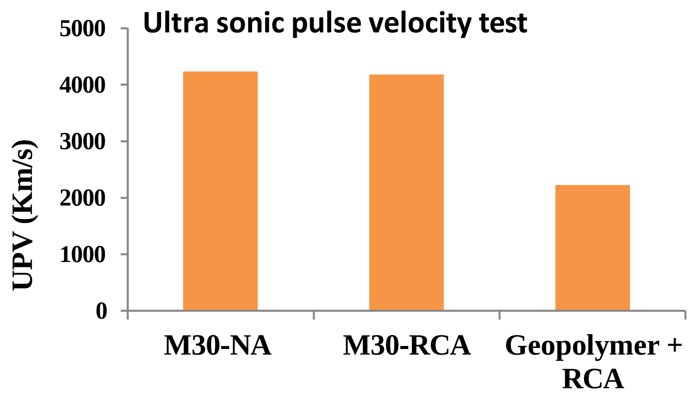

Fig. 11 UPV Test Result

Table 5: Compressive Strength

Concrete Type	Your Study (MPa)	Literature Values (MPa)	Key Observations
M30-NA	37.5	34–38 (IS 456:2000 for M30)	Matches design strength (M30 target = 38.25 MPa).
M30-RCA	34.0	28–35 (Kou et al., 2011)	Aligns with literature ;RCA reduces strength by 10–20%.
Geopolymer+RCA	20.6	25–40 (Singh et al., 2022)	Below typical geopolymer ranges, likely due to poor RCA – geopolymer bonding.

Key Insight: Geopolymer + RCA's low compressive strength contrasts with literature, where optimized mixes often exceed 30 MP.

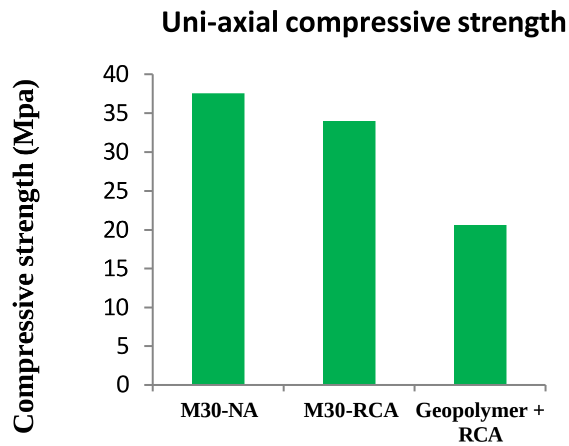

Fig. 12 Compressive Test result

Table 6: Flexural Strength

Concrete Type	This Study (MPa)	Literature Values (MPa)	Key Observations
M30-NA	2.79	2.5–3.5 (ACI 318-19)	Within the expected range for conventional concrete.
M30-RCA	3.07	2.8–3.3 (Xiao et al., 2018)	Slightly higher than literature, possibly due to RCA's improved interlocking.
Geopolymer+RCA	2.41	3.0–5.0 (Lloyd & Rangan, 2010)	Far below the literature, indicating brittleness or weak ITZ .

Key Insight: M30-RCA's flexural superiority aligns with studies showing RCA's benefits in bending, while Geopolymer+RCA's underperformance highlights mix design flaws.

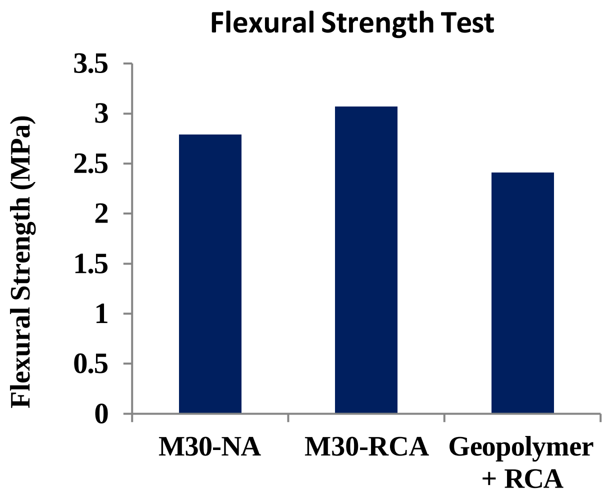

Fig. 13 Flexural Test result

4.2 Discussion of Divergences

M30-RCA

Flexural Strength: Outperformed M30-NA (3.07 vs. 2.79 MPa), consistent with studies where RCA's angularity enhances crack resistance (Silva et al., 2014).

Compressive Strength: Lower than M30-NA(34 vs. 37.5 MPa), matching trends from Kou et al. (2011),who attribute this to RCA's porosity.

Geopolymer + RCA

Underperformance :All parameters (UPV, rebound, compressive/flexural strength) lag literature For example:

- Singh et al. (2022) achieved 35 MPa compressive strength with geopolymer +RCA, whereas this study yielded only 20.6 MPa.
- Low UPV (2227 km/s) vs. literature (3000+ km/s) suggests incomplete polymerization or poor curing.

M30-NA

- **Consistency**: Results align with codal provisions (IS 456:2000), validating the experimental method.

Chapter 5: Conclusions and Scope for Future Work

M30-RCA performs comparably to literature in flexure but lags in compressive strength, making it suitable for non-load-bearing flexural elements.

Geopolymer + RCA underperforms across all metrics, likely due to:

- Inadequate alkali activation or curing conditions.
- Poor interfacial transition zone (ITZ) between RCA and geopolymer binder.

M30-NA validates conventional design practices, serving as a reliable benchmark.

Recommendations:

- For Geopolymer+RCA: Optimize alkali-activator ratios and pre-treat RCA (e.g., acid washing, nano silica coating).
- For M30-RCA: Use hybrid aggregates (NA + RCA) to balance compressive and flexural strengths.

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