ASSESSMENT OF THE COMPRESSIVE STRENGTH OF RECYCLED CONCRETE USING THE REBOUND HAMMER

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PLAGIARISM

This work **ASSESSMENT OF THE COMPRESSIVE STRENGTH OF RECYCLED CONCRETE USING THE REBOUND HAMMER** by Enehizena Adriel with **MAT.NO ENG2006176** of the Department of Civil Engineering, Faculty of Engineering, University of Benin, Benin City, Edo State, Nigeria, has **PASSED** the **PLAGIARISM TEST**.

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DEDICATION

This work is dedicated to the Almighty God and to my beloved parents, Mr. and Mrs. Enehizena, whose love and support have sustained me through every step of this journey.

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ABSTRACT

Concrete remains the most widely used construction material globally; however, its production is heavily reliant on natural aggregates, the continuous extraction of which causes considerable environmental impact. With increasing concerns over resource depletion and waste management, the utilisation of recycled coarse aggregates (RCA) derived from demolished concrete presents a sustainable alternative. This study, entitled "Assessment of the Compressive Strength of Recycled Concrete Using the Rebound Hammer," investigates the feasibility of partially replacing natural coarse aggregates (NCA) with RCA while maintaining acceptable mechanical performance for structural applications.

The research involves the preparation of concrete mixes of grades M20, M25, and M30, with RCA replacement levels of 0%, 25%, 50%, 75%, and 100%, at a constant water–cement ratio of 0.5. Fresh concrete is assessed through the slump test to evaluate workability, while hardened concrete specimens undergo compressive strength testing at 7, 14, and 28 days, in addition to non-destructive testing using the rebound hammer. The study aims to establish the relationship between the rebound number and compressive strength to develop calibration equations specific to Recycled Concrete.

It is anticipated that compressive strength will decrease with increasing RCA content; however, a 25% replacement level is expected to provide performance comparable to conventional concrete while enhancing material sustainability. The study further predicts a strong correlation between rebound hammer readings and compressive strength, supporting the use of the rebound hammer as a reliable tool for non-destructive evaluation of Recycled Concrete in both research and practical field applications.

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ACRONYMS

Acronym	Full Meaning
RC	Recycled Concrete
RCA	Recycled Coarse Aggregate
OPC	Ordinary Portland Cement
PPC	Portland Pozzolana Cement
SRC	Sulfate-Resisting Cement
RHC	Rapid Hardening Cement
SCM	Supplementary Cementitious Material
ITZ	Interfacial Transition Zone
NCA	Natural Coarse Aggregate
NDT	Non-Destructive Testing
CTM	Compression Testing Machine
ASTM	American Society for Testing and Materials
IS	Indian Standard
EN	European Norm (Standard)

ACI	American Concrete Institute
COREN	Council for the Regulation of Engineering in Nigeria
LEED	Leadership in Energy and Environmental Design
GGBS	Ground Granulated Blast Furnace Slag
C–S–H	Calcium Silicate Hydrate
CH	Calcium Hydroxide
C_3S	Tricalcium Silicate
C_2S	Dicalcium Silicate
C_3A	Tricalcium Aluminate
C_4AF	Tetra calcium Aluminoferrite
MPa	Megapascal
w/c	Water-Cement Ratio
UPV	Ultrasonic Pulse Velocity
C&DW	Construction and Demolition Waste
ACV	Aggregate Crushing Value

CHAPTER ONE

INTRODUCTION

1.1 Background of Study

A concrete construction substance consists of an adhesive agent, such as Portland cement, mixed with liquid and particles like fine aggregates, including sand and larger rocks, known collectively as aggregate. Over extended periods, this compound undergoes a transformation via its own internal reactions called hydration, resulting in an extremely durable material characterized by hardness and precise shape conformity to external forms. Concrete stands out because of its exceptional hardness against compression, flexibility for various applications, and durability, making it the most widely used building material globally.

In earlier eras, concrete existed. Traders from Nabatea had begun using freshly mixed concrete made from clay and lime for construction at least 7,143 years ago in modern-day Jordan and Syria. Ancient Egypt's builders employed a mixture made from earth, reeds, and lime in constructing their monumental structures, known as pyramids (Lea 1970).

However, Roman builders utilized an earlier form of cement dating back to around 275 BC. Roman builders combined quicklime, volcanic rock called pozzolan, and tiny stone fragments known as pumice into an enduring material used for constructing famous buildings such as the Pantheon and ancient water channels—their works remain intact millennia later (Jackson, Landis *et al.* 2013). During the fall of Rome, there was an extended period where advancements in engineering materials like concrete were not pursued due to societal changes.

In Europe around the late 1700s, concrete regained its prominence as an architectural material, which continued to evolve significantly by the early 20th century. Joseph Aspdin of Britain created Portland cement in 1824 by mixing clay and limestone; he called it "Portland" due to its resemblance to natural Portland stone colour. A new age in construction materials began when

advanced concrete techniques emerged. A reinforced concrete construction method incorporating steel for both compressive and tensile reinforcement emerged during the late 1800s, significantly reshaping architecture and civil engineering techniques thereafter.

Today, concrete serves as the foundation for much of our built environment; however, its extensive use poses challenges related to sustainable practices due to increased demand for resources during manufacturing processes involving cement. A novel challenge emerged through advancements in technology; specifically, using RC made from repurposed construction debris instead of traditional aggregates. In addition to these measures, switching to greener options minimizes waste during demolitions and constructions while also preserving scarce natural materials.

Despite Joseph Aspdin's significant involvement, he derives considerable fulfillment from projects such as RC and NDT methods because they allow efficient assessment of their structural integrity using tools like the rebound hammer (Neville 2011).

Reused quarry dust transforms into durable building blocks through recycling processes applied in urban renovation projects. Beyond addressing issues related to conventional concrete's impact on the environment, this method enhances sustainability by improving resource utilization. For years now, Recycled Concrete has sparked debate due to its potential for minimizing both construction debris and associated greenhouse gas emissions (Kou and Poon 2009).

1.2 Statement of Problem

Aspects related to the building sector now encounter more frequent occurrences of material shortages due to environmental factors, alongside an increase in volumes generated by activities such as constructing new buildings and demolishing existing ones. With its global prevalence in construction, there's an increasing focus on incorporating eco-friendly materials like Recycled Concrete into projects today (Silva, de Brito *et al.* 2014). In addition to promoting waste reduction efforts, RC endorses principles of the circular economy and ensures ecological preservation goals.

Nevertheless, certain technical and practical obstacles hinder widespread acceptance and application of RC for construction purposes. The issues this research endeavours to tackle are as follows:

i. Lack of effective non-destructive strength testing methods: Traditional testing methods, such as compressive strength tests, require breaking samples, which cannot be applied during site inspections or validating existing constructions. A rebound hammer serves as an alternative for assessing materials without causing damage; however, its effectiveness in measuring the compressive strength of heterogeneous RC remains unverified.
ii. Cost and accessibility of testing equipment: Using large-scale destruction tests involves high-priced machinery and specialised laboratories, which are typically unavailable at construction sites. Alternative techniques, such as the rebound hammer test, can be more economical and accessible; however, they necessitate customised settings for each job involving recycled materials.

1.3 Aim and Objectives

The aim of this study is to compare and analyse the compressive strength of concrete made from recycled concrete of various grades. The objectives of this work are to:

i. Assess the actual compressive strength of concrete having different levels of recycled aggregate through the compressive strength test.
ii. Check the correlation between rebound hammer readings and actual compressive strength.
iii. Analyse how the quantity of recycled aggregates affects the compressive strength of the resulting concrete.
iv. Ascertain the optimum level of recycled aggregate that can produce a structurally viable concrete mix.

1.4 Scope of Work

This study investigates the compressive strength of RC using the rebound hammer method. The tasks undertaken are:

i. Obtaining and preparing natural and recycled coarse aggregate materials.
ii. Preparing various concrete mixes with varying percentages of replacement by RCA (0–100%).
iii. Moulding and curing normal and Recycled Concrete cubes for 7, 14, and 28 days.
iv. Carrying out rebound hammer tests on every sample following standard procedures.
v. Correlating rebound readings through destructive compressive strength tests.
vi. Data analysis for the establishment of correlations and the assessment of usability of RC.
vii. Recommending research direction.

1.5 Justification of Study

During the past decade, there has been an increased demand for sustainability from the construction sector, especially in relation to environmental conservation and waste reduction. The prevalent use of conventional concrete has led to an unsustainable dependence on natural aggregates, leading to the continuous extraction of non-renewable resources and high emissions of pollutants into the environment as a result of the high energy required to manufacture cement. In response to this, RC has the potential to be a possible alternative that uses the construction and demolition waste either as a partial or full replacement for natural aggregates. However, despite possessing its possible environmental benefits, RC still faces limited application in structural applications, primarily due to the lack of confidence in its mechanical behaviour, variability in the material properties, and lack of standard test methods.

One of the critical issues is the accurate and effective measurement of RC's compressive strength to ascertain its structural sufficiency. The traditional compressive strength tests are destructive,

require advanced machinery, a controlled laboratory setting, and skilled personnel, all of which have a tendency to increase project expenses and limit its usage in the field. Conversely, a non-destructive test such as the rebound hammer test is a quicker and less expensive option. Nevertheless, these tests are usually calibrated against properties of conventional concrete and may not deliver a true result in the case of RC, whose internal character and surface texture are significantly different due to the presence of attached mortar and composite aggregate constitution.

This study is therefore justified by necessity, which is imperative, to research and verify the reliability of the rebound hammer test as a good practical method for assessing the compressive strength of RC. By creating RC-specific calibration relations and correlating results with normal concrete, the study aims to ensure better insight into the relationship between surface hardness and real compressive strength in recycled aggregate mixtures. Additionally, this research fills the gap in understanding in applying NDT techniques to alternative concrete technologies, hence boosting the confidence in RC adoption by designers, engineers, and policy-makers. To this purpose, the study further advances the broader goals of promoting environmentally friendly construction without forfeiting structural performance and safety.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The rapid pace of urbanisation and infrastructural development has led to an exceptional rise in the global demand for concrete, which remains the most widely utilised construction material. However, this same progress has also resulted in the demolition of older structures, generating vast quantities of construction and demolition (C&D) waste that present significant environmental challenges. One of the most effective and sustainable responses to this problem is RC. By incorporating aggregates reclaimed from demolished structures as a substitute for natural aggregates, RC promotes waste reduction, conserves natural resources, and supports more sustainable practices within the construction industry (Silva, de Brito *et al.* 2014).

Another important consideration in evaluating RC as a potential structural material is its mechanical performance, particularly its compressive strength in comparison with conventional concrete. Compressive strength is a crucial property that determines the load-bearing capacity and overall structural integrity of concrete. Although this property is usually assessed through destructive methods such as compression tests on cubes or cylinders, these procedures are often laborious, time-consuming, and result in the loss of the tested specimens. As a result, non-destructive methods such as the rebound hammer test have become popular alternatives. The rebound hammer is a simple and efficient tool that provides a quick, indirect measure of surface hardness, which can then be correlated with the compressive strength of the concrete (Malhotra and Carino 2004).

2.2 Concrete

Concrete is the world's most consumed building material after water in terms of volume consumption. It is a mixture of cement, fine aggregate (sand), coarse aggregate (gravel or crushed

stone), water, and sometimes admixtures to enhance its quality. Upon mixture, concrete changes from a chemical reaction to a hydration process whereby it hardens and gets stronger with time (Mehta and Monteiro 2014).

Concrete is valued for its:

i. Compression strength
ii. Fire and durability resistance
iii. Shape and finish versatility
iv. Economic feasibility for mass production works

2.3 Components of Concrete

2.3.1 Cement

Cement is a fine powder that is grey and is a hydraulic binder, hardening and setting when water is mixed with it. Cement is the principal binding agent used in concrete and mortar to bind aggregates into a composite as well as to provide structure strength to the aggregate. Cement hardens by becoming more powerful as it becomes hydrated through chemical interaction with water to form calcium silicate hydrate (C–S–H), the primary strength-contributing compound (Neville 2011). The widely applied cement globally is Ordinary Portland Cement (OPC), invented by Joseph Aspdin in 1824 and therefore so christened due to the fact that its hardened form is similar to that of Portland stone in England.

Cement is manufactured through a high-temperature process in a rotary kiln where raw materials like limestone, clay, and iron ore are heated to form clinker, which is then ground with gypsum to control the setting time. This process is energy-intensive and contributes significantly to CO_2 emissions globally (Neville 2011).

According to ASTM C150 and EN 197, various types of cement are designed to meet specific engineering requirements. Below are the most common types used in construction:

2.3.1.1 Ordinary Portland Cement (OPC)

Ordinary Portland Cement (OPC) is the most widely used type of cement in contemporary construction. As the principal binding material in grout, mortar, and concrete, it plays a central role in providing strength and rigidity to hardened cement-based products. The name “Portland” originates from its resemblance to Portland stone, a high-quality limestone once commonly used in early British construction. The widespread use of OPC can be attributed to its high compressive strength, durability, and adaptability to different environmental and structural conditions. It serves as the foundation of virtually all forms of infrastructure, including roads, bridges, buildings, and water-retaining structures (Mehta and Monteiro 2014).

Ordinary Portland Cement (OPC) is primarily composed of clay and limestone, which are heated together in a rotary kiln to produce a substance known as clinker. During the final stage of production, the clinker is finely ground and blended with a small quantity of gypsum to control the setting time of the cement. The chemical composition of OPC is mainly characterised by four principal compounds: tricalcium silicate (C_3S), which is responsible for early strength development; dicalcium silicate (C_2S), which contributes to long-term strength; tricalcium aluminate (C_3A), which affects the setting process and the heat generated during hydration; and tetracalcium aluminoferrite (C_4AF), which influences the colour of the cement and provides lower strength compared to the silicate compounds. When OPC is mixed with water, a chemical reaction known as hydration occurs, producing calcium silicate hydrate (C–S–H), the primary source of strength in hardened cement paste, and calcium hydroxide (CH), a by-product that helps maintain the high alkalinity of concrete and protects embedded steel from corrosion (Mehta and Monteiro 2014).

OPC is classified into five types according to performance properties and environmental conditions by ASTM C150. Type I is for general use, where no specific conditions are specified. Type II is with moderate sulphate resistance and lower heat of hydration and is employed in foundations and seashore work. Type III is for early strength and is applied primarily in precast concrete and cold weather construction. Type IV is employed in the mass structures, such as dams, where very little formation of heat is required. Type V is specifically meant for high sulphate exposure conditions (ASTM 2020). In the European EN 197-1 specification, OPC is identified by the label CEM I, i.e., it consists wholly of clinker with negligible gypsum content, and there are no other mineral admixtures (EN 2011).

Ordinary Portland Cement is in the form of fine, even grey colour and fineness value of 300-400 square meters per kilogram according to the Blaine test. It will set within 30 minutes once water is added and sets in 10 hours, though this could also be affected by surrounding conditions and mix ratio (Neville 2011).

OPC possesses a compressive strength of 20 MPa to 50 MPa at 28 days, depending on the grade of cement and curing conditions. It is also silent, i.e., during the setting time, volume stability is ensured, and its hydration heat will be of moderate to high depending upon the tricalcium aluminate and tricalcium silicate content (Mehta and Monteiro 2014).

Ordinary Portland Cement (OPC) is used extensively in a wide range of concrete structural elements, including columns, slabs, beams, and foundations. Beyond its structural applications, it is also an essential component in masonry mortars, plasters, and other general-purpose works. OPC is widely employed in the production of precast units, storage tanks, bridges, reservoirs, and highway pavements, owing to its strength and versatility. In addition, it serves as the base material for manufacturing blended cements and is commonly used as a reference standard in comparative studies and quality control testing within the construction industry (Neville 2011).

One of the key advantages of Ordinary Portland Cement (OPC) lies in its ability to develop both early and long-term strength, making it particularly suitable for projects that demand rapid construction schedules. It can also be combined with a wide range of chemical admixtures to adjust properties such as setting time, workability, and durability, depending on specific construction requirements. Because OPC is standardised and readily available worldwide, it has become a universally recognised material within the construction industry and remains the preferred choice referenced in most testing procedures and design codes (Mehta and Monteiro 2014).

Despite its numerous advantages, there are limitations to OPC as well. The production of OPC is very energy-intensive and contributes significantly to carbon dioxide emissions, approximately one ton of CO_2 for each ton of cement produced (Neville 2011). This environmental factor has raised doubts about its long-term viability. OPC also generates a significant amount of heat while hydrating, leading to thermal cracking in large pours. It also exhibits rather poor sulphate resistance and therefore, is not generally advised for use in hostile sea or ground environments unless supplemented or substituted by sulphate-resisting grades (IS 269, 2015)

OPC plays a significant role in the binding of recycled aggregates in RC, which may be weaker and more permeable than virgin aggregates.

However, when the recycled aggregates absorb more water, the desired workability and strength will require adjustment of the mix design and water-cement ratio. The experiments showed that the combination of OPC with other cementing material such as fly ash or silica fume raises interfacial transition zone (ITZ) of RC and strength and durability (Kou and Poon 2009).

2.3.1.2 Portland Pozzolana Cement (PPC)

Portland Pozzolana Cement (PPC) is a type of blended cement produced by combining pozzolanic materials with Ordinary Portland Cement (OPC) clinker. Pozzolanic materials are siliceous or siliceous–aluminous substances that, although they possess little or no cementing ability on their own, can react chemically with calcium hydroxide in the presence of water to form compounds with cementitious properties. During this reaction, additional calcium silicate hydrate (C–S–H) is generated, which contributes to the long-term strength and durability of the concrete matrix. Commonly used pozzolanic materials include fly ash, a by-product of coal combustion, as well as calcined clay and volcanic ash. The incorporation of these materials not only enhances the performance of concrete but also supports sustainability by utilising industrial and natural by-products (IS 1489, 1991)

Portland Pozzolana Cement (PPC) generally consists of about 65–75% Ordinary Portland Cement (OPC) clinker, 15–35% pozzolanic material, and 3–5% gypsum. The pozzolanic component reacts slowly, contributing to the gradual development of long-term strength, while gypsum is included to regulate the setting time of the cement. Blending OPC with pozzolana not only enhances the overall performance of the cement but also lowers its environmental impact by reducing the proportion of energy-intensive clinker and incorporating industrial by-products, thereby decreasing the carbon footprint associated with cement production (Mehta and Monteiro 2014).

PPC gains strength more slowly than OPC in early curing days, i.e., up to the first 7 days. However, it is stronger in the long term (after 28 days), owing to the ongoing pozzolanic reaction. PPC also possesses a lower heat of hydration, and therefore, it is suitable for mass concreting works where thermal cracking can be an issue. In addition, PPC also produces a more compact concrete microstructure that enhances resistance to chemical attack by sulphates and chlorides (Neville 2011).

One of the key advantages of Portland Pozzolana Cement (PPC) is its enhanced durability. The pozzolanic reaction refines the pore structure of concrete, thereby reducing permeability and improving resistance to aggressive environmental conditions such as acid rain, marine exposure, and sulphate-rich soils. As a result, PPC is particularly suitable for foundations, marine works, sewerage systems, and other structures exposed to harsh environments.

Another important advantage of PPC lies in its environmental contribution. By incorporating industrial by-products such as fly ash, PPC supports sustainable construction through the conservation of natural resources and the reduction of greenhouse gas emissions associated with clinker production. This makes it a more environmentally responsible alternative to traditional cement types (Kumar and Siddique 2011).

Also, PPC will generally have improved workability because of its smaller particles, which will function as a lubricant when mixed with the concrete. This will make the concrete easier to compact and place, especially in more densely reinforced areas.

Despite its long-term strength advantages, Portland Pozzolana Cement (PPC) also has certain limitations. The early strength development of PPC is generally lower than that of Ordinary Portland Cement (OPC), making it less suitable for applications where rapid strength gain is essential, such as in precast elements or fast-track construction projects. In addition, PPC tends to exhibit longer setting times, particularly under low-temperature conditions, which can delay construction schedules if not properly managed through appropriate mix design and curing practices.

PPC is most frequently used in general construction where long-term durability is needed. PPC is applied in (Kou and Poon 2009):

i. Foundations and basements.

ii. Retaining walls and dams.

iii. Marine and hydraulic structures.

iv. Mass concrete works (due to low heat of hydration).

v. Residential and commercial buildings.

vi. Road pavements and sidewalks.

For RC, Portland Pozzolana Cement (PPC) is particularly suitable. The inclusion of pozzolanic materials helps improve the interfacial transition zone (ITZ) between the cement paste and the recycled aggregates, thereby compensating for the inherently weaker and more porous nature of the recycled material. This interaction results in a denser microstructure and a stronger overall concrete composite, enhancing both the strength and durability of RC (Kou and Poon 2009).

Portland Pozzolana Cement (PPC) is regarded as a green, sustainable, and environmentally friendly alternative to Ordinary Portland Cement (OPC). Its ability to resist chemical attack, reduce permeability, and enhance the overall sustainability of concrete makes it a highly suitable material for modern construction. When used in combination with recycled aggregates, PPC not only contributes to the principles of green building and resource conservation but also enhances the long-term strength and durability of concrete structures.

2.3.1.3 Rapid Hardening Cement (RHC)

Rapid Hardening Cement (RHC) is a type of Portland cement specifically designed to achieve high early strength. Chemically, it is similar to Ordinary Portland Cement (OPC) but contains a higher proportion of tricalcium silicate (C_3S) and is ground to a finer particle size. These characteristics accelerate the hydration process, allowing the cement to gain strength at a much faster rate than OPC. As a result, RHC is particularly suitable for projects that require early formwork removal or rapid load application, as well as for use in cold weather conditions where the rate of hydration is typically reduced (Neville 2011).

Rapid Hardening Cement (RHC) is recognised in standards such as ASTM C150 Type III and IS 8041:1990, which specify its chemical composition and performance characteristics. Although it is produced from the same basic raw materials as Ordinary Portland Cement (OPC)—namely limestone, clay, and iron ore—RHC is manufactured at a higher kiln temperature and ground to a much finer particle size. The chemical composition is carefully adjusted to increase the proportion of tricalcium silicate (C_3S) while reducing dicalcium silicate (C_2S), resulting in a faster rate of hydration and, consequently, more rapid strength development.

The enhanced fineness of RHC exposes a greater surface area to water during hydration, which accelerates chemical reactions and leads to a higher early heat evolution. This characteristic requires careful temperature control in mass concrete applications to prevent thermal cracking. Under normal curing conditions, RHC is designed to attain approximately 70 per cent of its 28-day compressive strength within the first three days and can achieve a strength of about 20 MPa within 24 hours. Although it develops strength much more rapidly than OPC, its ultimate compressive strength is generally comparable to, or slightly higher than, that of conventional cement. (Neville 2011).

However, Rapid Hardening Cement (RHC) also exhibits a higher heat of hydration, particularly during the early stages of setting, which can lead to thermal stresses and cracking in large pours or massive concrete elements. For this reason, RHC is more suitably applied in thinner sections, precast components, and repair works, rather than in high-volume concreting unless adequate thermal control measures are implemented.

The principal advantage of RHC lies in its rapid strength development, which allows for early formwork removal, shorter construction cycles, and quicker utilisation of the structure. This feature can result in substantial cost savings on site, particularly in projects involving precast elements. Moreover, RHC is highly effective in cold-weather concreting, where reduced

temperatures typically slow down the hydration process. Its ability to gain strength rapidly also makes it ideal for emergency repair works—such as roads, pavements, and airport runways—where fast setting and early load-bearing capacity are of critical importance (Mehta and Monteiro 2014).

Although Rapid Hardening Cement (RHC) offers several advantages, it also presents certain drawbacks that require careful consideration. Its high heat of hydration can induce thermal cracking in large or massive concrete members if proper precautions—such as staged pouring or the use of active cooling systems—are not observed. In addition, the higher energy demand associated with its production makes RHC less environmentally sustainable compared to blended cements like Portland Pozzolana Cement (PPC) or those incorporating supplementary cementitious materials. The rapid-setting nature of RHC can also reduce workability, requiring that concrete be placed and compacted immediately after mixing. Consequently, its use is best suited to contractors with experience in handling fast-setting materials to prevent defects such as cold joints or inadequate surface finishes during construction (Kumar and Siddique 2011).

Rapid Hardening Cement is used extensively in:

i. Precast concrete components such as beams, slabs and columns.
ii. Repair of roads and runways where reopening quickly is required.
iii. Cold weather concreting where strength gain is normally retarded.
iv. Industrial bridge and floor deck construction.
v. Emergency or temporary structures.

In the context of RC, Rapid Hardening Cement (RHC) can be effectively used to offset the slower strength development often associated with the higher porosity and variable quality of recycled aggregates. However, careful attention must be paid to water demand and workability, as recycled

aggregates tend to absorb more water, which can influence both the setting time and the early strength of the mix.

RHC is a specialised, high-performance cement designed for applications that demand rapid strength gain, accelerated construction schedules, and quick project turnover. Its relevance in modern construction remains significant, particularly for fast-track projects and situations where standard curing cycles cannot be accommodated. Although its use must be carefully controlled due to the high heat of hydration and limited working time, RHC continues to represent a vital advancement in the cement industry—especially when integrated with sustainable practices such as the use of recycled aggregates and low-carbon concrete technologies (Mehta and Monteiro 2014).

2.3.1.4 Sulphate-Resisting Cement (SRC)

Sulphate-Resisting Cement (SRC) is a type of Portland cement specifically engineered to resist the damaging effects of sulphate attack—a common problem in concrete exposed to aggressive environments such as groundwater, seawater, sewage, and certain industrial effluents. In such conditions, conventional Ordinary Portland Cement (OPC) can deteriorate over time due to chemical reactions between sulphate ions and hydrated cement compounds, particularly tricalcium aluminate (C_3A). SRC mitigates this issue by limiting the C_3A content to less than five per cent, thereby improving the cement's resistance to sulphate-induced degradation and extending the service life of structures in sulphate-rich environments (ASTM 2020)

Sulphate attack is a chemical form of deterioration that occurs when sulphate ions present in soil or water react with the aluminates and calcium hydroxide in hardened cement paste. This reaction

leads to the formation of expansive compounds such as ettringite, which generate internal stresses within the concrete matrix. Over time, these stresses can result in cracking, spalling, and a progressive reduction in strength and durability. Among the various compounds in cement, tricalcium aluminate (C_3A) is the most vulnerable to sulphate attack; therefore, controlling its content is crucial for enhancing the sulphate resistance of concrete and ensuring long-term structural performance (Mehta and Monteiro 2014).

The production process of Sulphate-Resisting Cement (SRC) differs only slightly from that of Ordinary Portland Cement (OPC). The key distinction lies in the careful adjustment of the raw material composition to achieve a lower tricalcium aluminate (C_3A) content—typically below five per cent—and a reduced amount of calcium hydroxide. These modifications result in a hydrated cement paste that is less reactive to sulphate ions, thereby improving its resistance to chemical attack.

In terms of standards, sulphate-resisting cement is classified as ASTM C150 Type V under American specifications, IS 12330:1988 in India, and EN 197-1 CEM I-SR in Europe. The performance of SRC in terms of strength gain and workability is generally comparable to that of OPC, though it exhibits slightly lower early strength because of its reduced C_3A content. However, it provides superior long-term durability when exposed to sulphate-rich environments. Its setting time is similar to that of OPC, and it generates a moderate heat of hydration, making it particularly suitable for large-scale concrete pours in areas where sulphate exposure is a concern (ASTM C150 / C150M, 2020).

SRC is typically used where there is exposure of concrete to sulphate. Some of the applications are in:

i. Basements and foundations built on sulphate soils.
ii. Sewage treatment works and wastewater treatment works.

iii. Sea structures such as sea walls.

iv. Jetties and docks.

v. Bridges and culverts exposed to de-icing salts or industrial effluent.

vi. Irrigation canals.

vii. Dams.

viii. Canals with sulphate-water runs.

Sulphate-Resisting Cement (SRC) is particularly effective in extending the service life of concrete structures exposed to chemically aggressive environments, thereby reducing the overall cost of maintenance and repair. Its principal advantage lies in its ability to minimise the risk of sulphate attack, which significantly enhances the durability and long-term stability of concrete. By limiting deterioration in environments rich in sulphate ions, SRC ensures structural integrity and longevity, particularly under severe exposure conditions. Furthermore, the use of SRC helps prevent premature damage or structural failure, ultimately reducing the financial burden associated with frequent repairs and rehabilitation (Neville 2011).

Sulphate-Resisting Cement offers several advantages, but it is not without limitations. It is generally more costly than ordinary Portland Cement due to the requirements for precise raw material mix designs and stringent manufacturing controls. Moreover, SRC does not provide complete immunity to all forms of chemical attack, including acid and carbonation. Consequently, a site-specific assessment is essential prior to selecting SRC for a project.

In the context of Recycled Concrete, SRC proves particularly advantageous. It is especially effective when recycled aggregates are obtained from materials previously exposed to sulphates, or when new concrete is to be used in similar conditions. The combination of recycled concrete with SRC enables engineers to achieve both chemical durability and enhanced environmental sustainability in construction.

Sulphate-Resisting Cement is a critical material in contemporary construction where sulphate exposure can threaten the longevity of concrete structures. Its unique composition, characterised by a reduced C_3A content, provides effective resistance to sulphate attack, rendering it suitable for marine, underground, and wastewater structures. When employed alongside sustainable practices such as the use of recycled concrete, SRC facilitates the production of high-performance, durable, and environmentally responsible concrete, in alignment with modern standards for resilient infrastructure (Mehta and Monteiro 2014).

2.3.1.5 Low-Heat Cement

Low-Heat Cement is a specialised form of Portland cement developed to reduce the heat generated during the hydration process. It is particularly suitable for mass concrete applications, including dams, foundations, and retaining walls, where excessive temperature rise due to hydration may result in cracking. The production of Low-Heat Cement addresses the need to balance thermal control with structural performance, especially in thick concrete sections where the dissipation of heat is limited (Neville 2011).

Low-Heat Cement is generally classified as Type IV cement according to ASTM C150 and is also recognised under standards such as IS 12600:1989 and EN 197-1 CEM III/A in other countries. During hydration, it undergoes exothermic chemical reactions, primarily through the hydration of tricalcium silicate (C_3S) and tricalcium aluminate (C_3A), which release a considerable amount of heat. In mass concrete structures, this heat may become confined within the concrete, creating a temperature gradient between the interior and exterior. If not properly managed, this gradient can induce internal stresses and cracking, ultimately affecting the durability of the structure.

Low-Heat Cement is manufactured from a well-proportioned raw mix which results in:

i. Reduced C_3S content: Reduced development rate of strength and heat.
ii. Increased content of C_2S: Contributes long-term strength with minimal heat.

iii. Reduced content of C_3A: Minimizes initial heat peaks.

The overall fineness of Low-Heat Cement is deliberately lower than that of Ordinary Portland Cement (OPC), which reduces both the rate of hydration and the amount of heat generated. This type of cement is characterised by a slower strength development during the first seven days. However, it achieves adequate long-term strength, generally meeting or exceeding the standard 28-day requirements. The heat of hydration is significantly lower, at approximately 60–70 calories per gram, compared with 80–100 calories per gram for OPC (Neville 2011).

The setting times of Low-Heat Cement are slightly longer than those of Ordinary Portland Cement, while its workability remains comparable. However, adequate curing is essential due to the slower rate of hydration. The primary advantage of Low-Heat Cement lies in its ability to mitigate thermal cracking in large concrete pours. By controlling the internal temperature rise, it ensures both structural integrity and long-term durability. It is therefore most ideally applicable in:

i. Dams and giant piers.
ii. Thick walls of retention and foundation blocks.
iii. Subterranean construction and tunnels.
iv. Concrete, where additional hydration heat would be a problem.

An additional indirect benefit of Low-Heat Cement is its contribution to sustainability. Its composition typically contains a higher proportion of silicate phases and fewer energy-intensive compounds, which can help reduce the overall carbon footprint when the cement is used judiciously.

Despite its advantages, Low-Heat Cement is not suitable for all applications. Its slow early strength development makes it inappropriate in situations requiring rapid removal of formwork, fast-track construction, or urgent repairs. Furthermore, due to its specialised production process

and lower demand, it may not be as readily available and can be more expensive than Ordinary Portland Cement.

In the context of RC, Low-Heat Cement offers several benefits. The controlled heat generation can reduce shrinkage and microcracking around lower-quality recycled aggregates, thereby improving the integrity of the interfacial transition zone (ITZ). Additionally, since recycled concrete is often more susceptible to increased porosity and moisture migration, the regulated heat release helps to minimise stress concentrations and enhances the overall durability of the concrete matrix.

Low-Heat Cement is particularly valuable in large-scale concrete pours, such as in substantial building projects, where temperature management is critical to ensuring long-term durability. Although its strength develops more slowly than that of Ordinary Portland Cement, its ability to limit heat-induced cracking renders it essential in certain structural and environmental contexts. When combined with sustainable practices, including the use of recycled aggregates, Low-Heat Cement contributes to the production of durable, high-performance concrete in alignment with contemporary goals for sustainable construction.

2.3.2 Fine Aggregates

Fine aggregate is an essential component of concrete, serving primarily to fill the voids between coarse aggregates, enhance workability, and contribute to the overall strength and durability of the mixture. It is typically composed of natural sand or manufactured material that passes through a 4.75 mm sieve (No. 4 sieve) and is retained on a 75-micron sieve. The quality and selection of fine aggregate significantly influence concrete behaviour, affecting mix consistency, surface finish, and setting characteristics (Neville 2011).

Fine aggregates perform many essential roles in concrete:

i. They reduce voids within the concrete matrix by filling up the interstices between coarse aggregates.
ii. They provide an acceptable surface finish and enhance the cohesiveness of fresh concrete, resulting in a convenience advantage of pumpability and reduced risk of segregation.
iii. Fine aggregates influence mix water demand and workability—finer sand increases the water demand, but coarser sand increases the flowability.
iv. They contribute very little to compressive strength but major contributions to cement paste and aggregate bond properties.
v. Fine aggregate is basically a structural filler and functional mixture component.

The physical characteristics of fine aggregates most relevant are:

i. Grading (Particle Size Distribution): Well-graded sand allows for good packing and a smaller amount of cement paste required.
ii. Specific Gravity: Usually ranging from 2.6 to 2.7 for natural sands.
iii. Fineness Modulus (FM): Usually ranging from 2.3 to 3.1; gives an estimate of mean particle size.
iv. Moisture Content: Affects water-cement ratio and must be replaced during mix design.
v. Bulking: Increase in amount of sand due to surface moisture; batching is very important.
vi. Silt and Clay Content: Not much, as excessive content of fines will prevent bond as well as lead to excessive shrinkage.

Fine aggregates are classified based on source and method of treatment. The most prevalent ones are:

i. Natural Sand: Natural sand is obtained from river beds, streams, or pits. It typically consists of quartz, feldspar, and other siliceous materials.

a. River Sand: Well-cleaned, rounded grains, of very good quality for concrete due to good grading and workability.
b. Pit Sand: Coarse and angular in texture, which are unearthed from deep pits; may have impurities to be removed.
c. Sea Sand: Contains chloride and salt, which is not generally employed in reinforced concrete except after desalination.

The most desirable fine aggregate is natural sand where available and conditions allow, but increasing limitations on sand extraction have led to alternatives being sought.

ii. Manufactured Sand (M-Sand): M-Sand is produced by mechanically crushing stone, often granite or basalt, and grading the grains to specific sizes. It is advantageous because it:
    a. Offers consistent grading, angular grain, and reduced silt content.
    b. Needs less water with finer regulation.
    c. More environmentally friendly than the natural sand, with less environmental damage.
    d. Is used more in new building applications, especially where the use of natural sand is not feasible or not allowed.
iii. Recycled Fine Aggregate: They are manufactured from a crushed waste of masonry or concrete. They are utilized to a lesser extent and can be employed in environmental or non-structural applications. They have very unstable properties and are mostly processed to remove impurities and control grading (Kou and Poon 2009).

The following are considered during the selection of the fine aggregate of a concrete mix by engineers:

i. Grading spec and fineness modulus for optimal particle packing.

ii. Cleanliness (minimum amount of organic, clay, and silt content).
iii. Absorption and moisture content, affecting effective water-cement ratio.
iv. Shape and texture, affecting bond strength and workability.

The aggregate utilized should be as per specifications such as ASTM C33 or BS EN 12620, which have gradation, impurities, and physical properties similar to constraints.

In RC, the proportion of recycled fine aggregate (i.e., recycled crushed concrete sand) may be utilized partially as a replacement for natural sand. This is likely to lead to:

i. Higher water demand with higher absorption.
ii. Reduced workability and potentially reduced strength.
iii. Non-stable quality depending on the source material that was first employed.

For improved performance, RC mixes often incorporate recycled sand in combination with natural or manufactured sand, along with the addition of admixtures or supplementary cementitious materials to enhance bonding and reduce porosity (Poon, Shui *et al.* 2004).

Fine aggregate is a fundamental component of concrete, exerting considerable influence on both its fresh and hardened properties. The grading, type, and quality of fine aggregate directly affect the strength, workability, and durability of the concrete. In response to industry trends emphasising sustainability and resource conservation, materials such as manufactured sand and recycled fine aggregates are increasingly being used as substitutes for natural sand. Careful selection and quality control of fine aggregate remain essential to ensuring the durability, cost-effectiveness, and overall performance of concrete structures.

2.3.3 Coarse Aggregate

Coarse aggregate is a key component of concrete, typically accounting for 60–75% of its total volume. It consists of naturally occurring or artificially crushed stones, gravels, or rock fragments

that pass through a 4.75 mm sieve. The primary function of coarse aggregate is to provide bulk, dimensional stability, and mechanical strength to the concrete. Its shape, size, grading, and surface texture directly influence the strength, workability, and durability of both fresh and hardened concrete (ASTM 2018)

The coarse aggregates are the concrete's load-carrying material. They:

i. Reduce the volume of cement paste required, hence minimizing cost.
ii. Have significant contribution to compressive strength and stiffness.
iii. Provide dimensional stability by being resistant to excessive shrinkage or creep.
iv. Affect workability; angular aggregates reduce workability but increase bond; rounded aggregates enhance flow.
v. Contribute to durability, especially where well graded and selected.

In concrete, coarse aggregate selection affects not only performance but also long-term strength and stability of the structure.

Several physical properties affect quality of coarse aggregate in concrete:

i. Size and Grading: Sizes typically between 10 mm and 40 mm. Well-graded aggregates allow close packing and reduce voids.
ii. Specific Gravity: Typically, in range of 2.5 to 2.9; controls mix proportioning.
iii. Bulk Density: Influences weight calculation and batching.
iv. Moisture Content: Includes free surface moisture and absorption; affects water-cement ratio.
v. Shape and Texture: Angular aggregates provide better interlocking; rounded aggregates provide better workability.

vi. Hardness and Abrasion Resistance: Becomes important for concretes designed for severe wear or traffic.

vii. Soundness: Ability to resist weathering, especially freeze-thaw.

viii. Cleanliness: The aggregates must not include deleterious material like clay, silt, organic material, or salt.

All coarse aggregates to be used with concrete should be in compliance with such standards as ASTM C33 or EN 12620.

The coarse aggregates may be classified according to source, composition, and processing:

i. Natural Aggregates

They are extracted from natural rock deposits and consist of:

a. Gravel: Typically, rounded and smooth, sourced from riverbeds or pits; offers good workability but weaker bonding due to smooth surface.

b. Crushed Stone: Produced by mechanical reduction of rocks (granite, basalt, limestone); angular in shape, improves interlock and bond strength.

Natural aggregates are the most frequently found in structural concrete due to the fact that they are available at hand and mechanically strong.

ii. Artificial (Manufactured) Aggregates

It is made from waste products of industry or man-made products. The types include:

a. Expanded shale/clay/slate: used in lightweight concrete.

b. Air-cooled slag: By-product of steel manufacturing.

c. Sintered fly ash aggregates: light, porous, used in thermal insulation concrete.

They are usually utilized in light concrete applications where weight saving is of primary concern (e.g., precast cladding panels, high-rise slabs).

iii. Recycled Coarse Aggregates (RCA)

Produced from crushed dismantled buildings or waste concrete due to construction. RCA may include residual mortar, less dense and more porous than natural aggregate.

Though recycled aggregates are less strong and more water-absorbing, they are increasingly utilised in green infrastructure and RC. Its application helps in the prevention of waste, preservation of natural resources, and lowering carbon emissions (Kou and Poon 2009, Silva, de Brito *et al.* 2014).

The selection of coarse aggregate depends upon the:

i. Durability and strength of concrete according to design.
ii. Exposure conditions (e.g., freeze-thaw, marine).
iii. Workability and finish properties.
iv. Compatibility with fine aggregates and general grading.
v. Sustainability requirements, especially in the case of recycled aggregates' use.

Appropriate testing of coarse aggregates for properties such as crushing value (ACV), impact value, and water absorption is essential to ensure the structural adequacy of concrete.

In RC, coarse aggregates are partially or entirely replaced with recycled concrete aggregates (RCA). Although the presence of residual mortar in RCA can reduce strength and stiffness, these effects can be mitigated through suitable mix designs and the incorporation of supplementary cementitious materials (SCMs). Additionally, treatments such as acid washing, thermal processing, and particle size optimisation are commonly employed to improve the performance characteristics of RCA.(Silva, de Brito *et al.* 2014).

Despite inherent variability, properly designed concrete incorporating recycled concrete aggregates (RCA) can achieve acceptable mechanical properties while offering improved

environmental performance. Coarse aggregate remains a primary constituent of concrete, directly contributing to its mechanical strength, dimensional stability, and cost-effectiveness. The choice between natural, manufactured, or recycled coarse aggregate should be guided by the functional requirements of the structure, the prevailing environmental conditions, and sustainability considerations. With advancements in processing techniques and testing methods, recycled aggregates have become increasingly viable for use in structural-grade concrete, particularly when combined with high-performance binders and suitable admixtures.

2.3.4 Water

Water is a fundamental ingredient in the production of concrete. Although it constitutes a relatively small proportion of the total mix by weight, its physical and chemical roles are critical in developing concrete strength and workability. In a typical mix, water represents approximately 7–15% of the concrete's weight, yet it performs essential functions in hydration, setting, strength development, and durability. The use of clean and adequate water is therefore crucial to producing high-quality, long-lasting concrete (Taylor 1997).

Water performs chemical and physical roles in concrete, which:

i. Hydration: Chemical reaction of cement hydration is initiated by water, forming calcium silicate hydrate (C–S–H) and other binding material that bonds aggregates together. Cement will not become strong unless it has reacted with enough water.
ii. Workability: Water provides plasticity for transporting, placing, mixing, and finishing concrete. Excess water enhances workability, but excessive water leads to segregation, bleeding, and reduced strength.
iii. Curing: Once the initial setting is complete, water is essential for ongoing hydration over time. Adequate curing preserves the moisture retention of concrete, which allows strength and durability to develop completely, particularly between the first 7 and 28 days.

iv. Water-Cement Ratio: The water-cement ratio is the most significant one in obtaining concrete strength and durability. It is the relative weight of water to cement in the mixture. Reducing the w/c ratio (e.g., 0.40) enhances strength and decreases permeability. Raising the w/c ratio (e.g., 0.60 or more) improves workability but decreases strength and increases porosity. Strength of concrete, as per Abram's law, is directly proportional to the inverse of the water-cement ratio, with full compaction and curing (Abrams 1918, Mehta and Monteiro 2014)

v. Water Quality: Water quality is as crucial as quantity in concrete making. The water used must be devoid of the following impurities:

    a. Acids, which will suppress hydration or cause steel corrosion.
    b. Salts (chlorides or sulphates), which promote corrosion and expansive action.
    c. Organic compounds, which can slow down setting and reduce bond strength.
    d. Alkalis, which can cause alkali-silica reaction (ASR) in reactive aggregates.

The general principle is: if water is drinking water, it is fit for concrete. Non-potable water may be allowed provided it meets the requirements mentioned in ASTM C1602 or IS 456:2000, for instance, not lowering the compressive strength more than 10% compared to control specimens made with drinking water (BIS 2000, ASTM 2018).

Too much water aggravates the following unfavourable effects:

i. Lowered compressive and tensile strength.
ii. Increased porosity and permeability.
iii. Increased vulnerability to greater shrinkage and cracking.
iv. Decreased resistance to freeze-thaw action and chemical attack.
v. Poor bond between reinforcement.

Thus, the correct water content must be adhered to strictly, and admixtures (e.g., Super-plasticisers) may be employed so as to enhance workability without the addition of additional water.

In Recycled Concrete, the function of water is more crucial because of greater water absorption by the recycled aggregate. Excess mortar on the recycled aggregate absorbs more water, and thus, there is a reduced effective water-cement ratio along with workability and strength properties. Steps are taken to mitigate this as elaborated below:

i. Pre-soaking of recycled aggregates to prevent excessive water absorption during mixing.
ii. Adjusting the mix water to account for moisture in aggregates.
iii. Using admixtures or water-reducing admixtures to improve performance (Kou and Poon 2009).

In RC, careful control of water is necessary to counterbalance the instability introduced by recycled materials.

Water is not merely an inert component of concrete; it serves as a reactive, structural, and functional element that influences everything from mix performance to the long-term behaviour of the concrete. Achieving the correct quantity and quality of water is essential to producing durable, resilient concrete capable of resisting environmental deterioration. In sustainable concretes such as RC, water management assumes even greater importance due to the variability in aggregate properties and absorption characteristics. Therefore, proper selection, inspection, and control of water usage remain fundamental to the production of high-quality concrete.

2.3.5 Admixtures

Admixtures are materials, other than water, cement, aggregates, or fibre reinforcement, that are added to concrete either before or during mixing to modify its fresh or hardened properties.

Although typically used in small quantities—generally less than 5% by weight of cement—admixtures exert a significant influence on the behaviour and performance of concrete. Their use enables the production of concrete that is more workable, durable, cost-effective, and specifically tailored to meet the requirements of particular construction conditions (Aïtcin 1998, Mindess, Young *et al.* 2003, Mehta and Monteiro 2014).

Admixtures are very useful in RC, as they compensate for drawbacks such as higher water absorption and lower early strength (Kou and Poon 2009).

Several important functions control the use of admixtures in concrete:

i. To improve workability without increasing water content.
ii. To speed up or retard setting time.
iii. To enhance strength gain or durability.
iv. To control temperature-rise in mass concrete.
v. To reduce permeability, shrinkage, or segregation.
vi. To enable placing in adverse conditions, i.e., in heat or cold.
vii. To enhance compatibility in mixtures with marginal or reclaimed aggregates.

By achieving these goals, admixtures maximise concrete performance, conserve money, and enhance sustainability objectives.

There are several types of admixtures, which include:

i. Chemical Admixtures: Chemical admixtures are classified based on their primary function, and they include:
    a. Water-Reducing Admixtures (Plasticisers): These reduce the water requirement for a particular slump, developing strength and reducing permeability. They are

employed to an extensive degree to enhance workability at the cost of no decrease in durability.

b. High-Range Water Reducers (Super-plasticisers): Super-plasticisers deliver high water reduction (30% or more) and generate high-strength, high-flow concrete. Super-plasticisers are utilised in precast work and self-compacting concrete.

c. Accelerating Admixtures: These hasten the rate of hydration, thus faster setting and early strength are obtained. They are most useful in cold weather or in the case of repair work.

d. Retarding Admixtures: These slow down the setting time, thus there is increased workability when it is hot or when large pours are being produced and delays are unavoidable. Retarders also avoid cold joints between successive lifts.

e. Air-Entraining Admixtures: Used to incorporate micro air bubbles, improving freeze-thaw cycle and de-icing salt resistance. Of great importance in pavements and external concrete in cold climates.

f. Shrinkage-Reducing and Corrosion-Inhibiting Admixtures: These reduce drying shrinkage cracking and protect embedded steel from chloride-induced corrosion.

ii. Mineral (Supplementary) Admixtures: These are extremely fine powders, normally industrial waste material, that replace a portion of the cement to improve performance and reduce environmental impact. They include:

a. Fly Ash: Enhances long-term strength and durability, reduces the heat of hydration.

b. Silica Fume: Enhances strength and reduces permeability to a large extent.

c. Ground Granulated Blast Furnace Slag (GGBS): Enhances sulphate resistance and reduces heat evolution.

d. Metakaolin: Improves microstructure and enhances early strength.

These mineral admixtures or Supplementary Cementitious Materials (SCMs) are utilised on a massive scale in green concrete practice, especially in RC, to increase the interfacial transition zone (ITZ) and to compensate for the deficits brought by recycled aggregates. (Kou and Poon 2009).

Admixtures in RC play very important roles in addressing the following problems:

i. Increased water demand of recycled aggregates may be alleviated with the help of Super-plasticisers.
ii. Reduced early strength may be improved with the help of accelerators or pozzolanic admixtures like silica fume.
iii. Inadequate durability due to enhanced porosity can be compensated by air-entraining agents or SCMs.
iv. Bridging surface defects in the ITZ can be improved with the help of mineral admixtures that densify the microstructure.
v. Admixtures thus enable RC to equal, if not surpass, the performance of normal concrete in optimised environments.

The selection of an appropriate admixture and dosage is determined by:

i. Project needs (i.e., early strength, setting time, durability).
ii. Aggregates and cement compatibility.
iii. Environmental conditions (temperature and humidity).
iv. Concrete placing methods (pumped, vibrated, or self-compacting).

Trial mixes and laboratory testing are essential to determine the effectiveness and compatibility of admixtures within a given mix design. Admixtures form a cornerstone of modern concrete technology, enabling the development of concrete mixes that meet increasingly demanding structural, environmental, and economic requirements. By enhancing workability, strength, durability, and sustainability, admixtures have become vital in both conventional and Recycled Concrete applications. As the emphasis on green construction continues to grow, admixtures, in combination with supplementary cementitious materials, will remain central to the advancement of next-generation concrete technologies (Siddique 2008, Mehta and Monteiro 2014).

2.4 Recycled Concrete (RC)

RC is produced by reprocessing aggregates obtained from construction and demolition waste to partially or fully replace natural aggregates. These recycled aggregates primarily consist of crushed concrete from demolished buildings, pavements, and various other infrastructure elements. The utilisation of RC supports sustainable construction practices by conserving natural resources and reducing the volume of construction waste sent to landfills.

The characteristics of recycled aggregates are slightly different from natural aggregates. Experiments were conducted by Poon, Shui *et al.* (2004) and Hansen (1986) to prove that recycled aggregates generally exhibit higher water absorption, greater porosity, and lower specific gravity compared with natural aggregates. These characteristics are primarily due to the presence of residual bonded mortar on the surface of the recycled aggregates, which diminishes the bond between the aggregate and the cement matrix in fresh concrete. As a result, RC typically

demonstrates lower mechanical strength and reduced recoverability compared with conventional concrete.

However, other studies have managed to demonstrate that when a proper mix design, high-quality recycled aggregates, and Supplementary Cementitious Materials (SCM) mix ingredients are applied, RC can be manufactured with mechanical strength equal to or even better than structural demands. Limbachiya, Leelawat *et al.* (2000) as well as Kou and Poon (2009) have registered RC capability under ideal situations to be able to function in the same manner as ordinary concrete, and hence an effective substitute for application in construction.

2.5 Benefits of RC

The application of RC is followed by several advantages that guarantee sustainable construction and a circular economy. (Evangelista and de Brito 2007, Kou and Poon 2009, Kou, Poon *et al.* 2011, Silva, de Brito *et al.* 2014):

i. Protection of the Environment: Recycling of aggregates instead of natural aggregates reduces the requirement for quarrying and hence contributes to preserving natural landscapes and wildlife habitats.
ii. Reduction of Waste: Construction and demolition waste recycling minimises landfill usage, and also solid waste is properly managed.
iii. Energy Conservation: Production of RC is less energy-intensive than the production of new natural aggregates and thus conserves energy embodied in concrete.
iv. Reduced Carbon Footprint: Recycling saves on CO_2 emissions related to the processing and transport of aggregates.
v. Cost Savings: Where natural aggregates are scarce or expensive, RC offers a cheaper option, especially where locally recycled aggregates compete favourably at low prices.

vi. LEED Rating and Green Building Codes: RC supports LEED ratings and certification, and green building codes, through maximisation of resource productivity.

vii. Market Development and Innovation: The use of RC stimulates innovation in processing methods, as well as new marketplace opportunities in green building.

RC is a plus that makes it a default ingredient in reducing the environmental footprint of the building sector, especially when complemented with rigorous quality control and design techniques.

2.6 Limitations of RC

Despite the numerous environmental and practical benefits it offers, RC faces certain limitations that impact both its structural performance and its widespread adoption. (Gomez-Soberon 2002, Meyer 2002, Poon, Shui *et al.* 2004, Rahal 2007, Silva, de Brito *et al.* 2014):

i. Reduced Mechanical Strength: The Presence of old mortar and weak bonding interface makes RC have less compressive, tensile, and flexural strength as compared with natural aggregate concrete.

ii. Increased Water Absorption: The higher absorption of water by the recycled aggregates tends to create changes in the water-cement ratio, which will, in turn, change workability and strength development.

iii. Deterioration Facets: The increased porosity and permeability will allow the ingress of other chemicals (i.e., chlorides), carbonation, and alternate hostile environmental conditions to decrease resistance.

iv. Greater Variability: Different source material leads to properties that vary widely, resulting in unpredictable behaviour unless controlled.

v. Processing Requirements: For quality assurance purposes, more treatment such as cleaning, sorting, and possibly surface treatment of recycled aggregates is required, thereby increasing expense and process complexity.

vi. Structural Limitations: Certain specifications in some countries limit the use of RC to non-structural applications, mainly due to concerns over reduced long-term durability and performance.

These challenges also reflect the fact that, although viable alternatives exist, the adoption of RC must be preceded by comprehensive trial testing, the standardisation of quality assurance procedures, and appropriate adjustments to the mix design to ensure safety and structural reliability.

2.7 Physical and Mechanical Properties of RC

i. Density: Because of the presence of the old adhered mortar, which is more porous in nature and lightweight, the RC tends to have lower density when compared to the conventional concrete (Hansen, 1986).

ii. Water Absorption: Recycled aggregates traditionally exhibit water absorption of 6–10%, compared to 1–2% of natural ones (Poon, Shui *et al.* 2004).

iii. Compressive Strength: The RC usually shows a drop between 10% and 30% in compressive strength than normal concrete, depending on the type and quantity of recycled aggregate employed (Rahal 2007).

iv. Modulus of Elasticity and Tensile Strength: Lower tensile strength and modulus of elasticity values are observed for RC due to weaker aggregate-matrix bonding (Evangelista and de Brito 2007).

v. Interfacial Transition Zone (ITZ): The ITZ ones in RC tend to be highly porous and less dense, which is why it becomes a decisive factor affecting strength characteristics (Silva, de Brito *et al.* 2014).

2.8 Compressive Strength of RC

Among the key factors influencing structural stability and concrete durability, compressive strength is of primary importance. It plays a critical role in determining the load-carrying capacity of concrete elements and is therefore essential during both the design and quality control stages. The compressive strength of RC is influenced by several factors, including the quality of recycled aggregates, the percentage of replacement, the water–cement ratio, the formation of microcracks, and the porosity of the recycled aggregates.

Rahal (2007) subjected RC to demonstrate a loss of compressive strength between 10% and 30% compared to virgin aggregate concrete under normal circumstances, especially when the recycled aggregate proportion was extremely high. The reasons are low-strength ITZS and greater internal defects. The inclusion of SCMS such as fly ash, silica fume, or ground granulated blast furnace slag can even enhance the ITZ and reduce permeability, thus improving the strength and durability.

It has been further prolonged by recent technological advances in recycling aggregates like thermal treatment, mechanical grinding, and acid soaking. Silva, de Brito *et al.* (2014) demonstrated that wedged mortar removal pre-treatment of recycled aggregates considerably enhanced compressive strength. 30% replacement was also best placed to achieve sustainability and performance.

2.9 Supplementary Cementitious Materials (SCMs) in RC

RC is generally regarded as having lower mechanical and durability properties than conventional concrete due to the presence of residual mortar, microcracks, and higher porosity in recycled aggregates. However, the incorporation of Supplementary Cementitious Materials (SCMs) has been shown to enhance the performance of RC. SCMs react with calcium hydroxide produced

during cement hydration to form additional calcium-silicate-hydrate (C–S–H) gel, which refines the microstructure and strengthens the interfacial transition zone (ITZ).

2.10 Common SCMs Used in RC

Table 2.1 shows some of the common Supplementary Cementitious Materials (SCMs) used in Recycled Concrete.

Table 2.1: Common SCMs used in RC (Siddique 2008, Kou and Poon 2009, Silva, de Brito *et al.* 2014)

SCM	Description	Effect on RC
Fly Ash (FA)	Byproduct from coal combustion	Improves workability, reduces heat of hydration, enhances long-term strength
Silica Fume (SF)	Ultrafine waste from the silicon/ferrosilicon industry	Greatly improves strength, reduces porosity, enhances ITZ
Ground Granulated Blast Furnace Slag (GGBS)	Byproduct of iron production	Improves sulphate resistance, reduces permeability, enhances durability
Metakaolin (MK)	Calcined clay	Improves early strength and durability

Rice Husk Ash (RHA)	Agricultural byproduct	Reduces permeability, improves strength over time

2.11 Effects of SCMs on RC Properties

1) Fresh Properties
   - **a)** Workability: Fly ash and slag increase workability by their spherical shape and lower water demand. On the other hand, silica fume may reduce workability with its filling action and has to be used with a superplasticiser, which is a chemical compound that disperses cement particles in a concrete mix, reducing water demand and enhancing fluidity (Aïtcin 1998).
   - **b)** Water Demand: SCMs may offset in part the higher water absorption of recycled aggregates by improving the packing of particles.
2) Mechanical Strength
   - **a)** Compressive Strength: Silica fume and metakaolin intensify the refinement of the region called ITZ and considerably enhance strength. The long-term strength development of concrete by fly ash is more significant as it is a slow pozzolanic reaction.
   - **b)** Flexural and Tensile Strength: The better bond developed between the paste and recycled aggregate due to SCMs leads to improved flexural and tensile strengths.
3) Durability
   - **a)** Reduced Porosity: SCMs fill voids present in RC, thus reducing permeability and increasing the resistance to water ingress and some aggressive chemicals.
   - **b)** Chloride and Sulphate Resistance: GGBS and fly ash are generally very effective in reducing chloride penetration and improving sulphate resistance.
   - **c)** Carbonation and Freeze-Thaw Resistance: SCMs are generally good for durability, but their effect on carbonation must be carefully considered. Freeze-thaw resistance requires air entrainment.

2.12 Non-Destructive Testing (NDT) of Concrete

NDT methods provide strength and durability assessments without damaging the structure. Common techniques include (Malhotra and Carino 2004):

i. Rebound Hammer Test
ii. Ultrasonic Pulse Velocity (UPV)
iii. Penetration Resistance Test
iv. Pull-Out Test
v. Infrared Thermography

These methods are useful for quality control, structural evaluation, and condition assessment in existing structures. (Malhotra and Carino 2004).

2.13 Rebound Hammer Test

The rebound hammer test, also known as the Schmidt hammer test, is one of the most commonly employed non-destructive techniques for assessing the surface hardness of concrete. It was developed by Ernst Schmidt in the 1940s. During the test, a weight is projected onto the concrete surface using a spring-loaded mechanism, and the rebound distance is measured to evaluate the surface hardness and indirectly estimate the compressive strength of the concrete (Malhotra and Carino 2004).

Malhotra and Carino (2004) clarified that the rebound number (R-value) obtained during the test is influenced by several factors, including surface roughness, moisture content, carbonation, aggregate type, and the presence of voids. Consequently, the standard calibration curves provided by manufacturers are developed for specific conditions and may not be universally applicable. Therefore, it is essential to develop and utilise project-specific or material-specific calibration curves to achieve more accurate estimations of concrete strength.

Although limited in use, the rebound hammer is widely employed because it is convenient, portable, and inexpensive, and it provides instant results. It is best suited for preliminary testing and quality control of large concrete surfaces, where destructive testing would be impractical or detrimental.

2.14 Standards Governing the Rebound Hammer Test

Some of the standards governing the rebound hammer include:

1. ASTM C805 / C805M – 18: *Standard Test Method for Rebound Number of Hardened Concrete*

   Some of the key provisions of the guideline include:

   i) It specifies how to perform the rebound hammer test.

   ii) It describes surface preparation, impact angle corrections, and test limitations.

   iii) It emphasises that results should not be used as a substitute for compressive strength unless calibrated.

2. IS 13311 (Part 2) – 1992 Non-Destructive Testing of Concrete – Methods of Test, Part 2: Rebound Hammer

   a. It outlines procedures for rebound hammer use on both laboratory and field samples.

   b. It specifies test locations (minimum of 10 readings per test area).

   c. It categorises concrete quality based on the average rebound number.

2.15 Application of Rebound Hammer on RC

The rebound hammer test on RC has garnered significant interest in various experimental studies aimed at validating and making it usable. Evangelista and de Brito (2007) also stated that because

RC is heterogeneous and contains mature mortar, it may exhibit non-uniform surface hardness behaviour compared to regular concrete. Therefore, applying calibration curves derived from normal concrete could lead to misleading predictions of compressive strength.

Bairagi, Vidyadhara *et al.* (1990) conducted comparative tests for RC with normal concrete and found that, for the same compressive strength, RC produced lower rebound values. The explanation for this lies in the comparatively softer surface of RC due to microstructural variations and increased porosity. To address this, researchers have proposed enhancing the calibration curves of RC so that rebound values are very close to the actual compressive strength.

Thomas, Setién *et al.* (2013) emphasised the need to combine rebound hammer testing with other non-destructive tests, such as Ultrasonic Pulse Velocity (UPV), to enhance the reliability of strength predictions. Multi-parameter testing allows for compensation of RC property variability and provides a more integrated evaluation.

2.16 Previous Studies on RC

Reused concrete as aggregate was first widely studied by Hansen in the 1980s. Hansen (1986) conducted thorough tests demonstrating that concrete containing recycled coarse aggregates (RCA) has been found to exhibit acceptable mechanical properties for secondary structural applications. This work was also pioneering, demonstrating that the quality of RC is strongly influenced by the characteristics of the original concrete and the quantity of bonded mortar on the recycled particles. Hansen further highlighted that recycled aggregates are more heterogeneous than natural aggregates, which presents challenges for standardisation and quality control.

Since Hansen's pioneering work, several studies have focused on the mechanical properties of RC. Rahal (2007) mentioned that he compressive strength, modulus of elasticity, and tensile strength of RC are generally 10%–30% lower than those of conventional concrete, particularly when the replacement level of recycled coarse aggregates (RCA) exceeds 50%. Despite these reductions,

Rahal confirmed that properly designed RC can still satisfy structural requirements in most building applications. This is supported by Poon, Shui *et al.* (2004), who attributed the reduced performance to the porosity of the residual mortar and the diminished effectiveness of the interfacial transition zone (ITZ). These studies also emphasised the critical role of mix design and aggregate grading in ensuring the effective use of RCA.

Studies of durability have reported significant problems in using RC in aggressive environments. Gomez-Soberon (2002) analysed the porosity of RC and found increased permeability compared to normal concrete, making it susceptible to chemical attack, such as chloride ingress and carbonation. Kou, Poon *et al.* (2011) also confirmed that RC exhibits higher drying shrinkage and creep due to the porous nature of recycled aggregates. However, these limitations can be overcome through the addition of supplementary cementitious materials (SCMs) such as fly ash or slag to improve pore structure and reduce permeability.

Various studies have been conducted on the effect of SCMs in the optimisation of RC performance. Kou and Poon (2009) proved that the addition of silica fume and fly ash in RC not only improves compressive strength but also reduces water absorption and chloride ion penetration significantly. Silva, de Brito *et al.* (2014) extended this by examining the microstructure of ground granulated blast furnace slag (GGBS) blended RC and noting a denser ITZ and better sulphate resistance. These findings have supported the use of blended cements in RC, particularly in those that require durability in severe environmental conditions.

While destructive testing methods such as compressive strength tests are widely used for RC evaluation, non-destructive methods such as the rebound hammer test have been increasingly used for on-site evaluations. Evangelista and de Brito (2007) noted that RC is likely to provide lower rebound values compared to similar-strength natural aggregate concrete, primarily due to its softer surface character. Thomas, Setién *et al.* (2013) noted that RC is not likely to be well represented

on standard rebound hammer calibration curves and advised material-specific calibration for improved estimation of strength. These articles stress the need to adapt standard test practice for use with RC.

Meyer (2002) research into the structural suitability of RC for high-rise applications has concluded that, with appropriate quality control and under conservative design parameters, RC can be safely employed in load-bearing structures. However, it also highlighted the need for updated building codes and technical standards to address the unique characteristics of RC. This aligns with recent initiatives in several countries to develop standards for recycled aggregates in concrete, such as the recommendations provided by the European Committee for Standardisation (EN 206). In addition to structural considerations, the environmental impact of RC has been a prominent focus of recent research. Limbachiya, Leelawat *et al.* (2000) and Tam, Tam *et al.* (2006) conducted life cycle assessments that reported RC significantly reduces carbon emissions, consumption of raw materials, and construction site waste. The environmental benefits are maximised when RC is combined with supplementary cementitious materials (SCMs) and locally sourced materials. The literature also indicates that RC contributes effectively to sustainability measures, such as LEED certification and reductions in embodied energy, establishing it as a preferred material for green building applications.

CHAPTER THREE

METHODOLOGY

The research process for this project is laid out to analyse the compressive strength of RC using a non-destructive test method—the rebound hammer test. It includes material selection, concrete mix design, curing, rebound hammer testing, and data analysis. Each stage is carefully planned to obtain reliable and reproducible results.

3.1 Materials

i. Cement: Ordinary Portland Cement (OPC) conforming to ASTM C150 / C150M.

ii. Fine Aggregate: Clean, well-graded river sand conforming to ASTM C33 / C33M.

iii. Coarse Aggregate (NCA): Crushed granite, 20 mm maximum size conforming to ASTM C33.

iv. Recycled Coarse Aggregate (RCA): Obtained from crushed, cleaned concrete waste; sieved to 20 mm size.

v. Water: Potable water free of impurities meeting ASTM C1602 requirements.

vi. Admixtures (optional): Super-plasticiser (polycarboxylate-based, meeting ASTM C494 Type F) used in select mixes to maintain workability at lower w/c ratios.

3.2 Mix Design

The mix design process of the current study follows the guidelines given in COREN Concrete Mix Design Manual (2020) and relevant ASTM standards. The aim is to cast different grades of concrete — i.e., M20, M25, and M30 — with deliberate changes in recycled coarse aggregate (RCA) proportion with a fixed water-cement ratio (w/c) for comparative compressive strength testing by using a rebound hammer.

Every concrete mixture is formulated to a desired strength and workability suitable for casting 100mm × 100mm × 100mm cubes, and to an adequate level of durability for general structural use. Table 3.1 shows the concrete grades and their respective target strengths.

Table 3.1: Concrete Grades and Target Strengths (COREN 2020)

Grade	Characteristic Compressive Strength (f_{ck})	Target Mean Strength (f_{cm})
M20	20 MPa	29.84 MPa
M25	25 MPa	34.84 MPa
M30	30 MPa	39.84 MPa

NOTE: According to the COREN guideline, the target mean compressive strength f_{cm} is derived as follows

$$f_{cm} = f_{ck} + (1.64 \times s) \ldots\ldots (3.1)$$

Where:

- $\mathbf{f_{ck}}$ is the characteristic strength
- **s** is the assumed standard deviation (6 MPa for normal-quality control)

For uniformity across mixes and to isolate the influence of RCA content, a constant w/c ratio of 0.50 is used for all grades. Slump is targeted between 75–100 mm for moderate workability. Super-plasticisers may be introduced (not exceeding 1% of cement weight) for RC mixes that exhibit excessive stiffness.

Five replacement levels of RCA by weight of natural coarse aggregate are considered. This allows for detailed analysis of strength variation with increasing recycled content. The mix proportion are developed using COREN's volumetric batching method, corrected for bulk density, aggregate absorption, and specific gravity. The mix design details are as shown in Tables 3.2, 3.3 and 3.4:

Table 3.2: M20 Concrete Mix Design (0.50 w/c ratio) (COREN 2020)

RCA (%)	Cement (kg/m³)	Water (kg/m³)	Fine Agg. (kg/m³)	Coarse Agg. (NCA+RCA) (kg/m³)
0	320	160	660	1170 (100% NCA)
25	320	160	660	877.5 NCA + 292.5 RCA
50	320	160	660	585 NCA + 585 RCA
75	320	160	660	292.5 NCA + 877.5 RCA
100	320	160	660	1170 (100% RCA)

Table 3.3: M25 Concrete Mix Design (0.50 w/c ratio) (COREN 2020)

RCA (%)	Cement (kg/m³)	Water (kg/m³)	Fine Agg. (kg/m³)	Coarse Agg. (kg/m³)
0	360	180	620	1150 (100% NCA)
25	360	180	620	862.5 NCA + 287.5 RCA

50	360	180	620	575 NCA + 575 RCA
75	360	180	620	287.5 NCA + 862.5 RCA
100	360	180	620	1150 (100% RCA)

Table 3.4: M30 Concrete Mix Design (0.50 w/c ratio) (COREN 2020)

RCA (%)	Cement (kg/m³)	Water (kg/m³)	Fine Agg. (kg/m³)	Coarse Agg. (kg/m³)
0	400	200	600	1120 (100% NCA)
25	400	200	600	840 NCA + 280 RCA
50	400	200	600	560 NCA + 560 RCA
75	400	200	600	280 NCA + 840 RCA
100	400	200	600	1120 (100% RCA)

3.3 Sample Preparation

The specimen concrete was cast into standard cube moulds (100 mm × 100 mm × 100 mm), vibrated on a bench, and covered with wet towels for 24 hours. The cubes were then removed from the mould and cured in water tanks at 23 ± 2°C for 7, 14, and 28 days as per ASTM C192.

3.4 Rebound Hammer Testing Procedure

The rebound hammer test on the hardened specimens was conducted with a Schmidt Rebound Hammer in accordance with ASTM C805.

Figure 3.1: Schimdt Rebound Hammer

The adopted test procedure was as follows:

i. Surface Preparation: The Specimen surface was polished and wiped free from loose particles or dust.

ii. Testing: The test surface was at right angles to the gripped hammer, and ten readings on each side were recorded. The highest and lowest readings were discarded, and the mean of the rest was calculated.

iii. Calibration: The rebound hammer used for the test was factory-calibrated against 150mm X 150mm X 150mm concrete cubes so.

iv. Recording of Data: The rebound number (R-value) of every sample was noted, and a correlation curve between R-values and compressive strength was derived through statistical treatment.

3.5 Validation Through Destructive Testing

The compression testing machine, also referred to as a compressive strength testing machine, is an essential instrument in material testing laboratories, particularly in civil engineering. Its primary purpose is to determine the compressive strength of construction materials such as concrete, bricks, blocks, and mortar by applying a gradually increasing compressive load until the specimen fails. This testing procedure is of critical importance, as compressive strength remains a key indicator of the quality and structural performance of concrete, both in research contexts and practical field applications.

Figure 3.2: Compression Test Machine

The compression testing machine (CTM) is a robust assembly composed of several welded components. Its primary support is the loading frame, typically constructed from heavy steel or cast iron, designed to withstand the extreme stresses encountered during testing. Mounted on this

frame are the loading platens—hardened, level steel plates between which the concrete specimen is positioned. The platens serve to distribute the applied load evenly across the specimen. Load application is generally achieved using a hydraulic piston, actuated either by a motor-driven or hand-operated hydraulic pump system. This system includes a hydraulic fluid reservoir and pressure-controlling valves to ensure a uniform and controlled load during the test.

Another important feature of the CTM is its load measurement system, which may consist of an analogue pressure gauge in older models or a digital load indicator in modern machines. These systems provide real-time monitoring of the applied load, and in advanced configurations, data can be recorded and exported for subsequent analysis. Many modern CTMs are equipped with digital control screens, allowing for the initiation, suspension, or termination of tests, as well as the adjustment of parameters such as load rate and data sampling intervals. In fully automated systems, the entire process—from load application to strength calculation—is performed with precision and minimal human intervention.

During a typical test, a concrete cube or cylinder specimen is placed between the platens. As the machine operates, the top platen descends (or the bottom platen ascends, depending on the design), gradually imposing axial compressive stress on the specimen. Loading continues until the specimen reaches its ultimate capacity and fails. The maximum load at failure is then used to calculate the compressive strength of the material in accordance with this formula:

$$f_c = \frac{P}{A} \dots\dots (3.2)$$

Where:

$\boldsymbol{f_c}$ = compressive strength (MPa)

$\boldsymbol{P}$ = load at failure (N)

A = loaded surface area of the specimen (mm²)

To ensure accuracy and compliance with testing standards, compression testing machines (CTMs) are designed and operated in accordance with internationally recognised codes, including ASTM C39, ASTM C805, and ASTM C143. Periodic calibration, typically conducted every six to twelve months, is mandatory and carried out using certified proving rings or load cells.

In order to validate rebound hammer measurements, compressive strength tests were also performed on corresponding concrete cube specimens using a CTM in accordance with ASTM C39. The results from destructive and non-destructive tests were subsequently compared to assess the reliability and accuracy of the rebound hammer method in determining the compressive strength of RC (Bairagi, Vidyadhara *et al.* 1990).

The destructive tests in this study conform to ASTM C39 – Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.

The concrete samples were cast in 100 mm × 100 mm × 100 mm cube moulds, water cured at 27 ± 2°C, and tested after 7, 14, and 28 days.

The validation steps were carried out as follows:

i. Casting and Curing: For each mix combination (M20, M25, M30 with 0%, 25%, 50%, 75%, and 100% RCA), three replicate cube sets were cast resulting in a total number of 45 cubes. The cubes were demoulded after 24 hours, and water tanks were used for storing and curing them.
ii. Testing at Age Intervals: The cubes were surface-dried after each curing period (7, 14, and 28 days), tested with the rebound hammer, and the compressive strength tests were performed after the 28 days period using a calibrated digital compression testing machine (CTM) with a minimum capacity of 2000kN.

iii. Test Execution: Cubes were centrally placed on the lower plate of the CTM. Load was applied uniformly at a rate of 0.5 MPa/sec until failure. Ultimate load at failure was recorded, and compressive strength was calculated by the formula stated in equation 3.2

iv. Data Recording: Strength values for each of the cubes were obtained, and from the three repetitions for every age and RCA content level, an average was computed. Standard deviation and coefficient of variation were also determined to check reliability.

3.6 Data Analysis

The collected data were statistically analysed using regression models to establish a relationship between rebound numbers and actual compressive strength for each RC replacement level. Typically, this takes the form:

$$f_c = aR^2 + bR + c \ldots\ldots (3.3)$$

Where:

f_c = Predicted compressive strength (MPa)

R = Rebound number

a, b, c = Regression constants determined experimentally

The coefficient of determination (R^2) was used to evaluate the strength of the correlation. A higher R^2 value indicates a better predictive relationship between rebound values and actual compressive strength.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

The results obtained from the rebound hammer test, the compressive strength test and the data analysis are shown in the following tables and figures. It should be noted that the rebound test was carried out at 90° to the vertical, that is, the Schmidt hammer was held horizontally throughout the test.

Table 4.1: Compressive strength test results for M20 concrete mix

Replacement Levels	Curing Period	Average Compressive Strength (MPa)
0%	7 days	21.764
	14 days	24.587
	28 days	26.269
25%	7 days	19.010
	14 days	21.534
	28 days	22.854
50%	7 days	18.310
	14 days	19.597
	28 days	20.155
75%	7 days	17.500

Replacement Levels	Curing Period	Average Compressive Strength (MPa)
	14 days	18.385
	28 days	19.109
100%	7 days	16.583
	14 days	17.410
	28 days	18.066

Table 4.2: Rebound hammer test results for M20 concrete mix

Replacement Levels	Curing Period	Average Rebound Number
0%	7 days	13.3
	14 days	18.4
	28 days	20.7
25%	7 days	0
	14 days	11.3
	28 days	13.3
50%	7 days	0
	14 days	10.1

Replacement Levels	Curing Period	Average Rebound Number
	28 days	10.6
75%	7 days	0
	14 days	0
	28 days	0
100%	7 days	0
	14 days	0
	28 days	0

Table 4.3: Compressive strength test results for M25 concrete mix

Replacement Levels	Curing Period	Average Compressive Strength (MPa)
0%	7 days	27.201
	14 days	29.237
	28 days	31.905
25%	7 days	23.346
	14 days	25.549
	28 days	27.627

Replacement Levels	Curing Period	Average Compressive Strength (MPa)
50%	7 days	23.118
	14 days	25.201
	28 days	25.166
75%	7 days	22.848
	14 days	22.797
	28 days	23.379
100%	7 days	22.130
	14 days	21.583
	28 days	22.742

Table 4.4: Rebound hammer test results for M25 concrete mix

Replacement Levels	Curing Period	Average Rebound Number
0%	7 days	20.1
	14 days	22.3
	28 days	27.6
25%	7 days	16.6

	14 days	19.4
	28 days	22.5
50%	7 days	16.3
	14 days	18.6
	28 days	18.4
75%	7 days	14.9
	14 days	13.9
	28 days	13.8
100%	7 days	14.2
	14 days	12.9
	28 days	13.4

Table 4.5: Compressive strength test results for M30 concrete mix

Replacement Levels	Curing Period	Average Compressive Strength (MPa)
0%	7 days	32.630
	14 days	33.582
	28 days	35.983

25%	7 days	27.780
	14 days	30.579
	28 days	33.025
50%	7 days	27.321
	14 days	30.870
	28 days	30.592
75%	7 days	28.025
	14 days	27.395
	28 days	29.208
100%	7 days	26.469
	14 days	27.464
	28 days	28.684

Table 4.6: Rebound hammer test results for M30 concrete mix

Replacement Levels	Curing Period	Average Rebound Number
0%	7 days	27.8
	14 days	30.1

Replacement Levels	Curing Period	Average Rebound Number
	28 days	33.8
25%	7 days	22.0
	14 days	24.6
	28 days	28.9
50%	7 days	21.4
	14 days	25.8
	28 days	27.2
75%	7 days	21.2
	14 days	22.2
	28 days	24.6
100%	7 days	20.0
	14 days	21.2
	28 days	24.1

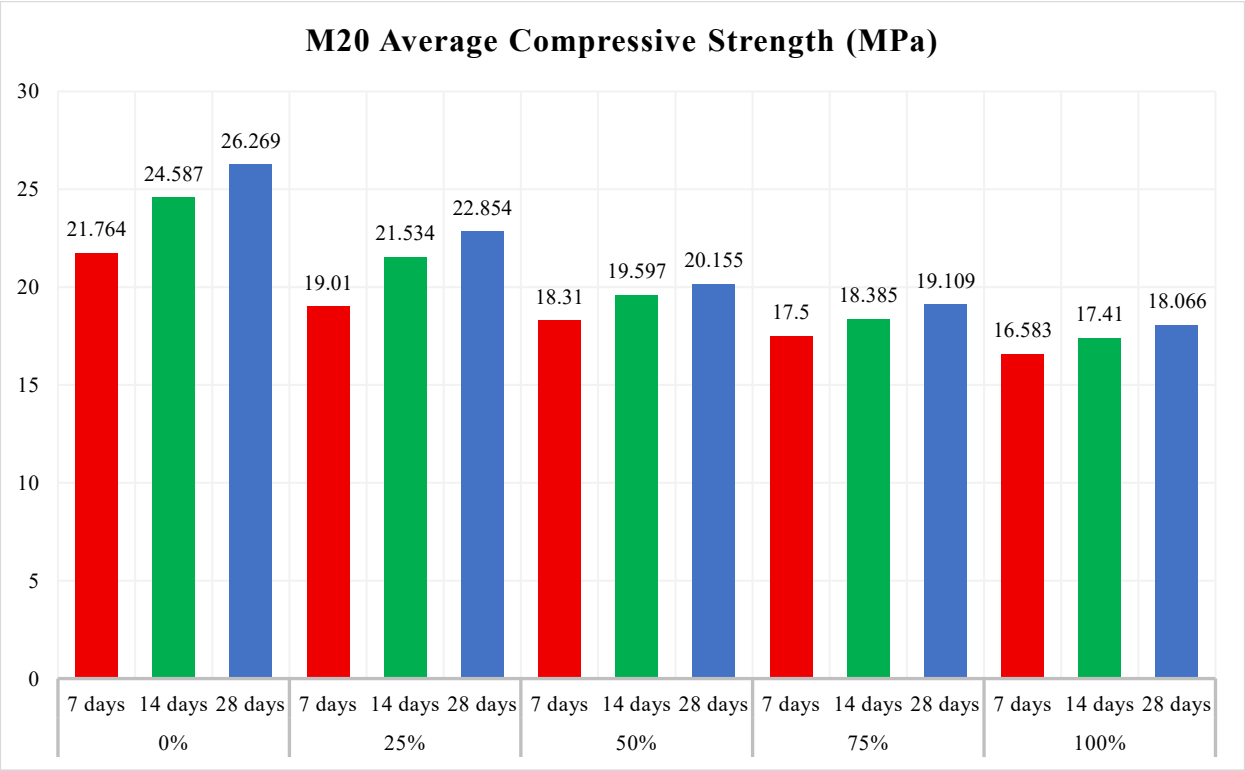

Figure 4.1: Column chart showing the variation of the compressive strength of concrete mix M20 with the different replacement levels at various curing periods

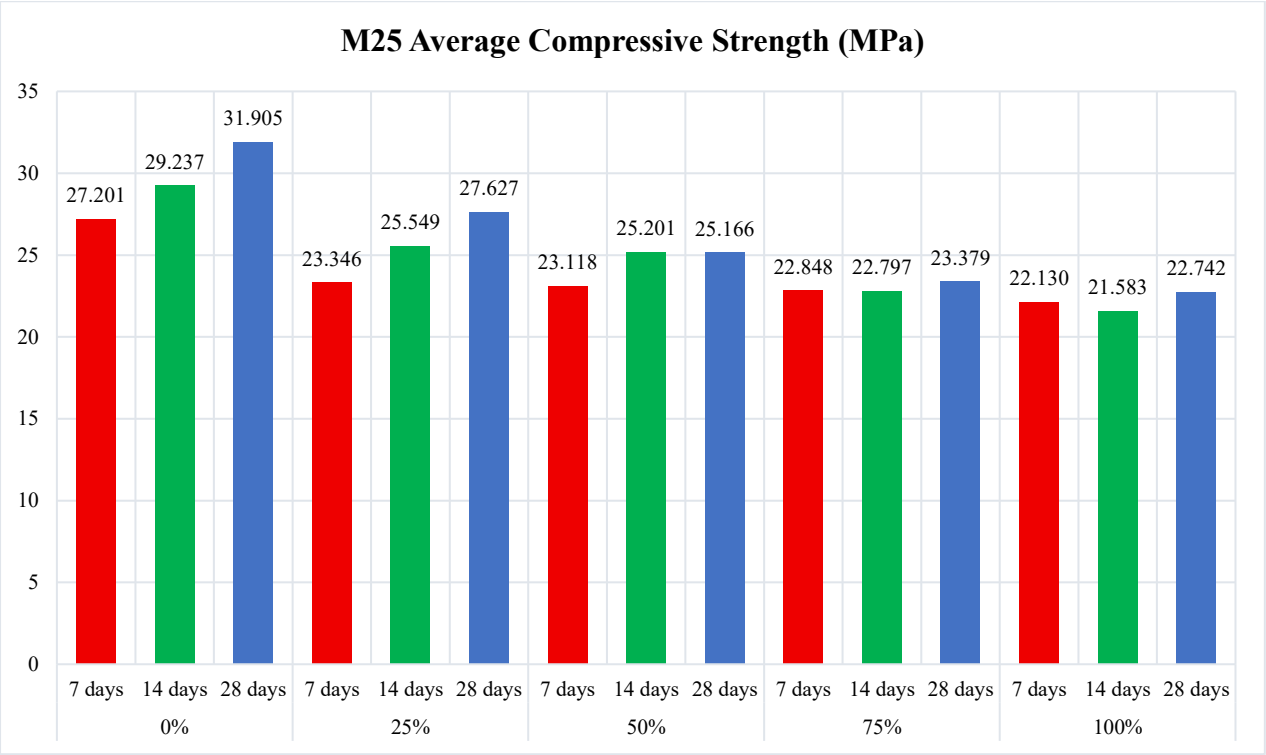

Figure 4.2: Column chart showing the variation of the compressive strength of concrete mix M25 with the different replacement levels at various curing periods

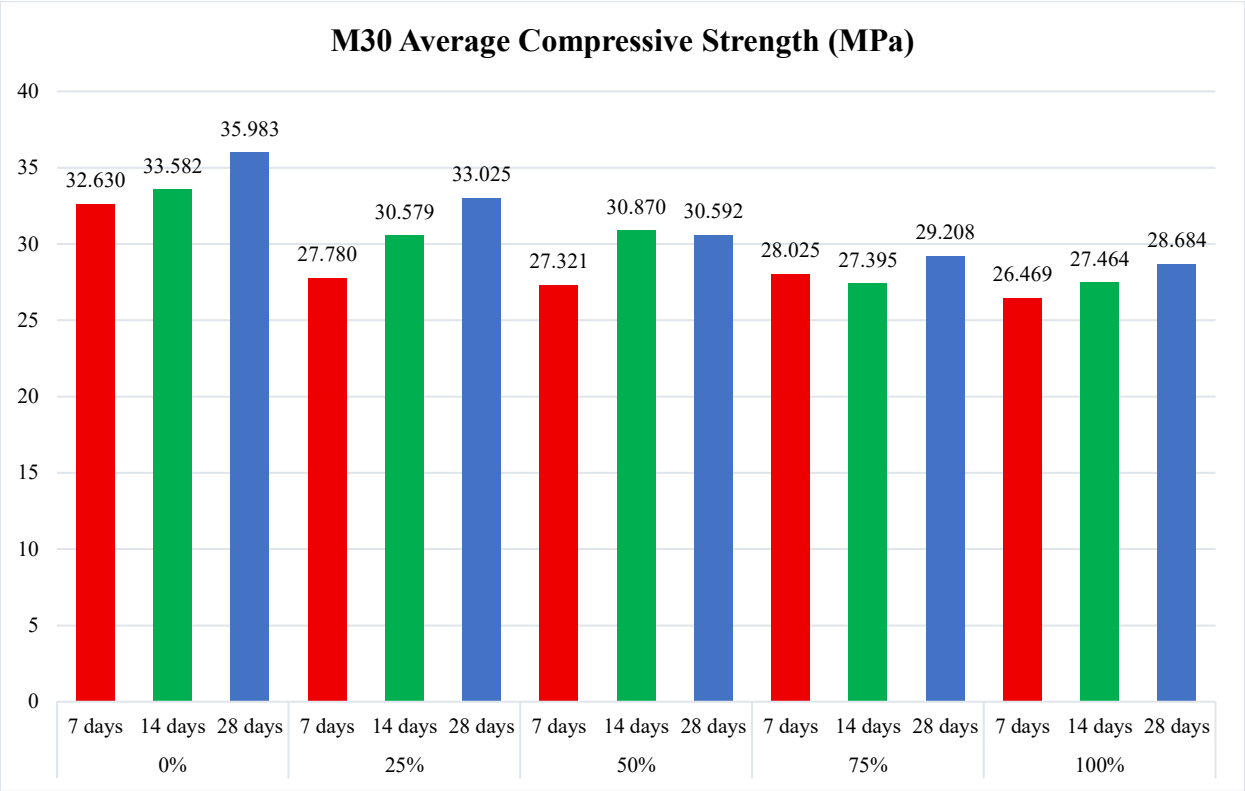

Figure 4.3: Column chart showing the variation of the compressive strength of concrete mix M30 with the different replacement levels at various curing periods

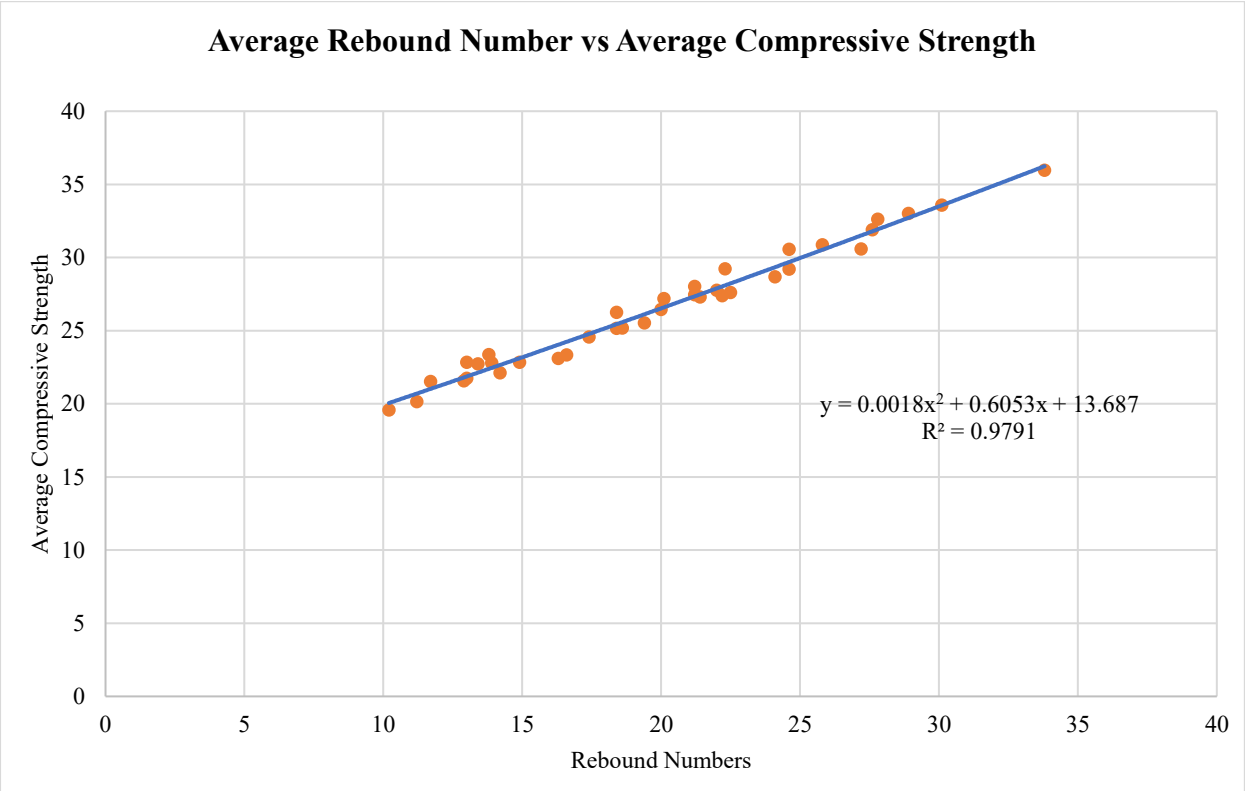

Figure 4.4: Scatter plot of average rebound numbers against average compressive strength obtained using Microsoft Excel data analysis software showing the coefficient of determination (R^2)

4.2 Discussion of Results

4.2.1 General Trend in Compressive Strength

The results show a diminishing trend of compressive strength with increasing proportions of replacement with Recycled Coarse Aggregate (RCA) in all the concrete grades (M20, M25, and M30). The trend aligns with most of the previous studies (Silva, de Brito *et al.* 2014, Xuan, Zhan *et al.* 2018, Li, Xiao *et al.* 2021) which attribute the strength reduction to the weaker Interfacial Transition Zone (ITZ) and increased porosity resulting from the cement-bonded mortar on RCA surfaces.

In the case of M20 mix, the 28-day average strength reduced from 26.27 MPa (0% RCA) to 18.07 MPa (100% RCA), which is about 31% reduction. M25 and M30 mixes also followed the same

trend but with slightly lower reductions, reflecting the fact that higher-grade concretes are relatively more resistant to RCA replacement. Such grade resistance may be due to the more compacted cement paste that better offsets the weaker aspect of RCA.

With all the mixtures, the compressive strength increased with the curing age (7 → 14 → 28 days), confirming continuous hydration. The rate of strength improvement decreased with an increased content of RCA due to the possibility of higher internal porosity and lower moisture retention capacity of RCA particles.

4.2.2 Effect of Curing Period

At 7 days, most mixes achieved 60–70% of their 28-day strength, in line with expectations for normal Portland cement concretes. For specimens removed from water curing after 7 or 14 days and exposed to air curing thereafter, minor reductions in strength were observed, consistent with interrupted hydration. The impact of air curing was more significant for high RCA contents, as recycled aggregates tend to absorb and lose moisture faster, limiting internal curing efficiency.

4.2.3 Relationship between Rebound Number and Compressive Strength

The rebound hammer test results generally followed the same pattern as the compressive strength results: rebound numbers decreased as RCA content increased and increased with curing age. The relationship between the average rebound number and compressive strength exhibited a strong positive correlation with a coefficient of determination $R^2 = 0.9791$ (Figure 4.4).

This high R^2 value demonstrates that rebound hammer readings can reliably estimate the compressive strength of both natural and Recycled Concretes when properly calibrated. The derived correlation equation:

$$f_c = 0.0114R^2 + 0.1898R + 17.887 \ldots\ldots (4.1)$$

provides a practical tool for estimating in-situ strength from non-destructive rebound measurements. However, since the rebound tests were conducted horizontally, a minor directional correction (±1–2 rebound units) may be necessary for comparison with vertically tested specimens (ASTM 2013).

4.2.4 Influence of Recycled Aggregate on Rebound Response

The lower rebound numbers recorded for mixes with higher RCA content confirm that recycled aggregates influence surface hardness. This effect is due to:

a. Increased surface roughness and microcracking within RCA,
b. Higher water absorption and residual mortar layers,
c. Weaker ITZ between old and new cement paste.

These characteristics cause a softer surface response to the rebound hammer impact, thereby reducing the rebound number even when the internal compressive strength remains moderately high. This reinforces the need for separate calibration curves for RC specimens rather than directly using calibrations from natural aggregate concretes.

4.2.5 Comparison Across Concrete Grades

Among the mixes, M30 concrete exhibited the least variation between 0% and 100% RCA replacement, followed by M25 and M20. This suggests that the negative influence of RCA on compressive strength and rebound response diminishes with increasing concrete grade, as richer cement pastes provide stronger bonding and lower effective porosity.

Moreover, for all grades, the close correlation between rebound and compressive values confirms the rebound hammer's potential as a viable non-destructive testing method for assessing RC—provided calibration is carried out using cubes of the same size and testing orientation.

4.2.6 Zero Rebound Numbers for M20 Specimens

Some M20 concrete cubes yielded abnormally low or zero rebound numbers. This was primarily due to the use of 100 mm cubes with a rebound hammer calibrated for 150 mm cubes. The smaller specimens lacked sufficient mass and rigidity to resist the hammer's impact, resulting in dampened or null rebounds. Consequently, these readings were treated as invalid and excluded from correlation analysis.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The experimental results have shown that the introduction of Recycled Coarse Aggregates significantly influences the compressive strength and surface hardness of concrete. As the percentage of recycled aggregate increased, both compressive strength and rebound numbers declined, reflecting the weaker interfacial bond and higher porosity associated with adhered mortar on the recycled aggregates. This effect was most pronounced in the M20 grade, where full replacement resulted in an approximate 31% reduction in strength, but less severe in higher grades such as M25 and M30, whose denser cement matrices provided better resistance to RCA-induced weaknesses.

Despite these reductions, the general pattern of strength development followed that of conventional concrete — with strength increasing with curing age — suggesting that hydration was not fundamentally disrupted, only less efficient. Continuous water curing proved crucial in maintaining hydration.

The rebound hammer results closely reflected the compressive strength trends, confirming a strong positive correlation ($R^2 = 0.9791$) between rebound number and actual compressive strength. This high degree of correlation indicates that the rebound hammer can serve as a dependable non-destructive testing tool for assessing RC, as long as calibration is performed using specimens of the same size, curing condition, and testing orientation. In this study, all rebound tests were conducted horizontally, and although this introduces minor direction-based variations, the results remain consistent enough to validate the reliability of the method.

5.2 Recommendations

Based on experimental results and considering variability and practical quality control, a 25% replacement of Natural Coarse Aggregate (NCA) by Recycled Coarse Aggregate (RCA) is recommended as the optimum level for M20, M25 and M30 mixes. At this replacement, the average 28-day compressive strengths (22.85 MPa, 27.63 MPa and 33.03 MPa respectively) exceeded their characteristic strengths while delivering the environmental benefits associated with RCA use. The 25% level strikes a balance between sustainability and structural performance, and should therefore be adopted as the recommended replacement level for practical application and further study.

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