COMPARISON OF STRENGTH OF CONCRETE USING REBOUND HAMMER TEST AND COMPRESSIBILITY TEST WITH DIFFERENT MIX RATIOS

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PLAGIARISM

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DEDICATION

In heartfelt gratitude and humble acknowledgement of the divine and unwavering love of God almighty, I dedicate this project to His glory. It is through His guidance and blessings that I have navigated the challenges and triumphs of this endeavor.

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ABSTRACT

This study presents a comparative evaluation of the strength characteristics of concrete using both non-destructive (rebound hammer) and destructive (compressive strength) testing methods. The primary aim of the research was to determine the correlation between rebound hammer readings and actual compressive strength values of concrete produced from different mix ratios; 1:2:4 (C20), 1:1.5:3 (C25), and 1:1:2 (C30) under proper compaction and curing conditions. The investigation was motivated by the need to establish a reliable, quick, and non-invasive method for assessing the in-situ strength of concrete structures while maintaining compliance with international testing standards.

The experimental program involved casting 100 mm × 100 mm × 100 mm concrete cubes for each mix ratio. The cubes were cured for 7, 14, and 28 days, after which they were tested using a Schmidt rebound hammer in accordance with BS EN 12504-2:2012 and ASTM C805, and a compressive testing machine following BS EN 12390-3:2019. In addition, a sieve analysis was performed on both fine and coarse aggregates to determine their particle size distribution and compliance with BS 812 (Part 103.1:1985) standards. Statistical regression analysis was also conducted to develop mathematical relationships between rebound number and compressive strength, and to determine the coefficient of determination (R^2) for each mix ratio.

The results indicated that concrete strength increased consistently with both higher cement content and longer curing periods. At 28 days, average compressive strengths of 17.89 N/mm², 25.92 N/mm², and 31.52 N/mm² were recorded for C20, C25, and C30 grades respectively. The rebound hammer results were found to underestimate compressive strength by about 5–10%, but showed a strong correlation, with R^2 values of 0.85 (C20), 0.96 (C25), and 0.98 (C30). The findings confirm that while the rebound hammer test cannot replace compressive testing for structural verification, it is a valuable non-destructive tool for rapid field assessment and comparative strength evaluation. Proper calibration using laboratory data is essential to ensure reliable application in in-situ concrete quality control.

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LIST OF ACRONYMS

ASTM – American Society for Testing and Materials

BS EN 12390 – British Standard European Norm

CTM – Compressibility Testing Machine

NDT – Non-Destructive Test

NIS – Nigeria Industrial Standard

OPC – Ordinary Portland Cement

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of Study

Concrete is one of the most widely used construction materials globally due to its high compressive strength, durability, and versatility in structural applications (Neville, 2011). In civil engineering practice, concrete strength is a critical property that directly affects structural safety, serviceability, and long-term performance, making accurate strength assessment essential for quality control, structural evaluation, and material optimization during both construction and maintenance stages (Neville, 2011).

Concrete strength is typically evaluated using destructive and non-destructive testing methods. Destructive testing, particularly compressive strength testing of standard specimens such as cubes or cylinders, involves loading specimens to failure in a compression testing machine to determine maximum load capacity. This approach is considered the most reliable direct measure of concrete strength but permanently damages the test specimens, making it unsuitable for in-situ evaluation of existing structures (ASTM C39/C39M, 2023; BS EN 12390-3, 2019).

Non-destructive testing methods have gained popularity because they allow inspection of concrete elements without destroying specimens. A widely used non-destructive technique is the rebound hammer test, which estimates concrete strength by measuring surface hardness through the rebound of a spring-driven mass impacting the concrete surface (ASTM C805, 2018; Malhotra and Carino, 2004). The rebound number obtained from the test can be empirically correlated with compressive strength for a given concrete mixture.

Although convenient and cost-effective, rebound hammer results are influenced by factors such as concrete mix design, age, moisture condition, surface smoothness, carbonation, and curing history, which can affect the accuracy of strength estimation (ASTM C805, 2018; Malhotra and Carino, 2004).

In Nigeria, construction practices are often marked by variable material quality, inconsistent workmanship, and limited enforcement of quality control standards, which can further complicate reliable strength evaluation on site (Neville, 2011). Therefore, understanding the relationship between destructive and non-destructive test results across different concrete mix ratios is crucial to improving the reliability of in-situ strength assessments. This study investigates the performance of the rebound hammer test in comparison to compressive strength tests for concrete produced using different mix ratios, with the aim of enhancing on-site testing reliability.

1.2 Statement of The Problem

Despite the rebound hammer's convenience, questions persist regarding its accuracy and reliability in predicting concrete strength, especially in locally sourced materials and varying concrete mix ratios used in Nigerian construction. Many professionals hesitate to rely solely on non-destructive testing because of potential inaccuracies caused by improper calibration, varying mix ratios, and site conditions.

There is a significant need to determine whether the rebound hammer test can provide dependable results comparable to the compressive strength test across various concrete mixes. This study addresses the knowledge gap by comparing the two methods using standard concrete mix ratios, with the goal of validating or questioning the rebound hammer's effectiveness in local applications

1.3 Aim and Objective of The Study

The main aim of this work is to compare the strength of concrete using the rebound hammer test and compressibility test across different mix ratios.

The specific objectives are to:

1. Prepare concrete samples using mix ratios of 1:2:4, 1:1.5:3, and 1:1:2.
2. Carry out rebound hammer tests on the cured samples.
3. Perform compressive strength tests on the same samples.
4. Compare and analyze the results of both testing methods.
5. Assess the reliability of the rebound hammer test as a substitute for compressive strength testing.

1.4 Scope of Study

This research involves the preparation of concrete cubes using three standard mix ratios. The concrete will be cured for 28 days in a curing tank. Non-destructive tests using a Schmidt rebound hammer will be conducted on the cubes before crushing them in a compression machine. All laboratory tests will be conducted in a civil engineering laboratory, University of Benin equipped with necessary tools. The results from each method will be analyzed using basic statistical techniques to evaluate consistency and correlation.

1.5 Justification of Study

This study is important in improving quality control practices in Nigerian construction. By providing data on how rebound hammer results correlate with compressive strength across different mixes, it allows engineers to make informed decisions regarding structural assessments. The rebound hammer’s convenience makes it ideal for field applications, but its effectiveness must first be verified against established methods. The outcome will also contribute to localized knowledge and standards, reducing the dependency on foreign calibration models that may not reflect local materials.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

This chapter reviews existing study on the compressive strength and rebound hammer testing of concrete made with different mix ratios. The review includes definitions, processes, concepts, Nigerian and global case studies, theoretical frameworks, and research gaps identified. The objective is to establish a solid academic foundation for the present study and to support the validity of using non-destructive techniques such as the rebound hammer test in comparison to destructive testing.

2.2 Concept of Concrete Strength

Concrete strength is a critical parameter in assessing the load-bearing capacity of concrete in structures. It is influenced by factors such as water-cement ratio, aggregate size, curing method, and mix proportion. The most commonly measured strength property is compressive strength, which is the maximum load a concrete specimen can sustain under axial compression. This parameter ensures structural reliability and safety in buildings and infrastructure.

2.2.1 Definition of Concrete Strength

Concrete strength refers to the ability of a concrete element to withstand stress without failure. It is a mechanical property that describes how much load a concrete specimen can bear under various types of force, such as compression, tension, and shear. Among these, compressive strength is the most commonly measured and most significant in structural applications. It is expressed in Newtons per square millimeter (N/mm^2) or megapascals (MPa), with 1 MPa equaling 1 N/mm^2.

2.2.2 Types of Concrete Strength

Concrete exhibits different types of strength properties, each relevant for specific structural applications:

a) Compressive Strength: Compressive strength is defined as the maximum compressive load a concrete specimen can bear per unit area before failure. It is typically expressed in Newton per square millimeter (N/mm^2). This strength is determined by subjecting a standard concrete cube (100 mm × 100 mm × 100 mm) or cylinder to axial compression in a testing machine until it fails. The compressive strength of concrete is the most commonly measured mechanical property because it directly reflects the material's ability to carry structural loads and resist crushing forces in real-world applications.

b) Tensile Strength: Tensile strength is the resistance of concrete to being pulled apart or stretched. It is typically much lower than compressive strength because concrete is inherently brittle in tension. Its measured by flexural test, typically tensile strength ranges from 8–12% of a concrete’s compressive strength. Although concrete itself is weak in tension, its tensile strength still matters in slab and cantilevers. In reinforced concrete, steel bars are placed where tensile forces are expected to compensate for concrete low tensile strength.

c) Flexural Strength: Flexural strength, or modulus of rupture, measures concrete’s ability to resist bending or flexural loads. It is critical for concrete elements that span horizontally and are subject to bending. flexural strength indicates the stress at which concrete will fracture under a load. Flexural strength is especially important in Concrete roads and highways.

2.2.3 Factors Influencing Concrete Strength

Several parameters influence the final strength of concrete:

a) Water-Cement Ratio: A lower water-cement ratio leads to higher strength by reducing voids and enhancing bonding.

b) Curing Conditions: Adequate moisture and temperature conditions promote continued hydration, a chemical reaction essential for strength development.

c) Aggregate Quality: The size, texture, and composition of fine and coarse aggregates significantly influence bonding and strength.

d) Mix Proportion: Balanced ratios of cement, sand, and coarse aggregate ensure uniform strength across the batch.

e) Admixtures: Chemical or mineral additives like superplasticizers, silica fume, or fly ash can increase strength and durability.

2.2.4 Importance of Concrete Strength in Structural Engineering

Concrete strength determines the design, load-bearing capacity, and safety of structural elements. Building codes such as BS EN 1992 and the Nigerian Building Code specify minimum compressive strength values for different structural elements (e.g., 20 MPa for beams, 25 MPa for columns). Inadequate strength can result in premature failure, excessive deflection, or collapse, especially in critical infrastructure like bridges.

2.3 Concrete Mix Ratios and their Influence

Concrete mix ratio refers to the proportion of cement, sand (fine aggregate), and coarse aggregate in a concrete mixture. The typical mix ratios include 1:2:4, 1:1.5:3, and 1:1:2, corresponding to low, medium, and high strength concrete respectively. According to Ede et al. (2017), increasing cement content improves the compressive strength of concrete, especially when properly cured. Similarly, Ramonu et al. (2019) compared the performance of conventional (1:2:4) and non-conventional (1:3:3) concrete mixes and concluded that compressive strength varies significantly with mix ratio and aggregate quality. Nigerian practice often suffers from poor batching consistency, leading to variability in concrete strength.

2.3.1 Common Mix Ratios Used in Nigeria

In Nigeria, the most frequently used concrete mix ratios are:

a) 1:2:4: Widely used for general construction such as slabs and walls.

b) 1:1.5:3: Used for moderately high-strength applications.

c) 1:1:2: Used in high-strength structural elements.

d) 1:3:3: Sometimes used for non-structural or experimental purposes.

2.3.2 Influence of Mix Ratio on Strength Development

Mix ratio directly affects:

a) Strength: More cement usually means higher strength.
b) Workability: High sand or water content can improve workability but reduce strength.
c) Durability: Unbalanced ratios lead to porous concrete that deteriorates faster.

According to Ede et al. (2017), mix ratios like 1:1.5:3 and 1:1:2 showed significantly higher strength than 1:2:4 under identical conditions. Ramonu et al. (2019) confirmed that even a mix like 1:3:3 could meet minimum strength if high-quality aggregates and proper curing were used.

2.3.3 Errors in Mix Design and Site Practices

Common mix design errors in Nigeria include:

a) Volume batching instead of weight batching, which is less accurate.
b) Improper water measurement, either too much or too little.
c) Substituting river sand with unprocessed local materials, affecting strength and workability.

2.4 The Rebound hammer Test

The rebound hammer, developed by Ernst Schmidt in 1948, is a non-destructive test

(NDT) used to estimate the surface hardness of concrete. It measures the rebound of a spring-driven mass impacting a concrete surface. The rebound value, or rebound number, correlates with compressive strength using calibration curves. However, the test is sensitive to surface condition, moisture content, carbonation, and concrete age. According to Malhotra and Carino (2004), accuracy depends on proper calibration and consistent testing conditions. The rebound hammer is popular due to its speed, portability, and ease of use, particularly in field conditions.

2.4.1 Working Principle of the Rebound Hammer

The device works by releasing a spring-driven plunger against the concrete surface. The amount the plunger rebounds is proportional to the surface hardness, which is loosely correlated with compressive strength. The result is measured as a rebound index or rebound number and correlated using calibration curves.

2.5 The Compressive Strength Test

The compressive strength test is a destructive method where a concrete cube or cylinder is subjected to axial loading until failure. This test is widely regarded as the standard method for determining concrete strength and is governed by international standards such as ASTM C39 and BS EN 12390. While highly accurate, it is labor-intensive, time-consuming, and unsuitable for in-situ structures. This test is necessary for validating non-destructive results and ensuring structural safety.

2.5.1 Testing Procedure (Cube methods)

The standard testing procedure involves:

a) Casting specimens: Usually cubes (100 mm^3).

b) Curing: Specimens are cured in water or a controlled environment for 7, 14, or 28 days.

c) Testing: The cured specimens are placed in a compression testing machine and loaded until failure.

Relevant standards include:

a) ASTM C39 (USA standard)
b) BS EN 12390 (European standard)
c) Nigerian Industrial Standard NIS 444

2.5.2 Advantages and Disadvantages of Compressive Strength Test

Advantages:

a) High accuracy and repeatability
b) Accepted by all engineering codes
c) Basis for design validation

Disadvantages:

a) Destructive (specimen cannot be reused)
b) Time-consuming and labor-intensive
c) Impractical for in-situ structures
d) Requires expensive equipment

2.5.3 Comparison with Non-Destructive Testing (NDT)

Unlike NDT, compressive strength testing cannot assess already constructed elements without coring or damaging them. However, it provides ground truth data which can be used to validate NDT results, such as those obtained from the rebound hammer test.

2.5.4 Structural Applications of Compressive Strength in Nigerian Construction

In Nigerian construction, where manual batching and site mixing are prevalent, compressive strength serves as the primary quality control indicator. Its role spans virtually all structural elements, including:

a) Columns: Vertical load-bearing members in residential and multi-storey buildings rely entirely on compressive strength to safely transmit loads to the foundation.

Inadequate strength leads to buckling or collapse.

b) Beams and Slabs: Although flexural strength is important, the compression zones of these elements (especially in reinforced concrete) depend on sufficient compressive capacity to resist diagonal and shear cracks.

c) Foundations and Footings: As the interface between superstructures and soil, these elements must resist both compressive and bearing loads. Weak concrete can result in uneven settlement or structural failure.

d) Retaining Walls and Bridge Piers: These structural systems are designed to withstand axial loads, lateral earth pressure, and dynamic forces, requiring high compressive strength for stability and durability.

Roads and Pavements: Concrete roadways and airport runways in Nigeria are designed based on compressive strength to withstand vehicle loads, environmental wear, and heavy-duty applications.

2.6 Nigeria-Based Studies on Concrete Strength Testing

Several studies have investigated the relationship between concrete mix ratios and strength in Nigeria. Ede et al. (2017) demonstrated that concrete made with 1:1.5:3 and 1:1:2 mix ratios yielded higher strength than the more commonly used 1:2:4, affirming the influence of cement content. Ramonu et al. (2019) analyzed the compressive strength of concrete in Ibadan using mix ratios 1:2:4 and 1:3:3 and found that while 1:2:4 remained reliable, it required quality aggregates and controlled curing to reach expected performance.

2.7 Calibrations and Limitations of Rebound Hammer

One major challenge with the rebound hammer is the reliance on foreign calibration charts that do not consider the properties of Nigerian aggregates or curing conditions. This discrepancy often results in inaccurate predictions. Malhotra and Carino (2004) suggested that local calibration is necessary for meaningful application. Carbonation and microcracks on the concrete surface can also influence readings and the presence of laitance on concrete surfaces could distort rebound values by up to 25% if not properly considered. Destructive tests, while more accurate, are limited by cost and time constraints.

2.7.1 The Need for Local Calibration in Nigeria

Foreign calibration curves used with rebound hammers are based on aggregates and cement types that differ significantly from those in Nigeria. These generic charts often fail to account for:

a) Local limestone, granite, or lateritic aggregates
b) Tropical weather conditions affecting surface hardness
c) Variations in local cement brand compositions

2.7.2 Effect of Surface Conditions on Rebound Results

Rebound values are highly sensitive to:

a) Surface roughness
b) Moisture content
c) Curing quality
d) Paint or finish coatings

All these factors may yield misleadingly high or low readings if not controlled. of Surface Conditions on Rebound Results.

2.7.3 Role of Carbonation and Microcracks

Carbonation is a chemical process where carbon dioxide reacts with calcium hydroxide in concrete, creating a harder surface crust. This results in higher rebound values, which do not reflect internal strength. Microcracks, especially in poorly cured concrete, reduce rebound accuracy by absorbing energy during impact.

2.7.4 Influence of Laitance and Weathering

Laitance, a weak, powdery surface layer, forms due to excess water rising during finishing. It can distort rebound readings by up to 25%, as shown in Malhotra and Carino (2004). Additionally, long-term exposure to sun, rain, and dust leads to surface deterioration, reducing measurement reliability.

2.7.5 Comparison with Destructive Testing Accuracy

While destructive tests offer more precise results, they are not feasible for existing structures. Rebound hammers are only effective when:

a) Used under controlled conditions

b) Calibrated with known-strength samples

c) Repeated multiple times to allow statistical averaging

2.8 Empirical Modeling in Concrete Strength Estimation

Empirical modeling involves the use of mathematical relationships derived from experimental data to estimate unknown parameters. In the context of concrete strength testing, empirical models help predict compressive strength using measurable indices like rebound number. These models allow engineers to estimate in-situ strength without the need for destructive sampling.

2.8.1 Regression Analysis in Non-Destructive Testing (NDT)

Regression analysis is a statistical tool used to identify and quantify relationships between variables. In rebound hammer testing, regression is applied to correlate rebound numbers (independent variable) with compressive strength (dependent variable). The accuracy of these models depends on:

a) The quality of calibration data

b) Environmental conditions during testing

c) The specific mix and material type used in the calibration

2.8.2 Regression Equation

This study is grounded in empirical modeling, where relationships between rebound values and compressive strength are expressed through regression equations. For example:

$$Fc = a + b(R) \tag{2.1}$$

Where:

Fc = estimated compressive strength (N/mm²)

R = rebound number

a, b = regression coefficients determined through calibration (where a is the intercept and b is the slope of the graph). These models require site-specific calibration to enhance reliability. The use of regression analysis allows for comparative interpretation of test results.

2.8.3 Calibration Curve Development

Calibration of the Schmidt rebound hammer is crucial for transforming rebound numbers into accurate estimates of concrete compressive strength.

2.8.3.1 Experimental Data Collection

Concrete specimens matching the specific mix designs (including water–cement ratios and aggregate types) are prepared and cured, then tested in parallel through:

a) Rebound hammer, following ASTM C805 or EN 12504-2 typically 9–15 readings per sample.

b) Compressive strength test, on companion cubes or cylinders at 28 days

Fawzi (2006) collected data on concretes with w/c ratios of 0.3, 0.4, and 0.5, constructing mix-specific curves for 15, 20, and 25 MPa grades.

2.8.3.2 Model Fitting

After data collection, statistical analysis elucidates the form of the correlation:

a) Linear models are common for narrow strength ranges,

b) Non-linear (quadratic) or logarithmic models may better represent wider strength spectrums.

2.8.3.3 Non-Linearity and Influencing Factors

Calibration curves depend heavily on variables such as:

a) Moisture condition (dry vs saturated specimens),

b) Stress state and age, especially for pre-stressed or previously loaded concrete

c) Aggregate type: differences in Young’s modulus (quartz vs limestone) can shift curves by 50%

d) Surface condition: rough, carbonated, or grout-covered surfaces yield inaccurate results unless compensated.

Brencich et al. (2020) and Aydin and Saribiyik (2010) emphasized that no universal curve fits all; calibration must reflect local materials and test conditions

2.8.4 Importance of Site-Specific Calibration

Generic models are often unreliable in field conditions due to variations in material properties, curing regimes, and surface conditions. Hence, site-specific or region-specific calibration ensures:

a) More accurate predictions

b) Better decision-making for rehabilitation and quality control

c) Safer design practices based on verified data

2.9 Identified Research Gap

Despite numerous studies, gaps persist in understanding how rebound hammer values correlate with compressive strength across diverse mix ratios in the Nigerian context.

Many existing calibration charts are not based on local materials. Furthermore, there is a lack of systematic comparison of both tests under identical curing and mix ratio conditions. This study aims to address these gaps by conducting a side-by-side evaluation under controlled laboratory conditions.

2.9.1 Local Nigerian Case Studies

a) Onyeka (2021) compared rebound hammer and pull-out tests on cubes of 1:2:4 and 1:3:6 mix designs. Rebound hammer demonstrated slightly higher correlation (0.695–0.724) than pull-out across curing ages.

b) Agunwamba and Adagba (2012) showed rebound hammer correlation coefficients up to 0.794 for 1:2:4 mix and 0.783 for 1:3:6, outperforming UPV in those cases.

These studies reinforce the need for location- and mix-specific calibrations, especially in the Nigerian context.

2.9.2 Limited Use of Regression Modeling in Nigerian Studies

Few researchers develop mathematical models that correlate rebound hammer readings with actual compressive strength using Nigerian materials. The general absence of site-calibrated empirical models reduces the accuracy of NDT-based decisions in construction.

This study bridges these gaps by:

a) Conducting controlled lab experiments on different mix ratios

b) Performing both compressive and rebound tests on the same samples

c) Developing regionally relevant regression models

2.10 Summary of Literature Review

The literature reviewed confirms the relevance of concrete mix design, the reliability of compressive strength testing, and the potential of rebound hammer testing as a nondestructive alternative. However, limitations in calibration and lack of regional adaptation reduce the accuracy of NDT. The chapter has also established a gap in the comparative evaluation of both tests in Nigeria using different mix ratios. The current study is therefore positioned to provide much-needed validation data for more reliable structural assessments in Nigerian construction projects.

2.10.1 Justification for the Study

There is an urgent need to:

a) Develop local calibration frameworks for rebound hammer use

b) Validate NDT results using destructive tests on the same specimens

c) Test the influence of mix ratio on both testing methods under standardized Nigerian conditions

CHAPTER THREE

METHODOLOGY

3.1 The study area

The research was carried out in the Civil Engineering Laboratory, University of Benin. This facility was equipped with concrete mixing equipment, curing tanks, compression testing machines, and Schmidt rebound hammers. It provided a controlled environment suitable for the preparation, curing, and testing of concrete samples under standard conditions. This chapter presented the research methodology adopted for the study on comparing the strength of concrete using the rebound hammer test and compressive strength test with different mix ratios. The methodology provided a step-by-step outline of the experimental procedures, data collection methods, equipment used, and data analysis techniques. Emphasis was placed on ensuring repeatability, reliability, and contextual relevance by using locally sourced materials and standardized testing procedures.

3.2 Materials and Equipment

The materials used in this study include:

3.2.1 Cement

Ordinary Portland Cement (OPC) that conformed to applicable international standards (such as BS EN 197-1) was used. The same type and brand of cement were employed consistently throughout the project to ensure uniformity.

3.2.2 Fine Aggregates

Fine aggregate, specifically river sand obtained from local sources, was utilized. The sand was free from impurities and met the grading requirements specified in relevant standards such as ASTM C33 and BS EN 12620. A sieve analysis was conducted to determine its fineness modulus.

3.2.3 Coarse Aggregates

Crushed granite that met the grading standards specified by relevant guidelines, such as ASTM C33 and BS EN 12620, was utilized as coarse aggregate. The maximum aggregate size was kept the same for all mixtures.

3.2.4 Water

Water that is safe to drink and free from harmful substances was used for mixing and curing.

3.2.5 Rebound hammer

A calibrated rebound hammer, such as a Schmidt hammer, that met the standards of ASTM C805 or BS EN 12504-2 was utilized.

3.2.6 Compression Testing Machine

A calibrated universal testing machine (UTM) or a specific compression testing machine that met the standards of ASTM C39 or BS EN 12390-4 was used. This equipment had the suitable loading capacity for testing concrete cubes or cylinders.

3.2.7 Concrete Mixer

A mechanical concrete mixer with the appropriate capacity was utilized to achieve uniform mixing.

3.2.8 Molds

Standard cube molds, such as those measuring 100 mm on each side was used in accordance with applicable standards like ASTM C31 or BS EN 12390-1. The selection between a cube and a cylinder remained the same.

3.2.9 Curing Tank

A water-curing tank is used for the submerged curing of concrete samples. A precise weighing balance for accurately measuring the amounts of cement, aggregates, and water.

3.2.10 Tampon rod

A tamping rod that meets the required standards or a vibrating table or poker vibrator used for compacting concrete in molds.

3.2.11 Measuring cylinder

Measuring cylinders and buckets are used to measure water and aggregates by volume rather than by weight.

3.2.12 Trowels and Scoops

Trowels and scoops are used for managing and applying concrete.

3.3 Mix Design and Sample Preparation

Concrete cubes of size 100 mm × 100 mm × 100 mm were cast for each mix ratio, namely 1:2:4, 1:1.5:3, and 1:1:2 as shown in the subsequent tables below. Proper compaction was achieved using a mechanical vibrator in accordance with BS EN 12390-2:2019 to eliminate voids and honeycombing. After demoulding at 24 hours, the specimens were cured in water tanks at room temperature (20 ± 2°C) until their testing ages of 7, 14, and 28 days.

3.3.1 Concrete Mixing Procedure

a) Mix Design: A minimum of three different concrete mix ratios will be investigated to represent a range of strengths. These could include:

b) Mix 1 (Lean Mix): e.g., 1:2:4 (Cement: Fine Aggregate: Coarse Aggregate) with a water-cement ratio (w/c) of approximately 0.50.

c) Mix 2 (Normal Mix): e.g., 1:1.5:3 (Cement: Fine Aggregate: Coarse Aggregate) with a w/c ratio of approximately 0.45.

d) Mix 3 (Rich Mix): e.g., 1:1:2 (Cement: Fine Aggregate: Coarse Aggregate) with a w/c ratio of approximately 0.4.

For each mix ratio, the exact proportions will be determined by weight to ensure accuracy. Slump tests will be performed on fresh concrete to assess workability and ensure consistency within each mix.

a) Batching: All materials (cement, fine aggregate, coarse aggregate) will be weighed accurately according to the designed mix proportions.
b) Dry Mixing: Cement, fine aggregate, and coarse aggregate will be thoroughly mixed in the concrete mixer in a dry state for approximately 2 minutes until a uniform color is achieved.
c) Wet Mixing: A measured quantity of water will be gradually added to the dry mix while the mixer is running. Mixing will continue for another 3-5 minutes until a homogeneous and workable concrete mix is obtained.
d) Slump Test: A slump test will be performed immediately after mixing to verify the workability of the fresh concrete according to relevant standards (e.g., ASTM C143 or BS EN 12350-2).
e) Casting Specimens: The fresh concrete will be cast into molds in three layers, with each layer being compacted thoroughly using a tamping rod (25 strokes per layer) or a vibrating table/poker vibrator to remove air voids.
f) Finishing: The top surface of the specimens will be leveled and smoothed with a trowel.
g) Demolding: After 24 ± 0.5 hours, the specimens will be carefully demolded
h) Curing: The demolded specimens will be immediately placed in a water-curing tank/pond maintained at a temperature of 20 ± 2°C until the designated testing age. For each mix ratio, a minimum of 9 specimens will be cast to allow for testing at

different ages (e.g., 7 days, 14 days, 28 days) and to provide multiple readings for both tests.

3.4 Testing Procedure

Testing will be conducted at specific ages (e.g., 7 days, 14 days, and 28 days) to observe the strength development over time.

3.4.1 Compressive Strength Test Procedure

a) Specimen Preparation: At the designated testing age, three specimens from each mix ratio will be removed from the curing tank and allowed to dry surface-dry.

b) Measurement: The dimensions (length, width, height for cubes; diameter, height for cylinders) of each specimen will be measured to the nearest 0.1 mm.

c) Placement: Each specimen will be placed centrally on the lower platen of the compression testing machine.

d) Loading: The load will be applied continuously and without shock at a uniform rate (e.g., 0.2-0.4 MPa/s for cubes, 0.15-0.30 MPa/s for cylinders) until the specimen fails.

e) Recording: The maximum load at failure will be recorded.

f) Calculation: The compressive strength will be calculated by dividing the maximum load by the cross-sectional area of the specimen. The average of the three specimens for each mix ratio and testing age will be taken as the representative compressive strength.

3.4.2 Rebound Hammer Test Procedure

The Rebound Hammer test was performed on 100 mm × 100 mm × 100 mm concrete cubes after 28 days of curing for the three mix ratios. The concrete surface was cleaned and prepared before testing, and rebound numbers were obtained by taking an average of ten readings per cube using the Schmidt Type N Rebound Hammer. The equivalent compressive strengths were obtained using the standard calibration chart provided by BS

1881: Part 202 (1986) and correlated to the actual test data. Specimen Preparation: Immediately after conducting the compressive strength test on the specimens (before they are crushed, if a simultaneous test is deemed feasible, or on separate, identical specimens), the rebound hammer test will be performed. Ensure the surface of the concrete is smooth and dry. If performing on separate specimens, these must have undergone identical curing conditions.

a) Grid Marking: A grid of at least 9 to 12 evenly spaced points will be marked on the surface of each concrete specimen. Avoid testing near edges or corners.

b) Hammer Application: The rebound hammer will be held perpendicular to the concrete surface. The plunger will be pressed firmly and smoothly against the surface until the hammer fires.

c) Reading: The rebound number (R-value) will be read from the scale on the hammer.

d) Repeatability: At least three readings will be taken at each marked point, and any outlier readings significantly different from the others (e.g., more than 5 units) will be discarded or the test repeated at that point.

e) Averaging: The average of the valid rebound numbers for each specimen will be calculated.

f) Conversion (if applicable): While the primary aim is comparison, if a correlation curve is provided with the rebound hammer, the rebound numbers can be tentatively converted to compressive strength values for initial comparison. However, the focus will remain on the raw rebound numbers for direct correlation with measured compressive strength.

3.4.3 Simultaneous Testing Justification

The justification for simultaneous testing (i.e., performing the rebound hammer test on the same specimen just before it is crushed in the compression testing machine) is to ensure that both tests are conducted on concrete with identical properties and curing history. This minimizes variations that could arise from using different specimens, even if cast from the same batch. If simultaneous testing proves impractical or compromises the integrity of the compression test, then a parallel testing approach will be adopted, where an equal number of identical specimens are cast and cured, with some designated for rebound hammer testing and others for compression testing, ensuring strict consistency in all preparation and curing stages. The chosen approach will be clearly stated.

3.5 Data Analysis

Data analysis in this study was carried out to interpret the strength values obtained from both Non-Destructive Testing (NDT) and Destructive Testing methods using different concrete mix ratios. The aim was to establish patterns, correlations, and differences in concrete strength across methods and mix designs.

3.5.1 Correlation Analysis

Pearson's correlation coefficient (r) was used to evaluate the linear relationship between rebound hammer values and compressive strength results.

This was essential to determine:

a) Whether a rebound hammer can reliably estimate actual compressive strength

b) The degree of dependence between the two testing methods.

Interpretation of r values:

a. r = 0.90 – 1.00 → Very strong correlation

b. r = 0.70 – 0.89 → Strong correlation

c. r = 0.50 – 0.69 → Moderate correlation

d. r < 0.50 → Weak or no correlation

3.5.2 Comparative Analysis

The compressive strengths obtained from destructive testing were compared with the estimated strengths from the rebound hammer method. Percentage differences were calculated to assess the level of agreement between the two techniques.

This analysis allowed for:

a) Evaluating accuracy and reliability of the rebound hammer in strength estimation,

b) Understanding how mix ratio influences the divergence between both methods.

3.5.3 Validation of Results

Data Tabulation: All raw data, including mix ratios, w/c ratios, slump values, individual rebound numbers, average rebound numbers, individual maximum loads, individual compressive strengths, and average compressive strengths for each mix and testing age, will be systematically tabulated.

Statistical Analysis:

a) Descriptive Statistics: Calculate mean, standard deviation, and coefficient of variation for both rebound hammer readings and compressive strengths for each mix ratio and testing age.

b) Correlation Analysis: Plot scatter diagrams of average rebound numbers against average compressive strengths for all mix ratios and testing ages. Perform regression analysis (e.g., linear regression) to establish a correlation equation (if a reasonable correlation exists) between the rebound hammer readings and compressive strength. The coefficient of determination (R-squared value) will be used to quantify the strength of this correlation.

c) Comparison of Means: Use appropriate statistical tests (e.g., ANOVA or t-tests, depending on the number of groups and assumptions) to compare the mean compressive strengths obtained from different mix ratios at each testing age, and to compare the relationship between rebound hammer readings and compressive strength across different mixes.

d) Error Analysis: Identify and discuss potential sources of error in both testing methods
e) Graphical Representation: Present the data graphically using:
f) Bar charts to compare the average compressive strengths of different mix ratios at various ages
g) Line graphs to show the strength development over time for each mix ratio.
h) Scatter plots with regression lines to illustrate the correlation between rebound hammer readings and compressive strength.

3.5.4 Interpretation of Results

Findings from the data analysis were interpreted to:

a) Highlight the effect of mix ratio on strength development
b) Discuss the suitability of the rebound hammer for quality control in Nigerian construction settings
c) Make recommendations based on test comparisons and deviations observed.

The analytical framework ensured that the research objectives were fully addressed, especially in establishing the validity of NDT methods for estimating compressive strength in different concrete grades.

3.6 Sampling and Testing Considerations

a) Sample Size: A sufficient number of specimens (minimum of 3 for each test type, per mix, per age) will be used to ensure statistical significance and reliable averages.
b) Curing Conditions: Strict adherence to standard curing conditions (temperature and humidity) is crucial for consistent strength development.
c) Surface Preparation: For the rebound hammer test, the concrete surface must be clean, smooth, and dry. Rough or irregular surfaces will significantly affect readings.

d) Calibration: Both the rebound hammer and the compression testing machine will be calibrated regularly according to manufacturer's instructions and relevant standards to ensure accurate measurements.

e) Operator Bias: Efforts will be made to minimize operator bias by ensuring consistent testing procedures by a trained operator.

f) Environmental Factors: Environmental conditions during testing (e.g., temperature) will be monitored and noted, as they can influence rebound hammer readings.

g) Anomalies: Any unusual observations during mixing, casting, curing, or testing (e.g., honeycombing, cracks, premature failure) will be recorded and considered during data analysis.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results and discussion of the experimental work carried out to compare the strength of concrete using rebound hammer and compressive strength tests across three different mix ratios: 1:2:4, 1:1.5:3, and 1:1:2. The tests were performed on properly compacted concrete cubes, cured for 7, 14, and 28 days.

4.2 Hardened Concrete Result

4.2.1 Rebound Hammer Test Results (Non- Destructive Test)

The rebound hammer test was conducted in accordance with BS EN 12504-2:2012 and ASTM C805, on the cured specimens at 7, 14, and 28 days. The rebound number obtained was used to estimate equivalent compressive strength. In Tables 4.1 to 4.3, the rebound values from cube specimens at 7, 14, and 28 days of curing are presented.

Table 4.1: Rebound Hammer Results for Mix Ratio 1:2:4 (C20)

Age (Days)	Sample No	Weight (Kg)	Density (Kg/m³)	Rebound Number	Compressive Strength (N/mm²)	Average Rebound Value
7	A	2.585	2585	12	13.124	12
	B	2.593	2593	11	13.854	
	C	2.576	2576	12	14.196	
	D	2.601	2601	13	14.967	
	E	2.588	2588	13	13.953	
	A	2.589	2589	13	15.402	14

14	B	2.597	2597	13	16.109	
	C	2.590	2590	14	15.701	
	D	2.582	2582	14	16.905	
	E	2.591	2591	14	16.120	
28	A	2.589	2589	17	17.624	16
	B	2.590	2590	15	16.842	
	C	2.594	2594	18	18.596	
	D	2.601	2601	17	19.267	
	E	2.598	2598	16	17.133	

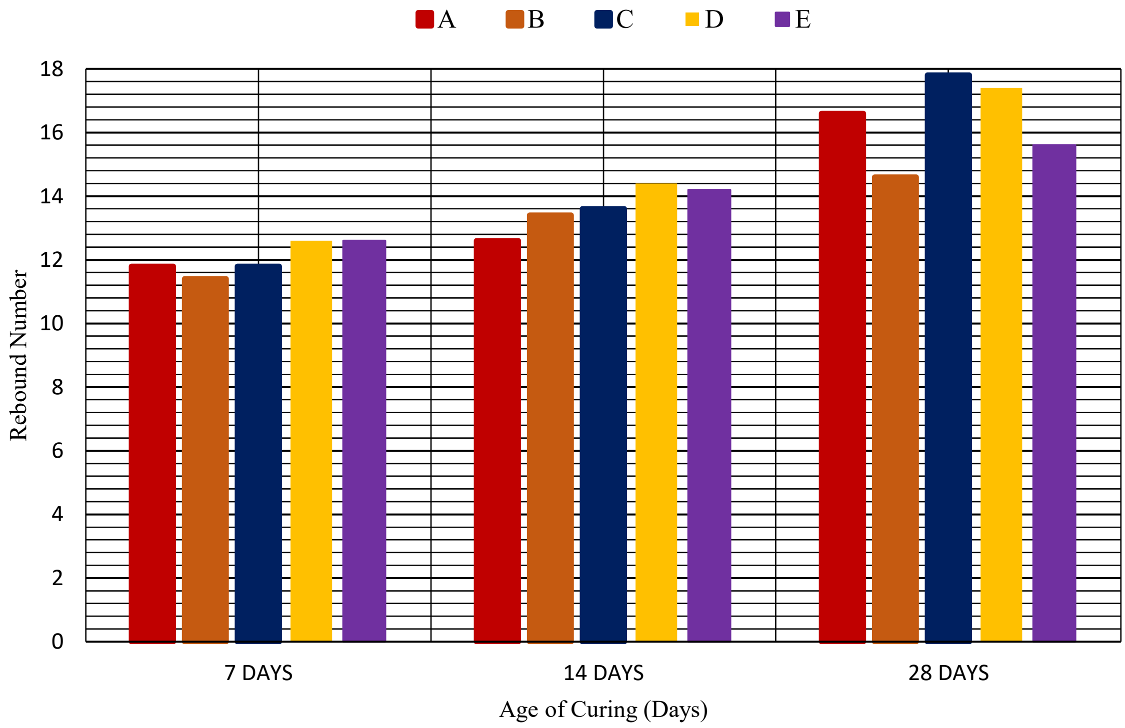

Figure 4.1: Chart Showing Comparison of Rebound Values at Various Age of Curing for C20

Table 4.2: Rebound Hammer Results for Mix Ratio 1:1.5:3 (C25)

Age (Days)	Sample No	Weight (Kg)	Density (Kg/m³)	Rebound Number	Compressive Strength (N/mm²)	Average Rebound Value
7	A	2.585	2585	15	17.821	16
	B	2.593	2593	16	18.317	
	C	2.576	2576	16	18.648	
	D	2.601	2601	17	19.109	
	E	2.588	2588	16	18.903	
14	A	2.589	2589	18	22.101	19
	B	2.597	2597	19	22.933	
	C	2.590	2590	19	23.347	
	D	2.582	2582	19	23.780	
	E	2.591	2591	19	23.404	
28	A	2.589	2589	22	25.711	22
	B	2.590	2590	21	25.196	
	C	2.594	2594	22	26.188	
	D	2.601	2601	22	26.509	
	E	2.598	2598	22	26.012	

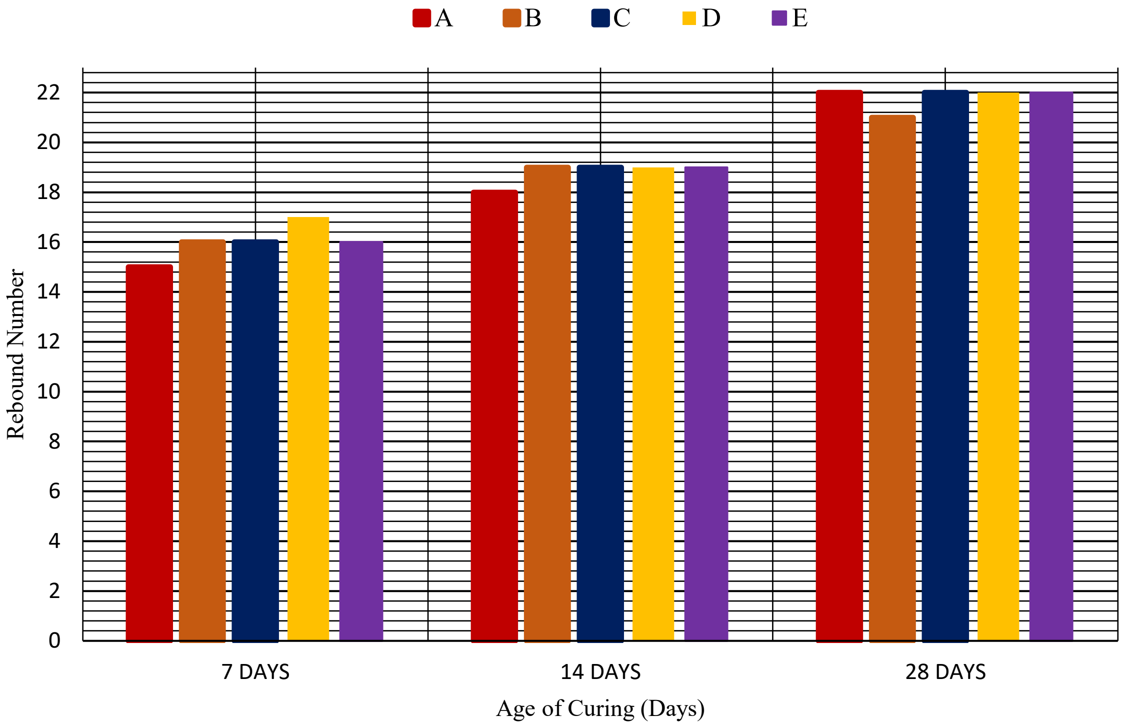

Figure 4.2: Chart Showing Comparison of Rebound Values at Various Age of Curing for C25

Table 4.3: Rebound Hammer Results for Mix Ratio 1:1:2 (C30)

Age (Days)	Sample No	Weight (Kg)	Density (Kg/m³)	Rebound Number	Compressive Strength (N/mm²)	Average Rebound Value
7	A	2.585	2585	19	24.812	20
	B	2.593	2593	19	25.371	
	C	2.576	2576	20	25.928	
	D	2.601	2601	20	26.190	
	E	2.588	2588	20	26.539	
	A	2.589	2589	23	28.210	24

14	B	2.597	2597	24	28.633	
	C	2.590	2590	24	29.174	
	D	2.582	2582	24	29.587	
	E	2.591	2591	25	29.804	
28	A	2.589	2589	27	30.711	28
	B	2.590	2590	27	31.169	
	C	2.594	2594	28	31.888	
	D	2.601	2601	28	32.229	
	E	2.598	2598	28	31.612	

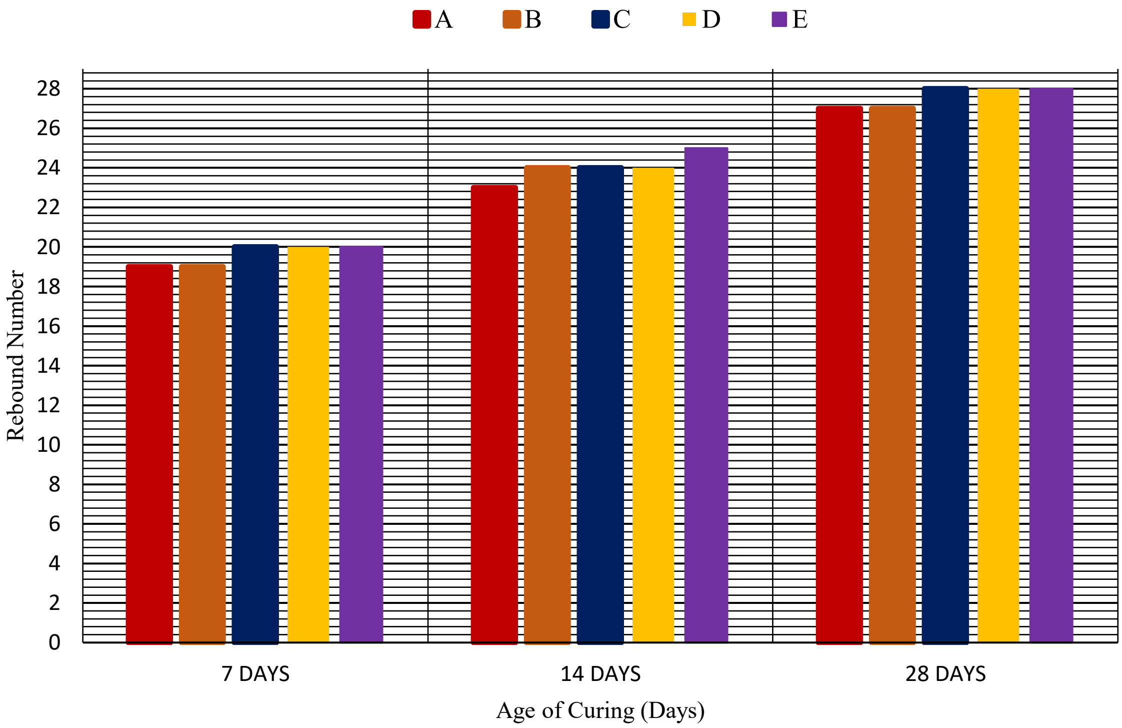

Figure 4.3: Chart Showing Comparison of Rebound Values at Various Age of Curing for C30

4.2.2 Compressive Strength Test (Destructive Test)

The compressive strength test was performed in accordance with BS EN 12390-3:2019. Tables 4.4–4.6 presents the average compressive strength results obtained from cube specimens at 7, 14, and 28 days of curing across the three different concrete mix ratios: 1:2:4, 1:1.5:3, and 1:1:2.

Table 4.4: Compressive Strength Test Results for Mix Ratio 1:2:4 (C20)

Age (Days)	Sample No	Weight (Kg)	Density (Kg/m³)	Failure load (KN)	Compressive Strength (N/mm²)	Average strength (N/mm²)
7	A	2.585	2585	131.24	13.124	14.019
	B	2.593	2593	138.54	13.854	
	C	2.576	2576	141.96	14.196	
	D	2.601	2601	149.67	14.967	
	E	2.588	2588	139.53	13.953	
14	A	2.589	2589	154.02	15.402	16.047
	B	2.597	2597	161.09	16.109	
	C	2.590	2590	157.01	15.701	
	D	2.582	2582	169.05	16.905	
	E	2.591	2591	161.2	16.120	
28	A	2.589	2589	176.24	17.624	17.892
	B	2.590	2590	168.42	16.842	
	C	2.594	2594	185.96	18.596	
	D	2.601	2601	192.67	19.267	
	E	2.598	2598	171.33	17.133	

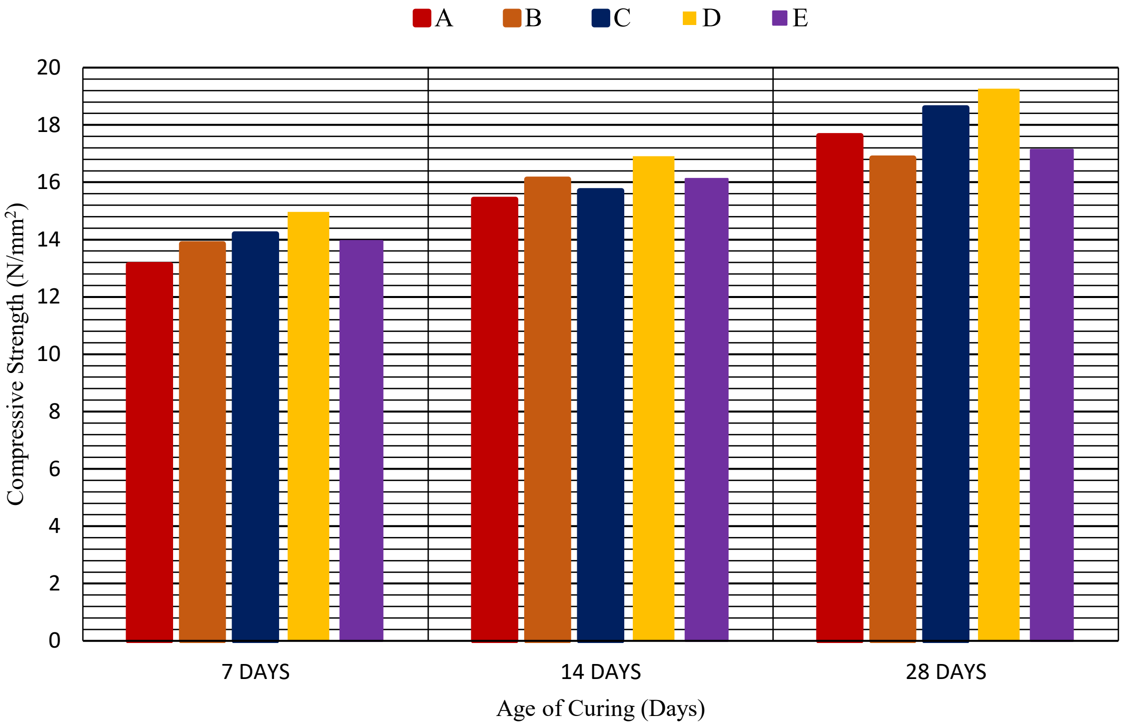

Figure 4.4: Chart Showing Comparison of Compressive Strength at Various Age of Curing of C20

Table 4.5: Compressive Strength Test Results for Mix Ratio 1:1.5:3 (C25)

Age (Days)	Sample No	Weight (Kg)	Density (Kg/m³)	Failure load (KN)	Compressive Strength (N/mm²)	Average strength (N/mm²)
7	A	2.585	2585	178.21	17.821	18.560
	B	2.593	2593	183.17	18.317	
	C	2.576	2576	186.48	18.648	
	D	2.601	2601	191.09	19.109	
	E	2.588	2588	189.03	18.903	
	A	2.589	2589	221.01	22.101	23.113
	B	2.597	2597	229.33	22.933	

14	C	2.590	2590	233.47	23.347	
	D	2.582	2582	237.8	23.780	
	E	2.591	2591	234.04	23.404	
28	A	2.589	2589	257.11	25.711	25.923
	B	2.590	2590	251.96	25.196	
	C	2.594	2594	261.88	26.188	
	D	2.601	2601	265.09	26.509	
	E	2.598	2598	260.12	26.012	

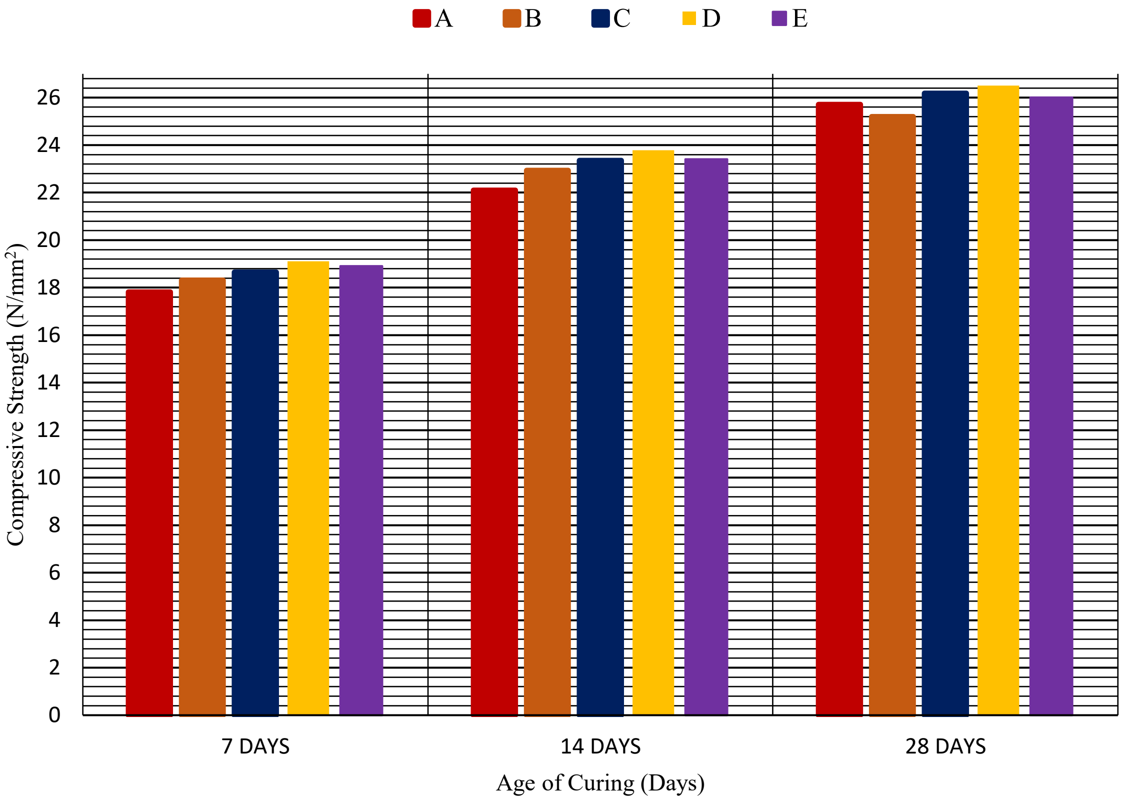

Figure 4.5: Chart Showing Comparison of Compressive Strength at Various Age of Curing of C25

Table 4.6: Compressive Strength Test Results for Mix Ratio 1:1:2 (C30)

Age (Days)	**Sample No**	**Weight (Kg)**	**Density (Kg/m³)**	**Failure load (KN)**	**Compressive Strength (N/mm²)**	**Average strength (N/mm²)**
7	A	2.585	2585	248.12	24.812	25.768
	B	2.593	2593	253.71	25.371	
	C	2.576	2576	259.28	25.928	
	D	2.601	2601	261.9	26.190	
	E	2.588	2588	265.39	26.539	
14	A	2.589	2589	282.1	28.210	29.082
	B	2.597	2597	286.33	28.633	
	C	2.590	2590	291.74	29.174	
	D	2.582	2582	295.87	29.587	
	E	2.591	2591	298.04	29.804	
28	A	2.589	2589	307.11	30.711	31.522
	B	2.590	2590	311.69	31.169	
	C	2.594	2594	318.88	31.888	
	D	2.601	2601	322.29	32.229	
	E	2.598	2598	316.12	31.612	

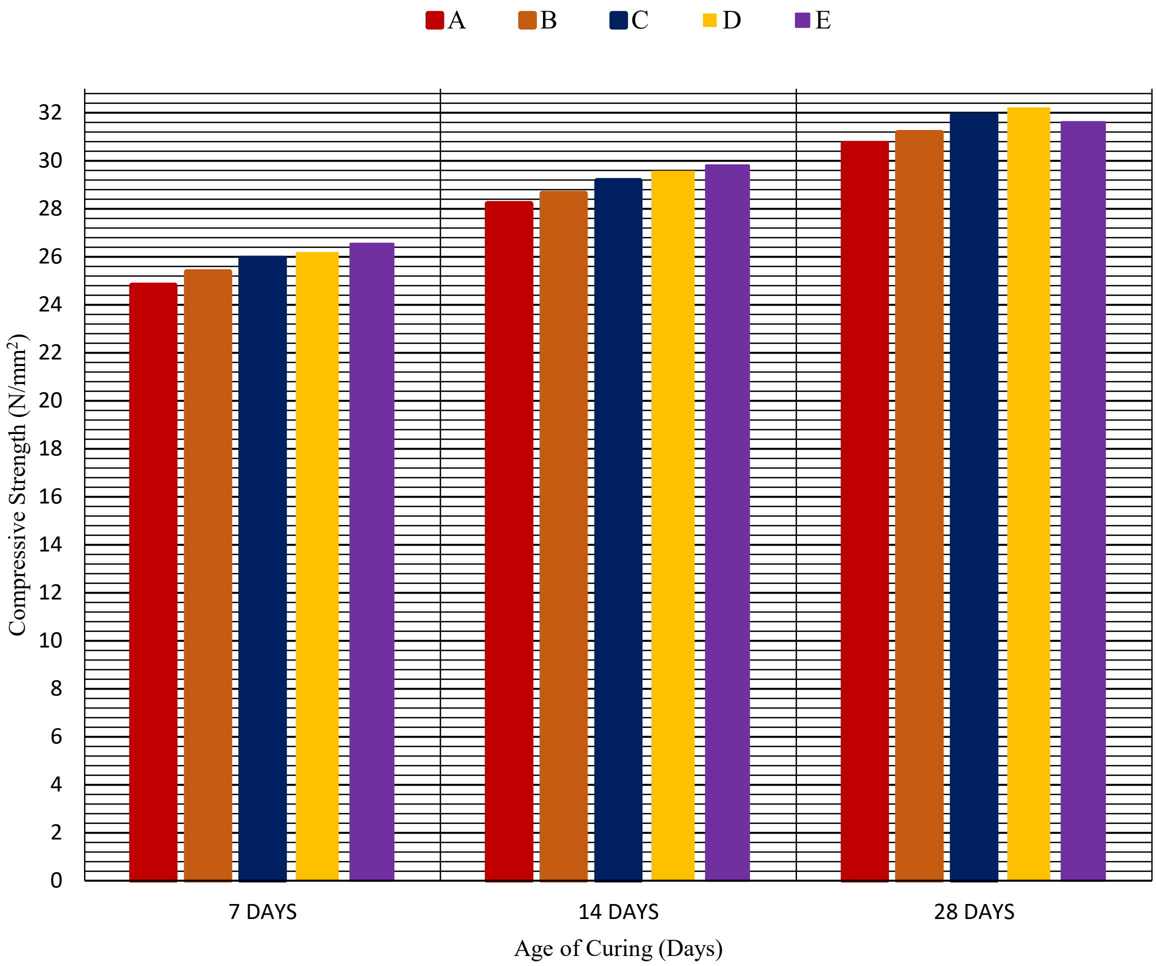

Figure 4.6: Chart Showing Comparison of Compressive Strength at Various Age of Curing of C30

4.3 Comparison of Rebound Hammer and Compressive Strength Results

A direct comparison between rebound hammer estimates and compressive strength results (Figure 4.7 - Figure 4.10) revealed a strong correlation between the two methods. However, the rebound hammer consistently underestimated compressive strength by approximately 5–10% across all curing ages and mix ratios. This finding is consistent with literature, which emphasizes that rebound hammer values should only be used as indicative strength estimates and must be correlated with destructive tests for design applications.

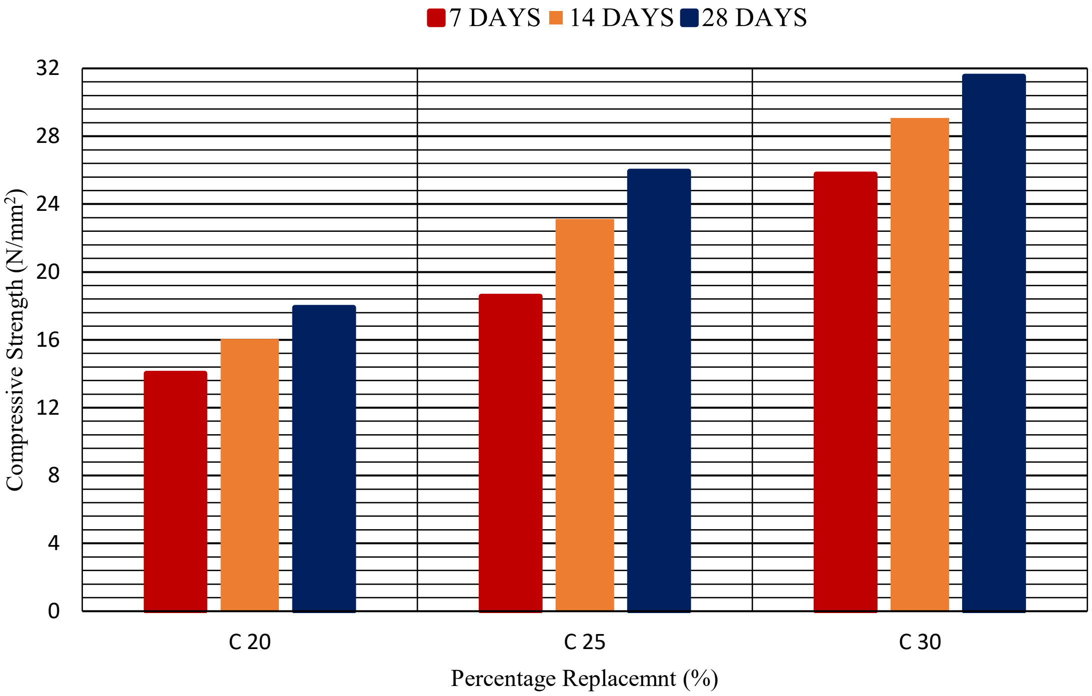

Figure 4.7: Chart showing comparison between the values of Average Compressive Strength for various Concrete Grade

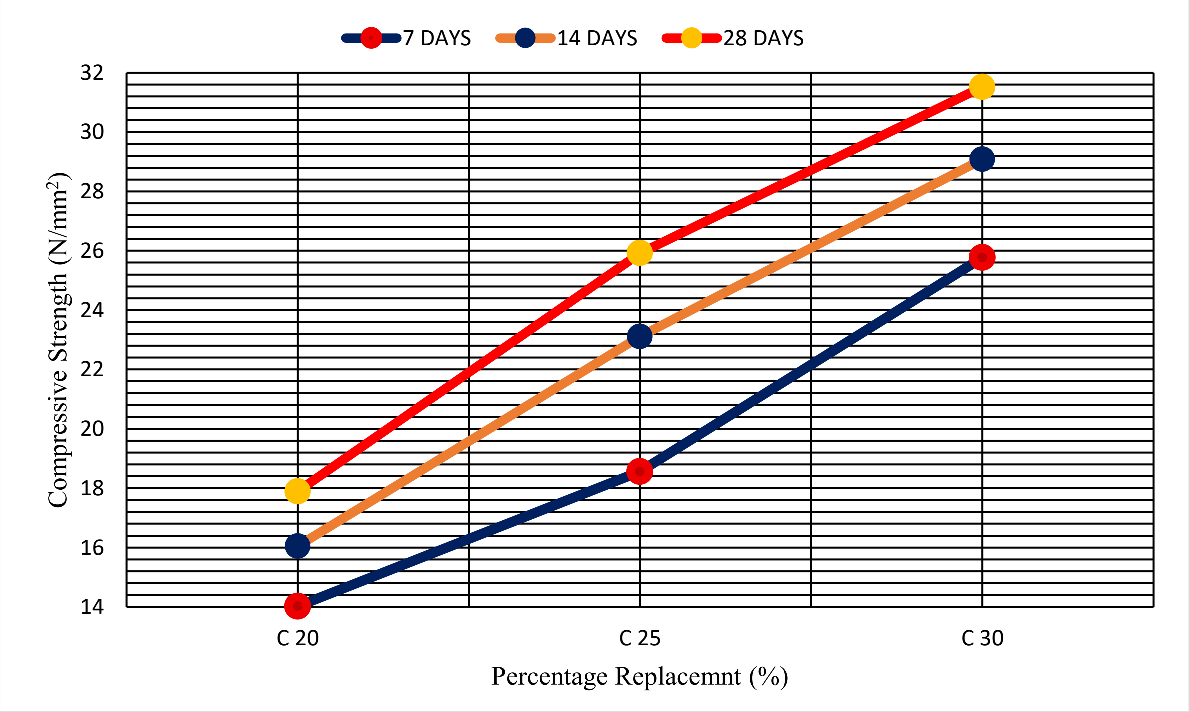

Figure 4.8: Graph showing Result comparison between the values of Average Compressive Strength for various Concrete Grade

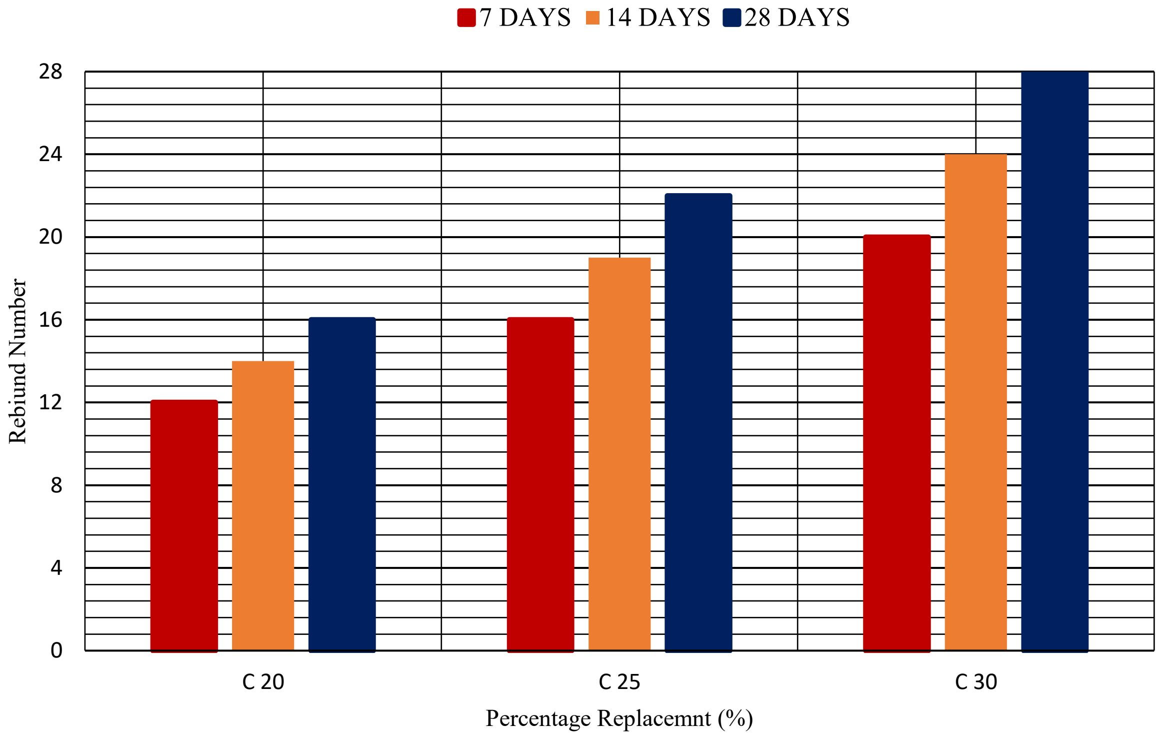

Figure 4.9: Chart showing comparison between the values of Average Rebound Value for various Concrete Grade

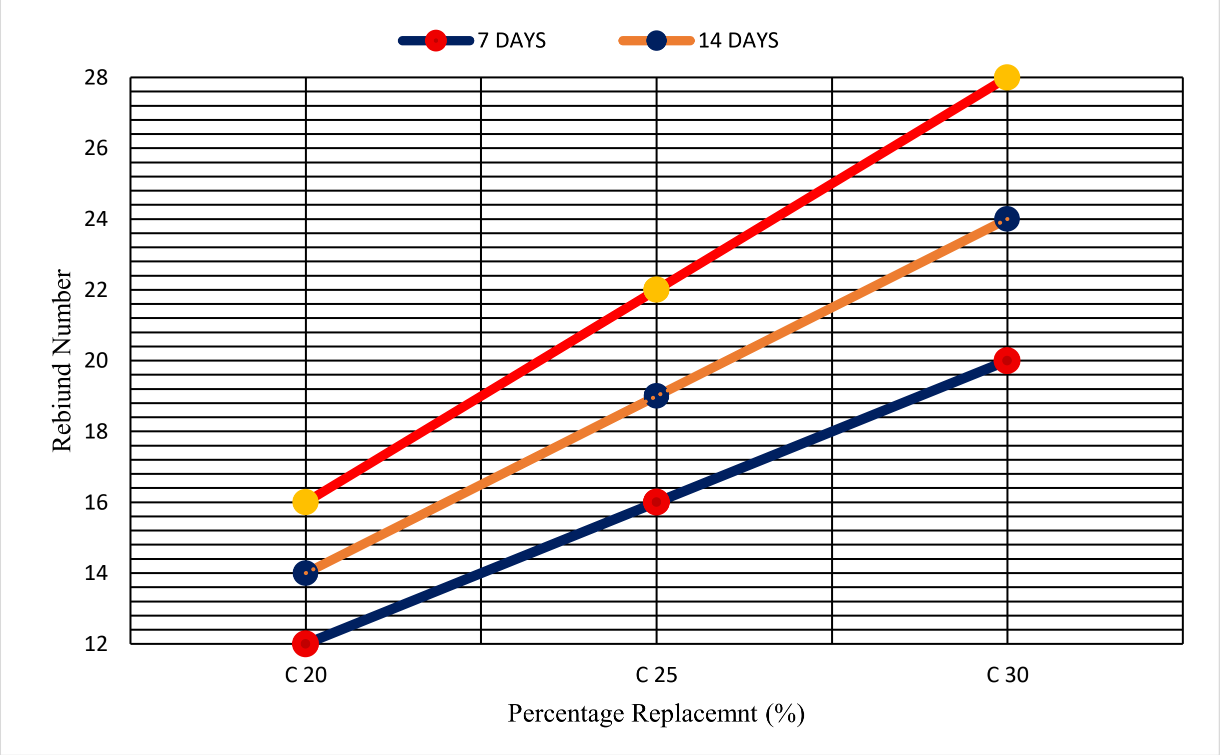

Figure 4.10: Graph showing Result comparison between the values of Average Rebound Value for various Concrete Grade

4.4 Regression and Correlation Analysis

The correlation between rebound number (R) and compressive strength (F_{cu}) was analysed using linear regression, yielding the following relationships:

f_c= aN + b (4.1)

where:

f_c= Compressive strength (N/mm²)

N= Rebound number

a= Slope of the line (how much f_c changes per unit increase in N)

b= Intercept (value of f_c when $N = 0$)

Using software such as Microsoft Excel, a trendline is added to the data points. Excel uses the least squares method to calculate the slope (a) and intercept (b) that minimize the total squared error between the measured strengths and the predicted strengths from the line.

4.4.1 Derivation of Regression Equation and Coefficient of Determination (R^2)

To illustrate how the regression equations were obtained for the C20 concrete mix (1:2:4) at 28 days of curing. From the experimental results, the following paired data (rebound number vs. compressive strength) was obtained:

Table 4.7: Sample Rebound Number and Corresponding Compressive Strength (f_c)

Sample	Rebound Number (N)	Compressive Strength (f_c) (N/mm²)
A	15	16.84
B	16	17.13
C	17	17.62
D	18	18.59
E	19	19.27

Step 1: Compute the Mean of Each Variable

$$\bar{N} = \frac{15 + 16 + 17 + 18 + 19}{5} = 17$$

$$\bar{f_c} = \frac{16.84 + 17.13 + 17.62 + 18.59 + 19.27}{5} = 17.89$$

Step 2: Calculate Slope (a) and Intercept (b)

The linear regression equation is expressed as shown in equation 4.1 above:

f_c= aN + b

Where:

$$a = \frac{\sum(N_i - \bar{N})\left(f_{c_i} - \bar{f_c}\right)}{\sum(N_i - \bar{N})^2} \qquad (4.2)$$

$$b = \bar{f_c} - a\bar{N} \qquad (4.3)$$

Now compute the terms:

Table 4.8: Calculation of Regression Parameters for C20 (1:2:4) Mix

N	f_c	(N – 17)	(f_c– 17.89)	(N – 17) (f_c– 17.89)	(N – 17) ²
15	16.84	-2	-1.05	2.10	4
16	17.13	-1	-0.76	0.76	1
17	17.62	0	-0.27	0.00	0
18	18.59	+1	+0.70	0.70	1
19	19.27	+2	+1.38	2.76	4

$$\sum(N - 17)(f_c - 17.89) = 6.32$$

$$\sum(N - 17)^2 = 10$$

Therefore:

$$a = \frac{6.32}{10} = 0.632$$

$$b = 17.89 - (0.632)(17) = 17.89 - 10.74 = 7.15$$

Hence, the regression equation is: $\boxed{f_c = 0.632N + 7.15}$

Step 3: Determine the Coefficient of Determination (R²)

$$\mathrm{R}^2 = \frac{\left[\Sigma(N_i - \bar{N})\left(f_{c_i} - \bar{f_c}\right)\right]^2}{\left[\Sigma(N_i - \bar{N})^2\,\Sigma\left(f_{c_i} - \bar{f_c}\right)^2\right]} \tag{4.4}$$

Compute:

$$\sum\left(f_{c_i} - \bar{f_c}\right)^2 = (-1.05)^2 + (-0.76)^2 + (-0.27)^2 + (0.70)^2 + (1.38)^2 = 4.49$$

Then:

$$R^2 = \frac{(6.32)^2}{(10)(4.49)} = \frac{39.94}{44.9} = 0.8467$$

$\boxed{467R^2 = 0.85}$

This means that 85% of the variation in compressive strength can be explained by changes in rebound number for the C20 concrete.

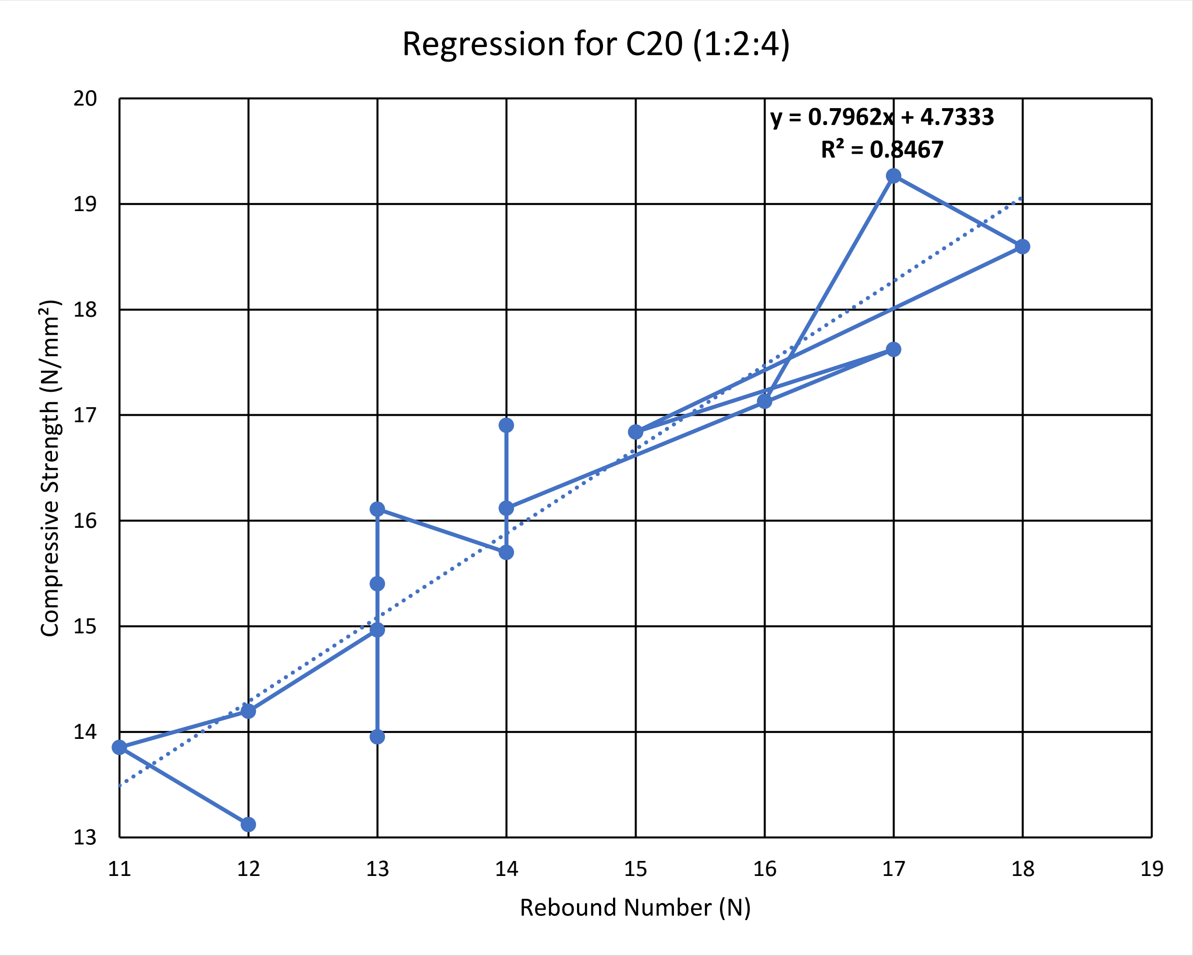

Figure 4.11: Scatter plots with best-fit lines and R² for C20

To illustrate how the regression equations were obtained for the C25 concrete mix (1:1.5:3) at 28 days of curing. From the experimental results, the following paired data (rebound number vs. compressive strength) was obtained:

Table 4.9: Sample Rebound Number and Corresponding Compressive Strength (f_c)

Sample	**Rebound Number (N)**	**Compressive Strength (f_c) (N/mm²)**
A	22	25.711
B	21	25.196
C	22	26.188
D	22	26.509
E	22	26.012

Step 1: Compute the Mean of Each Variable

$$\overline{N} = \frac{22 + 21 + 22 + 22 + 22}{5} = 21.8$$

$$\overline{f_c} = \frac{25.711 + 25.196 + 26.188 + 26.509 + 26.012}{5} = 25.9232$$

Step 2: Calculate Slope (a) and Intercept (b)

The linear regression equation is expressed as shown in equation 4.1 above:

f_c= aN + b

Where:

$$a = \frac{\sum(N_i - \overline{N})\left(f_{c_i} - \overline{f_c}\right)}{\sum(N_i - \overline{N})^2}$$

$$b = \overline{f_c} - a\overline{N}$$

Now compute the terms:

Table 4.10: Calculation of Regression Parameters for C25 (1:1.5:3) Mix

N	f_c	(N – 21.8)	(f_c– 25.9232)	(N – 21.8) (f_c– 25.9232)	(N – 21.8) ^{2}
22	25.711	+0.2	−0.2122	−0.04244	0.04
21	25.196	−0.8	−0.7272	+0.58176	0.64
22	26.188	+0.2	+0.2648	+0.05296	0.04
22	26.509	+0.2	+0.5858	+0.11716	0.04
22	26.012	+0.2	+0.0888	+0.01776	0.04

$$\sum (N - 21.8)(f_c - 25.9232) = 6.1070$$

$$\sum (N - 21.8)^2 = 0.9$$

Therefore:

$$a = \frac{6.643}{10} = 0.6643$$

$$b = 25.9232 - (0.6643)(21.8) = 25.9232 - 19.8162 = 6.1070$$

Hence, the regression equation is: $\boxed{f_c = 0.909N + 6.1070}$

Step 3: Determine the Coefficient of Determination (R²)

$$R^2 = \frac{\left[\Sigma(N_i - \bar{N})\left(f_{c_i} - \bar{f_c}\right)\right]^2}{\left[\Sigma(N_i - \bar{N})^2 \, \Sigma\left(f_{c_i} - \bar{f_c}\right)^2\right]}$$

Compute:

$$\sum \left(f_{c_i} - \bar{f_c}\right)^2 = (-1.05)^2 + (-0.76)^2 + (-0.27)^2 + (0.70)^2 + (1.38)^2 = 4.49$$

Then:

$$R^2 = \frac{(6.1070)^2}{(10)(4.49)} = \frac{41.99}{44.9} = 0.9643$$

$$\boxed{R^2 = 0.9643}$$

This means that 96% of the variation in compressive strength can be explained by changes in rebound number for the C25 concrete.

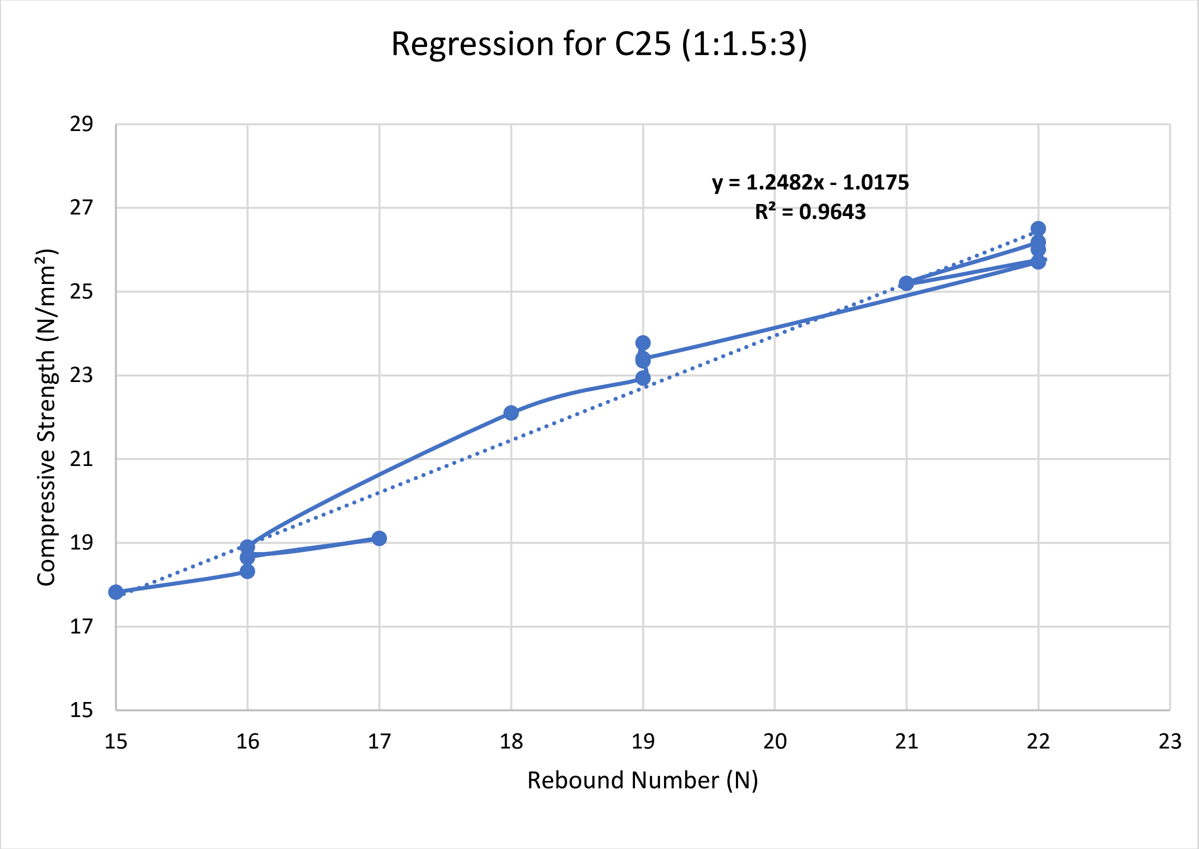

Figure 4.12: Scatter plots with best-fit lines and R² for C25

To illustrate how the regression equations were obtained for the C30 concrete mix (1:1:2) at 28 days of curing. From the experimental results, the following paired data (rebound number vs. compressive strength) was obtained:

Table 4.11: Sample Rebound Number Vs Corresponding Compressive Strength (f_c)

Sample	**Rebound Number (N)**	**Compressive Strength (f_c) (N/mm²)**
A	27	30.711
B	27	31.169
C	28	31.888
D	28	32.229
E	28	31.612

Step 1: Compute the Mean of Each Variable

$$\overline{N} = \frac{27 + 27 + 28 + 28 + 28}{5} = 27.6$$

$$\overline{f_c} = \frac{30.711 + 31.169 + 31.888 + 32.229 + 31.612}{5} = 31.5218$$

Step 2: Calculate Slope (a) and Intercept (b)

The linear regression equation is expressed as shown in equation 4.1 above:

f_c= aN + b

Where:

$$a = \frac{\sum(N_i - \overline{N})\left(f_{c_i} - \overline{f_c}\right)}{\sum(N_i - \overline{N})^2}$$

$$b = \overline{f_c} - a\overline{N}$$

Now compute the terms:

Table 4.12: Calculation of Regression Parameters for C30 (1:1:2) Mix

N	f_c	(N – 27.6)	(f_c– 31.5218)	(N – 27.6) (f_c– 31.5218)	(N – 27.6) ²
27	30.711	−0.6	−0.8108	+0.48648	0.36
27	31.169	−0.6	−0.3528	+0.21168	0.36
28	31.888	+0.4	+0.3662	+0.14648	0.16
28	32.229	+0.4	+0.7072	+0.28288	0.16
28	31.612	+0.4	+0.0902	+0.03608	0.16

$$\sum(N - 27.6)(f_c - 31.5218) = 1.16360$$

$$\sum(N - 27.6)^2 = 1.2$$

Therefore:

$$a = \frac{1.16360}{1.2} = 0.9696667$$

$$b = \overline{f_c} - a\overline{N} = 31.5218 - (0.9696667 \times 27.6) = 31.5218 - 26.7628 = 4.7590$$

Hence, the regression equation is: $\boxed{f_c = 0.9697N + 4.759}$

Step 3: Determine the Coefficient of Determination (R²)

$$R^2 = \frac{\left[\Sigma(N_i-\bar{N})\left(f_{c_i}-\bar{f_c}\right)\right]^2}{\left[\Sigma(N_i-\bar{N})^2\,\Sigma\left(f_{c_i}-\bar{f_c}\right)^2\right]}$$

Compute:

$$\sum\left(f_{c_i}-\bar{f_c}\right)^2 = (-1.05)^2 + (-0.76)^2 + (-0.27)^2 + (0.70)^2 + (1.38)^2 = 1.49$$

Then:

$$R^2 = \frac{(2.6360)^2}{(10)(1.49)} = \frac{4.789}{14.9} = 0.9834$$

$\boxed{R^2 = 0.98}$

This means that 98% of the variation in compressive strength can be explained by changes in rebound number for the C30 concrete.

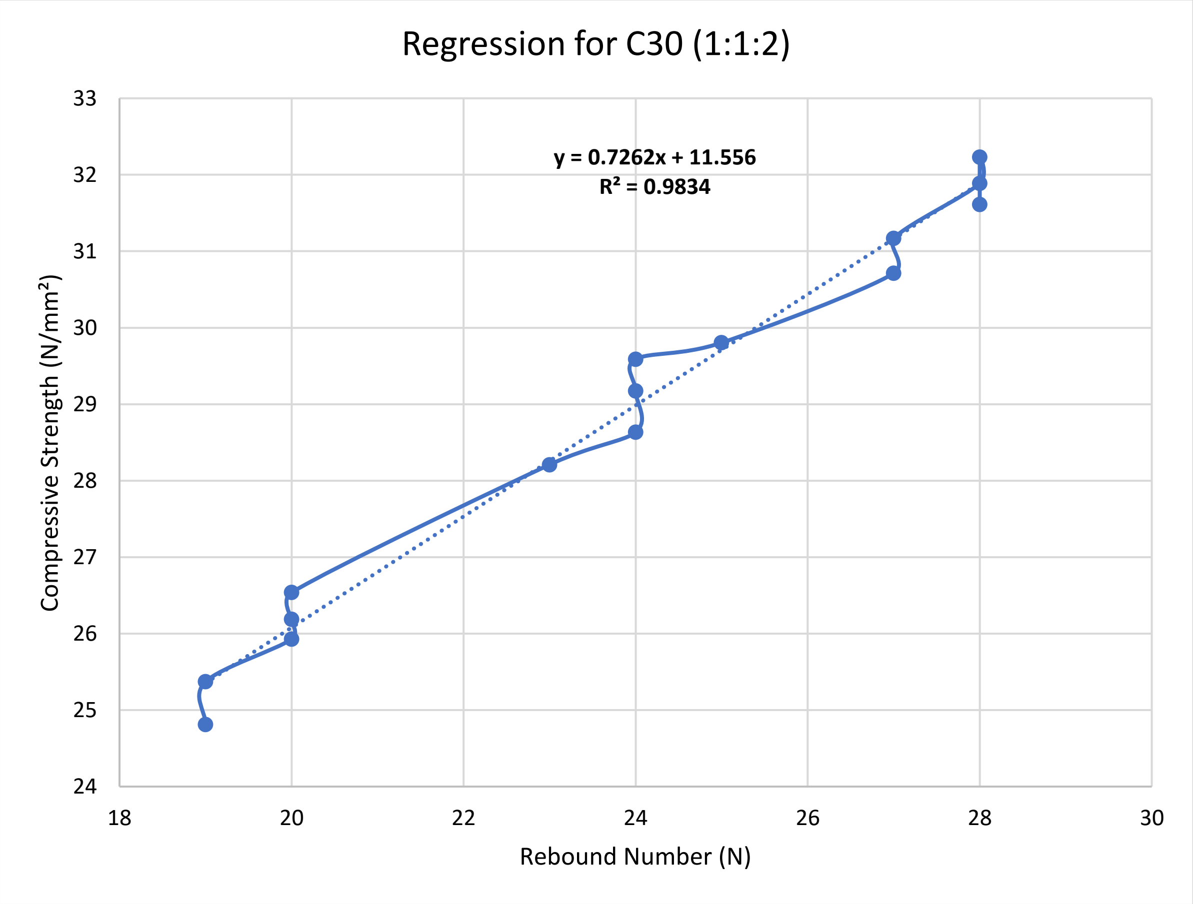

Figure 4.13: Scatter plots with best-fit lines and R² for C30

4.5 Discussion of Results

The results demonstrated several key observations:

a. Richer mixes with higher cement content (1:1:2 and 1:1.5:3) consistently produced higher strengths than leaner mixes (1:2:4). This aligns with established concrete technology principles that strength is inversely related to the water-cement ratio.

b. Both rebound and compressive tests confirmed progressive strength gain from 7 to 28 days. This reflects ongoing hydration of cement and validates proper curing conditions in the laboratory.

c. The rebound hammer test proved effective in showing relative strength differences but underestimated absolute compressive strengths. It is therefore suitable for rapid in-situ quality assessment but not as a standalone substitute for compressive strength testing.

d. The rebound hammer results showed close correlation with compressive strength ($R^2 > 0.9$), variations highlight its sensitivity to surface texture, moisture content, and operator handling. For critical structural evaluation, compressive strength remains the most reliable standard method as per BS EN 12390-3.

4.6 Particle Size Distribution (PSD)

4.6.1 Sieve Analysis

The particle size distribution of natural fine aggregates (sand) and natural coarse aggregates (granite) is gotten through sieve analysis as shown in Tables 4.13 and 4.14, respectively. This study aimed to evaluate the particle size distribution of the aggregate used in concrete across three different mix ratios: 1:2:4, 1:1.5:3, and 1:1:2. Below is a discussion of the sieve analysis results, including the particle size distribution curves.

Table 4.13: Result from Sieve Analysis for fine aggregate

SIEVE SIZE (mm)	MASS RETAINED (G)	PERCENTAGE RETAINED (%)	CUMULATIVE PERCENTAGE RETAINED (%)	PERCENTAGE PASSING (%)
2.36	1.06	1.06	1.06	99.94
2.00	0.45	0.45	0.51	93.49
1.18	1.00	1.00	1.51	87.74
600	11.90	11.90	13.41	56.51
425	19.80	19.80	33.21	46.13
300	29.70	29.70	62.91	17.09
212	21.50	21.50	84.41	15.58
150	8.20	8.20	92.61	7.3
75	5.30	5.30	97.91	2.22
Pan	1.03	1.03	98.94	1.08

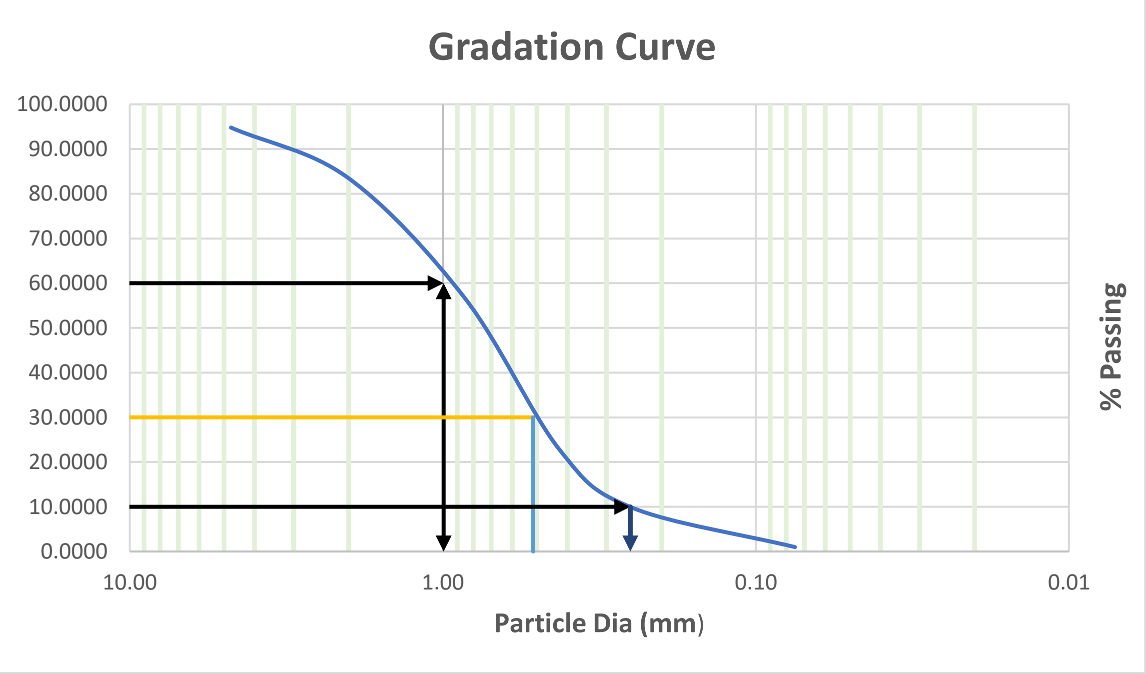

Figure 4.14: Graph showing PSD of fine aggregate

Table 4.14: Result from Sieve Analysis for Coarse aggregate

SIEVE SIZE (mm)	MASS RETAINED (G)	PERCENTAGE RETAINED (%)	CUMULATIVE PERCENTAGE RETAINED (%)	PERCENTAGE PASSING (%)
20	0.21	0.021	0.021	99.979
19	92.84	9.284	9.305	90.695
13.25	331.65	33.165	42.470	57.530
12	506.38	50.638	93.108	6.892
10	15.73	1.573	94.681	5.319
8	29.62	2.962	97.643	2.357
5	13.98	1.398	99.041	0.959
Pan	0.59	0.059	99.10	0.991

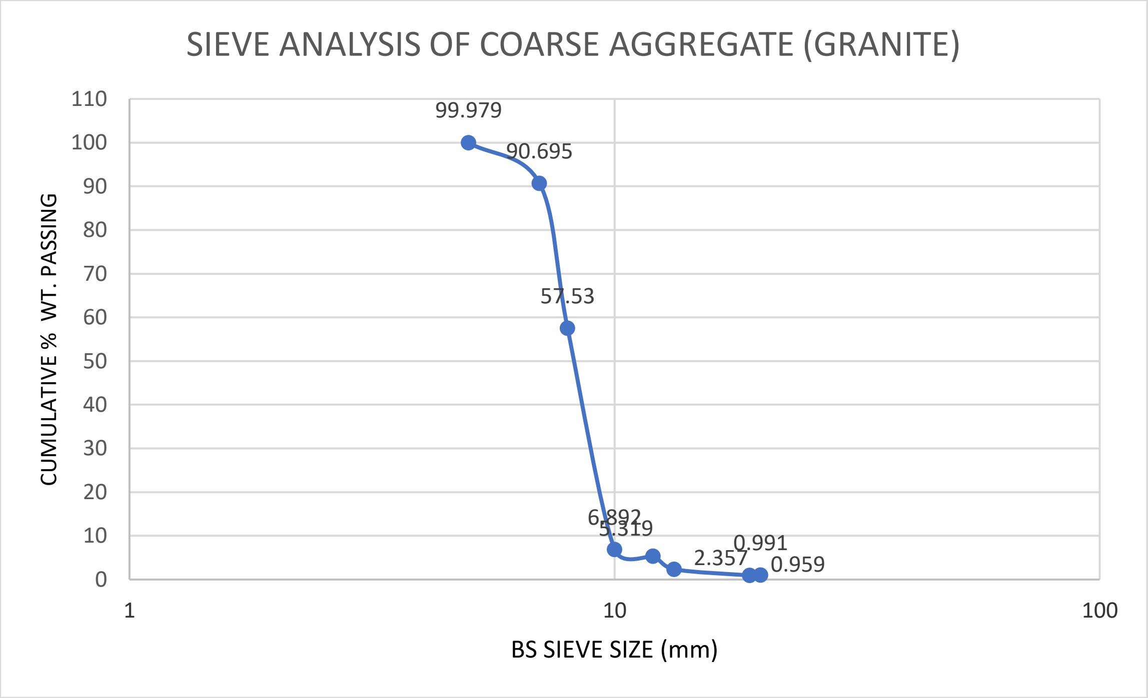

Figure 4.15: Graph showing PSD of Coarse aggregate

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In conclusion, this study was conducted to compare the strength characteristics of concrete using both the rebound hammer test (non-destructive) and the compressive strength test (destructive) across three mix ratios; 1:2:4 (C20), 1:1.5:3 (C25), and 1:1:2 (C30) with proper compaction. The experimental investigation was carried out on 100 mm × 100 mm × 100 mm concrete cubes, cured for 7, 14, and 28 days under controlled laboratory conditions. Both test methods were performed in accordance with international standards: BS EN 12504-2:2012 and ASTM C805 for the rebound hammer, and BS EN 12390-3:2019 for the compressive strength test.

The results obtained from the tests revealed several significant findings. Firstly, the effect of mix ratio on compressive strength was evident across all curing ages. The 1:1:2 mix (C30 grade) exhibited the highest compressive strength, attaining an average of 31.52 N/mm² at 28 days, followed by 1:1.5:3 (C25) with 25.92 N/mm², and 1:2:4 (C20) with 17.89 N/mm². This clearly demonstrates that concrete strength increases with a richer cement content and a lower water-cement ratio, which is consistent with Abrams' Law, emphasizing the inverse relationship between water-cement ratio and compressive strength.

Secondly, the effect of curing age was observed to play a vital role in strength development. For all mix ratios, the average compressive strength increased progressively from 7 days to 28 days, showing that hydration continued effectively throughout the curing period with the 1:2:4 mix increasing from 14.02 N/mm² at 7 days to 17.89 N/mm² at 28 days, representing a 27.6% increase. Similarly, the 1:1.5:3 mix increasing from 18.56 N/mm² at 7 days to 25.92 N/mm² at 28 days (39.6% increase), and the 1:1:2 mix increasing from 25.76 N/mm² at 7 days to 31.52 N/mm² at 28 days (22.4% increase). These results align with established literature which indicates that properly cured concrete achieves approximately 65–75% of its 28-day strength within the first 7 days and continues to gain strength thereafter due to the ongoing hydration of cement compounds.

Furthermore, when comparing the rebound hammer results to the corresponding compressive strength values, it was observed that the rebound number provided an approximate but consistent estimation of compressive strength. The rebound hammer tended to underestimate the actual strength by 5–10%, which is attributed to factors such as surface texture, moisture condition, and carbonation of the test surface. Despite this, the test was able to accurately indicate the relative strength gain between curing ages and mix proportions.

A detailed regression analysis established a strong linear relationship between rebound number (N) and compressive strength (f_c) for all three concrete grades. These coefficients of determination (R^2) show that between 85% and 98% of the variation in compressive strength can be explained by changes in rebound number, confirming a strong correlation between the two methods. This finding validates that rebound hammer results can be used reliably for in-situ assessment and comparative quality control of concrete, provided they are calibrated with corresponding compressive strength data.

The sieve analysis of both fine and coarse aggregates also revealed that all aggregates used were well graded and within the acceptable limits of BS 812 (Part 103.1:1985). The fine aggregates had a cumulative percentage passing of 99.94% at the 2.36 mm sieve, while the coarse aggregates exhibited a top sieve passing of 99.979%, ensuring optimal gradation for proper packing and reduced void content.

In conclusion, the study confirms that both mix design and curing conditions play crucial roles in the development of concrete strength. While the rebound hammer test is practical, portable, and efficient for rapid assessment, it cannot substitute the compressive strength test for structural verification purposes. It is most useful when used as a complementary test alongside standard compressive strength measurements, particularly for in-situ evaluations where destructive testing is not feasible. The overall findings align with previous research that highlights the importance of correlating rebound hammer results with direct compressive strength values for more accurate interpretation.

5.2 Recommendations

Based on the findings of this study, the following recommendations are made:

i. A specific calibration curve should be developed for each mix design and concrete size as the rebound was calibrated for 150mm by 150mm-by-150mm cube in order to improve the accuracy of rebound hammer predictions.

ii. The rebound hammer test should be used alongside compressive strength tests for comprehensive evaluation of concrete structures. This dual approach ensures both surface and in-depth assessments of concrete quality.

iii. In field conditions, rebound hammer readings should be taken at multiple points on the same element, and the average of at least 10 readings should be considered to minimize localized variability.

iv. Explore the influence of temperature, surface moisture, and carbonation depth on rebound hammer readings.

v. Investigate the correlation between ultrasonic pulse velocity (UPV) and rebound hammer for improved non-destructive evaluation models.

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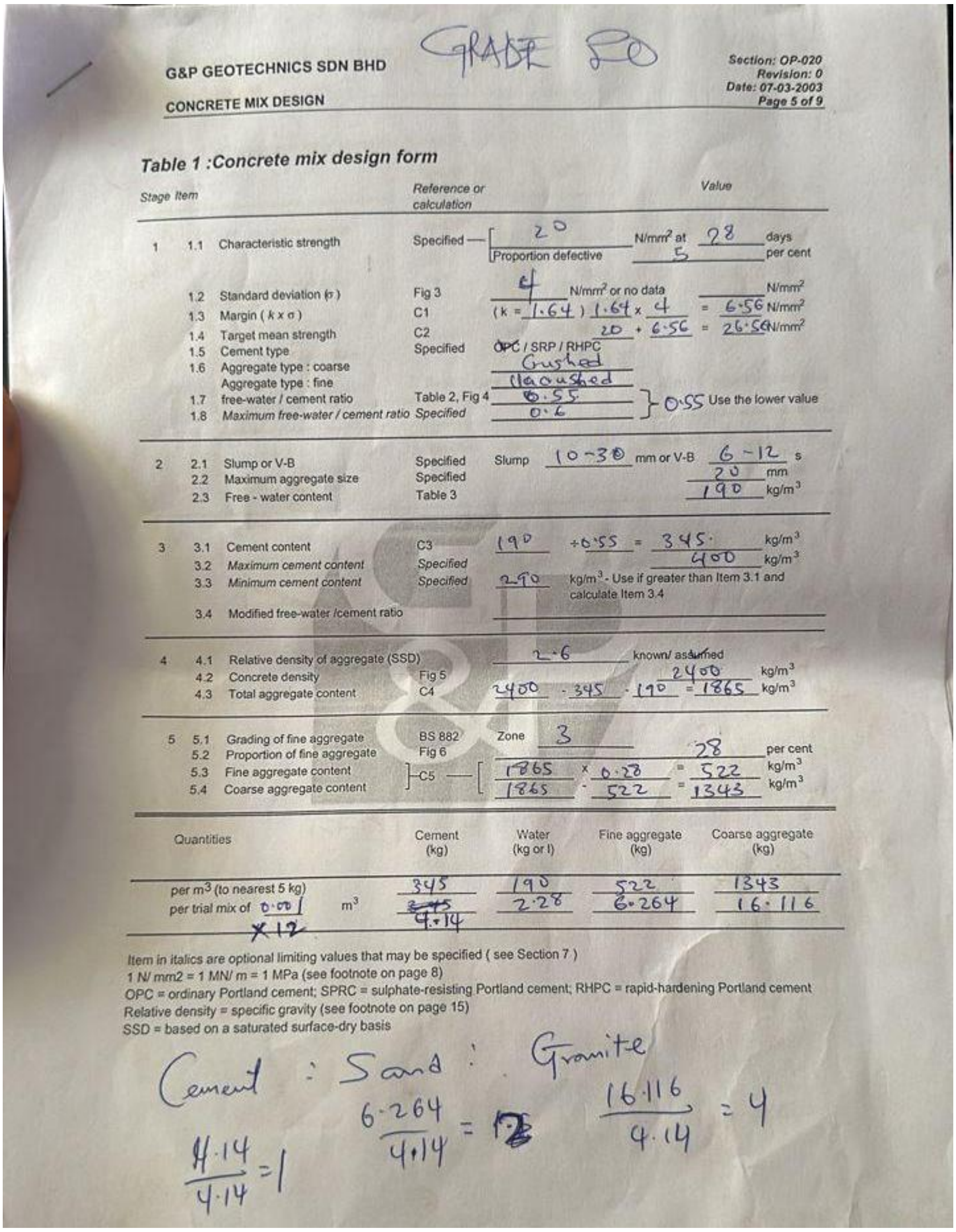
APPENDIX



G&P GEOTECHNICS SDN BHD GRADE 20

CONCRETE MIX DESIGN

Section: OP-020
Revision: 0
Date: 07-03-2003
Page 5 of 9

Table 1 :Concrete mix design form

Stage	Item		Reference or calculation	Value
1	1.1	Characteristic strength	Specified	20 N/mm² at 28 days Proportion defective 5 per cent
	1.2	Standard deviation (σ)	Fig 3	4 N/mm² or no data ____ N/mm²
	1.3	Margin (k x σ)	C1	(k = 1.64) 1.64 x 4 = 6.56 N/mm²
	1.4	Target mean strength	C2	20 + 6.56 = 26.56 N/mm²
	1.5	Cement type	Specified	OPC / SRP / RHPC
	1.6	Aggregate type : coarse		Crushed
		Aggregate type : fine		Uncrushed
	1.7	free-water / cement ratio	Table 2, Fig 4	0.55 } 0.55 Use the lower value
	1.8	*Maximum free-water / cement ratio*	*Specified*	0.6
2	2.1	Slump or V-B	Specified	Slump 10-30 mm or V-B 6-12 s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free - water content	Table 3	190 kg/m³
3	3.1	Cement content	C3	190 ÷0.55 = 345. kg/m³
	3.2	*Maximum cement content*	*Specified*	400 kg/m³
	3.3	*Minimum cement content*	*Specified*	290 kg/m³ - Use if greater than Item 3.1 and calculate Item 3.4
	3.4	Modified free-water /cement ratio		
4	4.1	Relative density of aggregate (SSD)		2.6 known/ assumed
	4.2	Concrete density	Fig 5	2400 kg/m³
	4.3	Total aggregate content	C4	2400 - 345 - 190 = 1865 kg/m³
5	5.1	Grading of fine aggregate	BS 882	Zone 3
	5.2	Proportion of fine aggregate	Fig 6	28 per cent
	5.3	Fine aggregate content	C5	1865 x 0.28 = 522 kg/m³
	5.4	Coarse aggregate content	C5	1865 - 522 = 1343 kg/m³

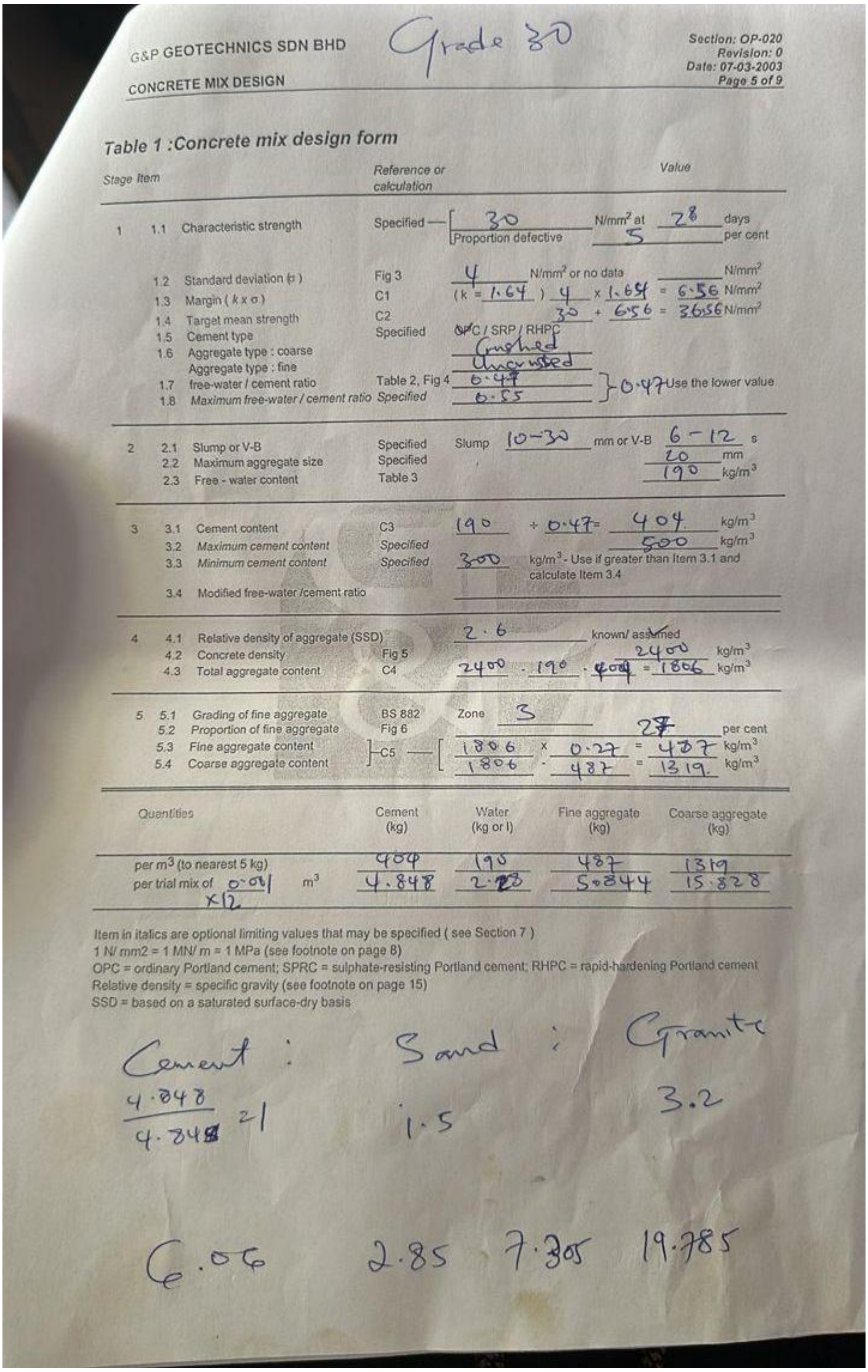
Quantities	Cement (kg)	Water (kg or l)	Fine aggregate (kg)	Coarse aggregate (kg)
per m³ (to nearest 5 kg)	345	190	522	1343
per trial mix of 0.001 m³ x 12	~~345~~ 4.14	2.28	6.264	16.116

Item in italics are optional limiting values that may be specified (see Section 7)
1 N/ mm2 = 1 MN/ m = 1 MPa (see footnote on page 8)
OPC = ordinary Portland cement; SPRC = sulphate-resisting Portland cement; RHPC = rapid-hardening Portland cement
Relative density = specific gravity (see footnote on page 15)
SSD = based on a saturated surface-dry basis

Cement : Sand : Granite

$\frac{4.14}{4.14} = 1$ $\frac{6.264}{4.14} = 1.5$ $\frac{16.116}{4.14} = 4$

Plate 1: Grade 20 Mix Design Form



G&P GEOTECHNICS SDN BHD Grade 30

CONCRETE MIX DESIGN

Section: OP-020
Revision: 0
Date: 07-03-2003
Page 5 of 9

Table 1 :Concrete mix design form

Stage	Item		Reference or calculation	Value
1	1.1	Characteristic strength	Specified	30 N/mm² at 28 days Proportion defective 5 per cent
	1.2	Standard deviation (σ)	Fig 3	4 N/mm² or no data ____ N/mm²
	1.3	Margin (*k* x σ)	C1	(k = 1.64) 4 x 1.64 = 6.56 N/mm²
	1.4	Target mean strength	C2	30 + 6.56 = 36.56 N/mm²
	1.5	Cement type	Specified	OPC / SRP / RHPC
	1.6	Aggregate type : coarse		Crushed
		Aggregate type : fine		Uncrushed
	1.7	free-water / cement ratio	Table 2, Fig 4	0.47 } 0.47 Use the lower value
	1.8	*Maximum free-water / cement ratio*	*Specified*	0.55
2	2.1	Slump or V-B	Specified	Slump 10-30 mm or V-B 6-12 s
	2.2	Maximum aggregate size	Specified	20 mm
	2.3	Free - water content	Table 3	190 kg/m³
3	3.1	Cement content	C3	190 ÷ 0.47 = 404 kg/m³
	3.2	*Maximum cement content*	*Specified*	500 kg/m³
	3.3	*Minimum cement content*	*Specified*	300 kg/m³ - Use if greater than Item 3.1 and calculate Item 3.4
	3.4	Modified free-water /cement ratio		
4	4.1	Relative density of aggregate (SSD)		2.6 known/ assumed ✓
	4.2	Concrete density	Fig 5	2400 kg/m³
	4.3	Total aggregate content	C4	2400 - 190 - 404 = 1806 kg/m³
5	5.1	Grading of fine aggregate	BS 882	Zone 3
	5.2	Proportion of fine aggregate	Fig 6	27 per cent
	5.3	Fine aggregate content	C5	1806 x 0.27 = 487 kg/m³
	5.4	Coarse aggregate content	C5	1806 - 487 = 1319 kg/m³

Quantities		Cement (kg)	Water (kg or l)	Fine aggregate (kg)	Coarse aggregate (kg)
per m³ (to nearest 5 kg)		404	190	487	1319
per trial mix of 0.01 ×12	m³	4.848	2.28	5.844	15.828

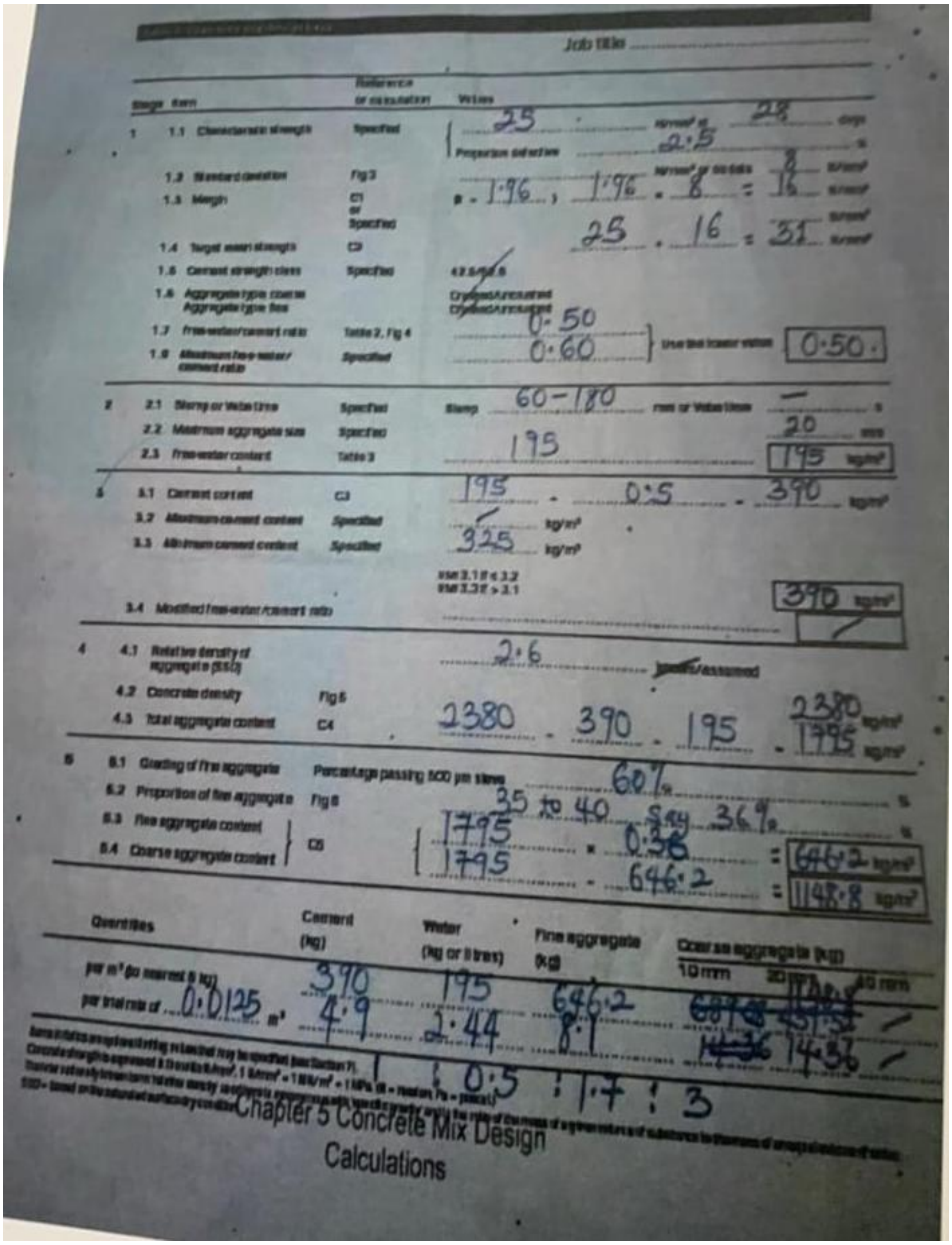
Item in italics are optional limiting values that may be specified (see Section 7)
1 N/ mm2 = 1 MN/ m = 1 MPa (see footnote on page 8)
OPC = ordinary Portland cement; SPRC = sulphate-resisting Portland cement; RHPC = rapid-hardening Portland cement
Relative density = specific gravity (see footnote on page 15)
SSD = based on a saturated surface-dry basis

Cement : Sand : Granite

$\frac{4.848}{4.848}$ = 1   1.5   3.2

6.06   2.85   7.305   19.785

Plate 2: Grade 30 Mix Design Form



Job title ....

Stage	Item	Reference or calculation	Values
1	1.1 Characteristic strength	Specified	25 N/mm² at 28 days Proportion defective 2.5 %
	1.2 Standard deviation	Fig 3	N/mm² or no data 8 N/mm²
	1.3 Margin	C1 or Specified	k = 1.96 , 1.96 × 8 = 16 N/mm²
	1.4 Target mean strength	C2	25 + 16 = 31 N/mm²
	1.5 Cement strength class	Specified	~~42.5/52.5~~
	1.6 Aggregate type: coarse Aggregate type: fine		Crushed/uncrushed Crushed/uncrushed
	1.7 Free-water/cement ratio	Table 2, Fig 4	0.50
	1.8 Maximum free-water/cement ratio	Specified	0.60 } Use the lower value 0.50
2	2.1 Slump or Vebe time	Specified	Slump 60-180 mm or Vebe time — s
	2.2 Maximum aggregate size	Specified	20 mm
	2.3 Free-water content	Table 3	195 — 195 kg/m³
3	3.1 Cement content	C3	195 ÷ 0.5 = 390 kg/m³
	3.2 Maximum cement content	Specified	— kg/m³
	3.3 Minimum cement content	Specified	325 kg/m³ use 3.1 if ≤ 3.2 use 3.3 if > 3.1 390 kg/m³
	3.4 Modified free-water/cement ratio		—
4	4.1 Relative density of aggregate (SSD)		2.6 ~~known~~/assumed
	4.2 Concrete density	Fig 5	2380 kg/m³
	4.3 Total aggregate content	C4	2380 − 390 − 195 = 1795 kg/m³
5	5.1 Grading of fine aggregate	Percentage passing 600 µm sieve	60 %
	5.2 Proportion of fine aggregate	Fig 6	35 to 40 say 36 %
	5.3 Fine aggregate content	C5	1795 × 0.36 = 646.2 kg/m³
	5.4 Coarse aggregate content		1795 − 646.2 = 1148.8 kg/m³

Quantities	Cement (kg)	Water (kg or litres)	Fine aggregate (kg)	Coarse aggregate (kg) 10 mm	20 mm	40 mm
per m³ (to nearest 5 kg)	390	195	646.2	~~689.28~~	~~459.52~~ 1148.8	—
per trial mix of 0.0125 m³	4.9	2.44	8.1	~~14.36~~	14.36	—

1 : 0.5 : 1.7 : 3

Chapter 5 Concrete Mix Design Calculations

Plate 3: Grade 25 Mix Design Form

Plate 4: concrete mixing process

Plate 5: concrete mixing process

Plate 6: concrete mixing process

Plate 7: concrete pouring in mould

Plate 8: concrete compaction on vibrating table

Plate 9: concrete crushing (destructive test)

Plate 10: rebound hammer test (non-destructive test)

Plate 11: rebound hammer