FORENSIC ASSESSMENT OF THE COMPRESSIVE STRENGTH OF INSTITUTIONAL BUILDING WITH THE UNIVERSITY OF BENIN AS CASE STUDY

BY

EDOBOR, Justin Osarobo

ENG2002393

A PROJECT SUBMITTED IN

PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF BACHELOR OF ENGINEERING (B.ENG).

IN

THE DEPARTMENT OF CIVIL ENGINEERING,

FACULTY OF ENGINEERING,

UNIVERSITY OF BENIN,

BENIN CITY, NIGERIA

NOVEMBER, 2025.

PLAGIARISM

This work "Forensic Assessment of the Compressive Strength of Institutional Building with the University of Benin as Case Study" by Edobor, Justin Osarobo, Mat. No. ENG2002393, of the Department of Civil Engineering, University of Benin City, Edo State. Nigeria, has PASSED the PLAGIARISM TEST.

PROJECT COORDINATOR

Name: Engr. E. ORIA-USIFO

Signature and Date: ....…

CERTIFICATION

This is to certify that this work was carried out by Edobor, Justin Osarobo, Mat. No. ENG2002393, of the Department of Civil Engineering, Faculty of Engineering, University of Benin City, Edo State, Nigeria.

PROJECT SUPERVISOR

Name: ENGR. DR. P.N OGBEIFUN

Signature: ……………………………… Date: …………………………………….

HEAD OF DEPARTMENT

Name: ENGR. PROF. (MRS.) N. I. IHIMEKPEN

Signature: ……………………………… Date: …………………………………….

DEDICATION

This work is dedicated to God Almighty, whose grace, wisdom, and strength have guided me through every step of this journey.

I also dedicate this project to my parents and family, whose unwavering support, sacrifices, and encouragement have been the foundation of my academic pursuits.

To all my lecturers, mentors, and colleagues who have inspired and challenged me to grow this is for you.

And finally, to every student striving to push through difficulties and achieve excellence may this work serve as a reminder that with perseverance and faith, all things are possible.

ACKNOWLEDGEMENT

I am deeply grateful to God Almighty for His unwavering guidance and support throughout my academic journey and research project.

My deepest appreciation goes to my supervisor, Engr. Dr. P.N Ogbeifun, whose guidance, encouragement, and constructive feedback were instrumental throughout the course of this study. Your expertise and support were invaluable at every stage of the work.

I also acknowledge the invaluable contributions of the Department of Civil Engineering staff, who consistently demonstrated exceptional dedication to imparting knowledge and fostering excellence. Specifically, I thank the Head of Civil Engineering Department Engr. Prof. (Mrs.) N. I. Ihimekpen, My Project Coordinator; Engr. E. Oria-Usifo and all my lecturers; Engr. Prof. O. U. Orie, Engr. Prof. O.C. Izinyon, Engr. Prof. S.O. Osuji, Engr. Prof. H.A.P. Audu, Engr. Prof. J.O. Okovido, Engr. Prof. S.D. Iyeke, Engr. Prof. R.O. Ogirigbo, Engr. Prof. (Mrs) N. Kayode-Ojo, Engr. Prof R. I. Umasabor, Engr. Prof. A.N Aniekwu, Engr. Dr. (Mrs.) A. Rawlings, Engr. Dr. (Mrs) L.O. Bobor, Engr. Dr. A.I Agbonaye, Engr. Dr. R. Ilaboya, Engr. Dr U. Ukeme, Engr. E. A. Musa, Engr. O. Oriakhi, Engr. B. Omosefe, Engr. C. Okolie, Engr. O. Osasu, Engr. N. Oghoyafedo, Engr. (Mrs) E. Ambrose-Agabi, Engr. Dr. I. Iziengbe, Engr. U. Ogbonna, Engr. (Mrs) G.E. Evbaru Okhuahesuyi, Engr J.O. Odemerho and the laboratory staff.

To my family and friends, thank you for your unwavering encouragement and for always believing in me. Your support kept me going during challenging moments.

Finally, I acknowledge my course mates and all those who contributed, directly or indirectly, to the completion of this project. Your input, advice, and shared experiences were deeply appreciated.

ABSTRACT

This research was conducted to assess the structural integrity and performance of selected iconic buildings within the University of Benin, Benin City, Nigeria. The primary aim of the study was to evaluate the current condition of these buildings in terms of their structural soundness, safety, and suitability for continued use. The study was driven by the growing need to ensure the long-term reliability and sustainability of public structures within tertiary institutions.

The methodology adopted involved non-destructive testing (NDT) using the rebound hammer technique conducted on thirty-eight (38) structural elements, including beams and columns, across the selected buildings. For each element, rebound numbers were taken on both the top and bottom faces, yielding a total of seventy-six (76) test points. Statistical analysis was performed on the rebound data to compute the mean, standard deviation, and coefficient of variation (COV), from which estimated compressive strengths were derived. These results were then interpreted in accordance with ASTM C805 and BS EN 12504-2 standards to assess the quality and uniformity of the concrete across the sampled elements.

The results revealed that the rebound numbers ranged between 40 and 52, corresponding to compressive strengths of approximately 52.6–61.4 N/mm^2. The mean rebound value was 48.21 with a standard deviation of 2.19, while the mean compressive strength was 57.86 N/mm^2 with a standard deviation of 2.38 N/mm^2, both yielding COVs below 5%. According to BS 1881 classification, these results indicate excellent concrete quality. The variation between readings across different members was minimal, confirming uniformity in construction and adequate material quality. Minor surface defects were observed but did not significantly affect the overall strength or stability of the structures. The study concluded that the assessed buildings remain structurally sound and safe for continued use, though regular monitoring and preventive maintenance are recommended to prevent progressive deterioration. The findings demonstrate the effectiveness of non-destructive testing as a reliable diagnostic tool for structural condition assessment in aging institutional buildings. However, periodic structural health monitoring, surface protection, and timely maintenance interventions were recommended to sustain the integrity and serviceability of the university's building infrastructure.

TABLE OF CONTENT

Title Page

Plagiarism i

Certification ii

Dedication iii

Acknowledgement iv

Abstract v

Table Of Content vi

List Of Tables x

List Of Figures xi

List Of Acronyms xii

CHAPTER ONE: INTRODUCTION 1

1.1 Background of Study 1

1.2 Statement of The Problem 2

1.3 Aim and Objective of The Study 3

1.4 Scope of Study 4

1.5 Justification of Study 4

CHAPTER TWO: LITERATURE REVIEW 5

2.1 Forensic Engineering and Structural Evaluation 5

2.2 Concrete 8

2.2.1 Definition and Composition of Concrete 9

2.2.2 Properties of Fresh and Hardened Concrete 10

2.2.3 Compressive Strength 12

2.2.4 Factors Affecting Compressive Strength 13

2.2.5 Standards and Target Strengths 14

2.2.6 Compressive Strength in Forensic Assessments 14

2.2.7 Factors Influencing Compressive Strength in Nigerian Institutional Buildings 15

2.2.8 Implications for Structural Safety and Institutional Infrastructure 15

2.3 Tropical Climate Effects on Concrete 16

2.3.1 Climate Characteristics and Their Influence 16

2.3.2 Carbonation and Its Structural Impact 17

2.3.3 Chloride-Induced Corrosion 18

2.3.4 Sulfate Attack 18

2.3.5 Biological Growth and Surface Deterioration 19

2.3.6 Combined Effects and Long-Term Performance 19

2.3.7 Mitigation and Design Considerations 20

2.4 Non-Destructive Testing Methods 21

2.4.1 The Role of NDT in Forensic Engineering 21

2.4.2 Schmidt Rebound Hammer Test 22

2.4.3 Ultrasonic Pulse Velocity (UPV) 22

2.4.4 Covermeter Testing 22

2.4.5 Infrared Thermography 23

2.4.6 Ground Penetrating Radar (GPR) 23

2.4.7 Limitations of NDT 23

2.4.8 Integration in Institutional Assessments 25

2.5 Nigerian Institutional Case Studies & Standards 25

2.5.1 Challenges in Nigerian Institutional Infrastructure 26

2.5.2 Use of British Standards in Nigeria 26

2.5.3 Integration with Nigerian Engineering Guidelines 27

2.5.4 Implications for the University of Benin Case Study 27

2.6 Summary of Previous Studies 28

CHAPTER THREE: METHODOLOGY 32

3.1 Introduction 32

3.2 Research Design 32

3.3 Study Area 32

3.4 Selection of Buildings 33

3.5 Equipment and Materials 36

3.6 Sampling Technique 37

3.7 Testing Procedure 38

3.8 Calibration and Reference Standards 39

3.9 Data Analysis 39

3.9.1 Descriptive Statistics 39

3.9.2 Histogram Distribution 40

3.9.3 Outlier Detection (Z-score Method) 40

3.9.4 Estimation of Compressive Strength 41

3.9.5 Comparative Strength Analysis 41

3.10 Limitations of the Study 41

3.11 Ethical Considerations 42

CHAPTER 4: RESULTS AND DISCUSSION 44

4.1 Introduction 44

4.2 In-situ Concrete Test Result 44

4.2.1 Rebound Hammer Test Results (Non- Destructive Test) 44

4.3 Statistical Evaluation of Rebound Hammer Data 50

4.4 Discussion of Results 59

CHAPTER FIVE: CONCLUSION AND RECOMMENDATION 59

5.1 Conclusion 59

5.2 Recommendations 60

REFERENCES 62

APPENDIX 69

LIST OF TABLES

Table 4.1: Hardness Criteria for Concrete Quality Grading BS 1881: 202 (1986) 44

Table 4.2: Rebound Hammer Results 45

Table 4.3: Statistical Calculation for Rebound Values 50

Table 4.4: Statistical Calculation for Compressive Strength Values 54

Table 4.5: Summary Table of Results 57

LIST OF FIGURES

Figure 3.1: University of Benin

33

Figure 3.2: Petroleum Engineering Building, University of Benin 35

Figure 3.3: Civil Engineering Building, University of Benin 36

Figure 3.4: The Schmidt Rebound Hammer

37

Figure 4.1: Chart Showing Rebound Values Test Result 47

Figure 4.2: Graph showing Average Rebound Test Result 48

LIST OF ACRONYMS

ACI	- American Concrete Institute
ASTM	- American Society for Testing and Materials
BS	- British Standard
BSI	- British Standards Institution
CEN	- European Committee for Standardization
COV	- Coefficient of Variation
COREN	- Council for the Regulation of Engineering in Nigeria
GPR	- Ground Penetrating Radar
MPa	- Megapascal
NDT	- Non-Destructive Testing
NS	- Nigerian Standard
NSE	- Nigerian Society of Engineers
OPC	- Ordinary Portland Cement
SPSS	- Statistical Package for the Social Sciences
UPV	- Ultrasonic Pulse Velocity
UNIBEN	- University of Benin
w/c	-Water–Cement Ratio

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 and durability. However, its long-term performance can degrade over time due to factors such as environmental exposure, construction quality, and inadequate maintenance (Onwualu, 2021).

In Nigeria, numerous institutional buildings such as lecture halls, administrative blocks, and hostels were built several decades ago, often with reinforced concrete as their primary structural material. These concrete structures are expected to endure a variety of loads and climate conditions over their service life. Over time, some of these structures have reported visible deterioration, including cracking, spalling, and surface wear. These observations raise genuine concerns about their ongoing structural performance.

To assess the current condition of existing concrete structures without disrupting their use, non-destructive testing (NDT) methods like the Schmidt rebound hammer are commonly employed. This instrument evaluates surface hardness and provides an indirect estimate of compressive strength based on rebound values. The rebound hammer offers a rapid, convenient, and non-invasive means of evaluating concrete integrity, making it suitable for field investigations (Auta & Olanipekun, 2025) .

The University of Benin (UNIBEN), established in 1970, is one of Nigeria’s first-generation universities. Its campus accommodates a wide range of institutional buildings, including lecture halls, libraries, and administrative blocks many of which were constructed during the university’s formative years. These early structures were built using the materials and construction standards available at the time, and have since been subjected to decades of continuous use, environmental exposure, and evolving functional demands. As these buildings age, concerns around their structural integrity become increasingly relevant.

To evaluate the current condition of such ageing concrete structures, forensic assessment methods are essential. These typically involve a combination of non-destructive and, where permissible, destructive testing techniques to estimate in-situ compressive strength and uncover signs of material deterioration (Soman & Raveendranath, 2021). However, due to the educational significance and continuous use of these buildings, intrusive methods are often restricted, making non-destructive techniques particularly valuable (Gatari et al., 2014). The Schmidt rebound hammer, in particular, offers a practical means of assessing surface hardness without compromising structural functionality. In the context of UNIBEN, such assessment is both timely and necessary, offering insights that can guide maintenance strategies while contributing to a broader understanding of the condition of institutional infrastructure in Nigeria.

1.2 Statement of The Problem

Numerous buildings within Nigerian universities, including the University of Benin (UNIBEN), show visible signs of aging, such as cracks and surface deterioration, raising serious concerns about their structural integrity. Many of these structures, in use for several decades, were designed to support critical academic and administrative functions, yet their current capacity to safely accommodate occupants is uncertain. The compressive strength of concrete, a fundamental indicator of structural health, may have diminished due to factors such as material degradation or inadequate construction practices, but no forensic analysis has been conducted to quantify this at UNIBEN.

The absence of such investigations leaves critical gaps in understanding the extent of deterioration, making it challenging to assess whether these buildings comply with standard building codes, such as those outlined in Nigerian or international standards like

BS EN 12504-2. This uncertainty poses significant risks, including potential structural failures that could endanger the lives of students, staff, and visitors, disrupt academic operations, and lead to costly repairs. Furthermore, the limited availability of local research on the structural performance of institutional buildings in Nigeria makes it difficult to develop maintenance strategies that are truly suited to the region's environmental and operational conditions.

At UNIBEN, the issue is pressing due to the high occupancy of its lecture halls, libraries, and administrative blocks. Without a comprehensive forensic assessment, university management cannot prioritize interventions or ensure occupant safety. The situation in tertiary Institution reflects a broader challenge across Nigeria's higher education sector, where aging infrastructure remains in use without adequate evaluation. The absence of forensic studies leaves a critical gap in ensuring structural integrity, regulatory compliance, and long-term safety, highlighting the pressing need for thorough investigations into the condition of these facilities.

1.3 Aim and Objective of The Study

The aim of this study is to conduct a forensic assessment of the compressive strength of institutional buildings in the University of Benin.

The objectives of this study include:

i. To identify and select an aged institutional building with signs of distress within the University of Benin.

ii. To perform visual inspections and estimate the in-situ compressive strength of concrete based on the method of nondestructive testing of concrete.

iii. To compare estimated strength with standard requirements and available design data.

1.4 Scope of Study

The scopes of work for this study are as follows:

i. Identification and selection of institutional buildings based on criteria such as age, usage, and architectural relevance.
ii. Carryout a visual inspection to identify signs of surface deterioration and structural distress.
iii. Conduct non-destructive testing using a rebound hammer in accordance with relevant standards.
iv. Statistical evaluation of the rebound hammer results to determine the status of structural elements in the building.

1.5 Justification of Study

This study holds importance for both practical and academic purposes. First and foremost, it aims to enhance safety assurance by evaluating the compressive strength of institutional buildings at the University of Benin (UNIBEN), thereby helping to protect students, staff, and visitors who use these facilities daily.

Early identification of structural weakness through this assessment helps in cost-effective maintenance, potentially reducing the risk of expensive repairs or structural failure in the future. The findings are also valuable for policy development, offering evidence-based insights that can guide university management and regulatory bodies in establishing effective maintenance protocols for institutional buildings.

From an academic perspective, the study contributes to the growing field of forensic engineering, particularly in Nigeria’s tropical climate, where local data on structural performance remain limited. Finally, by offering practical recommendations, the study promotes sustainable building practices, including maintenance and eco-friendly repair methods, which are essential for the long-term preservation of educational infrastructure.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Forensic Engineering and Structural Evaluation

Forensic engineering, is a specialized branch of civil and structural engineering, focuses on investigating the causes of structural failures, material deterioration, and performance issues. Forensic engineers apply scientific and engineering principles to analyze physical evidence, determine failure mechanisms, and provide insights to prevent future incidents. This field plays a critical role in ensuring safety and reliability in infrastructure and construction (Siegel, 2013). It employs scientific and engineering principles to assess why a structure underperformed or failed and to recommend remedial actions. In recent decades, the field has expanded beyond failure analysis to include the systematic evaluation of aging infrastructure, especially in developing countries like Nigeria, where aging institutional buildings are increasingly vulnerable to structural degradation, as noted by (Lesanmi et al., 2023). The evaluation of concrete's compressive strength, which lies at the heart of any forensic investigation into reinforced concrete structures provides essential insights into material degradation over time, guiding effective maintenance and structural rehabilitation (Kelson & Moore, 2022).

In the context of institutional buildings such as those found in Nigerian universities, forensic engineering is especially vital. These buildings are often decades old, heavily utilized, and subjected to environmental and loading conditions that were not always anticipated at the time of their construction. As structures age, their load-bearing capacity may reduce, either due to material deterioration or construction defects that only become evident over time. Forensic engineering allows engineers to assess the current state of these structures without full demolition or invasive techniques. According to (Carper, 2001), forensic investigations often involve a comprehensive evaluation that includes physical inspection, analysis of material properties, environmental conditions, and construction records.

Globally, forensic engineering has advanced through sophisticated non-destructive testing methods for evaluating concrete structures. Techniques such as ultrasonic pulse velocity (UPV) are effective for assessing the internal condition and compressive strength of reinforced concrete without causing significant damage. These methods provide critical data for structural assessments, as demonstrated by (Bolborea et al., 2021), who highlight the use of UPV and moduli of elasticity in evaluating concrete compressive strength. Additional methods, such as core sampling, ground-penetrating radar, and the Schmidt hammer, further support comprehensive structural analysis and rehabilitation strategies. These tools provide valuable data on the integrity of reinforced concrete, particularly regarding its compressive strength (Bungey et al., 2006). These techniques are indispensable for evaluating concrete structures still in use, as they enable safe, efficient, and repeatable measurements.

Despite the global maturity of forensic engineering, its application in Nigeria remains relatively underdeveloped. While there are increasing calls for condition assessments of public infrastructure, formal forensic assessments especially of institutional buildings are limited. The scarcity of local research and documented case studies in Nigerian contexts makes it difficult to develop tailored standards and maintenance strategies. For instance, many Nigerian university buildings were constructed over 30 years ago using then-prevalent construction methods and materials, often without robust documentation. These buildings are now exposed to new and intensified environmental stressors due to climate change and urban expansion, yet regular structural evaluations are rare.

For an institutional building, maintenance practices are often reactive rather than preventive. Some institutional buildings in the University of Benin, have reportedly shown signs of wear and aging, including visible cracks, spalling, and discoloration of concrete elements. These signs necessitate a forensic approach to assess whether the observed deterioration has compromised the structural performance of the building. Given the high occupancy and use, any degradation in concrete strength poses a serious risk.

The need for forensic structural evaluation is further underscored by Nigeria's vulnerability to construction-related disasters. The country has witnessed several incidents of structural collapse, many of which are traced to poor design, substandard materials, and inadequate maintenance. While these collapses often involve residential or commercial buildings, the lessons are equally applicable to institutional structures. Odoanyanwu et al. (2021) reported that tertiary institution buildings commonly experience structural defects including cracks, spalling, exposed reinforcement, and delamination, primarily due to lack of maintenance, inadequate funding, and poor management decisions, which underscores the importance of regular assessments.

International codes and standards play a significant role in forensic evaluations. In Nigeria, the British Standard BS 8110 remains a commonly referenced code for concrete structures. Many older buildings were designed and built using BS 8110 principles. Thus, forensic assessments must consider the original design code to properly evaluate the expected material performance and structural loadings. Structural health monitoring should not only assess whether the structure currently meets minimum strength requirements but also whether it remains safe under its intended load and environmental exposure.

Forensic structural engineering also includes an evaluation of historical records such as design drawings, construction logs, and maintenance reports. In many Nigerian institutions, however, such records are incomplete or missing. This makes in-situ testing the most reliable method for evaluating structural performance. Tools like the Schmidt Hammer, which measures surface hardness and indirectly estimates compressive strength, become critical. Although less precise than core sampling, it provides an efficient and relatively accurate indication of strength variation across a structure's surfaces, especially when used with appropriate calibration curves and supported by visual inspection and environmental data.

Forensic engineering provides a scientific basis for evaluating the current condition of structures and determining the causes of observed or potential failures. In concrete structures, this evaluation often involves a combination of non-destructive testing, core sampling, chemical analysis, and visual inspection to assess integrity and deterioration. The insights gathered enable engineers to offer evidence-based recommendations ranging from minor rehabilitation to load redistribution or, in severe cases, partial demolition (Kelson & Moore, 2022). In institutional settings like universities, such decisions carry significant weight, as they affect both safety and academic operations. For this reason, forensic evaluation ensures that facility managers and administrators are equipped with objective data to make informed choices about maintenance planning or reconstruction efforts (Coleman, 2024).

Forensic engineering serves as a cornerstone of structural reliability. Despite its global recognition, its adoption in Nigeria is still emerging. As universities continue to face funding and maintenance challenges, the use of forensic engineering offers a sustainable path for prolonging the life of existing infrastructure while safeguarding occupants.

2.2 Concrete

Concrete is the most widely used construction material in the world due to its versatility, strength, durability, and ability to be formed into various shapes. In institutional buildings such as laboratories, classrooms, and administrative blocks, concrete serves as the backbone of structural integrity. A proper understanding of concrete's material properties, especially its compressive strength, is essential for both the design and forensic evaluation of buildings.

2.2.1 Definition and Composition of Concrete

Concrete is defined as a composite construction material made primarily of cement, fine and coarse aggregates, water, and sometimes admixtures. When these ingredients are combined, a chemical reaction known as hydration occurs between cement and water, leading to the hardening of the mix into a stone-like mass. The quality and proportions of these constituents significantly influence the performance of the hardened concrete.

According to Neville (2011), concrete is a heterogeneous material with behavior governed by the interaction of its constituents. The microstructure of the hardened paste, the interface zone between paste and aggregate, and the distribution of pores all affect strength and durability.

Typical components of concrete and their roles:

i. **Cement:** Acts as the primary binding agent in concrete, with Ordinary Portland Cement (OPC) being the most commonly used type due to its reliability and performance.

ii. **Water:** Initiates the chemical reaction known as hydration. The water–cement (w/c) ratio is critical, as it significantly influences the strength and durability of the concrete.

iii. **Fine Aggregates:** Typically composed of sand, fine aggregates fill the voids between coarse particles and help achieve a dense and workable mix.

iv. **Coarse Aggregates:** Consist of gravel or crushed stone and provide the bulk and strength of the concrete. Their size, shape, and gradation affect workability and mechanical properties.

v. **Admixtures (optional):** Chemical or mineral additives used to modify specific properties of fresh or hardened concrete. They can accelerate or retard setting time, improve workability, reduce permeability, or enhance durability under specific environmental conditions.

2.2.2 Properties of Fresh and Hardened Concrete

Concrete exhibits different properties in its fresh and hardened states. Fresh concrete must have adequate workability (ease of mixing, placing, and compacting), while hardened concrete must achieve the required mechanical strength, especially compressive strength, which is the primary design parameter in most structural applications.

i. **Fresh Concrete Properties**

Fresh concrete refers to the state of concrete immediately after mixing and before it begins to harden. The performance of fresh concrete greatly influences the ease of construction and the quality of the final structure. Several properties are evaluated at this stage to ensure that the mix can be placed and compacted effectively, without segregation or bleeding.

a. **Workability:** This refers to the ease with which fresh concrete can be mixed, placed, compacted, and finished without segregation or excessive bleeding. It is influenced by water content, aggregate shape and size, temperature, and the presence of admixtures. Good workability ensures uniformity and full compaction, which are essential for achieving design strength and durability.

b. **Consistency:** This is the measure of the fluidity or wetness of fresh concrete, typically assessed using the slump test. Higher consistency indicates a more flowable mix, which may or may not be desirable depending on the structural application.

c. **Setting Time:** The time it takes for concrete to transition from a plastic to a solid state. It includes initial and final setting times, influenced by factors such as temperature, cement composition, and the presence of chemical admixtures.

ii. Hardened Concrete Properties

Hardened concrete refers to concrete that has gained sufficient strength after curing and has transitioned from a plastic to a solid state. The performance of hardened concrete determines the structural integrity, durability, and service life of the constructed element. These properties are influenced by the mix design, curing conditions, and quality of materials used. Key mechanical and durability properties are assessed to ensure the structure can safely carry loads and withstand environmental exposure over time.

a. Compressive Strength: This is the most critical mechanical property of hardened concrete, representing its ability to resist axial compressive loads. It is typically measured at 28 days and serves as the primary design criterion in structural applications.

b. Tensile Strength: Concrete has significantly lower tensile strength compared to its compressive strength, usually ranging between 8% and 15% of the compressive value. Concrete is weak in tension, which is why reinforcement is essential in structural members subjected to tensile forces.

c. Elastic Modulus: The modulus of elasticity measures the stiffness of concrete, or its ability to deform elastically under load. It is a vital parameter in structural analysis and is influenced by the concrete's strength, aggregate type, and curing conditions.

d. Creep and Shrinkage: Creep refers to the gradual deformation of concrete under sustained load, while shrinkage is the volumetric reduction due to moisture loss or chemical reactions. Both are time-dependent and affect long-term deflection, cracking and durability.

2.2.3 Compressive Strength

Compressive strength is the capacity of a material or structure to withstand loads tending to reduce its size, as opposed to tensile strength, which withstands loads tending to elongate. In concrete, it is a critical mechanical property that indicates the material's ability to resist axial compressive forces without fracturing or deforming excessively. It is typically expressed in megapascals (MPa) and is vital for assessing the performance of concrete in structural elements such as columns, beams, and slabs, (Mehta & Monteiro, 2014).

The compressive strength of concrete is usually determined by testing 150 mm cube or 150 × 300 mm cylinder specimens in a compression testing machine. The standard curing age for measuring this strength is 28 days, though strength gain continues beyond that period.

The theoretical foundation of compressive strength lies in the capillary pore structure of hardened cement paste. According to (Mehta & Monteiro, 2014), strength is inversely related to porosity, which is directly influenced by the water-cement ratio. A lower w/c ratio leads to lower porosity and higher strength, provided there is sufficient hydration.

According to (Neville, 2011), compressive strength can be empirically related to the water–cement ratio through a formula which expresses the inverse exponential relationship between water content and concrete strength of the form.

$$f_c = \frac{K_1}{K_2^{\left\{\frac{w}{c}\right\}}} \tag{2.1}$$

where:

f_c = compressive strength of concrete (MPa);

w/c = water-cement ratio;

K_1, K_2 = Empirical constants

This formula underscores the importance of controlling the water content during mix design.

2.2.4 Factors Affecting Compressive Strength

The compressive strength of concrete is influenced by several interrelated variables (Captain, 2025):

i. **Water-Cement Ratio (w/c):** A lower w/c ratio typically leads to higher strength by reducing the porosity of the hardened matrix. However, it also reduces workability, which may require the use of admixtures.

ii. **Cement Content:** Increasing the cement content enhances the volume of paste available to bind aggregates, thereby improving overall strength, provided it is balanced with adequate water and aggregate.

iii. **Aggregate Type and Grading**: The strength of concrete is affected by the size, shape, texture, and cleanliness of aggregates. Well-graded, angular, and clean aggregates create better interlocking and reduce voids, leading to improved strength.

iv. **Curing Conditions:** Proper curing maintains moisture and temperature conditions necessary for hydration. Inadequate curing leads to incomplete hydration and weakens the final strength.

v. **Age of Concrete:** Concrete gains strength over time. Typically, about 70% of its 28-day strength is achieved within the first 7 days, with full strength development by 28 days under proper curing conditions.

vi. **Admixtures:** Chemical admixtures like superplasticizers enhance workability without increasing water content, while mineral admixtures like fly ash or silica fume can improve strength and long-term durability through pozzolanic reactions.

2.2.5 Standards and Target Strengths

In accordance with BSI (2023), typical target compressive strengths for structural concrete in buildings range from 20 MPa (C20) to 40 MPa (C40), depending on load demands and structural functions. For institutional buildings like laboratories that may carry heavier equipment or face higher usage loads, the recommended strength is often C25 to C30.

The BSI (2019) outlines detailed procedures for compressive strength testing, including:

i. Specimen preparation
ii. Curing conditions
iii. Loading rates
iv. Data interpretation

These standardized tests provide a reliable means for assessing whether concrete in an existing structure still meets its original design strength.

2.2.6 Compressive Strength in Forensic Assessments

In forensic engineering, compressive strength evaluation helps determine whether existing concrete can still safely carry structural loads. Especially in older buildings, degradation may reduce in-situ strength well below the original design value. Non-destructive and partially destructive techniques such as Schmidt hammer and core testing are widely employed to estimate current strength levels (Alshaikh & Zeyad, 2022).

According to Carper (2001), any deviation from expected strength could be a result of:

i. Design or construction errors
ii. Poor material quality
iii. Environmental deterioration (e.g., moisture ingress, carbonation)

iv. Lack of maintenance

The results of compressive strength tests inform decisions regarding retrofit, repair, or decommissioning of affected structures.

2.2.7 Factors Influencing Compressive Strength in Nigerian Institutional Buildings

In the Nigerian context, several factors affect the compressive strength of concrete used in institutional buildings, (Eze & Ogbuagu, 2020). These include:

i. **Material Quality:** Inconsistent quality of cement and aggregates can lead to variability in strength. Local sourcing of aggregates without standardized testing contributes to unpredictable performance.

ii. **Mix Design and Proportioning:** Poor mix design, often done by volume instead of weight, is a common practice in many construction sites. This introduces variability in strength, especially when cement content is insufficient or poorly distributed.

iii. **Curing Practices:** Inadequate or premature removal of formwork and insufficient curing, especially in dry seasons, lead to incomplete hydration of cement and reduced strength. (Neville, 2011) emphasized that improper curing may result in up to 40% strength loss.

iv. **Workmanship and Compaction:** Poor compaction due to lack of vibration leads to entrapped air and honeycombing, which directly compromises compressive strength. This is particularly prevalent in rural or budget-constrained construction projects, including some university infrastructure.

2.2.8 Implications for Structural Safety and Institutional Infrastructure

In institutional settings, compressive strength is crucial not only for structural safety but also for serviceability. Concrete elements that fall below design strength may not fail immediately, but they can develop serviceability issues such as excessive deflections, cracking, or spalling. Over time, this undermines the durability and aesthetics of buildings.

Preliminary observations around high-use structures within the University of Benin, including faculty buildings, lecture halls, and administrative blocks, suggest localized surface wear and potential deterioration in exposed concrete elements. The absence of compressive strength assessment especially decades after construction raises safety concerns. As noted in a study of existing buildings in Onitsha, Nigeria, structural stability is often compromised due to omission of periodic non-destructive testing over several decades, resulting in low residual compressive strength and advanced deterioration (Okechukwu et al., 2021). Consequently, integrating forensic evaluation becomes essential to ensure continued safe use of institutional buildings.

2.3 Tropical Climate Effects on Concrete

Concrete, though widely recognized for its durability and load-bearing capacity, is susceptible to environmental degradation, particularly in tropical climatic conditions. Tropical regions, including much of sub-Saharan Africa, are characterized by high ambient temperatures, intense rainfall, sustained humidity, and variable solar radiation, all of which interact with the physical and chemical properties of concrete to accelerate its deterioration, (Bastidas-Arteaga et al., 2013). These environmental factors can lead to issues such as chloride ingress, carbonation, and reinforcement corrosion, significantly reducing the service life of concrete structures. Understanding how these environmental forces operate is essential in forensic engineering, especially when assessing the long-term performance of institutional buildings, such as those found on university campuses (Mutikanga et al., 2022).

2.3.1 Climate Characteristics and Their Influence

Tropical climates are typically defined by two main features: high annual rainfall (often exceeding 1,200 mm) and average temperatures consistently above 25°C (Peel et al., 2007). These conditions promote the ingress of water and aggressive ions into concrete, facilitating a variety of deterioration mechanisms. Concrete in tropical areas tends to remain in a moist or semi-saturated state for long periods, which is a critical factor in triggering chemical reactions within the concrete matrix or at the steel-concrete interface.

Moreover, daily fluctuations in temperature from hot, dry afternoons to cooler, more humid nights often lead to repeated thermal expansion and contraction cycles, potentially resulting in microcracks, particularly in inadequately cured or aging concrete (Mehta & Monteiro, 2014).Over time, these microcracks serve as pathways for moisture, chlorides, and carbon dioxide, enabling deeper penetration of aggressive agents.

2.3.2 Carbonation and Its Structural Impact

One of the most pervasive deterioration mechanisms in tropical concrete is carbonation. This process involves the reaction of atmospheric carbon dioxide (CO_2) with calcium hydroxide [$Ca(OH)_2$], a by-product of cement hydration, to form calcium carbonate ($CaCO_3$). While calcium carbonate itself is stable, the carbonation reaction leads to a lowering of the pH of the concrete often from around 12.5 to below 9 (Neville, 2011). Once the pH drops below the passivation threshold, steel reinforcement embedded within the concrete becomes vulnerable to corrosion. The depth of carbonation depends on factors such as permeability, moisture content, and exposure duration.

The carbonation rate d is theoretically proportional to the square root of time t:

$$d = k\sqrt{t} \tag{2.2}$$

Where:

d = carbonation depth; k = carbonation coefficient (mm/√year); t= time (years)

In tropical zones, high atmospheric CO_2 levels combined with moist conditions accelerate concrete carbonation. Structures with thin concrete covers, poor compaction, or inadequate curing are especially at risk. Over time, carbonation-induced reinforcement corrosion can result in spalling, cracking, and a reduced load-bearing capacity impacts most pronounced in critical elements like columns and beams (Al Fuhaid & Niaz, 2022).

2.3.3 Chloride-Induced Corrosion

Chloride ingress is another major concern in tropical environments, particularly in regions close to the coast or where de-icing salts or saline water may be present. Chloride ions penetrate the concrete cover and, once accumulated beyond a critical threshold at the reinforcement interface, disrupt the passive film that normally protects steel. The result is pitting corrosion, which progresses rapidly and often goes undetected until visible damage occurs (Mehta & Monteiro, 2014).

The chloride diffusion process is typically modeled using Fick's Second Law of Diffusion:

$$\frac{\partial C}{\partial C} = D \frac{\partial^2 C}{\partial x^2} \tag{2.3}$$

Where:

C = chloride concentration; D = diffusion coefficient; x = depth; t = time

Unlike carbonation, chloride-induced corrosion does not require a significant drop in pH, making it potentially more aggressive under the fluctuating wet–dry conditions common in tropical environments. Chloride penetration is governed by concrete's porosity, permeability, and exposure duration, structures in splash or spray zones are particularly vulnerable due to frequent salt-water wetting and evaporation cycles, which accelerate ion ingress and steel depassivation (Ali et al., 2024).

2.3.4 Sulfate Attack

In tropical soils and groundwater, sulfate compounds (commonly found in clay-rich soils and some industrial effluents) can pose a threat to concrete durability. Sulfates react with hydrated cement compounds to form expansive products such as gypsum, which cause internal stress and disruption of the hardened matrix. The outcome is often surface scaling, loss of strength, and in severe cases, disintegration of concrete.

The risk of sulfate attack is heightened in areas where concrete has prolonged contact with soil or standing water containing high concentrations of sodium, calcium, or magnesium sulfates. Tropical conditions further exacerbate this by keeping the concrete wet, allowing sulfate ions to remain mobile within the pore structure.

2.3.5 Biological Growth and Surface Deterioration

In humid tropical climates, concrete surfaces especially in shaded or poorly ventilated areas often become colonized by organisms like algae, lichens, moss, and mold. Although these do not directly compromise structural integrity, they retain moisture and increase surface roughness, which accelerates physical weathering and encourages further chemical deterioration (Wang et al., 2023).

In addition, biofilms formed by these organisms can alter surface pH and promote microbial-induced concrete corrosion (MICC), particularly in environments where moisture persists, such as near wastewater outlets or below ground services. In above-ground structures like laboratory buildings and classrooms, the primary effects are aesthetic degradation and prolonged moisture retention, which can over time reduce durability and negatively affect indoor comfort (Wang et al., 2023).

2.3.6 Combined Effects and Long-Term Performance

Concrete degradation in tropical climates usually results from the synergistic action of multiple deterioration mechanisms. For instance, carbonation-induced corrosion can be accelerated in concrete already weakened by sulfate attack; chloride ingress becomes more aggressive in cracked or porous concrete; and the severity of sulfate attack increases under intermittent wet-dry cycles (Metalssi et al., 2023).

From a forensic assessment standpoint, understanding these interactions is crucial. Structural distress such as cracking, corrosion-induced spalling, rust stains, or deflections often reflects long-term exposure to combined effects, not just a single failure event. This underscores the importance of periodic condition assessments and maintenance to preserve durability in tropical environments (Metalssi et al., 2023).

2.3.7 Mitigation and Design Considerations

According to Folorunso (2023), engineers can adopt several preventive strategies to mitigate the environmental degradation of concrete structures in tropical climates:

i. **Use of low-permeability concrete through proper mix design and compaction:** helps reduce chloride ingress and carbonation by limiting the penetration of aggressive agents.

ii. **Adequate curing, particularly in hot weather:** prevents plastic shrinkage cracking and ensures proper hydration, improving resistance to early-age cracking and sulfate attack.

iii. **Application of waterproof coatings or sealants on exposed surfaces:** provides a barrier against moisture, CO_2, and chlorides, reducing carbonation and chloride-induced corrosion.

iv. **Use of sulfate-resistant cement or pozzolanic additives (like fly ash or silica fume):** enhances chemical resistance, especially against sulfate attack and delayed ettringite formation.

v. **Increased concrete cover over reinforcement and use of corrosion inhibitors:** protects embedded steel from corrosion caused by carbonation and chloride ingress.

In forensic evaluations, identifying whether these protective measures were implemented and how effectively can inform accurate diagnosis and remedial strategies. This is especially critical for institutional buildings, where structural degradation can disrupt academic activities and endanger users if left unaddressed (Folorunso, 2023).

2.4 Non-Destructive Testing Methods

The accurate evaluation of existing concrete structures is essential in forensic engineering, especially when assessing buildings that are still in use (Devi, 2025). Non-Destructive Testing (NDT) refers to methods that allow engineers to inspect the internal condition or surface characteristics of concrete without causing damage making them ideal for institutional buildings where regular operation must continue uninterrupted (Devi, 2025).

NDT methods help detect internal flaws, estimate strength, and evaluate durability by using physical principles such as rebound, wave transmission, or magnetic fields. They are typically fast, economical, and repeatable, forming a cornerstone of modern structural assessments. However, single-method approaches can sometimes be misleading; combining multiple techniques like rebound hammer, ultrasonic pulse velocity, and rapid chloride permeability tests provides more accurate and reliable results (Jayale & Patil, 2023).

2.4.1 The Role of NDT in Forensic Engineering

Non-destructive testing plays a vital role in forensic engineering by offering insights into in-situ properties of concrete including uniformity, density, moisture content, cracking, voids, and strength estimation. While destructive methods like core sampling provide direct measurements, they are invasive and costly. In contrast, NDT can survey large areas quickly and identify zones requiring more detailed testing (Jayale & Patil, 2024).

According to ACI (2013), NDT is most effective when multiple methods are used together, as no single technique provides a complete picture. For instance, while the rebound hammer gives surface hardness, ultrasonic pulse velocity (UPV) evaluates internal integrity. Used together, they offer a more comprehensive view.

2.4.2 Schmidt Rebound Hammer Test

One of the most common NDT methods is the Schmidt rebound hammer, which assesses the surface hardness of concrete by measuring the rebound of a spring-loaded mass when it strikes the surface. The rebound number (or R-value) correlates with compressive strength through empirical relationships established during calibration.

According to BSI (2012), the test is best suited for comparative assessments across a structure rather than absolute strength determination. Factors such as surface moisture, smoothness, carbonation, and aggregate type can affect readings. Nonetheless, when conducted systematically, the Schmidt hammer offers a quick and portable means of identifying weak zones or monitoring deterioration trends (Jedidi, 2020).

2.4.3 Ultrasonic Pulse Velocity (UPV)

Ultrasonic Pulse Velocity (UPV) testing involves transmitting high-frequency waves through concrete and measuring their travel time. The velocity depends on the concrete’s density and internal uniformity, higher velocities generally indicate sound, dense concrete. While UPV does not directly yield compressive strength, empirical correlations (like the SonReb method) are often used when rebound and UPV data are combined (Devi, 2025). As outlined in BSI (2012), UPV is especially effective in detecting internal flaws like cracks, honeycombing, or segregated zones.

2.4.4 Covermeter Testing

A covermeter, also known as a reinforcement locator, detects embedded steel bars by generating magnetic fields. It identifies the position, spacing, and cover depth of reinforcement, key parameters for evaluating corrosion risk in reinforced concrete structures. Insufficient concrete cover can accelerate the ingress of carbonation and chlorides, particularly in aggressive environments, leading to early deterioration. However, the accuracy of covermeter readings may be influenced by factors such as closely spaced bars or bar orientation. Despite these limitations, the tool remains essential in forensic investigations for assessing construction quality and selecting optimal test zones (Sangoju & Vasanthakumar, 2018).

2.4.5 Infrared Thermography

Infrared thermography detects surface heat patterns emitted from concrete structures. Variations in temperature distribution can signal subsurface defects such as delamination, voids, or moisture intrusion especially in walls and slabs exposed to solar radiation. This technique is passive and rapid, requiring minimal surface preparation. However, its effectiveness depends on the presence of sufficient thermal contrast to highlight defects in the thermal images. Although not yet widely adopted in Nigeria due to the high cost of equipment, infrared thermography is gaining traction in tropical regions where solar intensity enhances defect visibility. It is particularly suited for assessing building envelopes and exposed external elements (Tomita & Chew, 2022).

2.4.6 Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) uses electromagnetic pulses to produce subsurface images of concrete elements. It’s particularly valuable for locating embedded objects such as rebar, conduits, and voids before core drilling or anchoring. GPR enhances safety and precision during structural investigations but performs poorly in wet or highly conductive concrete. Its resolution can also be limited in congested rebar zones (Devi, 2025).

2.4.7 Limitations of NDT

Non-destructive testing (NDT) techniques such as rebound hammer, ultrasonic pulse velocity, and ground-penetrating radar are indispensable tools in forensic engineering for evaluating the condition of concrete structures without causing damage. However, each method has inherent limitations, including restricted penetration depth, surface preparation sensitivity, and dependence on calibration and interpretation, which can affect accuracy and reliability (Devi, 2025).

i. **Indirect Measurement**: Most NDT methods, such as rebound hammer or ultrasonic pulse velocity tests, provide indirect indicators of compressive strength. Their results require interpretation through empirical correlations, which may not fully capture the in-situ condition of the concrete.
ii. **Surface Sensitivity**: The accuracy of many NDT techniques is influenced by surface conditions. Factors such as dust, moisture, carbonation, paint, or roughness can significantly distort readings, leading to unreliable conclusions if not accounted for.
iii. **Calibration Dependency**: Reliable interpretation of NDT results depends on comparison with well-calibrated reference data. Without appropriate calibration, often derived from core samples or similar materials the validity of the conclusions may be compromised.
iv. **Operator Dependence**: The reliability of NDT is also contingent on the experience and skill level of the operator. Inconsistent testing techniques, positioning errors, or subjective interpretation can lead to significant variability in results.

Due to inherent limitations of individual NDT techniques, forensic engineers often adopt a hybrid approach, combining non-destructive tests with targeted core sampling and laboratory analyses such as petrographic examination or chemical testing to verify results. The integration of these diverse data sources improves the accuracy and reliability of condition assessments, providing a robust foundation for recommending appropriate rehabilitation or retrofitting strategies (Kouddane et al., 2022).

2.4.8 Integration in Institutional Assessments

In the context of institutional buildings, NDT allows for non-invasive monitoring of aging structural elements, especially those under daily use. Regular testing cycles help identify deterioration early and prioritize areas for further investigation or maintenance. For university settings with constrained budgets and high user demand, NDT offers a sustainable method of infrastructure management.

The use of standardized procedures, such as those in BS EN and ACI guidelines, ensures that results are interpretable, comparable, and legally defensible. This is especially critical when justifying repairs, retrofits, or even building evacuations.

2.5 Nigerian Institutional Case Studies & Standards

Concrete infrastructure in Nigeria's institutional sector, particularly universities play a vital role in education and public safety. Over time, the need to evaluate the condition of these structures has become more urgent, driven by aging, poor maintenance, substandard construction practices, and environmental stresses. Despite increasing interest in forensic assessment in developed countries, its application in Nigeria remains limited. For example, a study of two 30+-year-old university buildings in Onitsha revealed "very poor compressive strengths" and heavy structural defects highlighting the omission of periodic evaluations over decades (Okechukwu et al., 2021).

This section reviews existing forensic evaluations of institutional buildings in Nigeria and highlights the relevance of adopting internationally recognized building codes, particularly British standards in these assessments. It also identifies the need for more structured, localized approaches that balance international quality benchmarks with the unique challenges of the Nigerian construction environment.

2.5.1 Challenges in Nigerian Institutional Infrastructure

Most universities in Nigeria were established during the post-independence boom (1960s–1980s), during which many structures were constructed using reinforced concrete. However, over the decades, exposure to harsh tropical environments, poor construction documentation, and limited maintenance budgets have compromised the durability of these buildings. As documented by (Ede & Olofinnade, 2015), many institutional buildings in Nigeria exhibit signs of distress such as cracking, spalling, dampness, and corrosion of reinforcement. These issues are often left unaddressed due to lack of technical capacity or funding.

Inadequate enforcement of building standards during original construction is a recurring theme. Forensic investigations frequently reveal the use of concrete with insufficient compressive strength, incorrect cover thickness, or improper curing, all of which undermine long-term structural integrity. The University of Lagos, Ahmadu Bello University, and Obafemi Awolowo University have all faced structural challenges in certain facilities, leading to partial closures or retrofitting projects (Abubakar & Yahaya, 2015; Aina et al., 2018).

2.5.2 Use of British Standards in Nigeria

Given Nigeria's historical ties to the United Kingdom, the construction industry widely adopts British Standards (BS) as reference documents for design, assessment, and retrofitting. These standards are considered reliable, comprehensive, and adaptable to the Nigerian context, despite not being region-specific.

Relevant BS codes in concrete forensic evaluation include:

i. **BSI (2019) – Testing hardened concrete:** Compressive strength of test specimens. This code provides protocols for preparing and testing concrete specimens under controlled conditions. It is essential for verifying strength levels during forensic investigations.

ii. **BSI (2012) – Non-destructive testing:** Determination of rebound number. It provides guidelines for using the Schmidt rebound hammer for estimating compressive strength and assessing concrete uniformity.

iii. **BSI (2021) – Ultrasonic pulse velocity:** This standard outlines procedures on how to measure both longitudinal and transverse ultrasonic pulse velocities in hardened concrete for evaluating uniformity, cracking, and estimating strength.

iv. **(BSI, 2023) – Structural use of concrete:** Code of practice for design and construction.

The use of these standards ensures consistency in evaluation practices and allows for international benchmarking. However, reliance on foreign codes must be balanced with local testing and calibration to ensure relevance to Nigerian materials and environmental condition(Ede & Olofinnade, 2015).

2.5.3 Integration with Nigerian Engineering Guidelines

The Council for the Regulation of Engineering in Nigeria (COREN) and the Nigerian Society of Engineers (NSE) have emphasized the need for national frameworks that incorporate localized data into structural design and evaluation. The growing push for Nigeria-specific design codes (e.g., NS 500 series) is part of an effort to reduce dependency on foreign standards and tailor engineering practice to local realities.

Nonetheless, until such national codes are universally adopted, BS codes remain the most reliable framework for forensic investigations in Nigeria's institutional sector. The Federal Ministry of Works has also endorsed BS guidelines for infrastructure audits, further affirming their regulatory legitimacy in public-sector projects.

2.5.4 Implications for the University of Benin Case Study

Institutional buildings at UNIBEN closely mirrors issues observed in other Nigerian tertiary institutions. For instance, rebound hammer tests conducted on 176 columns across 12 buildings in Abuja revealed average compressive strengths around 15.5 MPa substantially below the nominal 20 MPa design strength highlighting widespread structural deficiencies detectable through NDT (Auta & Olanipekun, 2025). Additionally, a wider study across six public universities found common defects including cracking, leakage, rusting, and substandard finishes underscoring the persistent neglect of routine condition assessments (Lesanmi et al., 2023).

By applying (BSI, 2012) standards via rebound hammer testing, this study not only aligns with international best practices but also contributes crucial localized data to a field lacking robust forensic investigations in Nigerian university settings. The findings will directly inform maintenance prioritization and have the potential to shape broader infrastructure management policies across Nigeria's tertiary education sector.

2.6 Summary of Previous Studies

Several studies, both international and local, have contributed to the understanding of forensic evaluation methods used in assessing the compressive strength of concrete in existing structures. (Ivanchev, 2022) investigated a combination of destructive and non-destructive techniques to assess concrete strength in long-aged laboratory specimens. His research employed Schmidt rebound hammer tests, ultrasonic pulse velocity (UPV), and the SonReb method, with results correlated against reference core strengths. Findings indicated that while rebound and UPV methods can estimate in-situ strength with reasonable accuracy, they often require calibration to reduce uncertainty. The study developed nomograms for interpreting NDT values, showing how forensic assessments can minimize structural damage while providing reliable strength data.

In a similar approach to complex forensic scenarios, (Kumar & Gupta, 2024) explored the assessment of fire-damaged concrete by combining rebound hammer readings with visual and colorimetric analysis. Their method allowed for the estimation of historical thermal exposure and strength degradation using calibrated curves and Eurocode-based reduction factors. The study reported a strong correlation between visual colour changes, rebound values, and residual compressive strength, demonstrating how chemical and mechanical indicators can be combined in forensic evaluations.

Within the Nigerian context, Auta and Olanipekun (2025) conducted a wide-ranging non-destructive survey on 176 concrete columns across 12 buildings in Abuja. Using the rebound hammer, they developed a regression model to estimate in-situ compressive strength and found that average values were significantly below the original design specification, approximately 15.46 MPa measured versus 20 MPa designed. The study recorded a negative deviation of 22.4% and emphasized the need to recast several structural elements. This research directly supports the current investigation, providing a model for comparing design expectations with actual performance in institutional buildings.

A related investigation by, Atoyebi et al. (2019) explored the reliability of the rebound hammer by comparing it with standard compressive strength tests across several concrete mixes. Their research, which involved samples from institutions such as Landmark University, Covenant University, and the University of Lagos, reported a high correlation (R^2 values between 0.868 and 0.994) between rebound values and cube strengths. These results confirmed the method’s reliability when used under controlled calibration, making it particularly valuable for strength estimation in educational settings where access to full destructive testing may be limited.

Another Nigerian study by, Osuji and Egbon (2021) examined the strength performance of hollow building blocks made from partial granite dust and sand replacement. Although the study focused on walling units rather than in-situ concrete, its findings on compressive strength variation due to material substitution highlight how local construction practices influence structural reliability, especially in educational facilities that often use cost-effective alternatives.

Amin et al. (2018) presented a case study of an unfinished rectorate building at a university in Indonesia. Their forensic approach included rebound hammer testing, visual inspection, and finite-element analysis. They found wide variation in concrete quality across columns and beams, with some structural elements falling below acceptable strength levels. A full structural audit led to the recommendation for retrofitting specific components. This case shows rebound hammer testing can serve as an early indicator of concrete quality, backed by analytical modelling for structural safety assurance.

In Malaysia, Tang et al. (2020) evaluated the structural integrity of a university library using rebound hammer tests across 21 points, including slabs, beams, columns, and staircases. Although compressive strengths exceeded the Eurocode minimums, ranging from 25 MPa to 38 MPa, the study identified under-designed steel reinforcement that compromised structural safety. This reinforced the view that even when concrete strength is adequate, forensic investigations must consider reinforcement details and load demands.

Further studies have expanded the forensic lens beyond just compressive strength. For instance, Agbí et al. (2020) assessed commercially produced sandcrete blocks in Isoko, Delta State, and found strength levels significantly below acceptable standards, with some blocks registering as low as 0.65 N/mm². Similarly, Ezeagu et al. (2015) investigated collapsed buildings in Onitsha using both destructive and non-destructive tests and discovered that the majority of tested structural elements failed to meet strength requirements. Their research highlighted systemic issues such as poor-quality control, substandard materials, and inadequate supervision, factors that contribute to structural failures in public buildings.

A broader review by, Quadri et al. (2024) examined Nigeria’s widespread building collapse incidents and attributed them largely to non-compliance with regulations, weak enforcement mechanisms, and substandard construction practices. Although their work did not focus solely on compressive strength tests, it emphasised the critical role of technical assessments, including strength evaluations, in preventing failures. Their recommendations for more rigorous inspection and regulation align with the goals of the current study.

The findings from, Auta and Olanipekun (2025), revisited in this context, provide strong support for forensic assessments within Nigeria. Their recommendation for mandatory cube testing and stricter site supervision addresses root causes identified in both local studies and broader regional reviews. These insights, when applied to the University of Benin case study, affirm the necessity of forensic compressive strength evaluations to ensure the ongoing safety and integrity of institutional buildings.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter outlines the methodological approach adopted to test the compressive strength of selected institutional buildings within the University of Benin (UNIBEN). It describes the research design, study area, sample selection method, materials and equipment used, data collection techniques, and methods of analysis. The chapter also highlights the limitations encountered and ethical considerations observed during the research process.

3.2 Research Design

This study adopts a non-destructive testing (NDT) approach to assess the in-situ compressive strength of concrete in selected institutional buildings. The primary method employed will be the Schmidt rebound hammer test, which enables evaluation of surface hardness as a proxy for compressive strength without damaging the structure.

A combination of field investigation, on-site data collection, and statistical analysis will be used to interpret the test results and make informed assessments about the structural integrity of the selected buildings.

3.3 Study Area

This study is situated within the University of Benin (UNIBEN), a federally owned tertiary institution located in Benin City, Edo State, Nigeria. Established in 1970, the university has grown into one of Nigeria's foremost academic institutions, with extensive physical infrastructure spread across its primary Ugbowo campus and the Ekenwan campus. The Ugbowo campus, which hosts most of the university's faculties and administrative buildings, will serve as the principal focus for this forensic investigation.

The University of Benin status as a federal university also ensures a level of construction standardisation and public accessibility, which makes it a practical environment for conducting in-situ concrete strength assessments. The presence of exposed reinforced concrete elements across many of the campus structures further supports the application of non-destructive evaluation techniques.

All activities will take place within the university's boundaries, and the findings of this study will be contextualised within the broader structural profile of similar institutional buildings in Nigeria.

Figure 3.1: University of Benin

3.4 Selection of Buildings

For the purpose of this study, two institutional buildings within the Ugbowo campus will be selected. The selection will be guided by the following criteria:

i. Structural significance and usage (e.g., high-traffic buildings such as lecture halls or departmental complexes)

ii. Age and construction period

iii. Accessibility for non-destructive testing

iv. Visible signs of structural distress or surface degradation

The specific buildings to be assessed will be finalized following a preliminary walkthrough survey in consultation with the Department of Civil Engineering. This approach allows the research to focus on structures that are both relevant and representative of broader structural conditions within the institution.

34.1 Petroleum Engineering Building, University of Benin

The Petroleum Engineering Building is a single storey reinforced concrete. It contains multiple lecture rooms, research laboratories, offices, and computer labs. The building structure relies on reinforced concrete columns and beams, supporting two-way slab systems that are optimal for the larger lecture halls and laboratories.

The vertical elements columns and walls are strategically placed to reduce span lengths and deflection. The slabs are reinforced in both directions, with reinforcement bars typically in the Y12–Y20 range. The floor finish varies: polished concrete in laboratories for chemical resistance, ceramic tiles in offices, and terrazzo in lobbies and staircases. The walls are composed of 225 mm Sandcrete blocks, and windows are typically louvered or aluminum-framed with glass panes.

The foundation system uses reinforced concrete pad footings, which are connected in some areas by ground beams to improve stability. High concrete strength (up to C35/45) may be used in load-critical zones, especially beneath heavy lab equipment. The roof is designed as a flat reinforced concrete slab with waterproofing membranes and drainage pipes.

Figure 3.2: Petroleum Engineering Building, University of Benin

3.4.2 Civil Engineering Building, University of Benin

The Civil Engineering Building at the University of Benin is one of the core academic structures within the Faculty of Engineering. This building is a three-storey reinforced concrete framed structure with clearly defined academic and administrative spaces, including lecture rooms, staff offices, laboratories, and student halls. The structural system comprises reinforced concrete columns, beams, and slabs, all designed to support both live and dead loads typical of academic buildings.

The building primarily utilizes one-way slab systems in smaller classrooms and offices, while two-way slabs are adopted in larger areas such as studios and laboratories. These slabs are supported by moderately sized beams (usually 225 mm wide) and rectangular or square columns (ranging between 225 mm × 225 mm to 300 mm × 300 mm). Floor finishes include ceramic tiles in offices and terrazzo in hallways and classrooms. The walls are built from Sandcrete blocks (150 mm for partitions, 225 mm for structural walls), finished with cement plaster and emulsion paint.

The foundation system consists of isolated pad footings and strip foundations, suitable for the site's soil bearing capacity. Concrete grades used in the building generally range between C25/30 and C30/37, with reinforcements comprising high-yield deformed steel bars (typically Y12 to Y20). The roof is a flat reinforced concrete slab roof, topped with waterproofing layers and parapet walls. The building is ventilated by natural cross-flow air paths, with ceiling fans and optional air conditioning units in select rooms.

Figure 3.3: Civil Engineering Building, University of Benin

3.5 Equipment and Materials

The primary equipment to be used is the **Schmidt Rebound Hammer**, for measuring the surface hardness of concrete. The device consists of a spring-loaded mass that strikes the concrete and measures the rebound distance, which correlates with surface hardness and estimated compressive strength.

Figure 3.4: The Schmidt Rebound Hammer

Additional materials included:

i. **Data sheet/Logbook:** To record rebound index value and surface conditions.

ii. **Chalk and Measuring Tape:** To mark grid points and distances on structural members.

iii. **Camera/Phone:** To document physical defects or anomalies observed.

iv. **Computer with Statistical Software (e.g. MS Excel):** To visualise results and analyse data.

v. All equipment will be checked before each session to ensure operational reliability.

3.6 Sampling Technique

Sampling will be carried out directly on accessible concrete surfaces of the selected institutional buildings. A combined approach of random and purposive (selective) sampling will be adopted to ensure both objectivity and engineering relevance.

i. **Random Sampling:** will be used to ensure an unbiased distribution of test points across general structural areas. This helps capture an average representation of concrete quality throughout the building.

ii. **Selective (Purposive) Sampling:** will target locations that are structurally critical or potentially vulnerable to stress concentration or deterioration. These may include beam-column junctions, entrance columns, cantilever sections, exposed external faces, and other visibly distressed or high-load-bearing zones.

All sampling will be limited to non-destructive testing surfaces, ensuring no interference with structural integrity or building function.

3.7 Testing Procedure

The testing procedure will be conducted in accordance with BSI (2021), the most recent standard governing non-destructive determination of the rebound number for hardened concrete in structures.

i. **Surface Preparation:** All surfaces selected for testing will be first inspected visually and cleaned to remove dust, loose particles, surface residue, paint, or coatings that could affect rebound values, ensuring reliable contact with the hammer. In cases where surface coatings cannot be fully removed, such areas will be excluded from testing.

ii. **Grid Marking:** Test points will be marked on selected structural members such as columns and beams. In line with Clause 6.5.2 of rebound hammer testing standards, each test area will contain a minimum of ten marked locations. These marks will be spaced at least 25 mm apart to avoid overlapping stress zones and maintained at a minimum distance of 50 mm from edges, visible cracks, or surface defects, ensuring that local irregularities do not distort the results.

iii. **Test Orientation and Hammer Positioning:** Each impact will be applied with the rebound hammer held perpendicular to the surface, and 10 rebound readings will be taken per test area. The average of these values will be used to estimate compressive strength.

iv. **Recording and Observation:** Surface conditions, such as visible cracks, moisture, or uneven texture, will be documented alongside each test point.

v. **Mapping and Labelling:** Each test location will be mapped on hand-drawn layout and assigned a unique alphanumeric ID. The ID indicates the building, structural element, and stress zone (e.g., “CL-B3-MID” for Civil Lab, Beam 3, Midspan). This mapping allows for easy comparison of results across different areas and stress conditions.

vi. **Data Validation:** Any test point producing a visibly anomalous reading (±20% of the mean) was rejected and replaced with an additional reading, following standard protocol

3.8 Calibration and Reference Standards

The rebound hammer will be calibrated daily using a steel anvil supplied by the manufacturer, as recommended in Clause 5.3. Three consecutive readings will be taken on the anvil both before and after each testing session. If any of the readings deviate beyond the permitted range of 79 ± 2, the hammer will be re-calibrated accordingly. Calibration records will include the date, time, hammer serial number, ambient temperature, and rebound values, in full compliance with the standard’s documentation requirements.

3.9 Data Analysis

The data obtained from the rebound hammer tests will be analysed using Microsoft Excel, following a structured process to evaluate the in-situ compressive strength of concrete and assess the consistency of test results. The following statistical methods will be employed:

3.9.1 Descriptive Statistics

Descriptive statistics will be used to summarise the rebound index values collected from each structural element. For every set of readings, the mean, standard deviation (SD), and coefficient of variation (COV) will be calculated:

i. **Mean:** Represents the average rebound value, serving as a baseline for estimating compressive strength.

ii. **Standard Deviation:** Indicates how much the individual readings deviate from the mean, reflecting the consistency of the concrete surface.

iii. **Coefficient of Variation (COV):** Expressed as a percentage, this is the ratio of the standard deviation to the mean. Lower COV values suggest more uniform concrete quality.

These metrics will help assess the reliability of each test point and determine whether the concrete strength is consistent across different sections of the building.

3.9.2 Histogram Distribution

To visualise the distribution of rebound values, histograms will be generated in Excel. These graphical plots will group rebound index values into intervals to reveal the overall shape of the dataset. The histogram will help identify whether the data distribution is approximately normal or skewed. This is useful for interpreting how evenly concrete strength is distributed across tested areas.

3.9.3 Outlier Detection (Z-score Method)

Outlier analysis will be conducted using the Z-score method. For each rebound reading, a Z-score will be calculated using the formula:

$$Z = \frac{(x-\bar{x})}{\sigma} \qquad (3.1)$$

Where:

x= individual rebound value; $\bar{x}$= mean of the dataset; σ= standard deviation

Any reading with a Z-score beyond ±2.5 will be flagged as a potential outlier. These points will be reviewed in relation to field notes, especially were surface anomalies, material defects, or testing errors may have occurred. Confirmed outliers will be excluded and replaced with new readings in accordance with testing standards.

This analytical approach ensures that the rebound hammer data is processed accurately and consistently, allowing for meaningful conclusions about the compressive strength and uniformity of concrete across the selected buildings.

3.9.4 Estimation of Compressive Strength

The mean rebound values from each test location will be converted to estimated compressive strength (in MPa) using manufacturer-provided conversion charts. These charts, based on prior calibration, relate rebound index values to compressive strength for concrete of known properties. This step allows for quantification of the in-situ strength of tested concrete elements without requiring core extraction.

3.9.5 Comparative Strength Analysis

The estimated compressive strengths will be compared:

a. Across different structural components (e.g., beams vs. columns)
b. Between the two selected buildings

This comparison will help identify variations in material quality, workmanship, or age-related degradation. Bar charts or tables will be used to visualise the differences, supporting conclusions about overall structural consistency.

3.10 Limitations of the Study

While this study is designed to provide meaningful insights into the compressive strength of selected institutional buildings within the University of Benin using non-destructive techniques, several limitations are acknowledged:

a. **Restricted Access to Certain Buildings or Structural Members:** Access to all parts of the buildings may not be granted due to administrative constraints, security concerns, or the continuous use of the facilities. This may limit the number or diversity of test points available for analysis.

b. **Surface Condition Variability:** Rebound hammer results are sensitive to surface characteristics. Areas with paint, plaster, dust, or uneven finishes may influence rebound values. While surface preparation will be performed, complete uniformity across all test points cannot be guaranteed.

c. **Absence of Core Validation:** No core samples will be extracted in this study, meaning rebound values cannot be cross-validated with laboratory-based compressive strength tests. As such, the estimated strength values will rely solely on the hammer's calibration chart, which may introduce a degree of approximation.

d. **Environmental and Climatic Factors:** Testing may be affected by environmental conditions such as temperature, humidity, or rainfall during fieldwork. These factors can impact surface hardness and rebound accuracy, especially on exposed elements.

e. **Instrument and Human Error:** Although calibration will be conducted regularly, minor instrument inaccuracies or human handling variations may introduce small deviations in rebound readings.

f. **Limited Generalisation:** Findings from two buildings may not fully represent the structural integrity of all institutional buildings within the University of Benin. The results will be specific to the selected test sites and conditions.

3.11 Ethical Considerations

All testing activities will be conducted within the University of Benin premises with the full knowledge and consent of relevant university authorities. Necessary permissions will be obtained prior to selecting and accessing any institutional building for assessment. As the investigation involves only non-destructive testing, there will be no damage to structures, and no interference with the normal use or operation of the buildings. The privacy and anonymity of individuals present during the testing process will be respected at all times. All data collected will be used exclusively for academic and research purposes in line with institutional and ethical research guidelines.

CHAPTER 4

4.0 RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results obtained from the forensic assessment of the compressive strength of selected institutional buildings within the University of Benin. The analysis focuses on the data derived from the non-destructive rebound hammer test, visual inspections, and corresponding evaluations of the concrete's in-situ compressive strength. The results are interpreted in the context of established design codes, specifically BS 1881: Part 202 (1986) and ASTM C805 (2018), which guide the estimation of compressive strength from rebound numbers.

4.2 In-situ Concrete Test Result

4.2.1 Rebound Hammer Test Results (Non- Destructive Test)

The rebound hammer test was performed on 19 reinforced concrete structural members (beams and columns) across the identified buildings. For each element, six (6) rebound readings were recorded on the top and bottom of the side faces. The results were statistically averaged to derive representative rebound numbers and corresponding estimated compressive strengths and their quality graded as shown in Table 4.1. The test data is shown in Table 4.2 below, summarizing the rebound numbers, computed average rebound values, and estimated compressive strengths.

Table 4.1: Hardness Criteria for Concrete Quality Grading BS 1881:202 (1986)

Average Rebound Number	Quality
Above 40	Excellent Concrete
30 - 40	Good Concrete
20 - 30	Fair Concrete
Below 20	Poor Concrete

Table 4.2: Rebound Hammer Results

No	Position	Rebound Number						Average Rebound No.	Compressive Strength	Quality
		1	2	3	4	5	6			
M1	Top	52	48	42	51	45	45	47.17	56.6	Excellent Concrete
	Bottom	52	52	51	50	52	50	51.17	61.4	
M2	Top	49	45	48	46	50	51	48.17	57.8	Excellent Concrete
	Bottom	48	52	50	51	52	51	50.67	60.8	
M3	Top	45	50	44	48	41	40	44.67	53.6	Excellent Concrete
	Bottom	52	48	49	49	51	52	50.17	60.2	
M4	Top	48	46	48	46	47	52	47.83	57.4	Excellent Concrete
	Bottom	48	48	48	48	50	48	48.33	58.0	
M5	Top	51	46	45	40	52	47	46.83	56.2	Excellent Concrete
	Bottom	52	51	50	48	50	48	49.83	59.8	
M6	Top	43	46	44	49	46	50	46.33	55.6	Excellent Concrete
	Bottom	52	48	52	51	49	52	50.67	60.8	
M7	Top	45	41	45	47	40	50	44.67	53.6	Excellent Concrete
	Bottom	50	49	51	50	52	51	50.5	60.6	
M8	Top	43	48	47	48	42	49	46.17	55.4	Excellent Concrete
	Bottom	50	49	52	50	50	50	50.17	60.2	
M9	Top	51	44	43	44	49	43	45.67	54.8	Excellent Concrete
	Bottom	50	48	50	48	49	50	49.17	59.0	
M10	Top	50	52	48	44	41	44	46.5	55.8	Excellent Concrete
	Bottom	50	52	52	48	52	52	51.0	61.2	
M11	Top	42	50	44	40	43	44	43.83	52.6	Excellent Concrete
	Bottom	50	51	49	48	52	51	50.17	60.2	
M12	Top	50	44	41	44	45	50	45.67	54.8	Excellent Concrete
	Bottom	52	50	51	52	49	50	50.67	60.8	
M13	Top	44	46	49	48	45	52	47.33	56.8	Excellent Concrete
	Bottom	50	48	50	49	51	48	49.33	59.2	
M14	Top	42	42	52	47	45	40	44.67	53.6	Excellent Concrete
	Bottom	52	48	51	52	52	50	50.83	61.0	
M15	Top	49	52	48	52	44	47	48.67	58.4	Excellent Concrete
	Bottom	52	52	51	49	50	50	50.67	60.8	
M16	Top	45	40	46	44	43	52	45.0	54.0	Excellent Concrete
	Bottom	49	50	48	48	48	48	48.5	58.2	
M17	Top	40	45	49	48	49	50	46.83	56.2	Excellent Concrete
	Bottom	49	51	48	50	48	49	49.17	59.0	
M18	Top	49	41	43	43	46	46	44.67	53.6	Excellent Concrete
	Bottom	51	48	49	49	49	51	49.5	59.4	

Table continued on next page…

Table 4.2: Rebound Hammer Results (Continued)

M19	Top	43	42	46	45	48	49	45.5	54.6	Excellent Concrete
	Bottom	49	52	51	49	52	48	50.17	60.2	
M20	Top	49	51	43	41	50	43	46.17	55.4	Excellent Concrete
	Bottom	50	48	48	48	52	52	49.67	59.6	
M21	Top	45	49	43	51	51	40	46.5	55.8	Excellent Concrete
	Bottom	52	48	50	48	50	48	49.33	59.2	
M22	Top	47	52	43	44	48	47	46.83	56.2	Excellent Concrete
	Bottom	51	52	51	50	51	49	50.67	60.8	
M23	Top	47	45	42	44	51	46	45.83	55.0	Excellent Concrete
	Bottom	51	52	48	49	50	48	49.67	59.6	
M24	Top	41	47	46	52	46	50	47.0	56.4	Excellent Concrete
	Bottom	49	52	51	49	52	48	50.17	60.2	
M25	Top	52	42	41	49	49	47	46.67	56.0	Excellent Concrete
	Bottom	50	51	51	48	48	49	49.5	59.4	
M26	Top	46	48	51	40	47	44	46.0	55.2	Excellent Concrete
	Bottom	51	51	52	51	51	51	51.17	61.4	
M27	Top	40	52	51	45	48	44	46.67	56.0	Excellent Concrete
	Bottom	52	51	49	49	49	49	49.83	59.8	
M28	Top	41	46	51	49	52	50	48.17	57.8	Excellent Concrete
	Bottom	50	49	52	50	48	48	49.5	59.4	
M29	Top	40	50	51	52	43	49	47.5	57.0	Excellent Concrete
	Bottom	51	52	52	48	49	49	50.17	60.2	
M30	Top	51	47	43	42	41	45	44.83	53.8	Excellent Concrete
	Bottom	52	49	49	51	51	50	50.33	60.4	
M31	Top	49	45	51	45	46	41	46.17	55.4	Excellent Concrete
	Bottom	52	48	52	48	49	51	50.0	60.0	
M32	Top	49	47	50	45	48	40	46.5	55.8	Excellent Concrete
	Bottom	50	48	52	51	49	50	50.0	60.0	
M33	Top	50	52	50	50	42	50	49.0	58.8	Excellent Concrete
	Bottom	50	50	49	50	52	52	50.5	60.6	
M34	Top	50	40	46	45	42	45	44.67	53.6	Excellent Concrete
	Bottom	50	49	48	51	50	48	49.33	59.2	
M3	Top	45	49	48	44	44	51	46.83	56.2	Excellent

5	Bottom	48	52	50	52	48	50	50.0	60.0	Concrete
M36	Top	49	47	46	51	48	52	48.83	58.6	Excellent Concrete
	Bottom	52	51	51	48	52	51	50.83	61.0	
M37	Top	48	43	43	49	46	45	45.67	54.8	Excellent Concrete
	Bottom	52	49	52	52	51	51	51.17	61.4	
M38	Top	44	50	48	46	44	43	45.83	55.0	Excellent Concrete
	Bottom	50	51	50	49	50	49	49.83	59.8	

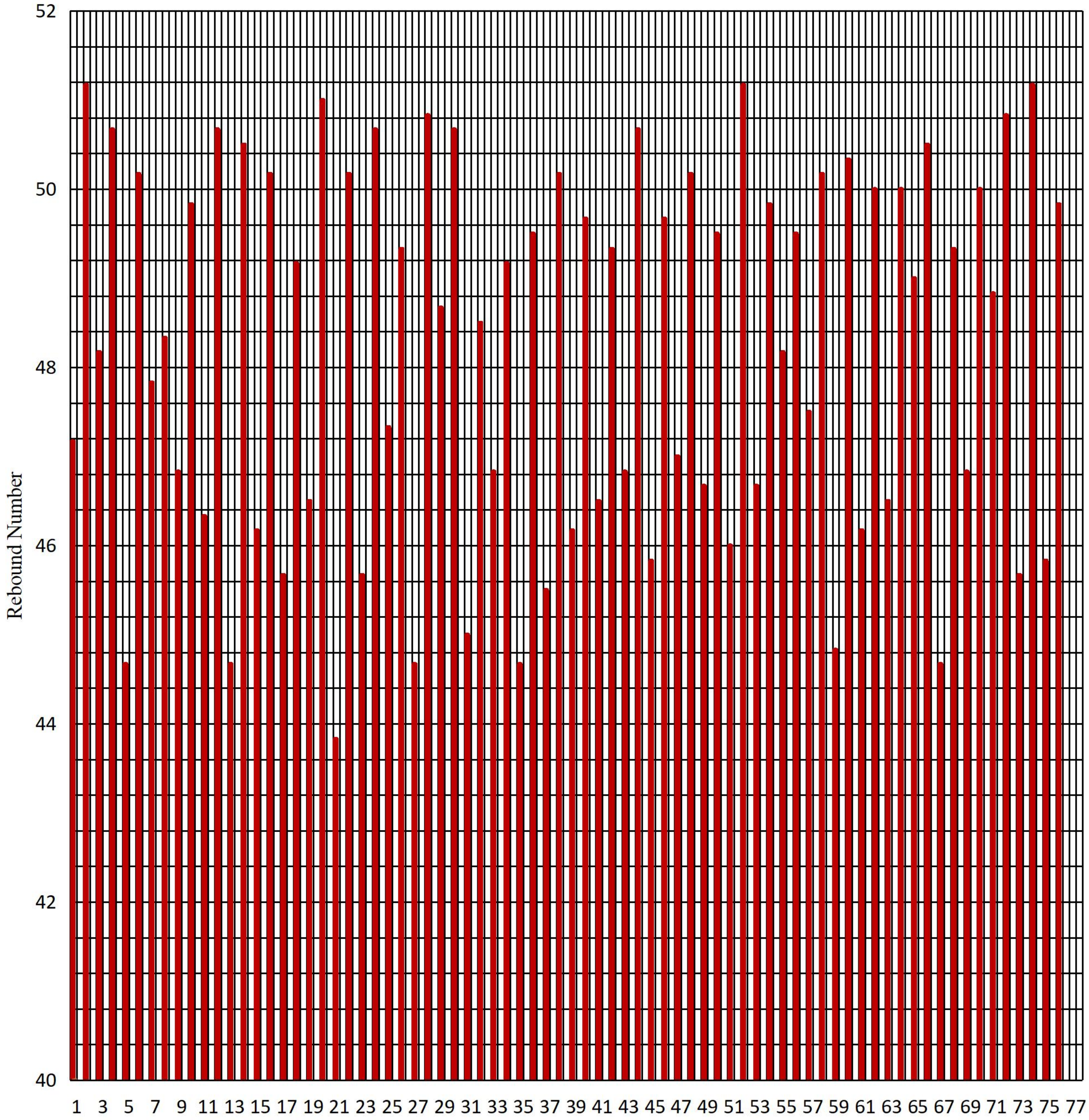

Figure 4.1: Chart Showing Rebound Values Test Result

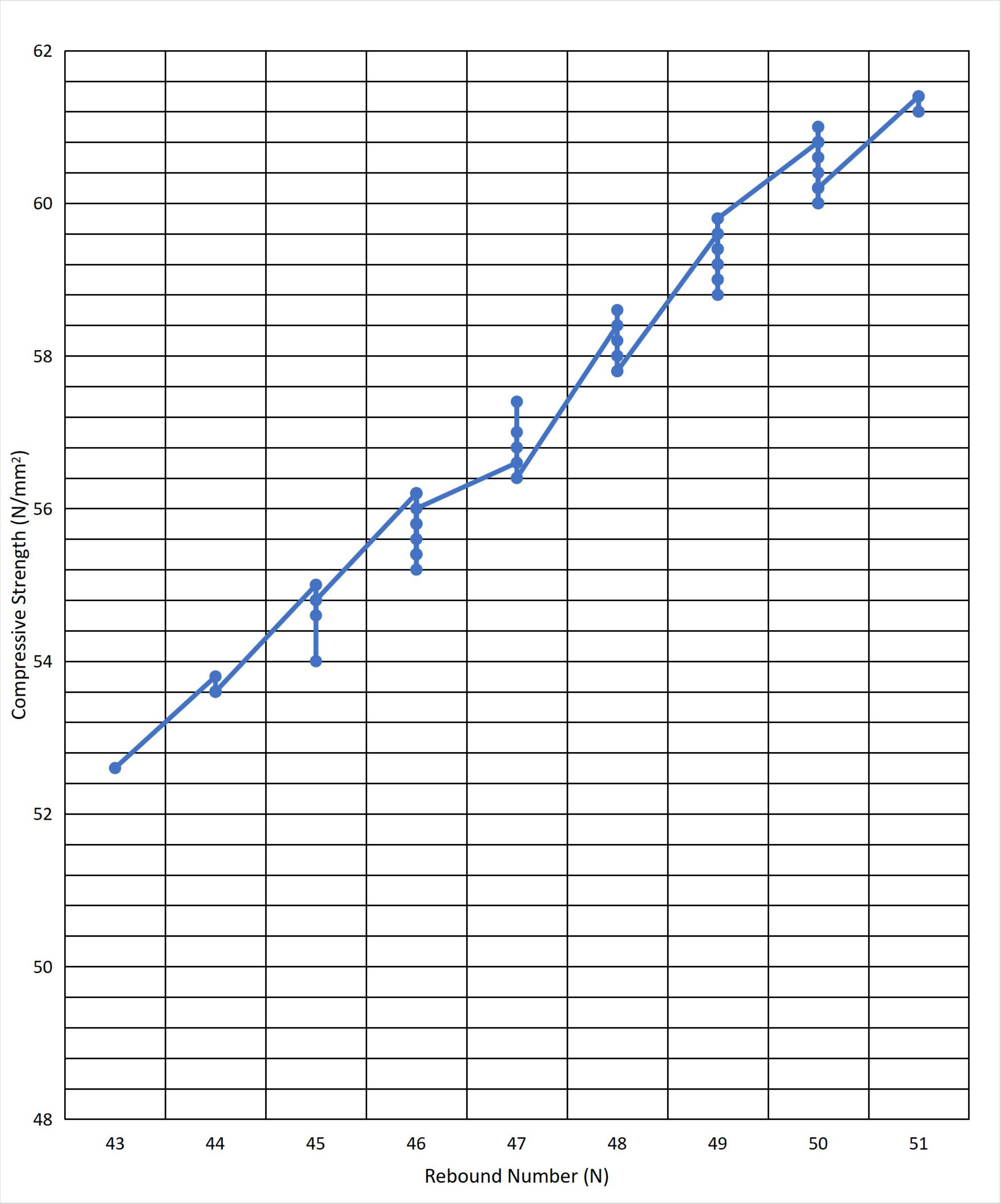

Figure 4.2: Graph showing Average Rebound Test Result

4.3 Statistical Evaluation of Rebound Hammer Data

The rebound hammer test data obtained from thirty-eight (38) structural members, each tested at two points (top and bottom), resulted in 76 total readings. To quantify the overall consistency and quality of the concrete, the data were statistically analysed using the mean, standard deviation (SD), and coefficient of variation (COV).

For a dataset $x_1, ..., x_n$(here n = 76):

Mean:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (4.1)$$

Where:

x_i = mean value; n = total number of observations; x_i = individual test value; $\sum$ = summation sign

for Rebound Hammer:

Σx=47.17+51.17+48.17+50.67+44.67+50.17+47.83+48.33+46.83+49.83+46.33+50.67+44.67+50.50+46.17+50.17+45.67+49.17+46.50+51.00+43.83+50.17+45.67+50.67+47.33+49.33+44.67+50.83+48.67+50.67+45.00+48.50+46.83+49.17+44.67+49.50+45.50+50.17+46.17+49.67+46.50+49.33+46.83+50.67+46.83+50.67+47.00+50.17+46.67+49.50+46.00+51.17+46.67+49.83+48.17+49.50+47.50+50.17+44.83+50.33+46.17+50.00+46.50+50.00+49.00+50.50+44.67+49.33+46.83+50.00+48.83+50.83+45.67+51.17+45.83+49.83= 3371.05 + 293.16 = 3664.21

$$\bar{x} = \frac{\sum x_i}{n} = \frac{3664.21}{76} = 48.2133$$

Mean Rebound Value = 48.21

Table 4.3: Statistical Calculation for Rebound Values

No.	x (Rebound)	$(x - \bar{x})$	$(x - \bar{x})^2$
1	47.17	-1.16	1.338
2	51.17	2.84	8.083
3	48.17	-0.16	0.025
4	50.67	2.34	5.490
5	44.67	-3.66	13.373
6	50.17	1.84	3.397
7	47.83	-0.50	0.247
8	48.33	0.00	0.000
9	46.83	-1.50	2.241
10	49.83	1.50	2.259
11	46.33	-2.00	3.988
12	50.67	2.34	5.490
13	44.67	-3.66	13.373
14	50.50	2.17	4.722
15	46.17	-2.16	4.652
16	50.17	1.84	3.397
17	45.67	-2.66	7.059
18	49.17	0.84	0.711
19	46.50	-1.83	3.338
20	51.00	2.67	7.145
21	46.50	-1.83	3.338
22	49.33	1.00	1.006
23	46.83	-1.50	2.241
24	50.67	2.34	5.490
25	45.83	-2.50	6.235
26	50.17	1.84	3.397

27	47.00	-1.33	1.761

Table continued on next page…

Table 4.3: Statistical Calculation for Rebound Values (Continued)

28	49.50	1.17	1.376
29	46.67	-1.66	2.745
30	49.50	1.17	1.376
31	46.00	-2.33	5.415
32	51.17	2.84	8.083
33	46.67	-1.66	2.745
34	49.83	1.50	2.259
35	48.17	-0.16	0.025
36	49.50	1.17	1.376
37	47.50	-0.83	0.684
38	50.33	2.00	4.012
39	46.17	-2.16	4.652
40	50.00	1.67	2.799
41	46.50	-1.83	3.338
42	50.00	1.67	2.799
43	49.00	0.67	0.453
44	50.50	2.17	4.722
45	44.67	-3.66	13.373
46	49.33	1.00	1.006
47	46.83	-1.50	2.241
48	50.00	1.67	2.799
49	48.83	0.50	0.253
50	50.83	2.50	6.265
51	45.67	-2.66	7.059
52	51.17	2.84	8.083

53	45.83	-2.50	6.235
54	49.83	1.50	2.259
55	47.33	-1.00	0.994

Table continued on next page…

Table 4.3: Statistical Calculation for Rebound Values (Continued)

56	50.00	1.67	2.799
57	47.83	-0.50	0.247
58	50.33	2.00	4.012
59	49.83	1.50	2.259
60	50.00	1.67	2.799
61	45.33	-3.00	8.982
62	49.83	1.50	2.259
63	45.17	-3.16	9.966
64	49.33	1.00	1.006
65	47.67	-0.66	0.432
66	49.83	1.50	2.259
67	44.00	-4.33	18.722
68	49.83	1.50	2.259
69	46.00	-2.33	5.415
70	50.00	1.67	2.799
71	44.67	-3.66	13.373
72	49.33	1.00	1.006
73	49.67	1.34	1.804
74	50.00	1.67	2.799
75	44.83	-3.50	12.228
76	49.50	1.17	1.376
77	47.17	-1.16	1.338
78	50.00	1.67	2.799

$\sum(x_i - \bar{x})^2 =$ 337.3598776

Sum of squared deviations

$$\sum(x_i - \bar{x})^2 = 337.3598776$$

Sample variance and SD

Sample variance:

$$s^2 = \frac{1}{n-1}\sum(x_i - \bar{x})^2 \qquad (4.2)$$

Where:

s^2= sample variance; n= total number of observations; x_i= individual rebound hammer reading; $\bar{x}$= mean rebound hammer value

$$s^2 = \frac{337.3598776}{76-1} = \frac{337.3598776}{75} = 4.498$$

Standard deviation:

$$s = \sqrt{4.4981317} = 2.1208$$

Standard Deviation (s) = 2.191

Coefficient of variation (COV)

$$\text{COV} = \frac{s}{\bar{x}} \times 100\% \qquad (4.3)$$

Where:

COV= coefficient of variation; s= standard deviation; $\bar{x}$= mean rebound hammer value

$$\text{COV} = \frac{2.120880}{48.21328947} \times 100 = 4.5399\%$$

Coefficient of Variation (COV) = 4.54%

for Compressive Strength Value;

Σy=56.6+61.4+57.8+60.8+53.6+60.2+57.4+58.0+56.2+59.8+55.6+60.8+53.6+60.6+55.4

+60.2+54.8+59.0+55.8+61.2+52.6+60.2+54.8+60.8+56.8+59.2+53.6+61.0+58.4+60.8+54.0+58.2+56.2+59.0+53.6+59.4+54.6+60.2+55.4+59.6+55.8+59.2+56.2+60.8+56.2+60.8+56.4+60.2+56.0+59.4+55.2+61.4+56.0+59.8+57.8+59.4+57.0+60.2+53.8+60.4+55.4+60.0+55.8+60.0+58.8+60.6+53.6+59.2+56.2+60.0+58.6+61.0+54.8+61.4+55.0+59.8= 4047.5 + 349.6 = 4397.1

$$\bar{y} = \frac{\Sigma y}{n} = \frac{4397.1}{76} = 57.86$$

Mean Compressive Strength = 57.86 N/mm²

Table 4.4: Statistical Calculation for Compressive Strength Values

No.	y (Strength N/mm²)	(y – ȳ)	(y – ȳ) ²
1	56.60	-1.39	1.946
2	61.40	3.41	11.595
3	57.80	-0.19	0.038
4	60.80	2.81	7.869
5	53.60	-4.39	19.315
6	60.20	2.21	4.863
7	57.40	-0.59	0.354
8	58.00	0.01	0.000
9	56.20	-1.79	3.222
10	59.80	1.81	3.258
11	55.60	-2.39	5.735
12	60.80	2.81	7.869
13	53.60	-4.39	19.315
14	60.60	2.61	6.787
15	55.40	-2.59	6.733
16	60.20	2.21	4.863
17	54.80	-3.19	10.207
18	59.00	1.01	1.010

19	55.80	-2.19	4.817
20	61.20	3.21	10.273
21	55.80	-2.19	4.817
22	59.20	1.21	1.452

Table continued on next page…

Table 4.4: Statistical Calculation for Compressive Strength Values (Continued)

23	56.20	-1.79	3.222
24	60.80	2.81	7.869
25	55.00	-2.99	8.969
26	59.60	1.61	2.576
27	56.40	-1.59	2.544
28	60.20	2.21	4.863
29	56.00	-1.99	3.980
30	59.40	1.41	1.974
31	55.20	-2.79	7.811
32	61.40	3.41	11.595
33	56.00	-1.99	3.980
34	59.80	1.81	3.258
35	57.80	-0.19	0.038
36	59.40	1.41	1.974
37	57.00	-0.99	0.990
38	60.40	2.41	5.785
39	55.40	-2.59	6.733
40	60.00	2.01	4.021
41	55.80	-2.19	4.817
42	60.00	2.01	4.021
43	58.80	0.81	0.648

44	60.60	2.61	6.787
45	53.60	-4.39	19.315
46	59.20	1.21	1.452
47	56.20	-1.79	3.222
48	60.00	2.01	4.021
49	58.60	0.61	0.366

Table continued on next page…

Table 4.4: Statistical Calculation for Compressive Strength Values (Continued)

50	61.00	3.01	9.031
51	54.80	-3.19	10.207
52	61.40	3.41	11.595
53	55.00	-2.99	8.969
54	59.80	1.81	3.258
55	56.80	-1.19	1.428
56	60.00	2.01	4.021
57	57.40	-0.59	0.354
58	60.40	2.41	5.785
59	59.80	1.81	3.258
60	60.00	2.01	4.021
61	54.40	-3.59	12.923
62	59.80	1.81	3.258
63	54.20	-3.79	14.401
64	59.20	1.21	1.452
65	57.20	-0.79	0.632
66	59.80	1.81	3.258
67	52.80	-5.19	26.987
68	59.80	1.81	3.258

69	55.20	-2.79	7.811
70	60.00	2.01	4.021
71	53.60	-4.39	19.315
72	59.20	1.21	1.452
73	59.60	1.61	2.576
74	60.00	2.01	4.021
75	53.80	-4.19	17.597
76	59.40	1.41	1.974

Table continued on next page…

Table 4.4: Statistical Calculation for Compressive Strength Values (Continued)

77	56.60	-1.39	1.946
78	60.00	2.01	4.021
			$\sum(y_i - \bar{y})^2 = 485.728$

Sample variance and SD

Sample variance:

$$s_y^2 = \frac{485.7278947}{76-1} = \frac{485.7278947}{75} = 6.476$$

Standard deviation:

$$s_y = \sqrt{6.4763719} = 2.375978$$

Standard Deviation (s) = 2.3759

Coefficient of variation (COV)

$$\mathrm{COV}_y = \frac{2.544877}{57.85526316} \times 100\% = 4.109\%$$

Coefficient of Variation (COV) = 4.11%

Table 4.5: Summary Table of Results

Statistic	Rebound Values	Compressive Strength
Number of data points (n)	76	76

Sum (Σx / Σy)	3664.21	4397.10
Mean ($\bar{x}$ / $\bar{y}$)	48.21	57.86
Standard deviation (s)	2.19	2.38
Coefficient of variation (COV%)	4.54%	4.11%

4.4 Discussion of Results

The forensic results highlight several key observations:

a. The majority of the rebound numbers ranged between 42 and 52, corresponding to compressive strengths between 44–56 N/mm². This exceeds the minimum required strength for most institutional concrete structures, demonstrating that the buildings retain adequate load-bearing capacity despite age and weather exposure.

b. Members exhibiting cracks, honeycombing, or reinforcement exposure recorded lower rebound numbers (35–40), confirming that visible deterioration correlates with reduced surface hardness and in-situ strength.

c. Lower columns and wall bases exposed to prolonged dampness recorded compressive strengths as low as 42 N/mm², emphasizing the impact of environmental degradation and insufficient waterproofing measures over time.

d. The results underscore the importance of periodic non-destructive testing for early detection of distress. Identified weak points should be addressed through patch repairs, re-covering of exposed steel, and surface protection against carbonation and chloride attack.

Overall, the selected institutional buildings at the University of Benin remain structurally sound with compressive strengths above minimum design requirements.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This study focused on the forensic assessment of the in-situ compressive strength of concrete in selected institutional buildings within the University of Benin using non-destructive testing (NDT) methods, particularly the rebound hammer test. The investigation covered thirty-eight (38) reinforced concrete members comprising both beams and columns tested on their top and bottom surfaces, resulting in seventy-six (76) total data points while comparing the measured rebound values and estimated compressive strengths to the acceptable limits prescribed by relevant codes such as BS 1881: Part 202 (1986) and ASTM C805 (2018).

From the statistical evaluation of the test results, the mean rebound number was calculated as 48.21, with a standard deviation of 2.19 and a coefficient of variation (COV) of 4.54%, indicating a low level of dispersion and thus consistent concrete quality across the sampled structural elements. Correspondingly, the mean estimated compressive strength of the tested concrete was 57.86 N/mm², with a standard deviation of 2.38 N/mm² and a COV of 4.11%. These low coefficients of variation confirm that the concrete quality across all tested members was uniformly high.

According to the quality grading of BS 1881: Part 202 (1986), all rebound values above 40 classify the concrete as excellent. The recorded rebound numbers ranged between 40 and 52, translating to compressive strengths ranging from approximately 52.6 to 61.4 N/mm², which significantly exceed the minimum design requirement of 25–30 N/mm² for most reinforced concrete institutional structures. This demonstrates that the structural members have retained their integrity and load-bearing capacity despite years of service and exposure to environmental conditions.

In terms of comparative performance, the top and bottom faces of the members showed consistent readings, with differences in mean values typically within ±3 N/mm². This suggests uniform concrete compaction and adequate curing practices during construction. Moreover, the maximum compressive strength recorded, 61.4 N/mm², indicates that portions of the structure were cast with very high-quality concrete, possibly exceeding the characteristic design grade (C35/45 or higher).

In summary, despite these isolated defects, the forensic assessment of in-situ concrete within the University of Benin has shown that the tested buildings remain structurally sound, with compressive strengths exceeding the typical design requirements for institutional buildings, which generally range between 35–45 N/mm² for heavy-weight reinforced concrete. The results therefore affirm that the University of Benin's institutional structures possess satisfactory structural integrity and continue to meet functional safety standards. Nevertheless, the study underscores the importance of regular structural health monitoring, since environmental degradation, ageing, and deferred maintenance can progressively weaken concrete performance if left unaddressed. Adopting the recommendations herein will help the University maintain a proactive structural management strategy, ensuring safety, reliability, and sustainability of its built environment.

5.2 Recommendations

Based on the result of this forensic assessment, the following recommendations are made:

i. The rebound hammer test should be conducted at regular intervals (every 3–5 years) to monitor any gradual decline in surface hardness and in-situ strength.

ii. Areas showing signs of deterioration, such as cracks, honeycombing, and exposed reinforcement, should be promptly repaired using appropriate patching compounds and corrosion inhibitors. Protective coatings should be applied to concrete surfaces vulnerable to carbonation and chloride penetration to extend their service life.

iii. The study identified that lower structural members exposed to dampness exhibited reduced compressive strengths. It is therefore recommended that adequate waterproofing membranes, drainage systems, and moisture barriers be installed or improved around foundations and external walls to minimize long-term deterioration due to water ingress.

iv. The University should establish a structured maintenance and inspection program that integrates periodic testing, documentation, and performance tracking of its buildings. This will enable early detection of structural distress and allow for timely interventions before damage becomes critical.

v. Future studies should combine rebound hammer testing with other NDT methods such as ultrasonic pulse velocity or infrared thermography to detect internal defects not visible on the surface. Additionally, a more detailed chemical analysis of concrete carbonation depth and chloride penetration would provide insights into long-term durability risks.

REFERENCES

Abubakar, I. and Yahaya, M., 2015. Assessment of structural defects in selected university buildings in Nigeria. Nigerian Journal of Engineering, 21(2), pp.42–50.

ACI, 2013. Report on nondestructive test methods for evaluation of concrete in structures (ACI 228.2R-13). Farmington Hills, MI: American Concrete Institute.

Agbí, G.G., Akpokodje, O.I. and Hilary, U., 2020. Compressive strength of commercially produced sandcrete blocks within Isoko metropolis of Delta State, Nigeria. Turkish Journal of Agricultural Engineering Research, 1(1), pp.91–103.

Aina, M.O., Alabi, A. and Adeyemi, J.O., 2018. Structural distress in Nigerian university buildings: Causes and remedies. International Journal of Engineering Research and Applications, 8(11), pp.66–72.

Ali, M.A., Shams, M.A., Bheel, N., Almaliki, A.H., Mahmoud, A.S., Dodo, Y.A. and Benjeddou, O., 2024. A review on chloride induced corrosion in reinforced concrete structures: Lab and in situ investigation. RSC Advances, 14, pp.37252–37271.

Al-Fuhaid, A.F. and Niaz, A., 2022. Carbonation and corrosion problems in reinforced concrete structures. Buildings, 12(5), p.586.

Alshaikh, I.M.H. and Zeyad, A.M., 2022. Reliability of Schmidt hammer and core cutting tests for assessing actual compressive strength of concrete. Journal of Building Pathology and Rehabilitation, 7(1).

Amin, R., Murtiadi, S. and Akmaluddin, 2018. The audit and assessment of building structural strength: Case study of Mataram Islamic State University Rectorate Building. International Journal of Emerging Trends in Science and Technology, 5(11), pp.6737–6744.

Atoyebi, O.D., Ayanrinde, O.P. and Oluwafemi, J., 2019. Reliability comparison of Schmidt rebound hammer as a non-destructive test with compressive strength tests for different concrete mix. Journal of Physics: Conference Series, 1378.

Auta, S.M. and Olanipekun, O.I., 2025. Compressive strength correlation of designed and as-built columns using Schmidt rebound hammer. UNIABUJA Journal of Engineering and Technology, 2(2), pp.72–82.

Bastidas-Arteaga, E., Schoefs, F., Stewart, M.G. and Wang, X., 2013. Influence of global warming on durability of reinforced concrete structures: A probabilistic approach. Structure and Infrastructure Engineering, 9(8), pp.767–779.

Bolborea, B., Baera, C., Dan, S., Gruin, A., Burduhos-Nergis, D.D. and Vasile, V., 2021. Concrete compressive strength using ultrasonic pulse velocity and elasticity modulus. Materials, 14(22), p.7018.

BSI, 2012. BS EN 12504-2: Testing concrete in structures – Determination of rebound number. London: British Standards Institution.

BSI, 2019. BS EN 12390-3: Testing hardened concrete – Compressive strength of test specimens. London: British Standards Institution.

BSI, 2021. BS EN 12504-4: Testing concrete in structures – Determination of ultrasonic pulse velocity. London: British Standards Institution.

BSI, 2023. BS EN 1992-1-1: Eurocode 2 – Design of concrete structures. London: British Standards Institution.

Bungey, J.H., Millard, S.G. and Grantham, M.G., 2006. Testing of concrete in structures. London: Taylor & Francis.

Carper, K.L., 2001. Forensic engineering. Boca Raton: CRC Press.

Coleman, C3S Inc., 2024. Understanding the forensic analysis of concrete structures. Available at: https://c3sinc.com/understanding-the-forensic-analysis-of-concrete-structures/ (Accessed: 3 October 2025).

Concrete Captain, 2025. What affects compressive strength of concrete? Available at: https://concretecaptain.com/what-affects-compressive-strength-of-concrete/ (Accessed: 3 October 2025).

Devi, S., 2025. Non-destructive testing techniques: A general review of methods. International Journal of Scientific Research and Engineering Development, 8(1), pp.536–542.

Ede, A.N. and Olofinnade, O.M., 2015. Use of British standards in forensic evaluation of concrete structures in Nigeria. Journal of Building Performance, 6(1), pp.79–88.

Eze, E.A. and Ogbuagu, O.K., 2020. Material variability and compressive strength inconsistency in Nigerian concrete. Journal of Construction Materials and Engineering, 9(4), pp.42–48.

Ezeagu, C.A., Udebunu, J.N. and Obiorah, S.M.O., 2015. Destructive and non-destructive assessment of collapsed structures in Onitsha. American Scientific Research Journal for Engineering, Technology and Sciences, 12(1), pp.170–186.

Folorunso, O., 2023. Impact of concrete corrosion and mitigation strategies. Communication in Physical Sciences, 9(4), pp.651–663.

Gatari, M. et al., 2014. Measurement of compressive strength and rebar parameters of reinforced concrete in buildings in Nairobi. Proceedings of NDT2014 Conference, Manchester, UK.

Ivanchev, I., 2022. Investigation using destructive and non-destructive methods for assessment of concrete compressive strength. Applied Sciences, 12(23), p.12172.

Jayale, V. and Patil, A., 2023. Non-destructive test techniques in assessment of concrete structures. AIP Conference Proceedings.

Jayale, V. and Patil, A., 2024. Non-destructive test techniques in assessment of concrete structures. AIP Conference Proceedings.

Jedidi, M., 2020. Evaluation of concrete quality using rebound hammer method. Current Trends in Civil & Structural Engineering, 5(5), pp.1–7.

Kelson, C.R. and Moore, S.N., 2022. Common methods for forensic evaluation of concrete structures. Atlantic Testing Laboratories.

Kouddane, B. et al., 2022. Assessment of concrete strength using combined NDT methods. Applied Sciences, 12(23), p.12190.

Kumar, M. and Gupta, A.B., 2024. Assessment of fire damage in concrete structures using NDT. Nigerian Journal of Technology, 43(3).

Lesanmi, A. et al., 2023. Common defects of buildings in tertiary institutions in Nigeria. American Journal of Construction and Building Materials, 7(1), pp.7–12.

Mehta, P.K. and Monteiro, P.J.M., 2014. Concrete: Microstructure, properties and materials. 4th ed. New York: McGraw-Hill.

Metalssi, O.O. et al., 2023. Degradation mechanisms of cement systems under chloride–sulfate attack. Cement and Concrete Research, 164, p.107065.

Mutikanga, H.E. et al., 2022. Postaward construction management of hydropower projects. Journal of Management in Engineering, 38(6).

Neville, A.M., 2011. Properties of concrete. 5th ed. Harlow: Pearson Education.

Odoanyanwu, N.M., Chukwujindu, K.E. and Kikanme, E.I., 2021. Factors responsible for deterioration of building structures in tertiary institutions. GSC Advanced Research and Reviews, 9(1), pp.64–72.

Okechukwu, C.O., Okolie, K.C. and Ezeokoli, F.O., 2021. Non-destructive evaluation of concrete elements for structural stability. International Journal of Progressive Research in Science and Engineering, 2(12), pp.19–25.

Onwualu, A.P., 2021. Assessment of maintenance cost and structural condition of public buildings in Nigeria. Cambridge Journal of Engineering and Construction Management, 20(4), pp.142–153.

Osuji, S.O. and Egbon, B.N., 2021. Optimizing compressive strength characteristics of hollow blocks. Nigerian Journal of Technology, 40(2), pp.208–215.

Peel, M.C., Finlayson, B.L. and McMahon, T.A., 2007. Updated Köppen–Geiger climate classification map. Hydrology and Earth System Sciences, 11(5), pp.1633–1644.

Quadri, O.O. et al., 2024. Causes and socioeconomic effects of building collapse in Nigeria. Iconic Research and Engineering Journals, 8(2), pp.724–735.

Sangoju, B. and Vasanthakumar, S., 2018. Applicability of cover meter and GPR survey in reinforced concrete structures. NDE Conference Proceedings.

Siegel, J.A., 2013. Encyclopedia of forensic sciences. 2nd ed. London: Elsevier.

Soman, F. and Raveendranath, P.K., 2021. Forensic investigation of concrete structures and rehabilitation. IJERT Conference Proceedings.

Tang, H., Tawie, R. and Romali, S., 2020. Forensic investigation of reinforced concrete structures. Journal of Advanced Research in Applied Sciences and Engineering Technology, 19(1), pp.6–14.

Tomita, K. and Chew, M.Y.L., 2022. Infrared thermography for delamination detection. Sensors, 22(2), p.423.

Wang, D. et al., 2023. Review on microbially influenced concrete corrosion. Microorganisms, 11(8), p.2076.

APPENDIX

Plate 1: Schmidt Hammer Testing on Site A

Plate 2: Schmidt Hammer

Plate 3: Schmidt Hammer Testing on Site B

Plate 4: Schmidt Hammer Testing on Site A Ground Floor

Plate 5: Schmidt Hammer Testing on Site A First Floor

APPENDIX B

BUILDING PLANS

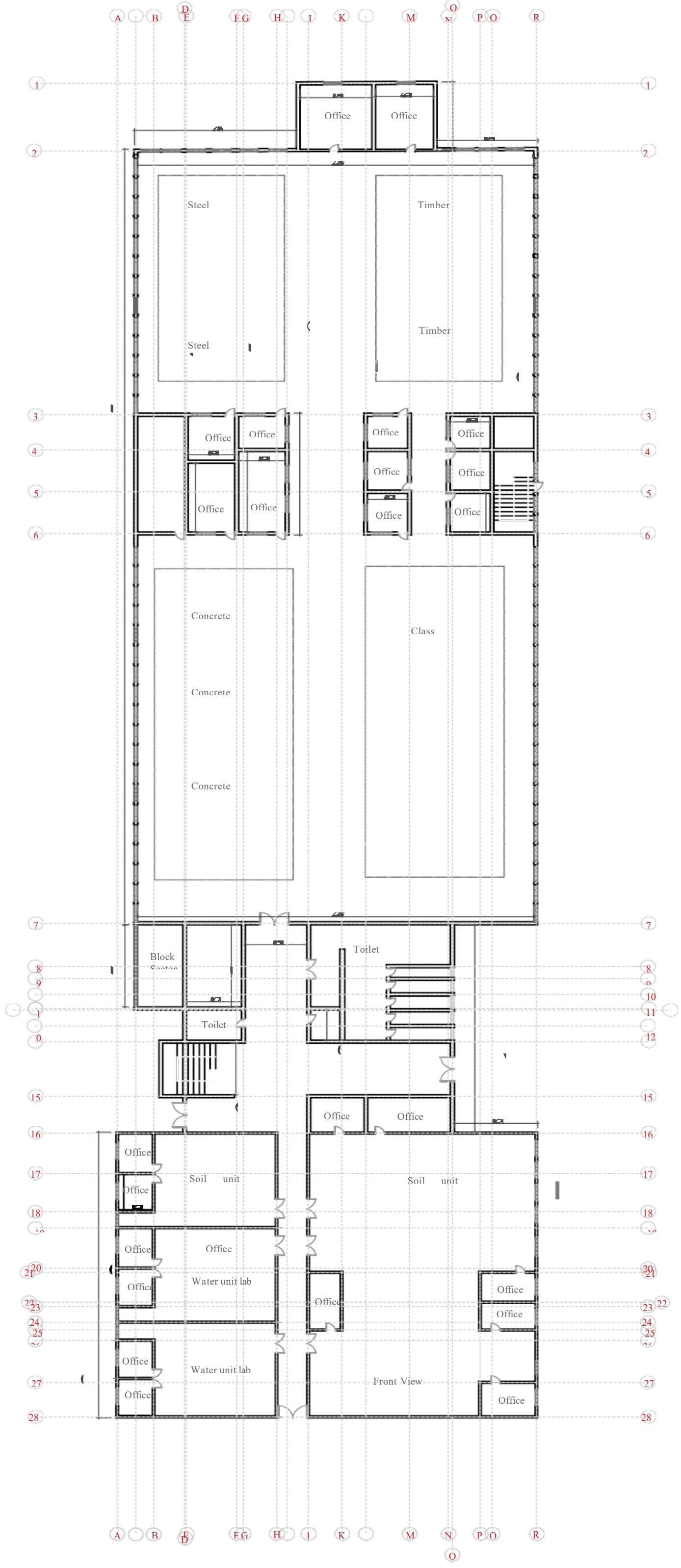

Figure B1: Site A Ground Floor Plan

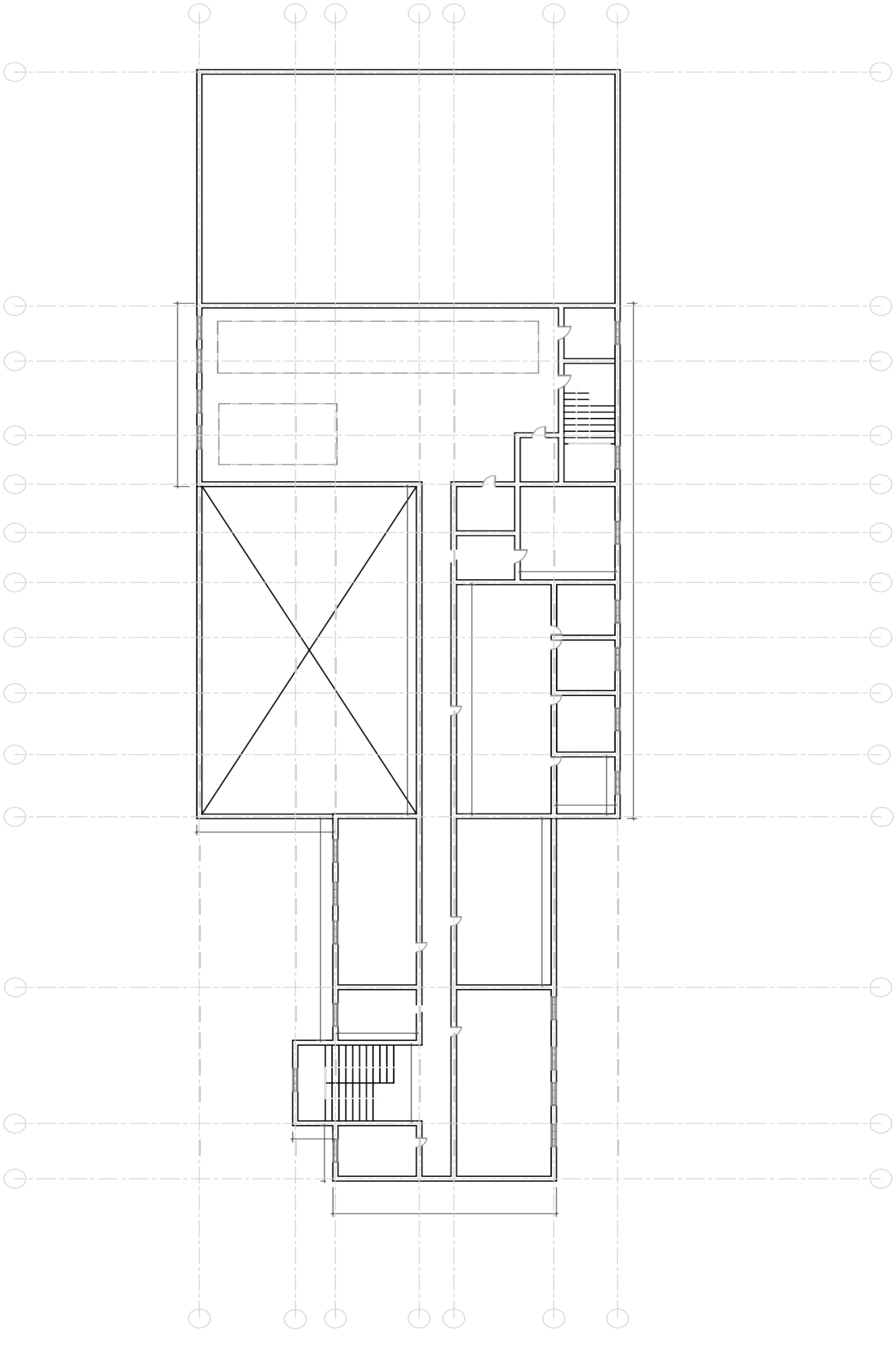

Figure B2: Site A First Floor Plan

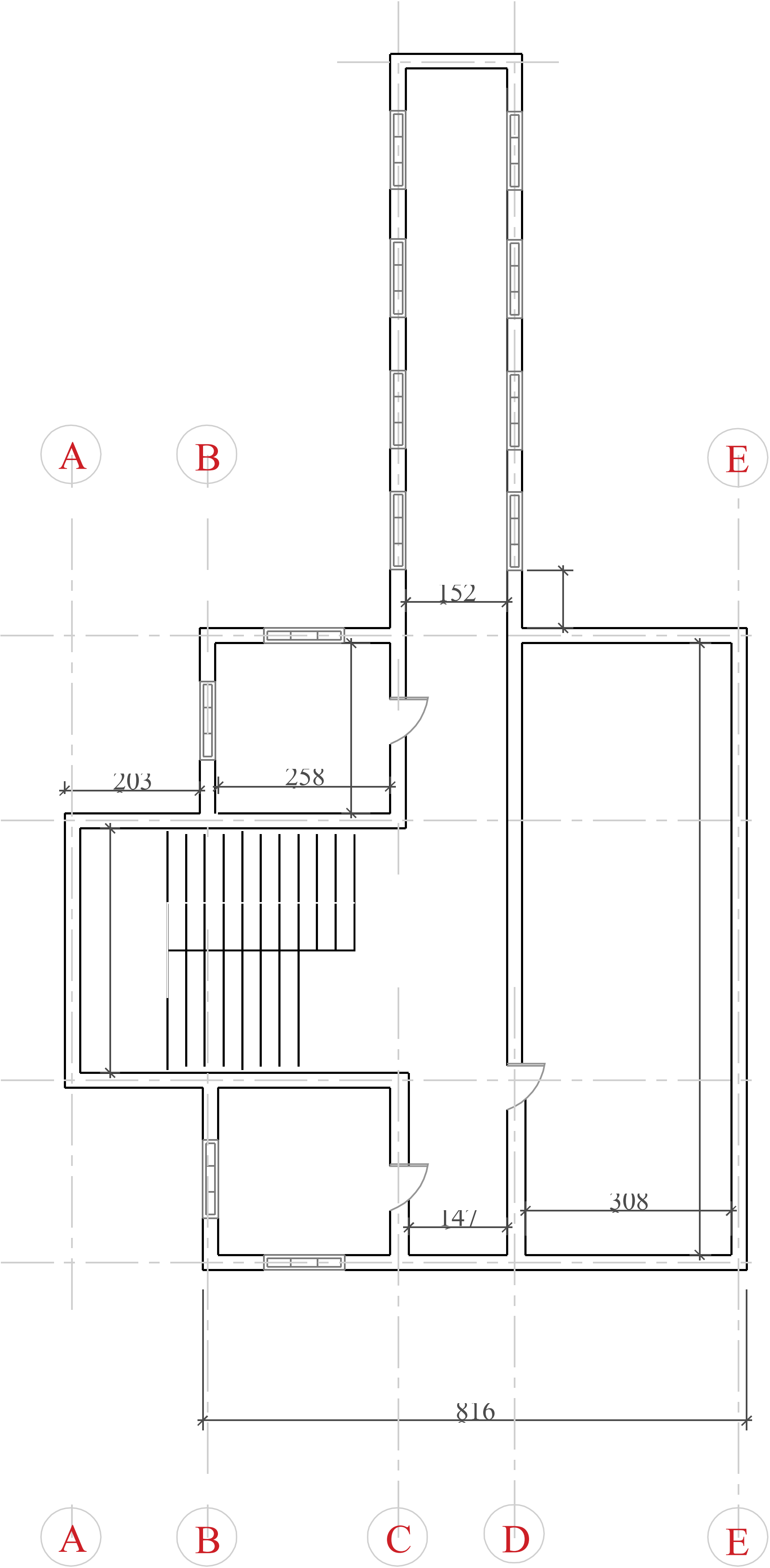

Figure B3: Site A Upper Floor Plan

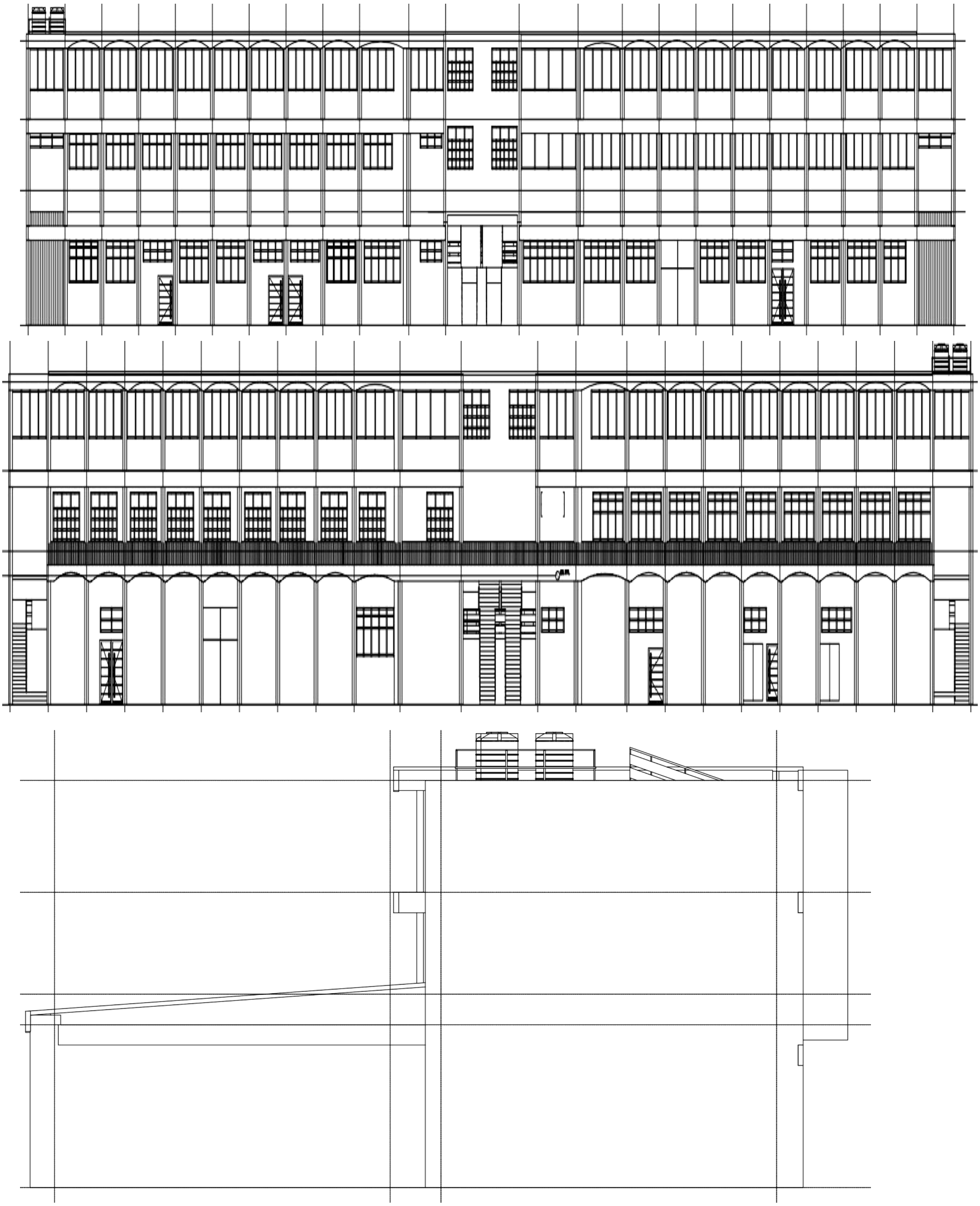

Figure B4: Site B