PERFORMANCE EVALUATION OF NDTS IN PREDICTING COMPRESSIVE STRENGTH OF CONCRETE

By

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Dedication

To my parents

and

To my beloved wife, infinitely supportive

Approval/Declaration by the Supervisor

This is to certify that Md. Imran Hossain has carried out this research work under my supervision, and that he has fulfilled the relevant Academic Ordinance of the Chittagong University of Engineering and Technology, so that he is qualified to submit the following Thesis in the application for the degree of MASTER of ENGINEERING in CIVIL ENGINEERING. Furthermore, the Thesis complies with the PLAGIARISM and ACADEMIC INTEGRITY regulation of CUET.

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Abstract

Accurate prediction of concrete compressive strength is imperative for investigating the in-situ concrete quality. To avoid destructive testing, developing reliable predictive models for concrete compressive strength using nondestructive tests (NDTs) is an active area of research. However, many of the developed models are dependent on calibration and/or concrete past history (e.g. mixture proportion, curing history, concrete mechanical properties, etc.), which limits their utility for in-situ predictions. The main objective of the study to establish a relationship between NDT test results with the compressive strength of the structures. This study developed predictive models for concrete compressive strength. In this study, concrete cylinders were casted with strength varied from 15 to 60 MPa. Ultrasonic pulse velocity (UPV) and rebound hammer (RH) tests were performed on 90 concrete cylindrical samples and 90 concrete core cylindrical samples. After that, compressive strengths were determined using destructive testing on 90 cylinders and 90 core cylinders. The rebound number at 7 days shows the concrete quality varied from fair to good for C15 to C60 grade of Concrete for both cylinder and core cylinder. For similar grade of concretes, the rebound number at 28 and 90 days shows the concrete quality varied from good to excellent. The UPV test results show that the concrete quality varied from very good to excellent for both cylinder and core cylinder. It is found that the strength obtained from rebound hammer and core cutting is well comparable with cylinder crushing strength. RH strength is found lower than the cylinder compressive strength for all grade of concrete by an amount of about 3% to 8%. Whereas, core strength is found lower than the cylinder compressive strength by an amount of about 8% to 11% for all grade of concrete. Finally, predictive equations were developed at 7, 28 and 90 days age of concrete cylinder and concrete core based on NDT results.

বিমূর্ত

কংক্রিটের কম্প্রেসিভ শক্তির সঠিক ধারনা ইন-সিটু কংক্রিটের গুণগতমান যাচায়ের জন্য অপরিহার্য। ধ্বংসাত্মক পরীক্ষা পরিহারের জন্য ননডেস্ট্রাকটিভ টেস্ট (NDTs) ব্যবহার করে কংক্রিট কম্প্রেসিভ শক্তির জন্য নির্ভরযোগ্য ভবিষ্যদ্বাণী/ধারনামূলক মডেল তৈরি করা গবেষণার একটি সক্রিয় ক্ষেত্র। অনেক উন্নত মডেল ক্যালিব্রেশন এবং/অথবা কংক্রিট অতীত ইতিহাসের উপর নির্ভরশীল (যেমন কংক্রিটের মিশ্রণ অনুপাত, কিউরিং এর ইতিহাস, কংক্রিটের মেকানিক্যাল বৈশিষ্ট্য ইত্যাদি), যা ইন-সিটু ভবিষ্যদ্বাণীমূলক মডেলগুলির জন্য তাদের উপযোগিতা হ্রাস করে। এই গবেষণার মূল উদ্দেশ্য কংক্রিটের কম্প্রেসিভ শক্তির সাথে এনডিটি পরীক্ষার ফলাফলের সম্পর্ক স্থাপন করা। এই থিসিস পেপারটি কংক্রিটের কম্প্রেসিভ শক্তির সঠিক ধারণামূলক মডেল এর বিকাশ। এই লক্ষ্যে, কংক্রিট সিলিন্ডারের কম্প্রেসিভ শক্তি ১৫ থেকে ৬০ এমপিএ ধরে ডিজাইন করা হয়েছিল। আলট্রাসনিক পালস্ ভেলোসিটি (UPV) এবং রিবাউন্ড হ্যামার (RH) পরীক্ষা ৯০ টি কংক্রিট সিলিন্ডার এবং ৯০টি কংক্রিট কোর সিলিন্ডারের উপর করা হয়েছিল। এরপরে, ৯০ টি সিলিন্ডার এবং ৯০ টি কোর সিলিন্ডারে ধ্বংসাত্মক পরীক্ষা ব্যবহার করে কংক্রিটের কম্প্রেসিভ শক্তি নির্ধারণ করা হয়েছিল। কংক্রিটের ১৫ থেকে ৬০ এমপিএ গ্রেডের জন্য ৭ দিনের সিলিন্ডার এবং কোর সিলিন্ডার উভয়ের জন্যই রিবাউন্ড সংখ্যা অনুযায়ী ক্রমাগতভাবে খারাপ থেকে ভাল পর্যন্ত কংক্রিটের গুণগতমান পরিলক্ষিত হয়। তবে, কংক্রিটের ১৫ থেকে ৬০ এমপিএ গ্রেডের জন্য ২৮ দিন এবং ৯০ দিনের রিবাউন্ড সংখ্যা সিলিন্ডার এবং কোর সিলিন্ডার উভয়ের জন্যই ক্রমাগতভাবে ভাল থেকে চমৎকার পর্যন্ত কংক্রিটের গুণগতমান প্রদর্শন করে। আলট্রাসনিক পালস্ ভেলোসিটি (UPV) পরীক্ষার ফলাফল দেখায় যে, কংক্রিটের গুণগতমান সিলিন্ডার এবং কোর সিলিন্ডার উভয়ের জন্য ক্রমাগতভাবে খুব ভাল থেকে চমৎকার পর্যন্ত প্রদর্শন করে। এই গবেষণায় পাওয়া যায় যে, রিবাউন্ড হ্যামার এবং কোর কাটিং থেকে প্রাপ্ত কম্প্রেসিভ শক্তি সিলিন্ডার ক্রাশিং শক্তির সাথে তুলনা করা হয়েছে। সমস্ত গ্রেডের কংক্রিটের সিলিন্ডারের কম্প্রেসিভ শক্তির তুলনায় রিবাউন্ড হ্যামার সংখ্যা থেকে প্রাপ্ত শক্তি প্রায় ৩% থেকে ৮% কম পাওয়া যায়। যেখানে, সমস্ত গ্রেডের কংক্রিটের সিলিন্ডারের কম্প্রেসিভ শক্তির তুলনায় কোর সিলিন্ডারের কম্প্রেসিভ শক্তি প্রায় ৮% থেকে ১১% কম পাওয়া যায়। আরও দেখা যায় যে, পানি ও সিমেন্টের অনুপাত বৃদ্ধি পেলে কংক্রিটের কম্প্রেসিভ শক্তি কমে যায়। অবশেষে, কংক্রিট সিলিন্ডার এবং কংক্রিট কোর সিলিন্ডারের ৭ দিন, ২৮ দিন এবং ৯০ দিন বয়সে ননডেস্ট্রাকটিভ টেস্ট (NDTs) এ প্রাপ্ত ফলাফলের উপর ভিত্তি করে ভবিষ্যদ্বাণীমূলক সমন্বিত সমীকরণ তৈরি করা হয়েছে, যা দিয়ে যে কোন বয়সের কংক্রিটের কম্প্রেসিভ শক্তি সম্পর্কে সঠিক ধারণা পাওয়া যাবে। কংক্রিট সিলিন্ডার এবং কংক্রিট কোরের ৭,২৮ এবং ৯০ দিন বয়সে অ-ধ্বংসাত্মক রিবাউন্ড হ্যামার (RH) শক্তি, আলট্রাসনিক পালস্ ভেলোসিটি (UPV) এবং আধা-ধ্বংসাত্মক কোর পরীক্ষার শক্তির সাথে কাঠামোগত কংক্রিটের কম্প্রেসিভ শক্তির সাথে সম্পর্কযুক্ত সমীকরণগুলি তৈরি করা হয়েছে। অধিকন্তু, কংক্রিট সিলিন্ডার এবং কংক্রিট কোরের ৭, ২৮ এবং ৯০ দিন বয়সে আলট্রাসনিক পালস্ ভেলোসিটি (UPV) এর সাথে কাঠামোগত কংক্রিটের রিবাউন্ড হ্যামার শক্তির সাথে সম্পর্কযুক্ত একটি সমীকরণ তৈরি করা হয়েছে।

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Nomenclature

NDT	Non-destructive Test
DT	Destructive Test
RH	Rebound Hammer
UPV	Ultrasonic Pulse Velocity
ASTM	American Society for Testing and Materials
OPC	Ordinary Portland Cement
PCC	Portland Composite Cement
ACI	American Concrete Institute
CT	Core Test

Chapter 1: INTRODUCTION

1.1 GENERAL

Concrete is the most used artificial material worldwide. Concrete is also the second most commonly used substance overall, after water. It is a significant building component that is extensively used in structures including highways, bridges, buildings, and dams. It can be used for everything from structural purposes to paviors, kerbs, pipes, and sewers. Concrete is a composite material. It is consisting mainly of aggregate (gravel, sand or rock), Portland cement and water.These ingredients combine to create a workable paste that gradually becomes harder with time. Concrete has been utilized by home builders and construction organizations for many years because of its strength. Concrete is extremely durable and can withstand extreme weather and natural disasters. It is resistant to corroding, fire, chemical reactions, erosion, compressive and tensile stress, and abrasion. It is also resistant to harsh weather conditions. Since the structural integrity of the concrete won't be compromised for a long time as a result, it can be used wherever else in the world. Due to its adaptability, construction firms can easily utilize it to build garages, sideways, roadways, and other types of structures. Depending on the needs of the building, its strength can be changed. To make original designs, it can also be molded into various sizes and forms. Additional advantages of concrete for the environment include its resistance against nature's calamities like floods, cyclone etc. and extending its lifespan even further by being recyclable and reusable. Since the mixture's primary elements are typically obtained from local sources, less transportation is needed for concrete.

Concrete cylinders or cubes are tested under compression as the traditional way of assessing the strength of hardened concrete. Before exposing concrete to the predicted loads, it is crucial to determine the concrete's compressive strength. Both destructive (DT) and non-destructive testing (NDT) methods can be used to measure the compressive strength of hardened concrete. Non-destructive testing (NDT) is performed without destroying the concrete specimen, whereas destructive testing (DT) approach involves crushing the cast specimen to failure. In industries like aerospace, pipelines, bridges, refineries, oil platforms, and power plants, NDT is essential as a quality control and quality assurance management tool because it can aid in preventing failures that could negatively affect safety, dependability, and the environment.

Non-destructive testing (NDT) methods are used to determine the properties of hardened concrete and to evaluate the condition of concrete in buildings, bridges, deep foundations, dams, pavements, and other concrete construction. NDT methods are applied to control quality of concrete of new construction, troubleshoot problems with new construction, condition evaluation of older concrete for the purposes of rehabilitation, and for concrete repair quality assurance. Estimating in-situ compressive strength is imperative for assessing the quality of existing concrete buildings during their service life. However, in many case, the actual state of the materials used in construction is highly variable, and the specifications of concrete are not available. These specifications include age, concrete materials, construction quality, curing process, and mechanical properties of concrete. In such cases, non-destructive tests (NDTs) can be used to estimate in-situ physical properties of concrete. NDT has gained popularity in recent years as the necessity for assessing damaged concrete structures, and several NDT procedures are available, including the cast in-place cylindrical core test, ultrasonic pulse velocity (UPV), rebound hammer (RH), and resonant frequency test. ACI 228.1R-13 outlines the procedures for performing these NDTs.

Rebound hammer testing is a simple nondestructive testing (NDT) method for determining the compressive strength of cast-in-place concrete. The rebound number (RN) is used to measure the test results. Several studies have attempted to establish a link between RN and compressive strength. RH is a non-electronic, in-place, additional approach for predicting the compressive strength of hardened concrete. Individual use of a rebound hammer to evaluate concrete strength is also unsuitable (Qasrawi, 2000).

The ultrasonic pulse velocity (UPV) method is used to measure the concrete elastic properties and to estimate the quality of in-situ concrete that includes the dynamic modulus of elasticity and compressive strength. UPV is used to investigate the effects of the water-cement ratio, maximum aggregate size, type of aggregate, and fly ash addition on the dynamic modulus of elasticity of low-quality concrete (Yildirim, 2011). The modulus of elasticity and ultrasonic pulse velocity were shown to have a strong relationship based on their findings. On the other hand, the UPV test is commonly used to detect discontinuities in hardened concrete and is more sensitive to internal properties such as concrete density.

Core tests are commonly used to determine whether or not questionable concrete in a new structure meets strength-based acceptance standards. It's also crucial for determining in-place concrete strengths in an existing structure for structural capacity evaluation. UPV and RH were used to predict concrete strength in conjunction with concrete mix proportions and density (Kheder, 1999.) They compared their findings to cores extracted from real structures and found that their predictions were more accurate. The benefit of combining RH and UPV can be explained by the fact that different properties of the hardened concrete influence the results of each test (Hannachi, 2012).

Due to the diversity of materials obtained, their characteristics, and irregular supervision, the real conditions of the structures may be significantly changeable spatially. As a result, in-situ predictions may not be possible due to a lack of information on concrete mixture proportions and construction. However, in the present study, accurate predictive models for compressive strength of concrete specimens at any age are derived using only NDT (RH, UPV) and semi-NDT (core test) results.

1.2 STATEMENT OF THE PROBLEM

The direct measurement of compressive strength of structural concrete is not possible. Moreover, structural assessment to determine strength for further modification and safety purpose may be needed after construction. In most of the case, destructive testing is not suitable or somehow not possible for the measurement of compressive strength of structural concrete after construction, but non-destructive testing method is perfect for those cases. The main benefit of non-destructive testing method is to avoid concrete damage to the performance of structural components of the building. Their use is simple and fast. Results of the tests are available on site. Non-destructive testing method for predicting Concrete strength in structures is developed where the cores cannot be drilled and less costly equipment is needed. Several non-destructive evaluation methods have been developed; based on the fact that certain concrete physical properties may be related to the concrete's compressive strength.

Sometimes it is required to determine the compressive strength of an existing structure for concrete quality control, structural assessment and safety purpose. So, this study will correlate the readings of the Rebound Hammer (RH) and Ultrasonic Pulse Velocity (UPV) measurements with the compressive strength of the concrete as an important method for investigating the in-situ concrete quality of the existing structure. This study also correlates with the core strength of the structural concrete.

1.3 OBJECTIVES OF THIS STUDY

The main purpose of this study is to establish a relationship between Non-Destructive Test (NDT) results with the compressive strength of the concrete in existing structures. The followings are the specific objectives and aims of this research study:

1. To correlate the compressive strength of structural concrete with non-destructive rebound hammer strength, ultrasonic pulse velocity and the semi-destructive core test strength and establish relationship.
2. To correlate and establish a relationship between the Rebound Hammer strength of structural concrete with ultrasonic pulse velocity.

1.4 SCOPE OF THE STUDY

This study focuses on non-destructive testing of concrete cylinder specimen and their relationship and prediction compared to 7, 28 and 90 days of concrete cylinder strength. Moreover, cylinder core cutting performed for all group of samples. All the concrete cylinder specimens and concrete core cylinder specimens were initially tested for taking concrete rebound number by using concrete hammer and ultrasonic pulse velocity by using UPV testing machine. These are the Non-Destructive Testing. After that all the concrete cylinder and core cylinder specimens were tested for compressive strength. After performing all the Non-Destructive test and Destructive test, a critical analysis of the results has been carried out and presented in graphical and tabular form for case in interpretation. Graphical charts between compressive strength of concrete vs rebound number for cylinder and core have been prepared. Similarly, graphical charts between compressive strength of concrete vs ultrasonic pulse velocity for cylinder and core have been prepared. Separately, graphical charts between Rebound Hammer (RH) and Ultrasonic Pulse Velocity (UPV) for cylinder and core have been prepared. Graphical chart between cylinder compressive strength and core compressive strength of concrete has also been developed. Finally, the Rebound Hammer (RH) strength, Ultrasonic Pulse Velocity (UPV) measurements were correlated with the compressive strength of the concrete for cylinder and core samples and an equation was developed to predict the compressive strength of structural concrete from the above each case. This correlation will be helpful for predicting the compressive strength of an existing concrete structure for concrete quality control, structural assessment and safety purpose.

1.5 OUTLINE OF THE PROJECT

This research work is divided into five chapters.

Chapter 1 of this project report is an introduction that lists the scope and objective of the research work.

Chapter 2 provides a review of the existing literature relevant to the Non-Destructive Testing of concrete including the previous studies. It also covers the physical and mechanical properties concrete composites.

Chapter 3 deals with the experimental investigation of the Non-Destructive Test. This chapter briefly describes the test details and instruments used for this project.

Chapter 4 investigates the variations in compressive strength of different grades of concrete. In addition to this, this chapter also includes ultrasonic pulse velocity analysis and Rebound Hammer test and core test results.

Chapter 5 summarizes the conclusions of this research project and presents some recommendations for future research.

Chapter 2: LITERATUREREVIEW

2.1 GENERAL

A continually changing world requires constantly improving construction methods. Concrete is one of the most commonly used construction materials in the modern world. This may be due to a variety of factors, including its behaviour, strength, affordability, durability, and flexibility, in addition to the wide range of uses it provides. Construction and building projects therefore trust concrete as a safe, sturdy, and straightforward object. It is used in many different types of structures, including residential and multi-story office buildings and infrastructure (roads, bridges, etc.). Construction of foundations, columns, beams, slabs, and other load-bearing elements all employ concrete.

Concrete is a composite material that is made by proportionally combining aggregate (sand, gravel, stone, brick chips, etc.), binding ingredient (cement or lime), water, and other additives to create an artificial stone-like mass. The mixing ratios determine the strength and quality.Concrete is a very valuable and important building material. After all the components - cement, aggregate, and water - have been combined in the proper ratios, the cement and water start reacting with one another to form a solid mass. The concrete's rock-like mass becomes harder as a result.Concrete is strong, simple to make, and can be shaped into a variety of sizes and shapes. In addition, it is affordable, quick to combine, and sensible. Concrete is a very durable material, so buildings made of it should be built to withstand tornadoes, hurricanes, typhoons, and earthquakes. Despite all the world's technological advancements, there is still no way to stop the harm caused by nature.

2.2 COMPOSITION OF BASIC CONCRETE MIX

Essential constituents can be identified in the concrete material mix:

1. Binding substances such as cement or lime
2. Fine aggregate (Sand).
3. Coarse aggregate (Brick chips or stone chips)
4. Water
5. Admixture (such as Pozzolana, plasticizer etc.)

The elements for the concrete are briefly described below:

Binding Materials

A concrete material mix's primary component is binding substance. The most often employed binding substance is cement. Lime may also be employed. Cement and water combine to form a paste that covers the particles in the mix. The paste binds the aggregates, hardens, and transforms into a solid resembling stone.

Aggregates

The coarse component of most mixes is gravel or crushed stone known as coarse aggregate. Natural sand, fine or coarse, acts as fine aggregate.

Water

Water is necessary for concrete to be workable and for chemicals to react with cement (hydration). The water/cement quantitative relation is the comparison of the total weight of water and cement. The concrete is stronger when the w/c quantitative ratio is smaller (More strength, less permeability).

2.3 TYPES OF CONCRETE MIX

Concrete is used in a variety of tasks, from little home renovations to large-scale academic buildings and structures. Along with many other purposes, it is utilized for floors, walls, pillars, basements, and walkways. The construction projects make use of a variety of concrete types.

Concrete can be divided into three fundamental groups based on the variances in its components and uses:

1. Lime Concrete
2. Cement Concrete
3. Reinforced Cement Concrete

2.4 CEMENT CONCRETE

Cement concrete composites are the primary building material used in the majority of engineering construction. It is made up of the right amounts of cement, sand, brick, or stone chips. The typical ratios are 1:2:4 or 1:3:6. The necessary quantities of concrete ingredients are mixed, and the mixture is then cured in water for 28 days to properly create strength.

The construction material cement concrete is adaptable and has many uses. It can be utilized for foundations, beams, columns, slabs, and other structural components. Additionally, it can be utilized in non-structural projects like pavement, curbing, and landscaping. For precast applications including pipes, paving stones, and sewer systems, cement concrete is a common choice.

The key benefits of cement concrete are its longevity, fire resistance, and strength. Additionally, it requires little maintenance and may be quickly fixed if it is broken. But working with cement concrete might be challenging because it is a pretty strong substance. In addition, it is crack-prone and vulnerable to damage from severe weather.

2.5 MAIN PROPERTIES OF CONCRETE

A variety of components are combined to form concrete. This heterogeneous material hardens to a mass that resembles stone. Concrete is a material that has widespread use in the construction industry. The main properties of concrete are explained below:

2.5.1 Strength

The following categories of concrete strength exist:

1. Compressive strength
2. Tensile strength
3. Flexural strength
4. Shear strength

Compressive Strength

In Bangladesh, cube and cylinder test specimens are both used.Concrete mix in the required proportion are cast as 6-inch cubes in steel or cast-iron molds. The conventional concrete cylinder specimen has a 6 inch diameter, a 12 inch height, and is cast in a mold that is typically made of cast iron;At the recommended ages, which are typically 28 days strength of standard cubes and cylinders are evaluated. Additional tests are frequently conducted at 1, 3, and 7 days. Under a testing apparatus, the specimens' capacity to withstand crushing is examined. The crushing strength numbers obtained from cube tests are significantly higher than those obtained from cylinders, typically 20 to 30% higher. According to British standards, a cylinder specimen's strength is equivalent to 75% of a cube specimen's strength.

Effect of age on Concrete Strength

Concrete becomes stronger over time. Ordinary cement concrete increases its final strength by around 70 to 75 percent in just 28 days and by roughly 90 to 95 percent over the course of a year. In many cases, it is preferable to evaluate the suitability of a concrete before the 28-day test results. When detailed information on the ingredients used to make concrete is lacking, it is possible to estimate that the 28-day strength that will be 1.5 times as strong as the 7-day strength. According to tests, the ratio of the 28-day strength to the 7-day strength for concrete built with regular Portland cement typically ranges between 1.3 and 1.7, with the bulk of findings coming in above 1.5.Therefore, it is highly reliable to extrapolate the strength of the 28 days from the strength of the 7 days.

2.5.2 Workability

The amount of compaction has a significant impact on the strength of concrete at a particular mix proportion. Therefore, it is crucial that the mix consistency allow for easy transportation, placement, and finishing of the concrete without segregation. A concrete is considered workable if it satisfies these requirements. Concrete's ability to be worked by many factors that includes:

- Mix Proportions
- Water Content
- Aggregates Size
- Shape of Aggregates
- Aggregate Grading
- Surface texture of aggregates
- Using admixture
- Utilization of Additional Cementitious Materials
- Temperature
- Time

Slump tests are typically conducted to measure the workability of a concrete mix.

2.5.3Elastic Properties

Concrete is not perfectly elastic for any range of loading; even with mild loads, a noticeable permanent setting occurs. At any point of loading, the deformation is not inversely proportional to the stress. Concrete's elastic characteristics change depending on the mixture's richness and the degree of stress. In addition, they change with concrete's age.

2.5.4 Durability

Concrete's durability is its capacity to survive the conditions for which it was created, without degrading over time. Both internal and external elements within the concrete might contribute to a lack of durability.Physical, mechanical, and chemical causes can all be grouped together. While mechanical causes are mostly connected to abrasion, physical causes are caused by the effect of frost and by changes in the thermal characteristics of aggregate and cement paste.

2.5.5 Impermeability

Concrete's endurance may be negatively impacted by the penetration of materials in solution, such as when $Ca(OH)_2$ is being leached out or an attack by acidic liquids occurs. Permeability significantly affects how susceptible concrete is to moisture and freezing temperatures. Steel will corrode in reinforced cement concrete as a result of moisture and air infiltration. This causes the volume of the steel to rise, which causes the concrete to crack and spall. Concrete's ability to be permeable is crucial for hydraulic and liquid retaining constructions.

2.5.6 Segregation

Segregation is the tendency for coarse aggregate grains to separate from the mass of concrete. When the concrete mixture is excessively moist and lean, it increases. When fairly large aggregate with a rough texture is employed, it also rises. The following can be done to prevent the segregation phenomenon:

1. little air-entraining agents are added to the mixture.
2. minimizing the water's presence and limiting it as much as feasible.
3. Care must be taken during every operation, including handling, putting, and consolidation.
4. It should not be permitted for concrete to fall from great heights.

2.5.7 Bleeding

Bleeding is the term for the water's propensity to rise to the top of freshly built concrete. Sand and cement particles are carried by the water as it rises to the surface, where they harden to produce a scum layer known as laitance. The following actions can be taken to stop concrete bleeding:

1. By boosting the cement
2. utilizing cement that is more finely ground
3. By accurately formulating the mixture and utilizing the least amount of water possible
4. Using a minimal air entraining agent
5. By making fine aggregates more refined

2.5.8 Fatigue

When flexure is applied, plain concrete exhibits fatigue. An endurance limit, whose value depends on how many times the load is applied, indicates the concrete's ability to resist flexure for a particular quality. The allowed flexural working stress in concrete pavement design is capped at 55% of the rupture modulus.

2.6 TYPES OF CONCRETE TESTS

The world's oldest and most significant building material is concrete. Concrete testing is crucial for determining the structure's strength, durability, and state. Tests on hardened concrete are classified into two types:

1. Destructive Test (DT)
2. Non-destructive Test (NDT

To ascertain the critical characteristics of concrete, such as compressive strength, flexural strength, tensile strength, etc., destructive tests and non-destructive testing are conducted.

2.6.1 Destructive Test (DT)

For construction, the quality of the concrete is crucial. Concrete that has been hardened grows stronger over time. The destructive test of concrete breaks the test specimen at specific loads, which helps to understand the behavior and quality. Casting test specimens from newly cast concrete serves as the foundation for the destructive test.

For the concrete specimens that are manufactured on a big scale, the destructive testing approach is appropriate and advantageous economically. Destructive tests are primarily used to examine product life and find design flaws that might not be apparent in everyday use. It covers the techniques that involve breaking a concrete specimen to ascertain its mechanical characteristics, such as hardness and strength. This kind of testing is much simpler to do, analyze, and produces more results.

Concrete is a fundamental building material, thus it ought to be strong enough to support enormous loads. The cement strength, water-cement ratio, concrete quality, and other factors heavily influence the outcomes of concrete tests. The following are the major goals of the test on hardened concrete:

1. quality assurance
2. approval of concrete
3. assessment of healing
4. to impart knowledge on the application of sand and aggregate.
5. for determining if concrete is uniform,
6. to estimate the concrete's quality using industry standards.
7. to ascertain the uniform distribution of stress.
8. to investigate concrete's behaviour.
9. to assess the strength of the concrete already in place.
10. To assessthe concrete's age etc.

Destructive tests are primarily used to examine product life and find design flaws that might not be apparent in everyday use. These tests identify the concrete's compressive, flexural, and tensile strengths. The hardened concrete can be examined using a variety of tests such as:

1. Compressive strength test
2. Tensile strength test
3. Flexural strength test

2.6.2 Non-Destructive Testing (NDT)

Nondestructive testing (NDT) is the process of inspecting, testing, or evaluating materials, components or assemblies for discontinuities, or differences in characteristics without destroying the serviceability of the part or system. In other words, when the inspection or test is completed, the part can still be used. In contrast to NDT, other tests are destructive in nature and are therefore done on a limited number of samples, rather than on the materials, components or assemblies actually being put into service.These destructive tests are often used to determine the physical properties of materials such as impact resistance, ductility, yield and ultimate tensile strength, fracture toughness and fatigue strength, but discontinuities and differences in material characteristics are more effectively found by NDT.

Today modern nondestructive tests are used in manufacturing, fabrication and in-service inspections to ensure product integrity and reliability, to control manufacturing processes, lower production costs and to maintain a uniform quality level. During construction, NDT is used to ensure the quality of materials and joining processes during the fabrication and erection phases, and in-service NDT inspections are used to ensure that the products in use continue to have the integrity necessary to ensure their usefulness and the safety of the public.

2.7 HISTORY OF NON-DESTRUCTIVE TESTING

Non-destructive testing has been used for a very long time and history does not give a specific beginning date. It is reported that in the Roman era, wheat and oil were employed to detect flaws in marble slabs. Blacksmiths have employed sonic NDT for ages when listening to the ring of various metals as they are hammered into shape; this method was also used by early bell manufacturers. In 1868, Englishman S.H. Saxby employed one of the earliest known applications of NDT when he used the magnetic properties of a compass to locate cracks in gun barrels.

X-RAY TESTING

The first NDT method to come into industrial application was the X-Ray technique. In 1895, German physicist Wilhelm Conrad Röntgen's experiments with cathode rays led him to discover X-rays, an invention that earned him the first-ever Nobel Prize. In his first publication on the topic, Röntgen described various uses including possible flaw detection.The industry did not need the invention at the time, but the medicine did, so medical equipment was the first to be developed. It wasn't until 1930 that the industrial use of X-ray technology came into being when Richard Seifert developed higher energy medical equipment expanding its use with other application through cooperation with welding institutes.

MAGNATIC PARTICLE TESTING (MPT)

Even before X-ray testing, magnetic particle fracture detection was used. In 1917, an American by the name of William Hoke also attempted to use magnetic indications to detect cracks in cannon barrels.

LIQUID PENETRATION TESTING (LPT)

The "Oil and Whiting Method," a primitive type of liquid penetrant testing that was used in the latter part of the 19th century, was one of the earliest NDT techniques. Early inspectors depended on this technique, which was primarily utilized in the railroad sector, to improve their "see ability" of problems that were not usually seen visually.

ULTRASONIC TESTING (UT)

The most recent NDT technology to enter industrial use was ultrasound testing. James Prescott Joule developed "exciting" ultrasonic techniques in 1847, and Pierre Curie and his brother Paul Jacques developed them in 1880. Following the catastrophic Titanic sinking, the first "industrial" application was suggested, and a Russian called Sokolov suggested using ultrasonography to test castings in 1929.

NDT FOLLOWING WORLD WAR II

The American Industrial Radium and X-ray Society, now known as ASNT, was established in 1941, which played a part in the development of NDT as an independent technique during World War II. Other industries began to use measurement tools and other visual aids, such as mirrors, telescopes, rigid borescopes (also known as endoscopes). The development of water-washable penetrants and "wet" developers began in WWII and continued far into the 1950s. The advantages of MPT were seen throughout the war, and in the years that followed, important advancements and improvements helped to broaden its use and applications. After the war, both radiographic testing and the application of UT underwent significant innovation.

Consequently, NDT has advanced significantly since its infancy, and those working in the sector now owe a debt of appreciation to these pioneers, many of whom did not survive to witness the results of their efforts. Non-destructive testing as an industry might not even exist if it weren't for their efforts.

2.8 NDT CODES AND STANDARDS

All types of inspections can be done using NDT techniques. Although assets like boilers and pressure vessels, which could be extremely dangerous if not properly maintained, are some of the most significant targets for NDT inspections. Most nations have regulations mandating businesses to comply to precise inspection rules and standards while conducting inspections because correct maintenance of these assets is so crucial for the safety of those working nearby (or even at a distance, when it comes to nuclear power plants). These standards and codes frequently demand that inspections be carried out on a regular basis while according to predetermined rules. These inspections must be carried out by a certified inspector and approved by a certified witness who works for an official inspection organization for the majority of assets that pose the highest risk.

The most commonly followed organizations in the world for creating NDT standards and codes are:

API (American Petroleum Institute)

ASME (American Society for Mechanical Engineers)

ASTM (American Society for Testing and Materials)

ASNT (American Society for Nondestructive Testing)

COFREND (French Committee for Non-destructive Testing Studies)

CSA Group (Canadian Standards Association)

CGSB (Canadian General Standards Board)

2.9 REASONS OF USES NDT

The following are the main reasons that NDT is being used worldwide:

Savings: NDT is more desirable than destructive testing because it allows the material or object being investigated to survive the inspection uninjured, which saves money and resources. This is the most obvious answer to the question.

Safety: Nearly all NDT procedures, with the exception of radiographic testing, are safe for people to employ, which makes NDT popular.

Efficiency: NDT techniques provide detailed and reasonably quick evaluation of assets, which might be essential for maintaining task site performance and safety. **Accuracy**: NDT methods have been shown to be accurate and predictable.When it comes to maintenance processes aims to protect the safety of employees and the durability of equipment. NDT methodologies and reproducible outcomes rely on highly skilled technicians with real-world knowledge and moral character. Certified experts use industrial NDT techniques, and they interpret the data. The technician needs to be proficient in operating the equipment being used to collect data in addition to having a specific NDT technique certification. Making an accept or reject decision depends on knowing the equipment's capabilities and limits.

2.10NDT FOR INDUSTRIAL USES

Since visual inspections (whether organized or informal) occur in practically every workplace in some capacity and it is employed in almost every industry in the world.However, some sectors have structured procedures for its use, as outlined by the organizations, such API and ASME, and these industries call for NDT.

These industries include:

- Oil & Gas
- Power Generation
- Chemicals
- Mining
- Aerospace
- Automotive
- Maritime
- Mining

2.11 APPLICATIONS AND IMPORTANCE OF NON-DESTRUCTIVE TESTS

Deep foundations, bridges, buildings, pavements, dams, and other concrete construction are all subjected to nondestructive testing (NDT) methods in order to assess the quality of the concrete and determine the qualities of hardened concrete. When building with concrete, NDT techniques are used to monitor the quality of new construction, address issues with new construction, assess the state of older concrete for rehabilitation needs, and ensure the quality of concrete restorations. Impact echo, ultrasonic echo, and visual examination are examples of NDT techniques.

Non-destructive tests (NDT) are frequently employed and are crucial to engineering projects, particularly those involving both freshly built and existing buildings. Applications for new constructions are mostly quality control or the clearing up of questions regarding the caliber of the materials or construction. Assessment of structural integrity or sufficiency is connected to testing of existing structures.

These tests are frequently conducted without causing concrete damage. Numerous concrete parameters, including density, elastic modulus, strength, surface hardness and absorption, and placement, size, and proximity to the surface of the reinforcement, can be identified using these tests.

Following are some scenarios where non-destructive testing is applied:

- to evaluatethe construction quality of in situ structures and precast modules.
- to assess the presence and size of flaws in concrete elements, such as honeycombing, cracks, voids, and other flaws.
- to verify the acceptability of the materials in the event that there is a clear violation of the specification.
- to tracking the strength growth of the concrete in relation to the removal of the formwork, the end of curing, prestressing, the application of loads, and other related operations.

• to confirm or refute any skepticism regarding the quality of the concrete batching, mixing, putting, compacting, or curing processes.

• to indicate the location and state of the steel reinforcements.

• to raise the level of assurance surrounding fewer harmful experiments.

• to assess the concrete's possible longevity.

• to identify the degree of concrete variability to assist in choosing sample sites that are indicative of the quality to be evaluated.

• to obtain information regarding any proposed changes to a structure's usage for insurance purposes or to reflect a change in ownership.

• to specify the uniformity of the concrete, perhaps as a prelude to core cutting, load testing, and other more costly or disruptive tests.

• for mining

2.12 ADVANTAGES OF NON-DESTRUCTIVE TESTING

There are four main advantages of Non-destructive testing:

2.12.1 SAFETY

Non-destructive testing is performed to determine whether a component is safe to use and whether it needs to be repaired. The tests are run to check both the product's safety and the worker's safety when working on any machinery or components. Although tests employing radiographies must be conducted in precise conditions, the majority of non-destructive procedures are safe for people to undergo. All testing must guarantee that the products are entirely unharmed. Professionally conducted non-destructive testing has the potential to save lives. especially if it is being done in fields that use machinery and equipment that is flammable or under high pressure. When applied correctly and test results are reliably used, its major goal is to find and fix issues that could otherwise have severe consequences.

2.12.2 RELIABILITY

Non-destructive testing will provide stability if industry personnel seek accurate and dependable outcomes. Any given piece of machinery or equipment can go through a variety of non-destructive testing to eliminate the possibility of an error or inaccurate result.

2.12.3 COST EFFECTIVE

Various industries must adhere to a variety of rules and regulations as well as varying safety requirements. As a result, different intervals will need to be required for machinery inspection. The least expensive method for evaluating and maintaining equipment will always be non-destructive testing. These tests can also provide information that can be used to effectively replace or repair parts or pieces of machinery before a true malfunction or breakdown takes place, which will ultimately result in greater financial savings.

2.12.4 REASSURANCE

Reassurance is incredibly straightforward, but it occasionally serves as the most significant benefit of non-destructive testing. It can offer all the stability, assurance, and peace of mind you need if a plant or factory knows that its machinery is ok and operating as it should. An additional layer of protection can be provided by knowing that protocols are in place to ensure that testing is done on a regular basis. When employees are confident in their safety, they are more likely to be productive and produce more overall.

2.13 DISADVANTAGES OF NON-DESTRUCTIVE TESTING

There are very few drawbacks to non-destructive testing. A slight issue may arise depending on the type of non-destructive testing performed on the component. These can be straightforward elements like:

- Components that must be cleaned both before and after inspection;
- The finish of a component may occasionally alter the sensitivity of the inspection.

• There may occasionally be an issue with depth sizing;

• Some non-destructive test methods can only inspect relatively non-porous surfaces;

• Some test methods require electricity;

• Some test can also be impacted by variations in magnetic permeability;

• Some tests can only be used on conductive materials.

2.14 DIFFERENT METHODS OFNON-DESTRUCTIVE TESTING

There are several non-destructive methods for evaluating the quality and compressive strength of concrete. These are:

- Visual inspection
- Drop test
- Schmidt rebound hammer
- Ultrasonic pulse velocity (UPV)
- Windsor probe penetration test
- Pull-out and pull-off resistance tests
- Instrumented hammers and modal analysis
- Embedded wireless sensors

In the following section, Schmidt Rebound Hammer and Ultrasonic Pulse Velocity (UPV) will be discussed briefly. Moreover, a semi-destructive test (Core Test) and a destructive test (Compressive Strength Test) will be discussed.

2.15 REBOUND HAMMER TEST

The Schmidt rebound hammer is shown in Fig. 2.1. The hammer weighs about 1.8 kg and is suitable for use both in a laboratory and in the field.

Fig. 2.1: A typical Schmidt Rebound Hammer(Malhotra, 2004)

A schematic cutaway view of the rebound hammer is shown in Figure 2.2. The main components include the outer body, the plunger, the hammer mass, and the main spring. Other features include a latching mechanism that locks the hammer mass to the plunger rod and a sliding rider to measure the rebound of the hammer mass. The rebound distance is measured on an arbitrary scale marked from 10 to100. The rebound distance is recorded as a “rebound number” corresponding to the position of the rider on the scale.

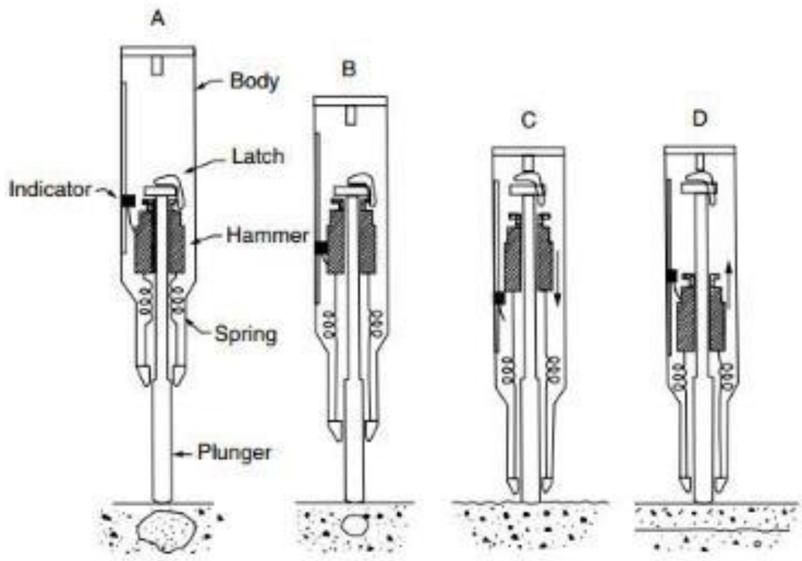


Fig. 2.2:A cutaway schematic view of the Schmidt rebound hammer (Malhotra, 2004)

To prepare the instrument for a test, the plunger is released from its locked position by pushing the plunger against the concrete and slowly moving the body away from the concrete. This causes the plunger to extend from the body and the latch engages the hammer mass to the plunger rod (Fig. 2.2A). The plunger is held perpendicular to the concrete surface and slowly the body is pushed toward the test object. As the body is pushed, the main spring connecting the hammer mass to the body is stretched (Fig. 2.2B). When the body is pushed to the limit, the latch is automatically released, and the energy stored in the spring propels the hammer mass toward the plunger tip (Fig. 2.2C). The mass impacts the shoulder of the plunger rod and rebounds. During rebound, the slide indicator travels with the hammer mass and records the rebound distance (Fig. 2.2D).

The test can be conducted horizontally, vertically upward or downward, or at any intermediate angle. Due to different effects of gravity on the rebound as the test angle is changed, the rebound number will be different for the same concrete and will require separate calibration or correction charts.Table 2.1 shows the relation between rebound number and quality of concrete for different rebound number.

Table 2.1: Non-destructive and In-place Tests
(Kvgd, Balaji & Yelisetty, Ajitesh, 2014)

Rebound Number	Quality of Concrete
>40	Excellent
30-40	Good
20-30	Fair
<20	Poor or Delaminated
0-10	Very Poor or Delaminated

2.16 OBJECTIVES OF REBOUND HAMMER TEST

The test's goals are as follows:

- to determine the concrete's compressive strength by comparing the rebound index to the compressive strength.
- to assess the concrete's homogeneity.
- to evaluate the concrete's quality in accordance with the required standards.
- to compare various concrete components based on their concrete quality.

These test procedures can also be used to compare the strengths of two different structures or to identify the elements of a concrete construction that are acceptable or uncertain.

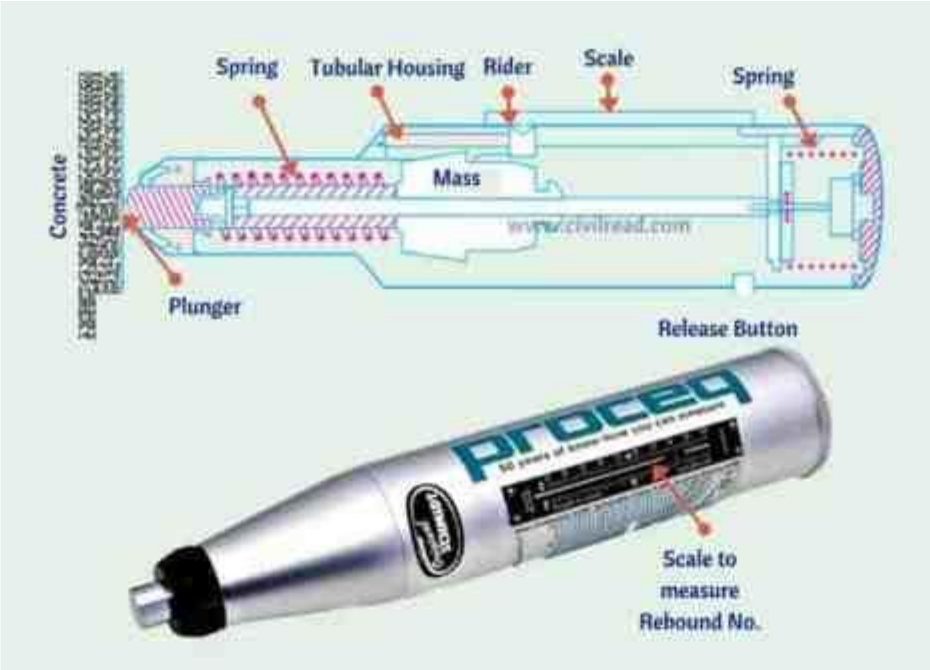


Fig.2.3: Rebound Hammer Details(Krishna,2018)

2.17 FACTORS THAT AFFECT THE REBOUND HAMMER INDEX

Although the rebound hammer provides a quick, inexpensive means of checking the uniformity of concrete, it has serious limitations and these must be recognized. The results of the Schmidt rebound hammer are affected by (Malhotra et al., 2004):

- smoothness of test surface
- size, shape, and rigidity of the specimens
- age of test specimens
- influence of Surface conditions
- type of coarse aggregate
- type of cement
- type of mold
- carbonation of the concrete surface

2.17.1 SMOOTHNESS OF TEST SURFACE

Surface texture has an important effect on the accuracy of the test results. When a test is performed on a rough textured surface, the plunger tip causes excessive crushing and a reduced rebound number is measured. More accurate results can be obtained by grinding a rough surface to uniform smoothness with a carborundum stone. It has been shown by Kolek and Greeneet al (1954) that trowelled surfaces or surfaces made against metal forms yield rebound numbers 5 to 25% higher than surfaces made against wooden forms. This implies that if such surfaces are to be used, a special correlation curve or correction chart must be developed. Further, trowelled surfaces will give a higher scatter of individual results and, therefore, a lower confidence in estimated strength.

2.17.2 SIZE, SHAPE, AND RIGIDITY OF THE SPECIMENS

If the concrete section or test specimen is small, such as a thin beam, wall, 152-mm cube, or 150 × 300- mm cylinder, any movement under the impact will lower the rebound readings. In such cases the member has to be rigidly held or backed up by a heavy mass. It has been shown by Mitchel and Hoagland et al (1961) that the restraining load for test specimens at which the rebound number remains constant appears to vary with the individual specimen. However, the effective restraining load for consistent results appears to be about 15% of the ultimate strength of 152 × 305-mm cylinders. Zoldners, Greene and Griebet al (1957) have indicated effective stresses of 1, 1.7, and 2.0 MPa, respectively, and these are considerably lower than the 15% value obtained by Mitchell and Hoaglandet al (1961).

2.17.3 AGE OF TEST SPECIMENS

Kolek et al (1958) has indicated that the rate of gain of surface hardness of concrete is rapid up to the age of 7 days, following which there is little or no gain in the surface hardness; however, for a properly cured concrete, there is significant strength gain beyond 7 days. It has been confirmed by Zoldners and Victor et al (1957) that for equal strength, higher rebound values are obtained on 7-day-old concrete than on 28-day-old concrete. It is emphasized that when old concrete is to be tested, direct correlations are necessary between the rebound numbers taken on the structure and the compressive strength of cores taken from the structure. The use of the Schmidt hammer for testing low-strength concrete at early ages, or where concrete strength is less than 7 MPa, is not recommended because rebound numbers are too low for accurate reading and the test hammer badly damages the concrete surface.

2.17.4 INFLUENCE OF SURFACE CONDITION

Szilágyi et al (2014) has found that the measurement uncertainty of the tests performed on-air dry surface is lesser than that of the tests performed on the wet surface. Although the testing criteria of the rebound hammer do not allow to perform the test on wet surfaces. It would be sensible to examine wet surfaces of different moisture contents to set an upper limit, which does not influence the rebound index.

2.17.5 TYPE OF COARSE AGGREGATE

It is generally agreed that the rebound number is affected by the type of aggregate used. According to Klieger et al. (1954), for equal compressive strengths, concretes made with crushed limestone coarse aggregate show rebound numbers approximately 7 points lower than those for concretes made with gravel coarse aggregate, representing approximately 7 MPa difference in compressive strength.

2.17.6 TYPE OF CEMENT

According to Kolek et al (1958), the type of concrete significantly affects the rebound number readings. High alumina cement concrete can have actual strengths 100% higher than those obtained using a correlation curve based on concrete made with ordinary Portland cement. Also, super sulfated cement concrete can have 50% lower strength than obtained from the ordinary Portland cement concrete correlation curves.

2.17.7 TYPE OF MOLD

Mitchell and Hoaglandet al (1961) have carried out studies to determine the effect of the type of concrete mold on the rebound number. When cylinders cast in steel, tin can, and paper carton molds were tested, there was no significant difference in the rebound readings between those cased in steel molds and tin can molds, but the paper carton-molded specimens gave higher rebound numbers. This is probably due to the fact that paper molds withdraw moisture from the fresh concrete, thus lowering the water-cement ratio at the surface and resulting in a higher strength. As the hammer is a surface hardness tester, it is possible in such cases for the hammer to indicate an unrealistically high strength. It is therefore suggested that if paper carton molds are being used in the field, the hammer should be correlated against the strength results obtained from test cylinders cast in similar molds.

2.17.8 CARBONATION OF THE CONCRETE SURFACE

Surface carbonation of concrete significantly affects the Schmidt rebound hammer test results. The carbonation effects are more severe in older concretes when the carbonated layer can be several millimeters thick and in extreme cases up to 20 mm thick.In such cases, the rebound numbers can be up to 50% higher than those obtained on an un-carbonated concrete surface. Suitable correction factors should be established in such cases, otherwise overestimation of concrete strength will result.

2.18 ULTRASONIC PULSE VELOCITY (UPV) TEST

The test instrument consists of a means of producing and introducing a wave pulse into the concrete (pulse generator and transmitter) and a means of sensing the arrival of the pulse (receiver) and accurately measuring the time taken by the pulse to travel through the concrete. The equipment may also be connected to an oscilloscope, or other display device, to observe the nature of the received pulse. A schematic diagram is shown in **Fig. 2.4**.A complete description is provided in ASTM Test Method C 597.11 Portable ultrasonic testing units are available worldwide. The equipment is portable, simple to operate, and may include a rechargeable battery and charging unit. Typically, pulse times of up to 6500 μs can be measured with 0.1-μs resolution. The measured travel time is prominently displayed. The instrument comes with a set of two transducers, one each for transmitting and receiving the ultrasonic pulse. Transducers with frequencies of 25 to 100 kHz are usually used for testing concrete. Transducer sets having different resonant frequencies are available for special applications: high-frequency transducers (above 100 kHz) are used for small-size specimens, relatively short path lengths, or high-strength concrete, whereas low-frequency transducers (below 25 kHz) are used for larger specimens and relatively longer path lengths, or concrete with larger size aggregates. These transducers primarily generate compressional waves at predominantly one frequency, with most of the wave energy directed along the axis normal to the transducer face.

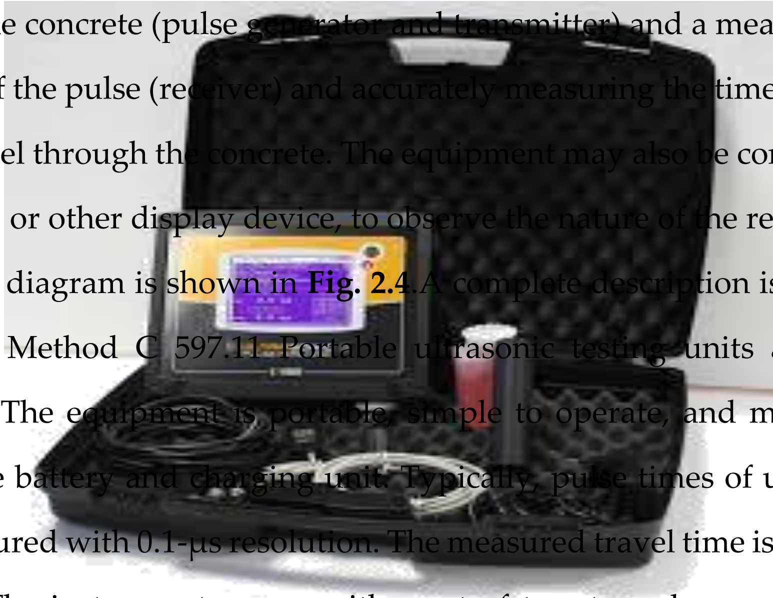


Fig. 2.4: Ultrasonic Pulse Analyzer(Controls, 2012)

A pulse of longitudinal vibrations is produced by an electro-acoustical transducer, which is held in contact with one surface of the concrete under test. When the pulse generated is transmitted into the concrete from the transducer using a liquid coupling material such as grease or cellulose paste, it undergoes multiple reflections at the boundaries of the different material phases within the concrete. A complex system of stress waves develops, which include both longitudinal and shear waves, and propagates through the concrete. The first waves to reach the receiving transducer are the longitudinal waves, which are converted into an electrical signal by a second transducer. Electronic timing circuits enable the transit time T of the pulse to be measured.

Longitudinal pulse velocity (in km/s or m/s) is given by:

$$v = \frac{L}{T}$$

Where,
v= Longitudinal pulse velocity
L= Path length
T= Time taken by the pulse to traverse that length

The equipment consists essentially of an electrical pulse generator, a pair of transducers, an amplifier and an electronic timing device for measuring the time interval between the initiation of a pulse generated at the transmitting transducer and its arrival at the receiving transducer. Two forms of electronic timing apparatus and display are available, one of which uses a cathode ray tube on which the received pulse is displayed in relation to a suitable time scale, the other uses an interval timer with a direct reading digital display. The equipment should have the following characteristics. It should be capable of measuring transit time over path lengths ranging from about 100 mm to the maximum thickness to be inspected to an accuracy of ±1%. Generally, the transducers used should be in the range of 20 to 150 kHz although frequencies as low as 10 kHz may be used for very long concrete path lengths and as high as 1 MHz for mortars and grouts or for short path lengths. High frequency pulses have a well-defined onset but, as they pass through the concrete, become attenuated more rapidly than pulses of lower frequency. It is therefore preferable to use high frequency transducers for short path lengths and low frequency transducers for long path lengths. Transducers with a frequency of 50 kHz to 60 kHz are suitable for most common applications.

The pulse velocity can be combined with rebound number. ASTM C 597 describes the test procedures. Table 2.2 shows the guidelines for qualitative assessment of concrete of concrete based on UPV test results.

Table 2.2: Concrete Quality based on UPV
(Kvgd, Balaji & Yelisetty, Ajitesh, 2014)

Pulse Velocity	Concrete Quality
>4.0 km/s	Very Good to Excellent
3.5 km/s – 4.0 km/s	Good to Very Good, slide porosity may exist
3.0 km/s – 3.5 km/s	Satisfactory, but loss of integrity is suspected

< 3.0 km/s	Poor, loss of integrity exist

2.19 OBJECTIVES OF UPV TEST

The ultrasonic pulse velocity test goals are as follows:

- to check concrete homogeneity.
- the availability of cracks, voids, and other imperfections.
- structural changes of concrete which may occur with time.
- to assess concrete quality.
- to compare the quality of one member of concrete with another.
- to measure the value of the dynamic modulus of elasticity.

2.20 FACTORS AFFECTING THE ULTRASONIC PULSE VELOCITY

2.20.1 MOISTURE CONTENT

The moisture content has two effects on the pulse velocity, one chemical the other physical. These effects are important in the production of correlations for the estimation of concrete strength. Between a properly cured standard cube and a structural element made from the same concrete, there may be a significant pulse velocity difference. Much of the difference is accounted for by the effect of different curing conditions on the hydration of the cement while some of the difference is due to the presence of free water in the voids.

2.20.2 TEMPERATURE OF THE CONCRETE

Variations of the concrete temperature between 10oC and 30oC have been found to cause no significant change without the occurrence of corresponding changes in the strength or elastic properties. Corrections to pulse velocity measurements should be made only for temperatures outside this range as given in Table 2.3.

Table 2.3: Effect of Temperature on Pulse Transmission
(BS 1881 Part 203, 1986.)

Temperature (˚C)	Correlation to the Measured Pulse Velocity	
	Air dried concrete (%)	Water Saturated Concrete (%)
60	5	4
40	2	1.7
20	0	0
0	-0.5	-1
-4	-1.5	-7.5

2.20.3 PATH LENGTH

The path length over which the pulse velocity is measured should be long enough not to be significantly influenced by the heterogeneous nature of the concrete. It is recommended that the minimum path length should be 100 mm for concrete where nominal maximum size of aggregate is 20 mm or less and 150 mm for concrete where nominal maximum size of aggregate is between 20 mm and 40 mm. The pulse velocity is not generally influenced by changes in path length, although the electronic timing apparatus may indicate a tendency for velocity to reduce slightly with increasing path length. This is because the higher frequency components of the pulse are attenuated more than the lower frequency components and the shape of the onset of the pulse becomes more rounded with increased distance travelled. Thus, the apparent reduction of pulse velocity arises from the difficulty of defining exactly the onset of the pulse and this depends on the particular method used for its definition. This apparent reduction in velocity is usually small and well within the tolerance of time measurement accuracy for the equipment.

2.20.4 SHAPE AND SIZE OF SPECIMEN

The velocity of short pulses of vibration is independent of the size and shape of the specimen in which they travel, unless its least lateral dimension is less than a certain minimum value. Below this value, the pulse velocity may be reduced appreciably. The extent of this reduction depends mainly on the ratio of the wavelength of the pulse vibrations to the least lateral dimension of the specimen but it is insignificant if the ratio is less than unity.

2.20.5 EFFECT OF REINFORCING BARS

The pulse velocity measured in reinforced concrete in the vicinity of reinforcing bars is usually higher than in plain concrete of the same composition. This is because the pulse velocity in steel may be up to twice the velocity in plain concrete and, under certain conditions, the first pulse to arrive at the receiving transducer travels partly in concrete and partly in steel. The apparent increase in pulse velocity depends on the proximity of the measurements to the reinforcing bar, the diameter and number of bars and their orientation with respect to the propagation path. The frequency of the pulse and surface conditions of the bar may both also affect the degree to which the steel influences the velocity measurements. Corrections to measured values to allow for reinforcement will reduce the accuracy of estimated pulse velocity in the concrete so that, wherever possible, measurements should be made in such a way that steel does not lie in or close to the direct path between the transducers.

2.20.6 EFFECT OF CONCRETE UNIFORMITY

Heterogeneities in the concrete within or between members cause variations in pulse velocity, which in turn are related to variations in quality. Measurements of pulse velocity provide a means of studying the homogeneity and for this purpose a system of measuring points which covers uniformly the appropriate volume of concrete in the structure has to be chosen.

2.21 CORETEST

Concrete cores are used for testing of actual properties of concrete in existing structures such as strength, permeability, chemical analysis, carbonation etc. Sampling of concrete cores and testing its strength is described. While Rebound Hammer, and ultrasonic pulse velocity tests give indirect evidence of concrete quality, a more direct assessment on strength can be made by core sampling and testing. In most structural investigations or diagnoses, extraction of core samples isunavoidableand often essential. Cores are usually extracted by drilling using a diamond tipped core cuttercooled with water. Broken samples, for example, due to popping, spalling and delamination,are also commonly retrieved for further analysis as these samples may provide additionalevidence as to the cause of distress. The selection of the locations for extraction of coresamples is made after non-destructive testing which can give guidance on the most suitablesamplingareas.

For instance, a cover meter can be used to ensure that there are no reinforcing bars where thecore is to be taken; or the ultrasonic pulse velocity test can be used to establish the areas ofmaximumandminimumpulsevelocitythatcouldindicatethehighestandlowe stcompressivestrengthareasinthestructure.Moreover, using non-destructive tests, the number of cores that need to be taken can bereduced or minimized. This is often an advantage since coring is frequently viewed as beingdestructive. Also, the cost of extracting cores is quite high and the damage to the concrete issevere.The extracted cores can be subjected to a series of tests and serve multiple functionssuchas:

(a) confirming the findings of the non-destructive testidentifyingthepresenceofdeleteriousmatterintheconcrete ascertaining the strength of the concrete for design purposes predictingthepotentialdurabilityoftheconcrete.
(b) confirmingthemixcompositionoftheconcretefordisputeresol

ution.

(c) determiningspecificpropertiesoftheconcretenotattainableby non-destructivemethods such asintrinsicpermeability.

2.22 FACTORS AFFECTING THE STRENGTH OF CONCRETE CORES

The factors that are significant which influence the core compressive strength of concrete are (Shraddhu, 2017):

1. Moisture and Voids
2. Length/Diameter Ratio of Core
3. Diameter of Core
4. Position of Cut out Concrete in Structure
5. Direction of Drilling
6. Effect of Age.

2.22.1 MOISTURE AND VOIDS

The moisture condition of the core influences the measured strength. A saturated specimen has a value of 10 to 15% lower than comparable dry specimen. Thus, while estimating the actual in-situ concrete strength the relative moisture conditions of the core and the in-situ concrete should be taken into consideration. Voids in the core concrete will reduce the measured strength. Peterson et al (1999) found that the ratio of core strength to standard cylinder strength at the same age is always less than 1.0, and decreases with the increase in the strength of cylinder strength. Up to cylinder strength of 20 MPa it is just less than 1 and 0.7 for 60 MPa strength.

2.22.2 LENGTH/DIAMETER RATIO OF CORE

The l/d ratio increases, the measured strength decreases due to the effect of specimen shape and stress distribution during the test.

2.22.3 DIAMETER OF CORE

The diameter of the core may influence the measured strength and its variability. Measured concrete strength decreases with the increase in the size of specimen. This effect is significant. However, this effect will be small for sizes above 100 mm, but for smaller sizes this effect is significant.

2.22.4 POSITION OF CUT OUT CONCRETE IN STRUCTURE

Cores taken from near the top surface have usually lowest strength may it be a column, beam, or wall or slab. With the increase in depth below the top surface the strength increases, but at depths more than 300 mm, there is no further increase in strength. The difference may be 10 to 20%. In case of slabs, poor curing increases this difference.

2.22.5 DIRECTION OF DRILLING

Due to the layering effect, the measured strength of specimen drilled vertically relative to the direction of casting is likely to be greater than that for a horizontally drilled specimen from the same concrete. The average value of 8% for this difference has been reported in literature.

2.22.6 EFFECT OF AGE

In-situ, concrete gains little strength after 28 days. The core strength increases with age up to 1 year, but remains lower than the 28 days standard cylinder strength. On the other hand, Petersons et al (1999) has suggested the increase in core strength over that of 28 days cylinder strength as 10% after 3 months and 15% after 6 months. But in the absence of definite moist curing, no increase in strength should be expected.

Moreover, the following types of factors are affecting the strength of the concrete core.

(a) Curing
(b) Micro - Cracking
(c) Moisture Content
(d) Compaction
(e) Place of drilling the Core

2.23 IMPORTANCE OF CONCRETE CORE TEST

The following requirements highlight the importanceof core test.

(a) The core test is required when the strength of concrete cubes is not giving satisfactory result.
(b) In case of doubt regarding the grade of concrete used either due to poor workmanship or based on the result of the cube strength test, a compressive strength test of the concrete core may be carried out.
(c) In addition, the core cutter test is used for determining the existing structural strength of the concrete and also evaluating the structural capacity or safety assessment of the existing structure.
(d) Also, the case of rehabilitation of the existing structure, the concrete element is the most important factor so this concrete is tested with the help of the core cutter test.
(e) The core cutter test provides the strength of the existing structure.

2.24 COMPRESSIVE STRENGTH OF CONCRETE CYLINDER

The compressive strength of the concrete cylinder is one of the most common performance measures carried by the engineers in the structural design. Here, the compressive strength of concrete cylinders is determined by applying continuous load over the cylinder until failure occurs. The test is conducted on a compression-testing machine. The diameter of the cylinder cast must be at least 3 times the nominal maximum size of the coarse aggregate used in the concrete manufacture. The apparatus required is mentioned below:

- compression testing machine
- cylinder mold of 150mm diameter and 300mm height
- weighing balance.

The compressive strength of cylindrical concrete specimens like molded cylinders and drilled cores is measured according to ASTM C39. Only concrete with a unit weight greater than 50 lb/ft3 (800 kg/m3) is allowed to use it. Molded cylinders or cores are subjected to a compressive axial load till failure. By dividing the maximum force attained during the test by the specimen's cross-sectional area, the compressive strength of the specimen is determined. The outcomes of this test procedure serve as the foundation for concrete quality control.

Two steel bearing blocks shall be installed in a testing device that can deliver the load rates outlined in the standard. One of the bearing blocks should be spherically seated to support the specimen's upper surface, and the other should be solid to support the specimen. It is crucial to study the whole specification in the applicable ASTM specification before performing ASTM C39.

2.25 FACTORS AFFECTING STRENGTH TEST RESULTS OF CONCRETE

The key characteristic of concrete is its compressive strength. In a lab setting under controlled circumstances, the compressive strength of concrete is measured. The quality of concrete is evaluated based on the test result. It can be challenging to draw any conclusions, however, when the results of the strength tests show such broad variations. If the proper steps are taken, this difference in test results can be prevented. There are 7 factors which influence strength of concrete when tested for compressive strength. These factors are mentioned below.

1. Shape and Size of Test Specimens
2. Height to Diameter Ratio
3. Rate of Application of Load

4. Moisture Content in the Test Specimen
5. Material Used for Capping
6. Concrete cylinder casting, curing and testing procedures
7. Grading of aggregates

2.25.1 SHAPE AND SIZE OF TEST SPECIMENS

The size & shape of the specimens greatly influence the outcome of the concrete strength test. When two cubes made of the same concrete but of different sizes are tested, the findings will differ. For instance, the strength of a cube specimen with a size of 10 cm is 10% lower than the strength of a cube specimen with a size of 15 cm. When two specimen of various shapes, such as cube and cylinder, are examined, the results will vary. According to an experiment, the strength of a cylinder with a 15 cm diameter and 30 cm length is 0.8 times that of a 15 cm cube.

2.25.2 HEIGHT TO DIAMETER RATIO

In general, the height to diameter ratio is set at 2 when testing cylindrical concrete specimens. However, when the core is removed from a road pavement, an airport, or any other element of the construction, it is occasionally impossible to maintain a height/diameter ratio of 2. Before testing, the length of the core can be reduced to a 2:1 h/d ratio if it is too long. However, if the length of the core specimen is short, a correction factor must be applied to the test result. A correction factor according to the height / diameter ratio of the specimen after capping is obtained from the curve as shown in **Fig.2.5**:

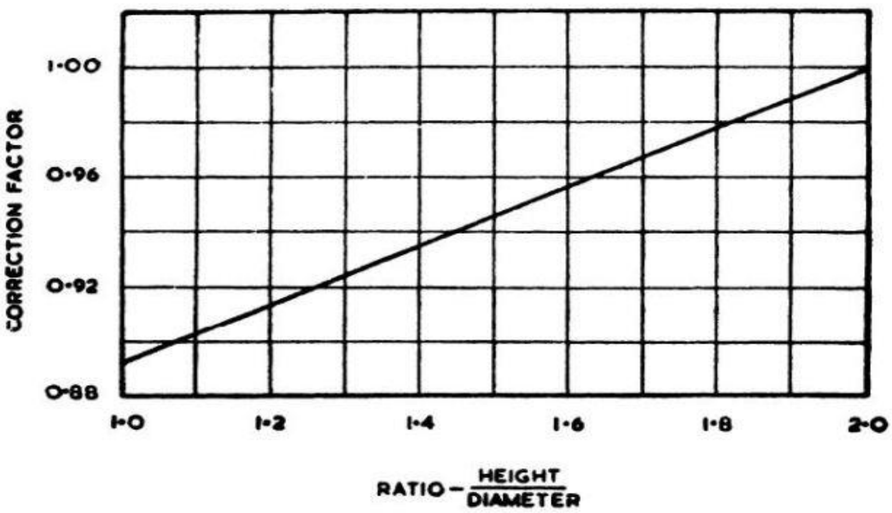


Fig. 2.5 Correction factor for height-diameter ratio of a core (Suryakanta, 2015)

The corrected compressive strength is calculated as the product of this correction factor and the observed compressive strength. The strength of a cylinder with a height to diameter ratio of 2 is comparable to this adjusted compressive strength. The concrete cylinder strength ratio is influenced by geometric elements such the concrete's volume, shape, and h/d ratio (height to lateral dimension of specimen).

2.25.3 RATE OF APPLICATION OF LOAD

The results of the strength test are significantly influenced by the rate at which the load is applied. if there is a delay in time or a slow pace of load application. Lower strength values will follow as a result. This is happening for a creepy reason. The specimen will experience some creep as a result of the delayed application of load, which raises the strain. And the failure of the test sample, which results in lower strength levels, is caused by this higher strain.

2.25.4 MOISTURE CONTENT IN THE TEST SPECIMEN

The test result is significantly impacted by the test specimen's moisture level. When two identical concrete cubes - one wet and the other dry - are tested at the same age, the dry cube will demonstrate more strength than the wet cube. This might be the result of the water in the concrete reducing the cohesiveness of the elements. The concrete cubes or cylinders should be examined right away after being removed from the curing tank in order to obtain repeatable results. Because the test findings will differ greatly if the concrete is tested when it is dry.

2.25.5 MATERIAL USED FOR CAPPING

Concrete cylinders can be capped using a variety of techniques, including Sulphur, gypsum, and cement mortar. The kind of capping material employed has some bearing on the result of the strength test as well. Therefore, it is recommended that one method of capping the concrete cylinders be used for a specific construction project. And there should never be a change to this particular approach. By using this technique, the quality of concrete can be assessed and prevent significant changes in test results.

2.25.6. EFFECTS OF SPECIMEN CASTING, CURING AND TESTING PROCEDURES

The method of casting and capping cylinder affects the strength ratios of both. The use of rigid and non-rigid molds affects the strength. Also, the method of capping these molds affects the strength as out of plane surface also influences their strength ratio.

2.25.7. GRADING OF AGGREGATES

Grading of aggregates in concrete affects the strength of any structure or specimen. The effect of compression test on concrete specimens are large due to relative size of aggregate particles to specimen dimensions. Most standards set limits for the ratio of diameter or size of specimen to maximum nominal size of aggregates. Typically, this allowable minimum is around 3 to 4.

2.26 PREVIOUS STUDIES ON VARIOUS NDT TEST

A number of research studies have been conducted to predict compressive strength of concrete using NDT. The most relevant studies outcomes are mentioned below:

Amini, K., Jalalpour, M., and Delatte, N. et al (2016) used solely results on UPV and RH for prediction and classification of concrete strength, without a need for information about the concrete history and mixture proportions. The intent was to align models for in-situ predictions of existing structures. A rigorous statistical analysis with threefold cross-validation and application to independent data showed that combined usage of UPV and RN appeared to outperform models based on a single test result. This may be because UPV and RN are sensitive to the different characteristic of concrete. Based on this observation, a model is put forward for predictions of concrete strength. The proposed model was tested on independent data, and showed a very good predictive accuracy. Moreover, a table was proposed for concrete quality classification based on combined UPV and RN results. This table may be useful for researchers and engineers in the field for a rough estimation of in-situ concrete strength.

Nihar, K. B., Datta, D., Islam, M.T., and Ali, Md. Shahjahan et al (2019) investigated the nondestructive and semi-destructive test of concrete and results were compared with representative cylinder strength to establish a relationship among them. Two developed equations had a relationship in between compressive strength and ultrasonic pulse velocity and R-squared values of those straight and exponential equations are 0.8689 and 0.8013 respectively. In comparison with compressive strength of cylinder, core strength of concrete showed more closed approximated than NDT strength calculated by using previously developed equations. Final analysis depicted that core strength of concrete decreased about 15.75% than cylinder strength where NDT prediction gave most fluctuating strength and those amounts were 1%-20% and 6%-30% respectively.

Hassan, A.M.T., Jones, S.W. et al (2012) studied on the ultrasonic pulse velocity (UPV) and resonant frequency methods, two non-destructive testing techniques which was used to measure the elastic properties of conventional concrete for many decades. This paper presents a study on these testing methods to determine the modulus of elasticity and Poisson's ratio of ultra high performance fiber reinforced concrete (UHPFRC) containing 2% steel fibers by volume. Measurements were taken on slab and prism specimens using compression wave ultrasonic transducers and resonant frequency testing. Empirical relationships to determine the secant modulus of elasticity were studied. Results of the dynamic tests and empirical equations are compared to static tests and found to be in close agreement. This study found that ultrasonic wave propagation is the most reliable, easy and cost effective testing technique to use in the determination of the elastic properties of the UHPFRC mix used in this study.

Albuthbahak, Oday M., Hiswa, Ashraf A. M. R. et al (2019) developed a non-destructive technique for concrete compressive strength assessment for existing concrete structures, Ultrasonic Pulse Velocity (UPV) test method has been used. Since the UPV affected by many factors, it is not easy to accurately assess the concrete compressive strength. Effect of some factors which are coarse aggregate grading type, slump, the water-cement ratio (w/c), sand volume ratio, coarse aggregate volume ratio, testing age, concrete density, and pressure of steam curing, were analyzed on the relationship between ultrasonic pulse velocity and concrete strength. 436 records of data, extracted from published research work, were used to build seven supervised machine learning regression models which are; Artificial Neural Network (ANN), Support Vector Machine (SVM), Chi-squared Automatic Interaction Detector (CHAID) decision tree, Classification and Regression Trees (CART) decision tree, non-linear regression, linear regression, and stepwise linear regression models. Also, the independent variable importance for each predictor was analyzed for each model. With an adequate tuning of parameters, ANN models have produced the highest accuracy in prediction, followed in sequent with SVM, CHAID, CART, non-linear regression. Linear and stepwise linear regression models presented low values of predictive accuracy, w/c was observed to be the highest importance factor in prediction of concrete strength, and the forecasting of the concrete strength was efficient when using w/c and UPV only as predictors in any of the used predictive models.

Said, Abdul Muttalib I., Ali, Baqer Abdul Hussein et al (2021) has carried out an experimental program to establish a relatively accurate relation between the ultrasonic pulse velocity (UPV) and the concrete compressive strength. The program involved testing concrete cubes of (100) mm and prisms of (100×100×300) cast with specified test variables. The samples are tested by using ultrasonic test equipment with two methods, direct ultrasonic pulse (DUPV) and surface (indirect) ultrasonic pulse (SUPV) for each sample. The obtained results were used as input data in the statistical program (SPSS) to predict the best equation representing the relation between the compressive strength and the ultrasonic pulse velocity. In this research, 383 specimens were tested, and an exponential equation was proposed for this purpose. The statistical program has been used to prove which type of UPV is more suitable, the (SUPV) test or the (DUPV) test, to represent the relation between the ultrasonic pulse velocity and the concrete compressive strength. In this paper, the effect of salt content on the connection between the ultrasonic pulse velocity and the concrete compressive strength has also been studied.

Rojas-henao, L., Fernández-gómez, J., López-agüí, J.C. et al (2012) describes a study designed to verify whether self-consolidating concrete (SCC) and conventional vibrated concrete (VC) react similarly to some of the most commonly used tests for strength estimation, such as rebound hammer, ultrasonic pulse velocity (PV), and core drilling. The areas compared include the type of fit and correction factors for estimating compressive strength with rebound hammer, ultrasonic PV and core tests, and the effect of variables such as casting direction, sample location, core diameter, core moisture conditions, concrete strength, and the possible effects of congested reinforcement. The findings revealed significant differences of these variables and correction factors for estimating strength affect SCC and VC strength measurement.

Szilágyi, K., Borosnyói, A., Zsigovics, I. et al (2011) observed that surface hardness testing of concrete is a long-established NDT method for in situ strength estimation. The rebound hammer is the surface hardness testing device for concrete and of the most widespread use. Based on a comprehensive literature review, it was realized that no general theory was developed in the last more than 50 years that could describe the relationship between surface hardness and compressive strength of concrete. The diversity of the numerous empirical proposals that can be found in the technical literature needs to be explained. It can be even found in some publications that the method is suitable only for assessing the uniformity of concrete. There is long a time need for a model that can clarify the rebound surface hardness of concrete. Present paper introduces a phenomenological constitutive model (SBZ-model) that can be formulated for the surface hardness of concrete as a time dependent material property. The generating functions of the model are based on the time dependent development of the capillary pore system of the hardened cement paste in concretes that is characterized by the water–cement ratio as a practical simplification. The modelling assumptions and the use of the model would add to the fundamental understanding of the rebound surface hardness of concrete. An extensive experimental verification study clearly demonstrated the reasonable application possibilities of the SBZ-model.

Qasrawi, H.Y. et al (2000) summarized the experience in the estimation of concrete strength by combined methods of nondestructive testing. Both the traditional well-known rebound hammer and ultrasonic pulse velocity tests were used in the study. Various charts showing the results are presented. All charts show the 95% prediction intervals, thus enabling professionals to predict concrete strength simply and reliably. Unlike other work, the research ended with one simple chart that requires no previous knowledge of the constituents of the tested concrete. The method presented is simple, quick, reliable, and covers wide ranges of concrete strengths. The method can be easily applied to concrete specimens as well as existing concrete structures. The final results were compared with previous ones from literature and also with actual results obtained from samples extracted from existing structures.

Huang, Q., Gardoni, P. & Hurlebaus, S. et al (2012) studied as a general index of concrete strength, where the compressive strength of concrete f_c was important in the performance assessment of existing reinforced concrete (RC) structures. Many nondestructive testing methods have been developed to estimate the in-place value of f'_c. In particular, the combination of rebound hammer and ultrasonic pulse velocity tests, known as SonReb, is frequently used. With the SonReb measurements, regression models are commonly applied to predict f_c The available regression models are not sufficiently valid, however, because of the limited range of data used for their calibration. This paper proposes a probabilistic multivariable linear regression model to predict f_c using SonReb measurements and additional concrete properties. The Bayesian updating rule and the all possible subsets model selection are used to develop the proposed model based on the collected data with a wide range of concrete properties. The proposed model is compared with currently available regression models and concludes that the proposed model gives, on average, a more accurate prediction.

Lasisi, A., Sadiq, O., and Balogun, I. et al (2019) investigated the use of Non-destructive tests as a tool for monitoring the structural performance of concrete structures. The investigation encompassed four phases; the first of which involved the use of destructive and non-destructive mechanisms to assess concrete strength on cube specimens. The second phase research focused on site assessment for a twin engineering theatre located at the Faculty of Engineering, University of Lagos using rebound hammer and ultrasonic pulse velocity tester. The third phase was the use of linear regression analysis model with MATLAB to establish a relationship between calibrated strength as well as ultrasonic pulse velocities with their corresponding compressive strength values on cubes and values obtained from existing structures. Results show that the root-mean squared (R^2) values for rebound hammer ranged between 0.275 and 0.742 while for ultrasonic pulse velocity, R^2 values were in the range of 0.649 and 0.952 for air curing and water curing systems respectively. It initially appeared that the Ultrasonic pulse velocity was more suitable for predicting concrete strength than rebound hammer but further investigations showed that the latter was adequate for early age concrete while the former was more suited for aging concrete. Hence, a combined use is recommended in this work.

Hannachi, S., & Guetteche, M.N. et al (2012) observed the Ultrasonic pulse velocity (UPV) and rebound hammer (RH) tests are often used for assessing the quality of concrete and estimation of its compressive strength. Several parameters influence this property of concrete such as the type and size of aggregates, cement content, the implementation of concrete, etc. To account for these factors, both of the two tests are combined and their measurements are calibrated with the results of mechanical tests on cylindrical specimens cast on site and on cores taken from the existing structure in work progress at the new-city Massinissa El-Khroub Constantine in Algeria. In this study; the two tests cited above have been used to determine the concrete quality by applying regression analysis models between compressive strength of in situ concrete on existing structure and the nondestructive tests values. The combined method is used and equations are derived using statistical analysis (simple and multiple regression) to estimate compressive strength of concrete on site and the reliability of the technique for prediction of the strength is discussed.

Abdul Rasoul, Zainab et al (2018) reviewed the literatures on ultrasonic pulse velocity (UPV) as a nondestructive test for evaluating the properties of concrete. Many researchers attempted to correlate compressive strength of concrete to (UPV) and they suggested many equations for this purpose. In this study the reliability of these equations has been investigated. It seems that none of these equations is reliable enough to be recommended to be used in practices. This conclusion may be interpreted on the basis that some properties of composite material, such as compressive strength, are a function of the weakest component. Griffith theory was also used to interpret this phenomenon.

Ali-Benyahia, K.; Sbartaï, Zoubir-Mehdi; Breysse, Denys; Ghrici, Mohamed; Kenai, Said et al (2019) studied for existing constructions, where there was a need to estimate the concrete mechanical strength for a more accurate evaluation of their structural capacity. The destructive evaluation of strength by coring is expensive, sometimes technically difficult and it may be impossible in some situations and the evaluation is limited to a restricted surface of the structure. Non-destructive testing (NDT) in conjunction with destructive testing by coring (DT) offers an interesting alternative for the strength assessment of concrete in existing buildings. For a reliable assessment of concrete strength, it is necessary to fully check the calibration quality of the conversion models between DT and NDT used for strength estimation. Because of technical and economic constraints, the professional practice is frequently based on a very limited number of cores. If this optimal number is not reached, the risk is high that the resulting conversion model is not reliable. This practical context, in which the common number of cores is small, forces to review the calibration procedure in order to take care of the relevance of the identified model. The procedure using conditional coring, which is based on the selection of critical locations of cores after an analysis of NDT test results, is the subject of methodological developments presented in this paper. The research works aim at analyzing the issue on a broad investigation program by NDT (Rebound Hammer and Ultrasonic Pulse Velocity) and coring realized on the structural elements (columns and beams) of an existing building. 205 data triplets (core strengths and NDT test results) were used to carry out the study. The thorough statistical data analysis allowed quantifying the potential interest of the conditional coring compared to the random coring with two measurement strategies of NDT (by using single or combined methods).

Rucka, M. et al (2020) proposed the special issue “Non-Destructive Testing of Structures” to present recent developments in the field of diagnostics of structural materials and components in civil and mechanical engineering. The papers highlighted the various aspects of non-invasive diagnostics, including such topics as condition assessments of civil and mechanical structures and connections of structural elements, the inspection of cultural heritage monuments, the testing of structural materials, structural health monitoring systems, the integration of non-destructive testing methods, advanced signal processing for the non-destructive testing of structures (NDT), damage detection and damage imaging, as well as modeling and numerical analyses for supporting structural health monitoring (SHM) systems.

Umap, Vaibhav S.; M Rao, Y. R. et al (2022) carried out an exhaustive review for different aspects of non- destructive testing (NDT) adopted for RCC structures. NDT evaluates the remaining operation life of different components of structure. It provides an accurate diagnosis which allows prediction of extended life operation beyond the designed life. Different aspects are considered which includes condition assessment, durability, corrosion, condition ranking and service life of structures. In this review, several non-destructive inspection methods are evaluated, with the aim of identifying those, which are practical for detecting defects at early in the production sequence as possible. The methods used for carrying out non destructive analysis used by different investigators are also discussed. Merits and demerits of each method are also stated. RCC structures such as reinforced buildings, bridges, ESRs, recently developed NDT techniques which are useful for prediction of performance of structure are also included.

Breysee, D. et at (2012) analyzed why and how nondestructive testing (NDT) measurements can be used in order to assess on site strength of concrete. It is based on (a) an in-depth critical review of existing models, (b) an analysis of experimental data gathered by many authors in laboratory studies as well as on site, (c) the development and analysis of synthetic simulations designed in order to reproduce the main patterns exhibited with real data while better controlling influencing parameters. The key factors influencing the quality of strength estimate are identified. Two NDT techniques (UPV and rebound) are prioritized and many empirical strength-NDT models are analyzed. It is shown that the measurement error has a much larger influence on the quality of estimate than the model error. The key issue of calibration is addressed and a proposal is made in the case of the SonReb combined approach. It is based on the use of a prior double power law model, with only one parameter to identify. The analysis of real data sets from laboratory studies and from real size buildings show that one can reach a root mean square error (RMSE) on strength of about 4 MPa. Synthetic simulations are developed in order to better understand the role played by the strength range and the measurement error.

Chapter 3: MATERIALS AND METHODOLOGY

3.1 GENERAL

In order to accomplish the study, testing of samples and the information about the material and mix descriptions, mixing techniques, casting and curing, and testing is provided in this chapter. Two nondestructive test (NDT) equipment known as Rebound Hammer and Ultrasonic Pulse Velocity are used. Electric core cutting machine is used to evaluate concrete core from the cylinder. In this chapter, the detail working principle of Schmidt Rebound Hammer, Ultrasonic Pulse Velocity, Core Test and Compressive Strength Test Techniques are described systematically. These tests are performed to establish a correlation between rebound number, ultrasonic pulse velocity, core test and concrete compressive strength.

3.2 MATERIALS

Concrete with a medium to high strength can be made by choosing the right materials and maintaining strong quality control. The material requires to comply with the requirements of ACI committee 211.1, 2002 and ACI committee 363R, 1997.

3.2.1 Cement

Cement is a powdery substance made with lime and clay. This study employed Ordinary Portland Cement (OPC) type I, obtained from Confidence Cement Company, Chattogram, Bangladesh. Type I cement conforming to ASTM C150. This cement complies with the required standards in terms of both its physical characteristics and chemical analysis. The physical and chemical properties of OPC Type I cement are summarized in **Table 3.1**.

Table 3.1: Physical properties and chemical composition of OPC (Talukder, Saidul & Roy, Emon & Islam, Safiul & Sakib, et al 2021)

Characteristics	Value
Blaine's Specific Surface (cm^2/gm)	4000
Normal Consistency	25%
Soundness by Le Chatelier's Test (mm)	5 mm
Specific gravity	3.15
Setting Time	
Initial (min)	150
Final (min)	230

Compressive Strength	
3 days (MPa)	16.4
7 days (MPa)	22.7
28 days (MPa)	30.7
Calcium Oxide (CaO)	64%
Silicon Dioxide (SiO_2)	21%
Aluminum Oxide (Al_2O_3)	6%
Ferric Oxide (Fe_2O_3)	3.5%
Magnesium Oxide (MgO)	1.2%
Sulfur Trioxide (SO_3)	2.5%
Loss on ignition	1.2%
Insoluble matter	0.6%

3.2.2 Fine Aggregate (FA)

In this investigation, natural Sylhet sand used as the fine aggregate (FA). The test results demonstrated that the grading and sulfate content met the necessary standards. Fine aggregate shall consist of natural sand, manufactured sand, or a combination thereof. According to ASTM C33, fine aggregate shall have not more than 45% passing any sieve and retained on the next consecutive sieve. **Fig. 3.1** exhibits the gradation curves of the fine aggregates. Other physical properties are found in **Table 3.2**.

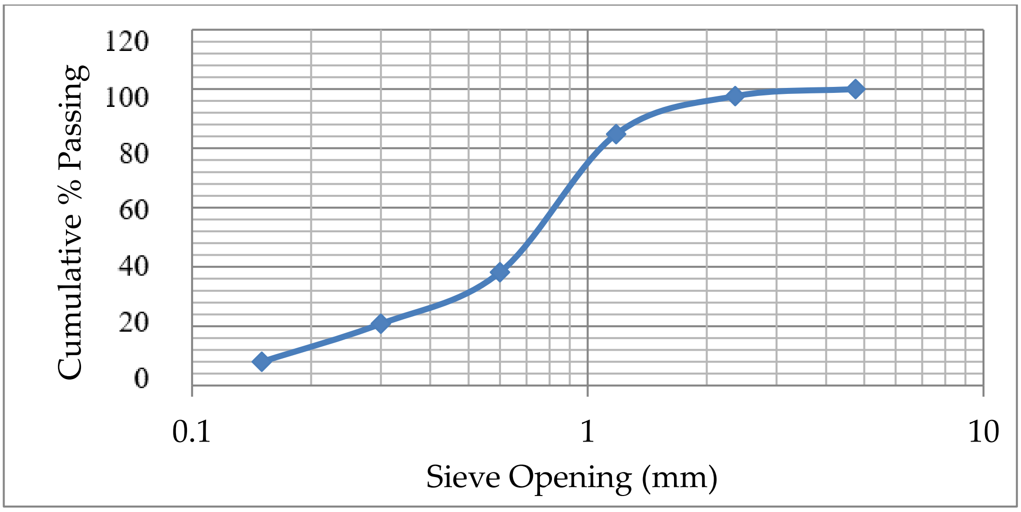


Fig. 3.1: Gradation of Fine Aggregate (Aneetha Vilventhan, 2022)

Table 3.2: Physical Properties of Fine Aggregate

(Talukder, Saidul & Roy, Emon & Islam, Safiul & Sakib, et al 2021)

Physical Properties	Value
Fineness Modulus	2.70
Specific Gravity	2.6
Surface Moisture	1.80%

3.2.3 Coarse Aggregate (CA)

The coarse aggregate (CA) used in this study was cleaned, and fully made of crushed gravel. Well-graded coarse aggregate was used. Coarse aggregate is considered as the structural component of the concrete mix because of their chemical and physical properties that contribute to the strength of the concrete. It consists of gravel, crushed gravel, crushed stone, air-cooled blast furnace slag, or crushed hydraulic-cement concrete, or a combination thereof, conforming to the requirements of ASTM C33. 100% aggregate passed the 25 mm (1 inch) sieve and 95% aggregate passed 19 mm ($\frac{3}{4}$ inch) sieve. Hence, the maximum size of the aggregate was 25 mm and maximum nominal size of aggregate was 19 mm. The gradation curve of aggregate is shown in **Fig. 3.2** and other physical properties of coarse aggregate are given in **Table 3.3**.

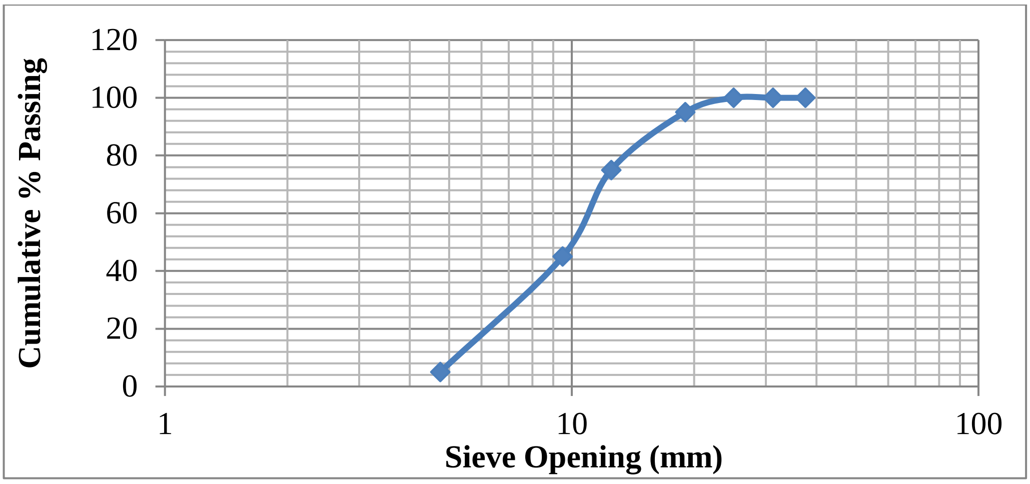


Fig. 3.2: Gradation of Coarse Aggregate (Shetty M.S. & Jain A. K., 2019)

Table 3.3: Physical Properties of Coarse Aggregate

(Talukder, Saidul & Roy, Emon & Islam, Safiul & Sakib, et al 2021)

Physical Properties	Value
Bulk Density	1470 kg/m^3
Specific Gravity	2.68
Absorption Capacity	0.50%

3.2.4 Superplasticizer (SP)

Superplasticizer (SP), commonly referred to as high range water reducers, are additives used to concrete with high strength. Superplasticizers provide a 30% or greater reduction in water content. These additives are used at a few weight percent level. Concrete's setting and hardening are additionally delayed by superplasticizers. A high range water reducing superplasticizer was used to generate medium to high strength concrete.

3.2.5 Water

In this work, both mixing and curing of concrete were done with tap water. Portable water confirming to the requirements of ASTM C1602 was taken for casting and curing of samples. Properties of water are summarized in **Table 3.4**.

Table 3.4: Properties of water

Parameters	Quantity	Unit
pH	7.5	None
Turbidity	10	NTU
Hardness	300	mg/l
Chloride Concentration	400	mg/l
Iron concentration	0.8	mg/l
Total Coliform	0	n/100 ml
Fecal Coliform	0	n/100 ml

3.3 CONCRETE MIX DESIGN

3.3.1 Grade of Concrete

Several trial mix ratios were obtained to arrive at final mix ratios. Final mix design was prepared following ACI 211 standards. This section briefly describes the different Grade of Concrete are as stated in table below:

Table 3.5: Different Grade of Concrete

Sl. No.	Concrete Grade	Sl. No.	Concrete Grade
1	C15	6	C40
2	C20	7	C45
3	C25	8	C50
4	C30	9	C55

5	C35	10	C60

3.3.2 Target Strength of Concrete

The Target strength was chosen from the design strength of concrete. A C20 concrete denotes a concrete with a typical compressive strength of 20N/mm². Actuality, one must build a stronger concrete in order to produce one with a minimum strength of 20 N/mm². The concrete will only be equal to or more than 20N/mm² once all potential losses, if any, have been taken into account. A strength value that is higher than planned is acceptable, but one that is lower is not.The target strength of different grade of concrete is shown in Table 3.6.

Table 3.6: Target Strength for different grade of Concrete

Grade	Strength (MPa)	Increment (MPa)	Target Strength (MPa)
C15	15	7	22
C20	20	7	27
C25	25	8.5	33.5
C30	30	8.5	38.5
C35	35	8.5	43.5
C40	40	9	49
C45	45	9.5	54.5
C50	50	10	60
C55	55	10.5	65.5
C60	60	11	71

3.3.3 Mix Design

A sample mix design has been shown below for C20 grade of concrete.

Mix Design Procedure for C20 Grade of Concrete:

	Value	Unit
Design strength, f'_c	20	MPa
Target compressive strength, f'_r	27	MPa

Step 1	Required material information	Tables 3.1 to 3.3	
Step 2	Desired slump value	25-50	mm
Step 3	Nominal maximum aggregate size	19	mm
Step 4	Water requirement	185	kgm^{-3}
	Approximate entrapped air content	2	%
Step 5	Water to cement ratio	0.45	
Step 6	Cement content	410	kgm^{-3}
Step 7	Volume of coarse aggregate	0.65	m^3
	Mass of coarse aggregate (OD)	1025	kg
Step 8	Volume of water	0.190	m^3
	Volume of cement	0.102	m^3
	Volume of coarse aggregate	0.375	m^3
	Volume of air content	0.020	m^3
	Total volume of known ingredients	0.705	m^3
	Hence, absolute volume of fine aggregate	0.295	m^3
	Mass of fine aggregate (OD)	730	kgm^{-3}
Step 9	Mass of fine aggregate (SSD)	755	kgm^{-3}
	Mass of coarse aggregate (SSD)	1070	kgm^{-3}
	Required water content	185	kgm^{-3}

Step 10 Estimated batch weights per m^3 are as follows

Water	185	liter
Cement	410	kg
Fine aggregate	755	kg
Coarse aggregate	1070	kg

3.4 CONCRETE MIX PROPOTIONING FOR DIFFERENT GRADE OF CONCRETE

The project is divided into ten sets of concrete mixes in order to accomplish the goals of this study. The mix proportions were used to create a total of 180 nos. of concrete cylinders. As per BS 8500-2 British/European standards the concrete grade is denoted as C15, C20, C25, C30, C35, C40 etc., which **'C'** means **Concrete Strength class** and the number behind **C** refers to characteristic Concrete's compressive strength in MPa at 28 days when tested with the 150 mm dia. & 300 mm height **cylinder** in a direct compression test**.** The summary of proposed mix proportions is as stated in Table 3.7:

Table 3.7: Mixing Proportion for 1 m^3 Concrete according to SSD Condition for different Grade of Concrete

	OPC Cement	WCR	Water	Course Aggregate	Course Sand	Admixture

Target Strength KN/m³	kg/m³		kg/m³	kg/m³	kg/m³	kg/m³
C15	370.00	0.50	185.00	1070.00	795.00	-
C20	410.00	0.45	185.00	1070.00	755.00	-
C25	450.00	0.40	180.00	1070.00	715.00	-
C30	480.00	0.38	180.00	1070.00	680.00	-
C35	500.00	0.36	180.00	1070.00	660.00	-
C40	510.00	0.34	175.00	1085.00	625.00	5.10
C45	520.00	0.34	175.00	1085.00	615.00	5.20
C50	530.00	0.33	175.00	1085.00	605.00	5.30
C55	540.00	0.33	175.00	1085.00	595.00	5.40
C60	550.00	0.32	175.00	1085.00	585.00	5.50

3.5 MATERIAL PREPARATION

Preparing the materials is an important process in maintaining the integrity of the mix design. The required materials used for each design strength is discussed in the following sections. The quantities of the course aggregates, fine aggregates, and cementitious materials were proportioned in such a way as to maintain the designed water to cement ratio. Moreover, specific quantity of admixture used for C40 to C60 grade of concrete as per mix design. Hence, maintaining the water to cement ratio was crucial so that the concrete mixes could be comparable to each other. The following sections describe the practices that were undertaken to ensure that the water to cement ratio was not disturbed.

3.5.1 Coarse Aggregate Preparation

Prior to use, the coarse aggregates were fully submerged in large volume tank that contains water. The coarse aggregates were removed from the water tank and placed in proper site to drain out water an hour before mixing. After the aggregates were drained, the aggregates were made ready by taking weight maintaining the mix design ratios. Prepared coarse aggregates are shown in **Fig. 3.3**.

Fig. 3.3: Prepared Coarse Aggregate

3.5.2 Fine Aggregate Preparation

The fine aggregates, which were the silica sand and after screenings, were stored in covered plastic bags. Prior to the concrete mix, the fine aggregates were distributed on dry iron sheet so that they became thoroughly mixed and made the moisture content uniform.

3.5.3 Admixture

Concrete specimens were prepared using specific quantity of admixture used for C40 to C60 grade of concrete as per mix design. Admixture played a vital role in preparing concrete specimens of C40 to C60 grade of concrete.

3.5.4 Mixing of Water

Concrete specimens were prepared using mix design ratios and subjected to compressive strength tests. Specimens were prepared following the mix design ratios and cured for different curing days. Mechanical strength tests were done on the prepared samples. Hence, maintaining proper water cement ratio played a vital role in preparing concrete specimens for this research work.

3.6 SPECIMEN PREPARATION

Cylindrical specimens were prepared according to ASTM C192. The 150 dia × 300 mm cylindrical specimens were filled in three equal layers and rodded 25 times in between the layers. The 150 mm cylindrical specimens are filled in thirds and also rodded 25 times in between each layer. After all of the specimens are filled, rodded, and finished, they were stored in a cool area for 24 hours. After 24 hours the specimens were de-molded and were placed in a water tank. **Fig. 3.4** shows the mixing of materials for making concrete specimen.

Fig. 3.4: Mixing of materials for making Concrete Cylinder

3.6.1 Slump Test

Newly mixed concrete is tested for slump immediately following the mixing process and prior to pouring the concrete into the molds. The ASTM C143 was followed when conducting the slump test. To prevent the concrete from adhering to the testing equipment, all tools, including the slump cone and base, were dampened with water before being set up on a level surface. The slump cone was filled in three layers with freshly mixed concrete that was taken immediately from the entire mixing procedure. Each layer comprised of a volume of concrete that was roughly equivalent to one-third the volume of the slump cone. With 25 mm diameter tamping rod with a rounded end was used to consolidate each layer. The first layer was rodded throughout its whole depth, while the middle and top layers were entirely pierced to reach 25 mm into the layer below.Following the last layer's consolidation, the top of the cone was finished and levelled while the surplus concrete was scraped off the device's sides. The cone's latches were taken off, and the attached handles kept the slump cone firmly in place so that no concrete leaked out the bottom.

The slump cone was raised in a single, constant vertical motion without any lateral or torsional motion as soon as the obstruction at the base was removed. Within three to five seconds, this action is finished. The recorded slump value of the concrete mixture was represented by the difference between the beginning height and the height after the concrete has slumped. Slump value of each mix was around 40-60 mm.The full test method, starting with the filling and ending with the removal of the mold, took 2.5 minutes to complete without any breaks. Thistestwasusedtodeterminetheworkabilityofconcretemixturebyusingstandards lumpcone. Fig. 3.5 shows the slump test of fresh concrete.

Fig. 3.5: Slump Test of Fresh Concrete

3.6.2 Specimen Size: 150mm diameter and 300mm height concrete cylinder was used throughout the study.

3.6.3 Castingandcuringoftestspecimens

The used molds were assembled, cleaned, and lubricated. Three layers of concrete were cast in molds, and each layer was compacted by rodding to release any trapped air. The specimens were demolded in the following day and placed in water for curing at a temperature of (24 + 3) °C until the day of testing.**Fig. 3.6** shows the casting of concrete cylinders.

Fig. 3.6: Casting of Concrete Cylinders

3.6.4 Curing period: The selected curing periods were7 days, 28 days and 90 days. The test specimens after 24 hours of casting were subjected to plain water curing until test. **Fig. 3.7** shows the curing of concrete cylinder. For core cylindrical specimens, after drilling at different age of curing, core sample was collected from the concrete core cylindrical specimens. Grinding was done to finish the surface of core specimens.

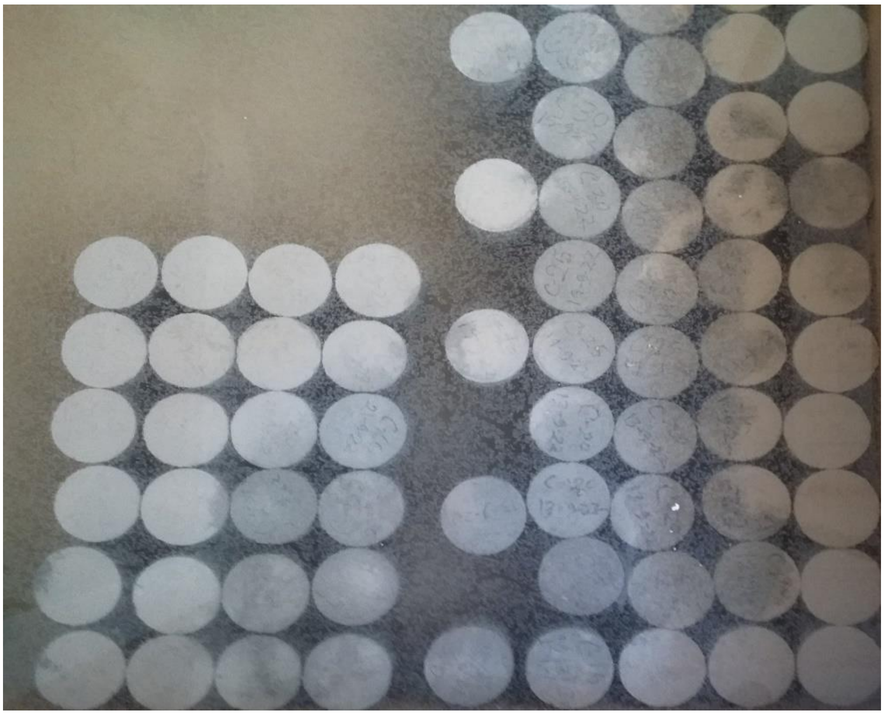
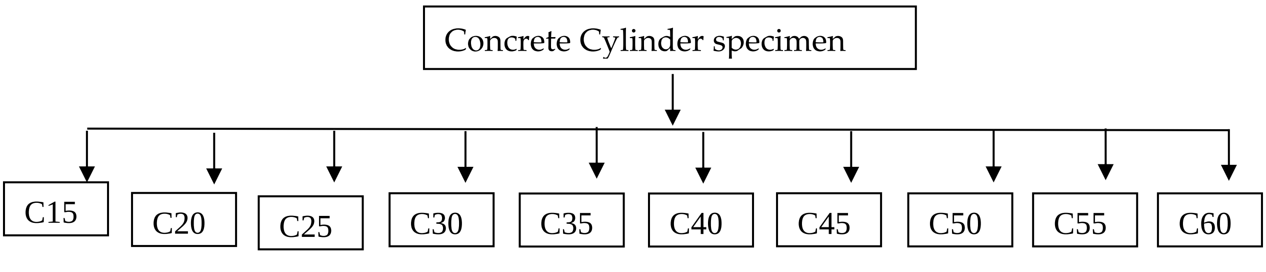


Fig. 3.7: Curing of Concrete Cylinders

3.7 FLOW DIAGRAMS FOR THE INVESTIGATION PROGRAM

The research program is displaced below with the help of a suitable flow diagram (**Fig.3.8**):



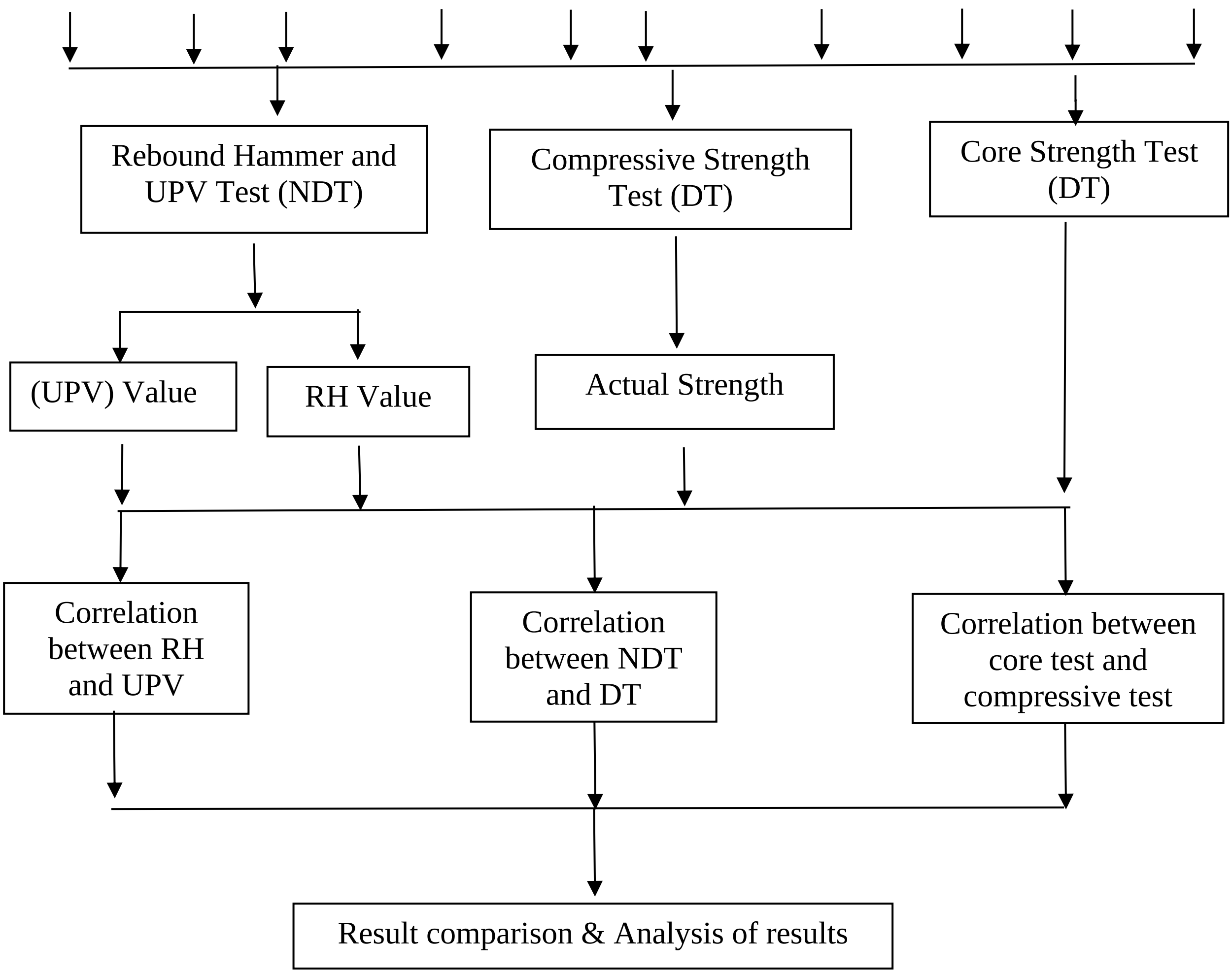


Fig.3.8. Flow diagram of experimental methodology.

3.8 TESTING PROCESS FOLLOWED IN THE LABORATORY

- Determiningtheworkabilityofconcretemixtureby performing Slump Test.
- Casting of 180 nos. cylinders having diameter 150mm and height 300mm. Eighteen (18) cylinders for each mix ratios.
- Three cylinders of each group had been used for core test at 7, 28 and 90 days of age.
- Three cylinders of each group and three core cylinders had been used for NDTs (Rebound Hammer & UPV) at 7, 28 and 90 days of age.
- On the same day of NDTs, cylinders and core compressive strength test had been performed.

3.9 TYPES AND NATURE OF TESTS

After specific curing period of different grade of concrete, the following tests were performed on the various concrete specimens:

a) Rebound Hammer Test
b) Ultrasonic Pulse Velocity Test
c) Core Test
d) Compressive Strength Test

3.9.1 REBOUND HAMMER TEST

Concrete can be tested non-destructively using the Rebound Hammer Test, which gives a quick, accurate indicator of the concrete's compressive strength. The Schmidt Hammer Test, often referred to as the concrete Rebound Hammer Test, utilizes a spring-controlled mass that slides on a plunger inside of a tubular casing. The rebound hammer test is used for concrete that has been hardened.

3.9.1.1 REBOUND HAMMER TESTING PROCESS

The process for a rebound hammer test on concrete cylinder was started with the calibration of the rebound hammer.

1) The rebound hammer was tested against the anvil made of steel having a Brinell hardness of about 5000 N/mm^2.

2) After calibration for accuracy on the test anvil, the rebound hammer was held at the right angle to the surface of the concrete structure for taking the readings.

3) The test thus was conducted horizontally on a vertical surface as shown in the **Fig. 3.9**.

4) The rebound number (rebound index) may produce different results for the same surface and concrete if the rebound hammer is held at an intermediate angle.

5) The hammer test's impact energy requirements vary depending on the application.

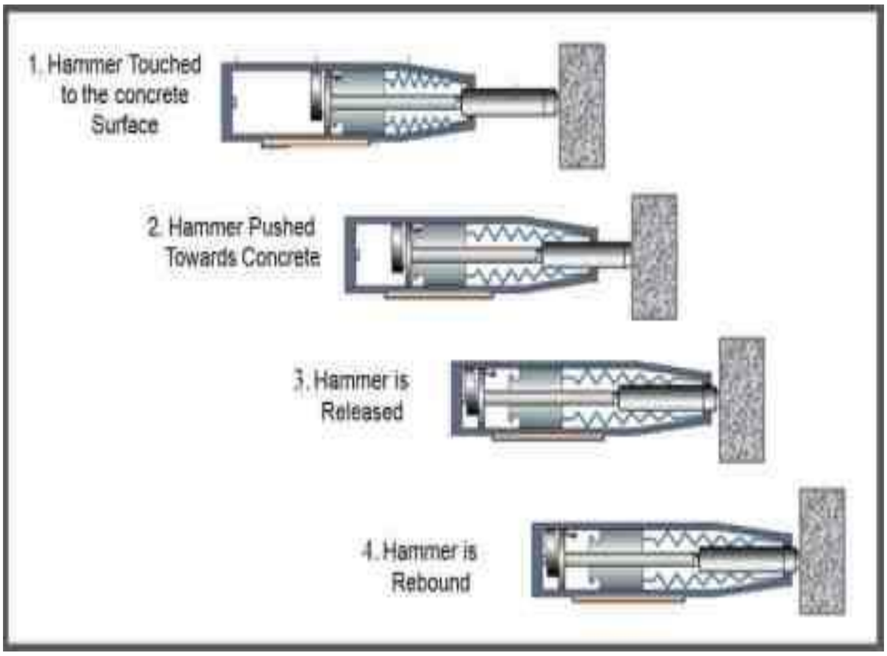


Fig. 3.9. Positions of Rebound Hammer on Concrete Structure (Szilagyi, 2011).

The rebound hammer (RH) test was performed according to ASTM C805 standards. The test was started with a careful selection and preparation of the test sample surface. For each sample, at least five measurements were taken, and the average was used to calculate the RN. High strength and high stiffness concrete absorbs less energy, leading to a greater rebound value and a higher RN (Szilagyi et al. 2011).

To perform rebound hammer test over cylinder top surface, the rebound hammer was applied to cylinder surface five times. Hammering was done at a perpendicular direction with respect to cylinder top surface. Average rebound hammer was considered to calculate the strength of concrete. **Fig. 3.10** shows the

Rebound Hammer Test Performance overCylinder and **Fig. 3.11** shows the Rebound Hammer Test Performance overCore Cylinder.

Fig. 3.10: Rebound Hammer Test Performed overCylinder

Fig. 3.11: Rebound Hammer Test Performed overCore Cylinder

3.9.2 ULTRASONIC PULSE VELOCITY TEST

The UPV Test calculates how long it takes for an ultrasonic pulse to travel through concrete. Ultrasonic Pulse Velocity Test is performed on concrete to test the quality of concrete by passing ultrasonic pulse velocity through it. High UPV Test and reduced time of travel indicate good quality of concrete. homogeneity, homogeneity, uniformity, etc.An electro-acoustical transducer produces the ultrasonic pulse. The pulse undergoes several reflections at the boundaries of the various material phases in the concrete when it is produced there by a transducer.

3.9.2.1 ULTRASONIC PULSE VELOCITY (UPV) TEST PROCESS

- Ultrasonic Pulse Velocity (UPV) test process that was performed in the laboratory is given below;
- Probe were placed at different distance to measure the travelling time of ultra-sonic pulse between transmitting transducer and receiving transducer.
- The test was performed on cylinder at 7, 28,90 days age and core at 90 days.
- Pulse travel time and pattern were seen in the display. Pulse travel time is displayed as in micro-second.
- ASTM C597 was used to conduct the ultrasonic pulse velocity (UPV) test. The UPV test can be performed in three different ways: direct, semi-direct, and indirect, with the direct approach being the most accurate (Ali, 2008) and was used in this work. However, applying a direct method in the field is unfeasible, so an indirect method is used instead. This test determines the amount of time it takes for an ultrasonic vibration pulse to go through a concrete specimen of known dimensions. As a result, the pulse velocity is determined and reported. The homogeneity, quality, and strength of testing specimens can be estimated based on the velocity obtained. The

fluctuation of wave speed indicates the change of dynamic modulus of elasticity and the density of the material (Ali, 2008). On each specimen, UPV tests were performed three times and the average values were recorded and reported. All of the cylinders were anchored against movement, and all of the tests were performed on the center of the cylinders' surfaces.**Fig. 3.12** shows the Ultrasonic Pulse Velocity (UPV) Test Performance over Cylinder and **Fig. 3.13** shows the Ultrasonic Pulse Velocity (UPV) Test Performance over Core Cylinder**.**

Fig. 3.12: Ultrasonic Pulse Velocity (UPV) Test Performed overCylinder

Fig. 3.13: Ultrasonic Pulse Velocity (UPV) Test Performed overCore Cylinder

3.9.3 CORE TEST

A core that needs to be tested for strength cannot be taken out of a structure until the concrete has hardened enough to make removal possible without damaging the link between the mortar and coarse aggregate. The concrete typically needs to be 14 days old before the samples are removed. For drilling cores, it is preferable that the concrete be 28 days old.

Typically, a core is cut using a rotary cutting tool and diamond bits. The portable concrete core drilling machine weighs a lot and needs to be supported and braced against the concrete in order to prevent relative movement that could lead to a cracked or distorted core. Water is also required to lubricate the cutter. For cores up to 75 mm in diameter, handheld equipment is available. If the ends of the cores do not fulfill the requirements for planeness and perpendicularity, they must be sawed, ground, or capped in accordance with normal practice.

3.9.3.1 Capping

Cores should be capped with high alumina cement mortar or a sulfur-sand mixture to give parallel end surfaces normal to the axis of the core, unless their ends are prepared by grinding. Other materials shouldn't be utilized because it has been demonstrated that they produce inaccurate outcomes. However, if the core is manually trimmed, caps may be as thick as the maximum aggregate size at their thickest point. Caps should be kept as thin as feasible. The cap must be extremely thin, ideally 1.5 to 3 mm. The capping material cannot be any weaker than the specimen's concrete.

3.9.3.2 Diameter and Length of Core

The diameter to maximum aggregate size ratio must be at least 3. It is well known that the compressive strength of cores with a 50 mm diameter is somewhat lower and more variable than that of cores with a 100 mm diameter. Testing error for cores with a diameter of 50 mm was roughly twice as much as testing error for cores with a diameter of 150 mm. Results from smaller cores tended to be more inconsistent.

The optimum length of the capped or ground specimen is between 1.9 and 2.1 times the diameter, per ASTM:C-42. The length of the core is to be reduced so that the ratio of the capped or ground specimen is between 1.9 and 2.1 if the ratio of the core's length to diameter (L/D) is more than 2.1. Corrections to the measured compressive strength are necessary for core specimens with L/D ratios of 1.75 or less. For L/D ratios higher than 1.75, no strength correction factor is needed. A core that is less than 95% of its diameter before capping, less than its diameter after capping, or less than its diameter after end grinding, cannot be tested.

3.9.3.3 Measurement of Core

Specimens that are capped or ground should have an average length that may be calculated to determine the L/D ratio before testing. Its average diameter is determined by averaging two measurements made at equal distances from one another at the specimen's mid-height.

3.9.3.4 Determination of the Core Density

The density is calculated by weighing the core before capping but after grinding it, then dividing the result by the core's volume, which is determined by its average diameter and length.

3.9.3.5 Testing of Core

The core must soak in water between 24 and 30 °C for 48 hours prior to testing. Carefully center the core on the machine's lower platen without applying shock, then gradually increase the load at a constant rate between 0.2 and 0.4 N/(mm^2/s) until no further load can be tolerated. Take note of any odd failures as well as the concrete's appearance. By dividing the highest load by the cross-sectional area, which is derived from the average diameter, one can determine the compressive strength of each core. The findings are translated to the nearest 0.5 N/mm^2 units.

3.9.3.6CORE SAMPLE COLLECTION PROCESS

The procedure of core sample collection process is given below:

- Core samples were taken after concrete was strong enough to permit sample removal without disturbing the bond between the mortar and coarse aggregate. The core cutting process is shown in **Fig. 3.14**.

Fig. 3.14: Core Cutting Process

- Cut surfaces didn't display erosion of the mortar and the exposed coarse aggregate particles was firmly embedded in the mortar.**Fig. 3.15** shows the finishing performance to the Surface of Core Cutting andthe finishing Surface of Core Cutting.

Fig. 3.15: Finishing the Surface of Core Cutting

- Cores were taken perpendicular to surface and not near formed joints or obvious edges of a concrete placement.
- A continuous flow of water was passed through the bottom of the core cutter. It helped to maintain an adequate temperature for core cutter because of producing excess heat during core cutting performance. If water doesn’t flow through the core cutter, the excessive heat generation will responsible to breakdown the core mold.
- Cores were taken near the middle of the concrete cylinder.**Fig. 3.16** shows core samples after core cutting.
- Adequately the core cutting machine wasn’t bolted with object from which the core was being drilled out. Otherwise, it will damage the core sample due to drilling.

Fig. 3.16: Core Sample after Core Cutting Performed

3.9.4 COMPRESSIVE STRENGTH TEST

Compressive strength of concrete is the capacity of a material or structure to support weights placed upon it without cracking or deflecting. When a material is compressed, its size tends to be reduced while in tension, size elongates. The compressive strength test performance is shown in **Fig. 3.17**.

Fig. 3.17: Specimen underCompressive Strength Testing Machine

One of the elements that regulates the loads that can be applied to a concrete structure is the concrete's compressive strength. As a result, it is crucial to test the compressive strength of a representative sample of concrete cylinders made from the same batches of concrete that were used to build the structure for every significant structure. The modulus of rupture is also significant for some structures, such as concrete pavements. The compressive strength test performance of Concrete Cylinder is shown in **Fig. 3.18**. Some cylinder samples are shown in **Fig. 3.19**.

Fig. 3.18: Compressive Strength Test Performance of Concrete Cylinder

The compressive strength test performance of Concrete Core Cylinder is shown in **Fig. 3.20**. When the test is properly conducted, a maximum load is obtained at the point at which the sample ruptures.

Fig. 3.19: Cast Concrete Cylinders for Test Purpose

Fig. 3.20: Compressive Strength Test Performed of Core Concrete Cylinder

The compressive strength was tested according to ASTM C39. As shown in **Table 3.8**, the compressive tests were completed at different test ages. The specimens were taken from the water tank and dried.

After that, the specimen was place within the testing machine directly under the spherically seated bearing block. The spherically seated bearing block was then lowered to the surface of the test specimen. Load was applied gradually at an incremental rate. The compressive load was applied until the load indicator showed that the load was decreasing steadily and the specimen shows a well-defined fracture pattern. When the pattern was formed, the machine was stopped and the load was recorded.

Table 3.8: Required tests of specimensat different ages

Test Procedure	Sample Dimensions	Test Day	Sample Nos.
Slump Test	Slump Cone	0	10
Compressive Strength	Cylinder (150mm dia × 300 mm Height) Core 100mm dia	7, 28, 90 7, 28, 90	90 90
Rebound Hammer	Cylinder (150mm dia × 300 mm Height) Core 100mm dia	7, 28, 90 7, 28, 90	90 90
UPV Analysis	Cylinder (150mm dia × 300 mm Height) Core 100mm dia	7, 28, 90 7, 28, 90	90 90

After completion of all NDTs, the compressive strengths of all specimens were determined destructively in accordance with ASTM C39. The cylinders were loaded till the failure in a compression machine and the maximum compressive strength of each concrete cylinder was recorded. The in-house data for this study is made up of a combination of UPV, RH, and compressive test results.

Chapter 4: RESULTSAND DISCUSSIONS

4.1 GENERAL

In this chapter, all results that are obtained from laboratory test and their analysis are represented. This chapter contains the cylinder strength results, core cylinder strength results, Rebound Hammer (RH) test results, ultrasonic pulse velocity (UPV) test results with qualitative grading and strength prediction from correlation for cylinder compressive strength results with RH test results, UPV test results and core cylinder compressive strength respectively. The test results are presented in both graphical and tabular form. The strength tables are given in Appendices.

4.2 CYLINDER STRENGTH OF CONCRETE

Cylinder compressive strength of concrete which was obtained by destructive test is shown in Appendices. **Table C.1**shows the strength results at 7 days curing, Table C.2 shows the strength results at 28 days curing and **Table C.3**shows the strength results at 90 days curing. Three cylinders for each mix had been tested by compressive strength testing machine. At the same day, RH and NDT tests were performed before compressive strength test.**Fig 4.1** shows the graphical presentation for compressive strength of different grades of concrete at different ages.

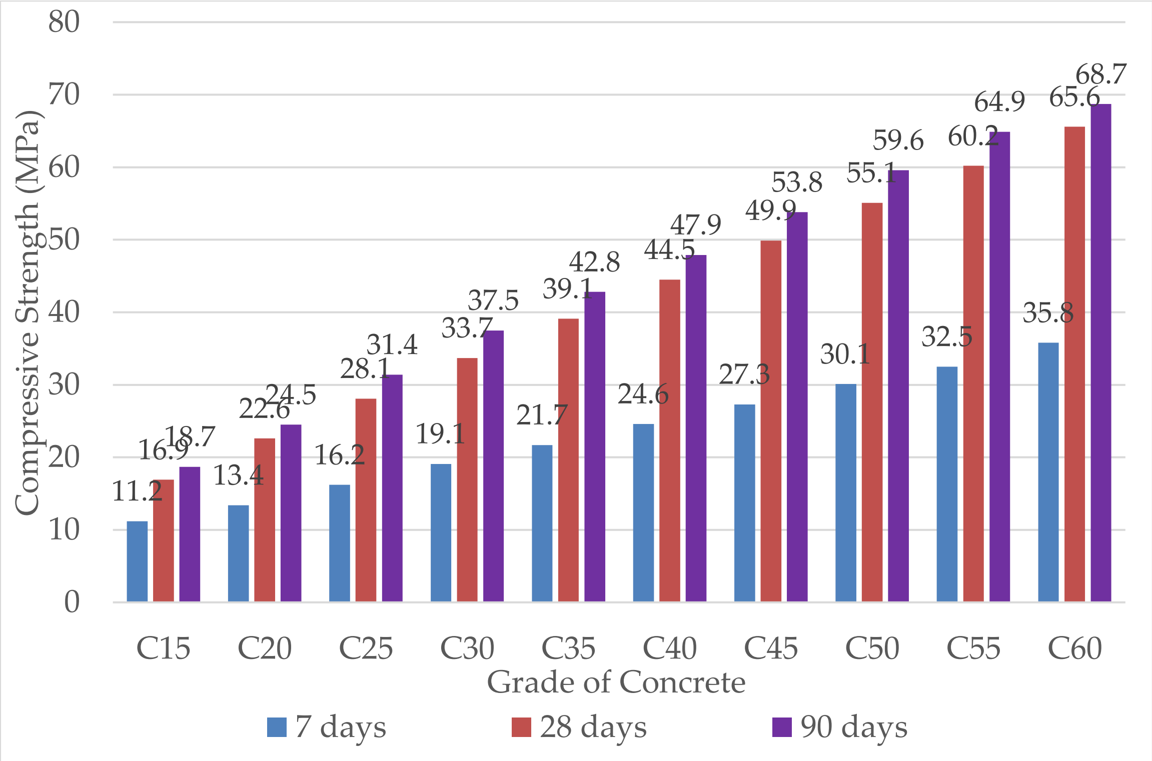


Fig. 4.1: Compressive Strength of Cylinder for different grade of Concrete at 7, 28, and 90 days curing.

4.3 CORE CYLINDER STRENGTH OF CONCRETE

The compressive strength of cores which were drilled from concrete cylinder is shown in Appendices. **Table C.4**shows the strength results at 7 days curing, **Table C.5**shows the strength results at 28 days curing and Table C.6 shows the strength results at 90 days curing. The strength results are also presented in **Fig. 4.2**. Same as cylinder, at the same day, RH and NDT testsand the compressive strength of drilled core cylinder had been tested in compressive strength testing machine.

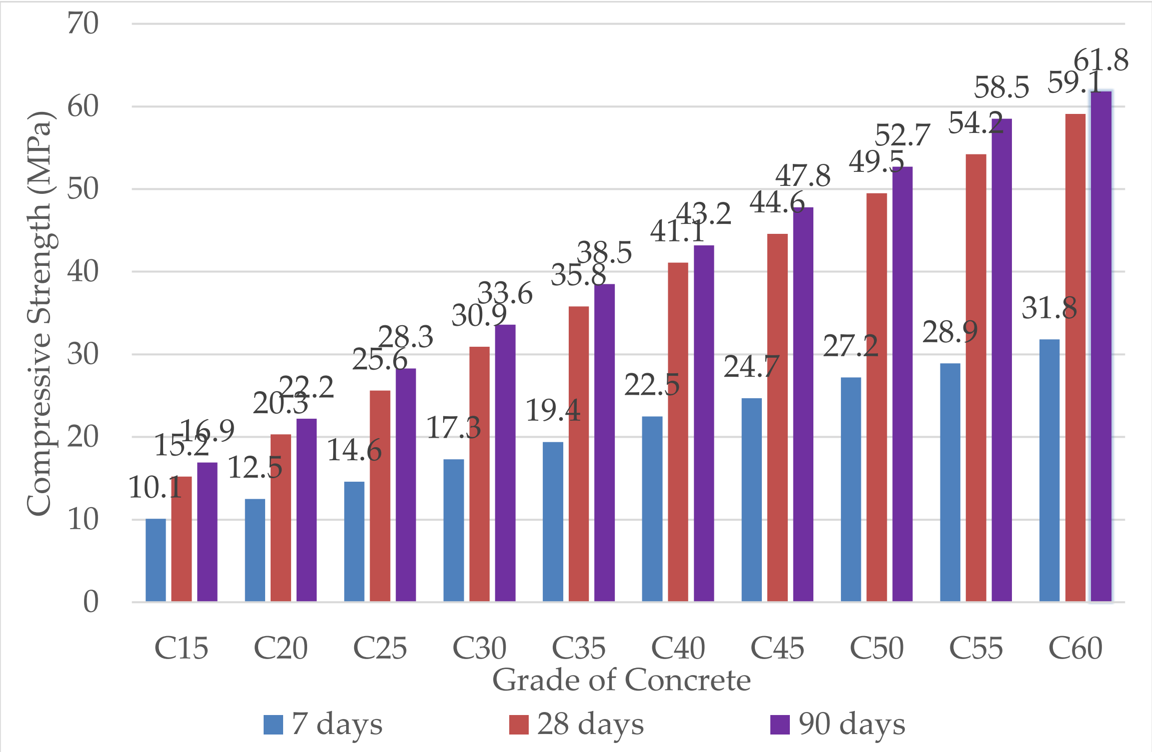


Fig. 4.2: Compressive Strength of Core Cylinder for different grade of Concrete at 7, 28, and 90 days curing.

4.4 REBOUND HAMMER (RH) TESTWITH QUALITATIVE GRADING

As discussed before, the rebound hammer test indicates the near surface properties of concrete. The surface texture affects the rebound values, with smooth hard-troweled surface gives higher values than rough-textured surfaces. **Table A.1-A.6** shows the concrete quality predicted by rebound hammer number for different grade of concrete. **Fig. 4.3** and **Fig. 4.4**shows the graphical presentation for RH strength of different grades of concrete at different ages. RH test were performed after 7 days, 28 days and 90 days age of concrete cylinder and concrete core cylinder. For each grade of concrete cylinder, the rebound number and compressive strength are shown in **Table A.1** at 7 days curing, **Table A.2** at 28 days curing and **Table A.3** at 90 days of curing. Moreover,for each grade of concrete core cylinder, the rebound number and compressive strength are shown in **Table A.4** at 7 days curing, **Table A.5** at 28 days curing and **Table A.6** at 90 days of curing. The rebound number at 7 days shows the concrete quality varied from poor to good for C15 to C60 grade of Concrete accordingly for both cylinder and core cylinder. The rebound number at 28 days and 90 days shows the concrete quality varied from delaminated to excellent for C15 to C60 grade of Concrete accordingly for both cylinder and core cylinder.

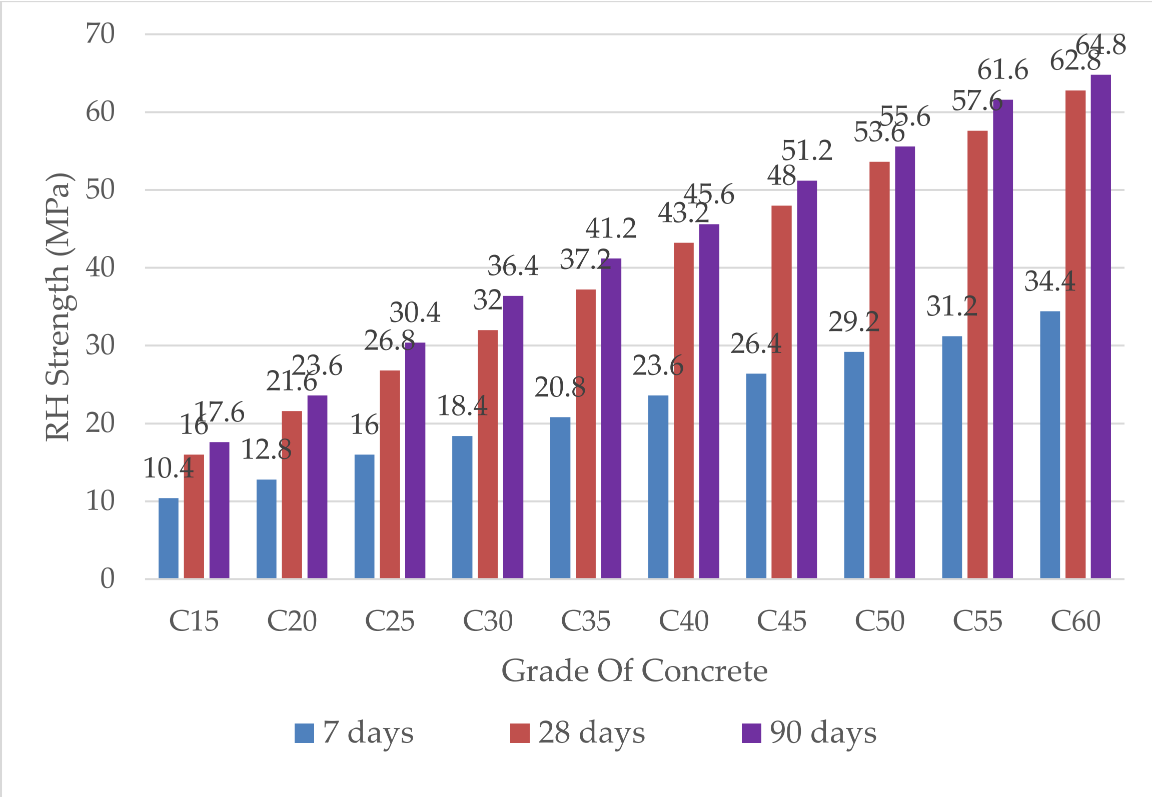


Fig. 4.3: Rebound Hammer Strength of Cylinder for different grade of Concrete at 7, 28, and 90 days curing.

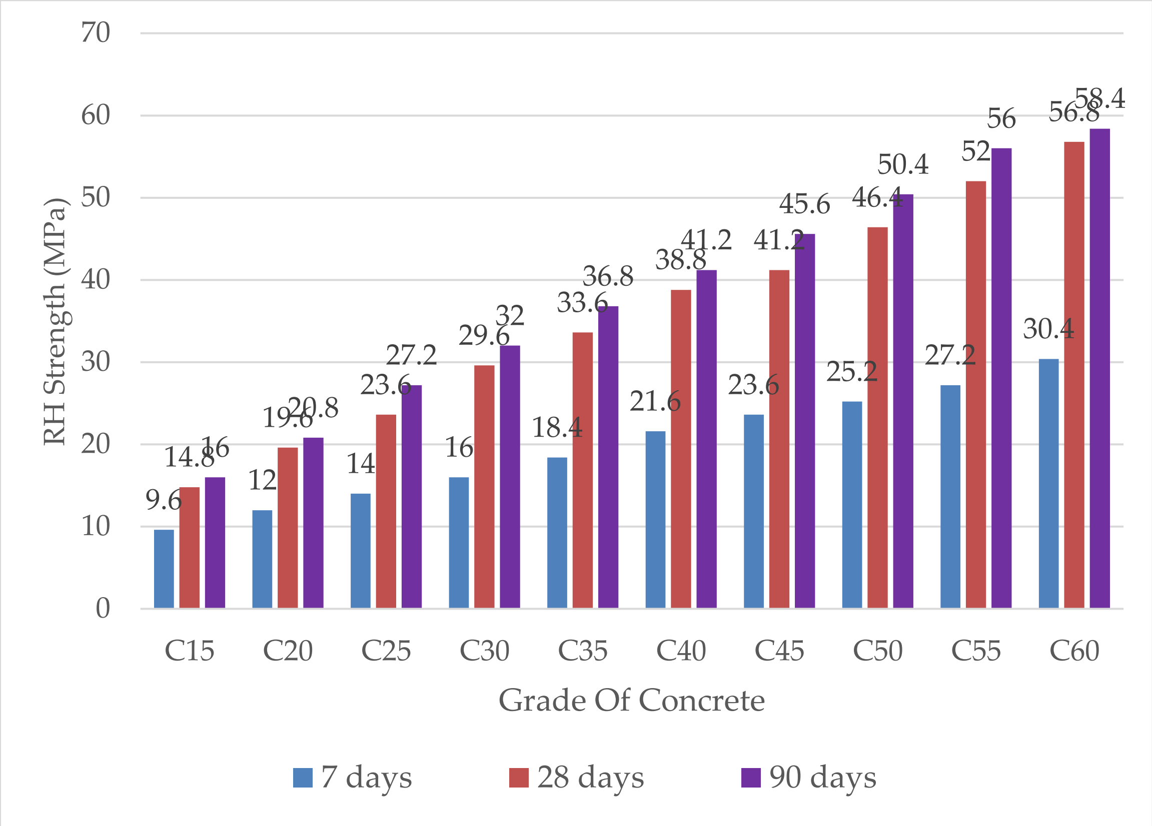


Fig. 4.4: Rebound Hammer Strength of Core Cylinder for different grade of Concrete at 7, 28, and 90 days curing.

4.5 UPV TEST WITH QUALITATIVE GRADING

Ultrasonic Pulse Velocity test performances were performed after 7 days, 28 days and 90 days age of concrete cylinder. For each grade of concrete cylinder, the values are shown in **Table B.1** at 7 days curing, **Table B.2** at 28 days curing and **Table B.3** at 90 days of curing. Moreover,for each grade of concrete core cylinder, the UPV test results are shown in **Table B.4** at 7 days curing, **Table B.5** at 28 days curing and **Table B.6** at 90 days of curing. Also, the UPV results of different grade of concrete cylinder and cores cylinder were presented in **Fig. 4.5** and **Fig. 4.6** respectively. The UPV test results show that the concrete quality varied from very good to excellent for both cylinder and core cylinder.

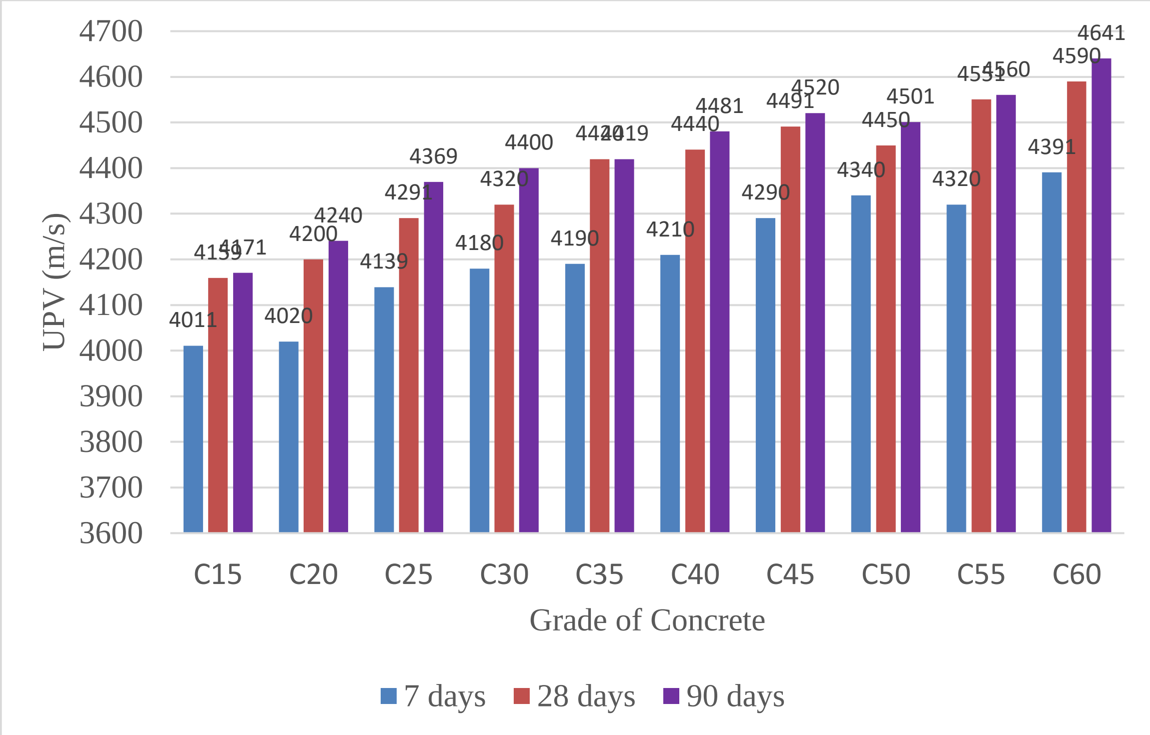


Fig. 4.5: UPV of Cylinder for different grade of Concrete at 7, 28 and 90 days curing.

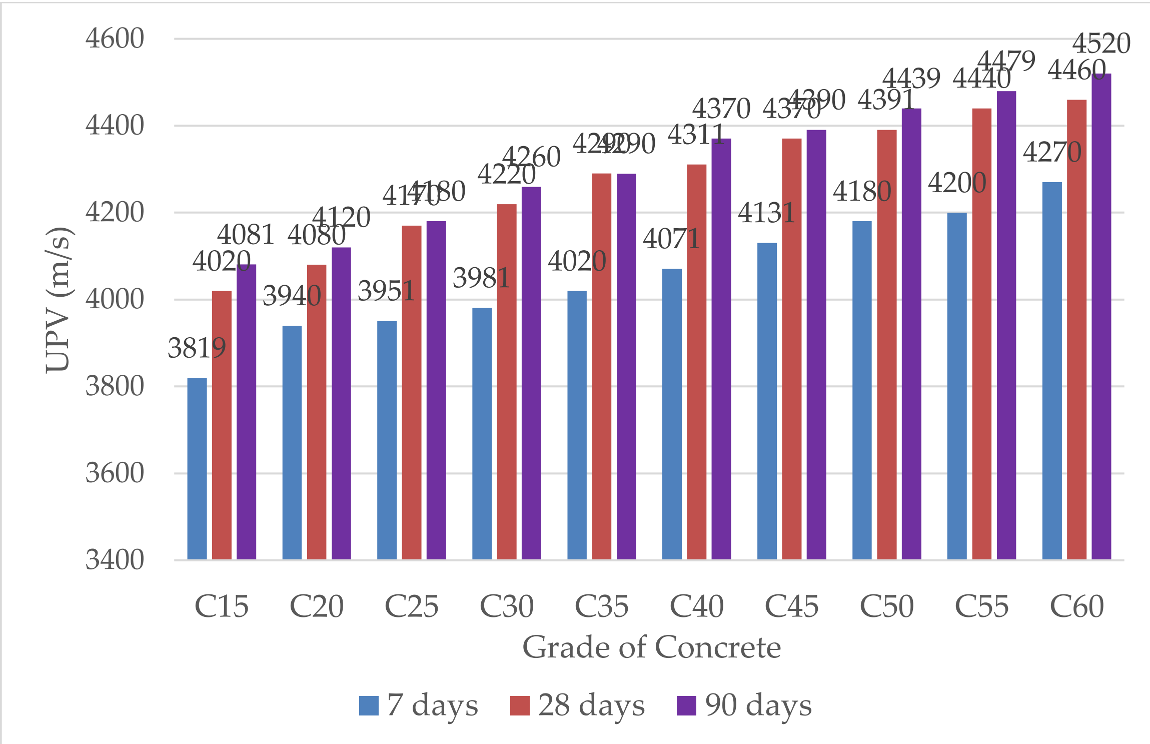


Fig. 4.6: UPV of core cylinder for different grade of Concrete at 7, 28 and 90 days curing.

4.6 GRAPHICAL REPRESENTATION

4.6.1 Correlation Between Concrete Compressive Strength and Rebound Hammer Strength

Fig. 4.7 shows the relation between concrete compressive strength and rebound hammer strength. It has been seen that the data after plotting shows a linear relation between compressive strength and rebound hammer strength for cylinder at 7, 28 and 90 days curing. The equation, **y = 0.9495x + 0.2679** is obtained from the graph. The R-squared value is **0.9993** when it is straight line. **Fig. 4.8** shows the linear relation between concrete compressive strength and rebound hammer strength for core cylinder at 7, 28 and 90 days curing. The equation, **y = 0.9523x - 0.0936** is obtained from the graph. The R-squared value is **0.9992** when it is also straight line.

Where "x" is the compressive strength of the concrete cylinder or core

"y" is the rebound hammer strength of the concrete cylinder or core

R^2 is the correlation coefficient

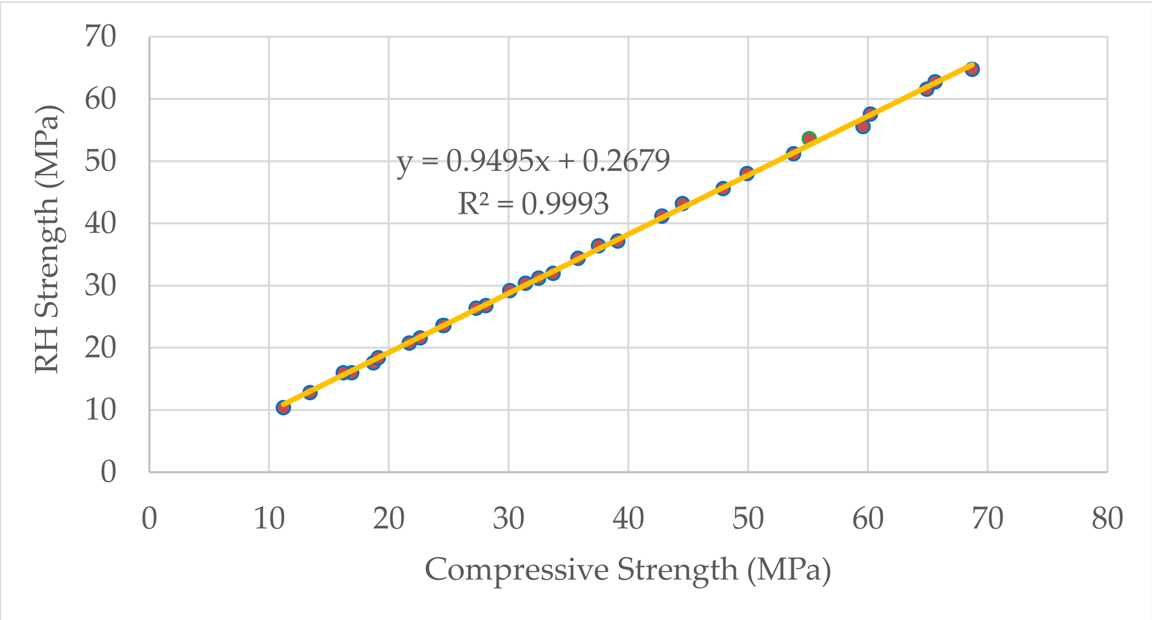


Fig. 4.7: Linear relation between Compressive strength and Hammer Strength for cylinder at 7, 28 and 90 days curing.

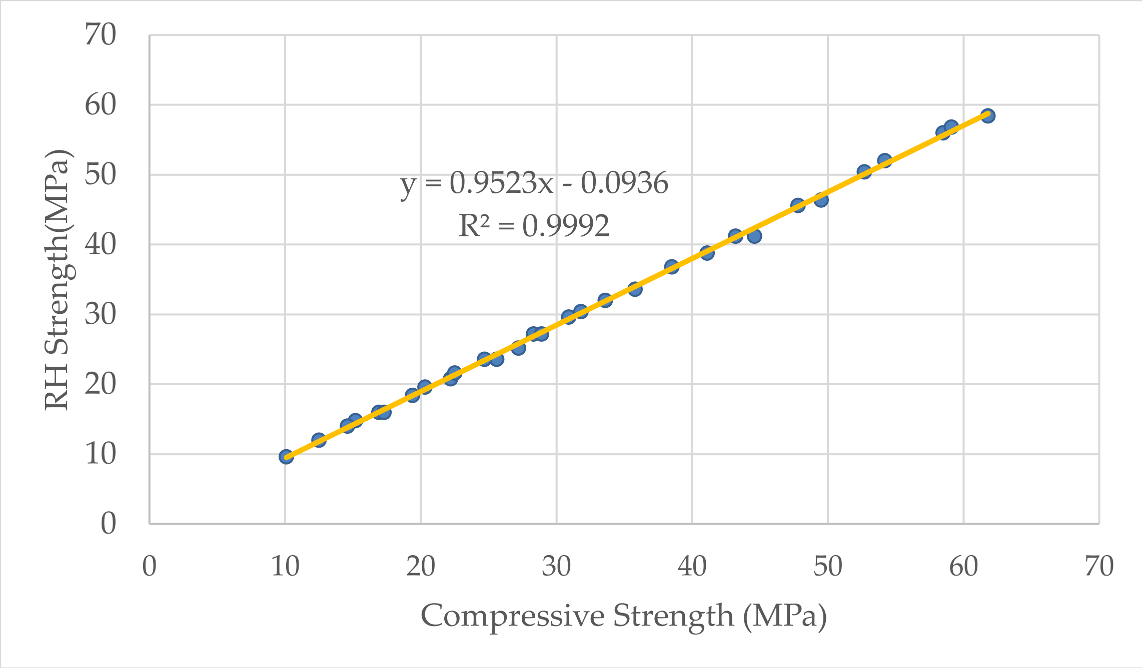


Fig. 4.8: Linear relation between Compressive strength and Hammer Strength for core cylinder at 7, 28 and 90 days curing.

The regression value indicates an acceptable relationship between compressive strength and rebound hammer strength of the concrete cylinder or core. It indicates that 99.93% data of the regression model fits actual observationsfor cylinder and 99.92% data of the regression model fits actual observations for core.

An exponential relation between compressive strength and rebound hammer strength for cylinder and core cylinder are not shown because a linear relation between compressive strength and rebound hammer strength for cylinder and core cylinder are best fit to predict the strength.

4.6.2 Correlation Between Concrete Compressive Strength and Ultrasonic Pulse Velocity

The relation between concrete compressive strength and ultrasonic pulse velocity is shown in **Fig. 4.9**. It has been seen that the data after plotting shows a linear relation between compressive strength and ultrasonic pulse velocity for cylinder at 7,28 and 90 days curing. The equation, **y = 9.436x + 3998.3** is obtained from the graph. The R-squared value is **0.9325** when it is straight line. **Fig. 4.10** shows the linear relation between concrete compressive strength and ultrasonic pulse velocity for core cylinder at 7, 28 and 90 days curing. The equation, **y = 11.71x + 3828.8** is obtained from the graph. The R-squared value is **0.9482** when it is also straight line.

Where "x" is the compressive strength of the concrete cylinder or core

"y" is the UPV of the concrete cylinder or core

R^2 is the correlation coefficient

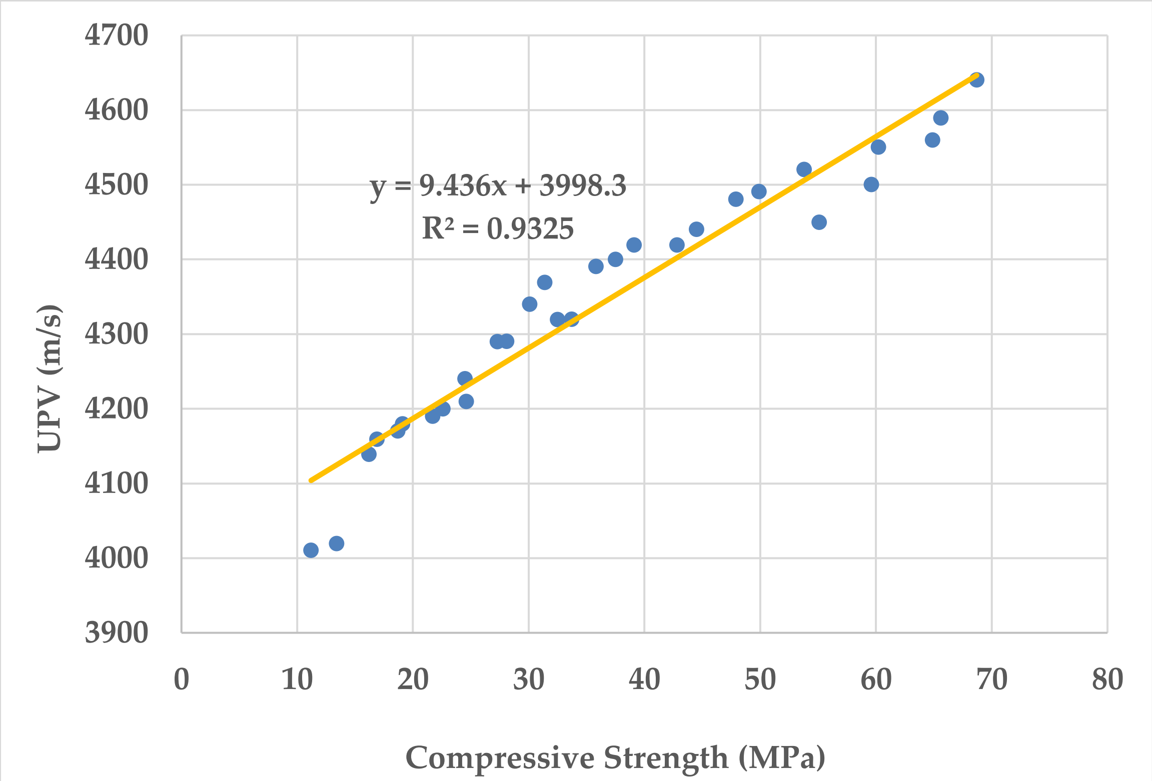


Fig. 4.9: Linear relation between Compressive strength and UPV for cylinder at 7, 28 and 90 days curing.

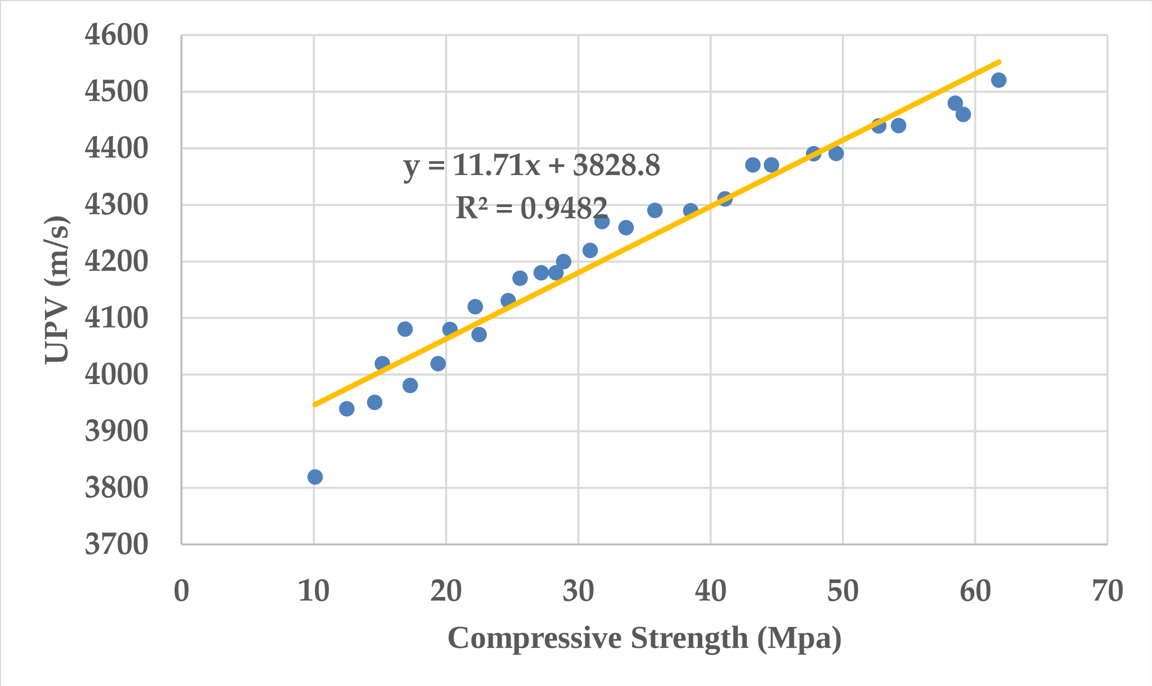


Fig. 4.10: Linear relation between Compressive strength and UPV for core cylinder at 7, 28 and 90 days curing.

The regression value indicates an acceptable relationship between compressive strength and UPV of the concrete cylinder or core. It indicates that 93.25% data of the regression model fits actual observations for cylinder and 94.82% data of the regression model fits actual observations for core.

An exponential relation between compressive strength and ultrasonic pulse velocity for cylinder and core cylinder are not shown because a linear relation between compressive strength and ultrasonic pulse velocity for cylinder and core cylinder are best fit to predict the strength.

4.6.3 Correlation Between Ultrasonic Pulse Velocity and Rebound Hammer Strength

An exponential relation between ultrasonic pulse velocity and rebound hammer strength for cylinder at 7, 28 and 90 days curing is shown in **Fig. 4.11**. It is found that the R-squared value is **0.957**. The equation, $\mathbf{y = 7E\text{-}05e^{0.003x}}$ is obtained from the graph. **Fig. 4.12** shows an exponential relation between ultrasonic pulse velocity and rebound hammer strength for core cylinder at 7, 28 and 90 days curing. The equation, $\mathbf{y = 0.0003e^{0.0027x}}$ is obtained from the graph. The R-squared value reduce to **0.9813**.

Where "x" is the UPV of the concrete cylinder or core

"y" is the Rebound Hammer strength of the concrete cylinder or core

R^2 is the correlation coefficient

The regression value indicates an acceptable relationship between UPV and Rebound Hammer strength of the concrete cylinder or core. It indicates that 95.7% data of the regression model fits actual observations for cylinder and 98.13% data of the regression model fits actual observations for core.

An exponential relation between ultrasonic pulse velocity and rebound hammer strength for cylinder and core cylinder are best fit to predict the strength, that's why a linear relation between ultrasonic pulse velocity and rebound hammer strength for cylinder and core cylinder are not shown here.

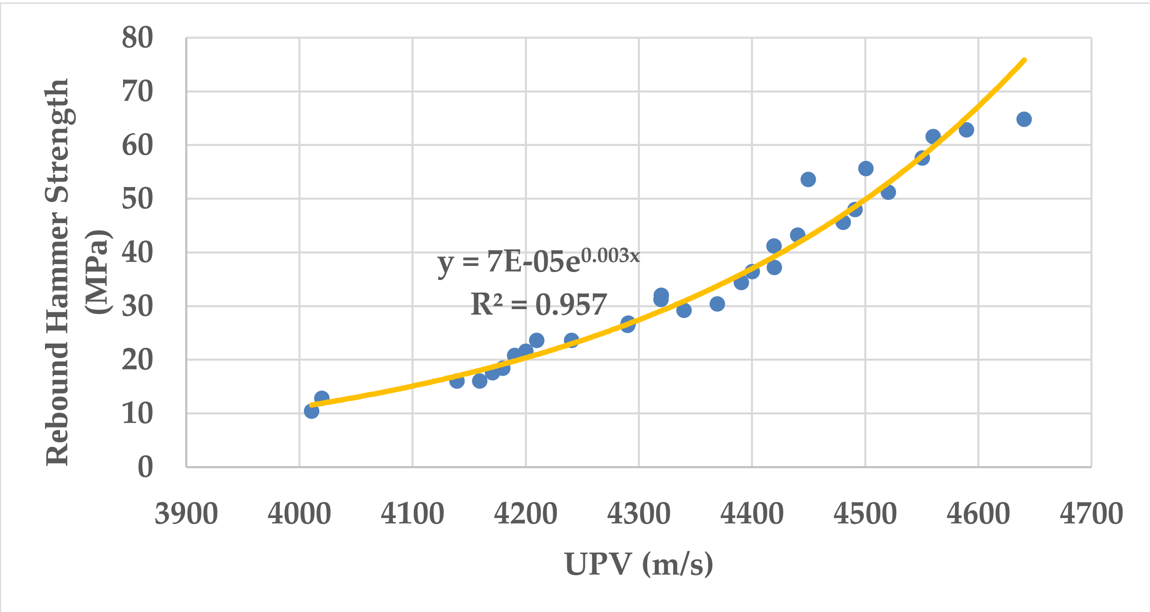


Fig. 4.11: Exponential relation between UPV and RH Strength for cylinder at 7, 28 and 90 days curing.

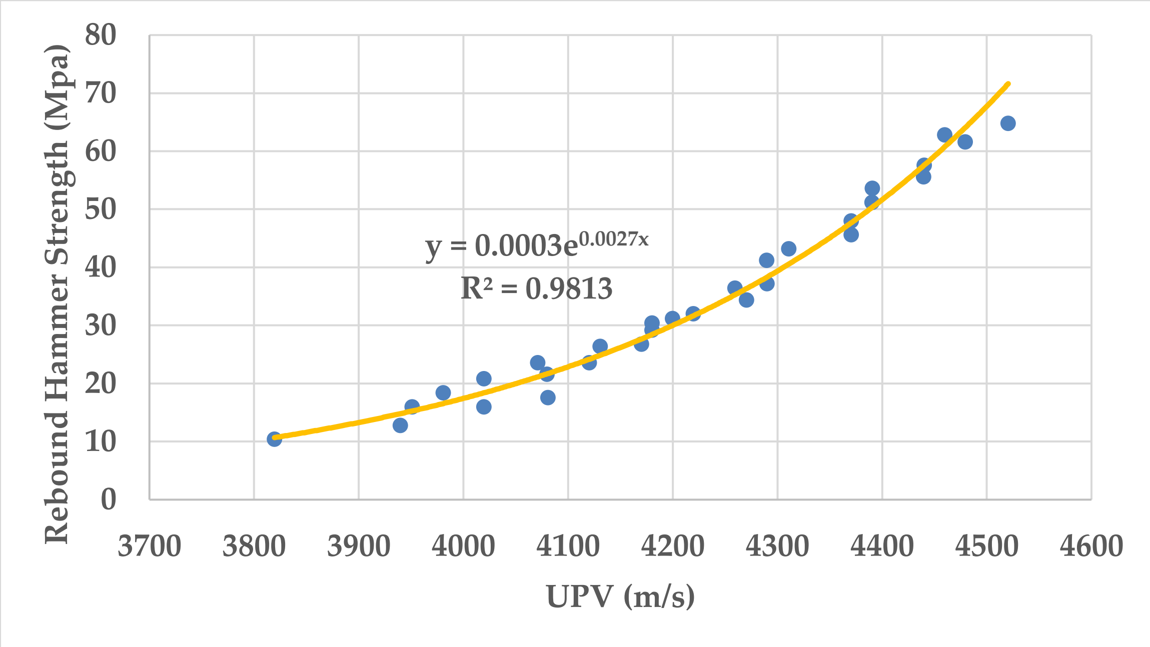


Fig. 4.12: Exponential relation between UPV and RH Strength for core cylinder at 7, 28 and 90 days curing.

4.6.4 Correlation Between Cylinder Compressive Strength and Core Cylinder Compressive Strength

The relation between cylinder compressive strength and core cylinder compressive strength is shown in **Fig. 4.13**. It has been seen that the data after plotting shows a linear relation between cylinder compressive strength and core cylinder compressive strength at 7, 28 and 90 days curing. The equation, **y = 0.8945x + 0.239** is obtained from the graph. The R-squared value is **0.9994** when it is straight line.

Where "x" is the compressive strength of the concrete core cylinder

"y" is the compressive strength of the concrete cylinder

R^2 is the correlation coefficient

The regression value indicates an acceptable relationship between cylinder compressive strength and core cylinder compressive strength of concrete. It indicates that 99.94% data of the regression model fits actual observations.

An exponential relation between cylinder compressive strength and core compressive strength are not shown because a linear relation between cylinder compressive strength and core compressive strength are best fit to predict the strength.

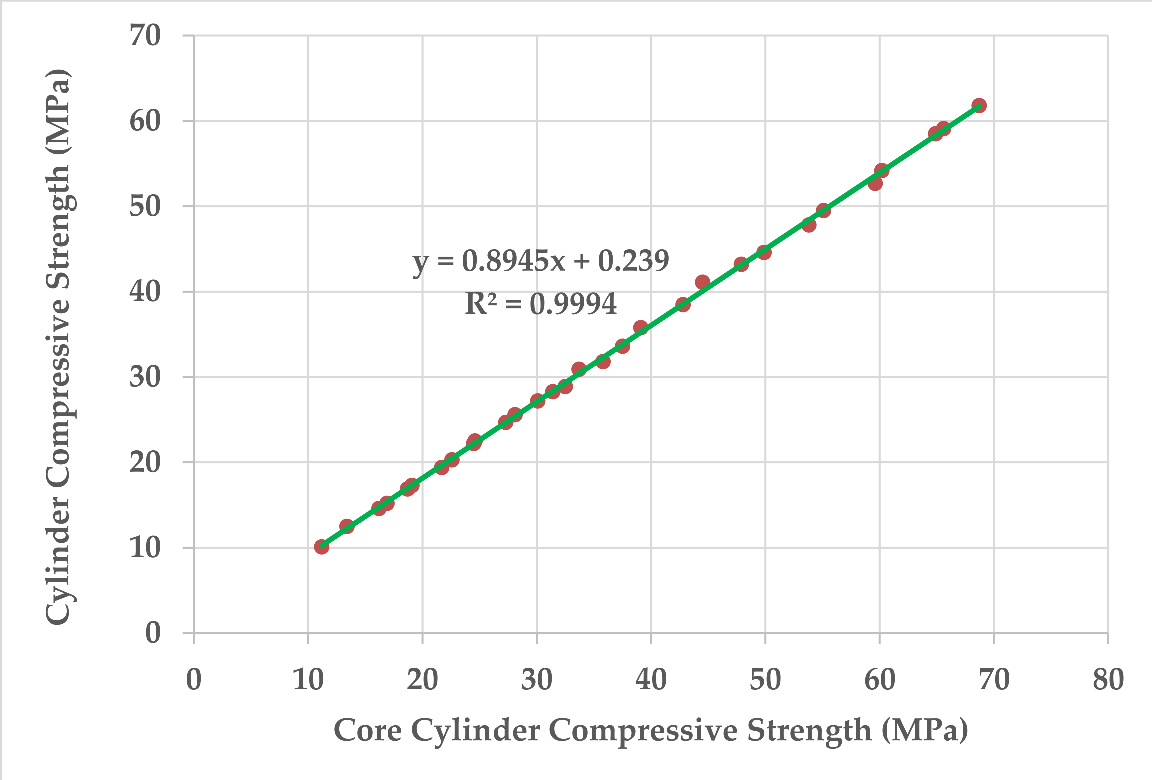


Fig. 4.13: Linear relation between Cylinder Compressive Strength and Core Cylinder Compressive Strength at 7, 28 and 90 days curing.

Chapter 5: CONCLUSIONS

5.1 GENERAL

This study based on the UPV and RH values to predict the strength of the concrete; it was not necessary to know anything about the composition of the concrete or its history. The goal was to align models for in-situ predictions of strength of existing structures. The use of UPV, RN or core test based on a single test result, according to a rigorous statistical study using threefold cross-validation and application to independent data are reliable. These non-destructive methods are employed in a variety of sectors, including the manufacturing, aerospace, and civil infrastructure industries. In this study, correlations are proposed for the prediction of concrete strength based on this fact. On independent data, the proposed correlations underwent testing and displayed very high predicted accuracy. These correlations aremore appropriate to on-site inspections, very convenient, fast and with a reasonable cost. Once the correlations are established between the compressive strength values of samples derived from mechanical tests and measurements from non-destructive techniques (the rebound hammer and ultrasonic pulse velocity), the prediction of concrete strength value becomes more reliable.The strength of concrete cylinder in this study varied from 15 to 60 MPa at curing ages of 7, 28 and 90 days, which represent medium to high strength concrete.

Mix design were prepared considering target strength for different grade of concrete from C15 (22MPa) to C60 (71MPa), but compressive strength of concrete for different grade of concrete were found 3% to 11% lower than the target strength. The variation of strength results occurred from the variation of properties of ingredients and lack of control of accuracy in batching, mixing, placing, curing and testing. The higher grade of concrete was achieved by lowering the water-cement ratio. Moreover, in the same water-cement ratio, a liner mix gives better strength. So, a non-liner mix with low water contents might be causes of this variation of strength.

5.2 CONCLUSIONS

Based on the limited no of test results and variable studied, the following conclusions are drawn:

- The rebound number at 7 days shows the concrete quality varied from poor to good for C15 to C60 grade concrete for both cylinder and core cylinder. However, the corresponding rebound numbers at 28 and 90 days show the concrete quality varied from delaminated to excellent for C15 to C60 grade concrete.
- The UPV test results shows that the concrete quality varied from very good to excellent for both cylinder and core cylinder.
- It is found that the strength obtained from rebound hammer and core cutting specimen is well comparable with cylinder crushing strength. RH strength is found lower than the cylinder compressive strength for all grade of concrete by an amount of about 3% to 8%. Whereas, Core strength is found lower than the cylinder compressive strength for all grade of concrete by an amount of about 8% to 11%.
- Based on the analysis of laboratory test results at 7, 28 and 90 days curing, compressive strength may be predicted at any age of concrete to know about the composition of the concrete or its history by applying the following formula:

    (i) Linear expressions are obtained torepresentthe relationship betweenconcrete compressive strength and rebound hammer strength asfollows:

    For Cylinder, $\mathbf{y = 0.9495x + 0.2679}$ R^2 = **0.9993**

For Core, $y = 0.9523x - 0.0936$ $R^2 = 0.9992$

Where "x" is the compressive strength of the concrete cylinder or core

"y" is the RH strength of the concrete cylinder or core

R^2 is the correlation coefficient

(ii) Linear expressions are obtained torepresentthe relationship betweenconcrete compressive strength and ultrasonic pulse velocity asfollows:

For Cylinder, $y = 9.436x + 3998.3$ $R^2 = 0.9325$

For Core Cylinder, $y = 11.71x + 3828.8$ $R^2 = 0.9482$

Where "x" is the compressive strength of the concrete cylinder or core

"y" is the UPV of the concrete cylinder or core

R^2 is the correlation coefficient

(iii) Exponential expressions are obtained torepresentthe relationship betweenultrasonic pulse velocity and rebound hammer strength forasfollows:

For Cylinder, $y = 7E\text{-}05e^{0.003x}$ $R^2 = 0.957$

For Core Cylinder, $y = 0.0003e^{0.0027x}$ $R^2 = 0.9813$

Where "x" is the UPV of the concrete cylinder or core

"y" is the RH strength of the concrete cylinder or core

R^2 is the correlation coefficient

(iv) Linear expressions are obtained torepresentthe relationship betweencylinder compressive strength and core cylinder compressive strength forasfollows:

$y = 0.8945x + 0.239$ $R^2 = 0.9994$

Where "x" is the compressive strength of the concrete core cylinder

"y" is the compressive strength of the concrete cylinder

R2 is the correlation coefficient

(v) The regression values for all the equations indicate an acceptable relationship between cylinder compressive strength (DT) and NDT strength of concrete.

5.3 RECOMMENDATIONS FOR FURTHER STUDIES

In this study, the relation obtained among the NDT and DT test results was for medium to high strength concrete only. The following additional study could be conducted in this regard:

- Other non-destructive tests such as windsor probe penetration test, pull-out and pull-off resistance tests, instrumented hammers and modal analysis, embedded wireless sensors etc. can be correlated with this study to establish good relations among the strength found by different testing methods.
- Test includes higher strengths are required to establish good relations among the strength found by different testing methods.
- Non-destructive tests for in-situ inspection of different types of structure can be performed.
- Impact of Non-destructive testing can be studied in details for 4th industrial revolution.
- The combination of two or more methods can be applied to improve the effectiveness of such study.
- The reliability and confidence level of non-destructive tests can be studied in the field of composite material testing.
- Increased number of test sample cylinders is suggested for better correlation of both rebound hammer test, UPV and compressive strength test values.
- Cubes may be used as test sample to correlate with this study for better correlation of both rebound hammer test results, UPV results and compressive strength test values.
- Similar studies can be performed with higher age of concrete specimen to predict the strength behaviour of the existing structures.

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Appendices

Appendix A: Rebound Hammer Test Results

Table A.1: Cylinder Rebound Hammer Test results for 7 days curing of different grade of concrete cylinder

Sl. No.	Sample Designation	7 days Curing		
		Hammer Value	Avg. Hammer Value	Hammer Strength (Cylinder) (MPa)
1	C15	23.2	22.5	10.4
		23.3		
		21.5		
		23.3		
		21.2		
2	C20	24	24.5	12.8
		24.5		
		24.3		
		25		
		24.7		
3	C25	28	27	16
		26		
		26.5		
		27.5		
		27		
4	C30	29.5	29	18.4
		30		
		27.5		
		30.2		
		27.8		
5	C35	33	31	20.8
		30		
		30.5		
		28		
		33.5		
6	C40	35	33	23.6
		36		
		32.5		
		30		
		31.5		
7	C45	34.3	35	26.4
		36.7		
		36.4		
		35		
		32.6		
8	C50	36.2	37	29.2
		39.1		
		38.5		
		33.3		
		37.9		
9	C55	35.9	38.5	31.2
		42.1		
		41.5		
		38.4		
		34.6		
10	C60	42.8	40.5	34.4
		39.6		
		36.8		
		37.8		
		45.5		

Table A.2: Cylinder Rebound Hammer Test results for 28 days curing of different grade of concrete cylinder

Sl. No.	Sample Designation	28 days Curing		
		Hammer Value	**Avg. Hammer Value**	**Hammer Strength (Cylinder) (MPa)**
1	C15	28	27	16
		26		
		26.5		
		27.5		
		27		
2	C20	31.6	31.5	21.6
		33		
		32.5		
		29.3		
		31.1		
3	C25	34.7	35.5	26.8
		36.9		
		36.4		
		36.6		
		32.9		
4	C30	35.9	39	32
		42.7		
		41.5		
		40.3		
		34.6		
5	C35	42.8	42.5	37.2
		43.7		
		40.9		
		39.6		
		45.5		
6	C40	50.7	46.5	43.2
		47.4		
		49.1		
		43.8		
		41.5		
7	C45	47.9	49.5	48
		51.6		
		53.1		
		47.3		
		47.6		
8	C50	52.8	53	53.6
		51.6		
		55.3		
		54.1		
		51.2		
9	C55	52	55	57.6
		57.9		
		58.8		
		53		
		53.3		
10	C60	55.7	60	62.8
		63.4		
		63.3		
		62.5		
		55.1		

Table A.3: Cylinder Rebound Hammer Test results for 90 days curing of different grade of concrete cylinder

Sl. No.	Sample Designation	90 days Curing		
		Hammer Value	Avg. Hammer Value	Hammer Strength (Cylinder) (MPa)
1	C15	29.5 30 25 30.2 27.8	28.5	17.6
2	C20	35.5 35.2 32.5 30.3 31.5	33	23.6
3	C25	35.9 37.7 41.5 40.3 34.6	38	30.4
4	C30	42.8 43.7 40.9 39.6 43	42	36.4
5	C35	42.7 47.4 49.1 43.8 42	45	41.2
6	C40	47.9 50.8 48.5 47.3 45.5	48	45.6
7	C45	52.8 51.6 52 52.3 48.8	51.5	51.2
8	C50	49.5 57.9 58.8 53 53.3	54.5	55.6
9	C55	55.7 60.4 63.3 60.5 55.1	59	61.6
10	C60	65.8 62.7 65.4 67.1 69	66	64.8

Table A.4: Core Cylinder Rebound Hammer Test results for 7 days curing of different grade of concrete core cylinder

Sl. No.	Sample Designation	7 days Curing		
		Hammer Value	Avg. Hammer Value	Hammer Strength (Cylinder) (MPa)
1	C15	18.2 23.3 21.5 23.3 21.2	21.5	9.6
2	C20	24 24.5 24.3 20 24.7	23.5	12
3	C25	26.8 24.5 27.3 23.6 25.3	25.5	14
4	C30	27.7 26.3 26.5 27.2 27.3	27	16
5	C35	29.5 28.5 29 30.2 27.8	29	18.4
6	C40	34.3 30.6 30.9 28.2 33.5	31.5	21.6
7	C45	35.8 35.2 32.5 30.3 31.2	33	23.6
8	C50	35.8 36.2 34.5 32.3 31.2	34	25.2
9	C55	34.5 37.7 36.3 35.4 33.6	35.5	27.2
10	C60	35.2 42.1 41 38.2 33.5	38	30.4

Table A.5: Core Cylinder Rebound Hammer Test results for 28 days curing of different grade of concrete core cylinder

Sl. No.	Sample Designation	28 days Curing		
		Hammer Value	Avg. Hammer Value	Hammer Strength (Cylinder) (MPa)
1	C15	27.8	26	14.8
		25.5		
		28.3		
		23.6		
		24.8		
2	C20	29.5	30	19.6
		28.5		
		32.9		
		31.3		
		27.8		
3	C25	35.8	33	23.6
		35.2		
		32.5		
		30.3		
		31.2		
4	C30	35.2	37.5	29.6
		42.1		
		38.6		
		38.2		
		33.4		
5	C35	39.2	40	33.6
		42.5		
		42.7		
		38.1		
		37.5		
6	C40	41.2	43.5	38.8
		42.5		
		45.7		
		45.6		
		42.5		
7	C45	43.5	45	41.2
		42		
		45.5		
		45.6		
		48.4		
8	C50	46.9	48.5	46.4
		47.9		
		45.6		
		50.8		
		51.3		
9	C55	49.5	52	52
		50.4		
		55.6		
		53.2		
		51.3		
10	C60	56.5	55	56.8
		56.4		
		55.6		
		53.8		
		52.7		

Table A.6: Core Cylinder Rebound Hammer Test results for 90 days curing of different grade of concrete core cylinder

Sl. No.	Sample Designation	90 days Curing		
		Hammer Value	Avg. Hammer Value	Hammer Strength (Cylinder) (MPa)
1	C15	27.6	27	16
		26.4		
		26.5		
		27.1		
		27.4		
2	C20	34.1	31	20.8
		30.6		
		30.7		
		28.2		
		31.4		
3	C25	34.7	35.5	27.2
		37.5		
		36.3		
		35.7		
		33.3		
4	C30	37.2	39	32
		42.5		
		40.7		
		38.1		
		36.5		
5	C35	41.2	42	36.8
		42.5		
		45.7		
		38.1		
		42.5		
6	C40	43	45	41.2
		42.5		
		45.4		
		45.6		
		48.5		
7	C45	46.9	48	45.6
		47.7		
		45.2		
		48.8		
		51.4		
8	C50	48.5	51	50.4
		48.9		
		55.6		
		50.7		
		51.3		
9	C55	56.5	54.5	56
		55.4		
		55.1		
		53.3		
		52.2		
10	C60	56.5	57	58.4
		56.4		
		55.6		
		57.8		
		58.7		

Appendix B: Ultrasonic Pulse Velocity (UPV) Test Results

Table B.1: Cylinder UPV Test results for 7 days curing of different grade of concrete cylinder

Sl. No.	Sample Designation	7 days Curing		
		Time (μs)	UPV (m/s)	Average UPV (m/s)
1	C15	74.3	4037.69	4010.80
		75.2	3989.36	
		74.9	4005.34	
2	C20	74.8	4010.70	4019.87
		73.9	4059.54	
		75.2	3989.36	
3	C25	74	4054.05	4139.20
		70.9	4231.31	
		72.6	4132.23	
4	C30	71.8	4178.27	4179.85
		74.4	4032.26	
		69.3	4329.00	
5	C35	71.9	4172.46	4190.21
		72.1	4160.89	
		70.8	4237.29	
6	C40	71.2	4213.48	4209.81
		70.6	4249.29	
		72	4166.67	
7	C45	70.1	4279.60	4290.14
		70.6	4249.29	
		69.1	4341.53	
8	C50	69.2	4335.26	4340.05
		70.1	4279.60	
		68.1	4405.29	
9	C55	69.4	4322.77	4319.63
		70.8	4237.29	
		68.2	4398.83	
10	C60	68.7	4366.81	4390.57
		68.8	4360.47	
		67.5	4444.44	

Table B.2: Cylinder UPV Test results for 28 days curing of different grade of concrete cylinder

Sl. No.	Sample Designation	28 days Curing		
		Time (μs)	UPV (m/s)	Average UPV (m/s)
1	C15	72.2	4155.12	4159.40
		73	4109.59	
		71.2	4213.48	
2	C20	74.8	4010.70	4200.25
		69.5	4316.55	
		70.2	4273.50	
3	C25	71.3	4207.57	4290.62
		69.4	4322.77	
		69.1	4341.53	
4	C30	71.1	4219.41	4319.92
		69.1	4341.53	
		68.2	4398.83	
5	C35	69.6	4310.34	4419.67
		66.8	4491.02	
		67.3	4457.65	
6	C40	68.2	4398.83	4440.45
		66.7	4497.75	
		67.8	4424.78	
7	C45	65.5	4580.15	4490.96
		68.9	4354.14	
		66.1	4538.58	
8	C50	67.8	4424.78	4449.87
		69.5	4316.55	
		65.1	4608.29	
9	C55	66.9	4484.30	4550.62
		65.1	4608.29	
		65.8	4559.27	
10	C60	68.9	4354.14	4589.65
		64.9	4622.50	
		62.6	4792.33	

Table B.3: Cylinder UPV Test results for 90 days curing of different grade of concrete cylinder

Sl. No.	Sample Designation	90 days Curing		
		Time (μs)	UPV (m/s)	Average UPV (m/s)
1	C15	72.3	4149.38	4170.62
		72	4166.67	
		71.5	4195.80	
2	C20	69.2	4335.26	4240.50
		71	4225.35	
		72.1	4160.89	
3	C25	69.5	4316.55	4369.38
		68.7	4366.81	
		67.8	4424.78	
4	C30	67.8	4424.78	4400.13
		67	4477.61	
		69.8	4297.99	
5	C35	67.1	4470.94	4419.47
		69.5	4316.55	
		67.1	4470.94	
6	C40	66.4	4518.07	4480.73
		66.2	4531.72	
		68.3	4392.39	
7	C45	66.1	4538.58	4520.49
		66.9	4484.30	
		66.1	4538.58	
8	C50	69	4347.83	4500.60
		65	4615.38	
		66.1	4538.58	
9	C55	65.2	4601.23	4560.15
		65.1	4608.29	
		67.1	4470.94	
10	C60	66.1	4538.58	4640.62
		65.9	4552.35	
		62.1	4830.92	

Table B.4: Core Cylinder UPV Test results for 7 days curing of different grade of concrete core cylinder

Sl. No.	Sample Designation	7 days Curing		
		Time (μs)	UPV (m/s)	Average UPV (m/s)
1	C15	52.4	3816.79	3819.48
		50.1	3992.02	
		54.8	3649.64	
2	C20	50.8	3937.01	3939.62
		50.9	3929.27	
		50.6	3952.57	
3	C25	50.6	3952.57	3950.89
		51.6	3875.97	
		49.7	4024.14	
4	C30	50.5	3960.40	3980.75
		48.8	4098.36	
		51.5	3883.50	
5	C35	49.8	4016.06	4019.54
		50.6	3952.57	
		48.9	4089.98	
6	C40	49.2	4065.04	4070.86
		50.8	3937.01	
		47.5	4210.53	
7	C45	48.8	4098.36	4130.58
		47.3	4228.33	
		49.2	4065.04	
8	C50	47.9	4175.37	4180.08
		48.04	4163.20	
		47.6	4201.68	
9	C55	47.1	4246.28	4199.78
		47.1	4246.28	
		48.7	4106.78	
10	C60	46.1	4338.39	4270.31
		48.6	4115.23	
		45.9	4357.30	

Table B.5: Core Cylinder UPV Test results for 28 days curing of different grade of concrete core cylinder

Sl. No.	Sample Designation	28 days Curing		
		Time (μs)	UPV (m/s)	Average UPV (m/s)
1	C15	49.8	4016.06	4019.54
		50.6	3952.57	
		48.9	4089.98	
2	C20	49	4081.63	4079.88
		48.1	4158.00	
		50	4000.00	
3	C25	47	4255.32	4170.21
		47	4255.32	
		50	4000.00	
4	C30	47.6	4201.68	4219.65
		47.7	4192.87	
		46.9	4264.39	
5	C35	46.3	4319.65	4289.94
		47.7	4192.87	
		45.9	4357.30	
6	C40	46.2	4329.00	4310.72
		46	4347.83	
		47	4255.32	
7	C45	45.8	4366.81	4370.42
		46.3	4319.65	
		45.2	4424.78	
8	C50	45.6	4385.96	4390.73
		44.5	4494.38	
		46.6	4291.85	
9	C55	44.6	4484.30	4440.18
		46.5	4301.08	
		44.1	4535.15	
10	C60	44.5	4494.38	4459.73
		46.2	4329.00	
		43.9	4555.81	

Table B.6: Core Cylinder UPV Test results for 90 days curing of different grade of concrete core cylinder

Sl. No.	Sample Designation	90 days Curing		
		Time (μs)	UPV (m/s)	Average UPV (m/s)
1	C15	47.8	4184.10	4080.63
		49	4081.63	
		50.3	3976.14	
2	C20	48.6	4115.23	4120.18
		49.9	4008.02	
		47.2	4237.29	
3	C25	47.1	4246.28	4180.12
		49.3	4056.80	
		47.2	4237.29	
4	C30	47.3	4228.33	4259.50
		47.7	4192.87	
		45.9	4357.30	
5	C35	45.9	4357.30	4289.63
		47.5	4210.53	
		46.5	4301.08	
6	C40	47.4	4219.41	4370.37
		44.2	4524.89	
		45.8	4366.81	
7	C45	45.1	4434.59	4390.47
		44.1	4535.15	
		47.6	4201.68	
8	C50	44.1	4535.15	4439.50
		44.9	4454.34	
		46.2	4329.00	
9	C55	43.5	4597.70	4479.45
		45.7	4376.37	
		44.8	4464.29	
10	C60	43.1	4640.37	4520.49
		45.6	4385.96	
		44.1	4535.15	

Appendix C: Compressive Strength Test Results

Table C.1: Cylinder Compressive Strength results for 7 days curing of different grade of concrete cylinder

Sl. No.	Sample Designation	7 days Curing		
		Load (KN)	Strength (MPa)	Average Strength (MPa)
1	C15	195.3	11.047	11.200
		198	11.200	
		200.7	11.353	
2	C20	237	13.406	13.400
		239.2	13.531	
		234.5	13.265	
3	C25	286	16.178	16.200
		291.2	16.472	
		282	15.952	
4	C30	338	19.119	19.100
		336	19.006	
		339	19.176	
5	C35	384	21.721	21.700
		386.9	21.885	
		380	21.495	
6	C40	435	24.606	24.600
		440.7	24.928	
		429	24.267	
7	C45	483	27.321	27.300
		475.4	26.891	
		489.5	27.689	
8	C50	532	30.093	30.100
		539.2	30.500	
		525.2	29.708	
9	C55	575	32.525	32.500
		581.5	32.893	
		567.15	32.081	
10	C60	633	35.806	35.800
		628.7	35.563	
		637	36.032	

Table C.2: Cylinder Compressive Strength results for 28 days curing of different grade of concrete cylinder

Sl. No.	Sample Designation	28 days Curing		
		Load (KN)	Strength (MPa)	Average Strength (MPa)
1	C15	299	16.913	16.900
		304.5	17.224	
		292.8	16.562	
2	C20	400	22.626	22.600
		404.5	22.881	
		394.1	22.293	
3	C25	497	28.113	28.100
		493	27.887	
		500.3	28.300	
4	C30	599.3	33.900	33.700
		596	33.713	
		592	33.487	
5	C35	684.7	38.731	39.100
		698	39.483	
		691	39.087	
6	C40	787	44.517	44.500
		796.1	45.032	
		777	43.952	
7	C45	882.9	49.942	49.900
		882	49.891	
		881.6	49.868	
8	C50	976.25	55.222	55.100
		972	54.982	
		974	55.095	
9	C55	1064	60.186	60.200
		1054.3	59.637	
		1074.45	60.777	
10	C60	1150.1	65.056	65.600
		1160	65.616	
		1169.05	66.128	

Table C.3: Cylinder Compressive Strength results for 90 days curing of different grade of concrete cylinder

Sl. No.	Sample Designation	90 days Curing		
		Load (KN)	Strength (MPa)	Average Strength (MPa)
1	C15	335	18.949	18.700
		328.7	18.593	
		328.05	18.556	
2	C20	434.4	24.572	24.500
		438	24.776	
		427	24.154	
3	C25	552.6	31.258	31.400
		560.5	31.705	
		552.2	31.236	
4	C30	669.55	37.874	37.500
		657.8	37.209	
		661.5	37.418	
5	C35	750.8	42.469	42.800
		760.15	42.998	
		759	42.933	
6	C40	840.8	47.560	47.900
		852.1	48.200	
		847.5	47.939	
7	C45	960.5	54.331	53.800
		945.5	53.483	
		947.3	53.585	
8	C50	1054	59.620	59.600
		1050.5	59.422	
		1056.45	59.759	
9	C55	1141	64.541	64.900
		1150	65.051	
		1151	65.107	
10	C60	1218.4	68.920	68.700
		1200.15	67.887	
		1225	69.293	

Table C.4: Core Cylinder Compressive Strength results for 7 days curing of different grade of concrete core cylinder

Sl. No.	Sample Designation	7 days Curing		
		Load (KN)	Strength (MPa)	Average Strength (MPa)
1	C15	80	10.182	10.100
		76.07	9.682	
		82	10.436	
2	C20	93.2	11.862	12.500
		99.4	12.651	
		102.05	12.988	
3	C25	114.15	14.528	14.600
		114	14.509	
		116	14.764	
4	C30	136.4	17.360	17.300
		140.08	17.828	
		131.3	16.711	
5	C35	157	19.982	19.400
		146.28	18.617	
		154	19.600	
6	C40	177.6	22.604	22.500
		171.5	21.827	
		181.26	23.069	
7	C45	188.2	23.953	24.700
		198.02	25.203	
		196	24.945	
8	C50	214.15	27.255	27.200
		209.5	26.664	
		217.5	27.682	
9	C55	227.02	28.893	28.900
		225.2	28.662	
		229	29.145	
10	C60	249.8	31.793	31.800
		250.36	31.864	
		249.4	31.742	

Table C.5: Core Cylinder Compressive Strength results for 28 days curing of different grade of concrete core cylinder

Sl. No.	Sample Designation	28 days Curing		
		Load (KN)	Strength (MPa)	Average Strength (MPa)
1	C15	120.48	15.334	15.200
		122.6	15.604	
		115.2	14.662	
2	C20	158.5	20.173	20.300
		161	20.491	
		159	20.236	
3	C25	204	25.964	25.600
		204.02	25.966	
		195.4	24.869	
4	C30	242.3	30.838	30.900
		246.06	31.317	
		240	30.545	
5	C35	279.1	35.522	35.800
		281.66	35.848	
		283.1	36.031	
6	C40	320.18	40.750	41.100
		323.5	41.173	
		325.1	41.376	
7	C45	352.68	44.887	44.600
		347.8	44.265	
		350.8	44.647	
8	C50	384.6	48.949	49.500
		388	49.382	
		394.18	50.168	
9	C55	421.48	53.643	54.200
		430.1	54.740	
		426	54.218	
10	C60	458.06	58.299	59.100
		465	59.182	
		470	59.818	

Table C.6: Core Cylinder Compressive Strength results for 90 days curing of different grade of concrete core cylinder

Sl. No.	Sample Designation	90 days Curing		
		Load (KN)	Strength (MPa)	Average Strength (MPa)
1	C15	133	16.927	16.900
		135.35	17.226	
		130	16.545	
2	C20	175	22.273	22.200
		178.1	22.667	
		170.18	21.659	
3	C25	220	28.000	28.300
		222.05	28.261	
		225.02	28.639	
4	C30	264	33.600	33.600
		260.3	33.129	
		267.7	34.071	
5	C35	307	39.073	38.500
		305.2	38.844	
		295.3	37.584	
6	C40	341.48	43.461	43.200
		340.3	43.311	
		336.5	42.827	
7	C45	376.02	47.857	47.800
		370.5	47.155	
		380.2	48.389	
8	C50	416	52.945	52.700
		414.02	52.693	
		412.2	52.462	
9	C55	451	57.400	58.500
		467.5	59.500	
		460.42	58.599	
10	C60	486.1	61.867	61.800
		480.11	61.105	
		490.5	62.427	

Appendix D: Summary of Test Results

Table D.1: Summary of Cylinder test results for 7 days curing of different grade of concrete cylinder

Sl. No.	Sample Designation	7 days Curing		
		Compressive Strength (MPa)	Hammer Strength (Cylinder) (MPa)	UPV (m/s)
1	C15	11.2	10.4	4010
2	C20	13.4	12.8	4020
3	C25	16.2	16	4140
4	C30	19.1	18.4	4180
5	C35	21.7	20.8	4190
6	C40	24.6	23.6	4210
7	C45	27.3	26.4	4280
8	C50	30.1	29.2	4330
9	C55	32.5	31.2	4320
10	C60	35.8	34.4	4390

Table D.2: Summary of Cylinder test results for 28 days curing of different grade of concrete cylinder

Sl. No.	Sample Designation	28 days Curing		
		Compressive Strength (MPa)	Hammer Strength (Cylinder) (MPa)	UPV (m/s)
1	C15	16.9	16	4160
2	C20	22.6	21.6	4200
3	C25	28.1	26.8	4290
4	C30	33.7	32	4320
5	C35	39.1	37.2	4420
6	C40	44.5	43.2	4440
7	C45	49.9	48	4490
8	C50	55.1	53.6	4510
9	C55	60.2	57.6	4540
10	C60	65.6	62.8	4590

Table D.3: Summary of Cylinder test results for 90 days curing of different grade of concrete cylinder

Sl. No.	Sample Designation	90 days Curing		
		Compressive Strength (MPa)	Hammer Strength (Cylinder) (MPa)	UPV (m/s)
1	C15	18.7	17.6	4170
2	C20	24.5	23.6	4240
3	C25	31.4	30.4	4370
4	C30	37.5	36.4	4400
5	C35	42.8	41.2	4430
6	C40	47.9	45.6	4480
7	C45	53.8	51.2	4520
8	C50	59.6	55.6	4510
9	C55	64.9	61.6	4560
10	C60	68.7	64.8	4640

Table D.4: Summary of Core Cylinder test results for 7 days curing of different grade of concrete core cylinder

Sl. No.	Sample Designation	7 days Curing		
		Compressive Strength (MPa)	Hammer Strength (Core Cylinder) (MPa)	UPV (m/s)
1	C15	10.1	9.6	3820
2	C20	12.5	12	3940
3	C25	14.6	14	3960
4	C30	17.3	16	3990
5	C35	19.4	18.4	4020
6	C40	22.5	21.6	4060
7	C45	24.7	23.6	4130
8	C50	27.2	25.2	4190
9	C55	28.9	27.2	4210
10	C60	31.8	30.4	4270

Table D.5: Summary of Core Cylinder test results for 28 days curing of different grade of concrete core cylinder

Sl. No.	Sample Designation	28 days Curing		
		Compressive Strength (MPa)	Hammer Strength (Core Cylinder) (MPa)	UPV (m/s)
1	C15	15.2	14.8	4020
2	C20	20.3	19.6	4080
3	C25	25.6	23.6	4170
4	C30	30.9	29.6	4220
5	C35	35.8	33.6	4290
6	C40	41.1	38.8	4320
7	C45	44.6	41.2	4360
8	C50	49.5	46.4	4390
9	C55	54.2	52	4440
10	C60	59.1	56.8	4470

Table D.6: Summary of Core Cylinder test results for 90 days curing of different grade of concrete core cylinder

Sl. No.	Sample Designation	90 days Curing		
		Compressive Strength (MPa)	Hammer Strength (Core Cylinder) (MPa)	UPV (m/s)
1	C15	16.9	16	4080
2	C20	22.2	20.8	4120
3	C25	28.3	27.2	4190
4	C30	33.6	32	4250
5	C35	38.5	36.8	4300
6	C40	43.2	41.2	4360
7	C45	47.8	45.6	4390
8	C50	52.7	50.4	4450
9	C55	58.5	56	4490
10	C60	61.8	58.4	4520