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Advanced Analysis of Concrete Compressive Strength: Combining NDT Techniques with Digital Image Processing

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Abstract
Concrete is a fundamental material in civil engineering, widely used for its durability, versatility, and load-bearing capacity in infrastructure and building projects. The compressive strength of concrete is crucial as it directly impacts structural integrity, longevity, and safety. This study investigates the compressive strength of M50 grade concrete through a comprehensive approach that combines non-destructive and destructive testing techniques. Methods employed include the Rebound Hammer (RBH) test, Ultrasonic Pulse Velocity (UPV) test, Digital Image Processing (DIP), and conventional destructive testing. The integration of these techniques aims to provide accurate and reliable estimates of compressive strength, critical for evaluating concrete quality in structural applications. Specifically, this research compares the non-destructive techniques (RBH, SonReb Method, and DIP) against standard destructive testing results across different curing ages. Findings reveal a strong correlation between DIP and destructive testing, suggesting that image-based processing can serve as an effective non-destructive alternative in compressive strength assessment. The comprehensive analysis of M50 grade concrete presented in this study offers valuable insights for researchers and practitioners seeking enhanced, non-invasive methods for concrete strength evaluation.
Keywords: *Concrete, Digital Image Processing Method, Rebound Hammer Test, SonReb Method, Ultrasonic Pulse Velocity*

1. Introduction
Concrete is a cornerstone of modern civil engineering, serving as the primary material for constructing durable and resilient infrastructure. Its versatility, strength, and cost-effectiveness make it the material of choice for a vast range of structures, from residential buildings to highways, bridges, and large-scale dams. The performance of concrete in these structures, especially in terms of its ability to withstand compressive forces, is vital to ensuring long-term stability and safety. As infrastructure demands grow, the need to assess and assure the quality of concrete has become increasingly critical, particularly in high-strength applications. One of the most significant indicators of concrete quality is its compressive strength, which reflects its capacity to resist compressive loads without cracking or failing. This property not only influences the structural integrity of buildings but also determines their durability under various environmental and load conditions. Accurate and reliable measurement of compressive strength is therefore essential in both quality control during construction and in evaluating existing structures. Traditionally, destructive testing methods have been the standard for compressive strength measurement, providing highly accurate results but requiring the physical destruction of the test samples. This process can be labor-intensive and costly, particularly when frequent testing is needed.

To overcome these limitations, non-destructive testing (NDT) methods have been developed as effective alternatives [1,6]. Techniques such as the Rebound Hammer (RBH) test and Ultrasonic Pulse Velocity (UPV) test offer rapid, in-situ evaluation of concrete strength without damaging the material [2,9,10]. Additionally, advances in Digital Image Processing (DIP) provide new possibilities for assessing concrete characteristics based on visual data, offering the potential for even more accurate,

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non-invasive measurements [3,4]. Integrating these NDT techniques alongside traditional destructive tests allows for a comprehensive analysis of concrete strength, which can benefit researchers and industry professionals alike by delivering both precision and practicality [5]. In this study, M50 grade concrete was selected for its application in high-strength structural projects. By applying a combination of RBH, SonReb, DIP, and conventional destructive testing to M50 concrete, this work aims to deliver a detailed understanding of the material's compressive strength at various stages of curing. This approach not only validates the effectiveness of individual methods but also evaluates their combined potential to deliver robust, reliable strength assessments [13,14].

2. Methodology

2.1. Rebound Hammer (RBH) Method

The Rebound Hammer (RBH) method, also known as the Schmidt hammer test, measures the surface hardness of concrete to estimate its compressive strength. In this method, a spring-driven hammer impacts the concrete surface, and the rebound distance of the hammer is recorded as the rebound number and the apparatus is shown in the Figure 1. This rebound number correlates to the surface hardness, which can be used to estimate compressive strength through calibration curves. Although the RBH method is quick and non-invasive, it has limitations; results can be affected by surface moisture, texture, and carbonation, leading to potential inaccuracies. Additionally, it primarily assesses only the surface layer, which may not fully represent the core strength of the concrete.
Figure 1 Shows Schmidt's Rebound Hammer.

Figure 1 Schmidt's Rebound Hammer

2.2. SonReb (Sonic-Rebound) Method

SonReb Method is the combination of RBH and UPV Tests. The Ultrasonic Pulse Velocity (UPV) test assesses the quality of concrete by measuring the speed of ultrasonic waves passing through it. The apparatus of UPV is shown in Figure 2. Higher velocities typically indicate denser, more uniform material, suggesting good internal quality. However, UPV alone cannot directly determine compressive strength, as it primarily reflects material homogeneity rather than strength. To estimate compressive strength more accurately, UPV results are often combined with Rebound Hammer measurements through the SonReb method, which integrates surface hardness with internal quality for a more reliable strength estimation [6,9,10]. Figure 2 shows Ultrasonic Pulse Velocity Test Apparatus.

Figure 2 Ultrasonic Pulse Velocity Test Apparatus

2.3. Digital Image Processing (DIP) Method

The Digital Image Processing (DIP) method uses visual data from concrete images to analyze texture, color distribution, and surface features, which can correlate with material properties like compressive strength. Through algorithms and software tools, DIP evaluates surface characteristics to estimate strength without physical contact. This technique offers flexibility and precision, especially for quality control and in-situ applications. However, DIP's accuracy depends on factors like image quality, lighting conditions, and surface cleanliness. The method may also require extensive calibration and testing to develop reliable strength estimation models, particularly for different concrete grades and compositions.

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2.4.Destructive Test

The conventional destructive test is a standard method for directly determining the compressive strength of concrete by crushing standardized test specimens under controlled conditions. Typically performed on cube or cylinder samples, the test involves subjecting the specimen to axial compressive loads until failure occurs, with the maximum load recorded as the compressive strength. This method is widely regarded as the most accurate and reliable approach for strength measurement, serving as the benchmark for calibrating non-destructive techniques. However, it has limitations, including its destructive nature, which renders the sample unusable post-testing, and its inability to evaluate in-situ structures. Despite these drawbacks, CDT remains indispensable in validating and correlating results from non-destructive methods like RBH, UPV, and DIP.

3. Experimentation

3.1.Preparation of Specimen

The M50 grade concrete mix was designed following the guidelines of IS 10262:2009 [12] to achieve a target compressive strength of 50 MPa at 28 days. The design mix ratio used was 1:1.47:2.67 (cement: fine aggregate: coarse aggregate) with a water-cement ratio of 0.35. Concrete cube specimens of dimensions 150 × 150 × 150 mm were cast for testing. To enhance the workability and strength characteristics of the concrete, a high-range water-reducing admixture (superplasticizer) was incorporated into the mix at 1% of the cementitious content by weight. The concrete mix was thoroughly mixed, placed in the moulds, and compacted to ensure uniformity and minimize air voids before curing. The mix is placed in the moulds for day for hardening and later it is placed in the curing tank. After curing period, the samples were removed and made ready for testing.

3.2.RBH Method

Rebound Hammer (RBH) testing was performed in accordance with the guidelines specified in IS 13311 (Part 2): 1992 [8] to estimate the surface hardness and compressive strength of concrete. This non-destructive testing method involves striking the concrete surface with a spring-loaded hammer and measuring the rebound distance, which is recorded as the rebound number. Multiple readings were taken on the surfaces of the 150 × 150 × 150 mm cube specimens to reduce variability and ensure reliable results. The rebound numbers were then correlated with compressive strength using the calibration curves provided in the IS Code. Special attention was given to factors such as surface smoothness, moisture content, and carbonation depth to minimize potential inaccuracies. The RBH method provided a quick, in-situ estimation of compressive strength while preserving the integrity of the test specimens.

3.3.SonReb Method

The SonReb (Sonic-Rebound) method combines Ultrasonic Pulse Velocity (UPV) testing and Rebound Hammer (RBH) testing to provide a more accurate and reliable estimation of compressive strength by leveraging both internal quality and surface hardness of concrete. UPV testing, conducted as per IS 13311 (Part 1): 1992 [7], measures the time taken for ultrasonic waves to pass through the concrete specimen. Higher wave velocities indicate denser and more homogeneous material. RBH testing, as per IS 13311 (Part 2): 1992, measures the surface hardness of the specimen. By integrating the results from these two complementary methods, the SonReb method enhances the reliability of compressive strength predictions. The empirical formula used in this research work to estimate compressive strength through the SonReb method is [6]:

$$f_{ck} = 7.695 \times 10^{-11} \times (RN)^{1.4} \times (V)^{2.6} \quad (1)$$

$$f_{ck} = 1.2 \times 10^{-9} \times (RN)^{1.058} \times (V)^{2.446} \quad (2)$$

$$f_{ck} = 0.0286 \times (RN)^{1.246} \times (V)^{1.85} \quad (3)$$

f_{ck}=Compressive Strength of Concrete (N/mm^2)
RN = Rebound Number
V = Ultrasonic Pulse Velocity (in m/s)

This approach not only addresses the limitations of individual methods but also provides a comprehensive understanding of concrete quality, making it a robust tool for assessing compressive strength.

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3.4.Digital Image Processing

The test setup for Digital Image Processing (DIP) was meticulously arranged to ensure the acquisition of consistent and high-quality images of the concrete specimens. A high-resolution camera was used a fixed height and angle relative to the 150 × 150 × 150 mm concrete cubes. A uniformly lit environment was created using artificial lighting to eliminate shadows and reflections that could interfere with image analysis. The concrete specimens were cleaned to remove any dust or debris that might distort surface features. A neutral-colored background was used to enhance contrast and focus exclusively on the concrete surface. The test setup is shown in Figure 3. This setup was designed to maintain consistency across all images, thereby reducing variability in the image data. It allowed for the accurate capture of surface features such as texture, voids, and cracks, which are critical for correlating surface characteristics with compressive strength through image analysis. The controlled conditions ensured that the extracted features were purely representative of the specimen's surface and not influenced by external factors, enhancing the reliability of the DIP results [3,4,5]. The experimentation involved the following step-by-step procedure:

Image Acquisition
↓
Cropping of the Image
↓
Convert to Grey Scale
↓
Histogram
↓
Finding ratio of Cement: Aggregate: Voids
↓
Prediction of Strength

The strength is predicted by the following Empirical formula [3,4,5]:

$$f_{ck} = \frac{(Aggregate)^{0.021}}{(Cement)^{-1.004}} - (AirVoids)^{-1.251} \quad (4)$$

(4)

f_{ck} = Compressive Strength of Concrete in N/mm^2

This method offered a non-destructive alternative for compressive strength evaluation by leveraging surface characteristics and advanced computational techniques. The results obtained through DIP were compared with conventional destructive testing to validate the accuracy and reliability of this approach.

Figure 3 Test Setup for Digital Image Processing

4. Results and Discussion

4.1.Results

As mentioned above Experimentation is conducted on Concrete samples and the results of each NDT Method are compared with Destructive results and are shown in Table 1, Table 2 and Table 3. The results are as follows and the comparison of Graph is shown in Figure 4.

Table 1 Results of RBH Vs Destructive Test

Days of Curing	RBH Method (f_{ck} in MPa)	Destructive Test (f_{ck} in MPa)	% Difference
3 Days	21.50	24.30	11.52%
7 Days	34.40	39.50	12.91%
14 Days	41.20	46.80	11.97%
28 Days	46.10	56.20	17.97%

**f_{ck} = Compressive Strength of Concrete*

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Table 2 Results of Sonreb Vs Destructive Test

Days of Curing	SonReb Method (f_{ck} in MPa)	Destructive Test (f_{ck} in MPa)	% Difference
3 Days	22.00	24.30	9.47%
7 Days	36.50	39.50	7.59%
14 Days	44.50	46.80	4.91%
28 Days	52.50	56.20	6.58%

Table 3 Results of DIP vs Destructive Test

Days of Curing	DIP Method (f_{ck} in MPa)	Destructive Test (f_{ck} in MPa)	% Difference
3 Days	19.50	24.30	19.75%
7 Days	33.40	39.50	15.44%
14 Days	42.20	46.80	9.83%
28 Days	45.10	56.20	19.75%

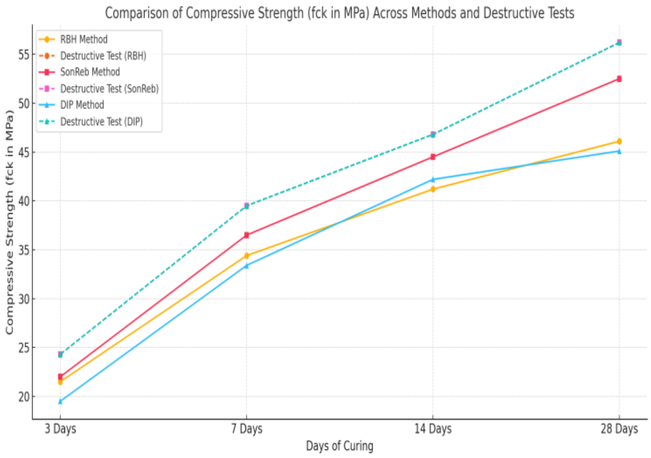

Figure 4 Comparison of Concrete Compressive Strength Across Non-Destructive and Destructive Testing Methods

Conclusion

- All three non-destructive testing (NDT) methods (RBH, SonReb, and DIP) showed consistent trends in compressive strength with curing age, aligning reasonably well with the destructive test results.
- Among the methods, the SonReb Method demonstrated the lowest percentage difference across all curing durations (average difference ~7%), indicating higher accuracy and reliability in estimating the compressive strength compared to RBH and DIP methods.
- The RBH Method exhibited moderate accuracy, with an average percentage difference of ~13%. This suggests it is suitable for initial assessments but may require calibration or supplementary methods for precise results.
- The DIP Method had the highest percentage difference (~16%) across curing durations, particularly at 3 days and 28 days, highlighting its potential limitations for early-age and mature concrete evaluations.
- As curing age increased, the percentage difference between non-destructive and destructive methods generally decreased for SonReb and RBH methods, indicating improved accuracy with longer curing times.
- The DIP method, however, exhibited consistent discrepancies at both early and late curing durations, suggesting variability in its estimation capability.
- The SonReb method is the most suitable for practical applications where higher precision is required without destructive testing, especially for quality control during intermediate and final stages of curing.
- The RBH method can be used effectively for preliminary evaluations or when a faster, cost-effective assessment is needed.
- The DIP method, while less accurate, may be used as a supplementary tool or in scenarios where other methods are not feasible.
- These results emphasize the importance of selecting the appropriate NDT method based on the required level of accuracy, concrete age, and project constraints.
- Proper calibration of non-destructive techniques to match the specific mix design and environmental conditions can further enhance their reliability.

Further research may focus on refining the algorithms used in these NDT methods or developing hybrid approaches to minimize discrepancies with destructive test results.

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