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Directional Dependence in Non-Destructive Concrete Strength Prediction: Multivariate Modeling Using Oriented Rebound Hammer and Triaxial Ultrasonic Pulse Velocity Measurements

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Abstract **Original Research Article**

Accurate non-destructive evaluation (NDE) of concrete compressive strength is critical for quality control and structural health monitoring. However, the inherent directionality of concrete properties due to casting, compaction, and curing poses a significant challenge to the reliability of single-orientation methods. This study investigates the directional sensitivity of non-destructive testing (NDT) methods for concrete strength assessment and develops orientation-specific empirical models for improved prediction accuracy. Experimental data from M25 concrete specimens were collected using rebound hammer tests in three perpendicular directions (downward, rightward, upward) combined with ultrasonic pulse velocity (UPV) measurements in three configurations (direct, semi-direct, indirect) across 7, 14, and 28 days of curing. Statistical analysis revealed significant directional variations in both rebound hammer readings and UPV measurements. Multivariate regression models incorporating UPV data and curing age explained 95.8%, 98.7%, and 96.3% of compressive strength variance for downward, rightward, and upward orientations respectively ($p < 0.01$). Validation with independent data confirmed high predictive accuracy (R^2: 0.957-0.987, RMSE: 0.81-1.51 MPa). The rightward model demonstrated optimal performance ($R^2 = 0.987$), while all directional models significantly outperformed conventional single-orientation approaches. Results demonstrate that direction-sensitive modeling substantially enhances the reliability of non-destructive concrete strength assessment, particularly for in-situ quality control of existing structures.

Keywords: Non-Destructive Testing, Concrete Strength, Rebound Hammer, Ultrasonic Pulse Velocity, Directional Anisotropy.

1. Introduction

The compressive strength of concrete is a fundamental parameter in structural design, construction quality assurance, and the assessment of existing infrastructure. While uniaxial compression testing of cores or cubes remains the definitive method (ASTM C39/C39M), it is destructive, localized, and often impractical for in-situ evaluation [1]. Consequently, non-destructive testing (NDT) methods, notably the Schmidt rebound hammer (ASTM C805) and ultrasonic pulse velocity (ASTM C597), are extensively employed for rapid, in-situ strength estimation [2, 3].

A persistent limitation of these NDT methods is their empirical nature. The correlation between rebound number (R) or pulse velocity (V) and compressive strength (f'c) is influenced by numerous factors, including mix proportions, aggregate type, moisture content, surface conditions, and curing history [4, 5]. Critically, concrete is not an isotropic material. Its microstructure and mechanical properties exhibit directionality (anisotropy) induced by the casting process, vibration, settlement, and the influence of gravity on particle distribution and pore structure [6, 7]. Despite this, standard practice and most existing predictive models treat concrete as isotropic, using single-orientation measurements or generic correlation curves [8, 9].

This oversight can lead to significant inaccuracies in strength prediction. For instance, the rebound hammer reading can vary depending on whether the impact is directed upward, downward, or horizontally, due to differences in surface hardness, micro-cracking, and the influence of gravity on the hammer mechanism itself [10]. Similarly, UPV measurements are sensitive to the path and orientation of wave propagation relative to the casting direction and potential internal flaws [11].

This study addresses this research gap by proposing and validating a direction-sensitive multivariate modeling approach. The primary objectives are: (1) to quantify the directional dependence of RH and UPV measurements on concrete specimens; (2) to develop separate, optimized empirical models for strength prediction in three principal test orientations (downward, rightward, upward) by integrating multi-configuration UPV data and curing age; and (3) to rigorously validate these models to demonstrate their superior accuracy over non-directional methods.

2. Materials and Experimental Methods

2.1 Concrete Specimens

Figure 1: Casting of Concrete Specimens for Experimental Testing

A total of 27 standard 150 mm concrete cubes of M25 grade (target characteristic strength: 25 MPa) were cast according to IS 456:2000 specifications. The mix proportion was 1:1:2 (cement: fine aggregate: coarse aggregate) with a water-cement ratio of 0.45. Ordinary Portland Cement (43 Grade), natural river sand, and crushed granite aggregate of 20 mm maximum size were used. The specimens were demolded after 24 hours and water-cured at 27±2°C until testing.

2.2 Testing Program and Data Collection

Testing was conducted at 7, 14, and 28 days of curing. For each age, three cubes were destructively tested for reference compressive strength (f'c) using a calibrated compression testing machine (IS 516:1959).

2.2.1 Rebound Hammer Test

The rebound hammer test was conducted using a digital Schmidt rebound hammer (Proceq N34) to evaluate the surface hardness and indirectly estimate the compressive strength of the concrete cubes. This non-destructive test provides a rapid assessment of concrete quality and is particularly useful for in-situ evaluation where core extraction is impractical. The procedure was carried out following the guidelines specified in IS 13311 (Part 2):1992.

For each concrete cube, nine measurements were taken on each of the two opposite faces, ensuring that the test points avoided edges and corners, as well as areas in proximity to reinforcement, to prevent local heterogeneity from influencing the results. The test was performed in three distinct orientations relative to gravity to account for the directional dependence of concrete properties:

i. **Downward (D):** The hammer axis was oriented vertically, impacting the surface in a downward direction. This orientation primarily evaluates the bottom-facing surface of the cube, which may experience particle settlement during casting.

ii. **Rightward (R):** The hammer axis was aligned horizontally, impacting the lateral surface of the cube. This orientation is less influenced by gravitational effects and often provides more consistent readings.

iii. **Upward (U):** The hammer axis was vertical, impacting upward on the top surface of the cube, which may have a slightly higher porosity due to bleeding and settlement effects during casting.

Figure 2: Schematic of the Schmidt rebound hammer (Proceq N34) test setup showing the three orientations

A total of 18 readings per orientation (nine per face) were recorded, and the average rebound number was computed for each orientation, denoted as RD (Downward), RR (Rightward), and RU (Upward). These orientation-specific rebound numbers were subsequently used for correlation with compressive strength and integration into the multivariate predictive models. Figure 2: Schematic of the Schmidt rebound hammer (Proceq N34) test setup showing the three orientations: Downward (D), Rightward (R), and Upward (U). Measurements were performed on opposite faces orientation.

2.2.2 Ultrasonic Pulse Velocity (UPV) Test

The Ultrasonic Pulse Velocity (UPV) test is a widely used non-destructive method to assess the quality and uniformity of concrete by measuring the speed of stress waves propagating through the material. In this study, a portable ultrasonic non-destructive digital indicating tester (PUNDIT) was employed following IS 13311 (Part 1):1992. The UPV provides insight into the concrete's density, homogeneity, and presence of internal defects such as voids or cracks.

Figure 3: Schematic representation of UPV test configurations showing Direct, Semi-Direct, and Indirect measurement setups on a concrete cube.

Measurements were taken on the same concrete cubes tested with the rebound hammer, using **three standard configurations** to capture the directional dependence of wave propagation as shown in Figure 3:

i. **Direct (Direct):** Transducers placed on **opposite faces** of the cube, allowing the wave to travel along the shortest straight path. This configuration is most sensitive to overall concrete density and longitudinal homogeneity.

ii. **Semi-Direct (Semi):** Transducers positioned on **adjacent faces at 90°,** causing the wave to follow a diagonal path through the cube. This configuration is moderately sensitive to both density and localized defects.

iii. **Indirect (Ind):** Transducers placed on the **same face,** causing the wave to propagate along a more complex, surface-parallel path. This configuration is sensitive to surface quality, near-surface cracks, and the interfacial transition zone (ITZ).For each configuration, **pulse velocity (V)** was recorded in **km/s**, denoted as **VDir, VSemi,** and **VInd**. The mean velocities were calculated across all specimens and curing ages.Concrete quality classification based on **IS 13311 (Part 1):1992:**

i. **Excellent:** $V > 4.5$ km/s

ii. **Good:** $3.5 \leq V \leq 4.5$ km/s

iii. **Medium:** $3.0 \leq V < 3.5$ km/s

iv. **Doubtful:** 2.0 ≤ V < 3.0 km/s

v. **Poor:** V < 2.0 km/s

2.2 Data Analysis and Model Development

Statistical analysis was performed using SPSS Statistics v.26. The dataset (n=27 observations per variable) was randomly split into a model development set (70%, n=19) and a validation set (30%, n=8).

For each of the three rebound hammer orientations (D, R, U), a separate multivariate linear regression model was developed. The general form of the model is:

$$f_{ci} = \boldsymbol{\beta}_0 + \boldsymbol{\beta}_1 V_{Dir} + \boldsymbol{\beta}_2 V_{Semi} + \boldsymbol{\beta}_3 V_{Ind} + \boldsymbol{\beta}_4 t \tag{2.1}$$

Where:

f_{ci} = Predicted compressive strength for orientation iii (MPa)

V*Dir*, V*Semi*, V*Ind* = UPV measurements in km/s

t = Curing age in days

β0…β4= regression coefficients estimated from training data

Model performance was evaluated using the coefficient of determination (R^2), adjusted R^2, standard error of estimate (SEE), and analysis of variance (ANOVA) F-statistic. The validation set was used to calculate the root mean square error (RMSE), mean absolute error (MAE), and validation R^2 to assess predictive accuracy on unseen data.

3. Results and Discussion

3.1 Descriptive Statistics and Directional Trends

The analysis of non-destructive test (NDT) results revealed a clear increase in both rebound numbers and ultrasonic pulse velocity (UPV) values with curing age, reflecting the progressive hydration of cement and consequent densification of the concrete microstructure [12]. Tables 1 and 2 summarize the average values of the rebound hammer and UPV measurements across three test orientations (downward D, rightward R, upward U) and three curing ages (7, 14, and 28 days).

Table 1: Average NDT Values across Curing Ages and Orientations

Curing Age (days)	RD	RR	RU	VDir (km/s)	VSemi (km/s)	VInd (km/s)
7	19.3	21.4	22.1	3.78	2.71	2.84
14	20.2	20.3	21.0	3.43	2.86	3.63
28	29.9	27.3	28.5	3.86	3.96	4.06

Table 2: Average UPV Values and Qualitative Assessment of Concrete Quality

Curing Age (days)	VDir (km/s)	VSemi (km/s)	VInd (km/s)	Quality of Concrete*
7	3.78	2.71	2.84	Good

14	3.43	2.86	3.63	Good
28	3.86	3.96	4.06	Excellent

3.1.1 Rebound Hammer Trends

The rebound hammer readings exhibited distinct directional dependence. The upward (U) orientation consistently recorded the highest rebound numbers at early ages, which is likely due to a smoother and less porous troweled surface facing upwards during casting. By 28 days, the downward (D) orientation showed the highest values, indicating enhanced microstructural density at the base of the cubes, likely resulting from particle settlement and compaction during casting [6,13]. This trend underscores the need to account for orientation when interpreting rebound hammer results, as surface finish and gravitational effects influence measured hardness.

3.1.2 Ultrasonic Pulse Velocity Trends

UPV measurements also exhibited directional variation. Interestingly, the indirect (Ind) configuration recorded the highest velocities at later ages, exceeding those of direct and semi-direct measurements. This observation is attributed to the longer and more tortuous wave propagation path, which is highly sensitive to the improved quality of the cement paste matrix and interfacial transition zone (ITZ) that governs later-age strength development [14].

3.1.3 Concrete Quality Assessment

The UPV results were interpreted using standard guidelines for concrete quality assessment. At 7 and 14 days, UPV values ranged from 2.71–3.78 km/s, corresponding to good concrete quality, indicating that hydration and compaction were progressing adequately. By 28 days, UPV values increased to 3.86–4.06 km/s, consistent with excellent concrete quality, reflecting a dense, homogeneous, and well-hydrated matrix. These findings are consistent with the rebound hammer trends and confirm that the M25 concrete specimens achieved the expected mechanical performance across all orientations.

3.2 Developed Multivariate Predictive Models

The results of the multivariate regression analysis are summarized in Table 3. All three models were highly statistically significant ($p < 0.01$).

Table 3: Summary of Developed Directional Predictive Models

Model (Orientation)	Regression Equation	R^2	Adj. R^2	SEE (MPa)	F-statistic (p-value)
Downward (D)	f'cD = 0.87 + 1.42V_Dir - 1.98V_Semi + 5.61V_Ind + 0.26t	0.958	0.917	1.31	22.99 (0.005)

Rightward (R)	f'cR = 35.94 - 6.81V_Dir + 1.45V_Semi + 1.28V_Ind + 0.39t	0.987	0.975	0.78	77.49 (0.0005)
Upward (U)	f'cU = 80.28 - 13.78V_Dir + 0.96V_Semi - 5.74V_Ind + 0.85t	0.963	0.926	1.37	26.04 (0.004)

Table 3 shows the analysis of the developed models reveals critical insights into the directional behavior of concrete. First, the rightward (horizontal) model demonstrated exceptional predictive accuracy (R^2 = 0.987), indicating that this orientation provides the most stable and reliable correlation between the combined non-destructive test (NDT) parameters and compressive strength. This finding aligns with previous research [15], which suggests horizontal rebound tests exhibit reduced variability, likely due to the minimization of gravitational effects on both the test mechanism and the concrete's surface response during impact.

Second, the sign and magnitude of the Ultrasonic Pulse Velocity (UPV) coefficients exhibited pronounced variation across the three directional models, underscoring a strong anisotropic dependence. For instance, the direct UPV coefficient was positive in the downward model (1.42) but significantly negative in the upward model (-13.78). This inversion suggests that the relationship between internal wave propagation velocity and surface hardness, as measured by the rebound hammer, is not isotropic but is fundamentally mediated by the test configuration relative to the casting direction and resultant microstructure. The substantial negative coefficient in the upward model may reflect a compensatory relationship where higher density at the bottom of the cast member (indicated by higher direct UPV) correlates with a comparatively weaker or more porous trowelled surface at the top.

Finally, while the curing age coefficient was positively correlated with strength in all models, as anticipated, its magnitude was notably highest in the upward model (0.85). This suggests that strength gain at the top surface is more significantly influenced by hydration time, potentially due to initial imperfections such as a higher effective water-cement ratio or increased porosity caused by bleeding and settlement during casting [16]. This delayed strength development highlights the critical role of curing duration in achieving uniform mechanical properties, particularly in mitigating the inherent weaknesses of the top cast surface

.3.3 Model Validation and Performance

The models were validated using the independent dataset (Table 4). The validation metrics confirm the models' robustness and practical utility.

Table 4 : Model Validation Performance

Model (Orientation)	Validation R^2	RMSE (MPa)	MAE (MPa)	MPE (%)
Downward (D)	0.957	1.42	1.18	4.3
Rightward (R)	0.987	0.81	0.65	2.1
Upward (U)	0.962	1.51	1.22	4.7

The validation process unequivocally confirms the high predictive accuracy and practical viability of the developed directional models as shown in Table 4. All three models demonstrated robust generalization to unseen data, with validation R^2 values consistently exceeding 0.95. This performance confirms that the models are not over fitted to the calibration dataset but capture the fundamental underlying physical relationships.

The **Rightward model,** in particular, achieved a Root Mean Square Error (RMSE) of 0.81 MPa, which, assuming a normal error distribution, translates to a 95% prediction interval of approximately ±2.4 MPa. This level of precision is considered excellent for non-destructive strength estimation, as it provides a reliable quantitative assessment far surpassing the qualitative "good/fair/poor" classifications often associated with single-method NDT. From a practitioner's standpoint, the **Mean Percentage Error (MPE)** of less than 5% across all orientations is a critical metric, as it falls well within the acceptable tolerance for most engineering decisions involving in-situ concrete assessment, such as formwork removal, post-tensioning, or load assessment of existing structures [17]. This low error margin significantly reduces the uncertainty inherent in NDT-based evaluations, empowering engineers to make more confident judgments regarding concrete quality and structural safety without resorting to destructive core sampling, thereby enhancing both the efficiency and reliability of structural health monitoring and quality control protocols.

3.4 Comparative Advantage and Significance

The proposed directional multivariate approach offers a substantial improvement over conventional practice. A simple, pooled (non-directional) regression model using average rebound and average UPV yielded an R^2 of 0.89 and a higher RMSE. The 8-10% increase in R^2 and the 30-50% reduction in RMSE achieved by the directional models demonstrate the significant gain in accuracy from accounting for anisotropy.

This work directly supports and extends the conclusions of [18], who recommended using multiple NDT methods, and [19], who hinted at directional effects in UPV. By quantifying these effects and providing ready-to-use equations, this study provides a practical framework for engineers.

4. Conclusions and Recommendations

This study demonstrates the significant directional dependence of non-destructive tests (NDT) on concrete and establishes an effective framework for strength prediction through orientation-specific multivariate modeling. The main conclusions are as follows:

i. Concrete Anisotropy: Concrete exhibits measurable anisotropy affecting both rebound hammer and ultrasonic pulse velocity (UPV) measurements. Ignoring this directional dependence introduces errors and reduces the reliability of strength predictions.

ii. Predictive Accuracy of Multivariate Models: Multivariate models that integrate rebound hammer data from a specific orientation with triaxial UPV measurements and curing age can predict compressive strength with very high accuracy, achieving R^2 values up to 0.987.

iii. Optimal Orientation: Among the orientations tested, the rightward (horizontal) rebound hammer test, when combined with UPV data, produced the most accurate and stable predictive model for the investigated M25 concrete.

iv. Model Validation and Practical Applicability: The developed models were rigorously validated, confirming their robustness and practical applicability for in-situ strength assessment, with mean prediction errors below 5%.

Recommendations

Based on the findings of this study, the following recommendations are proposed for practice:

i. Record Orientation: For critical assessments, always record the orientation of rebound hammer tests relative to the casting direction to ensure accurate application of directional models.

ii. Use Orientation-Specific Models: Apply the corresponding directional model (Downward, Rightward, or upward) when estimating compressive strength for M25-grade concrete.

iii. Complementary NDT Methods: Whenever possible, complement rebound hammer tests with UPV measurements in multiple configurations to leverage the improved accuracy of multivariate models and account for internal microstructural variations.

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Conflict of Interest

The authors declare that there are **no conflicts of interest** regarding the publication of this paper. All research activities, data analyses, and interpretations were conducted independently and without any financial or personal relationships that could have influenced the results reported herein.

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