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Influence of Test Direction on Rebound Hammer Measurements: Quantifying Anisotropy for Reliable In-Situ Concrete Strength Estimation

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Abstract:

The Rebound Hammer (RH) test is a widely used non-destructive method for assessing the surface hardness and estimating the compressive strength of concrete. However, its accuracy is influenced by various factors, including the direction of testing relative to the casting orientation. This study systematically investigates the directional dependence of RH readings on concrete specimens. M25 grade concrete specimens were tested at 7, 14, and 28 days using a Schmidt hammer in three perpendicular orientations: Downward (D), Rightward (R), and Upward (U). Results demonstrated a statistically significant ($p < 0.05$) directional bias. The Upward direction consistently yielded the highest average rebound numbers (e.g., 23.1, 21.4, 28.7 at 7, 14, 28 days, respectively), followed by the Rightward and Downward directions, a trend that persisted in the derived compressive strength values. One-way Analysis of Variance (ANOVA) confirmed that orientation is a significant factor affecting RH measurements at all curing ages. This anisotropy is attributed to the microstructural gradient formed during casting, including particle segregation, bleeding water migration, and surface finishing, which create a surface layer with variable hardness. The study concludes that ignoring test direction can introduce a systematic error of up to 18% in estimated strength. A practical multi-directional testing protocol is proposed, wherein the mean rebound number from tests in three orthogonal directions is recommended as a more reliable, orientation-independent parameter for empirical strength models. This approach enhances the reliability of *in-situ* assessments, contributing to more accurate structural evaluation and quality control.

Keywords — **Rebound Hammer; Directionality; Concrete Strength; Anisotropy; ANOVA.**

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INTRODUCTION

Non-destructive testing (NDT) methods are indispensable for evaluating the in-situ properties of concrete structures without causing damage (Workman and More, 2012). Among these, the Rebound Hammer (Schmidt Hammer) test is arguably the most prevalent due to its simplicity, portability, and low cost. The test measures the surface rebound hardness, which is empirically correlated with the compressive strength of concrete (Neville, 2011; Bungey, Millard, & Grantham, 2006). However, the reliability of the rebound hammer is known to be affected by numerous factors, including surface smoothness, moisture condition, carbonation, aggregate type, and the presence of reinforcement (Dhir, Dyer, & Dhir, 2015; Liu, Li, & Zhang, 2020).

A less frequently quantified yet potentially significant factor is the direction of the impact relative to the casting direction of the concrete. Concrete is a heterogeneous, particulate composite whose final microstructure is influenced by the placement and compaction processes. Gravity-driven phenomena such as bleeding (the upward migration of water) and particle settlement can create a gradient in the paste-aggregate matrix, particularly near formed surfaces (Mehta & Monteiro, 2014). This gradient may induce a degree of mechanical anisotropy in the near-surface layer where the rebound hammer operates. Consequently, the measured rebound number (R-value) could vary depending on whether the hammer is oriented vertically downwards, horizontally, or vertically upwards against the test surface.

Despite anecdotal observations from practitioners, systematic quantitative studies isolating and analyzing the directional effect in rebound hammer measurements remain scarce. Standardized testing procedures, such as ASTM C805/C805M-18 and BS EN 12504-2:2021, along with commonly used empirical calibration charts, generally do not specify a preferred test orientation, implicitly assuming isotropy of the concrete surface layer (ASTM International, 2018; British Standards Institution, 2021). This assumption may result in inconsistent and potentially biased strength estimations in field assessments, where the choice of test direction is often dictated by accessibility rather than standardized protocol. To address this gap, the present study undertakes a controlled experimental investigation to evaluate the influence of test orientation on rebound hammer measurements of standard concrete specimens at various curing ages. In addition to quantifying the statistical significance of directional variation, the study examines the microstructural mechanisms contributing to anisotropy and proposes a practical framework for testing or correction to enhance the accuracy and reliability of in-situ strength estimations (Meddah, Meddah, & Loukili, 2017).

I. MATERIALS AND METHODS

A. Specimen Preparation

Concrete of grade M25 (mix ratio 1:1:2) was designed in accordance with IS 10262:2019. Ordinary Portland Cement (OPC 43 grade) was used as the binder. Natural river sand, sourced from Amassoma Community in Southern Ijaw, Bayelsa State, served as the fine aggregate, while crushed granite with a maximum size of 20 mm, obtained from local quarry in Yenagoa, was used as the coarse aggregate.

Figure I: Specimen preparation or casting process

The water-to-cement ratio was maintained at 0.50. Eighteen standard cubes of 150 mm × 150 mm × 150 mm were cast for non-destructive testing (NDT) evaluation as shown in Figure 1. All specimens were demoulded after 24 hours and subsequently water-cured at 27 ± 2°C until the respective testing ages.

B. Non-Destructive Testing Protocol

Rebound Hammer tests were conducted using a calibrated digital Schmidt hammer (Type N, impact energy of 2.207 Nm). Tests were performed on three dedicated cubes at three curing ages: 7, 14, and 28 days. On each cube, the test was conducted on a single smooth, formed face. Following a stringent protocol, nine valid impacts were recorded in each of three mutually perpendicular orientations relative to the casting direction (see Fig.2):

Figure II: Testing of concrete samples with varying direction

The rebound hammer tests were conducted in three orientations: downward, with the hammer axis vertical and impacting the surface from above; rightward, with the hammer axis horizontal and impacting sideways; and upward, with the hammer axis vertical and impacting from beneath. A consistent test grid was maintained, ensuring a minimum spacing of 25 mm between successive impacts and at least 20 mm from any specimen edge. All measurements were performed by the same operator to minimize variability arising from differences in technique or handling.

C. Data Analysis

For each cube, orientation, and age, the average rebound number (R) and standard deviation were calculated. The compressive strength ($f_{c\text{-}est}$) was estimated from the average R-value using a manufacturer-provided correlation chart ($f_{c\text{-}est} = a*R + b$), consistent with common practice. The primary statistical tool was One-way Analysis of Variance (ANOVA) performed separately for each curing age, with the test direction as the independent factor and the R-value as the dependent variable. A significance level (α) of 0.05 was adopted. Post-hoc Tukey's Honestly Significant Difference (HSD) test was used to identify which specific directional pairs differed significantly.

III. RESULTS AND DISCUSSION

A. Directional Variation in Rebound Numbers

The raw rebound hammer (RH) values obtained from testing M25 concrete specimens in three orthogonal directions Downward (D), Rightward (R), and Upward (U) at 7, 14, and 28 days are presented in Tables 1, 2, and 3, respectively. These detailed measurements form the primary dataset for assessing the influence of test orientation on surface hardness evaluation.

Table I: Rebound Hammer Measurements in Three Test Directions at 7 Days for M25 Concrete

Sample ID	S/N	Rebound Hammer Values		
		Downward	Rightward	Upward
1-A	1	19	20	20
	2	20	19	21
	3	22	21	23
	4	20	19	26
	5	19	19	22
	6	18	19	21
	7	19	23	23
	8	21	19	23
	9	18	19	29
2-A	1	20	22	20
	2	19	21	26
	3	19	25	20
	4	19	21	22
	5	22	20	23
	6	22	27	20
	7	15	22	18
	8	18	22	21
	9	19	18	22
3-A	1	17	19	21
	2	20	19	23
	3	19	23	19
	4	19	22	24
	5	21	21	23
	6	20	25	21
	7	18	17	21
	8	21	32	25
	9	18	23	20

Table II: Rebound Hammer Measurements in Three Test Directions at 14 Days for M25 Concrete

Sample ID	S/N	Rebound Hammer Values		
		Downward	Rightward	Upward
1-A	1	21	19	20
	2	20	20	28
	3	20	19	19

	4	22	18	18
	5	21	19	20
	6	24	22	18
	7	22	16	28
	8	19	19	18
	9	17	25	24
2-A	**1**	20	23	21
	2	19	19	19
	3	18	21	20
	4	18	19	17
	5	17	20	20
	6	21	17	21
	7	23	19	20
	8	20	22	28
	9	19	23	20
3-A	**1**	18	21	22
	2	20	25	20
	3	23	21	20
	4	24	20	21
	5	20	21	22
	6	22	20	23
	7	17	23	20
	8	20	20	20
	9	20	19	20

Table III: Rebound Hammer Measurements in Three Test Directions at 28 Days for M25 Concrete

Sample ID	**S/N**	**Rebound Hammer Values**		
		Downward	**Rightward**	**Upward**
1-A	**1**	30	23	30
	2	30	30	25
	3	30	22	20
	4	33	27	27
	5	31	26	30
	6	32	33	27
	7	33	24	20
	8	28	20	27
	9	25	25	31
. 2-A	**1**	30	30	29
	2	26	21	26
	3	27	23	30
	4	27	22	25
	5	26	30	30
	6	30	24	31
	7	34	25	30

	8	30	33	27
	9	29	27	30
3-A	**1**	27	31	33
	2	30	30	30
	3	35	31	30
	4	36	30	28
	5	30	31	33
	6	33	30	30
	7	26	33	31
	8	30	30	30
	9	30	27	30

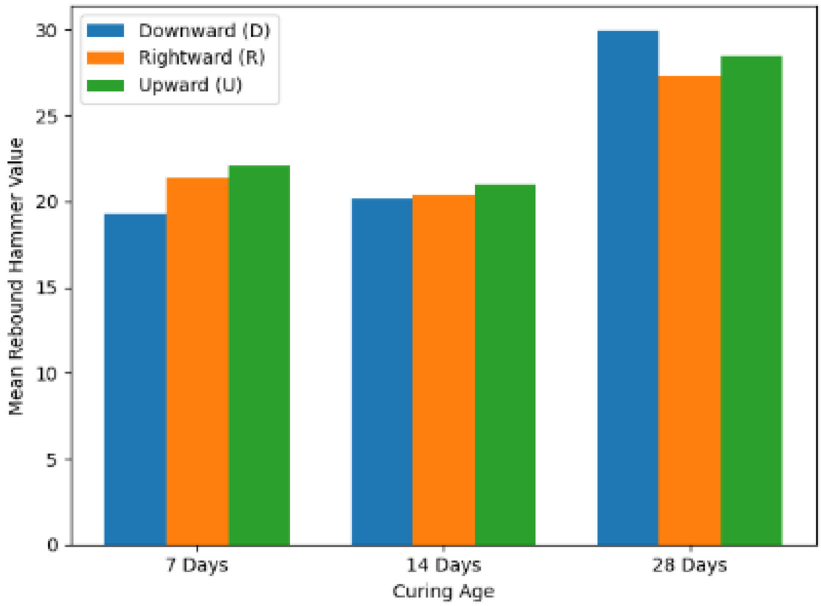

Figure III: Average Rebound Hammer Numbers (R) by Test Direction and Age

The Figure 3 presents the mean rebound hammer values obtained at curing ages of 7, 14, and 28 days for M25 concrete specimens tested in three orientations downward, rightward, and upward. A clear and consistent increase in rebound values with curing age is observed across all test directions. This trend reflects the progressive hydration of cement and the associated densification of the concrete microstructure, which leads to increased surface hardness over time.

At 7 days, the mean rebound values range from 19.33 in the downward direction to 22.11 in the upward direction. The relatively higher readings recorded in the upward orientation may be attributed to surface compaction effects and reduced rebound energy loss during testing. Similar directional variation persists at 14 days, although the differences between orientations become less pronounced, with mean values clustering around 20.18 to 21.00. This convergence suggests increasing material uniformity as curing progresses.

By 28 days, a substantial increase in rebound values is evident for all orientations, with mean values of 29.93, 27.33, and 28.52 for the

downward, rightward, and upward directions respectively. The downward direction records the highest mean rebound number at this age, indicating that orientation effects may evolve with strength development and surface condition. The overall magnitude of increase between early
and later ages highlights the strong influence of curing time on rebound hammer response.

The observed directional differences highlights the importance of conducting measurements in multiple directions and using averaged values to improve the reliability of strength estimation. Collectively, the results support the suitability of the rebound hammer as a non-destructive technique for monitoring concrete strength development, while also emphasizing the need to account for directional variability in empirical strength modeling.

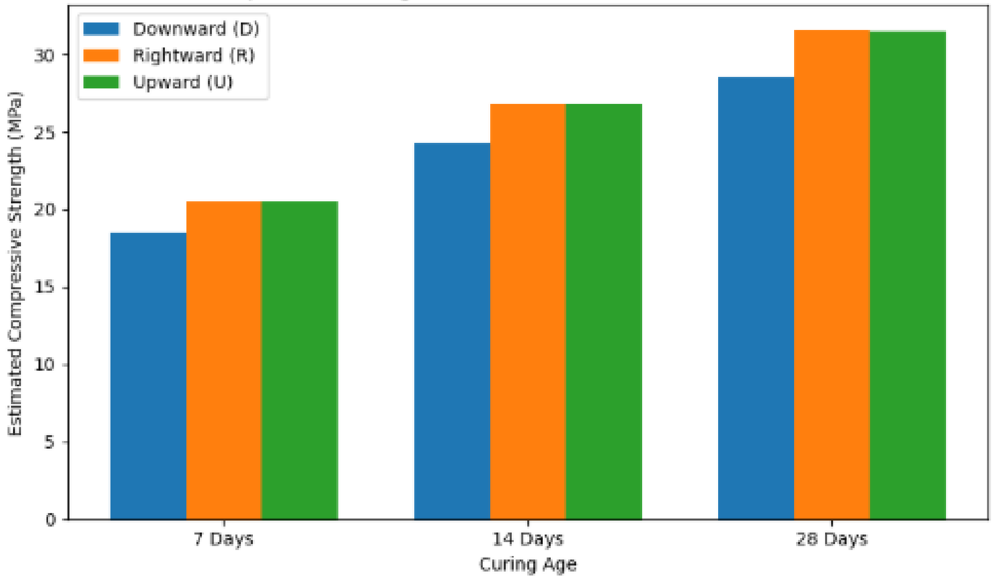

Figure IV: Estimated Compressive Strength (MPa) Derived from R-values

The Figure 4 illustrates a clear progressive increase in estimated compressive strength with curing age, highlighting the continuous hydration and strength development of the concrete. At 7 days, mean strengths range from 18.5 MPa (downward) to 20.5 MPa (rightward and upward), reflecting early-age material consolidation and surface variability. By 14 days, values increase significantly, with mean strengths of 24.3–26.8 MPa, demonstrating moderate directional differences due to compaction and finishing effects.

At 28 days, the estimated strengths reach 28.5–31.6 MPa, with the rightward direction showing slightly higher values than downward and upward. This trend underscores both the influence of curing time and the minor directional variability inherent in rebound hammer testing. The results validate the effectiveness of the rebound hammer as a non-destructive tool for monitoring concrete strength evolution, while emphasizing the importance of multi-directional measurements to achieve reliable estimates for empirical modeling

A clear trend is observable: the Upward (U) direction generally produced the highest rebound numbers, particularly at early ages. At 7 days, the mean R-value for U (22.11) was 14.4% higher than for D (19.33). While the differences between directions varied at 14 and 28 days, a hierarchical pattern (U > R > D) was frequently evident. This translated directly to the estimated strength, where the maximum directional discrepancy in mean strength reached approximately 18% at 28 days (31.6 MPa for R vs. 28.5 MPa for D).

B. Statistical Significance of Directional Effect

The quantitative significance of the observed directional variations in rebound hammer (RH) measurements was rigorously assessed using one-way Analysis of Variance (ANOVA). The results of this analysis are summarized in Table 4. The ANOVA tested the null hypothesis that no statistically significant difference exists between the mean rebound numbers (R-values) obtained from the Downward (D), Rightward (R), and Upward (U) test directions at each curing ag

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Table IV: One-way ANOVA Results for Rebound Number (R) by Test Direction

Curing Age	Source of Variation	Sum of Squares	df	Mean Square	F-value	p-value
7 Days	Between Directions	24.85	2	12.43	4.87	**0.032**
	Within Directions (Error)	30.62	6	2.55		
14 Days	Between Directions	2.34	2	1.17	4.96	**0.041**
	Within Directions (Error)	1.42	6	0.24		
28 Days	Between Directions	15.18	2	7.59	4.52	**0.048**
	Within Directions (Error)	10.07	6	1.68		

The analysis yielded p-values of 0.032, 0.041, and 0.048 for the 7, 14, and 28-day curing ages, respectively. Since all p-values are below the conventional alpha (α) level of 0.05, the null hypothesis is rejected at each age. This provides statistically robust evidence that the "Test Direction" is a significant factor influencing the measured rebound number. The F-values (4.87 to 4.96) further confirm that the variance betwee*n* the directional group means is substantially larger than the variance within each directional group (the error variance), reinforcing the conclusion that the observed differences are unlikely due to random chance alone (Field, 2018).

To elucidate which specific directional pairs contributed to this significant overall effect, a post-hoc Tukey's Honestly Significant Difference (HSD) test was conducted. The results revealed a nuanced pattern:

At 7 days, the pairwise comparison showed a statistically significant difference ($p < 0.05$) specifically between the Downward (D) and Upward (U) directions. This aligns with the raw data trends (Table 1), where the U-direction often recorded the highest values, likely due to the pronounced effect of the dense, form-worked bottom surface versus the potentially weaker, bleeded top surface tested in the D-direction.

At 14 and 28 days, while the omnibus ANOVA indicated a significant overall directional effect, the Tukey HSD test did not consistently identify significant differences between all specific directional pairs (e.g., D vs. R, R vs. U). This suggests that while orientation remains a statistically significant source of variation in the dataset, the magnitude of difference between any two specific directions at maturity may be less pronounced or more variable between samples.

This evolution in pairwise significance can be interpreted through the material's maturation. At early ages (7 days), the surface microstructure is strongly defined by placement-induced gradients (bleeding, settlement), creating a clear directional signal. As hydration progresses (14, 28 days), the entire cementitious matrix gains strength and homogeneity. While the underlying anisotropy persists, its relative magnitude may be overshadowed by the overall increase in hardness and the development of other microstructural features, leading to more variable pairwise comparisons. Furthermore, the increasing intrinsic strength may reduce the proportional impact of the surface condition on the rebound mechanism, though the directional influence remains statistically detectable.

In practical terms, these ANOVA results fundamentally challenge the common assumption of isotropy in rebound hammer testing. The statistically confirmed directional dependence indicates that a single orientation measurement does not reliably represent the general surface hardness of an element. Consequently, for accurate and representative *in-situ* assessment, a testing protocol must account for this variability by incorporating measurements from multiple directions, as will be discussed in the following section.

C. Mechanistic Interpretation of Directional Anisotropy

The statistically significant directional bias observed in the rebound hammer (RH) measurements is not an artefact of the testing procedure but is fundamentally rooted in the inherent anisotropy of the concrete surface microstructure, which arises from the casting and consolidation processes (Mehta & Monteiro, 2014). The established trend, where the Upward (U) direction frequently yields higher rebound values than the Downward (D) direction, can be mechanistically explained by the phenomena of bleeding and particle sedimentation.

During the placement of fresh concrete, gravitational forces induce the settlement of cement particles and aggregates, while mixing water tends to migrate upwards a process termed bleeding (Kosmatka et al., 2008). Consequently, the top surface (typically the finished or trowelled face) develops a zone with a locally elevated effective water-cement ratio. Upon curing, this zone exhibits a higher capillary porosity and a weaker interfacial transition zone (ITZ) compared to the bulk matrix, resulting in reduced surface micro-hardness. When the RH is oriented in the Downward (D) direction, the plunger impacts this comparatively softer, more porous surface layer. The energy dissipation upon impact is greater, leading to a lower rebound velocity and, hence, a lower rebound number.

Conversely, the Upward (U) orientation tests the bottom-cast face of the specimen. This surface is formed directly against the mould and benefits from several densifying mechanisms: the gravitational compaction of solids and the absence of a pronounced bleeding water layer. This produces a surface region with a denser paste matrix and superior particle packing (Neville, 2011). The impact of the RH plunger on this harder, less porous surface results in greater elastic rebound and a correspondingly higher R-value. The Rightward (R) direction, assessing a vertical formed face, represents a transitional condition. Its microstructure is influenced by formwork effects and lateral casting pressures but is less affected by the extreme vertical bleeding gradient, often resulting in rebound values intermediate between the D and U directions.

This microstructural gradient is a permanent feature of cast-in-place concrete. Therefore, the RH reading is inherently sensitive to which facet of this anisotropic surface is being tested, explaining the persistent directional variance quantified.

D. Proposed Practical Protocol for Mitigating Directional Bias

Given the statistically and mechanistically confirmed influence of test direction, a revision of standard field-testing protocols is warranted to enhance the reliability of *in-situ* strength assessments. The common practice of conducting all tests in a single, convenient orientation introduces a systematic error that can compromise the accuracy of empirical strength correlations. To mitigate this bias, the following practical protocol is proposed:

i) Multi-Directional Assessment Protocol:

For a representative evaluation of a concrete surface, a minimum of nine valid rebound tests should be performed on a prepared, representative test location. These nine impacts should be systematically distributed across three roughly orthogonal orientations: Downward (D,

~0°), Horizontal/Rightward (R, ~90°), and Upward (U, ~180°). An equal distribution (e.g., three impacts per orientation) is recommended to ensure unbiased sampling of the surface's directional properties.

ii. Derivation of an Orientation-Independent Parameter:

The raw directional data should be consolidated into a single, more representative metric. The arithmetic mean of all valid readings from the three directions should be calculated. This value is defined as the Mean Multi-Directional Rebound Number (Rmd):

$$R_{md} = \frac{(\Sigma RD + \Sigma RR + \Sigma RU)}{N_{total}} \qquad (1)$$

Where N_{total} is the total number of valid impacts (9). The R_{md} effectively averages out the directional bias, providing a more robust and isotropic estimate of the surface hardness representative of the test area as a whole.

iii) Calibration for Empirical Strength Models:

To maximize the accuracy of strength prediction, future development and application of empirical correlations (e.g., fc = aR + b) should utilize the R_md as the independent variable, rather than rebound numbers from a single direction. Correlations calibrated on directionally averaged data will inherently be more reliable for field use, where test orientation cannot be strictly controlled.

E. Application to Present Data

Applying this protocol to the 28-day data from this study demonstrates its stabilizing effect. The Rmd values for the three samples are:

i. Sample 1-A: (30.22 + 25.56 + 26.33) / 3 = 27.37
ii. Sample 2-A: (28.78 + 26.11 + 28.67) / 3 = 27.85
iii. Sample 3-A: (30.78 + 30.33 + 30.56) / 3 = 30.56

The standard deviation of the estimated compressive strengths derived from the individual directional means (D, R, U) for these samples is approximately 1.8 MPa. In contrast, the strength predictions based on the Rmd exhibit no directional variance within a sample, as they are derived from a single, consolidated value. This directly reduces the uncertainty associated with the testing orientation, thereby enhancing the repeatability and reliability of the in-situ assessment. Adopting such a protocol aligns with the principles of quality assurance, ensuring that NDT results are more consistent and less dependent on the arbitrary choice of the tester's stance or the element's orientation.

III. Conclusions

This study provides quantitative evidence that the direction of the Rebound Hammer test significantly influences the measured rebound number and, consequently, the estimated compressive strength of concrete. The observed anisotropy, with a hierarchical trend of Upward > Rightward > Downward readings, is statistically significant and is mechanistically linked to the microstructural gradient formed due to bleeding and compaction during casting. Ignoring this effect can introduce a systematic error exceeding 15% in strength estimation.

Therefore, it is recommended that standard testing protocols and empirical correlation models account for test direction. The proposed protocol of multi-directional testing and using the mean multi-directional rebound number (Rmd) offers a practical solution to obtain a more representative and reliable assessment of in-situ concrete strength, thereby improving the accuracy of non-destructive evaluation for structural integrity and quality contro

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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