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# Variability and Reliability Assessment of In-Situ Concrete Strength Using Schmidt Hammer Testing: A Statistical-Probabilistic Case Study of an Academic Building in Indonesia

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***Abstract***— *This study evaluates the variability and reliability of in-situ concrete compressive strength in an academic building using Schmidt hammer testing. A total of 55 rebound measurements were analyzed using statistical-descriptive and probabilistic approaches. The results show significant variability in rebound-derived compressive strength, with a coefficient of variation indicating non-uniform concrete quality. The strength data exhibited a lognormal-like distribution, and outlier analysis revealed potential localized weak zones. A reliability index was estimated to quantify the influence of material uncertainty on structural performance, highlighting the limitations of rebound ha mmer-based strength estimation without calibration. The proposed statistical–probabilistic framework provides a rapid and cost-effective approach for preliminary assessment of existing reinforced concrete structures, supporting reliability-based decision-making in structural evaluation.*

***Keywords***— *Schmidt hammer test; in-situ concrete strength; statistical variability; probabilistic reliability; existing concrete structures.*

## I. INTRODUCTION

Concrete is the most widely used construction material worldwide due to its versatility, durability, and economic efficiency. However, the in-situ mechanical properties of concrete in existing structures often exhibit significant uncertainty due to variations in material composition, construction practices, curing conditions, and environmental exposure. This uncertainty poses a critical challenge for structural assessment, maintenance planning, and reliability evaluation of existing buildings.

Non-destructive testing (NDT) methods have been widely adopted to assess in-situ concrete properties without damaging structural components. Among these methods, the Schmidt hammer test is one of the most commonly used techniques for estimating surface hardness and correlating rebound values with compressive strength. Despite its widespread application, the reliability and accuracy of the Schmidt hammer test have been questioned due to its sensitivity to surface conditions, moisture content, carbonation, and aggregate properties (Malhotra & Carino, 2004; ACI 214R-02). Recent studies continue to emphasize that Schmidt hammer results should be interpreted cautiously and preferably calibrated with destructive testing methods to improve accuracy. For instance, modern modifications of Schmidt hammer devices have been developed to improve measurement reliability and calibration accuracy, highlighting ongoing concerns regarding traditional rebound-based strength estimation [1], [2].

In addition to measurement uncertainty, spatial variability of concrete strength is a critical factor affecting structural performance and reliability. Concrete is inherently heterogeneous, and its mechanical properties may vary spatially within a structure due to casting sequences, workmanship, and quality control inconsistencies. Recent probabilistic studies have demonstrated that spatial variability significantly influences structural reliability and safety assessment, and ignoring such variability may lead to unconservative design or assessment results [3].

Reliability-based approaches have been increasingly applied to account for uncertainties in material properties, environmental effects, and construction variability. Probabilistic modeling and random field theory have shown that material variability directly affects reliability indices and failure probabilities in civil infrastructure systems [4]. Moreover, previous research has highlighted that long-term degradation mechanisms and environmental factors further exacerbate the uncertainty of concrete strength in existing structures, emphasizing the need for field-based statistical data to support structural reliability assessment [5].

Although numerous studies have investigated concrete strength variability using laboratory specimens, limited research has focused on field-based NDT data from existing buildings, particularly in developing countries where quality control practices and construction variability may differ significantly from developed regions. This gap indicates the necessity for comprehensive statistical and reliability-based evaluation of in-situ concrete strength using NDT data.

Therefore, this study aims to evaluate the variability and reliability of in-situ concrete strength using Schmidt hammer test data from an academic building in Indonesia. The objectives of this research are: (1) to quantify the statistical variability of in-situ concrete strength across different structural elements, (2) to assess the reliability implications of observed variability using probabilistic metrics, and (3) to discuss the limitations and practical implications of using Schmidt hammer test results for structural assessment in existing buildings. The findings of this study provide empirical evidence on concrete strength variability and contribute to the development of more reliable structural assessment practices in developing countries.

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## II. Method

The case study was conducted on an academic reinforced concrete building located in Indonesia. The building is a multi-storey structure designed for educational activities and consists of reinforced concrete columns, beams, and slab systems. The structural system follows a conventional cast-in-place reinforced concrete frame, which is widely adopted in academic and institutional buildings in developing countries.

The building was constructed approximately 10 years prior to the investigation, and no major structural retrofitting had been reported at the time of testing. The building represents typical construction practices in the region, including on-site batching, manual casting, and variable curing conditions, which may contribute to spatial variability in concrete quality.

The study focuses on evaluating in-situ concrete strength variability using non-destructive testing (NDT) data rather than determining absolute compressive strength values.

### A. Grid Pattern and Test Location Selection

A systematic grid pattern was adopted to ensure spatially representative sampling across the building. Test points were distributed across different structural elements, including columns, beams, and slabs, and across multiple floor levels. The spacing between test points was selected to capture spatial variability while avoiding clustering effects.

For each test location, a minimum of 12 rebound readings were recorded, and the median value was used to represent the local rebound index, following standard NDT practice.

Fig. 1. Implementation of testing on one of the beams

### B. Surface Preparation

Prior to testing, concrete surfaces were prepared by removing loose particles, laitance, dust, and surface coatings using wire brushing and light grinding. Surface moisture was minimized to reduce rebound variability caused by wet surfaces. The testing surfaces were selected to be free from visible cracks, honeycombing, and reinforcement interference.

### C. Orientation Correction

The Schmidt hammer was applied in different orientations depending on structural element accessibility. Orientation correction factors were applied to the rebound numbers based on manufacturer guidelines to account for gravitational effects on the hammer mass. This correction ensured comparability between measurements taken in different orientations.

Fig. 2. Implementation of testing in the horizontal direction

Fig. 3. Implementation of testing in the vertical Upward direction

### D. Descriptive Statistical Parameters

The statistical properties of the in-situ concrete strength dataset were evaluated using:

- Mean compressive strength

$$f_{cr} = \frac{1}{n}\sum_{i=1}^{n} f_{ci}$$

- Standard deviation

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(f_{ci} - f_{cr})^2}{n-1}}$$

- Coefficient of variation (CV)

$$\text{CV} = \frac{\sigma}{f_{cr}}\ x\ 100\%$$

The coefficient of variation was used to assess concrete quality uniformity, where lower CV indicates higher uniformity.

### E. Outlier Detection

Outliers were identified using two statistical approaches:

- Interquartile Range (IQR) Method

$$IQR=Q_3-Q_1$$

Data points outside:

$$Q_1-1.5(IQR)$$
$$Q_3+1.5(IQR)$$

were classified as potential outliers.

- Grubbs Test

$$G=\frac{\max|f_{ci}-f_{cr}|}{\sigma}$$

The calculated $G$ was compared with critical Grubbs values to detect statistically significant outliers. Outliers were analyzed and, if justified, excluded to reduce measurement noise and local defect bias.

### F. Distribution Fitting

The probability distribution of in-situ concrete strength was evaluated using:

- Normal distribution
- Lognormal distribution

Histogram analysis and goodness-of-fit tests (Kolmogorov–Smirnov test and Anderson–Darling test) were conducted to determine the most representative statistical distribution. The probability density function (PDF) for normal distribution is given by:

$$\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-f_{cr})^2}{2\sigma^2}\right)$$

### G. ACI 214R-02 Statistical Framework

The statistical evaluation followed the ACI 214R-02 guideline for in-place concrete strength evaluation. The characteristic compressive strength was estimated as:

TABLE I. Standards of concrete control for fc′ ≤ 5000 psi (35 MPa)

| Overall variation | | | | | |
|---|---|---|---|---|---|
| Class of operation | Standard deviation for different control standards, psi (MPa) | | | | |
| | Excellent | Very good | Good | Fair | Poor |
| General construction testing | Below 400 (below 2.8) | 400 to 500 (2.8 to 3.4) | 500 to 600 (3.4 to 4.1) | 600 to 700 (4.1 to 4.8) | Above 700 (above 4.8) |
| Laboratory trial batches | Below 200 (below 1.4) | 200 to 250 (1.4 to 1.7) | 250 to 300 (1.7 to 2.1) | 300 to 350 (2.1 to 2.4) | Above 350 (above 2.4) |
| .Within-batch variation | | | | | |
| Class of operation | Standard deviation for different control standards, psi (MPa) | | | | |
| | Excellent | Very good | Good | Fair | Poor |
| Field control testing | Below 3.0 | 3.0 to 4.0 | 4.0 to 5.0 | 5.0 to 6.0 | Above 6.0 |
| Laboratory trial batches | Below 2.0 | 2.0 to 3.0 | 3.0 to 4.0 | 4.0 to 5.0 | Above 5.0 |

### H. Reliability Assessment

To evaluate the structural reliability implications of in-situ concrete strength variability, a simplified reliability index was calculated based on statistical strength parameters. The reliability index $\beta$ was defined as:

$$\beta=\frac{f_{cr}-f_{design}}{\sqrt{\sigma^2_{material}+\sigma^2_{model}}}$$

where:

- $f_{cr}$ = mean in-situ compressive strength,
- $f_{desigm}$ = design compressive strength,
- $\sigma_{material}$ = standard deviation of measured in-situ concrete strength,
- $\sigma_{model}$ = model uncertainty (0.1 $f_{cr}$).

The reliability index was used to evaluate the probability of non-compliance of in-situ concrete strength with design requirements, providing a probabilistic interpretation of material variability.

## III. Result and Discussion

*Result*

### A. Descriptive Statistics of In-Situ Concrete Strength

A total of 55 Schmidt Hammer test points were obtained from various structural elements of the academic building.

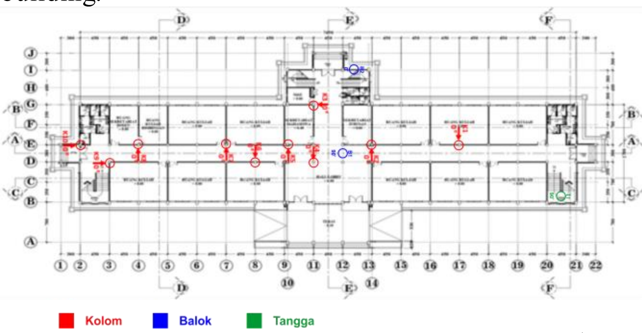


Fig. 4. Spatial distribution of Schmidt Hammer test points on the 1st floor.

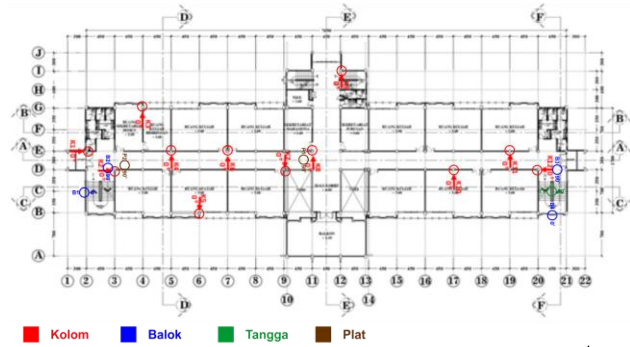


Fig. 5. Spatial distribution of Schmidt Hammer test points on the 2nd floor.

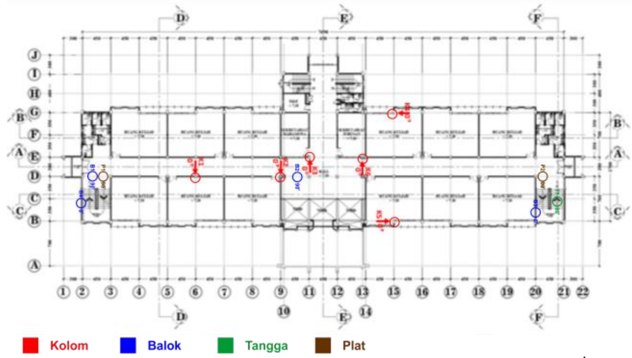


Fig. 6. Spatial distribution of Schmidt Hammer test points on the 3th floor.

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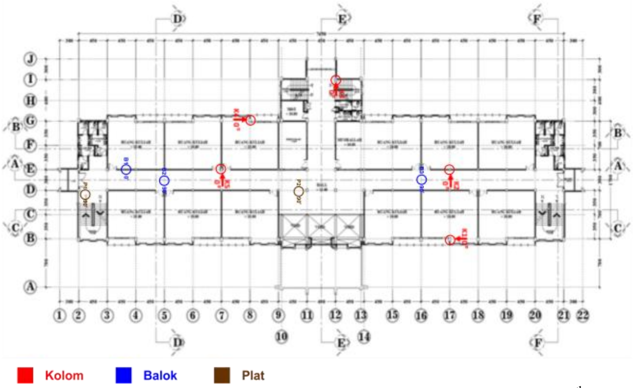


Fig. 7. Spatial distribution of Schmidt Hammer test points on the 4th floor.

The estimated in-situ concrete compressive strength ($f_{ci}$) exhibited a wide variance, ranging from a minimum of 112.77 kg/cm² to a maximum of 683.35 kg/cm². The primary statistical parameters are summarized in Table II.

TABLE III. Statistical summary of in-situ concrete strength

| Statstical Parameter | Value |
|---|---|
| Sample Size (n) | 55 |
| Mean ($f_{cr}$) | 335.48 kg/cm² |
| Standar Deviation (σ) | 120.27 kg/cm² |
| Coefficient of Variation (CV) | 35.85% |
| Minimum | 112.77 kg/cm² |
| Maximum | 683.35 kg/cm² |

The Coefficient of Variation (CV) of 35.9% indicates a high degree of non-uniformity in the concrete quality, significantly exceeding the threshold for "good" quality control (CV < 15%) as established by ACI 214R-02. Consequently, the concrete within this structure is categorized as having poor uniformity. This high variability suggests inconsistencies in the original mixing process, placement, or potential degradation over time [6].

### B. Outlier Identification and Data Dispersion

Outlier analysis was performed utilizing the Interquartile Range (IQR) method and Grubbs' test. Extreme values were identified on both tails of the distribution:

- Lower outliers: approximately 112.77–160.44 kg/cm²
- Upper outliers: 621.63–683.35 kg/cm²

The occurrence of these extreme values indicates: (1) Inconsistencies in the casting quality; (2) Aggregate segregation or variations in the water-cement ratio; (3) Disparities in curing conditions and localized concrete maturity. The high dispersion of the data is reflected by the significant standard deviation (σ = 120.27 kg/cm²). This suggests that the mean strength alone is not a representative indicator of the overall structural quality [7].

### C. Distribution Characteristics of Concrete Strength

Probabilistic distribution analysis reveals that the concrete compressive strength data deviates from a pure normal distribution, instead exhibiting positive skewness, which indicates a tendency toward a lognormal distribution. The observed distributional characteristics are as follows:

- The majority of the data is concentrated within the 250–400 kg/cm² range.
- The presence of extreme high values creates a long right tail.
- The asymmetrical distribution is characteristic of brittle materials.

Lognormal distributions are commonly observed in concrete materials due to the multiplicative nature of production uncertainties and material degradation processes.

### D. Reliability Index Estimation

The reliability index ($\beta$) was calculated using a simplified probabilistic approach to evaluate the structural safety margin. The index is defined as follows:

$$\beta = \frac{f_{cr} - f_{design}}{\sqrt{\sigma^2_{material} + \sigma^2_{model}}}$$

- $f_{cr}$ = 335.48 kg/cm²
- $f_{desigm}$ = 250 kg/cm² (equivalent to $f'_c$ 25 MPa)
- $\sigma_{material}$ = 120.27 kg/cm²
- $\sigma_{model}$ (0.1 $f_{cr}$) = 33.55 kg/cm²

$$\beta = \frac{335.48 - 250}{\sqrt{120.27^2 + 33.55^2}} = 0.69$$

A reliability index of $\beta < 3.0$ generally signifies a low reliability level according to international structural codes, while $\beta < 1.0$ indicates a critically limited material safety margin. This result confirms that material variability is the dominant factor undermining the reliability of the existing structure. The high dispersion of in-situ strength significantly increases the probability of localized failure, even if the mean strength exceeds the design requirement.

*Discussion*

The statistical evaluation of rebound-derived in-situ concrete compressive strength revealed significant variability across the investigated academic building. The coefficient of variation (CV) obtained in this study indicates that the concrete quality is not fully homogeneous, which is typical for cast-in-place reinforced concrete structures constructed under field conditions. According to ACI 214R-02, CV values exceeding 15% reflect poor uniformity and potential inconsistencies in construction practices, material batching, compaction, and curing processes (ACI 214R-02). Similar findings have been reported in previous investigations, where in-situ concrete exhibited substantially higher dispersion than laboratory-cured specimens due to workmanship and environmental effects [8]–[10].

Spatial heterogeneity in rebound values was observed across different structural elements, suggesting non-uniform material properties within the building. Vertical elements such as columns typically exhibit better compaction and lower variability, while horizontal elements such as beams and slabs are more susceptible to segregation, bleeding, and finishing inconsistencies. Moreover, carbonation and environmental exposure can artificially increase surface hardness, leading to potential overestimation of compressive strength when using rebound hammer tests [11]. Therefore, rebound hammer results should be interpreted as indicators of relative surface quality rather than absolute material strength.

Outlier detection identified anomalous rebound-derived strength values, which may indicate localized defects such as honeycombing, voids, microcracking, or inadequate curing. Previous research has emphasized the importance of identifying such anomalies in NDT datasets, as localized weak zones may govern structural performance and durability. Consequently, these zones should be prioritized for further investigation using destructive or semi-destructive testing methods.

The probabilistic analysis indicated that the strength distribution follows a lognormal-like pattern, which is consistent with widely accepted models for concrete material variability. Lognormal distributions are commonly adopted in probabilistic structural engineering due to the multiplicative nature of uncertainties in concrete production, placement, and curing [12]. This distribution assumption supports the application of reliability-based assessment frameworks for existing concrete structures.

The calculated reliability index $\beta$ provides a probabilistic measure of structural performance relative to the design compressive strength. However, it should be emphasized that the uncertainty associated with rebound-strength correlation models is significant and may dominate the reliability estimation. Previous studies reported moderate correlations between rebound hammer values and actual compressive strength, with correlation coefficients typically ranging between 0.6 and 0.8 depending on aggregate type, mix design, and surface condition [13]. Therefore, the reliability indices derived in this study should be considered preliminary indicators rather than definitive safety metrics, especially in the absence of core test calibration.

Comparison with international case studies confirms that rebound hammer testing is effective for assessing concrete uniformity and identifying potential weak zones, but it requires calibration with destructive testing for accurate strength quantification [14], [15]. Hybrid NDT approaches combining rebound hammer and ultrasonic pulse velocity (UPV) have been shown to significantly improve prediction accuracy and reduce epistemic uncertainty, suggesting that multi-parameter assessment frameworks are preferable for comprehensive structural evaluation.

From a practical perspective, the results demonstrate that rebound hammer testing offers a rapid, cost-effective preliminary assessment tool for academic buildings, particularly in developing regions where destructive testing may be limited. The method can support maintenance planning, identify critical structural zones, and provide baseline datasets for long-term structural health monitoring. Nevertheless, for structural safety certification and retrofitting design, rebound hammer data should be complemented by core sampling or advanced NDT techniques to reduce uncertainty and enhance reliability.

This study has several limitations. First, rebound hammer testing measures surface hardness rather than internal compressive strength, which may be influenced by carbonation and moisture conditions. Second, the absence of core test calibration limits the accuracy of strength estimation. Third, environmental and aging effects were not explicitly quantified. These limitations are consistent with the inherent constraints of rebound hammer-based assessment reported in previous research [9], [14], [16].

Future research should focus on calibrating rebound hammer results with core test data, integrating multi-NDT approaches such as UPV and pull-out testing, developing AI-based prediction models for in-situ concrete strength, monitoring long-term degradation trends in academic buildings, and establishing regional correlation models for Indonesian concrete materials. Such advancements would significantly improve the reliability and applicability of NDT-based structural assessment frameworks.

## IV. Conclusion

This study investigated the variability and reliability of in-situ concrete compressive strength in an academic building using Schmidt hammer testing combined with statistical and probabilistic analyses. The results demonstrated that rebound-derived compressive strength values exhibit significant dispersion, indicating non-uniform concrete quality across the investigated structural elements. The coefficient of variation exceeded typical thresholds for good construction quality, highlighting the influence of field construction practices, material variability, and curing conditions on in-situ concrete performance.

The statistical analysis revealed a wide range of estimated compressive strength values, with several outliers indicating potential localized defects or anomalous zones. Distribution fitting suggested that the concrete strength data follow a lognormal-like distribution, consistent with established probabilistic models for concrete material properties. These findings confirm that mean strength values alone are insufficient for evaluating existing structures and that variability metrics must be considered in structural assessment.

The reliability analysis indicated that material variability significantly influences structural reliability indices. The derived reliability index values should be interpreted as preliminary indicators due to the inherent uncertainty associated with rebound-strength correlation models. Nevertheless, the probabilistic framework adopted in this study demonstrates the feasibility of integrating NDT data into reliability-based structural assessment, providing a quantitative basis for decision-making in existing building evaluation.

From a practical perspective, the results confirm that Schmidt hammer testing is an effective and cost-efficient tool for preliminary assessment of concrete structures, particularly in academic and institutional buildings where destructive testing may be limited. The methodology presented can support maintenance prioritization, identification of critical structural zones, and baseline data generation for long-term monitoring programs.

However, this study has limitations. The rebound hammer test measures surface hardness rather than internal compressive strength, and no core test calibration was conducted. Environmental effects such as carbonation and moisture conditions were not explicitly quantified. Therefore, the strength estimates and reliability indices should be considered conservative and indicative rather than definitive. Future studies should integrate core sampling, ultrasonic pulse velocity testing, and multi-parameter NDT frameworks to improve prediction accuracy and reduce epistemic uncertainty.

Overall, this research contributes a statistical-descriptive and reliability-based framework for assessing in-situ concrete strength using rebound hammer data in existing academic buildings. The findings provide empirical evidence of material variability in real structures and highlight the importance of probabilistic approaches in structural evaluation. The proposed methodology can be extended to other building types and regions, contributing to the development of regional calibration models and performance-based assessment strategies for aging concrete infrastructure.

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