P-ISSN : 2598-1277
E-ISSN : 2621-3966

JOURNAL OF GREEN SCIENCE AND TECHNOLOGY

LIMITATIONS OF UPV-BASED COMPRESSIVE STRENGTH ESTIMATION FOR STRUCTURAL ACCEPTANCE ASSESSMENT OF REINFORCED CONCRETE COLUMNS

Heri Khoeri[1*], Muhammad Aziz Komarudin[2], Dini Sofiana[3]
[1] *Tama Jagakarsa University, Jakarta.*
Corresponding Author's Email: hkhoeri@gmail.com
Corresponding Author's Phone Number: 08158255374
[2] *PT Hesa Laras Cemerlang. https://hesa.co.id*
Email: kontak@hesa.co.id
[3] *Postgraduate Program, Faculty of Engineering, University of Indonesia.*
Email: dini@hesa.co.id

ABSTRACT

Ultrasonic Pulse Velocity (UPV) is widely used for evaluating concrete quality and estimating in situ compressive strength. However, its suitability for structural acceptance assessment remains questionable when workmanship-related defects are present. This study investigates the limitations of UPV-based strength estimation through a case study involving 38 reinforced concrete columns exhibiting segregation, geometric irregularities, twisting, out-of-plumbness, and suspected construction joint defects. The investigation included visual inspection, review of 45 concrete cylinder test results, 570 UPV measurements, development of a project-specific UPV-strength correlation using five calibration specimens, and 75 apparent crack-depth measurements. The concrete cylinder tests satisfied the specified design strengths, while UPV results generally classified the concrete as Medium/Fair to Good according to IS 13311 (Part 1):1992. However, UPV-based strength estimates ranged from 3.27 MPa to 73.31 MPa, indicating considerable uncertainty, which may also reflect the limited calibration dataset. Apparent crack-depth evaluation showed that 80% of the calculated values exceeded the physical dimensions of the tested columns, indicating that these results should be interpreted as evidence of loss of continuity, lack of bond, or construction joint discontinuities rather than actual crack depths. The findings demonstrate that satisfactory concrete strength and acceptable UPV classifications do not necessarily indicate satisfactory structural acceptability. Therefore, UPV-based strength estimation should not be used as the sole basis for acceptance assessment, and structural decisions should incorporate visual inspection, construction quality, and evidence of structural continuity.

Keywords: assessment, concrete discontinuity, crack depth, structural acceptance, UPV.

1. INTRODUCTION

Concrete compressive strength is one of the most important parameters used for quality control and acceptance of reinforced concrete structures. In most construction projects, structural acceptance is primarily based on the compressive strength of standard concrete specimens tested during construction. However, satisfactory compressive strength results do not necessarily guarantee the integrity and overall quality of the completed structure. Various construction-related defects, such as segregation, honeycombing, inadequate consolidation, poor workmanship, geometric irregularities, and defective construction joints, may significantly affect structural performance despite compliance with specified concrete strength requirements [1], [2].

In this study, structural acceptability refers to the engineering judgment regarding whether a completed structural element can be accepted for service based on the combined evaluation of concrete quality,

P-ISSN : 2598-1277
E-ISSN : 2621-3966

workmanship, geometric compliance, structural continuity, and visual inspection findings. Accordingly, this study distinguishes three different aspects of structural evaluation: concrete quality, which describes the material properties of concrete; structural integrity, which concerns the continuity and physical condition of the constructed member; and structural capacity, which refers to the load-carrying resistance of the structural element. The present study addresses only the first two aspects and does not include analytical evaluation of the axial-flexural capacity of the investigated columns.

Among various non-destructive testing (NDT) techniques, Ultrasonic Pulse Velocity (UPV) has become one of the most widely used methods because of its simplicity, rapid implementation, and ability to assess large concrete areas without causing damage [3], [4]. UPV measures the travel time of ultrasonic waves through concrete and is commonly applied to evaluate concrete uniformity, detect internal discontinuities, estimate apparent crack depth, and predict compressive strength using empirical correlations [4], [5].

Numerous studies have investigated the relationship between UPV and concrete compressive strength. Previous research generally indicates that higher ultrasonic pulse velocities tend to correspond to higher compressive strengths [6], [7], [8]. Consequently, many researchers have proposed empirical equations relating UPV measurements to concrete strength. However, the applicability of such correlations remains highly dependent on concrete composition, aggregate type, moisture condition, curing history, specimen geometry, and testing configuration [2], [6]. Therefore, a correlation developed for one project may not be directly applicable to another without proper calibration.

International standards and technical guidelines also recognize these limitations. ASTM C597 states that UPV is primarily intended for evaluating concrete uniformity and detecting internal discontinuities rather than directly assessing structural performance [4]. Likewise, ACI 228.1R recommends that non-destructive testing be used together with destructive verification methods whenever reliable strength evaluation is required [2]. These recommendations emphasize that UPV results should be interpreted within the broader context of construction quality and engineering judgment.

Recent investigations have likewise demonstrated that the reliability of UPV-based strength prediction depends strongly on the calibration dataset and project-specific material characteristics [9], [10]. Discrepancies between UPV-estimated strengths and measured strengths obtained from core specimens have also been reported in existing concrete structures [11]. Although previous studies have primarily focused on improving prediction accuracy and developing empirical UPV-strength correlations, comparatively few have examined situations in which acceptable UPV classifications coexist with severe workmanship-related defects affecting structural integrity. Such cases raise important questions regarding the suitability of UPV-based strength estimation for structural acceptance assessment.

This study investigates a real construction case involving reinforced concrete columns in a multipurpose building. Although concrete cylinder tests satisfied the specified design strengths and UPV measurements generally indicated acceptable concrete quality, visual inspections revealed significant workmanship-related defects, including segregation, poor finishing quality, column twisting, out-of-plumbness, and suspected construction joint deficiencies. To further assess structural integrity, UPV testing and crack depth measurements were conducted.

The objective of this study is to evaluate the limitations of UPV-based strength estimation for acceptance assessment of reinforced concrete columns. Particular attention is given to the discrepancy between UPV-derived strength estimates and structural acceptability as influenced by workmanship quality, construction joint integrity, and structural continuity. The novelty of this study lies in demonstrating that satisfactory UPV classifications and acceptable estimated concrete strengths do not necessarily imply satisfactory structural acceptability. By integrating visual inspection, compressive strength records, UPV measurements, and crack depth evaluation, this study highlights the limitations of relying solely on UPV-based strength estimation for acceptance decisions.

P-ISSN : 2598-1277
E-ISSN : 2621-3966

2. RESEARCH METHOD

2.1. Research Framework

This study was conducted as a field investigation of reinforced concrete columns in a multipurpose building project that exhibited visible construction defects during construction. Although the available concrete cylinder test results satisfied the specified design strength requirements, concerns were raised regarding the overall quality and integrity of the completed columns due to observed workmanship-related deficiencies. To evaluate the condition of the structure, a comprehensive assessment program was carried out consisting of visual inspection, review of concrete compressive strength records, Ultrasonic Pulse Velocity (UPV) testing, crack depth measurements, and statistical analysis of the obtained results. The methodology adopted in this study is illustrated in Figure 1.

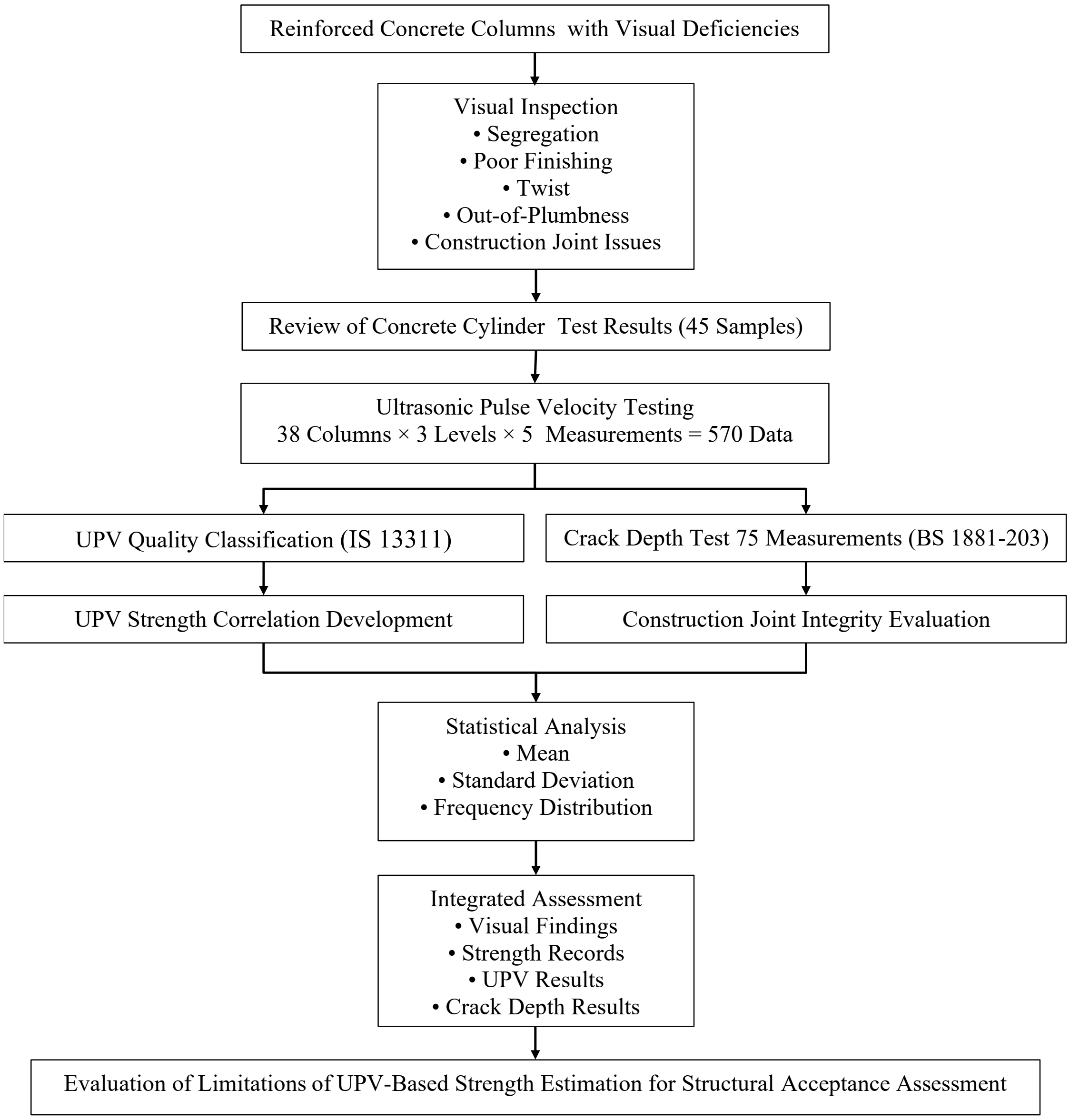


Figure 1. Research Methodology Flowchart for Evaluation of UPV-Based Strength Estimation in Reinforced Concrete Columns

The objective of this methodology was to investigate whether UPV-based strength estimation alone could provide sufficient confidence for structural acceptance decisions when significant workmanship-related defects were present.

 P-ISSN : 2598-1277
E-ISSN : 2621-3966

2.2. Case Study Description

This study investigated 38 reinforced concrete columns in a multipurpose building, consisting of 24 columns with dimensions of 400 × 400 mm (K1) and 14 columns with dimensions of 300 × 300 mm (K2), as shown in **Figure 2**. All columns had a clear height of approximately 4.0 m. Visual inspection identified various workmanship-related defects, including segregation, honeycombing, poor finishing quality, twisting, out-of-plumbness, and suspected construction joint deficiencies.

The UPV investigation was conducted 35 days after concrete casting, when the concrete had reached the normal age for early acceptance evaluation. All tested columns were designed with a specified concrete compressive strength of FC30, whereas the FC25 concrete was used for other structural components and was not included in the UPV investigation. The construction joints were intentionally located approximately 1.0 m below the beam-column joint, corresponding to the planned interruption of concrete placement during construction.

Concrete placement was carried out using a truck-mounted concrete pump, followed by internal vibration for consolidation. After casting, the concrete was subjected to standard water curing for seven days, followed by exposure to normal ambient conditions until the time of testing. During the UPV measurements, the concrete surface was in a normal air-dry condition, with an estimated surface moisture content of approximately 4–6%, and no free surface water was present. The transducer surfaces were coupled using ultrasonic coupling gel to ensure adequate acoustic transmission during testing.

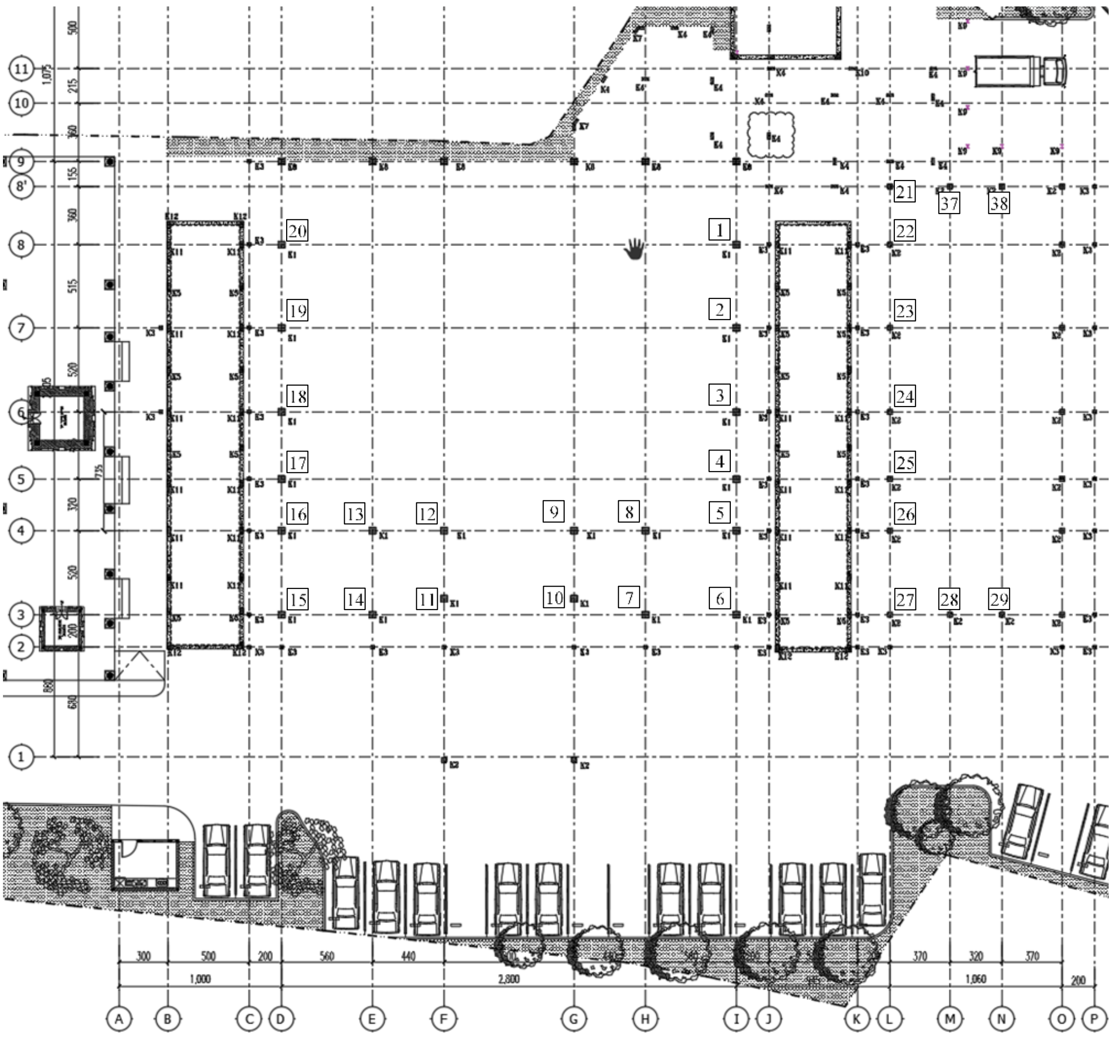


Figure 2. Plan View Showing the Locations of Tested Columns

P-ISSN : 2598-1277
E-ISSN : 2621-3966

Because concerns were primarily associated with construction quality rather than material supply, both destructive and non-destructive evaluation data were reviewed to determine the acceptability of the constructed columns.

2.3. Review of Concrete Compressive Strength Records

Concrete compressive strength data were obtained from standard cylinder tests conducted during construction quality control activities. A total of 45 concrete cylinder specimens representing various casting batches were reviewed. The compressive strength records were evaluated with reference to the acceptance criteria specified in SNI 2847:2019 [1]. The cylinder test results were used to verify whether the supplied concrete met the specified design compressive strengths and to provide a reference for subsequent UPV-strength correlation analysis.

2.4. Ultrasonic Pulse Velocity Testing

Ultrasonic Pulse Velocity (UPV) testing was performed in accordance with [4], [12], using a Proceq Pundit PL-200 ultrasonic pulse velocity tester equipped with 54 kHz exponential transducers. Measurements were conducted at three elevations along each column: lower zone, middle zone, and upper zone. At each elevation, five individual readings were recorded to reduce local measurement variability. Consequently, the total number of UPV measurements was 570 test readings (38 columns × 3 elevations × 5 measurements).

The direct transmission method was selected because it provides the highest measurement reliability by placing the transmitting and receiving transducers on opposite faces of the concrete member. Prior to testing, loose particles, laitance, and surface contaminants were removed to provide adequate contact between the transducers and the concrete surface. A commercial ultrasonic coupling gel was applied at each measurement point to minimize acoustic impedance at the transducer–concrete interface.

Measurements were conducted on air-dry concrete surfaces under normal ambient conditions, approximately 35 days after casting. The ultrasonic travel path was oriented perpendicular to the column cross-section, resulting in nominal path lengths of 300 mm for K2 columns (300 × 300 mm) and 400 mm for K1 columns (400 × 400 mm). The measured pulse velocity was calculated by dividing the known path length by the recorded travel time.

To minimize the influence of embedded reinforcement on pulse velocity measurements, the transducer locations were selected such that the direct transmission path avoided intersecting the longitudinal reinforcing bars whenever practicable. Measurements were taken through concrete regions with minimal reinforcement interference, and locations directly crossing reinforcement or embedded metallic components were avoided based on the reinforcement drawings and field observations. Consequently, no numerical correction for reinforcement effects was applied.

At each measurement location, stable readings were verified before recording the final value. Measurements showing unstable coupling or obvious operational errors were repeated immediately. Because the purpose of the investigation was to evaluate the actual variability of the constructed columns, no statistical outlier removal was performed. All valid measurements were retained for subsequent analysis. A schematic illustration of the direct transmission configuration used in this study is presented in Figure 3.

The pulse velocity was calculated as:

$$V = \frac{L}{T} \qquad (1)$$

where:
V = ultrasonic pulse velocity (km/s)
L = travel distance (m)
T = pulse travel time (s)

P-ISSN : 2598-1277
E-ISSN : 2621-3966

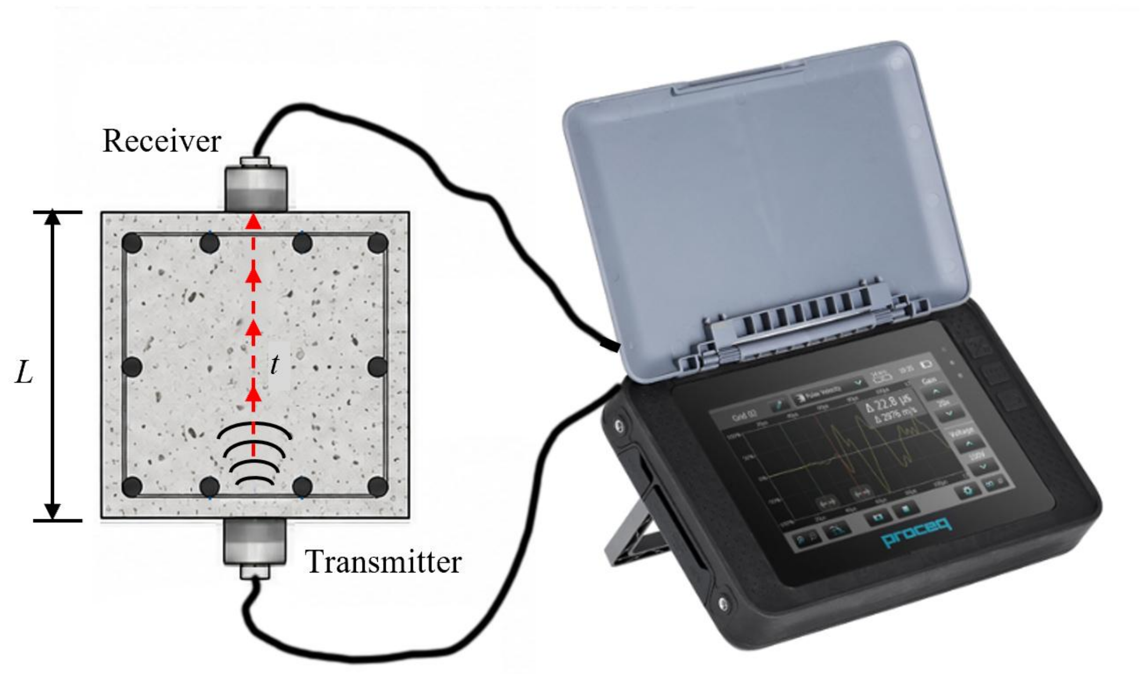


Figure 3. Schematic Illustration of the direct transmission configuration

The obtained UPV values were classified according to IS 13311 (Part 1):1992 [3] as shown in Table 1.

Table 1. UPV Quality Classification According to IS 13311 (Part 1):1992

Pulse Velocity (km/s)	Concrete Quality
> 4.5	Excellent
3.5–4.5	Good
3.0–3.5	Medium/Fair
< 3.0	Doubtful/Poor

The UPV results were subsequently used to evaluate concrete uniformity and to estimate compressive strength through empirical correlation.

2.5. Crack Depth Measurement

To investigate the integrity of construction joints, crack depth measurements were performed using the indirect ultrasonic transmission method based on the principles described in BS 1881: Part 203:1986 [5]. A total of 75 crack depth measurements were conducted at locations corresponding to construction joints and areas exhibiting visible discontinuities.

The crack depth was calculated using:

$$d = \frac{x}{2}\sqrt{\left(\frac{t_2}{t_1}\right)^2 - 1} \qquad (2)$$

where:

d = estimated crack depth;

P-ISSN : 2598-1277
E-ISSN : 2621-3966

x = distance between transducers;

t_1 = transit time measured away from the crack;

t_2 = transit time measured across the crack.

The measured crack depths were compared with the actual dimensions of the investigated columns. Particular attention was given to cases where the calculated crack depth exceeded the column dimensions, as such results may indicate discontinuities or lack of bond at construction joints rather than actual crack penetration depth [13].

2.6. Development of UPV–Strength Correlation

To investigate the applicability of UPV-based strength estimation, empirical correlations were developed using five representative concrete samples for which both compressive strength and UPV measurements were available [14]. Regression analysis was performed to establish a project-specific relationship between compressive strength and pulse velocity. The resulting correlation equation was subsequently applied to estimate the compressive strength of the remaining columns based on their measured UPV values. The estimated strengths were not used as acceptance criteria but were employed to evaluate the limitations of UPV-based assessment when compared with visual observations and crack depth findings [15], [16].

2.7. Statistical Analysis

Statistical analysis was performed to evaluate the distribution and variability of UPV-derived concrete strength estimates. The following statistical parameters were calculated: mean value, standard deviation, coefficient of variation, and frequency distribution. The estimated concrete strengths were analyzed to identify trends, variability among columns, and potential differences between lower, middle, and upper column regions.

2.8. Structural Acceptance Assessment

The final assessment was conducted by integrating: (1) Visual inspection findings; (2) Concrete cylinder test results; (3) UPV classifications; (4) UPV-based strength estimations; and (5) Crack depth measurements. Rather than relying solely on estimated compressive strength values, the acceptance assessment considered the overall structural condition, workmanship quality, and indications of continuity or discontinuity within the investigated columns. This integrated approach was adopted to evaluate the suitability and limitations of UPV-based strength estimation as a decision-making tool for acceptance assessment of reinforced concrete structures.

3. RESULTS AND DISCUSSION

3.1. Visual Inspection Findings

Visual inspection revealed several workmanship-related deficiencies affecting the investigated reinforced concrete columns. The observed defects included surface segregation, poor concrete finishing, local surface voids, geometric distortion, column twisting, and out-of-plumbness as presented in Figure 4. In addition, irregularities were observed at several construction joint locations, suggesting possible deficiencies in the bonding between successive concrete pours.

Unlike material-related defects, these observations indicate potential issues associated with construction practices and quality control during casting operations. Therefore, the visual findings raised concerns regarding the overall integrity and monolithic behavior of the constructed columns.

P-ISSN : 2598-1277
E-ISSN : 2621-3966

Figure 4. Representative Workmanship-Related Deficiencies Identified During Visual Inspection: (a) Severe honeycombing and inadequate concrete consolidation; (b) Construction joint with localized segregation and surface defects; and (c) Severe segregation at the column base with evidence of improper patch repair

3.2. Concrete Cylinder Strength Results

A total of 45 concrete cylinder specimens (25 FC25 and 20 FC30) were evaluated. As summarized in **Table 2**, all specimens exceeded the specified design strengths, with average compressive strengths of 35.8 MPa for FC25 and 38.5 MPa for FC30.

Table 2. Summary of Concrete Cylinder Test Results

Parameter	FC25	FC30
Number of Samples	25	20
Average Strength (MPa)	35.8	38.5
Minimum Strength (MPa)	29.4	32.1
Maximum Strength (MPa)	42.6	46.8

According to SNI 2847:2019, all 45 concrete cylinder test results satisfied the specified acceptance criteria. No individual test result was below the specified design compressive strength, indicating that the concrete supplied to the project complied with the required strength provisions. The concrete cylinder test results are presented to confirm that the specified concrete strength requirements were achieved during construction. Therefore, the discrepancies observed between the cylinder test results and the UPV-based strength estimates are unlikely to be attributed to inadequate concrete strength, but rather to the limitations of UPV interpretation in the presence of workmanship-related defects and concrete discontinuities.

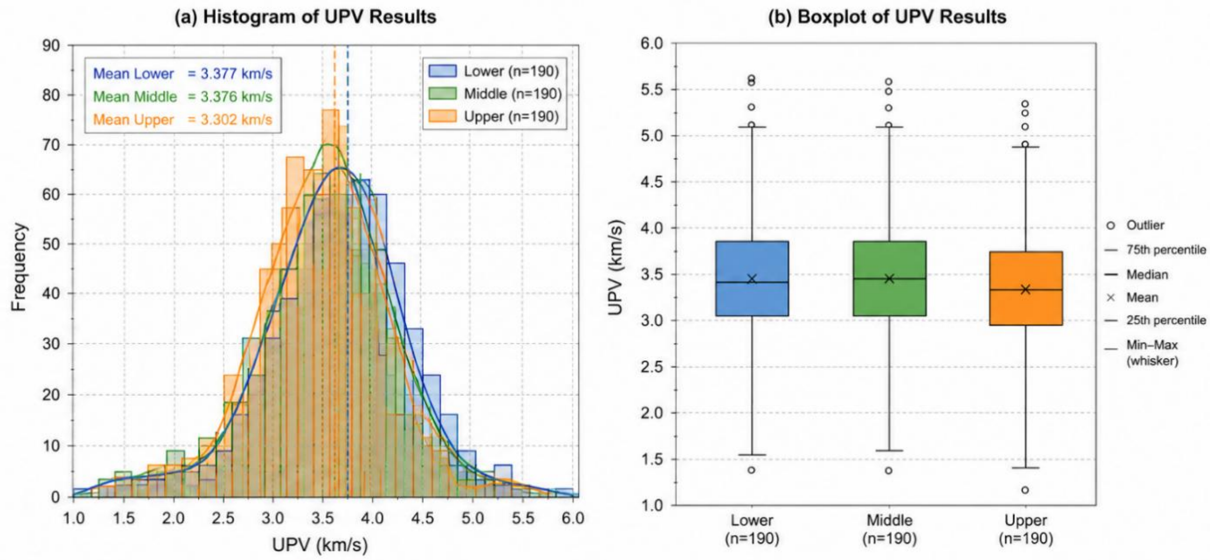
3.3. UPV Test Results

UPV measurements were conducted at three elevations of each column: lower, middle, and upper regions. A total of 570 UPV measurements were obtained from 38 reinforced concrete columns, with measurements performed at three elevations and five repetitions at each location. Statistical analysis of the complete dataset is summarized in Table 3.

P-ISSN : 2598-1277
E-ISSN : 2621-3966

Table 3. Statistical Summary of UPV Results

Elevation	Mean (km/s)	SD (km/s)	CoV (%)
Lower	3.377	0.565	16.74
Middle	3.376	0.45	13.33
Upper	3.302	0.422	12.77
Overall	3.351	0.482	14.39



Elevation	N (data)	Mean (km/s)	SD (km/s)	CoV (%)	Min (km/s)	Q1 (km/s)	Median (km/s)	Q3 (km/s)	Max (km/s)
Lower	190	3.377	0.565	16.74	1.343	2.985	3.361	3.738	5.164
Middle	190	3.376	0.450	13.33	2.421	3.061	3.390	3.704	5.164
Upper	190	3.302	0.422	12.77	0.898	3.030	3.306	3.571	4.548

Notes: CoV = Coefficient of Variation (SD / Mean × 100%).

Figure 5. Distribution of UPV Results by Elevation: (a) Histogram and (b) Boxplot

The average pulse velocities measured at the lower and middle regions were nearly identical, amounting to 3.377 km/s and 3.376 km/s, respectively. In contrast, the upper region exhibited a slightly lower average pulse velocity of 3.302 km/s. This trend indicates a modest reduction in concrete quality toward the top portion of the columns.

The coefficient of variation (CoV) ranged from 12.77% to 16.74%. The lower region exhibited the highest variability, suggesting greater heterogeneity of concrete quality near the base of the columns. Conversely, the upper region showed the lowest CoV, indicating more consistent, although generally lower, UPV values. Overall, the measured average UPV values fall predominantly within the Medium/Fair to Good quality range according to IS 13311 (Part 1):1992. Nevertheless, the statistical distribution demonstrates that concrete quality is not completely uniform throughout the column height, which is consistent with the visual observations and subsequent crack-depth investigation. The UPV measurements were classified according to the quality categories specified in IS 13311 (Part 1):1992, as presented in Table 4.

Table 4. Frequency Distribution of UPV Classification

Category	Lower	Middle	Upper
Good (3.5–4.5 km/s)	39%	37%	21%
Medium/Fair (3.0–3.5 km/s)	45%	50%	63%
Doubtful/Poor (<3.0 km/s)	16%	13%	16%
Excellent (>4.5 km/s)	0%	0%	0%

The majority of measurements were classified as Medium/Fair, representing 45%, 50%, and 63% of the measurements in the lower, middle, and upper regions, respectively. The proportion of measurements classified as Good ranged from 21% to 39%, while Doubtful/Poor results accounted for approximately 13%–16% of the measurements. No measurements were classified as Excellent. These results indicate that the investigated concrete columns generally exhibited moderate ultrasonic quality rather than high-quality concrete characteristics. Furthermore, the relatively consistent presence of Doubtful/Poor classifications across all elevations suggests that localized quality deficiencies were not confined to a particular region of the columns.

An interesting trend can be observed in the upper region, where the percentage of Good-quality measurements decreased from 39% in the lower region to 21%, while the proportion of Medium/Fair measurements increased to 63%. This observation is consistent with the slight reduction in average UPV values reported in the statistical analysis and may indicate reduced concrete quality or increased heterogeneity toward the upper portions of the columns. Overall, the UPV classification results suggest that although the concrete cannot be categorized as severely deteriorated, its quality is predominantly within the Medium/Fair range. Therefore, the UPV results alone do not provide sufficient evidence to confirm satisfactory structural acceptability, particularly when significant workmanship-related defects and construction joint discontinuities are also present.

3.4. Correlation Between UPV and Compressive Strength

Five representative concrete samples with known compressive strengths were used to develop a project-specific correlation between UPV and concrete strength.

The resulting empirical equation is expressed as:

$$fc' = 1.6965e^{0.7293V} \quad (3)$$

The coefficient of determination obtained from the regression analysis was:

$$R^2 = 0.7736 \quad (4)$$

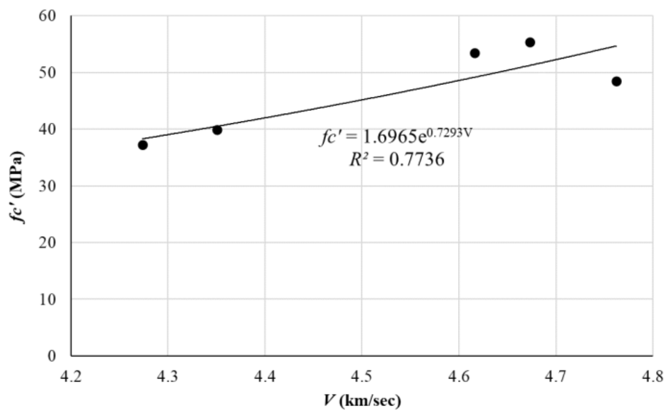


Figure 6. Project-Specific Correlation Between UPV and Compressive Strength

Although the coefficient of determination (R^2 = 0.7736) indicates a reasonably good correlation, the calibration model was developed from only five samples and therefore should be interpreted with caution.

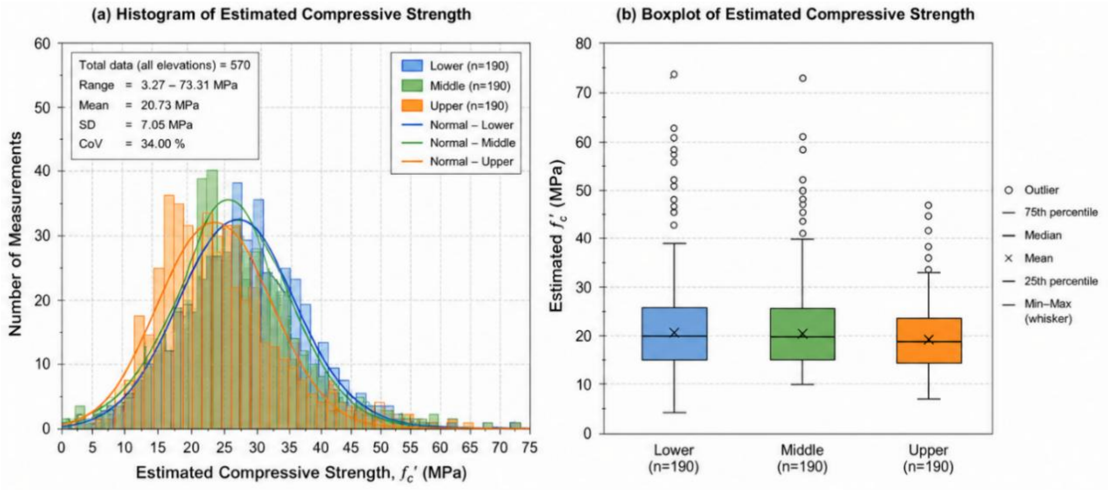
3.5. Estimated Concrete Strength Based on UPV

The project-specific correlation developed from five calibration samples was subsequently applied to estimate the compressive strength of all investigated columns. A total of 570 strength estimates were generated from the UPV measurements collected at the lower, middle, and upper regions of the columns.

P-ISSN : 2598-1277
E-ISSN : 2621-3966

Table 5. Statistical Summary of UPV-Based Strength Estimation

Elevation	Mean (MPa)	SD (MPa)	CoV (%)
Lower	21.4	7.3	34.11
Middle	21.05	7.76	36.87
Upper	19.72	5.86	29.72
Overall	20.73	7.05	34



Elevation	N (data)	Min (MPa)	Q1 (MPa)	Median (MPa)	Mean (MPa)	Q3 (MPa)	Max (MPa)	SD (MPa)	CoV (%)
Lower	190	3.27	16.25	20.28	21.40	25.63	36.96	7.30	34.11
Middle	190	9.92	15.35	19.84	21.05	25.61	73.31	7.76	36.87
Upper	190	7.38	15.22	18.97	19.72	23.52	46.78	5.86	29.72
Overall	**570**	**3.27**	**15.60**	**19.97**	**20.73**	**24.65**	**73.31**	**7.05**	**34.00**

Notes: f_c' = estimated compressive strength from UPV using project-specific correlation (developed from five calibration samples).

Figure 7. Distribution of UPV-Based Compressive Strength Estimates: (a) Histogram and (b) Boxplot

The estimated compressive strengths ranged from 3.27 MPa to 73.31 MPa, with an overall average of 20.73 MPa and a standard deviation of 7.05 MPa. The coefficient of variation reached approximately 34%, indicating substantial dispersion in the estimated strength values. The middle region exhibited the highest variability (CoV = 36.87%), while the upper region showed slightly lower variability (CoV = 29.72%). Nevertheless, all regions demonstrated considerable scatter in the estimated strengths. Such high coefficients of variation indicate pronounced local heterogeneity in ultrasonic wave propagation, which is likely associated with concrete segregation, construction joint conditions, and other workmanship-related defects identified during the visual inspection. The wide range of estimated strengths is illustrated in **Figure 7**. While several measurements produced strength estimates exceeding 40 MPa, other measurements yielded values below 10 MPa. Such variability is difficult to reconcile with the relatively consistent concrete cylinder test results obtained during construction.

These findings suggest that UPV-based strength estimation is highly sensitive to local variations in wave propagation characteristics. Factors such as segregation, construction joint discontinuities, poor compaction, geometric irregularities, and measurement uncertainty may significantly influence the estimated strength values. Consequently, although the developed correlation provides a practical means for estimating in situ concrete strength, the resulting values should be interpreted with caution. The substantial variability observed in this study demonstrates that UPV-based strength estimation alone may not provide a sufficiently reliable basis for structural acceptance decisions.

Interestingly, all concrete cylinder specimens satisfied the specified design strength requirements, whereas the UPV-based strength estimates varied from as low as 3.27 MPa to as high as 73.31 MPa. This discrepancy highlights a fundamental limitation of UPV-based strength estimation when used for acceptance assessment. The results indicate that wave propagation characteristics may be affected not only by material strength but also by workmanship quality, construction joint integrity, and local concrete heterogeneity. Therefore, direct interpretation of UPV measurements as equivalent compressive strength may lead to misleading conclusions regarding structural acceptability.

3.6. Crack Depth Evaluation and Interpretation of Construction Joint Integrity

A total of 75 crack depth measurements were performed at suspected construction joint locations using the Ultrasonic Pulse Velocity (UPV) method. The measured crack depths ranged from 0.110 m to 1.020 m, with an average value of 0.564 m and a standard deviation of 0.232 m. The relatively high coefficient of variation (41.2%) indicates significant variability in the continuity condition of the investigated columns.

Table 6. Summary of Crack Depth Measurement Results

Parameter	Value
Number of Measurements	75
Minimum Crack Depth (m)	0.11
Maximum Crack Depth (m)	1.02
Average Crack Depth (m)	0.564
Standard Deviation (m)	0.232
Coefficient of Variation (%)	41.2

The investigated columns consisted of K1 columns (400 mm × 400 mm) and K2 columns (300 mm × 300 mm). A comparison between measured crack depth and actual column dimensions revealed that many calculated crack depths exceeded the physical dimensions of the corresponding columns. Specifically, 60 out of 75 measurements (80%) produced crack depths greater than the column dimensions.

Table 7. Comparison Between Crack Depth and Column Dimensions

Interpretation	Number of Measurements	Percentage
Within Column Dimension	15	20%
Exceeding Column Dimension	60	80%

According to BS 1881: Part 203 and the fundamental principles of ultrasonic crack-depth measurement, the crack-depth equation assumes that the investigated discontinuity is a finite crack embedded within an otherwise continuous concrete medium. Under such conditions, the calculated crack depth represents the approximate penetration depth of the crack.

However, when the calculated crack depth exceeds the physical dimensions of the structural element, the result can no longer be interpreted as an actual crack depth. Instead, it indicates that the ultrasonic pulse is unable to establish a continuous transmission path through the investigated section. This condition is commonly associated with loss of continuity, lack of bond between successive concrete pours, separation at construction joints, and non-monolithic behavior of the concrete element. Therefore, the results obtained in this investigation strongly suggest that the detected discontinuities are not merely localized cracks but may represent significant defects at the construction joints [17], [18].

 P-ISSN : 2598-1277
E-ISSN : 2621-3966

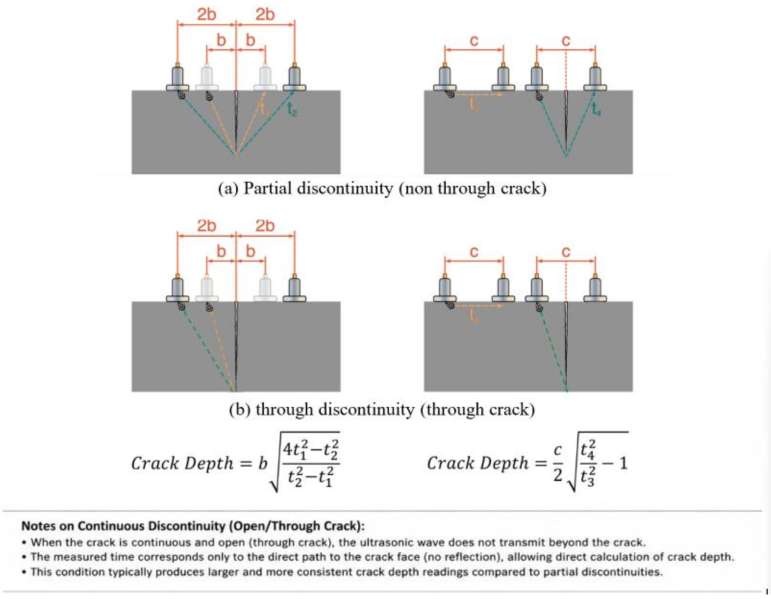


Figure 8. Interpretation of UPV Crack Depth Measurements in Partial and Through Discontinuities

The crack depth findings are consistent with the visual observations made during the field inspection. Several columns exhibited segregation, poor concrete finishing, geometric irregularities, twisting, and indications of unsatisfactory construction joint execution. Although the UPV classification generally indicated Medium/Fair to Good concrete quality, the crack depth measurements revealed evidence of discontinuities that cannot be adequately captured through conventional UPV classification alone. Consequently, the crack depth investigation provides an important complementary assessment of structural integrity.

The combination of visual deficiencies and extensive indications of loss of continuity suggests that the investigated columns may not behave as fully monolithic structural elements. Therefore, the structural acceptability of the columns cannot be established solely based on concrete compressive strength records or UPV-derived strength estimates [19].

3.7. Discussion: Limitations of UPV-Based Strength Estimation for Acceptance Assessment

The assessment of the investigated reinforced concrete columns was performed by integrating visual inspection findings, concrete cylinder strength records, UPV measurements, UPV-based strength estimation, and crack depth evaluation. This integrated approach was adopted to evaluate the reliability of UPV-based strength estimation as a basis for structural acceptance assessment.

The concrete cylinder test results indicated that all tested specimens satisfied the specified design compressive strengths. From a material strength perspective, the supplied concrete generally complied with the project requirements. However, compliance with concrete cylinder strength requirements alone does not necessarily ensure the quality and integrity of the completed structural elements. The UPV measurements generally classified the concrete as Medium/Fair to Good according to IS 13311 (Part 1):1992. Statistical analysis showed average pulse velocities ranging from 3.302 km/s to 3.377 km/s, suggesting moderate concrete quality throughout the investigated columns. Furthermore, the majority of measurements fell within the Medium/Fair and Good categories, which could lead to an initial impression that the concrete quality was generally acceptable. A project-specific correlation developed from five calibration samples was subsequently used to estimate the in situ compressive strength of the columns. The estimated strengths ranged from 3.27 MPa to 73.31 MPa, with substantial variability observed throughout the dataset. Such a wide range highlights the sensitivity of UPV-based strength estimation to local variations in wave propagation characteristics and demonstrates the uncertainty associated with extrapolating strength from a limited calibration dataset. More importantly, the crack depth investigation revealed substantial evidence of discontinuities within the investigated columns.

A total of 60 out of 75 measurements (80%) produced crack depths exceeding the physical dimensions of the tested columns. Since crack depths greater than the member dimensions cannot physically represent actual crack penetration, these results are interpreted as indications of loss of continuity, lack of bond, separation at construction joints, or non-monolithic behavior of the concrete elements.

These findings were further supported by visual observations, which identified segregation, poor finishing quality, geometric irregularities, column twisting, and out-of-plumbness. The consistency between visual observations and crack depth measurements suggests that the observed deficiencies are not merely superficial defects but may reflect fundamental issues related to construction quality and structural integrity [20]. The findings of this study demonstrate a significant limitation of UPV-based strength estimation when used for acceptance assessment [21]. Although the UPV classifications generally indicated Medium/Fair to Good concrete quality and the cylinder strength tests satisfied the specified design requirements, the visual inspection and crack depth investigation revealed substantial evidence of construction-related deficiencies and discontinuities [22]. Consequently, satisfactory UPV results do not necessarily imply satisfactory structural acceptability [20].

Therefore, UPV-based strength estimation should be regarded primarily as a supplementary assessment tool rather than a standalone acceptance criterion. Structural acceptance decisions should integrate material strength data, visual inspection findings, construction quality assessment, and verification of structural continuity to ensure that the completed elements are capable of performing as intended within the structural system. The findings of this study are consistent with the recommendations of ASTM C597, ACI 228.1R, and ACI 562, which emphasize that non-destructive testing results should be interpreted together with visual observations, destructive verification, and engineering judgment when evaluating structural acceptability [2], [4], [14].

4. CONCLUSION

This study evaluated the applicability of UPV-based strength estimation for acceptance assessment of reinforced concrete columns exhibiting significant workmanship-related defects. The concrete cylinder test results indicated that all tested specimens satisfied the specified design compressive strengths, while the UPV measurements generally classified the concrete as Medium/Fair to Good. However, the UPV-based strength estimates exhibited substantial variability, ranging from 3.27 MPa to 73.31 MPa, indicating significant uncertainty in the estimation process. The crack depth investigation revealed that 80% of the measurements exceeded the physical dimensions of the tested columns, indicating potential loss of continuity, lack of bond, separation at construction joints, or non-monolithic behavior of the concrete elements. These findings were consistent with the visual observations, which identified segregation, poor finishing quality, geometric irregularities, twisting, and out-of-plumbness. The results demonstrate that satisfactory concrete strength and acceptable UPV classifications do not necessarily imply satisfactory structural acceptability. Although UPV is effective for evaluating concrete quality and uniformity, it may not adequately identify construction-related deficiencies affecting structural integrity and continuity. Therefore, UPV-based strength estimation should not be used as the sole basis for acceptance assessment. Structural acceptance decisions should be based on an integrated evaluation that considers material strength, visual condition, construction quality, and evidence of structural continuity. In the investigated project, the combined evidence obtained from visual inspection and crack depth evaluation ultimately led to the decision to demolish and reconstruct the affected columns despite satisfactory concrete cylinder strengths. This case highlights the importance of considering construction quality and structural integrity, in addition to material strength, when evaluating reinforced concrete structures.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to PT Hesa Laras Cemerlang (https://hesa.co.id) for the support provided during the field testing and data processing stages of this study.

P-ISSN : 2598-1277
E-ISSN : 2621-3966

REFERENCES

[1] BSN, *SNI 2847:2019, Persyaratan Beton Struktural untuk Bangunan Gedung*. Jakarta, Indonesia: Badan Standardisasi Nasional, 2019.

[2] ACI, *ACI 228.1R-19 Report on Methods for Estimating In-Place Concrete Strength*. American Concrete Institute, 2019.

[3] BIS, *IS 13311 (Part 1):1992 (reaffirmed 2004), Non-Destructive Testing of Concrete - Methods of Test, Part 1 Ultrasonic Pulse Velocity*. New Delhi: Bureau of Indian Standards, 2004.

[4] ASTM International, *ASTM C597-22: Standard Test Method for Ultrasonic Pulse Velocity Through Concrete*. 2023.

[5] British Standards Institution, *BS 1881-203:1986; Testing concrete - Recommendations for measurement of velocity of ultrasonic pulses in concrete*, BSI. British Standards Institution, 1986.

[6] J. H. Bungey and S. G. Millard, *Testing of Concrete in Structures, Third Edition*, 4th ed. Taylor & Francis, 2006. [Online]. Available: https://books.google.co.id/books?id=tq4eAQAAIAAJ

[7] Y.-C. Lin, Y. Lin, and C.-C. Cheng, "A Unified Equation for Prediction of Concrete Strength at Various Ages Using the Ultrasonic Pulse Velocity," *Applied Sciences*, vol. 12, no. 17, p. 8416, Aug. 2022, doi: 10.3390/app12178416.

[8] N. S. Ahmed and A. A. Ahmed, "Predicting the Strength of Submerged and Saturated Concrete Structures using Non-Destructive Ultrasonic Pulse Velocity Testing," *Engineering, Technology & Applied Science Research*, vol. 15, no. 3, pp. 23840–23845, Jun. 2025, doi: 10.48084/etasr.11219.

[9] E. F. Saleh, A. N. Tarawneh, and H. N. Katkhuda, "A comprehensive evaluation of existing and new model-identification approaches for non-destructive concrete strength assessment," *Constr. Build. Mater.*, vol. 334, p. 127447, Jun. 2022, doi: 10.1016/j.conbuildmat.2022.127447.

[10] Y. Almashakbeh and E. Saleh, "Evaluation of ultrasonic pulse velocity (UPV) for reinforced concrete corrosion," *Journal of Applied Engineering Science*, vol. 20, no. 4, pp. 1226–1233, 2022, doi: 10.5937/jaes0-38140.

[11] S.-H. Kwon, J.-S. Lee, G.-B. Ji, and H.-K. Kim, "Consideration on Application of Nondestructive Test to Estimate In-Situ Compressive Strength of Concrete: A Case Study," *Int. J. Concr. Struct. Mater.*, vol. 19, no. 1, p. 19, Mar. 2025, doi: 10.1186/s40069-024-00752-2.

[12] BSN, *SNI ASTM C597:2012, Metode Uji Kecepatan Rambat Gelombang Melalui Beton*. Jakarta, Indonesia: Badan Standardisasi Nasional, 2012.

[13] H. Khoeri, W. Isvara, and P. Nugroho, "Formulasi Kuat Tekan Perkerasan Landasan Pacu Dari Sampel Acak Terstruktur Transmisi Permukaan Ultrasonik," *Jurnal Konstruksia*, vol. 16, no. 27, 1376, doi: 10.24853/jk.16.1.131-141.

[14] ACI Committee 562, *ACI CODE-562-21: Assessment, Repair, and Rehabilitation of Existing Concrete Structures*. American Concrete Institute, 2021.

[15] N. R. Rizqullah, H. Khoeri, H. K. Buwono, and B. Badaruddin, "Pemodelan berbasis Uji Non-Destruktif dan Semi-Destruktif yang Divalidasi Uji Vibrasi pada Asesmen Reliabilitas Pondasi Jibcrane," in *Prosiding Seminar Nasional Teknik Sipil UMS*, Program Studi Teknik Sipil Universitas Muhammadiyah Surakarta, 2024.

[16] H. Khoeri, W. Isvara, R. Pradana, and D. Sofiana, "Formulation of Concrete Compressive Strength Based on Building Age, Density, and Non-Destructive Testing with Ultrasonic Pulse Velocity Tests," *Clean Energy and Smart Technology*, vol. 2, no. 2, pp. 71–80, 2024.

[17] S. Suhariyanto, D. P. Arystianto, and B. A. Raharjo, "The effect of transducer distance on the concrete crack depth measurement using PUNDIT," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 1073, no. 1, p. 012014, Feb. 2021, doi: 10.1088/1757-899X/1073/1/012014.

[18] Y. Wang *et al.*, "Crack depth measurement and key points of accurate identification in concrete structures: a review," *Nondestructive Testing and Evaluation*, vol. 39, no. 8, pp. 2073–2107, Nov. 2024, doi: 10.1080/10589759.2024.2340645.

[19] S.-H. Kwon, J.-S. Lee, G.-B. Ji, and H.-K. Kim, "Consideration on Application of Nondestructive Test to Estimate In-Situ Compressive Strength of Concrete: A Case Study," *Int. J. Concr. Struct. Mater.*, vol. 19, no. 1, p. 19, Mar. 2025, doi: 10.1186/s40069-024-00752-2.

[20] E. M. Abdelkader, T. Zayed, and N. Faris, "Synthesized Evaluation of Reinforced Concrete Bridge Defects, Their Non-Destructive Inspection and Analysis Methods: A Systematic Review and Bibliometric Analysis of the Past Three Decades," *Buildings*, vol. 13, no. 3, p. 800, Mar. 2023, doi: 10.3390/buildings13030800.

P-ISSN : 2598-1277
E-ISSN : 2621-3966

[21] S. Hassani and U. Dackermann, "A Systematic Review of Advanced Sensor Technologies for Non-Destructive Testing and Structural Health Monitoring," *Sensors*, vol. 23, no. 4, p. 2204, Feb. 2023, doi: 10.3390/s23042204.

[22] A. K. S. Sangeeta Pandey, "Visual Inspection of Structures - Primary Aspect of Structural Health Assessment," *Tuijin Jishu/Journal of Propulsion Technology*, vol. 44, no. 3, pp. 4127–4135, Nov. 2023, doi: 10.52783/tjjpt.v44.i3.2254.