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RESEARCH

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Consideration on Application of Nondestructive Test to Estimate In-Situ Compressive Strength of Concrete: A Case Study

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Abstract

To comprehensively explore the utility of non-destructive tests (NDT) results for structural diagnosis, this study collected NDT results and core compressive strength test results from aged bridges. Girders and slabs were obtained from seven such bridges, and after sectioning, rebound hardness test (RHT) or ultrasonic pulse velocity test (UPVT) were conducted alongside coring. The standard equations for estimation in South Korea were applied and a comparison between core strength and strength estimated using NDT results was conducted. In addition, the relationship between the static modulus and core specimen strength was determined to assess the soundness of the concrete cores, a factor that influences NDT signals. Based on the experimental results, this study deliberates on the practical applications of NDT results in structural diagnosis. A protocol for calculating the characteristic in-situ compressive strength using NDT results without coring was proposed and statistically validate this protocol via a probabilistic simulation.

Highlights

– NDT and coring were applied for actual concrete bridges.
– Relationship between NDT results and core strength was analyzed.
– Proposed protocol for estimating in-situ compressive strength using NDT signals.
– Statistical validation of the protocol's reliability, demonstrating high accuracy.

Keywords Non-destructive tests (NDT), Rebound hardness test (RHT), Ultrasonic pulse velocity test (UPVT), Case study, Characteristic in-situ compressive strength

1 Introduction

Non-destructive tests (NDT) to assess the compressive strength of in-situ concrete, such as the rebound hardness test (RHT) or ultrasonic pulse velocity test (UPVT), represent fundamental methods for diagnosing existing structures in various situation (Breysse & Balayssac, 2021; Samia & Mohamed Nacer, 2012; Shariq et al., 2013). Nevertheless, the inherent limitations of these technologies have sparked debates regarding their accuracy when evaluating

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characteristic strength (Breysse et al., 2020; Helal et al., 2015; Malhotra & Carino, 2003). Various studies have endeavored to establish a relationship between NDT results and actual core strength; however, the accuracy of such relationship is notably low (Crawford, 1997; Maierhofer, 2010; Pucinotti, 2015; Saleh et al., 2022).

In the case of RHT, relevant regulations from the US and the EU, including ASTM C805, BS EN 12504-2, and BS1881-202, exist. Similarly, regulations governing UPVT encompass ASTM C 597 and BS EN 12504-4. Despite extensive research, no universally applicable equation linking NDT signals and the compressive strength of concrete in existing structures has emerged (Mahmoudipour, 2009; Shariq et al., 2013; Soutsos, et al., 2012). This is primarily due to the multifaceted influence of factors like surface condition, aggregate type, and structural geometry on this relationship (Ali-Benyahia et al., 2023).

Typically, equations for estimating concrete strength are provided separately for each NDT device (No, 2002). However, it's worth noting that these relationships have primarily been established using young concrete, which has not undergone surface degradation processes such as freeze–thaw or fatigue (Garnier, et al., 2014). Notably, Shariq et al. (Shariq et al., 2013) proposed a relationship between UPVT results and the strength of young concrete, achieving an estimation error within 10%, signifying high accuracy. In a similar vein, Hong et al. (Hong et al., 2020) derived a strength–UPV relationship for young concrete specimens unaffected by environmental loads, featuring compressive strengths ranging from 24 to 40 MPa, with a coefficient of determination, R^2, for strength estimation exceeding 0.9. Similar results has been widely reported in literature (Alwash et al., 2015; Creasey et al., 2017; Galvão et al., 2018; Hamidian et al., 2012; Hannachi & Guetteche, 2014; Hoła & Schabowicz, 2005; Kumar et al., 2021; Liu et al., 2009; Martín-del-Rio et al., 2020; Revilla-Cuesta et al., 2022).

However, the situation differs when dealing with aged concrete in actual structures, particularly evident in various reports from Japan. For instance, in Ishigami et al. (Ishigami, et al., 2018), the value of R^2 in the relationship between NDT signals (specifically RHT and UPVT results) and the compressive strength of core specimens ranged from 0.1 to 0.3, with estimation errors exceeding 30%. Similarly, Mahmoudipour (Mahmoudipour, 2009) observed R^2 values in the linear regression between NDT signals and core strength from a building structure ranging from 0.2 to 0.6, accompanied by substantial estimation errors of approximately 60%. In efforts like those of Samia and Mohamed Nacer (Samia & Mohamed Nacer, 2012), several methods combining multiple NDT techniques were proposed to enhance strength estimation accuracy, but even these yielded relatively low R^2 values around 0.5, rendering practical application challenging.

Attempts to improve accuracy by increasing the number of NDT test locations, as suggested by Breysse et al. (Breysse & Balayssac, 2021; Breysse et al., 2020) and Ali-Benyahia et al. (Ali-Benyahia et al., 2023), focused on young concrete, lacking results for actual aged concrete structures. Previous studies also confirmed significant variation in core specimen compressive strength within a single structure (Kwon et al., 2024). For instance, the in-situ strength of a concrete structure with a design strength, f_{ck}, of 35 MPa exhibited dramatic variations, ranging from 10 to 70 MPa. These variations were attributed to the ongoing hydration reaction and the accumulation of damage due to mechanical loads and environmental attacks (Imam et al., 2021; Kumar & Rai, 2019; Shah et al., 2023; Sharma et al., 2020).

Consequently, from a practical standpoint, utilizing these results directly to estimate concrete strength via NDT signals is deemed inappropriate. Ali-Benyahia et al. (Ali-Benyahia et al., 2023) and EN 13791-2019 deployed NDT as a means to locate areas with the weakest strength within a structure. Characteristic in-situ strength was then determined through coring, with NDT used to minimize the number of required cores. Conversely, Pucinotti (Pucinotti, 2015) employed a method to estimate strength at various locations in a structure using NDT and the proportional relationship between core strength and NDT results obtained from that specific structure. In other words, a unique equation was formulated and applied for each individual structure. Pfister et al. (Pfister et al., 2014) introduced a method to calculate the lower limit of core strength in a structure based on the relationship between core strength and UPVT results. Meanwhile, in Saint-Pierre et al. (Saint-Pierre et al., 2016), UPVT was employed to assess the approximate quality or level of damage of concrete, rather than estimating concrete strength.

To comprehensively explore the utility of NDT results for structural diagnosis, this study collected NDT results and core compressive strength test results from aged bridges scheduled for dismantling. Girders and slabs were obtained from seven such bridges, and after sectioning, RHT and UPVT tests were conducted alongside coring. Instead of utilizing newly proposed equations for strength estimation, the standard equations for estimation in South Korea were applied and a comparison between core strength and strength calculated using NDT results was conducted. In addition, the relationship between the static modulus and core specimen strength was determined to assess the soundness of the concrete cores, a factor that influences NDT signals. Based on the

Table 1 Information on the bridges (Kwon et al., 2024)

Name of bridges	Original location	Type of bridge	Service duration (completed/ demolished)	Total span (m)
Ahyeon Overpass	Seoul (N37.557371°/ E126.959196°)	PSC I girder + RC slab	46 years (1968/2014)	771
Seoul Station Overpass	Seoul (N37.557822°/ E126.973130°)	RC slab + steel I girder	17 years (2000/2017)	113
Guro Overpass	Seoul (N37.479243°/ E126.889949°)	PSC I girder + RC slab	43 years (1977/2019)	153
Mojeon-yukgyo Bridge	Gyeongsangnam-do (N35.582231°/ E128.462949°)	RC-Rahmen slab	45 years (1975/2019)	113
Gunseonganggyo Bridge	Gyeongsangbuk-do (N35.977606°/ E129.140112°)	PSC I girder + RC slab	45 years (1975/2019)	61
Sanseong-Ucheongyo Bridge	Gyeongsangbuk-do (N35.999842°/ E128.883524°)	PSC I girder + RC slab	45 years (1975/2019)	153

The damage and performance degradation of Gunseonganggyo Bridge was also studied in (Lee et al., 2021)

experimental results, this study deliberates on the practical applications of NDT results in structural diagnosis.

2 Obtaining NDT Results and Concrete Core Strength from Actual Bridges

The bridges used in this study were the same as those in our previous research on determining the characteristic in-situ compressive strength from cores (Kwon et al., 2024). Tables 1 and 2 summarize information about the six bridges used in this study. These bridges have either been demolished or replaced with new structural members, and old elements were collected for this research. Among these bridges, only the Seoul Station Overpass served for 20 years, while the others exceeded 40 years in service life. Figure. 1 illustrates the data collection process from the structural elements of the bridges.

Table 2 Numbers of cores for the cases, designed strength of concrete, and actual strength of cores (Kwon et al., 2024)

Name of bridges	Cored section	Numbers of cores (EA), (core diameter) – coring direction	Designed strength of concrete f_{ck} (MPa)	Actual compressive strength of cores, f_c		
				Ave. $f_{ave,all}$ (MPa)	Std. Dev., σ_c (MPa)	CoV, V (%)
Ahyeon Overpass	Slab	70 (Ø100 mm) – longitudinal	24	22.0	6.7	30.5
	Girder	50 (Ø100 mm) – longitudinal	35	28.5	6.3	22.1
Seoul Station Overpass	Slab	87 (46 for Ø100 mm, 41 for Ø150 mm) – longitudinal	27	40.7 (39.9 for Ø100 mm, 42.3 for Ø150 mm)	4.4	10.7
Guro Overpass	Slab	26 (Ø100 mm) – longitudinal	24	47.6	11.3	23.7
	Girder 1	38 (34 for Ø100 mm, 4 for Ø150 mm) – longitudinal	35	55.1	9.4	17.1
	Girder 2	19 (Ø100 mm) – orthogonal	35	54.0	7.1	13.2
Mojeon-yukgyo Bridge	Slab	44 (20 for Ø100 mm, 24 for Ø150 mm) – longitudinal	27	31.9 (33.7 for Ø100 mm, 30.3 for Ø150 mm)	12.1	37.8
Gunseonganggyo Bridge	Slab	37 (Ø100 mm) – 35 for longitudinal, 2 for orthogonal	24	52.2	9.1	17.5
	Girder	55 (Ø100 mm) – 44 for longitudinal, 11 for orthogonal	35	33.2 (33.3 for longitudinal, 30.3 for orthogonal)	7.1	21.3
Sanseong-Ucheongyo Bridge	Slab	42 (Ø100 mm) – 39 for longitudinal, 3 for orthogonal	24	43.8	12.8	29.1
	Girder	59 (Ø100 mm) – 45 for longitudinal, 14 for orthogonal	35	37.3 (38.0 for longitudinal, 35.0 for orthogonal)	7.8	20.9

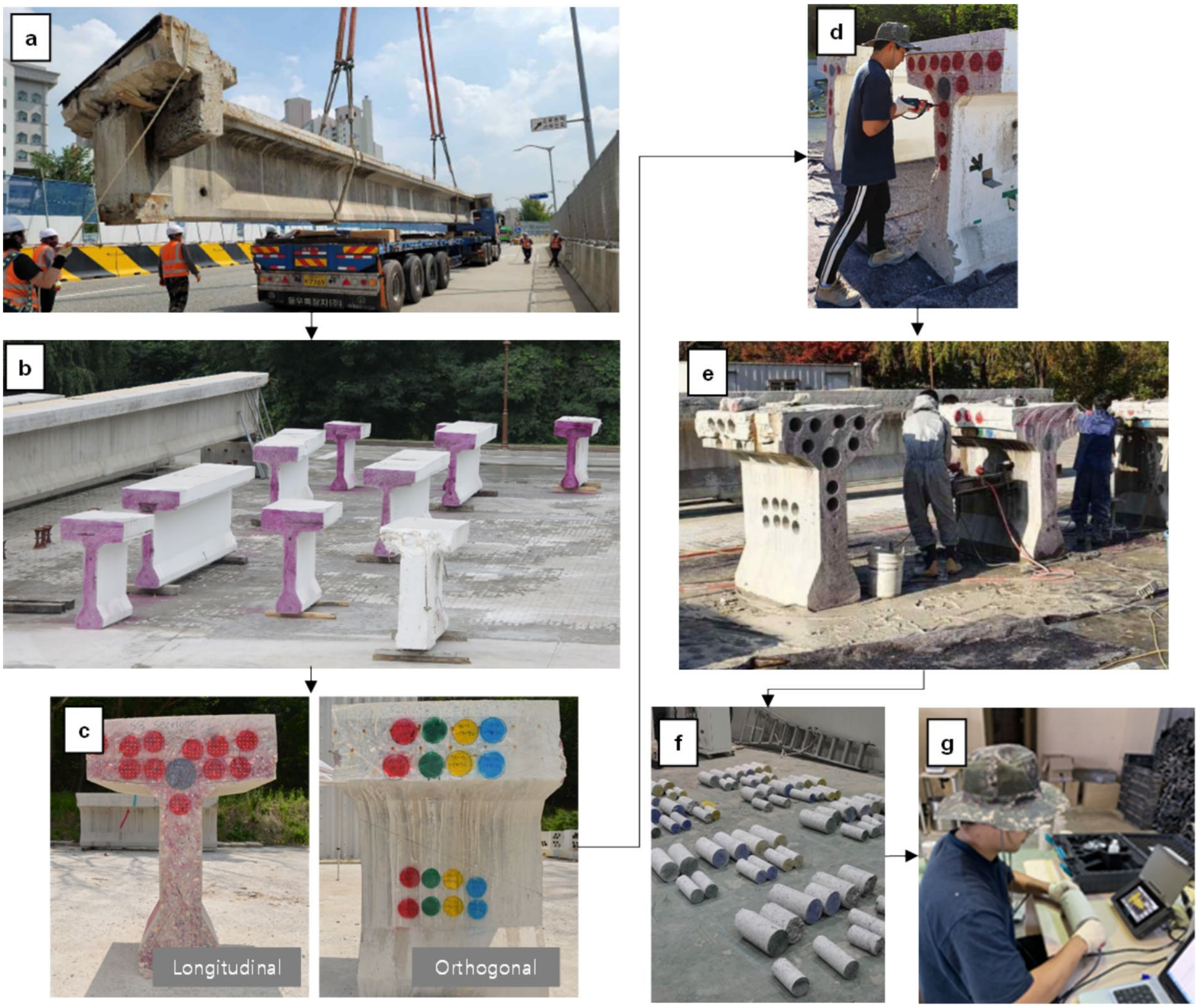

Fig. 1 Core sampling process from the target structures: **a** Collection of structural members from the target structures, **b** section zoning and cutting the members into sections, **c** marking the coring positions, **d** testing the rebound hardness for coring position, **e** coring from various directions, **f** precuring of cores before testing (48 h in air), and **g** measuring ultrasonic pulse velocity

From each bridge, approximately two or three girder-slabs were acquired. Sections subjected to shear load were identified and longitudinally cut to approximately 1.5 m. In these prepared sections, areas without embedded rebars were identified, marked, and subjected to rebound hardness tests (RHT) according to the Korean standard (KS) F 2730, which aligns with ASTM C805. Although these standards suggest acquiring 10–20 rebound numbers at a certain location, in this study, 2–3 rebound numbers were obtained only for the locations to be cored (as indicated by color in Fig. 1c). This data was then compared with the compressive strength results. Due to insufficient data at one location, outliers were not removed. Subsequently, these areas were cored with diameters of either 100 mm or 150 mm, and the aspect ratio ranged from 1.5 to 2.0. Some specimens were collected even though they were close to the edge. Out of more than 500 cores collected, any specimens exhibiting visible defects were excluded from consideration.

After collection, the cores were exposed to air at room temperature (10–20 °C, RH 30–70%) for 2 days. The core specimens were then used for ultrasonic pulse velocity testing (UPVT) and subsequent compressive strength testing. The compressive strength of core specimens was determined following modifications in the Korean Standard (KS) F 2422:2022, which aligns with ACI 214.4R-10, taking into account specimen dimensions and pretreatment. A detailed explanation of the correction due to the dimensions of the concrete core specimens has already been presented in our previous work (Kwon et al., 2024). UPVT was conducted in accordance with KS F 2731 (ASTM C597), using commercial UPV measurement equipment with a pair of 54 kHz frequency transducers (Pundit 200, Proceq/Screening Eagle Technologies Co.).

Table 3 Estimation equations for in-situ compressive strength used in South Korea (Cho, et al., 2014; Hong et al., 2020; Ju et al., 2017)

Guidance		Estimation equation for in-situ compressive strength (MPa)	Accepted range of compressive strength (MPa)
RHT	Japan society for testing materials (JSTM)	$f_c = 1.27R_0 - 18$	10–40
	Architectural institute of japan (AIJ)	$f_c = (7.3R_0 + 100) \times 0.098$	15–40
	US army	$f_c = \left(-120.6 + 8.0R_0 + 0.0932{R_0}^2\right) \times 0.098$	-
	Korea ministry of science and technology (KMST)	$f_c = (15.2R_0 - 112.8) \times 0.098$	15–40
UPVT	Japan society for testing materials (JSTM)	$f_c = (215V_d - 620) \times 0.098$	10–40
	Architectural institute of japan (AIJ)	$f_c = (102V_d - 117) \times 0.098$	10–40

In addition, the elastic modulus of concrete core specimens was measured in accordance with ASTM C 469. For reference, instances of unusually low compressive strength and elastic modulus were rarely confirmed.

The raw data from RHT and UPVT, including rebound numbers and ultrasonic pulse velocities, were processed using the estimation equations commonly employed in South Korea. These equations are detailed in Table 3. In South Korea, the compressive strength is estimated by selecting one of these equations (Cho, et al., 2014; Ju et al., 2017).

3 Experiment Results

3.1 NDT Results and Core Strength

In Fig. 2, the strength estimated using the rebound number before core extraction from the structure was compared with the strength of the core specimens. Similarly, in Fig. 3, the strength estimated using the UPV value of the core collected from the structure compared with the strength of the core. In most cases shown in Figs. 2 and 3, the core strengths were greater than the estimated values.

There are instances where the minimum estimated compressive strength through both RHT and UPVT is close to the minimum value of the core strength. When these two values align, NDT can effectively identify the position of minimum strength in the structure, and core specimens for obtaining characteristic in-situ strength should be taken from this position. This method, recommended by the EN 13791-2019, helps minimize the number of core specimens required. However, it's worth noting that, based on the results in Figs. 2 and 3, the minimum values estimated by NDT often did not match the minimum value of core strength. For instance, in the case of the Guro Overpass slab, the minimum estimated compressive strength measured by RHT or UPVT was around 20 MPa, while the corresponding core strength value was approximately 40 MPa.

Interestingly, the ranges of the minimum values of estimated compressive strength from NDT often appeared similar to those of the minimum value of core strength, even though they didn't always align. Figure 4 provides a visual representation of statistical values through a box-and-whisker plot, comparing estimated strength with core strength for each bridge. This visualization includes the following metrics:

- Lower, middle, and upper lines of the box: 1st quartile (Q1, the lower 25% of data), median (Q2, the middle of the data), 3rd quartile (Q3, the upper 25% of data).
- Square within the box: overall mean value.
- Whiskers: mean value ± 1.5 times the interquartile range (IQR), where IQR = Q3–Q1.
- Data points: individual data set values.
- Curves: normal distribution derived from the data set.

In addition, when using the equations listed in Table 3, NDT tends to underestimate the compressive strength of concrete in existing structures. Core strength typically follows a normal distribution, and this tendency is also visible in the NDT results. In most cases shown in Fig. 4, except for the Ahyeon Overpass, the distribution of estimated strength is lower than that of the core strength.

Figure 5 presents the ratio of the average estimated strength with NDT, $f_{\mathrm{NDT,ave}}$, to the average core strength, $f_{\mathrm{core,ave}}$, for each bridge depicted in Fig. 4. With the exception of two cases, Ahyeon Overpass slab and girder, this ratio fell within the range of 0.4–1.0. Notably, this ratio exhibited a relatively narrow dispersion range when using the AIJ method, whereas the dispersion range was broader when employing the KMST method.

On the other hand, Fig. 6 illustrates the probability that the estimated strength using NDT exceeded the core strength, denoted as $P(f_{\mathrm{NDT},i} > f_{\mathrm{core},i})$. This probability was calculated by applying a formula based on the difference between two normal distributions. In the majority of cases, the probability of the estimated strength surpassing the core strength was less than 0.2, rendering it negligible.

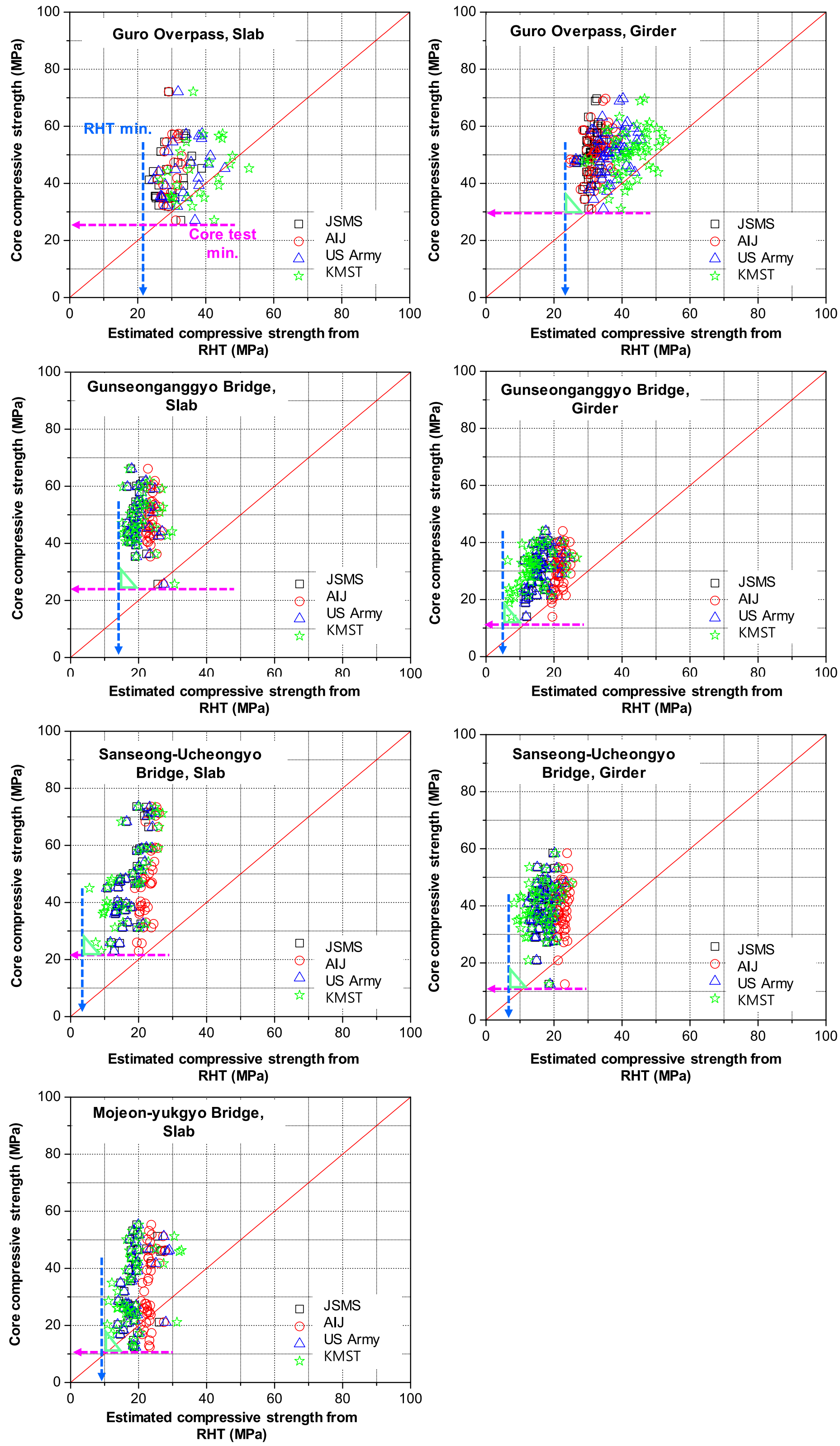

Fig. 2 Relationship between compressive strength estimated from rebound numbers and those from core specimens

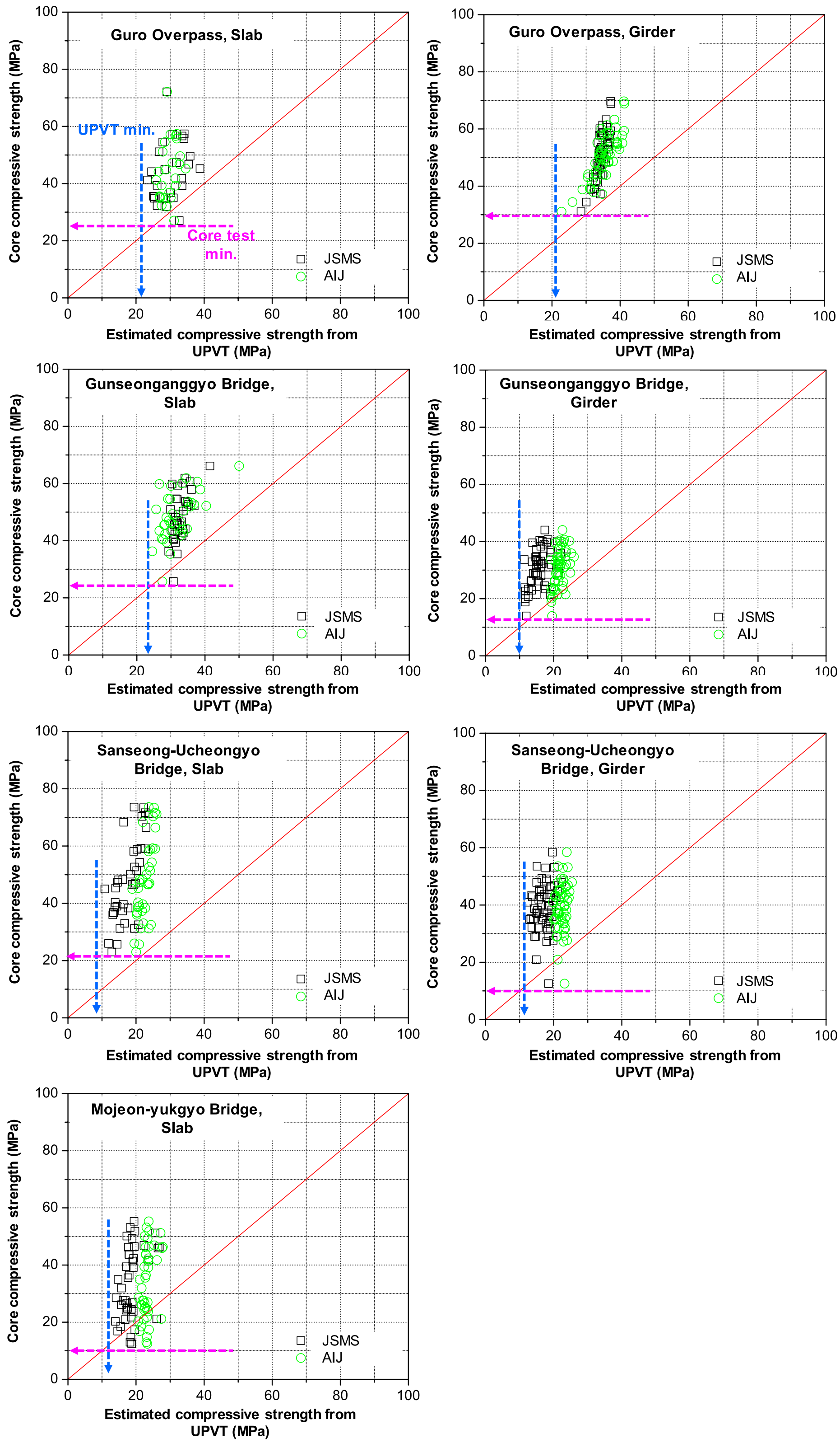

Fig. 3 Relationship between compressive strength estimated from ultrasonic pulse velocity of cores and those directly measured by destruction of core specimens

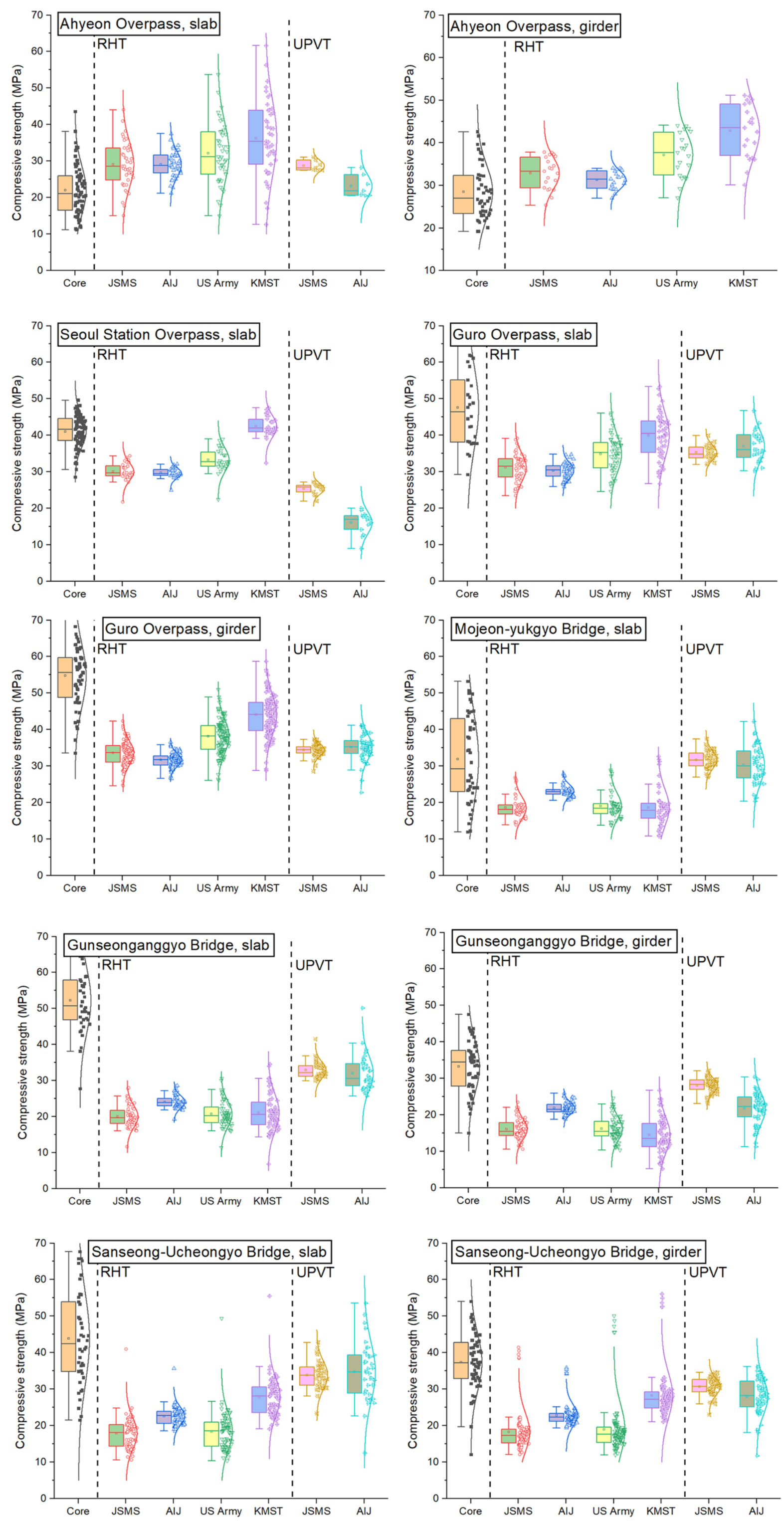

Fig. 4 Probabilistic diagrams illustrating the compressive strength of concrete, measured with core specimen and estimated by NDT from each bridge in South Korea

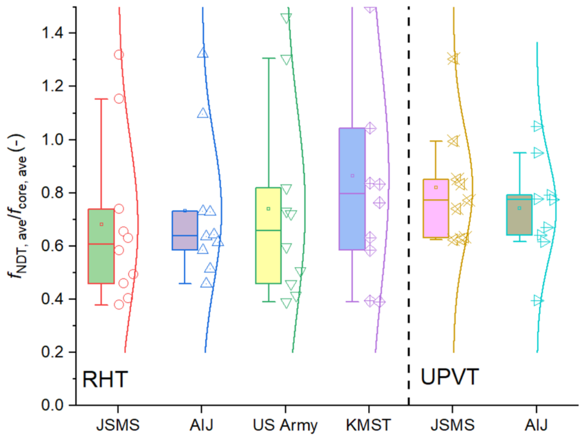

Fig. 5 Ratio of average value of the estimated strength with NDT, fNDT, ave, to the average value of the core strength, fcore, ave, for actual bridges (dots: data from each bridge)

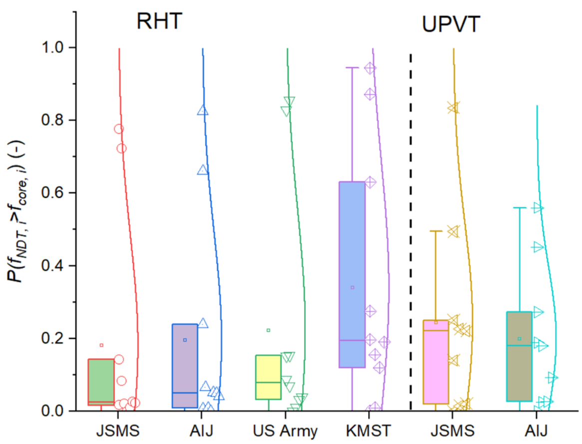

Fig. 6 P($f_{NDT,i} > f_{core,i}$) for actual bridges (dots: data from each bridge)

3.2 Modulus of Elasticity of Core Specimens

Figure 7 displays the elastic modulus values measured using core specimens along with the compressive strength, categorized by f_{ck} values of 24, 27, and 35 MPa. In the figure, the curves representing the elastic modulus-concrete strength relationship according to the Korea Structural Concrete Design Code (KDS 14 20 10: 2021) ($E = 8500\sqrt[3]{f_c}$) are shown, along with fitting curves based on the results from this study ($E = a\sqrt[3]{f_c}$). It can be observed that the experimental results closely align with the KCI 2012 standard curve.

The static modulus of elasticity is calculated using the stress–strain relationship up to 40% of the ultimate load of concrete. The results of this study indicate that, for this range of deformation, the mechanical properties of concrete obtained from existing structures do not significantly differ from those of newly constructed

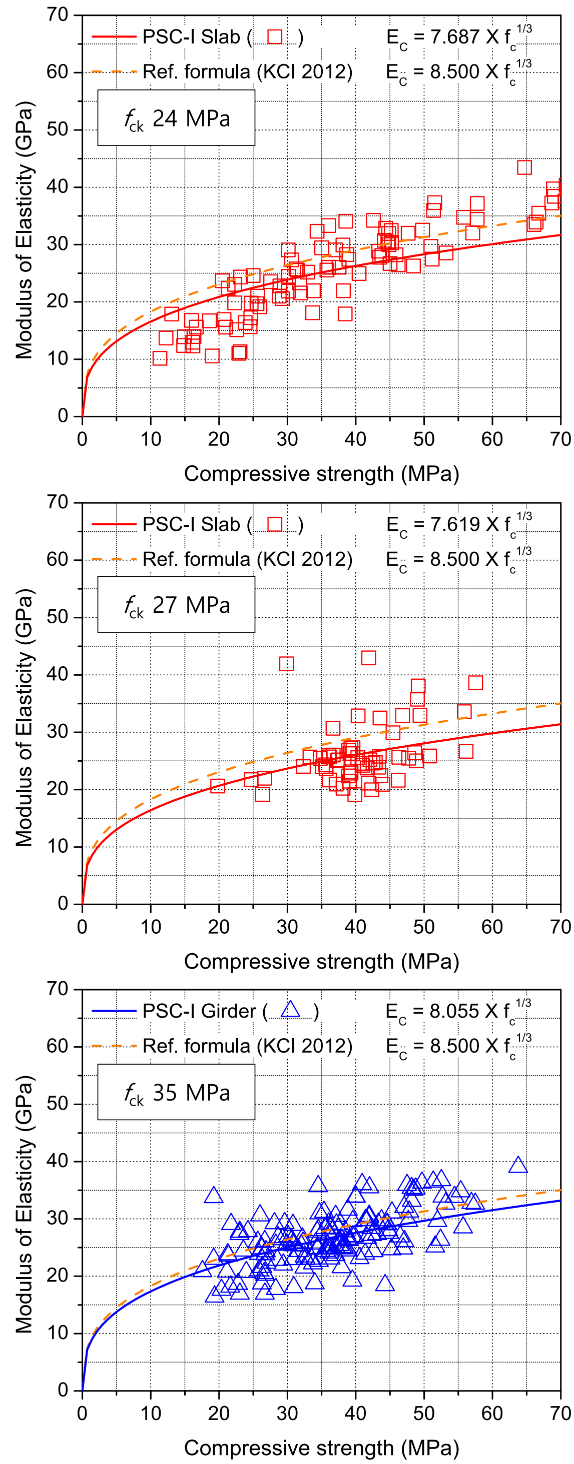

Fig. 7 Relationship between compressive strength and modulus of elasticity of core specimens from actual bridges

structures. On the other hand, it has been reported that rebound numbers and UPV values are influenced by surface hardness and the dynamic modulus of elasticity

Table 4 Application scenario of NDT for structural maintenance by confidence level

Confidence level	Application	Method
1	predicting or estimating the compressive strength of concrete without coring	Adoption of standard relationships between strength and NDT signals
2	predicting or estimating the compressive strength of concrete with coring	Deriving in-situ relationships between core strength and NDT signals specific to the construction site
3	Finding the ideal point for coring	Identifying positions within the structure with minimum values of NDT signals and subsequently measuring the core strength at these positions
4	Determining the minimum range of compressive strength	Applying standard relationships between strength and NDT signals and then determining the minimum values
5	Evaluation of soundness of concrete structure	Assessing the uniformity of NDT signals by examining various positions within the structure

(initial tangent modulus), respectively (Hamidian et al., 2012; Kumar et al., 2021; Soutsos, et al., 2012). These values are susceptible to variations caused by concrete damage, such as carbonation, freeze–thaw damage, and fatigue (Creasey et al., 2017; Galvão et al., 2018; Hannachi & Guetteche, 2014). Since these types of damage typically affect the surface layer of concrete over a few centimeters, they may not significantly impact the modulus of elasticity of the core specimens but can influence the rebound numbers and UPV values measured at the surface. Unfortunately, this study could not compare the direct relationship between the elastic modulus and rebound number or UPV due to data problems.

4 Discussion

This study aimed to explore the practical use of NDT for structural maintenance in critical point of view. Five application methods of NDT based on the reliability were discussed (Table 4). In cases we believe that the reliability of NDT is high (confidence level #1), standard equations relating NDT signals to in-situ concrete compressive strength (Table 3) can be adopted. While such equations were proposed in the past, they are not commonly presented by most countries today. The equation presented in Table 3 was also proposed from the 70s to the early 90s (Crawford, 1997).

Confidence level #2 suggests utilizing NDT in conjunction with coring concrete specimens. This approach relies on a strong linear or non-linear relationship between core strength and NDT results, with debate over the number of core specimens needed to establish this relationship. ASCE/SEI 41-17 and ACI PRC-228.1 follow this protocol, employing a linear regression equation between NDT results and core strength from a selected point, which is then applied to estimate in-situ strength for other points using NDT.

Confidence level #3, as adopted in EN 13791-2019, involves using NDT to locate positions with minimum concrete strength when a limited core specimen is available. Nevertheless, Figs. 2 and 3 demonstrate that the minimum NDT signal value does not always correspond to the minimum core strength. It is possible that only the surface of a concrete structure is degraded while the interior remains sound. In only two out of seven cases (the girder of Gunseonganggyo Bridge and the slab of Mojeon-yukgyo Bridge), the minimum core strength coincided with the minimum estimated strength from NDT. Therefore, from a critical standpoint, selecting the point with the minimum in-situ concrete strength via NDT methods is questionable.

In this context, confidence level #4 appears more suitable, utilizing NDT signals to establish a minimum range of in-situ compressive strength. When employing the guidance in Table 2, the minimum strength ranges estimated using NDT for various locations in each structure were found to be similar to the minimum ranges of core strengths. Furthermore, the probability that the estimated strength exceeded the core strength was very low, less than 20% (Fig. 6). The ratio between $f_{\mathrm{NDT,ave}}$, and $f_{\mathrm{core,ave}}$, for each bridge ranged from 0.4 to 1.0 (Fig. 5). This suggests that when estimating the strength of various locations using NDT results and the equations in Table 2, a strength level generally falls within 40% to 100% of the actual in-situ concrete strength distribution. In a previous study (Kwon et al., 2024), the characteristic in-situ compressive strength was calculated using data from the same bridges and core strength results in the present work, resulting in values ranging from 60% to 80% of the core strength. For reference, if the calculated characteristic in-situ strength is significantly lower than the average core strength, it indicates underestimation, and if it is significantly higher, it indicates overestimation. Although there is no definitive numerical limit, a range of

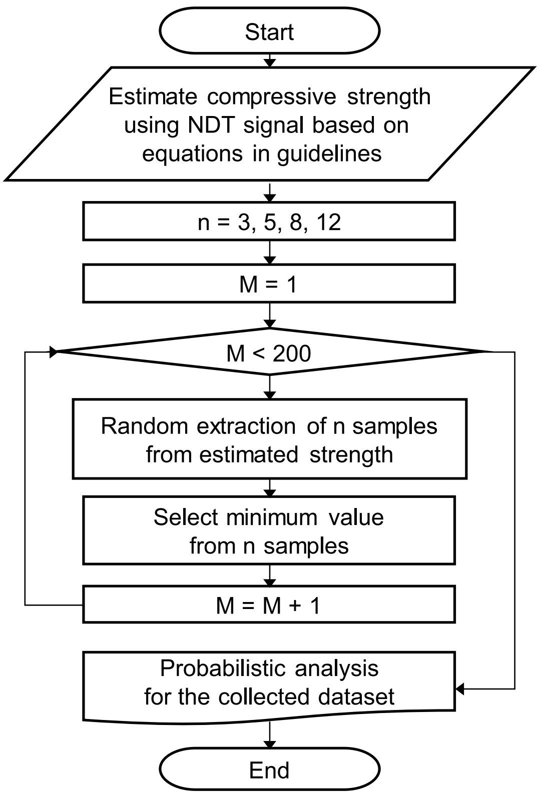

Fig. 8 Flowchart illustrating the probabilistic analysis process with random selection of estimated strength data

60–80% of the average core strength is generally considered the most appropriate estimation (Kwon et al., 2024). Considering this, using NDT results and the equations in Table 2, a stable minimum range of in-situ compressive strength can be obtained, demonstrating potential for use as a characteristic strength for structural maintenance.

Based on the findings of this study and the reliability of NDT signals, a protocol for calculating the characteristic in-situ compressive strength was proposed:

(1) Acquire NDT signals from various locations within the structure.
(2) Calculate the minimum compressive strength estimate using various standard equations for NDT signals. These equations are selected based on their applicability to the specific NDT method employed.
(3) Set the minimum estimated value as the representative value for the characteristic in-situ compressive strength.

To statistically validate this protocol, a probabilistic simulation was conducted in this study (Fig. 8). The estimated strengths from the NDT method were randomly selected. The number of selected samples was adjusted to 3, 5, 8, and 12, corresponding to the number of locations where NDT assessments would be performed within the structures. The minimum value of estimated strength among the selected samples was designated as the characteristic strength. This random selection process was repeated 200 times for each design strength.

Figure 9 illustrates the distributions of characteristic strength obtained using aforementioned protocol using NDT results with various sample numbers. It is evident that the majority of characteristic in-situ compressive strengths, determined using the minimum NDT results, are concentrated below Q3 (bottom 25%) of the core strength. The coefficient of variation (CoV) for these values ranges from 10% to 30%, indicating a high level of reliability. This demonstrates that the proposed method allows for the calculation of a dependable range for the characteristic in-situ compressive strength of a structure using NDT results, without the need for coring. Importantly, it was observed that using NDT results from more than 5 locations within each structure is necessary to obtain a stable value of characteristic in-situ strength with a CoV of variation range less than 30%.

In addition, when the estimation of strength using NDT signals is considered to be not very reliable, NDT can still be valuable for assessing internal voids, extensive damage, or other structural issues, as outlined in confidence level #5 as used in Saint-Pierre et al., 2016.

In conclusion, this study highlights a practical approach to leverage NDT in structural assessments. By gathering NDT signals from multiple locations, estimating strength using various standard equations without coring, and setting the minimum range of these estimates as the characteristic in-situ compressive strength, it is possible to obtain a reliable and non-destructive measure of structural performance.

5 Conclusion

This study investigates how to effectively utilize results obtained from NDT for structural diagnosis and maintenance. Data on estimated strength and actual strength were collected through RHT, UPVT, and coring on girders and slabs of actual bridges. The distribution of the data and their relationships were analyzed and are discussed. The key findings are as follows:

- The estimated strength through NDT may vary depending on the standard equations used, but it generally exhibits lower variance compared to actual core concrete strength. Moreover, it was observed that NDT-estimated strength values were lower than the actual core strength in general.
- A linear relationship between estimated strength and actual core strength had notably broad ranges

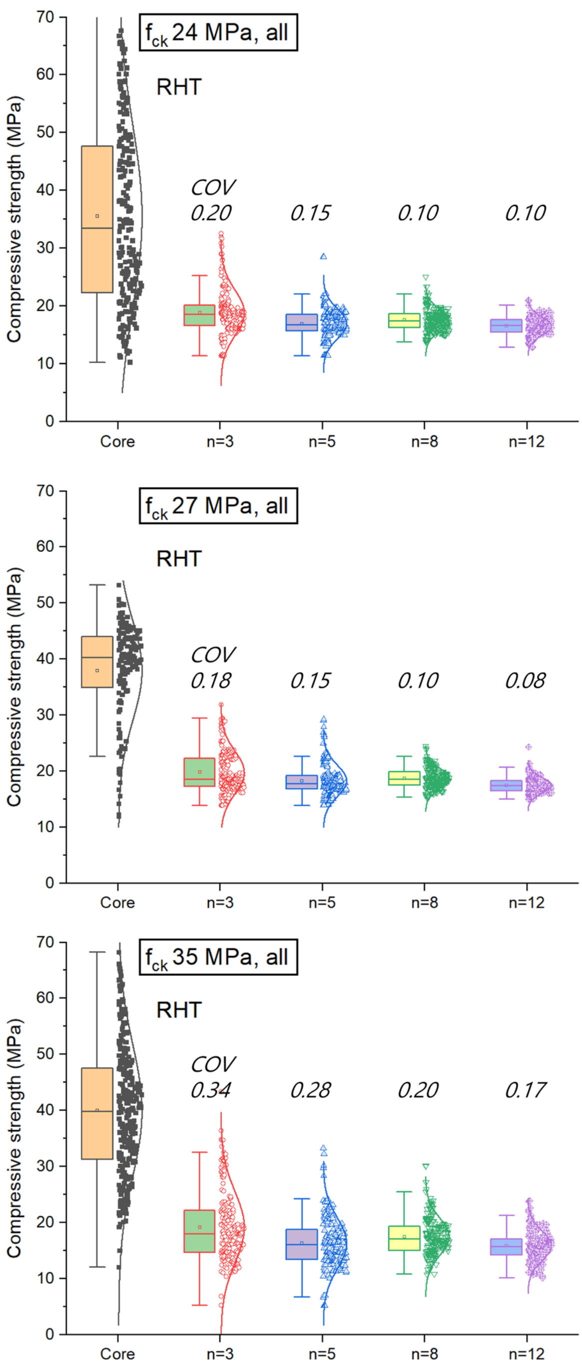

Fig. 9 Distributions of characteristic in-situ compressive strength obtained using a proposed protocol using NDT results with various sample numbers

of variation. It is important to note that locating the minimum core strength does not always align with the point of minimum strength estimated through NDT. Nevertheless, when considering the overall distribution, the minimum range of strengths estimated via NDT aligns closely with the minimum range of core strengths.

– Taking these findings into account, a method for determining the characteristic in-situ compressive strength of a concrete structure using only NDT results was proposed, eliminating the need for coring. Probabilistic simulations with random sample selection of estimated strength confirmed that the proposed method can achieve a CoV of less than 30% for characteristic strength values obtained solely through NDT. In other words, the proposed method demonstrates robustness and reliability.

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Availability of data and materials
All the data sets associated with this study are available from the corresponding author upon request.

Declarations

Ethics approval and consent to participate
All authors of the manuscript confirm the ethics approval and consent to participate following the Journal's policies.

Consent for publication
All authors of the manuscript agree on the publication of this work in the International Journal of Concrete Structures and Materials.

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