Assessing Concrete Strength: Insights from Schmidt Rebound Hammer and Ultrasonic Pulse Velocity Techniques

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Abstract

Concrete strength assessment is pivotal in ensuring the structural integrity and longevity of various constructions. Non-destructive testing (NDT) methods have emerged as indispensable tools for predicting concrete strength in situ, facilitating timely interventions and quality assurance protocols. Among these methods, the Schmidt rebound hammer (RH) and ultrasonic pulse velocity (UPV) techniques have gained prominence due to their simplicity, cost-effectiveness, and on-site applicability. This study delves into the relevance and efficacy of RH and UPV techniques for predicting concrete strength, focusing on the development of mathematical correlation models between NDT parameters and compressive strength. The research involves conducting comprehensive experimental investigations on a diverse range of concrete specimens encompassing different mix designs, strength ranges, and ages. Compressive strength, the gold standard for concrete strength determination, was evaluated through destructive testing methods. Concurrently, non-destructive assessments employing RH and UPV were performed on the same specimens. The rebound values from Schmidt Rebound Hammer test and the velocity of ultrasonic pulses were correlated with compressive strengths to establish predictive models. Uni-parametric (RH-Strength and UPV-Strength) correlation models, as well as combined models, were developed to explore the relationship between NDT parameters and concrete compressive strength. In evaluating concrete strength using the Schmidt rebound hammer test, it was observed that this surface test exhibited less sensitivity to variations in concrete mix design within the same strength range. Instead, its sensitivity primarily stemmed from variations in concrete strength, attributed partly to the density of the cement paste at the surface. Conversely, the Ultrasonic Pulse Velocity test emerged as more relevant for assessing concrete strength, given its ability to investigate concrete depth. However, it displayed lower sensitivity to variations in concrete mix design when dealing with high-strength concretes. Despite these nuances, the proposed correlation models demonstrated reliability and accuracy, evident from the coefficients of correlation obtained. Furthermore, the utilization of combined models facilitated an improvement in prediction accuracy compared to uni-parametric models alone. Notably, it was observed that concrete mix design and the age of concrete exerted significant influence as factors diminishing the precision of concrete strength prediction using non-destructive testing (NDT) methods. These findings underscore the importance of considering such influencing factors and refining model calibration processes to further improve the reliability of NDT-based concrete strength assessments. RH and UPV techniques offer valuable insights into concrete strength prediction, aiding rapid on-site assessments and quality control during construction projects. While both methods present strengths and limitations, integrating them alongside conventional testing approaches enhances the reliability and efficiency of concrete strength evaluation. The development of correlation models facilitates quantitative predictions of concrete strength based on NDT parameters, advancing the state-of-the-art in non-destructive evaluation of concrete. Further research focusing on refining testing protocols and calibration techniques is warranted to optimize the accuracy and applicability of these techniques in concrete engineering practices.

Keywords: *Non destructive testing, rebound hammer, ultrasonic pulse velocity, compressive strength, correlation models*

1. Introduction

While significant progress has been made in understanding the behavior of construction materials and in developing design methodologies, the issue of structural degradation remains a major concern [1,2]. The need to assess the current condition of reinforced concrete (RC) structures and predict their future performance continues to grow, especially in the context of preventive maintenance strategies [3-5]. This calls for the development of diagnostic and monitoring tools adapted to in-service structures, and for continuous collaboration between engineers and researchers [6,7].

In construction practice, there is a constant need to control and monitor the condition of hardened concrete, particularly its compressive strength, which is a key indicator of structural safety and performance [4,8-11]. Compressive strength, in particular, is regarded as one of the most critical mechanical properties of concrete, alongside Young's modulus and Poisson's ratio [12]. Strength evaluation is required in various scenarios: when damage has occurred, when structural loading conditions change, or when new regulatory constraints emerge. For newly constructed structures, it serves to validate design assumptions and confirm immediate safety.

Traditional strength assessment methods based on core extraction and destructive testing while reliable, have significant limitations. The standard quality control practice of crushing samples cast during construction does not reflect actual in-situ conditions due to differences in placement, compaction, and curing [13]. Core extraction, although more representative, is invasive, localized, and often constrained by access, cost, or the need to preserve structural integrity [14-16]. Consequently, standards now promote the use of non-destructive testing (NDT) techniques, either to replace or supplement core testing when the number of available cores is limited [17–19].

Among the most widely used NDT methods are the Schmidt rebound hammer (RH) and ultrasonic pulse velocity (UPV) tests. The RH test is primarily used to assess surface hardness and uniformity [20], while UPV is employed to detect internal flaws, monitor concrete quality, and evaluate strength development [21]. These techniques are not only widely accessible and cost-effective but also suitable for field applications. Both have proven valuable for compressive strength prediction when calibrated properly [22-25], and their combined use in the SonReb method has been shown to enhance accuracy by compensating for the individual limitations of each technique [22,24].

However, the reliability of NDT-based strength estimation is strongly influenced by various material and environmental factors, including concrete age, curing conditions, moisture content, surface carbonation, and particularly the properties of aggregates [26-28]. Aggregate mineralogy and maximum size significantly affect wave propagation and impact both RH and UPV measurements [19,29]. For instance, larger and denser aggregates (e.g., crushed limestone or basalt) increase stiffness and improve pulse transmission, potentially resulting in higher UPV readings and rebound indices. Therefore, using predictive models developed with concretes having different aggregate types or sizes can introduce substantial errors. Ensuring compatibility between the tested material and the reference model, especially in terms of aggregate characteristics, is essential for reducing uncertainty and improving prediction reliability.

Moreover, in the case of UPV, the presence and distribution of steel reinforcement can significantly affect wave propagation [19,26,27,30-32]. Steel, being much denser than concrete, accelerates ultrasonic wave propagation, and its influence depends on bar diameter, spacing, orientation, and proximity to the measurement path. Few studies have proposed correction approaches to address this issue [30-32], yet their application remains complex in real structures due to unknown or irregular reinforcement layouts.

This study contributes to the ongoing effort of improving in-situ concrete strength evaluation using NDT methods by (i) developing uni-parametric and bi-parametric correlation models (RH, UPV, and SonReb) from a controlled experimental program on concretes with well-characterized aggregate properties and strength classes, and (ii) validating these models through an application on reinforced prefabricated beams. The case study specifically considers beams made with the same type and size of aggregates as used in model development to minimize uncertainty. The influence of factors such as concrete strength class, aggregates type and maximum size, and reinforcement presence is explicitly addressed, with particular attention given to the reliability of UPV measurements in reinforced elements. The results aim to provide insight into the applicability of such models under realistic field conditions and to contribute to refining calibration protocols for improved strength prediction accuracy.

2. Experimental program and research methodology

This study considers three concrete mix designs in order to cover a broad range of compressive strengths. Three strength classes were selected: high-performance concrete (HPC), medium strength concrete (MSC), and normal strength concrete (NSC). Notably, the variation in strength was achieved without altering the granular skeleton, which was kept constant across all mixes.

The aggregate content was maintained constant for all three concrete types to limit the effects of influencing factors and thus to reduce the sources of variability and uncertainty in destructive and non-destructive measurements. The strength variation ranges for these concretes were obtained by varying the water to cement ratio and superplasticizer dosage. The superplasticizer was used to improve the workability, it is based on Polycarboxylate polymers, with a specific gravity of 1.06 ± 0.01 and 30.2 ± 1.3 % solid content

All three concretes were designed using a Portland cement (CPJ-CEM II/A – 52.5) with a specific gravity of 2.24 and a specific surface area of 23 m²/g. Silica fumes were used as additives in high performance concrete mix. Local limestone coarse aggregates (crushed limestone rock) with a specific gravity of 2.69 were used in two classes, 3/8 and 8/15. Coarse aggregates physical and mechanical characteristics are given in table 1.

Tab. 1. Coarse aggregates physical and mechanical properties.

Fraction	Loose bulk density	Density	Los Angeles	Flakiness index
3/8	1.49	2.69	29	11.87%
8/15	1.45	2.69	28	8.73%

A mix of two types of local sands was used as fine aggregates: 75% coarser river sand with a fineness modulus of 3.68 and a specific gravity of 2.65, and 25% dune sand with a fineness modulus of 0.32 and a specific gravity of 2.63. The fineness modulus of the mixture was 2.8. The physical and mechanical properties of the used sands are presented in table 2.

Tab. 2. Fine aggregates physical and mechanical properties

Type of sand	Region	Fraction	Fineness modulus	Loose bulk density	Density	Sand equivalent	
						SEV(%)	SEP(%)
River sand	Baghlia	0/8	3.37	1.53	2.63	81%	76%
Dune sand	Boussaàda	0/1	0.49	1.39	2.62	84%	57%
Mix	25% -75%	0/8	2.7	/	/	80%	75%

The water to cement ratio (W/C) of the mixes was 0.315, 0.35, and 0.55 for high performances concrete, medium strength concrete, and normal strength concrete, respectively. After demoulding, the specimens were weighed and placed outdoors until the age of testing to reproduce in-situ curing conditions. These concretes' experimentally determined densities are 2.5 for HPC, 2.49 for MSC, and 2.44 for NSC. All three concrete mixes are given in table 3.

A number of 63 cylindrical specimens in high strength concrete, 36 in medium strength concrete, and 36 in ordinary strength concrete was made. HPC concrete specimens were tested at the ages of 3, 7, 14, 28, 56, 91, and 182 days. Medium strength concrete and normal strength concrete specimens were tested at 7, 28, 91, 182 days.

In accordance with standard NF P18-417 [33] specifying the method for determining the rebound index of a hardened concrete surface, 27 measurements must be taken on cylindrical specimens of dimensions (16x32 cm) in the casting direction, maintained under compressive stress of 0.5 MPa (Fig. 1). The value of the rebound index is the median of the 27 measurements.

Tab. 3. Concrete mixes proportions and characteristics.

Constituent		Content			Unit
		High performances concrete	Medium strength concrete	Ordinary strength concrete	
Aggregates	Fine sand	177	177	177	kg (/m3)
	Coarse sand	536	536	536	kg (/m3)
	Gravel 3/8	119	119	119	kg (/m3)
	Gravel 8/15	1168	1168	1168	kg (/m3)
Cement CPJ 52.5		450	400	300	kg (/m3)
Silica fume		36 (8%)	/	/	kg (/m3)
Superplasticizer		9 (2%)	8 (2%)	0%	kg (/m3)
Water		142	140	165	kg (/m3)
W/C		0.315	0.35	0.55	/
slump		16	16	0	cm
Density of fresh concrete		2.516	2.515	2.456	(g/cm3)
Density of hardened concrete		2.496	2.485	2.443	(g/cm3)

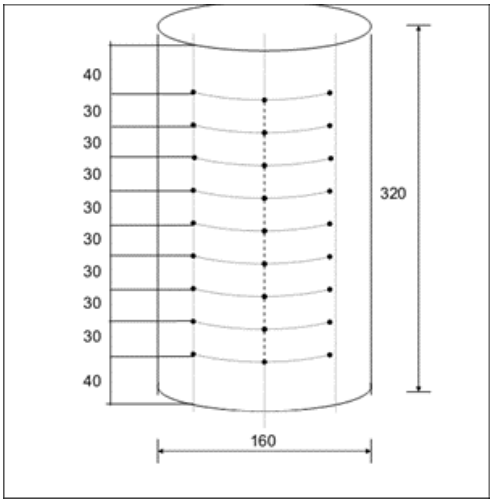

Fig. 1. Rebound index measurements distribution on cylindrical specimen.

The longitudinal ultrasonic pulse velocity was measured in accordance with the standard NF EN 12504-4 [34]. UPV measurements were taken in the longitudinal direction. Transit time was measured in three locations, and the mean value of the transit time was used to determine the specimen's UPV value (Fig. 2).

Fig. 2. UPV measurements performed on cylindrical specimens.

3. Results and discussion

Fig. 3 and 4 illustrate the variation of the rebound number (RN) and ultrasonic pulse velocity (UPV) with concrete age for High Performances Concrete (HPC), Medium Strength Concrete (MSC), and Normal Strength Concrete (NSC). The non-destructive measurements recorded for HPC and MSC exhibit similar trends and are relatively close, which is consistent with their comparable strength classes. The UPV values obtained for NSC are lower than those of HPC and MSC. However, the differences remain limited, likely due to the use of an identical granular skeleton across all mixtures, a parameter known to significantly influence ultrasonic wave propagation.

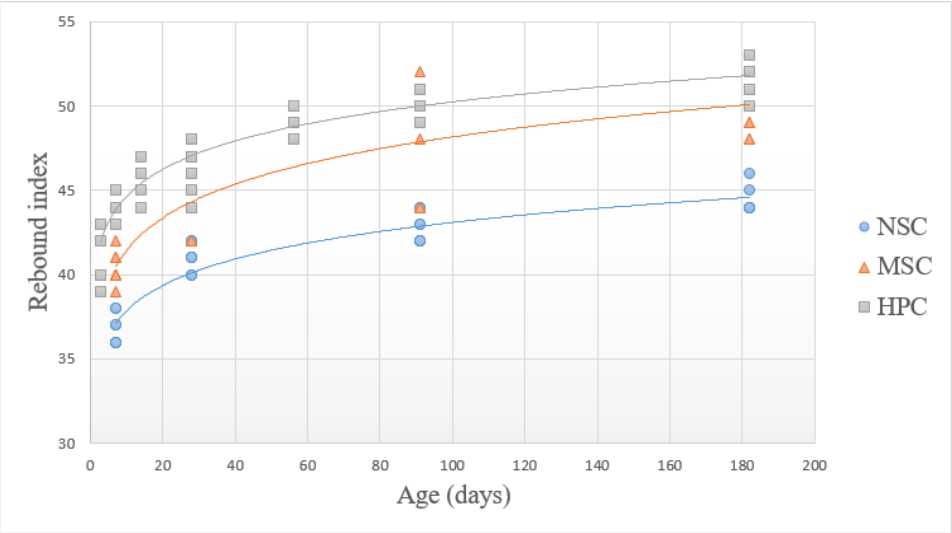

Fig. 3. Rebound index evolution with age.

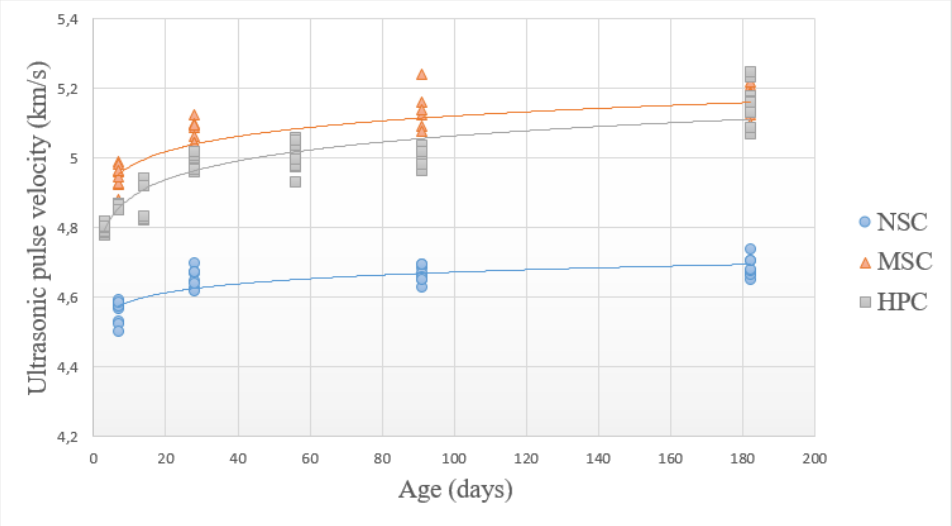

Fig. 4. Ultrasonic pulse velocity evolution with age.

All cylindrical specimens were crushed to determine the concrete strength. The development of compressive strength for high-performance concrete (HPC), medium strength concrete (MSC), and normal-strength concrete (NSC) is presented in Fig. 5, 6, and 7, respectively. HPC exhibits a strength increase from 55 MPa at 3 days to 95 MPa at 182 days. MSC shows a progression from 54 MPa at 7 days to 72 MPa at 182 days. In the case of NSC, compressive strength rises from 30 MPa at 7 days to 43 MPa at 182 days.

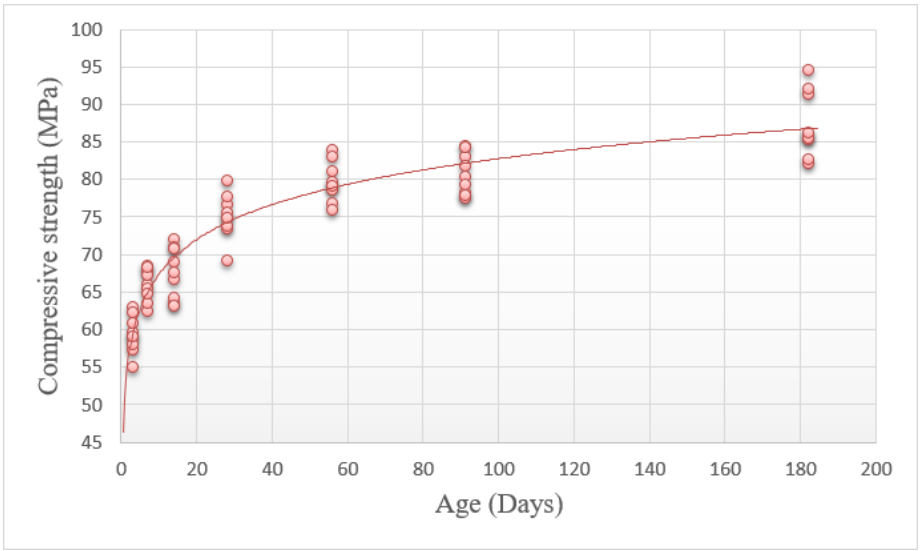

Fig. 5. HPC strength evolution with age.

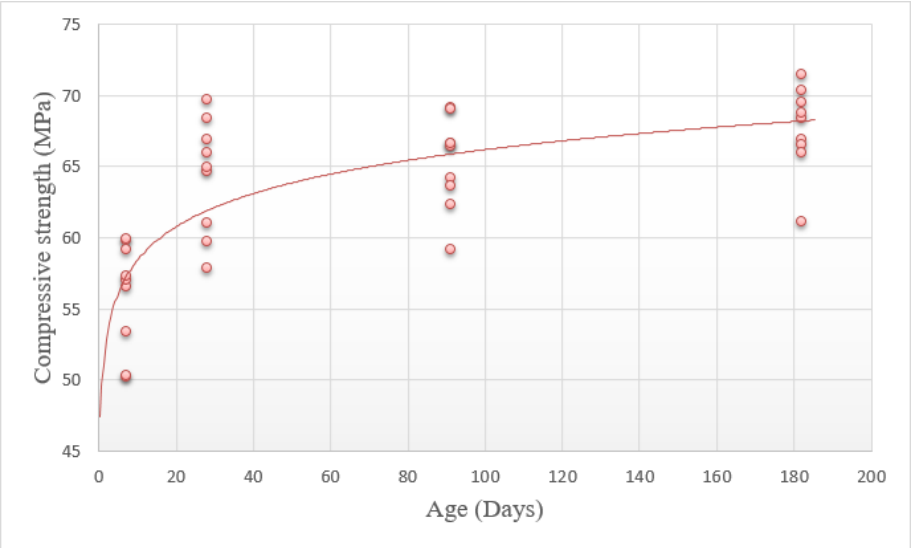

Fig. 6. MSC strength evolution with age.

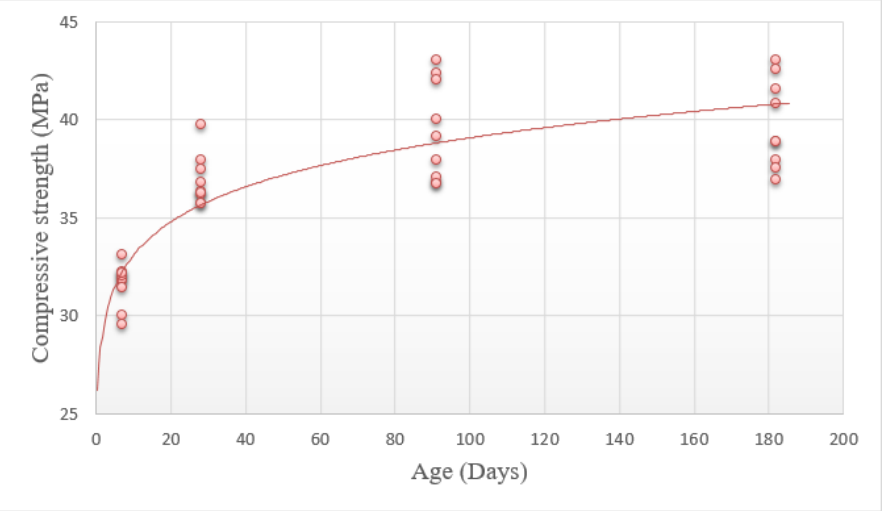

Fig. 7. NSC strength evolution with age.

Destructive and non-destructive tests conducted on cylindrical specimens were used to establish correlation models for predicting compressive strength based on NDT results. The regression analysis tool in Microsoft Excel was employed to perform the correlations, using a 95% confidence level, between the NDT measurements and the compressive strength values. The resulting models for the three types of concrete are presented in table 4.

All proposed models follow an exponential trend. The regressions demonstrate strong reliability, as indicated by the correlation coefficient R^2 (see table 4). For all three concrete types, the R^2 values are higher for the combined models than for the single-parameter models. This confirms that the combined use of two NDT methods enhances the accuracy of predicting compressive strength from NDT data. However, achieving a higher correlation coefficient was limited as one of the most influential factors on NDT measurements, which is the testing age, was not accounted for. The age of the concrete specimens at the time of testing varied widely from 3 to 182 days across all three mixes. This significant variation led to increased data scatter, thereby reducing the precision of the regression models.

Tab. 4. Concrete mixes proportions and characteristics.

Model type	RN-Strength	R^2	UPV-Strength	R^2	SonReb	R^2
HPC	$f_c = 13.677 \exp(0.0357\ R)$	0.863	$f_c = 0.4704 \exp(1.0175\ V)$	0.789	f_c = 3.533 exp (0.0247 R+ 0.3771 V)	0.889
MSC	$f_c = 31.648 \exp(0.0156\ R)$	0.632	$f_c = 3.2771 \exp(0.5881\ V)$	0.604	f_c = 9,1617 exp (0.0094 R+ 0.2993 V)	0.691
NSC	$f_c = 10.044 \exp(0.0315\ R)$	0.804	$f_c = 0.0457 \exp(1.4412\ V)$	0.578	f_c = 4.4533 exp (0.0285 R+ 0.2020 V)	0.808

To evaluate the applicability of the proposed models, a case study was conducted demonstrating their use on a real reinforced concrete structure. The initial step involved selecting an existing structure for a non-destructive testing campaign. The Algiers subway structures were chosen, specifically targeting prefabricated high strength concrete beams approximately three months old (Fig. 8). These beams had an actual strength of 64 MPa at 28 days in average. The actual compressive strengths of the HPC beams were derived from the results of destructive tests conducted on cubic control specimens at 28 days.

Fig. 8. Prefabricated beams of the Algiers subway structures.

The main reason for selecting these beams was the type of the aggregates used in the concrete mix, which are the same in mineralogy and size as used in the present study: limestone crushed rock aggregates of 15 mm maximum size. The aggregate size and mineralogy being one of the most influencing factors on NDT measurements, targeting the same aggregate will minimize the effects of influencing factors and hence will reduce the sources of variability and uncertainty in NDT measurements.

A total of 14 beams were selected. To measure the rebound index, six points were selected on each of the two opposite faces of the beam. The rebound number is taken as the median of the 12 measurements recorded (Fig.9 (a)). The UPV test was carried out at the extreme end of each beam, where 06 spots were marked along a vertical line on the opposite sides of the beam. When taking transit time measurements, a special attention was paid to having the transducer emitter at the exact opposite face as the transducer receiver (Fig. 9 (b)). After measuring the path length, the UPV was determined for the six spots and their mean value was taken as the ultrasonic pulse velocity for the tested beam.

(a) (b)

Fig. 9. UPV measurements Prefabricated beams of the Algiers subway structures. (a) RN measurements. (b) UPV measurements.

The in-situ NDT measurements were subsequently employed to estimate the compressive strength of the tested beams. This estimation was carried out using the RN-Strength model, the UPV-Strength model, and the SonReb model. The comparison of the beams actual strength and the estimated strength using the proposed models is plotted in fig.10, 11 and 12.

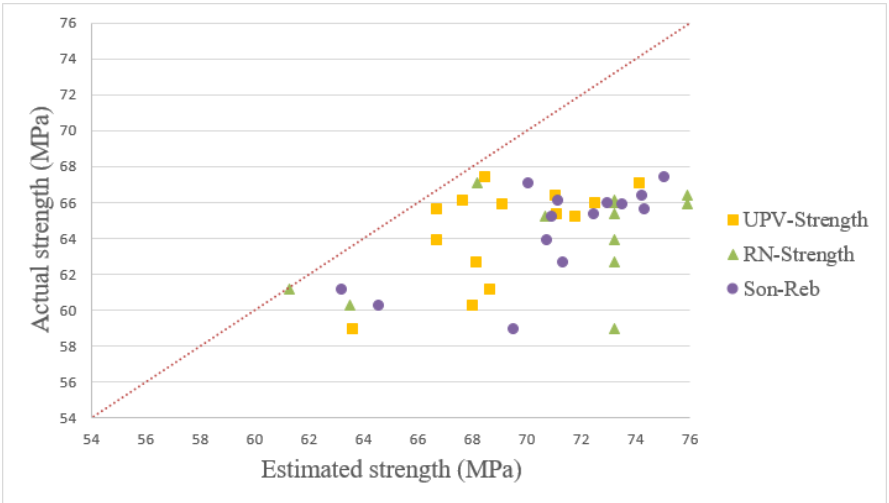

Fig. 10. Comparison of the beams actual strength to the strength estimated using the proposed models for HPC.

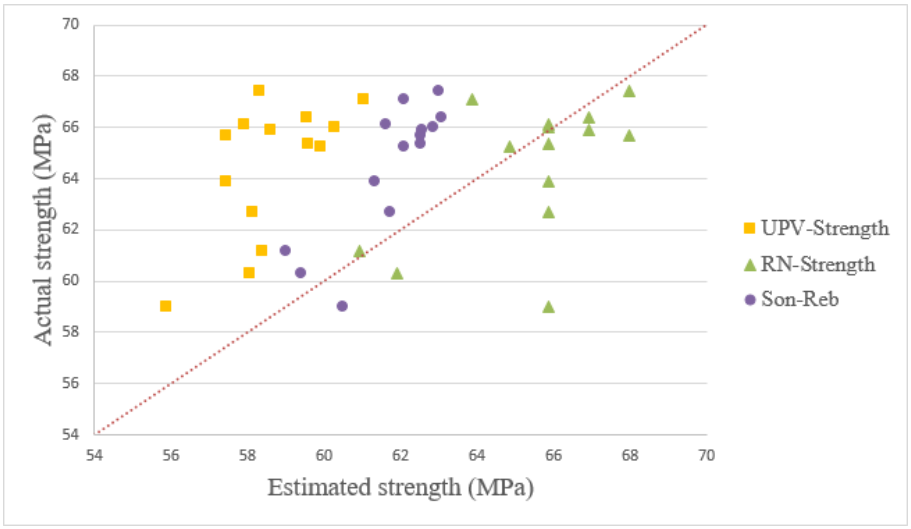

Fig. 11. Comparison of the beams actual strength to the strength estimated using the proposed models for MSC.

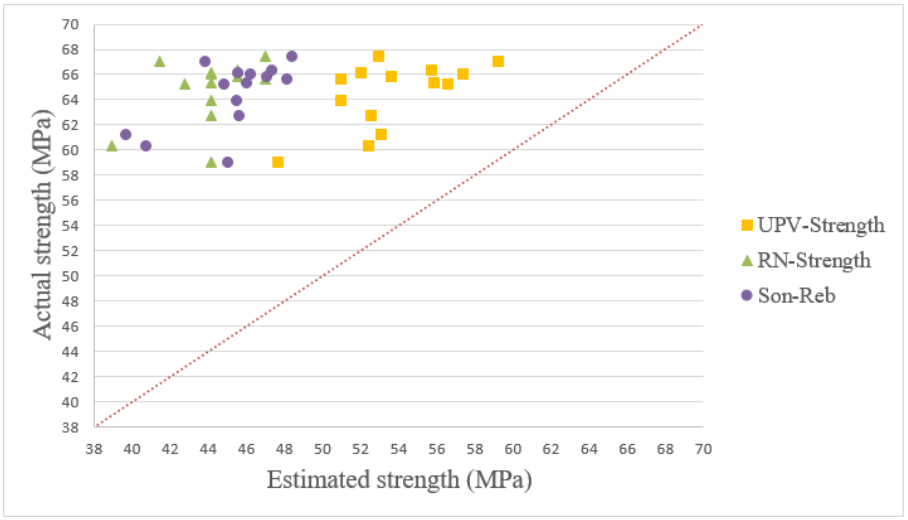

Fig. 12. Comparison of the beams actual strength to the strength estimated using the proposed models for NSC.

When the actual compressive strength of the beams is compared with that estimated using models developed for normal-strength concrete (NSC), an underestimation is observed. This is evident from the distribution of data points lying predominantly above the 45° equality line (Fig.12). This discrepancy can be attributed to the fact that the NSC models were developed using concrete with lower strength levels than those of the tested beams, whose average compressive strength was approximately 64 MPa.

A similar observation is made when using the models developed for high performances concrete (HPC). These models were built based on concrete strengths ranging from 54 MPa to 94 MPa, they tend to overestimate the strength of the beams, as shown in Fig. 10. These findings are further supported by the statistical parameters presented in table 5, namely the mean absolute error (MAE) and mean absolute percentage error (MAPE).

As mentioned above, despite significant differences in compressive strength ranges among the normal strength concrete (NSC), the medium strength concrete (MSC), and the high performances concrete (HPC), the rebound hammer and the ultrasonic pulse velocity non-destructive measurements do not exhibit significant variation. While an increase in concrete quality (and thus compressive strength) generally leads to an increase in non-destructive measurements, the rate of increase is not proportional. As a result, when a set of non-destructive measurements obtained from a given concrete is used with a model developed for a concrete class with substantially different strength characteristics, the estimated strength tends to align with the strength range on which the model was originally based. This leads to the conclusion that, for reliable estimation of in-situ concrete strength, it is advisable to employ a model developed for a strength class close to that of the investigated concrete.

The models developed for MSC provide a good estimation of the compressive strength of the tested beams, as demonstrated by the distribution of values around the 45° equality line (Fig. 11). The quality of the estimation is also reflected in the MAE values obtained for the different models—uniparametric and combined— built for this concrete (Table 5). For MSC, the MAE for the RN-Strength model was 1.63 MPa, corresponding to a MAPE of 2.59%. The UPV-Strength model yielded an MAE of 5.85 MPa and a MAPE of 8.97%, while the combined SonReb model produced an MAE of 3.05 MPa and a MAPE of 4.67%. It should be noted that the compressive strength of the specimens used to develop these models ranged from 54 MPa to 72 MPa, which matches the strength range of the tested beams. Therefore, MSC is more representative of the concrete used in the beams, which explains the accuracy of the strength estimates. This highlights the importance of considering the concrete strength class, and, more specifically, the cement paste parameters, when estimating compressive strength using non-destructive techniques.

Tab. 5. Mean absolute error (MAE) and mean absolute percentage error (MAPE) for strength estimation based on the proposed models.

Model type	RN-Strength		UPV-Strength		SonReb	
Statistical parameter	MAE (MPa)	MAPE (%)	MAE (MPa)	MAPE (%)	MAE (MPa)	MAPE (%)
HPC	7.84	12.18	4.65	7.29	6.55	10.18
MSC	1.63	2.59	5.85	8.97	3.05	4.67
NSC	20.81	32.28	10.81	16.75	19.20	29.73

In the case of compressive strength class (MSC), the SonReb model yielded a higher coefficient of determination (R^2) compared to the RN-Strength and UPV-Strength models, indicating superior predictive capability. However, within the case study considered in this research, the application of the SonReb model did not result in improved accuracy for estimating the compressive strength of the tested concrete beams. The RN-Strength model provided the most accurate predictions, with a mean absolute percentage error (MAPE) of 2.59%, followed by the SonReb model (4.67%) and the UPV-Strength model (8.97%).

In some instances, combining a highly accurate non-destructive testing (NDT) technique with another of lower precision can lead to an intermediate level of accuracy [22]. In the present study, the rebound hammer measurements obtained on the beams were consistent with those from the reference concrete used to develop the MSC models given the similar concrete density, since the rebound hammer test primarily assesses surface quality. The UPV test, which characterizes the internal quality of concrete, was expected to yield comparable results due to the similarity in strength class and aggregate type between the tested and reference concretes, hence similar densities. However, discrepancies were observed, resulting in reduced estimation accuracy for the UPV-Strength model. This decline is attributed to the presence of dense reinforcement in the tested beams, particularly at their ends, where both passive reinforcement and ducts containing prestressing tendons are concentrated (Fig.13). Given the higher density of steel compared to concrete, reinforcement along the ultrasonic wave path affects the pulse velocity measurement, often leading to overestimated values. The extent of this influence depends on the orientation and density of the reinforcement, as well as concrete quality [32]. Consequently, to enhance the reliability of compressive strength estimations using UPV, the influence of embedded steel must be explicitly considered in the interpretation of ultrasonic measurements.

Fig. 13. Reinforcement density at the beams end

4. Conclusion

This study investigated the effectiveness of Schmidt rebound hammer (RH) and ultrasonic pulse velocity (UPV) techniques in predicting the compressive strength of concrete through non-destructive testing (NDT). Correlation models, both uni-parametric and combined (SonReb), were developed using data obtained from cylindrical specimens across a broad range of mix designs, strength levels, and concrete ages. Regression analysis confirmed that the combination of RH and UPV measurements improves the accuracy of strength prediction compared to individual methods.

Application of these models to a real case study involving precast high strength concrete beams revealed that model accuracy is highly dependent on the alignment between the concrete class used in model development and that of the in-situ material. Models developed for medium strength concrete (MSC) provided the best agreement with actual compressive strength, achieving a mean absolute percentage error (MAPE) as low as 2.59% for the RN-Strength model. While the SonReb model showed the highest coefficient of determination (R^2), it did not consistently outperform the rebound-based model in practical application. The UPV-based model was more sensitive to internal variations but yielded less accurate estimates due to interference from dense reinforcement, especially in prestressed regions.

These findings highlight several critical factors influencing the accuracy of NDT-based strength estimation, including aggregate type, strength class and the presence of embedded steel. In particular, UPV measurements were shown to be significantly affected by reinforcement layout, which can distort wave propagation and lead to strength overestimation. Thus, future model development should incorporate correction factors or classification schemes that account for reinforcement effects.

Overall, the RH and UPV methods, particularly when used in combination, offer a practical and efficient approach to in-situ concrete strength evaluation. Their successful integration into structural assessment protocols requires careful calibration and contextual adaptation to the specific characteristics of the tested material. Further research is needed to refine model applicability across a broader range of concrete types and structural configurations.

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