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Correlation of rebound hammer and ultrasonic pulse velocity methods for instant and additive-enhanced concrete

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Abstract. This study aims to determine the characteristics of concrete as identified by Rebound Hammer and Ultrasonic Pulse Velocity (UPV) tests, focusing particularly on their efficacy in estimating compressive strength of concrete material. The study involved three concrete samples designed to achieve a target strength of 29 MPa, comprising normal concrete, instant concrete, and concrete with additives. These were cast into cube specimens measuring 150×150×150 mm. Compressive strength values were determined through both destructive and non-destructive testing on the cubic specimens. As a result, the non-destructive methods yielded varying outcomes for each correlation approach, influenced by the differing constituent materials in the tested concretes. However, normal concrete consistently showed the most reliable correlation, followed by concrete with additives, and lastly, instant concrete. The study found that combining Rebound Hammer and UPV tests enhances the prediction accuracy of compressive strength of concrete. This synergy was quantified through multivariate regression, considering UPV, rebound number, and actual compressive strength. The findings also suggest a more significant influence of the Rebound Hammer measurements on predicting compressive strength for BN and BA, whereas UPV and RN had a similar impact on predicting BI compressive strength.

Keywords: compressive strength; concrete; non-destructive test; rebound hammer test; ultrasonic pulse velocity

1. Introduction

Concrete, the most extensively utilized material in construction Continues to grow in field application due to its high compressive strength, excellent workability, and resilience under various conditions (Mehta and Monteiro 2013). Recognizing compressive strength as a critical attribute, modifications in material proportions or constituent substitution are often performed to

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achieve desired outcomes, such as higher strength, higher resistance, etc. (Hossain and Islam 2021).

The increasing use of various admixtures in concrete mixtures is a noteworthy trend, with some countries reporting that up to 80% of their concrete production incorporates these additives (Mehta and Monteiro 2013). These admixtures, which include accelerators, water reducers, and other types, serve to modify the fundamental properties of concrete. Their roles range from accelerating the hardening process to reducing water content and enhancing other performance characteristics. This additive has given the impact of such diverse such faster setting time, overall quality of concrete, with a view towards optimizing the construction process.

A transformation towards enhanced effectiveness, efficiency, speed, and sustainability of concrete material has pushed the emergence of instant concrete. Instant concrete is a term used to describe a packed of concrete materials including cement and aggregates that have been precisely measured. The precise measurement ensures that the resulting composition constantly achieves the desired compressive strength. The aim is to minimize all the mistakes during mixing while also speeding up the overall process of concrete casting.

Recently, the use of non-destructive methods has become popular for the determination of the concrete properties, among others, the Hammer test and Ultrasonic Pulse Velocity (UPV) test (Hannachi and Guetteche 2012), specifically for practical testing in construction field. These latter tests have been regarded as convenient methods to predict the compressive strength of concrete (Brožovský 2009, Poorarbabi *et al.* 2020). However, discrepancies between local measurements from non-destructive tests and sample-scale measurements from destructive tests have been observed (Güçlüer 2020, Benaicha *et al.* 2015, Kong *et al.* 2021, Kumavat *et al.* 2021). It may arise from the discrete nature of the different components of the concrete, their aggregates gradation, and the age of the specimen (Malhotra & Carino, 2004).

Measurement of hammer test and UPV test, respectively, has been regarded as a means to potentially predict the compressive strength of a concrete structure (Brožovský 2009, Poorarbabi *et al.* 2020). However, the drawback of non-destructive tests might emerge due to its limitation in accurately measuring compressive strength. The findings have consequently imposed limitations on efficacy of non-destructive tests in evaluating concrete properties which lead to the variation of value in predicting the compressive strength.

As regulated in SNI 2847:2019 standard, a compressive strength value is deemed acceptable if it falls within a 10% variation from the designated value. However, research conducted by Kolek (1958) and Maltora (1976) revealed doubts regarding the correlation between compressive strength and the Schmidt hammer. The results indicated considerable variability, with an average coefficient of variation of 18.8%.

Gavela *et al.* (2023) have conducted a study in improvement of lowering the uncertainty of the concrete's compressive strength of uniaxial compressive test by adding the measurement of rebound hammer and. It was done by performing destructive and non-destructive tests on cubic specimens at the age of 28 days. The result was taken by combining the average prediction of compressive strength from each method to obtain the estimated measurement. As a result, the uncertainties of the determined compressive strength were lower due to the combining method of the non-destructive test.

This study delves into the analysis of local property variations in concrete samples, as determined by non-destructive testing methods, specifically the Hammer test and Ultrasonic Pulse Velocity (UPV) test. With the advancement in research of this field, we have witnessed comprehensive evidence of improvement in non-destructive testing in predicting concrete's

Table 1 Mixed Design for Concrete Sample

Parameter	BN*	BA	BI
W/C	0.450	0.450	0.480
Cement (kg/m^3)	428.9	428.9	Target Strength of 29 MPa
Crushed Stone (kg/m^3)	1107.36	1107.36	
Sand (kg/m^3)	648.8	648.8	
Concrete Additive (kg/m^3)	-	3.43	-
Slump (cm)	8 ± 2	8 ± 2	8 ± 2

*BN: Normal Concrete; BA: Concrete with Additive; BI: Instant Concrete

compressive strength (Tahwia *et al.* 2021, Erdal *et al.* 2018, Amini *et al.* 2016). However, with the diverse characteristics that each concrete mix has, the outcome of each prediction will vary.

This study will try to investigate and compare the behavior of commonly used concrete mix to its modified model, particularly instant concrete, and concrete with additives This study aims to expand the horizon for the utilization of combined methods and implement the method on the alternatives to conventional concrete. The research is conducted through experimental investigations on cubic specimens of three distinct types of concrete—normal concrete, instant concrete, and concrete with additives. Each specimen undergoes both non-destructive and destructive testing to establish a comprehensive understanding of the relationship between compressive strength, UPV, and rebound number. This comparative study was conducted with the dual purpose of enhancing the reliability of non-destructive testing in concrete assessment and expanding the practical application of these methods in the field.

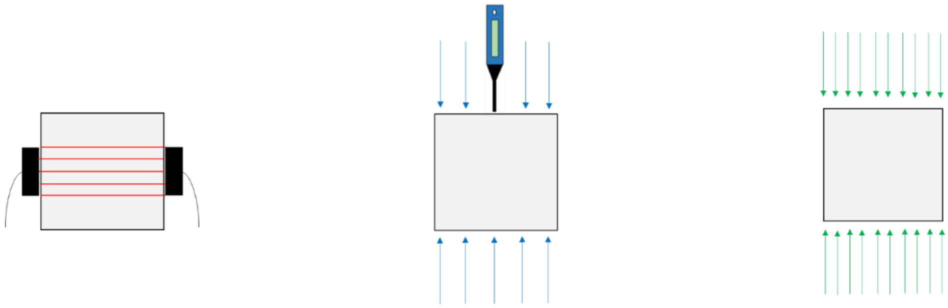
2. Materials

This study evaluates three types of concrete mix: Normal Concrete (BN), Concrete with Additive (BA), and Instant Concrete (BI). These concrete mixes were chosen due to their prevalent use in construction practices, offering a representative analysis of commonly used concrete types.

Normal Concrete (BN): BN was utilized as the control sample in this experiment. The mix design for achieving the targeted compressive strength of 29 MPa was formulated in accordance with Indonesian Standard SNI 7657:2012 (Badan Standardisasi Nasional 2012). The mix comprised fine aggregates (from Bangka), characterized by a fineness modulus of 2.31 and a specific gravity of 2.63. Coarse aggregates (type of crushed aggregate) had a maximum size of 25.4 mm and a specific gravity of 2.64.

Concrete with Additive (BA): The BA mix shared the same base ingredients as BN. However, it was distinguished by the inclusion of specific admixtures, constituting approximately 0.8% of the cement's weight (Table 1). This proportion was determined on previous studies by Novrianti *et al.* (2014) and Jamal *et al.* (2017), which recommended the incorporation of a concrete additive to modify properties such as setting time and workability.

Instant Concrete (BI): For BI, pre-packaged mixes locally manufactured and having a specific gravity of 2.35 were used. The packages comprised Portland cement, silica sand, and screening stone with sizes ranging between 5 to 10 mm. Water was added as per the instruction of manufacturer to achieve a slump value of 8 cm (± 2 cm). The material ratios in these packages were meticulously calibrated to consistently reach the desired compressive strength of 29 MPa.



(a) UPV test (b) Hammer Test (c) Compression Test

Fig. 1 The placement of each test on the cubic specimen

3. Research methodology

Cubic specimens, each possessing dimensions of 150x150x150 mm³, were employed to establish correlations among Ultrasonic Pulse Velocity (UPV), rebound number (RN), and compressive strength (CS) of concrete.

Specimen Preparation and Testing Schedule. The specimens were tested at different ages—3, 7, 14, and 28 days—to observe the influence of concrete maturity on test results. The testing sequence involved non-destructive tests (Rebound Hammer Test and UPV Test) followed by destructive Compressive Strength Test. This approach allowed for a comprehensive assessment of the specimens without compromising their integrity prior to the compressive test.

Testing Procedures. The non-destructive tests were performed on flat surface of cube specimens, as illustrated in Figs. 1 (a) and 1(b) first, then followed by destructive test (Fig. 1(c)). Non-destructive tests will be focused on the Hammer test and UPV test. In the UPV test, equipment was used to propagate the ultrasonic waves through the concrete, with the velocity measured using UPV equipment. The Proceq Pundit Lab Ultrasonic Instrument was utilized to perform the test. The frequency of the ultrasonic wave was set at 54 Hz as recommended by (Panzera *et al.* 2011, Turgut and Kucuk 2006). For Rebound Hammer Test, Proceq Silver Schmidt type N hammer was used to estimate the RN, assessing the hardness of the concrete based on the rebounding principles of the tool (Mehta and Monteiro 2013). The compressive strength value (fc') was achieved by adapting the ASTM C 39 (2021) procedure to the cubic specimens. To compensate the utilization of cube form, the conversion factor from Arijoeni and Setiadi (1998) were applied.

Standard Adherence for Non-Destructive Tests: Procedures for the non-destructive tests adhered strictly to ASTM C 805 (2018) for the Rebound Hammer Test and ASTM C 597 (2022) for the UPV Test. UPV measurements were taken on two sides perpendicular to the compressive test loading axis. RN measurements were performed on the sides where the platens of the press apparatus would be applied during the compressive tests.

4. Results and discussion

This section shows the empirical relationships derived from non-destructive testing (NDT) methods—Rebound Hammer (RN) and Ultrasonic Pulse Velocity (UPV)—and their correlation

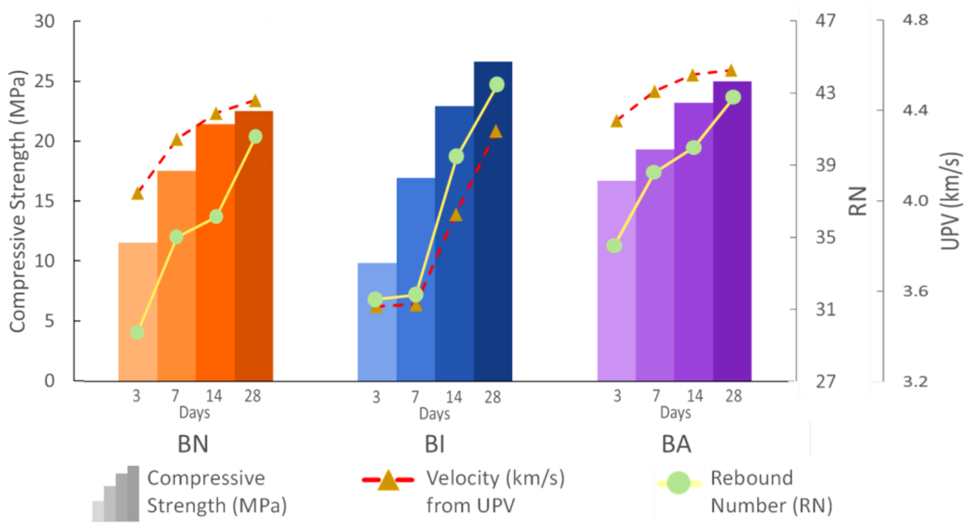


Fig. 2 Comparison of the development trend between destructive test and non-destructive test

with the compressive strength (CS) of three different concrete types. The analysis commences with a quantitative assessment of RN and UPV results across various maturation stages of concrete—spanning from 3 to 28 days—facilitating a comprehensive understanding of their mechanical properties' evolution. Subsequently, the study advances to a comparative exploration, connecting the experimental data against established standard and existing curves. This juxtaposition not only validates the experimental approach but also reveals nuanced insights into the behaviour of each concrete type—Normal Concrete (BN), Instant Concrete (BI), and Concrete with Additive (BA).

4.1 Development of the value and comparative analyses of non-destructive tests

Consistent with the findings of Norman *et al*. (2016), normal concrete (BN) typically achieves its maximum strength after a 28-day curing period, with a progressive increase in compressive strength in a function to its age. The strength development pattern observed in our study indicated that at 3 days, the concrete reached 35-40% of its maximum strength, at 7 days it achieved 65-70%, and by 14 days, it attained 85-90%. This progression is attributed to the hydration rate of cementitious materials, which plays a crucial role in strength development.

The rebound hammer test focuses on surface hardness, while the UPV test evaluates concrete through the compactness of its volume (Lawson *et al.* 2011). The comparative development of these non-destructive tests across the ages of 3, 7, 14, and 28 days was examined and is illustrated in Fig. 2. Fig. 2 depicts the developmental trends of compressive strength (CS), rebound number (RN), and Ultrasonic Pulse Velocity (UPV) for three different types of concrete over a 28-day period. The chart is a combined bar and line graph, with the bars representing CS and the lines indicating RN and UPV values. Each concrete type is color-coded as follow: Normal Concrete (BN) in orange, Instant Concrete (BI) in blue, and Concrete with Additive (BA) in purple.

RN (indicated by the lines with round markers) is measured on a secondary *y*-axis scaled from 27 to 47. RN also increases over time, which generally correlates with the increasing hardness of the concrete surface as it hardens. The growth pattern in RN for each concrete type is more or less similar to the growth pattern of their CS, suggesting a direct correlation between surface hardness and the compressive strength of the concrete, exception for the first week of BI samples. At 7 days, RN did not increase significantly compared to CS. UPV values (tertiary *y*-axis scaled from 3.2 to 4.8 km/s), indicated by the dashed lines with triangle markers, show an increasing trend over the 28 days, reflecting the progressive hardening of the concrete.

The development on each concrete, for both normal concrete (BN) and concrete with additive (BA), the rebound number (RN) exhibited rapid growth, with a slight sign of slowing down between 7-14 days period. The sudden change on rebound number describes how the cement reaction was delayed the hardening process on the surface area on the period. Conversely, the UPV measurements indicated a more gradual development of density throughout the concrete volume. The disparity between the development of concrete density describe by the UPV measurements and surface hardness shows that for BA and BN hardness initially developed on their surface which later followed by its concrete core.

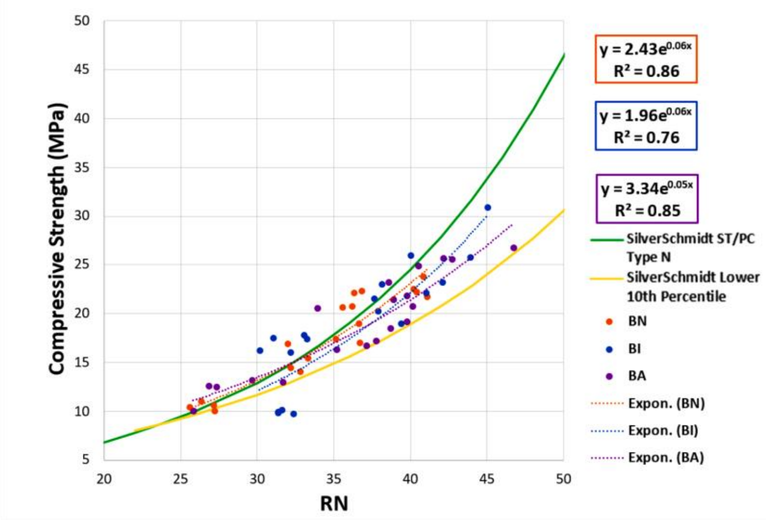
In contrast, instant concrete (BI) exhibited a consistent trend in both UPV and RN values, with lower measurements observed during the early development, followed by significant growth. This pattern implies the poor results in both surface hardness and overall density in the first seven days. During this period, BI gives a low and constant numbers from the non-destructive testing while in contrast the destructive test results lead to a convincing growth. This contradiction is due to a slow reaction from the binding agent in BI. It produces a premature state of concrete for non-destructive testing to be performed on which led to unsatisfactory reading.

These observations indicate potential deviations between non-destructive and destructive testing, particularly in the initial stages of curing. However, the results also suggest promising prospects for combining non-destructive testing methods to provide a more comprehensive assessment of the material properties of concrete at various stages of maturity. Furthermore, in engineering perspective, the correlations observed provide practical insights into the maturity of concrete, offering a means for engineers to predicting the in-situ strength of concrete without resorting to destructive testing. These findings support the use of RN and UPV as complementary methods for assessing the condition and quality of concrete during the curing process.

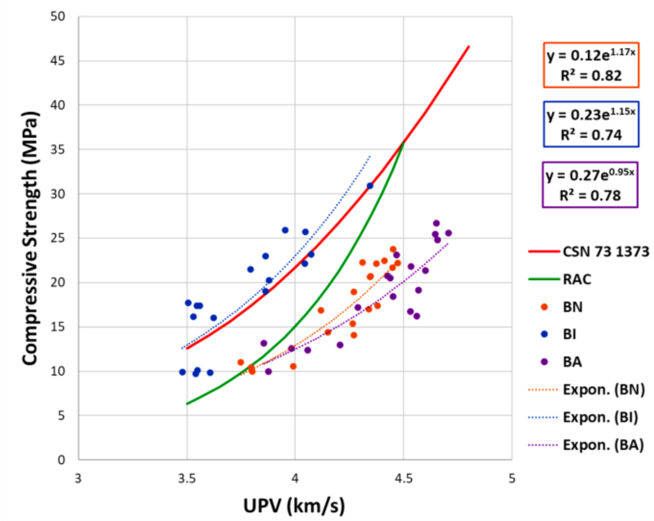
4.2 Correlation and comparison analysis of compressive strength with non-destructive testing

Following the guidelines of ACI Committee 228 (2000), this research sought to establish empirical relationships between the measurements obtained from rebound hammer and UPV tests with compressive strength (CS) values derived from cubic specimens. The correlations, directly linked to concrete's compressive strength, are presented graphically and compared with existing studies in Fig. 3. The UPV-CS relationship in our samples was compared with the normal concrete data from Brožovský (2009), while the rebound hammer test results were juxtaposed with the reference graph from the silver Schmidt type-N hammer manual (Proceq 2017). In line with ACI Committee 228 (2003), the correlations were modelled using a non-linear, specifically exponential, function, reflecting the intrinsic relationship between non-destructive test measures and compressive strength (Table 2).

The equations provided are exponential functions representing the empirical relationships between non-destructive test results and compressive strength (CS) for three types of concrete: BN, BI, and BA. In these equations, n_{RN} represents the rebound number from the rebound hammer test, and v_{UPV} represents the velocity measurement from the Ultrasonic Pulse Velocity (UPV) test.



(a)



(b)

Fig. 3 Relation between compressive strength and non-destructive test: (a) Rebound hammer test and (b) UPV test

The numbers provided after each equation represent the coefficient of determination (R^2) for the respective model.

The coefficient of determination (R^2) was employed to gauge the accuracy of non-destructive tests in estimating the value of CS. The RN-CS correlation exhibited a stronger relationship compared to UPV-CS, as evidenced by higher R^2 values for BN, BI, and BA in the RN-CS model. This suggests a more robust and consistent relationship between surface hardness and compressive strength, especially in later stages of concrete curing (Chin 1998). The R^2 values across all three concrete types followed a consistent pattern, with BN showing the strongest correlation, followed

Table 2 Non-linear Functions of Non-destructive Test in Estimating Compressive Strength

Specimens	Formulation *	R^{2} **
Normal concrete	$CS(n_{RN}) = 2.43\ e^{0.05\ (n_{RN})}$	0.86
	$CS(v_{UPV}) = 0.12\ e^{1.17\ (v_{UPV})}$	0.82
Instant concrete	$CS(n_{RN}) = 1.96\ e^{0.06\ (n_{RN})}$	0.76
	$CS(v_{UPV}) = 0.23\ e^{1.15\ (v_{UPV})}$	0.74
Concrete with additive	$CS(n_{RN}) = 3.34\ e^{0.05\ (n_{RN})}$	0.85
	$CS(v_{UPV}) = 0.27\ e^{0.95\ (v_{UPV})}$	0.78

* CS = compressive strength; n_{RN} = number of Rebound Hammer; v_{UPV} = velocity in km/s obtained from UP V measurement
** R^2 = coefficient of determination

by BA, and then BI. The lower correlation in BI is attributed to the discordance between non-destructive and destructive test progression, as discussed earlier.

The correlation between RN and Compressive Strength yields a notably compelling outcome, as shown in Fig. 3(a). In comparison to the reference graph for the rebound hammer, the relation graphs established in this research exhibit great similarity. The predicted CS trendline obtained by the correlation graph align within the range defined by the provided references, encompassing both the average measurement and the lower 10^{th} percentile measurement. This alignment further bolsters the reliability and accuracy of the correlation established in this study. It showed the consistency of Silver Schmidt hammer in predicting the compressive strength Among different concrete varieties. Moreover, this founding also implies that the chosen instrument may affect the accuracy of the prediction.

Alternatively, the established correlations within this research for UPV and CS exhibit some variation when compared to the CSN 73 1373 relation as shown in Fig. 3(b). The BI graph shows a great resemblance to the CSN 73 1373 which is acquired from the correlation performed on normal concrete. To give another perspective, the correlation graph in the case of recycle aggregate concrete (RAC) provided by Handika *et al.* (2020) was added to the comparison. Even with the similar range of UPV measurements, the graph is showing a steeper trend compared to the correlation performed in this research.

However, it is noteworthy the similarities in the correlation between UPV and CS and RN and CS for both BN and BA types of concrete. The subtle distinctions observed between these samples stem from the inclusion of an admixture, which influences concrete properties by enhancing strength and density.

In predicting the compressive strength on concrete, it is observed that the UPV measurements are more reflective of the characteristics of the constituent materials than the type of the concrete. Since they were built upon a similar material, BN have a comparable result BA. On the other hand, the normal concrete correlation graph by Brožovský (2009) diverge from the BN and lean better toward the BI graph. The BI's trendline, which employs a finer aggregate, exhibits a similarity to the CSN 73 1373 standard, suggesting that aggregate size plays a significant role in the material properties. This nuanced understanding of material properties and their impact on non-destructive test readings is crucial for advancing concrete testing methodologies and could provide a foundation for future research to explore these influences in greater detail.

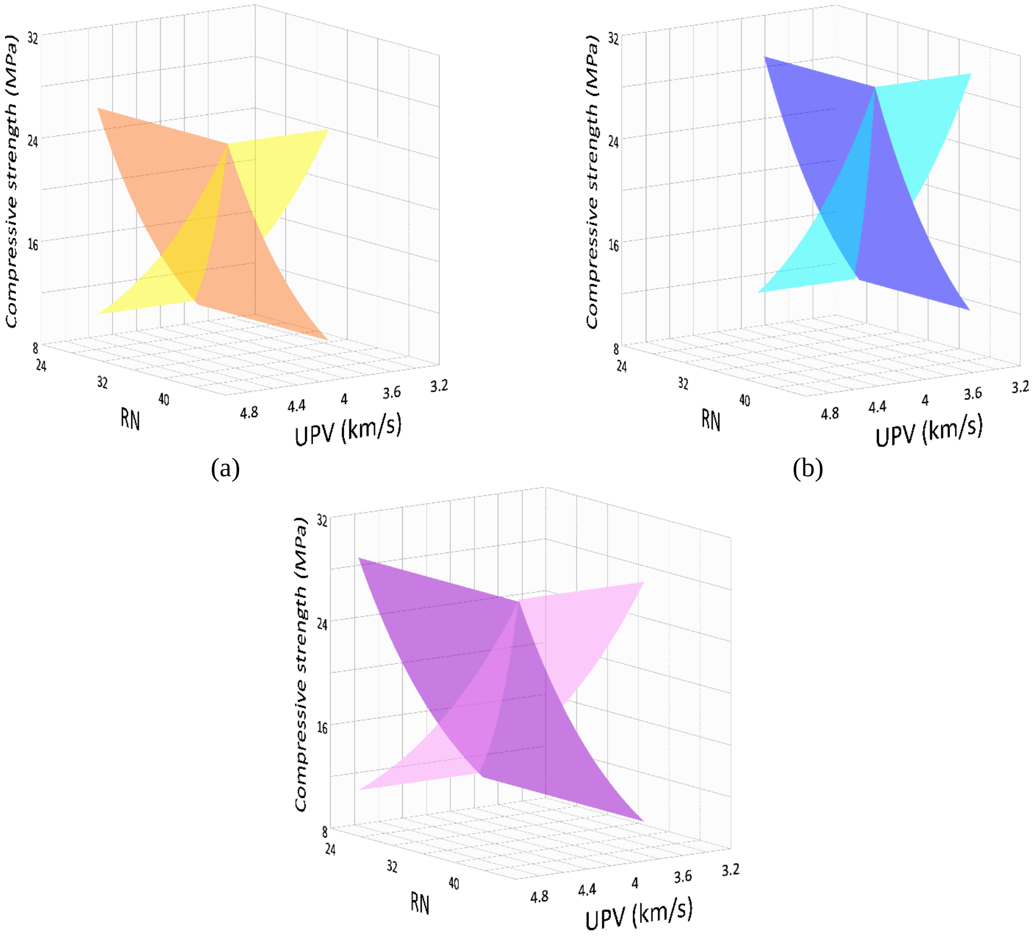


Fig. 4 The 3D illustration of established relation of compressive strength to rebound number (RN) and ultrasonic pulse velocity (UPV): (a) normal concrete (BN), (b) instant concrete (BI), and (c) concrete with additive (BA)

4.3 Correlation of compressive strength with rebound hammer test and UPV test

The combination of two non-destructive techniques is done in effort to refine the precision of concrete strength prediction. By combining data from each measurement, potential variations stemming from diverse factors that influence readings can be mitigated (Craeye *et al*. 2017, Jain *et al.* 2013). However, the increasing value of the measurement will only be attained if the limitation of the combining measurements is well described (Breysse 2012).

To achieve enhanced results in Compressive Strength (CS) predictions, the measurements of RN and UPV are combined. This fusion of methods is anticipated to yield improved accuracy in predicting compressive strength. After establishing the distinctive behaviour of rebound test and UPV test toward the properties of concrete, it brings up the opportunity of complimentary value between the two methods.

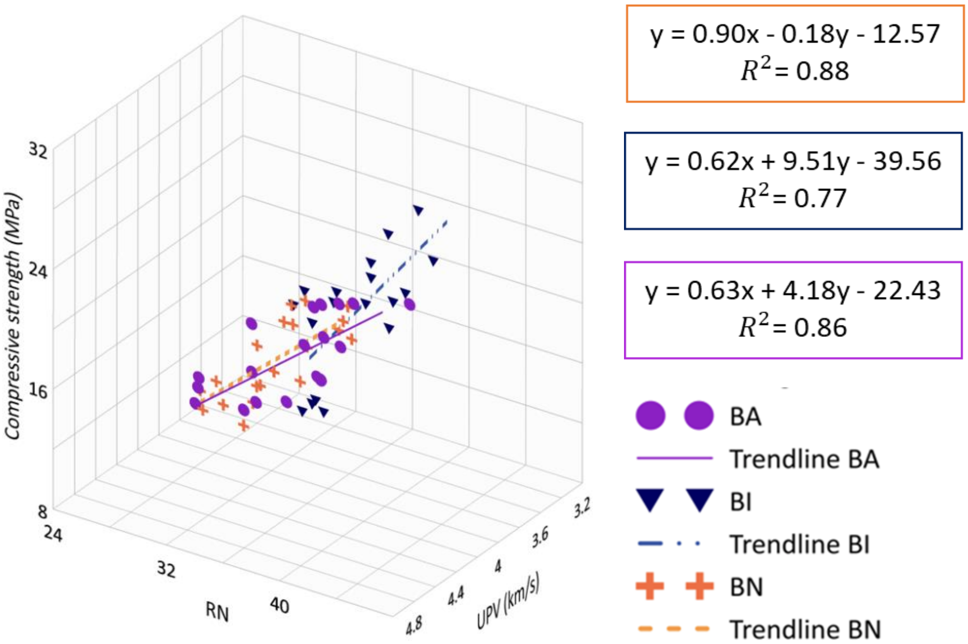


Fig. 5 3D illustration for $CS(n_{RN}, v_{UPV})$ relationship from the combination of three types of concrete samples

The established correlations from a single non-destructive method were put on the 3D plane graph. The illustration in Figs. 4(a)-4(c) demonstrates the comparison of CS estimation between rebound hammer test and UPV test. The x-axis represents RN, the y-axis stands for CS in MPa, and the z-axis corresponds to UPV in km/s. Within Fig. 4, the planes resulting from the correlation of each UPV and RN with CS intersect linearly on the xz-plane. This unique alignment forms the basis for establishing the combined correlation.

Multivariate linear regression is employed to model the relationship between compressive test measurements, UPV test measurements, and hammer test results on cubic specimens. The resultant formulation is encapsulated within the function $CS(n_{RN}, v_{UPV})$ for each individual sample. The correlation among the three variables is vividly portrayed using a 3D graph. Although the function is within the three-dimensional plane, the trendline is constructed to demarcate the specific domain of UPV and RN values encompassed by this study.

As shown in Fig. 5, the pattern for the three variables correlation is corresponding to the two variables correlation. The Normal Concrete (BN) trendline is in orange, whilst (Instant Concrete) BI trendline is in blue and Concrete with additive (BA) in purple. The BI trendline show a noticeable deviation from the BN and BA. This condition showed that the characteristics of each method are carried out in the combination of both methods.

Another finding worth mentioning is the comparison between the correlated surface from combining two methods (Figs. 6(a)-6(c)) and the plane obtained from a single method in Figs. 4(a)-4(c). The combined surface uniquely inclines similarly to the CS-RN correlation plane. It is applied for all concrete samples with a similar constituent, BN and BA, even with some variation to the skewness between the two planes. This tendency should imply that the rebound hammer test has a greater effect on predicting the compressive strength, better than predicted by UPV test. In

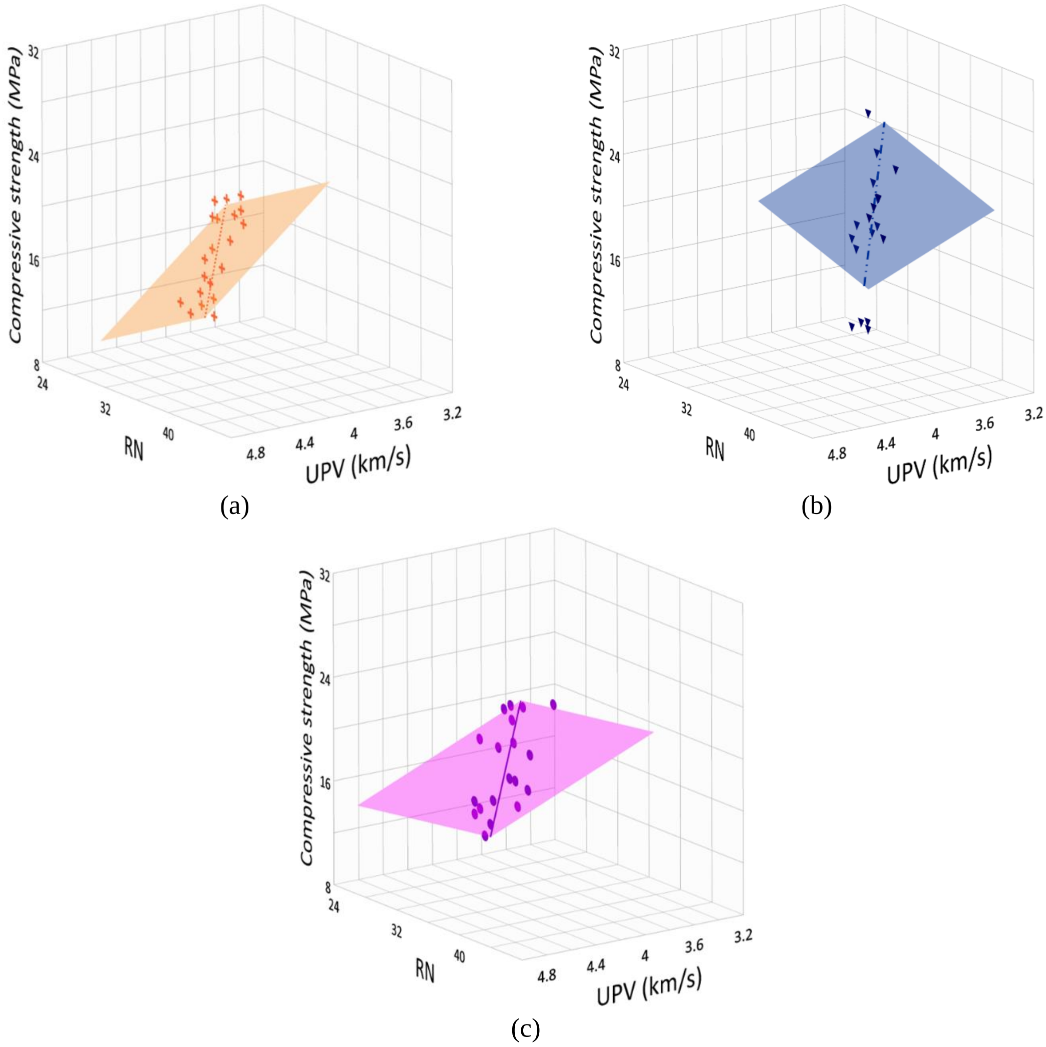


Fig. 6 3D illustration for CS (RN, UPV) function: (a) normal concrete, (b) instant concrete, and (c) Concrete with additive

contrast, the BI samples show that the rebound number and UPV have a balance proportion in determining the compressive strength.

Indeed, the integration of the three-variable correlation results in the formulation of equations for the studied sample (Eqs. (1)-(3)). The incorporation has elevated the R^2 value for estimating CS in each sample which exhibiting the success in enhancing level of confidence in utilizing non-destructive tests for accurate CS estimation. It is noteworthy that the level of confidence for the combining method between the samples still follow an identical order to the single testing with BN being the highest, and BI being the lowest. The relatively low accuracy for the BI sample is influenced by the unstable data which are taken in the early stage of BI age development, as supported by Fig. 2.

Normal concrete

$$CS(n_{RN}, v_{UPV}) = 0.90\ n_{RN} - 0.18\ v_{UPV} - 12.57 \quad (1)$$
$$R^2 = 0.88$$

Instant mix concrete

$$CS(n_{RN}, v_{UPV}) = 0.62\ n_{RN} + 9.51\ v_{UPV} - 39.56 \quad (2)$$
$$R^2 = 0.77$$

Concrete with additive

$$CS(n_{RN}, v_{UPV}) = 0.63\ n_{RN} + 4.18\ v_{UPV} - 22.43 \quad (3)$$
$$R^2 = 0.86$$

5. Conclusions

This research has systematically investigated the correlations among Compressive Strength (CS), Rebound Number (RN), and Ultrasonic Pulse Velocity (UPV). The behaviour of each test was evaluated using normal concrete, instant mix concrete, and concrete with additive to give a better understanding about the limitation and the potential of rebound hammer test and UPV test. Through comparative and combined analyses, this work has identified the correlation between these methods and their efficacy in predicting concrete strength.

The study reveals that the reactivity of the cement matrix affects the non-destructive measurements in describing the concrete compressive strength at the early age. In comparison to the maturity development (hardening) in concrete, RN for BN and BA grows rapidly in the first seven days compared to the UPV measurement which increases more gradually over 28 days period. On the other hand, the RN and UPV value in BI recorded low figure for the early stage due to the slow setting cement.

Moreover, the constituent of each concrete strongly influenced the correlation between UPV test and compressive strength. The comparison between various graphs reveals that concrete with similar components tend to produce a similar correlation. However, it is also shown that similarity may also occur between concrete with different structural elements. Therefore, the UPV-CS graph is only applicable if it is obtained from identical material.

In the case of rebound hammer, the correlation showed a satisfactory result. The functions that represent the relationship between RN and CS correspond with the established graphs which are suitable for the application of Silver Schmidt hammer. This compatibility gives a higher confidence in utilizing Silver Schmidt hammer in estimating the concrete's compressive strength.

To improve the accuracy of non-destructive tests to predict the compressive strength of concrete, the combination method was performed in this study. The method was proven effective as it increases the correlation confidence which is illustrated by the coefficient of determination for the established CS (RN, UPV) function.

In the analysis, it was observed that RN exerts a greater influence to determine the predicted value of compressive strength for BN and BA while, in contrast, UPV and RN provide a similar influence in predicting BI compressive strength. The results show a clearly defined pattern where the BN always yields a better relationship for each correlation and BI being the last, even with the improvement in combining method. Additionally, it is not recommended to carry out tests at the initial age of concrete in the case of instant concrete.

The combined analysis of RN and UPV alongside CS across different concrete types and curing times presents a comprehensive view of the material's development. The data supports the hypothesis that non-destructive test measurements can provide a reliable prediction of concrete strength, which could be highly beneficial for construction practices and quality assurance processes.

Acknowledgments

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