Prediction of Concrete Compressive Strength Using Ultrasonic Pulse Velocity: Experimental Evaluation of Direct and Surface Wave Methods

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ABSTRACT

Reliable evaluation of in-situ concrete compressive strength remains a major challenge in civil engineering practice, particularly where destructive testing is impractical or may compromise structural integrity. Non-destructive testing (NDT) techniques, especially ultrasonic pulse velocity (UPV), have been widely investigated as indirect methods for assessing concrete quality and mechanical performance [1,2]. This study experimentally evaluates the use of UPV for predicting concrete compressive strength, with emphasis on comparing direct ultrasonic pulse velocity (DUPV) and surface ultrasonic pulse velocity (SUPV) measurement techniques. Sixty standard concrete cube specimens (150 × 150 × 150 mm) were produced using multiple mix proportions at a constant water–cement ratio of 0.6 and cured for 7, 14, 21, and 28 days. UPV measurements were obtained using a portable ultrasonic tester and correlated with compressive strength results from standard compression testing. Linear and exponential regression models were developed and statistically validated using correlation analysis and analysis of variance. The results show a strong relationship between ultrasonic pulse velocity and compressive strength, with surface ultrasonic measurements providing superior predictive accuracy. The optimal linear model, C = 11.48S - 18.43, achieved a correlation coefficient of 0.83. The study confirms that surface UPV offers a practical and reliable approach for non-destructive estimation of concrete compressive strength.

Keywords-Ultrasonic pulse velocity; non-destructive testing; concrete compressive strength; surface wave method; quality control

INTRODUCTION

Concrete is the most extensively used construction material worldwide due to its versatility, durability, and high compressive strength [3]. Ensuring that concrete elements achieve their specified strength is fundamental to structural safety, serviceability, and durability [4]. Conventionally, concrete strength is assessed through destructive compression testing of laboratory-cured specimens. While this approach provides standardized strength values, it often fails to represent the actual in-place strength of concrete in structures, where differences in compaction, curing conditions, and workmanship may exist [5,6].

The increasing demand for reliable in-situ assessment methods has drawn significant attention to non-destructive testing techniques. NDT methods allow repeated evaluation of concrete properties without impairing structural performance and are particularly valuable for existing structures, quality control during construction, and post-construction condition assessment [1,7]. Among these methods, ultrasonic pulse velocity testing has gained wide acceptance because of its simplicity, low cost, and rapid execution [2,8].

Ultrasonic pulse velocity testing measures the travel time of high-frequency stress waves through concrete. The measured velocity is influenced by elastic properties, density, internal continuity, and moisture condition of the

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material [9]. Although UPV does not directly measure compressive strength, numerous studies have demonstrated that empirical correlations can be established between pulse velocity and strength when appropriate calibration is performed [10–12]. However, the reliability of these correlations depends on several factors, including mix composition, aggregate characteristics, curing age, and the ultrasonic measurement configuration employed [13,14].

Two principal UPV measurement configurations are commonly used: direct transmission and surface (indirect) transmission. Direct UPV involves wave propagation through the full thickness of the concrete element, whereas surface UPV is confined to the near-surface region. Previous studies suggest that surface wave measurements may be more sensitive to cement paste properties, which largely govern compressive strength [11,15]. Despite this, comparative experimental evidence remains limited, particularly for standardized specimens under controlled laboratory conditions.

This study therefore aims to:

(i) establish empirical relationships between ultrasonic pulse velocity and concrete compressive strength,

(ii) compare the predictive performance of direct and surface UPV measurement methods, and

(iii) examine the influence of curing age on the UPV–strength relationship.

The findings are intended to support the application of UPV as a practical tool for concrete quality control and structural assessment.

LITERATURE REVIEW

Non-destructive evaluation of concrete has been the subject of extensive research for several decades. Early work by Jones and Kaplan demonstrated that ultrasonic wave velocity increases with concrete stiffness and integrity, laying the foundation for UPV-based strength estimation [10,16]. Subsequent studies confirmed that UPV is sensitive to microstructural development, particularly during the early stages of hydration [9,17].

Malhotra and Carino [2] emphasized that UPV should be regarded as an indirect method, requiring calibration for specific concrete mixes to achieve reliable strength prediction. Several researchers have reported linear and exponential relationships between UPV and compressive strength, with correlation coefficients typically ranging between 0.55 and 0.85 depending on testing conditions and material variability [11,12,18].

The influence of measurement configuration has also been widely discussed. Direct UPV measurements capture wave propagation through both aggregate and cement paste phases, often resulting in reduced sensitivity to strength variations [13]. In contrast, surface ultrasonic waves are restricted to a shallow depth near the concrete surface, where paste concentration is higher due to the wall effect during casting [15,19]. As a result, surface UPV has been reported to exhibit stronger correlation with compressive strength in some studies [14,20].

Concrete age is another critical factor affecting UPV–strength relationships. As hydration progresses, increases in elastic modulus and reduction in porosity lead to higher pulse velocities [17,21]. Several authors have shown that correlation between UPV and compressive strength improves with curing age, particularly beyond 14 days [12,22].

Despite extensive research, variability in reported models highlights the need for experimental validation under controlled conditions. This study contributes to the existing body of knowledge by providing a systematic comparison of direct and surface UPV methods using standardized laboratory specimens and robust statistical analysis.

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MATERIALS AND METHODS

Ordinary Portland cement, natural river sand, crushed coarse aggregate with a maximum size of 20 mm, and potable water were used for all concrete mixes. Aggregate grading tests confirmed that the fine aggregate was well graded, while the coarse aggregate satisfied standard requirements for structural concrete [23].

Sixty concrete cube specimens of dimensions 150 × 150 × 150 mm were cast using different mix proportions while maintaining a constant water–cement ratio of 0.6. After demoulding at 24 hours, the specimens were cured in water until testing at ages of 7, 14, 21, and 28 days.

Ultrasonic pulse velocity measurements were carried out using a portable ultrasonic testing device in accordance with BS 1881-203 and ASTM C597 [24,25]. Both direct and surface measurement configurations were employed. Compressive strength tests were subsequently performed using a calibrated compression testing machine in accordance with BS 1881-116 [26].

Statistical analysis involved correlation analysis, linear and exponential regression, and analysis of variance to assess model significance. A significance level of 5% was adopted throughout the analysis.

RESULTS AND DISCUSSION

Compressive Strength and UPV Results

A summary of the experimental results grouped by curing age is presented in Table 1, while the complete dataset used for analysis is provided in Appendix A

Table 1. Summary of experimental results by curing age

Curing age (days)	Compressive strength (MPa)	DUPV (km/s)	SUPV (km/s)
	Min – Mean – Max	Min – Mean – Max	Min – Mean – Max
7	8.93 – 13.85 – 19.84	3.14 – 4.52 – 4.93	2.33 – 4.88 – 5.27
14	19.64 – 27.96 – 32.24	4.42 – 4.74 – 4.87	4.75 – 5.02 – 5.13
21	27.23 – 33.71 – 37.72	4.68 – 4.80 – 5.02	4.69 – 5.04 – 5.11
28	29.24 – 43.75 – 58.04	4.13 – 4.78 – 4.91	3.47 – 4.87 – 5.19

The results indicate a progressive increase in compressive strength with curing age, ranging from approximately 8.9 MPa at 7 days to about 58.0 MPa at 28 days. Corresponding UPV measurements also increased with age, reflecting improvements in concrete stiffness and internal continuity.

Relationship Between Compressive Strength and UPV

Regression analysis results for both direct and surface ultrasonic measurements are presented in Table 2.

Table 2: Regression models and statistical performance for DUPV and SUPV.

UPV Method	Regression Type	Predictive Model	R	R^2
DUPV	Linear	$C = 24.87D - 81.71$	0.772	0.596
DUPV	Exponential	$C = 0.325e^{0.984D}$	0.886	0.785

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SUPV	Linear	C = 11.48S − 18.43	0.827	0.684
SUPV	Exponential	$C = 4.18e^{0.441s}$	0.923	0.851
UPV Method	**Regression Type**	**Predictive Model**	**R**	**R^2**

Both linear and exponential models show statistically significant relationships between UPV and compressive strength. However, surface ultrasonic pulse velocity consistently achieved higher correlation coefficients and coefficients of determination than direct measurements, indicating superior predictive capability.

Comparison of Direct and Surface UPV Methods

A direct comparison of predictive performance is provided in Table 2 and further supported by the multiple regression results in Table 3.

Table 3: Multiple regression model combining DUPV and SUPV.

Model Type	Regression Equation	R	R^2	Significance (p-value)
Combined DUPV + SUPV	C = −35.92 + 9.19S + 6.02D	0.832	0.692	< 0.001

The results show that surface ultrasonic pulse velocity is the dominant predictor of compressive strength, while the contribution of direct UPV becomes statistically insignificant when both variables are included. This finding supports earlier observations regarding the sensitivity of surface waves to cement paste properties [15,19].

Effect of Concrete Age on UPV–Strength Relationship

The influence of concrete age on the relationship between ultrasonic pulse velocity and compressive strength is summarized in Table 4a and 4b. The results show that both direct and surface ultrasonic measurements exhibit statistically meaningful correlations with compressive strength at all curing ages considered.

For the linear regression models (Table 4a), the strength of correlation generally improves with increasing curing age, although some fluctuations are observed. These variations are attributed to mix heterogeneity and the relatively small sample size at each age group. Surface ultrasonic pulse velocity consistently demonstrates higher or comparable coefficients of determination than direct ultrasonic measurements, particularly at 7 and 21 days, indicating greater sensitivity to strength development.

Table 4(a): Effect of concrete age on UPV – compressive strength relationship (Linear regression models)

Concrete age (days)	DUPV (Linear) R^2	SUPV (Linear) R^2
7	0.749	0.945
14	0.939	0.695
21	0.792	0.905
28	0.863	0.877

The exponential regression models (Table 4b) show uniformly higher coefficients of determination than the corresponding linear models for all curing ages. This improvement reflects the non-linear nature of concrete strength development with respect to ultrasonic wave propagation. In particular, exponential SUPV models achieve R^2 values exceeding 0.94 at early and intermediate ages, confirming their robustness in capturing strength evolution during hydration.

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Table 4(b): Effect of concrete age on UPV–compressive strength relationship (Exponential regression models)

Concrete age (days)	**DUPV (Exponential) R^2**	**SUPV (Exponential) R^2**
7	0.858	0.966
14	0.961	0.824
21	0.884	0.941
28	0.917	0.902

Overall, the results indicate that the reliability of UPV-based strength estimation improves as concrete matures. Surface ultrasonic pulse velocity, especially when modeled using exponential regression, provides the most consistent and accurate representation of the relationship between ultrasonic response and compressive strength across curing ages.

Statistical Validation

The statistical significance of the developed models was confirmed using analysis of variance, with results summarized in Tables 2 to 4. All accepted models exhibited p-values less than 0.05, indicating statistically significant relationships.

Based on statistical performance, simplicity, and practical applicability, the optimal predictive model identified in this study is the linear surface ultrasonic pulse velocity equation:

$$C = 11.48S - 18.43$$

CONCLUSIONS

The study confirms that ultrasonic pulse velocity testing provides a reliable non-destructive means of estimating concrete compressive strength. Surface ultrasonic pulse velocity demonstrates superior predictive capability compared to direct measurements, and the reliability of UPV-based strength estimation improves with curing age. The proposed linear SUPV model offers a practical tool for in-situ concrete quality control and structural assessment.

RECOMMENDATIONS

Surface ultrasonic pulse velocity testing is recommended for routine non-destructive assessment of concrete strength. Calibration should be performed for specific mix designs, and further studies should investigate combined NDT approaches to enhance prediction reliability.

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APPENDIX

Table A1 contains the complete dataset of sixty (60) concrete cube specimens, including mix identification, curing age, compressive strength, direct ultrasonic pulse velocity (DUPV), surface ultrasonic pulse velocity (SUPV)

Table A1: Full experimental results of compressive strength and Ultrasonic pulse velocity

Specimen ID	Curing age (days)	Compressive Strength (MPa)	DUPV (Km/s)	SUPV (Km/s)
A1	7	8.93	3.14	2.33
A2	7	12.95	3.17	2.36
A3	7	13.84	4.13	2.38
A4	7	13.84	4.24	2.39
A5	7	19.64	4.32	3.31
A6	7	19.84	4.38	3.35
A7	7	20.09	4.42	3.47
A8	7	22.32	4.44	3.66
A9	7	23.44	4.61	4.01
A10	7	27.23	4.61	4.03
A11	7	27.68	4.67	4.06
A12	7	27.96	4.67	4.51
A13	7	28.35	4.68	4.69
A14	7	28.57	4.68	4.7
A15	7	28.58	4.7	4.75
A16	14	28.87	4.72	4.75
A17	14	29.02	4.72	4.76
A18	14	29.24	4.72	4.9
A19	14	29.31	4.72	4.91
A20	14	29.91	4.72	4.91
A21	14	30.8	4.74	4.92
A22	14	31.25	4.74	4.92
A23	14	31.7	4.74	4.92

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A24	14	31.92	4.75	4.94
A25	14	32.24	4.75	4.95
A26	14	32.81	4.75	4.97
A27	14	33.04	4.76	4.97
A28	14	33.48	4.76	4.99
A29	14	33.71	4.76	4.99
A30	14	35.27	4.76	4.99
A31	21	35.62	4.76	5
A32	21	35.71	4.77	5
A33	21	35.71	4.77	5
A34	21	35.71	4.78	5
A35	21	36.16	4.79	5.02
A36	21	37.72	4.8	5.02
A37	21	37.72	4.8	5.02
A38	21	38.39	4.8	5.02
A39	21	38.84	4.8	5.04
A40	21	39.29	4.8	5.04
A41	21	39.29	4.81	5.05
A42	21	40.4	4.81	5.05
A43	21	41.07	4.82	5.05
A44	21	42.43	4.82	5.06
A45	21	42.86	4.82	5.07
A46	28	43.3	4.83	5.08
A47	28	43.31	4.83	5.08
A48	28	43.74	4.84	5.08
A49	28	43.75	4.84	5.1
A50	28	43.75	4.87	5.1
A51	28	44.19	4.87	5.11

A52	28	44.2	4.87	5.11
A53	28	46.88	4.89	5.12
A54	28	46.88	4.89	5.13
A55	28	48.21	4.9	5.13
A56	28	53.04	4.91	5.14
A57	28	53.04	4.91	5.16
A58	28	53.57	4.93	5.19
A59	28	53.57	4.94	5.2
A60	28	58.04	5.02	5.27