https://doi.org/10.37375/bsj.v8i21.4057

Development of ultrasonic pulse velocity for Portland cement concrete at elevated temperature

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تاريخ الاستلام:2026/2/14 تاريخ إجازة النشر:2026/4/15 تاريخ النشر:2026/5/12

Abstract: Ultrasonic Pulse Velocity (UPV) is a widely adopted non-destructive testing method that has been used for more than sixty years to assess the condition of concrete structures and identify possible areas of weakness. In practice, it is frequently applied as an indirect means of estimating the compressive strength of concrete.

This paper examines how temperature affects the early evolution of Ultrasonic Pulse Velocity (UPV) in Portland cement concrete immediately after casting, along with its correlation to strength prediction. The approach was used to analyze the influence of different temperature conditions on UPV development during the initial curing stage.

The experimental findings show that UPV is highly sensitive to temperature during the first 24 hours after casting. Elevated curing temperatures accelerate the rate of increase and produce higher pulse velocity values compared to lower temperature conditions.

Furthermore, the relationship between compressive strength and UPV was evaluated. The results indicate that an exponential relationship offers a dependable model for estimating compressive strength from UPV measurements.

Keywords: Ultrasonic Pulse Velocity, Early-age concrete, Temperature effect, Curing temperature, Compressive strength.

تطور سرعة النبضات فوق الصوتية في خرسانة الأسمنت البورتلاندي عند درجات الحرارة المرتفعة

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المستخلص: سرعة النبضات فوق الصوتية هي إحدى طرق الفحص غير الإتلافي واسعة الاستخدام، والتي تم اعتمادها لأكثر من ستين عاماً لتقييم حالة المنشآت الخرسانية وتحديد مناطق الضعف المحتملة فيها. وفي التطبيقات العملية، تُستخدم هذه الطريقة بشكل متكرر كوسيلة غير مباشرة لتقدير مقاومة الانضغاط للخرسانة.

تتناول هذه الدراسة تأثير درجة الحرارة على التطور المبكر لسرعة النبضات فوق الصوتية في خرسانة الأسمنت البورتلاندي مباشرة بعد الصب، بالإضافة إلى علاقتها بتنبؤ مقاومة الخرسانة. وقد تم استخدام هذا النهج لتحليل تأثير ظروف درجات الحرارة المختلفة على تطور خلال مرحلة المعالجة الأولية.

أظهرت النتائج التجريبية أن سرعة النبضات فوق الصوتية تتأثر بشكل كبير بدرجة الحرارة خلال أول 24 ساعة بعد الصب، حيث تؤدي درجات الحرارة المرتفعة إلى تسريع معدل الزيادة في قيم السرعة وإعطاء قيم أعلى مقارنة بظروف درجات الحرارة المنخفضة.

علاوة على ذلك، تم تقييم العلاقة بين مقاومة الانضغاط وسرعة النبضات فوق الصوتية، وأظهرت النتائج أن العلاقة الأسّية تمثل نموذجاً موثوقاً لتقدير مقاومة الانضغاط اعتماداً على قياسات سرعة النبضات فوق الصوتية.

الكلمات المفتاحية: سرعة النبضات فوق الصوتية، العمر المبكر، الخرسانة، درجة حرارة المعالجة، مقاومة الانضغاط.

Introduction

Ultrasonic Pulse Velocity (UPV) is a flexible non-destructive testing technique with a wide range of uses. It is applied to identify internal cracking and other structural imperfections, as well as to track changes in concrete properties caused by processes such as chemical

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deterioration or freeze–thaw action. In addition, UPV is frequently used as an indirect method for estimating concrete compressive strength.

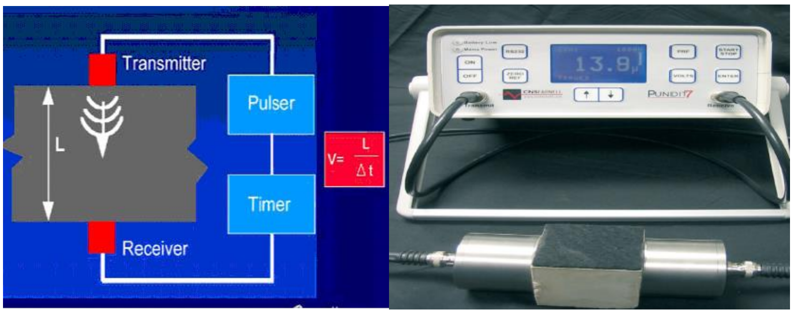
The UPV procedure has been formalized in a number of international standards. Among the most recognized are ASTM C597 and BS 1881: Part 203, although the latter has since been replaced by BS EN 12504-4[1, 2].

The theory of ultrasonic pulse velocity method, when a solid mass is subjected to impulse or vibratory load, three types of waves are generated:

- Compressional waves (also known as longitudinal or P-waves)
- Shear waves (also referred to as transverse or S-waves)
- Surface waves (commonly called Rayleigh waves)

Among the different wave types, compressional waves exhibit the highest velocity, while surface waves travel at the lowest speed. The Ultrasonic Pulse Velocity (UPV) testing system (Figure 1-a) comprises a unit that generates an ultrasonic pulse, transmits it through the concrete, and receives it on the opposite side to measure the travel time. During the test, both the pulse transit time and the path length defined as the distance between the two transducers are recorded. Pulse velocity is determined by dividing the distance traveled (path length) by the measured travel time of the pulse.

In concrete testing, transducers with frequencies typically ranging from 20 kHz to 150 kHz are employed. One of the most widely used devices for this technique is the Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT), illustrated in Figure 1-b.



a) *b)*

Figure 1: Diagram of UPV measurement and commercial PUNDIT[1]

The velocity can be determined as follows:

$$\boxed{V=\frac{L}{\Delta t}} \qquad (1)$$

Where:

V= Velocity, km/s

L= the distance, which the pulses travel in the concrete, mm

Δt= transit time, second

To obtain reliable results from a pulse velocity test, it is important that the measured velocity reflects only the characteristics of the concrete under examination. However, several parameters may influence the results, such as the size, type, and proportion of aggregates, the type of cement used, the water-to-cement ratio, the age of the concrete, and the temperature and curing conditions. In addition, the path length, as well as the shape and dimensions of the specimen, can also have a significant effect on pulse velocity measurements.

When concrete is subjected to elevated temperatures, its chemical composition and physical structure undergo substantial transformations, resulting in a pronounced deterioration of mechanical properties such as strength, modulus of elasticity, and volume stability[3]. Numerous studies have shown that higher isothermal curing temperatures result in a more rapid increase in pulse velocity during the early curing period. In addition, at higher temperatures, the pulse velocity curve tends to stabilize earlier, reflecting accelerated development of concrete properties [4]. It has also been observed that concrete cured under saturated conditions exhibits higher pulse velocity values compared to concrete cured under dry conditions[5, 6, 7]. The variation in concrete strength under elevated temperatures is influenced by multiple factors, such as the degree and duration of heat exposure, initial compressive strength, and mix composition. It is well recognized that high temperatures cause significant degradation in the mechanical properties of concrete, particularly in its compressive strength, tensile strength, and modulus of elasticity[8, 9].

Other applications of the ultrasonic pulse velocity method[5,6,10] include assessing concrete homogeneity (uniformity), evaluating durability, detecting cracks and honeycombing, and determining the dynamic modulus of elasticity. However, the reliability of UPV measurements varies depending on the application. It tends to be less reliable for estimating compressive strength, but more accurate for assessing uniformity and detecting cracking.

Over the past few decades, the UPV method has been widely used in both laboratory and field settings across a broad range of applications. Numerous research studies have been conducted to explore and improve the accuracy of compressive strength estimation using ultrasonic pulse velocity[8-9]. Compressive strength can be estimated using a pre-established graphical correlation between strength and ultrasonic pulse velocity. Numerous researchers have developed relationships linking these two parameters; among the most widely recognized is the model proposed by Tharmaratnam et al. [10], which is expressed as follows:

$$\boxed{S = a\ exp^{bV_C}} \qquad \textbf{(2)}$$

Where:

S = compressive strength, N/mm^2

a and b = parameters dependent upon the material properties

VC = ultrasonic Pulse velocity, km/s

This relationship is not universally valid for all types of concrete, as it is affected by several parameters such as cement type and content, water-to-cement (w/c) ratio, moisture condition, and the size and type of aggregates[5, 8]. Accordingly, many researchers have stressed that compressive strength should not be directly estimated from UPV results unless a specific calibration relationship has been developed for the particular concrete being investigated [12, 6, 13–15].

Concrete strength may also be predicted using the Freiesleben Hansen and Pedersen strength–maturity model [18, 19]. Introduced in 1985, this approach assumes that strength development follows a pattern similar to the heat of hydration process. The model is commonly expressed through a Three-Parameter Exponential (TPE) equation, which accurately represents the nonlinear progression of strength gain with time. The equation is given as follows:

$$\boxed{S = S_{\infty} e^{-\left(\frac{\tau}{M}\right)^{\alpha}}} \qquad \textbf{(3)}$$

Where:

S$_\infty$ = Limiting strength, N/mm^2
M = Maturity index, °C-hours

τ = Characteristic time constant

α = Shape parameter

It should be noted that adjusting the time constant in the TPE equation preserves the overall shape of the strength–maturity curve, but results in a horizontal shift of the curve either to the left or right. According to Carino [15], variation in the shape parameter (α) also influences the curve form; increasing α produces a more pronounced S-shape, which reflects slower initial strength development followed by a more rapid gain at later ages.

This study investigates the effect of temperature on pulse velocity development and evaluates the applicability of the UPV method for predicting the strength development of Portland cement concrete. In addition, the three-parameter exponential (TPE) model is employed to enhance the smoothness and clarity of the predicted strength–time relationships.

Material and methods

As discussed in the introduction, the standard UPV testing instrument was used; however, for continuous UPV measurement, a PUNDIT "add-on unit" was employed. This unit converts the pulse width into a voltage signal, which was then connected to an ADC-16 High-Resolution Data Logger. The logger continuously recorded the voltage data to a computer system.

Figure 2 shows a specially designed mould developed for this study. The experimental setup consists of an ultrasonic transmitter and receiver, an ultrasonic pulse generator (PUNDIT), and a computer linked to a PicoLog data acquisition system. The recorded data were processed using PicoLog software [14]. Comparable commercially developed UPV systems are also available, including FreshMor and FreshCon, which were developed by the Institute of Construction Materials at the University of Stuttgart, Germany [15].

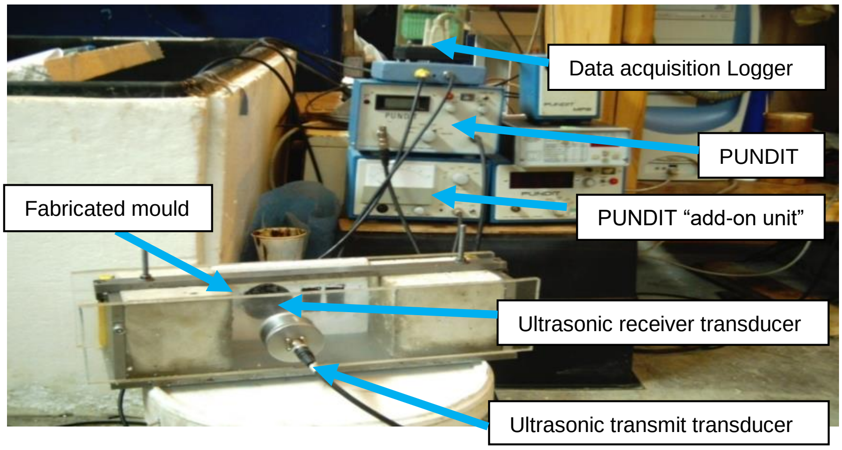


Figure 2: UPV continuous measurement equipment

UPV measurements of the concrete specimens were performed under four curing temperatures: 20, 30, 40, and 50°C. Continuous monitoring of UPV was carried out during the first 14 days, after which additional manual readings were taken at 17, 19, 21, 23, 25, 28, 56, and 91 days for each temperature regime.

During the very early and early stages of UPV development, readings were simultaneously collected from both the PUNDIT display screen and the PicoLog software at regular intervals. This was done to establish a reliable correlation between the recorded voltage data (in mV) and the corresponding UPV values (in m/s).

The following steps were used to convert the recorded voltage data into ultrasonic pulse velocity:

- A correlation between the pulse readings obtained from the PUNDIT device and the voltage readings recorded by the Pico Logger (mV) was established and is presented in Figure (3).

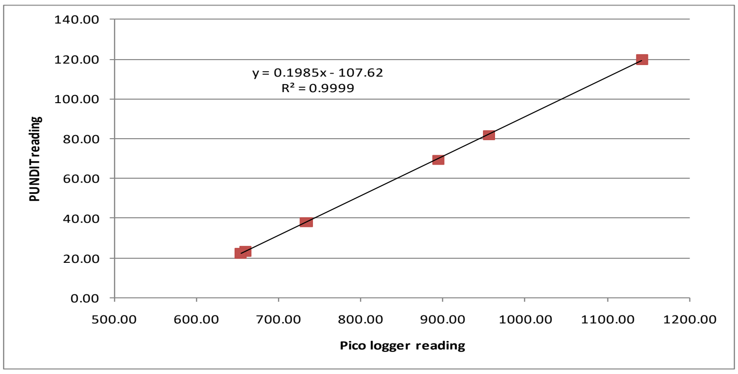


Figure 3: Correlation between PUNDIT reading pulse and Pico logger reading mV

- The equation below was used to determine the transit time, expressed in microseconds (µs):

Transit time µs = 0.1985 * recorded data in mV – 107.62

- The UP-velocity m/s is determined as follows:

UPV m/s = (Distance between the transducer (sample width) / Transit time µs) * 1000

The concrete mix investigated was Grade 60 Portland cement. The mix proportions are presented in Table 1. The concrete samples were cast in moulds, wrapped with cling film to prevent moisture loss, and then placed in a curing tank for controlled curing.

Table 1: Material Proportions for the Concrete Mixture

Portland cement	**Aggregate**		**Free Water**	**Superplasticizer** (% of the binder)	**Free W/C**
	Coarse	**Fine**			
kg/m^3				**(%)**	
317	1426	612	146	0.2	0.46

and discussion

The development of UPV at 20°C, 30°C, 40°C, and 50°C for Portland cement concrete is shown in Figure 4. UPV measurements commenced approximately 15 minutes after the addition of water to the mix. During the first 4 hours, the recorded pulse velocities remained nearly constant for the Portland cement samples. This behavior is attributed to the fact that the concrete was still in its fresh (plastic) state during this initial period. This observation is highlighted in blue within the circle in Figure 6. Similar trends have been reported by Guang et al.[12], Sayers et al.[13], and Keating et al.[14], who suggested that the lack of change in velocity during the early stage is likely due to the presence of entrapped air in the fresh concrete, which affects the transmission of ultrasonic pulses.

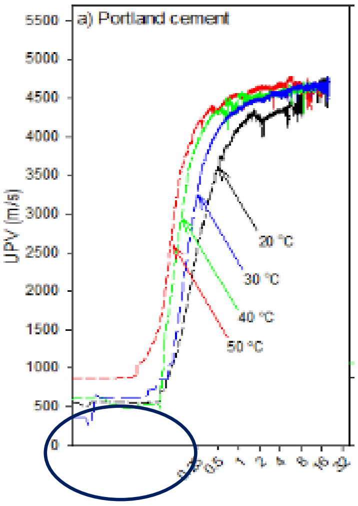


Figure 4: UPV development at 20, 30, 40 and 50 °C

The time interval from the start of UPV measurement to the point at which the UPV begins to rise is considered to represent the setting time of the concrete being tested. This setting point appears to be influenced by temperature. Once setting begins, the UPV increases rapidly until it reaches approximately 4000 m/s, after which it continues to rise but at a slower rate. The overall pattern of UPV development with age resembles that of concrete strength development, although the UPV tends to plateau earlier than strength does.

Figures 4 and 5 illustrate the influence of temperature on UPV development. Similar to strength gain, higher isothermal curing temperatures accelerate the initial increase in UPV during the first 24 hours. In addition, as the curing temperature increases, the UPV reaches its steady-state value in a shorter period of time. However, at later ages, the effect of temperature becomes less pronounced. This is attributed to the continued hardening of the concrete, where other parameters such as aggregate size and content, and the water-to-binder ratio play a more dominant role in governing UPV.

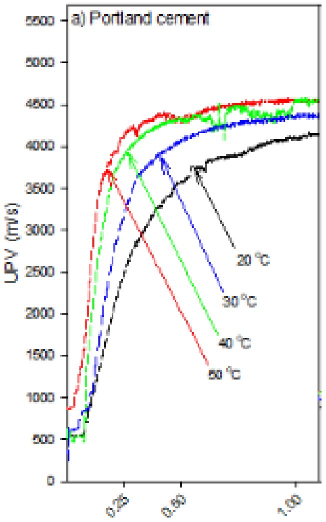


Figure 5: UPV development at 20, 30, 40 and 50 °C up to 1 day

To further analyses UPV behavior, the rate of UPV development over time was calculated and plotted as a ratio in Figure (6) for Portland cement. The graph clearly reveals two distinct peaks occurring within the first 24 hours. The initial peak is notably high but declines rapidly after a few hours. This decline corresponds to the period when the concrete is still in its fresh state, characterized by a relatively stable rate of Ultrasonic Pulse Velocity development.

This is followed by an acceleration phase leading to the second peak, which is believed to mark the onset of setting. After this second peak, the development ratio gradually declines to near zero over an extended period.

The timing and magnitude of the second peak are influenced by curing temperature—occurring earlier and reaching higher values as temperature increases. Additionally, the curves for curing temperatures of 20, 30, 40, and 50°C begin to converge after the second peak, eventually merging into a single curve. This convergence point is thought to represent the final setting time of the concrete.

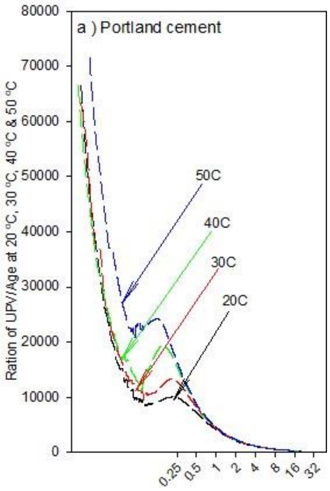


Figure 6: Ratio of UPV/age at 20, 30, 40 and 50 º

Compressive strength can be estimated from UPV measurements using a pre-established graphical correlation between UPV (m/s) and compressive strength (MPa), as illustrated in Figure 7 for Portland cement specimens cured at 20°C, 30°C, 40°C, and 50°C.

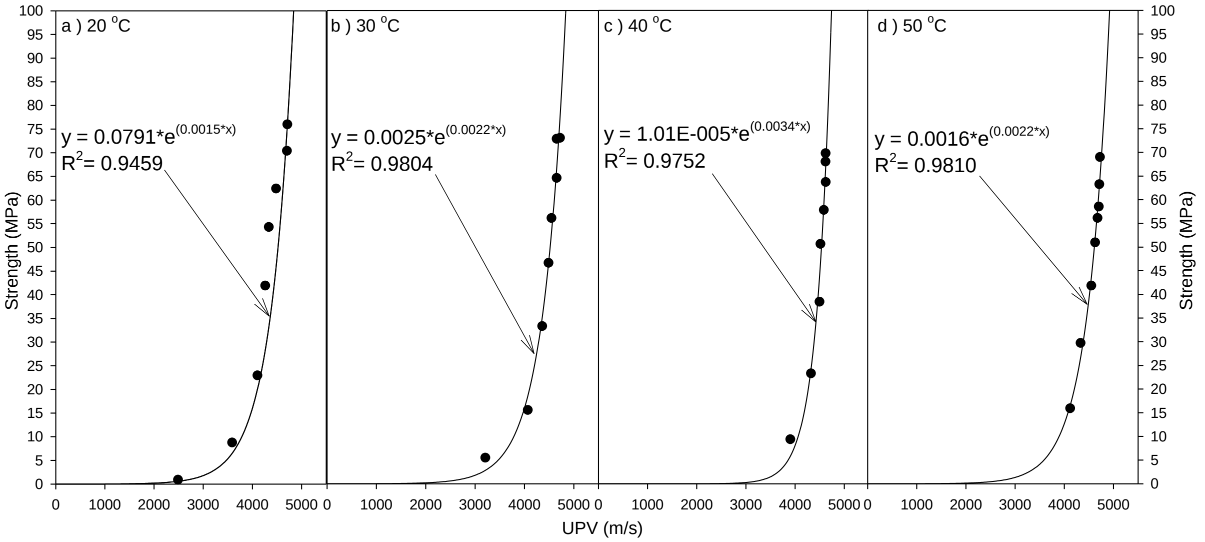


Figure 7: UPV-Strength relationship at 20, 30, 40 and 50 ºC

An exponential regression model was employed to describe the relationship between UPV and compressive strength development. The model provided a strong fit for most of the concrete mixes investigated, with coefficients of determination (R^2) exceeding 0.90. This indicates that more than 90% of the variation in compressive strength can be explained by the UPV data using the proposed exponential relationship.

- The empirical relationship between UPV and compressive strength, derived from experimental results and fitted using exponential regression, can be expressed as follows:

$$\boxed{S = a \times exp^{b \times V}} \qquad \textbf{(4)}$$

Where:

a & b = Parameters dependent upon the material properties
S = Compressive strength (MPa)
V = Ultrasonic pulse velocity (m/s)

Table 2 shows the equation determined by exponential regression analysis, and R^2 values of Portland concrete at 20, 30, 40 and 50 ºC curing temperatures.

Table 2: Equations to estimate the strength development of the concrete

20 °C		30 °C		40 °C		50 °C	
S	R^2	S	R^2	S	R^2	S	R^2
$0.0800*e^{0.0015*V}$	0.95	$0.0025*e^{0.0022*V}$	0.98	$1.01E005*e^{0.0034*V}$	0.97	$0.0016*e^{0.0022*V}$	0.98

The relationships between UPV and compressive strength were used to model the actual strength development of Portland cement concrete at all curing temperatures, as shown in Figure 8.

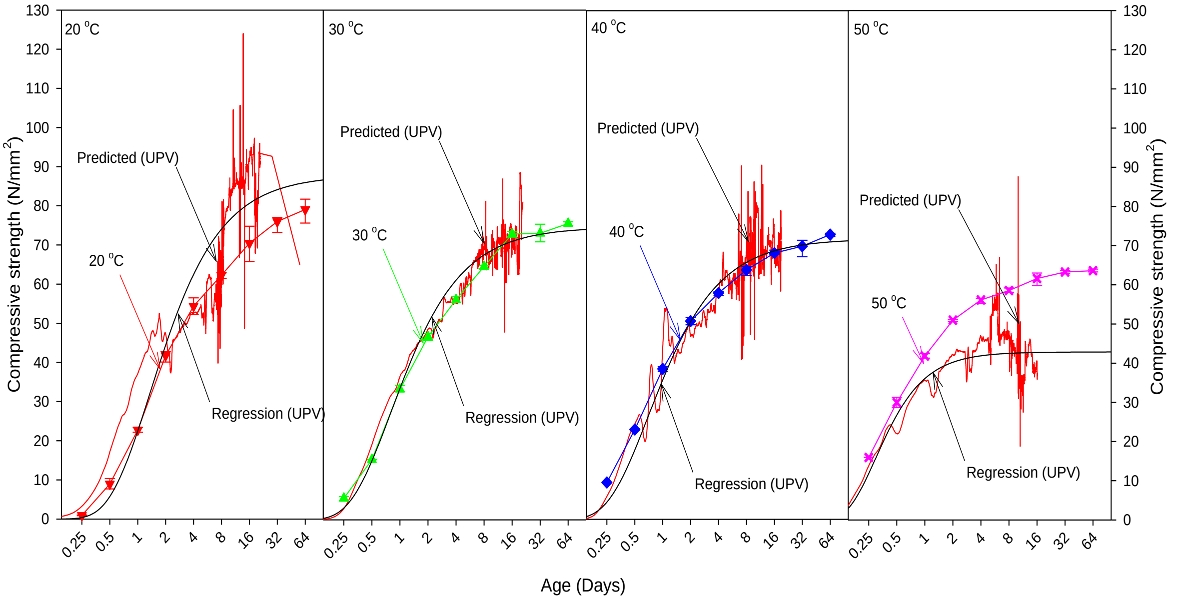


Figure 8: Predicted strength development of PC concretes using UPV-strength relationships

The predicted strength values showed good agreement with the measured strength data, particularly at very early ages. However, at both early and later ages, the agreement between predicted and experimental strengths was less consistent. In some cases, especially at specific curing temperatures, the predicted strengths aligned reasonably well with the experimental results. At later ages, the presence of noise in the UPV measurements negatively impacted the accuracy of strength predictions. The reliability of strength estimation from UPV measurements is highly dependent on the precision of the pulse velocity data and the accuracy of the established strength-UPV relationship. To improve the smoothness and clarity of the predicted strength curves, a regression line was fitted using the three-parameter equation (TPE) in SigmaPlot. This approach provided smoother curves and a better visual representation of the data, as illustrated in Figure 8.

Conclusion

The Ultrasonic Pulse Velocity (UPV) method was employed to investigate the effect of temperature on UPV development in fly ash concrete. The experimental results indicate that UPV is strongly influenced by curing temperature during the first 24 hours. Higher curing temperatures lead to a more rapid increase in UPV and result in higher pulse velocity values compared to lower temperatures.

The relationship between compressive strength and UPV was also examined. An exponential correlation was found to effectively describe this relationship, providing reasonably accurate strength predictions. However, the accuracy of these predictions is highly dependent on the precision of the UPV measurements. To ensure reliable results, UPV data should be collected with minimal noise, as measurement noise can significantly affect continuous UPV monitoring.

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