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Influence of Elevated Curing Temperatures on Ultrasonic Pulse Velocity in Portland Cement and Fly Ash Concretes

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Keywords:
Concrete.
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ABSTRACT

Ultrasonic Pulse Velocity (UPV) is a well-established non-destructive testing (NDT) technique that has been employed for over seven decades to evaluate the integrity and quality of concrete structures. It is extensively utilised to detect internal cracks, voids, and other discontinuities, as well as to monitor deterioration arising from exposure to aggressive chemical environments or repeated freeze–thaw cycles. Moreover, UPV is commonly applied as an indirect method for estimating the compressive strength of concrete. This paper investigates the influence of temperature on the development of UPV in Portland cement and fly ash concretes immediately after casting, with the objective of predicting early-age compressive strength. The technique was employed to assess the effect of varying curing temperatures on the early evolution of pulse velocity in these materials. In addition, the correlation between UPV and compressive strength was analysed, highlighting that the reliability of strength prediction is strongly dependent on the accuracy of UPV measurements. The paper demonstrates that ultrasonic pulse velocity (UPV) is a reliable and sensitive method for assessing early-age behaviour and predicting compressive strength in Portland cement and fly ash concretes (15–45% replacement). Curing temperature significantly accelerates UPV development, while fly ash delays early-age response without altering the overall trend. A strong exponential correlation confirms the robustness of UPV for strength estimation, highlighting its practical value for non-destructive evaluation and optimisation of curing conditions.

تأثير درجات الحرارة المرتفعة أثناء المعالجة على سرعة النبضة فوق الصوتية في خرسانات الأسمنت البورتلاندي والرماد المتطاير

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الكلمات المفتاحية:
الخرسانة.
الأسمنت.
الرماد المتطاير.
درجة الحرارة.
سرعة النبضة فوق الصوتية (*UPV*).

الملخص

تُعد سرعة النبضة فوق الصوتية (UPV) تقنية راسخة للاختبار غير المدمر(NDT) ، وقد استخدمت لأكثر من سبعة عقود لتقييم سلامة وجودة هياكل الخرسانة. تُستخدم هذه التقنية على نطاق واسع لاكتشاف الشقوق الداخلية والفراغات والانقطاعات الأخرى، وكذلك لمراقبة التدهور الناتج عن التعرض لبيئات كيميائية عدوانية أو لدورات تجميد وذوبان متكررة. علاوة على ذلك، تُعتبر UPV طريقة غير مباشرة شائعة لتقدير مقاومة الضغط للخرسانة. تهدف هذه الدراسة إلى استقصاء تأثير درجات الحرارة على تطور سرعة النبضة فوق الصوتية في خرسانات الأسمنت البورتلاندي والرماد المتطاير مباشرة بعد الصب، بغرض التنبؤ بمقاومة الضغط في مراحل العمر المبكر. وقد تم استخدام التقنية لتقييم أثر اختلاف درجات المعالجة على تطور سرعة النبضة في هذه المواد. كما تم تحليل العلاقة بين UPV ومقاومة الضغط، مع الإشارة إلى أن موثوقية التنبؤ بالمقاومة تعتمد بشكل كبير على دقة قياساتUPV . تُظهر نتائج الدراسة أن سرعة النبضة فوق الصوتية (UPV) تمثل وسيلة موثوقة وحساسة لتقييم السلوك المبكر للخرسانة والتنبؤ بمقاومة الضغط في خرسانات الأسمنت البورتلاندي والرماد المتطاير (بنسب استبدال 15–45%). كما أظهرت النتائج أن ارتفاع

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درجات الحرارة خلال المعالجة يسرع بشكل ملحوظ من تطور UPV، في حين يؤدي استخدام الرماد المتطاير إلى تأخير الاستجابة في مرحلة العمر المبكر دون التأثير على الاتجاه العام لتطور السرعة. وتؤكد العلاقة الأسية القوية بين UPV ومقاومة الضغط متانة هذه التقنية في تقدير المقاومة، مما يبرز أهميتها العملية في التقييم غير المدمر وتحسين ظروف المعالجة.

1. Introduction

Ultrasonic Pulse Velocity (UPV) is a versatile non-destructive testing method with numerous applications. It can be used to detect internal cracks and other structural defects, as well as to monitor changes in concrete due to factors such as chemical degradation or freeze-thaw damage. Moreover, UPV is commonly applied for estimating the compressive strength of concrete.

The UPV method has been standardized in several countries. Notable standards include ASTM C597 and BS 1881: Part 203, the latter of which has been superseded by BS EN 12504-4[1, 2].

The theory of the Ultrasonic Pulse Velocity (UPV) method is based on the principle that when a solid material is exposed to an impulse or vibratory load, three different types of waves are generated:

- Compressional waves (Longitudinal or P-waves)
- Shear waves (Transverse or S-waves)
- Surface waves (Rayleigh waves)

The highest velocity is compressional waves and the lowest is surface waves. The compressional wave velocity is given by:

$$V = \sqrt{\frac{K.E}{\rho}} \qquad \textbf{Equation 1}$$

Where:

V= Compressional wave velocity, for concrete typically ranges between 3000 and 5000 m/s

K= (1– μ) / ((1– μ). (1– 2μ))

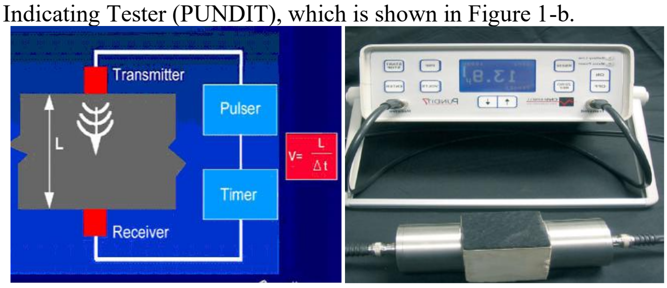
μ= Dynamic Poisson's ratio

E= Dynamic modulus of elasticity, (N/mm^2)

ρ= density, (kg/m^3)

The Ultrasonic Pulse Velocity (UPV) testing apparatus (Figure 1-a) consists of a device that generates an ultrasonic pulse, transmits it into the concrete, and then receives and measures the time it takes for the pulse to travel through the material to the opposite side. During testing, the travel time of the pulse is recorded along with the path length and the distance between the two transducers. The pulse velocity is calculated by dividing the path length by the travel time.

For testing concrete, transducers operating at frequencies between 20 kHz and 150 kHz are typically used. A commonly used instrument for this method is the Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT), which is shown in Figure 1-b.



a) b)

Figure 1: Diagram of UPV measurement and commercial PUNDIT

The velocity can be determined as follows:

$$V = \frac{L}{\Delta t} \qquad \textbf{Equation 2}$$

Where:

V= Velocity, km/s

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

Δt= transit time, second

For a pulse velocity test to provide accurate results, the measured velocity should depend only on the characteristics of the concrete under investigation. However, several parameters may influence the pulse velocity values, such as the size, type, and proportion of aggregates, the type of cement used, the water–cement ratio, the age of the concrete, as well as temperature and curing conditions, as well as path length, shape, and size of the specimen.

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 stages of curing. Additionally, at elevated temperatures, the pulse velocity curve tends to level off earlier, indicating faster development of concrete properties[4]. Concrete cured in saturated conditions exhibits higher pulse velocity values compared with 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 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 specific application. It is generally more accurate for assessing concrete uniformity and detecting cracks, whereas it is less reliable for estimating compressive strength[5, 6, 10].

For fly ash concretes, previous studies have concluded that the pulse velocity increases with the stiffness of the material. The propagation velocity also rises with higher lime content, although the rate of increase varies depending on the mix composition[11].

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]. Concrete strength can be estimated using a previously established graphical correlation between compressive strength and ultrasonic pulse velocity. An example of this relationship is presented in Figure (2). Several researchers have developed correlations between strength and UPV, with one of the most widely recognized being the relationship proposed by Tharmaratnam and colleagues[10] relationship given as:

$$S = a\, exp^{bV_c} \qquad \textbf{Equation 3}$$

Where:

S = compressive strength, N/mm^2

a and b = parameters dependent upon the material properties

VC = ultrasonic Pulse velocity, km/s

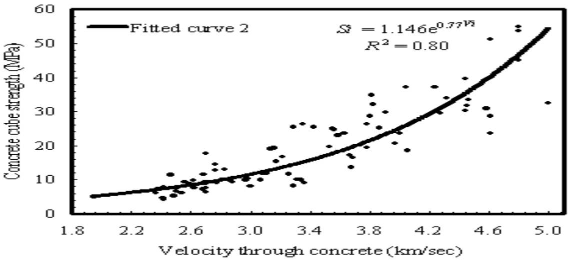


Figure 2: Correlation between concrete strength and UPV[12]

This relationship cannot be considered universally valid for all concrete types because it is affected by several factors, such as the type and content of cement, the water-to-cement (w/c) ratio, moisture condition, and the size and type of aggregates used [5, 8]. Many researchers have emphasized that strength should not be estimated from UPV measurements unless a specific correlation has been previously established for the particular type of concrete being tested[13, 6, 14,15,16].

Concrete strength can be estimated using the Freiesleben Hansen and Pedersen strength–maturity relationship[19, 20]. This model, introduced in 1985, is founded on the assumption that the development of concrete strength follows a trend similar to that of the heat of hydration curve. The relationship is expressed using a Three-Parameter Exponential (TPE) equation, which effectively captures the non-linear nature of strength gain over time. The equation is as follows:

$$S = S_{\infty} e^{-\left(\frac{\tau}{M}\right)^{\alpha}} \qquad \textbf{Equation 4}$$

Where:

S_∞ = Limiting strength, N/mm^2

M = Maturity index, °C-hours

τ = Characteristic time constant

α = Shape parameter

It is important to note that modifying the value of the time constant in the TPE equation maintains the general shape of the strength–maturity curve but shifts it horizontally-either to the left or right. According to Carino[16], changing the shape parameter (α) affects the curve's form: as α increases, the curve becomes more S-shaped, indicating a more gradual initial strength gain followed by a sharper increase.

The influence of fly ash on ultrasonic pulse velocity, as well as its correlation with compressive strength, has not been extensively studied. This research examined the suitability of the UPV technique and the (TPE) equation for predicting the strength development of fly ash concrete.

UPV measurements were continuously recorded in specially fabricated molds under isothermal curing conditions at 20, 30, 40, and 50 °C. These data were used to assess strength development and calculate activation energy, and were compared with heat of hydration results to identify setting times.

Overall, this paper investigates how temperature influences the strength development of fly ash concrete and assesses the effectiveness of ultrasonic pulse velocity (UPV) as a method for predicting strength gain.

2. Methodology

The concrete mixes investigated were Portland cement, 15, 30 and 45% cement replacement by fly ash of grade 60. The mix proportions are shown in table 1. A single, consistent set of materials was used throughout the experimental programme.

Table 1: Mix proportions of the concrete mixes

	Fly ash of total binder (%)			
	0	15	30	45
Total Binder	317	335	349	369
Portland cement	317	285	244	203
Fly ash	-	50	105	166
Coarse aggregate	1426	1426	1426	1426
Fine aggregate	612	612	612	612
Free water	146	136	124	110
Superplasticizer (% of the binder)	0.2	0.25	0.27	0.35
Free W/ B	0.46	0.406	0.355	0.3

CEM I 52.5N Portland cement (PC) was used in all mixes. The cement conformed to BS EN 197-1:2000. Class F fly ash (FA) was used as a supplementary cementitious material. The chemical composition of Portland cement and fly ash are shown in table 2.

Table 2: Chemical composition of Portland cement and fly ash

	(%) Composition	Cement	Fly ash
Oxides	CaO	63.4	3
	SiO_2	20.6	48.1
	Al_2O_3	5.5	29.5
	Fe_2O_3	2.4	8
	SO_3	2.8	0.8
	MgO	2.6	2.5
	K_2O	0.7	2.5
	Na_2O	0.2	1.2
	LOI	1.8	4.8
Clinker compounds	C_3S	58.4	
	C_2S	17.1	
	C_3A	9.9	
	C_4AF	7.7	

The coarse aggregate was crushed granite with a nominal particle size of 5–20 mm. Grading compliance was confirmed by sieve analysis in accordance with BS 882:1992. The fine aggregate was a well-graded medium sand. Polycarboxylate-based superplasticiser Structuro 11180 was used. The active solid content was 25% by weight and was considered when determining both the free and total water-to-binder ratios of the concrete mixes. Trial mixes were conducted to optimise the dosage level. The manufacturer specified a maximum recommended dosage ranging between 0.2 and 0.8 litres per 100 kg of cement.

Concrete was mixed in pan mixers. All mixing procedures complied with BS 1881-125:1986. Specimens for compressive strength testing were cast in 100 mm cube mould. Compaction was performed using a vibrating table in two stages initial vibration at half-fill followed by final vibration after complete filling to ensure uniform consolidation. The concrete sample was than wrapped with cling film and placed into the curing tanks at four temperatures: 20, 30, 40 and 50 °C.

For continuous measurement of UPV, the PUNDIT “add-on unit” was employed to convert the pulse width into an electrical voltage signal. This output was connected to an ADC-16 high-resolution data logger, which continuously recorded the voltage data and transferred it to a computer for analysis. Figure (3) shows the specially designed mould that was manufactured and assembled together with the ultrasonic transmitter and receiver, the pulse generator (PUNDIT), and a data acquisition system connected to PicoLog software. Data processing and analysis were performed using the commercially available PicoLog software[19].

Comparable UPV measurement systems have been developed commercially, including devices designed at the University of Stuttgart, Institute of Construction Materials (Germany), known as FreshMor and FreshCon[20].

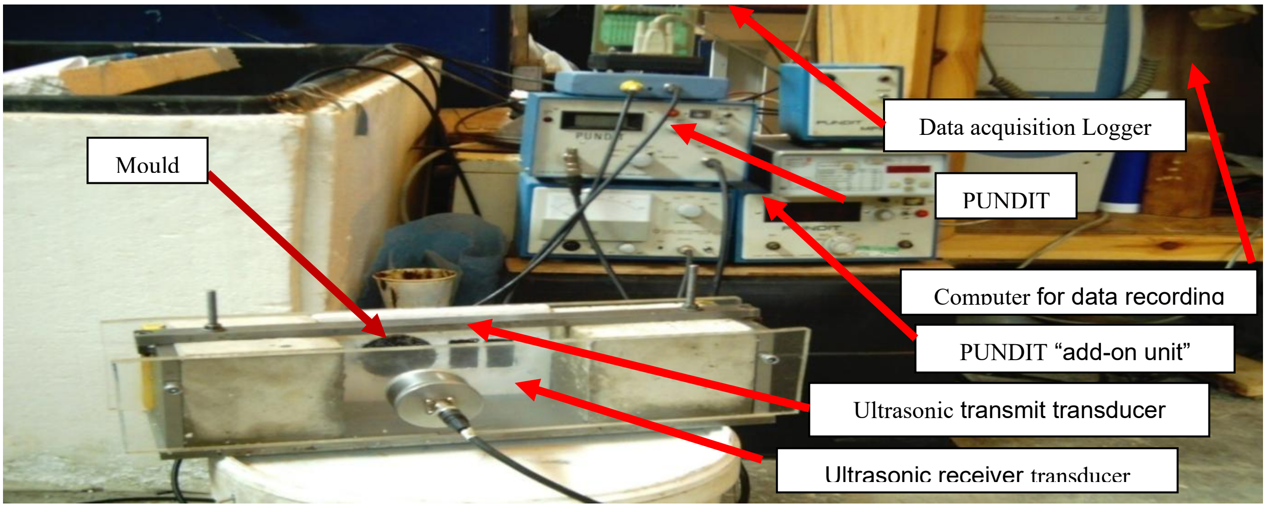


Figure 3: UPV continuous measurement equipment

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

During the very early and early stages of UPV development, simultaneous readings were recorded from both the PUNDIT display and the Pico software at the same time. This was carried out to enable the conversion of recorded millivolt (mV) signals into ultrasonic pulse velocity values (m/s). The procedure used for this conversion is outlined below:

- A correlation between the PUNDIT pulse readings and the Pico Logger output (mV) was established and plotted, as illustrated in the corresponding figure (4).

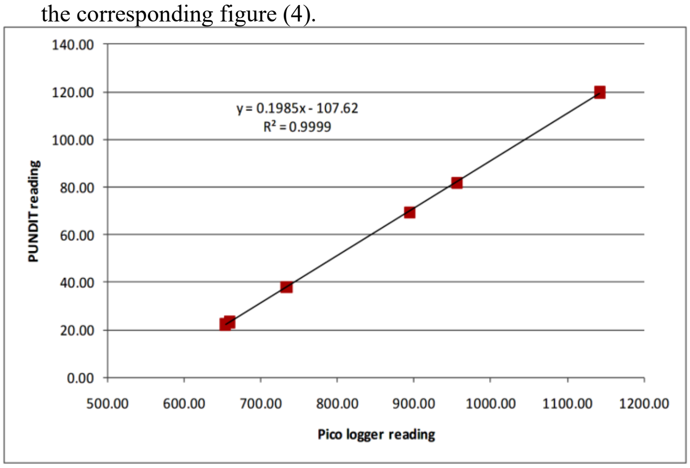


Figure 4: correlation between the PUNDIT reading pulse and Pico logger reading

- The Equation below (from figure 4) was used to define the Transit time µs (Micro second):

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

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

3. Results

a. Ultrasonic pulse velocity development of fly ash concrete

Continuous recording of UPV development was carried out over a period of 14 days using the experimental setup. For later ages, UPV measurements were obtained manually.

Figure 5 presents the progression of UPV at curing temperatures of 20, 30, 40, and 50 °C for Portland cement concrete, as well as for mixes containing 15%, 30%, and 45% fly ash as a replacement for cement. UPV measurements commenced approximately 15 minutes after the addition of water. During the initial stages of testing, the pulse velocities remained nearly constant for the first four hours in the Portland cement and 15% fly ash mixtures, and for about six hours in the 30 and 45% fly ash mixtures. This behavior corresponds to the plastic phase of the concrete, during which the material remains fresh and has not yet begun to harden. The region of constant UPV is highlighted in blue in Figure (5). Similar findings have been reported by Guang et al.[2], Sayers et al.[21], and Keating et al.[22], who attributed this behavior to the presence of entrapped air within fresh concrete.

The period between the commencement of UPV measurement and the point at which the velocity begins to increase is considered to represent the setting point of the concrete, which appears to be temperature dependent. Once setting began, UPV increased rapidly until reaching approximately 4000 m/s, after which the rate of increase gradually diminished. The overall trend of UPV development with time closely resembles that of compressive strength development, although UPV tends to plateau earlier than strength gain.

The effect of curing temperature on UPV development is illustrated in Figures (5) and (6). Consistent with strength development, higher isothermal curing temperatures resulted in a more rapid increase in UPV during the first 24 hours. Moreover, the time required to reach a constant UPV value decreased with increasing temperature. After this initial period, temperature exerted a diminishing influence on UPV, likely because other factors—such as aggregate size and content, water-to-binder ratio, and fly ash content—become more dominant as the concrete matures. The influence of 15, 30, and 45% cement replacement by fly ash at the four curing temperatures is presented in Figure (7). Results indicate that UPV values decreased with increasing fly ash content across all curing temperatures, particularly at early ages. This suggests that higher fly ash replacement levels lead to lower UPV values during the early stages of hydration.

To further interpret the UPV behavior, the rate of UPV development over time was calculated and plotted in Figure 8 for Portland cement and the various fly ash replacement levels. Two distinct peaks were observed within the first 24 hours. The first, a sharp peak occurring at very early age, corresponds to the constant UPV phase when the concrete remains plastic. This is followed by a second peak, associated with the onset of setting. Thereafter, the rate of UPV development decreases gradually to near zero over an extended period. The second peak occurred earlier and attained a higher magnitude with increasing curing temperature. As shown in Figure (8), the curves corresponding to 20, 30, 40, and 50 °C converge to a common point, which is believed to represent the final setting time of the concrete.

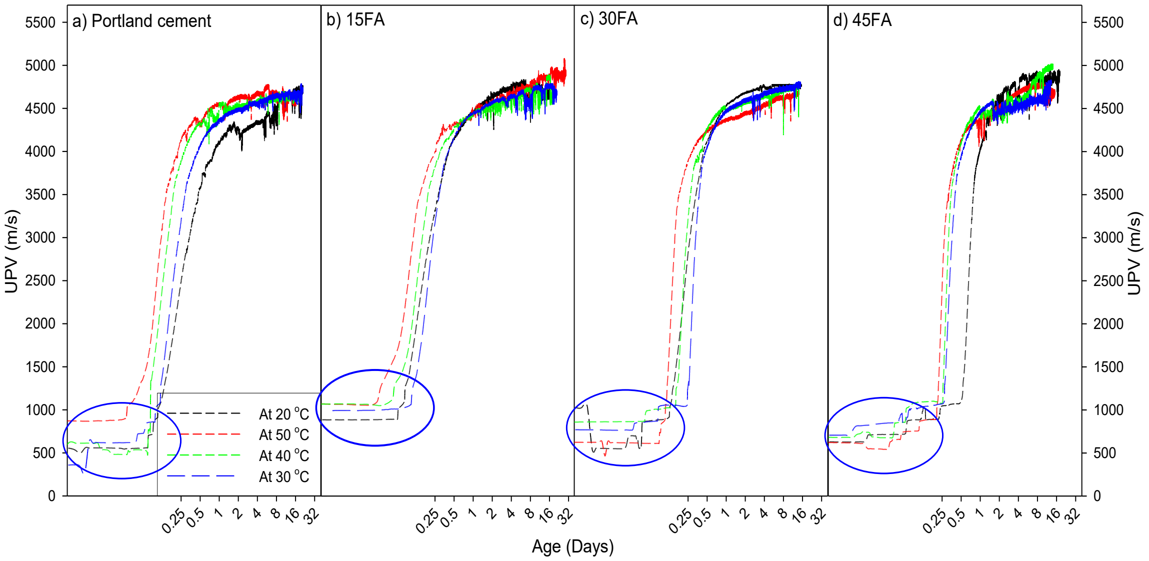


Figure 5: development of UPV at 20, 30, 40 and 50 °C up to 32 days

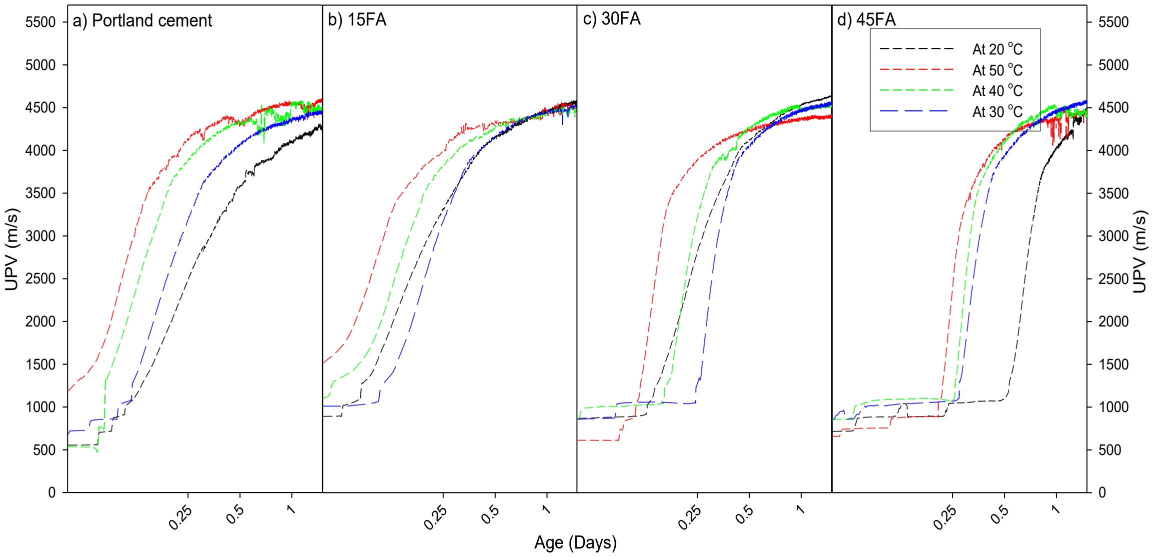


Figure 6: development of UPV at 20, 30, 40 and 50 ºC up to 1 day

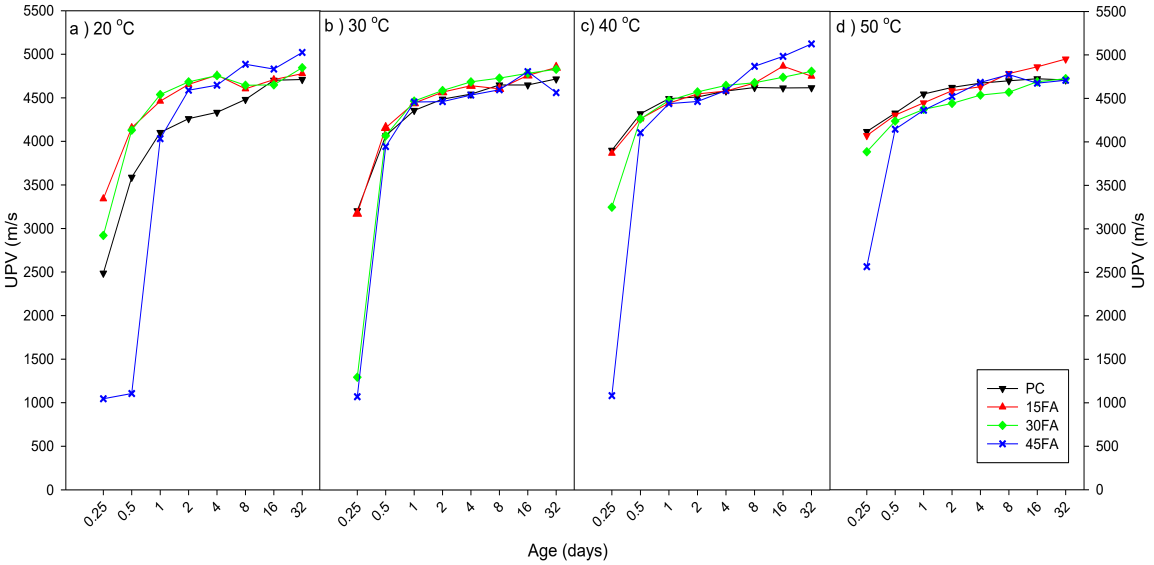


Figure 7: UPV Development of PC and FA at 20, 30, 40 and 50 ºC

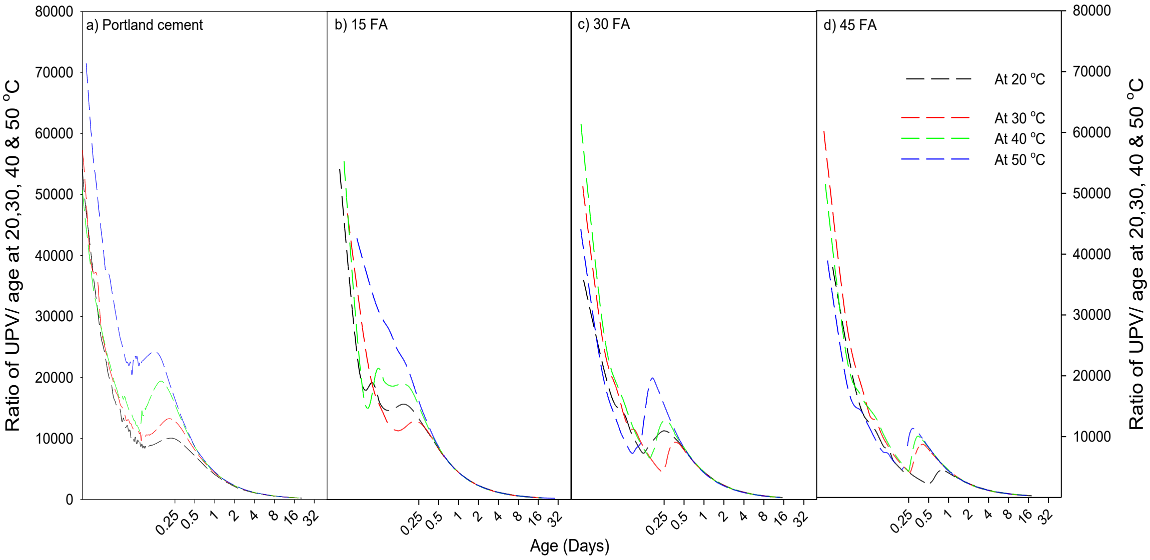


Figure 8: Ratio of UPV/age at 20, 30, 40 and 50 ºC

4. Discussion

Compressive strength can be predicted from ultrasonic pulse velocity (UPV) measurements using previously established graphical relationships between pulse velocity (m/s) and compressive strength (MPa), as illustrated in the relevant figures (9–12) for Portland cement and mixtures containing 15, 30, and 45% fly ash at curing temperatures of 20, 30, 40, and 50 °C, respectively.

The relationship between ultrasonic pulse velocity and strength development was established using exponential regression analysis. The proposed model showed a strong fit for most of the investigated concrete mixes, with coefficients of determination (R^2) greater than 0.90. This suggests that more than 90% of the variation in compressive strength can be attributed to its exponential correlation with UPV. Based on the experimental results, the empirical equation relating

UPV to compressive strength is given as follows:

$$S = a \times exp^{b \times V} \qquad \textbf{Equation 5}$$

Where:

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

Table 3 presents the equations obtained from exponential regression analysis, along with the corresponding R² values for Portland cement concrete and mixes containing 15%, 30%, and 45% fly ash as cement replacement, cured at temperatures of 20, 30, 40, and 50 °C.

Table 3: Equations to estimate the strength development of the concrete

	20 ºC		30 ºC		40 ºC		50 ºC	
	S	R^2	S	R^2	S	R^2	S	R^2
PC	$0.0800*e^{0.0015*V}$	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
15%FA	$0.0004*e^{0.0026*V}$	0.85	$0.0100*e^{0.0019*V}$	0.96	$0.019000*e^{0.0017*V}$	0.94	$0.0706*e^{0.0014*V}$	0.97
30%FA	$0.0005*e^{0.0025*V}$	0.80	$0.0007*e^{0.0024*V}$	0.99	$0.000400*e^{0.0026*V}$	0.99	$0.0002*e^{0.0028*V}$	0.98
45%FA	$0.1629*e^{0.0012*V}$	0.97	$0.0015*e^{0.0018*V}$	0.97	$0.154900*e^{0.0013*V}$	0.97	$0.0125*e^{0.0019*V}$	0.93

The developed correlations between ultrasonic pulse velocity (UPV) and compressive strength were used to estimate strength development at all curing temperatures. The predicted results for Portland cement concrete and the different fly ash mixtures are presented in Figures (13–16). The predicted strengths derived from these relationships show good agreement with the experimentally measured values, particularly at very early ages. However, at intermediate and later ages, the fit between predicted and actual strengths was less consistent, except in certain temperature conditions where reasonable agreement was still observed. At later ages, measurement noise in the UPV data likely contributed to the observed deviations between predicted and actual strengths.

The accuracy of compressive strength estimation based on ultrasonic pulse velocity (UPV) measurements mainly depends on the accuracy of the measured pulse velocity values and the validity of the established empirical correlation between UPV and compressive strength. To obtain smoother predictive curves, regression lines were generated using SigmaPlot software, employing the TPE equation, which provided the best curve fitting among the methods tested. The resulting smoothed curves are presented in Figures (13–16).

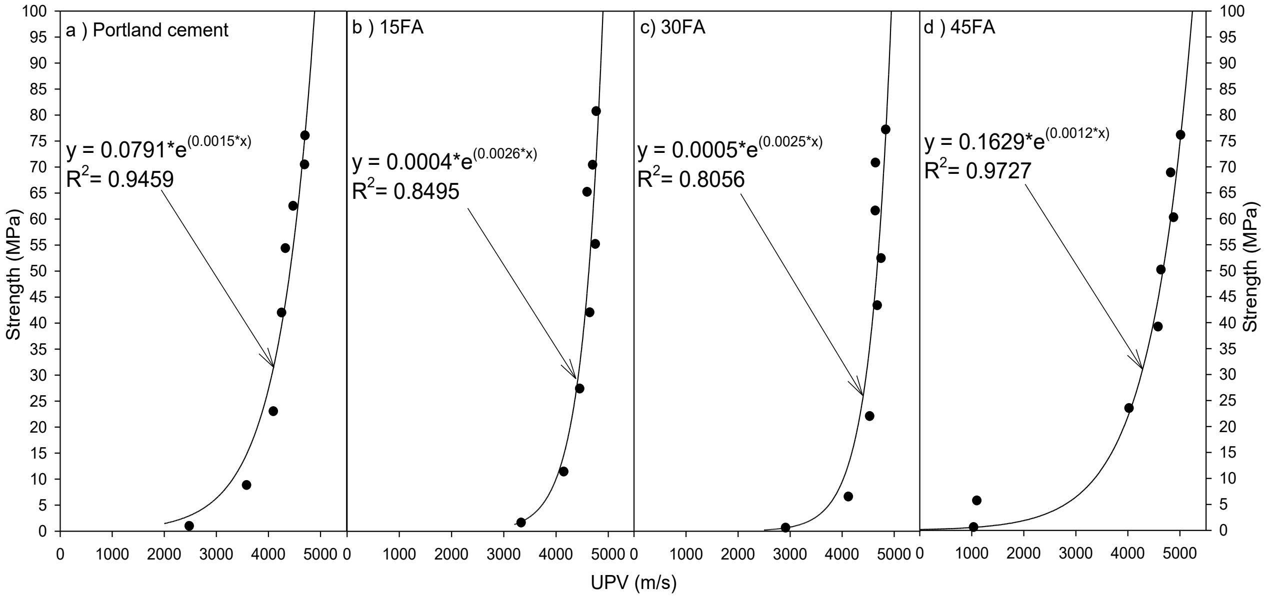


Figure 9: UPV-Strength relationship at 20 ºC

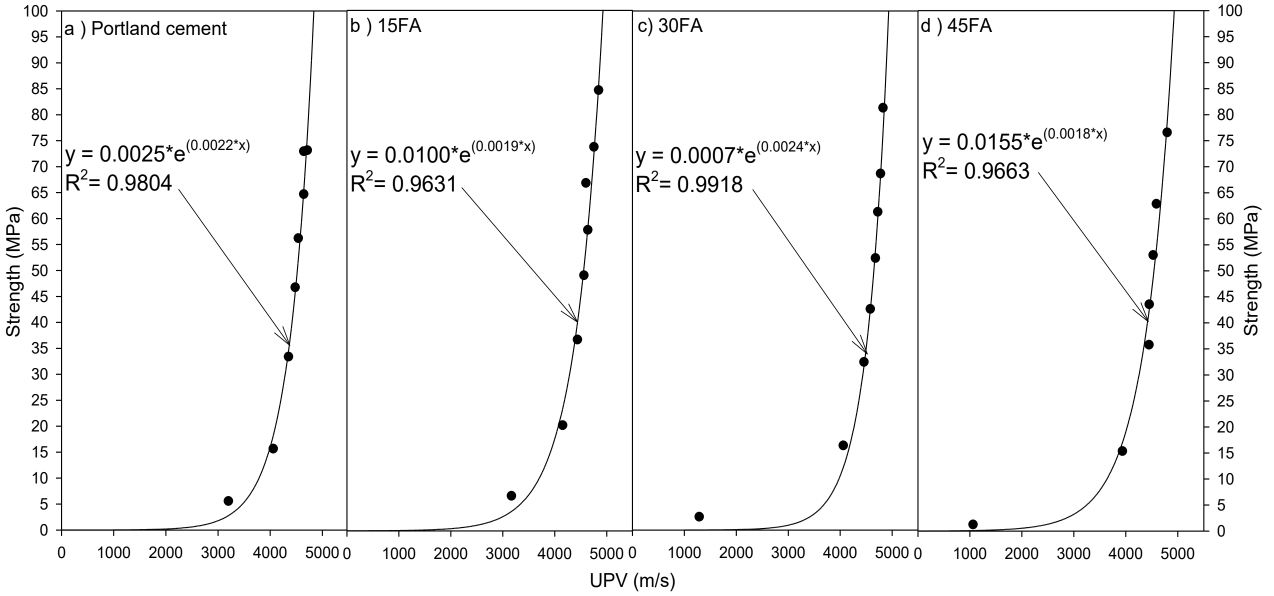


Figure 10: UPV-Strength relationship at 30 ºC

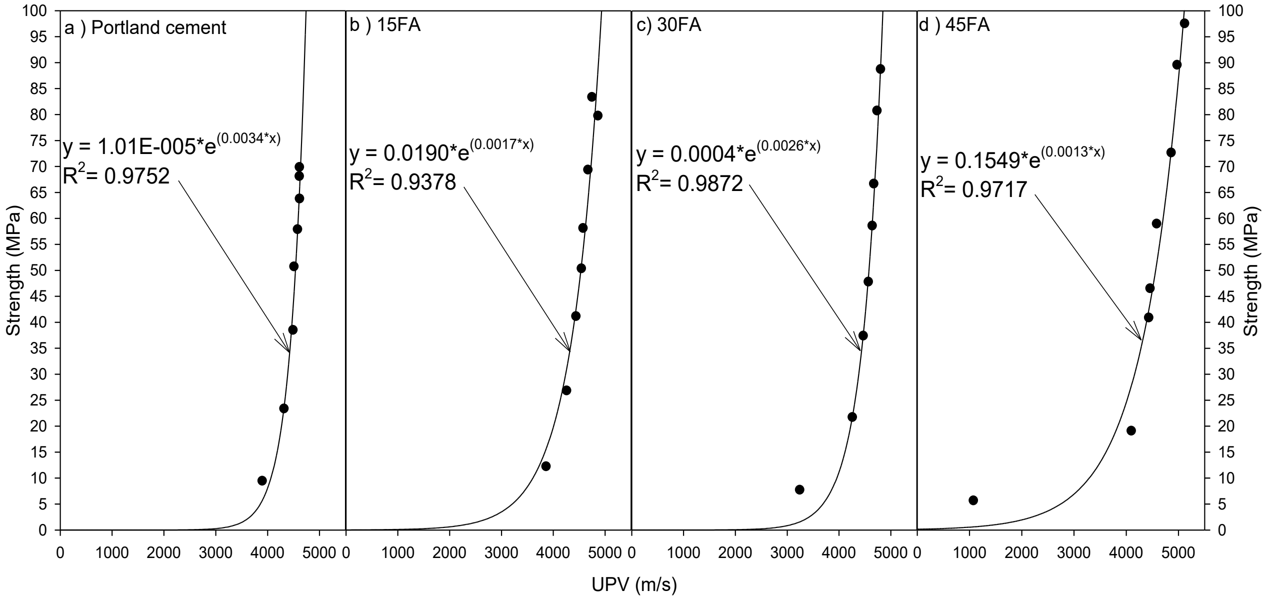


Figure 11: UPV-Strength relationship at 40 ºC

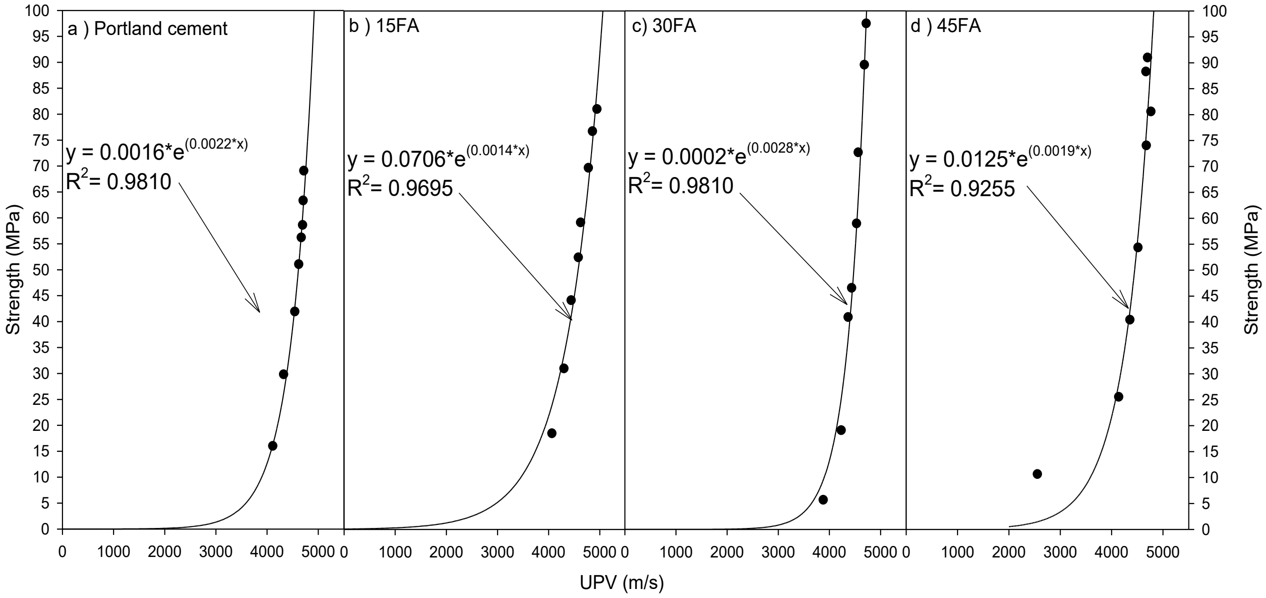


Figure 12: UPV-Strength relationship at 50 ºC

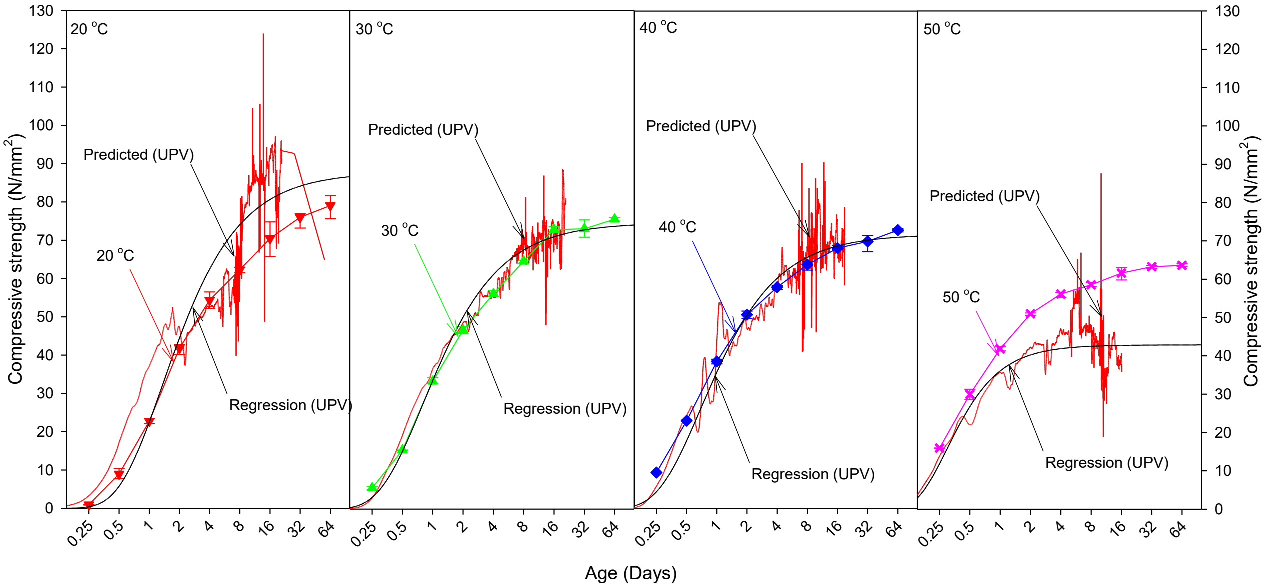


Figure 13: Predicted strength development of concretes using UPV-strength relationships for PC concrete

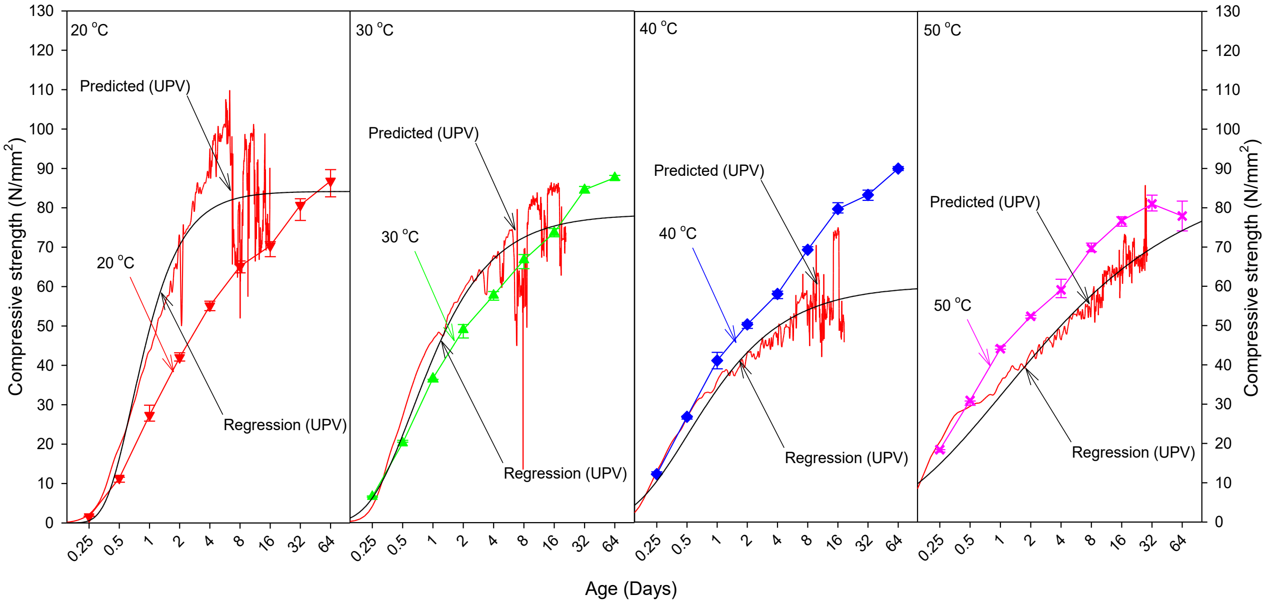


Figure 14: Predicted strength development of concretes using UPV-strength relationships for 15%FA concrete

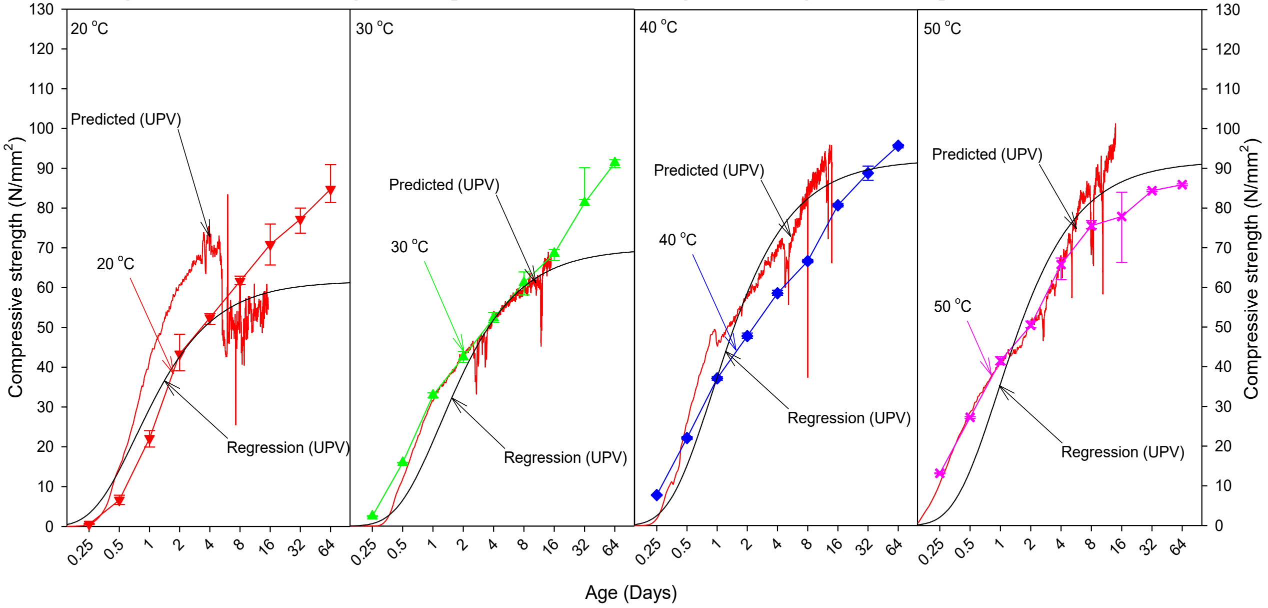


Figure 15: Predicted strength development of concretes using UPV-strength relationships for 30%FA concrete

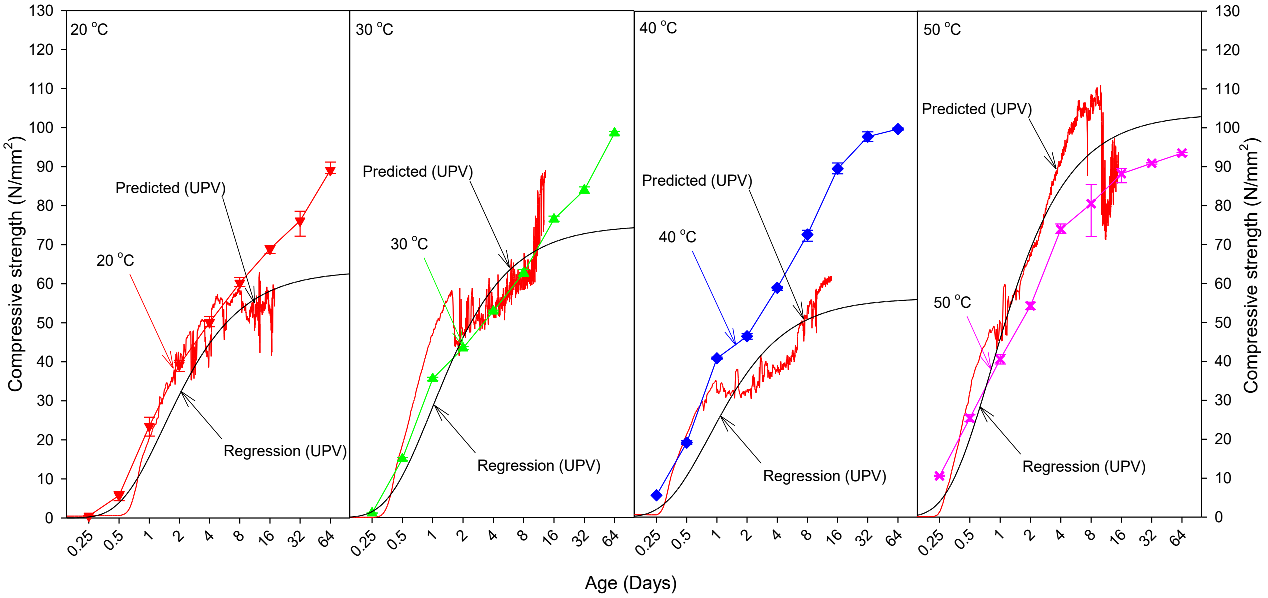


Figure 16: Predicted strength development of concretes using UPV-strength relationships for 45%FA concrete

5. Conclusion

This study confirms the effectiveness of ultrasonic pulse velocity (UPV) as a robust and sensitive tool for monitoring early-age behavior in Portland cement concrete and fly ash mixtures with 15%, 30%, and 45% replacement levels. Curing temperature was found to strongly control UPV development, with higher temperatures significantly accelerating hydration, advancing setting, and reducing the time to reach stable velocity values across all mixtures.

Fly ash incorporation systematically delayed UPV evolution and reduced early-age velocities, with the effect becoming more pronounced as replacement levels increased. Nevertheless, all mixtures exhibited a similar overall UPV development pattern, indicating consistent underlying hydration mechanisms.

A strong exponential relationship ($R^2 > 0.90$) between UPV and compressive strength was established for all mixtures and curing conditions, demonstrating the reliability of UPV for early-age strength prediction. While excellent agreement was achieved at early ages, reduced accuracy at later stages highlights the influence of measurement noise and decreasing sensitivity.

Overall, UPV is validated as a reliable non-destructive technique for early-age assessment and strength estimation of both Portland cement and fly ash concretes, with significant potential for improving quality control and optimizing curing practices.

6. References

[1] Bungey, J.H., S.G. Millard, and M. Grantham, Testing of Concrete in Structures T. Vol. 4 2006: Taylor & Francis. 286

[2] Malhotra, V.M. and N.J. Carino, The ultrasonic pulse velocity method in Handbook on nondestructive testing of concrete, T. Naik, V.M. Malhotra, and J. Popovics, Editors. 2003, CRC Press: West Conshohocken. pp. 14.

[3] L. d. Kirchhof, A. lorenzi, L. S Filho, Assessment of Concrete Residual Strength at High Temperatures using Ultrasonic Pulse Velocity .20 No.7 2015- The e-Journal of Non-destructive Testing - ISSN 1435-4934.

[4] Kaplan, M.F., The effects of age and water to cement ratio upon the relation between ultrasonic pulse velocity and compressive strength of concrete. Magazine of Concrete Research, 1959. 11 (32).

[5] Grantham, M., Diagnosis, inspection, testing and repair of reinforced concrete structures, in Advanced Concrete Technology Set, N. John and C. Ban Seng, Editors. 2003, Butterworth-Heinemann: Oxford. pp. 1-54.

[6] Tanigawa, Y., K. Baba, and H. Mori, Estimation of concrete strength by combined non-destructive testing method. ACI-American Concrete Institute, 1984. 82: pp. 57-76.

[7] Bungey, J.H., The validity of ultrasonic pulse velocity testing of in-place concrete for strength. NDT International 1980. 13 (6): pp. 296-300.

[8] Alcaino P, Maria HS, Cortes M, et al. Fast assessment of post-fire residual strength of reinforced concrete frame buildings based on non-destructive tests. MDPI Proc 2018; 2: 515.

[9] Li YH and Franssen J. Test results and model for the residual compressive strength of concrete after a fire. J Struct Fire Eng 2011; 2: 29-44.

[10] Tharmaratnam, K. and B.S. Tan, Attenuation of ultrasonic pulse in cement mortar. Cement and Concrete Research, 1990. 20 (3): pp. 335-345.

[11] Behera, B. Ultrasonic properties of fly ash composites, International Research Journal of Advanced Engineering and Science, Volume 2, Issue 1, pp. 190-193, 2017.

[12] Turgut, P., Research into the correlation between concrete strength and UPV values. NDT.net, 2004. 12 (12).

[13] Anderson, D.A. and R.K. Seals, Pulse velocity as a predictor of 28- and 90-day strength. ACI-American Concrete Institute, 1981. 78 (116).

[14] Sturrup, V.R., F.J. Vecchio, and H. Caratin, Pulse velocity as a measure of concrete compressive strength. In-Situ/Nondestructive Testing of Concrete, SP-82, V. M. Malhotra, ed., ACI-American Concrete Institute, 1984: pp. 201-227.

[15] Rao, S.K.; Sravana, P.; Rao, T.C. Experimental studies in ultrasonic pulse velocity of roller compacted concrete pavement containing fly ash and M-sand. Int. J. Pavement Res. Technol. 2016, 9, 289–301.

[16] Chen, T.T.; Wang, W.C.; Wang, H.Y. Mechanical properties ultrasonic velocity of lightweight aggregate concrete containing mineral powder materials. Constr. Build. Mater. 2020, 258, 119550.

[17] Pico, T. The TC-08 Thermocouple Data Logger offers industry–leading performance and is an inexpensive answer to your temperature measuring needs. 2005; Available from: http://www.picotech.com/thermocouple.html.

[18] Grosse, C.U., H.W. Reinhardt, M. Krüger, and R. Beutel, Ultrasound through-transmission techniques for quality control of concrete during setting and hardening. Workshop: Advanced testing of fresh cementitious materials, 2006.

[19] Guang, Y., K.v. Breugel, and A. Fraaij, Experimental study on ultrasonic pulse evalua-tion of microstructure of cementitious materials at early age. Material Search HERON 2002 2001. 46(3): pp. 161-168.

[20] Sayers, C.M. and A. Dahlin, Propagation of ultrasound through hydrating cement pastes at early times. Advanced Cement Based Materials, 1993. 1(1): pp. 12-21.

[21] Keating, J., D.J. Hannant, and A.P. Hibbert, Comparison of shear modulus and pulse velocity techniques to measure the build-up structure in fresh cement pastes used in oil well cementing. Cement and Concrete Research, 1989. 9: pp. 554-566.