EFFECT OF PASTE VOLUME AND MATRIX MODIFICATION ON STRENGTH AND ULTRASONIC PULSE VELOCITY

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ABSTRACT

The Ultrasonic Pulse Velocity Test method is a very effective method in estimating the properties of concrete by nondestructive means. This paper presents the results of an experimental investigation to evaluate properties of cement paste, mortar, and concrete using ultrasonic techniques as well as conventional testing to study the effects of paste volume and matrix modification. Matrix modification was achieved through partial replacement of cement with two types of pozzolans, silica fume or metakaolin. Cylindrical specimens with different paste volume and matrix were subjected to ultrasonic testing at 1, 3, 7 and 28 days, and compression testing was performed on the same set of samples. Total of 108 specimens with select mixture proportions were tested to arrive at reliable conclusions. An exponential model was developed to correlate Ultrasonic Pulse Velocity with compressive strength for specific matrix and mixture proportion. Also, linear regression models were established to correlate compressive strength with Ultrasonic Pulse Velocity, paste volume, and age.

Keywords: Compressive Strength, Matrix Modification, Nondestructive Testing, Paste Volume, Pozzolan, Ultrasonic Pulse Velocity.

INTRODUCTION

The properties of concrete are dependent on a number of parameters like: properties of ingredients, water/cement ratio, compaction, curing, etc. Analyzing the performance of concrete structures over a period of time is one of the challenges posed in determining its durability and serviceability. In order to evaluate the performance of existing structures, nondestructive test methods were developed.[1-3] The advantage of performing nondestructive tests on structures is that these tests do not cause any damage to the structure and permit re-testing at the same locations to evaluate changes in properties with time.[4] The most popular method of nondestructive testing that is being used in practice for the evaluation of existing concrete structures is the Ultrasonic Pulse Velocity method (ASTM C 597). The basic principle of the Ultrasonic Pulse Velocity method involves the propagation of ultrasonic pulses through a concrete member. Piezoelectric transducers are used to generate and receive the pulses. The measurements of pulse velocities can be used to determine the quality of concrete and its compressive strength as well as detect flaws within concrete mass.

CORRELATION BETWEEN COMPRESSIVE STRENGTH AND ULTRASONIC PULSE VELOCITY

Correlation between pulse velocity and compressive strength is extremely complicated because of the complex nature of concrete.[5-8] In general there is no physical relation between compressive strength and ultrasonic pulse velocity. However, modulus of elasticity of concrete is related to compressive strength. Both modulus of elasticity and Ultrasonic Pulse Velocity are related to density and hence a relation between concrete compressive strength and Ultrasonic Pulse Velocity could be established. However, there is no unique relation between concrete compressive strength and Ultrasonic Pulse Velocity. The relationship is influenced by many factors, such as, mix ingredients and their proportions, age, curing conditions and moisture content. Thus mathematical models developed to establish a correlation between Ultrasonic Pulse Velocity and compressive strength are limited to the specific mix proportions and age. Many researchers have arrived at different empirical models to correlate two parameters at any given age, since there is no unique relationship.

USE OF SUPPLEMENTARY CEMENTITIOUS MATERIALS IN CONCRETE

Supplementary cementitious materials, such as silica fume, fly ash, and metakaolin are increasingly being used to modify the pure cement matrix to achieve improvements in strength and permeability.[9-10] Matrix modification using the additives improves the water-tightness of cement paste as well as the interface zone (interface between aggregate and binder). Both silica fume and metakaolin are classified as natural pozzolans. However, their influence on strength and permeability of concrete differ. To achieve full benefits, studies have suggested that the optimum percentage replacement of cement with these pozzolans should be around 15 to 20% by weight.

RESEARCH SIGNIFICANCE

Addition of pozzolans, such as, silica fume or metakaolin to modify pure cement matrix has significant effect on the overall properties of concrete. Much of the research data available are on strength and permeability. There is a great desire to understand the behavior of concrete containing pozzolans through nondestructive testing, such as the Ultrasonic Pulse Velocity method and correlate the results with compressive strength. However, the relationship between strength and Ultrasonic Pulse Velocity is complex and is influenced by many factors. Also, the mathematical model developed to establish a correlation between Ultrasonic Pulse Velocity and compressive strength is limited to the specific mix proportion and age. This paper presents the development of linear regression model to estimate compressive strength from pulse velocity, paste volume and age for select mix proportions containing pozzolans.

EXPERIMENTAL PROGRAM

TEST SERIES

The cementitious materials used in this investigation were ASTM C 150 Type I Portland cement, silica fume (air-densified microsilica conforming to ASTM C-1240) and metakaolin (Metamax conforming to ASTM C 618). Local river sand with a fineness modulus of 2.97 and specific gravity of 2.68 was used as fine aggregate. Crushed granite with a maximum nominal size of 6.25 mm (0.25 in) and a specific gravity of 2.7 was used as coarse aggregate. Cementitious binder along with fine aggregates, coarse aggregates, water, and plasticizer binder were properly proportioned to achieve the objectives of this research.

Details of matrix mixture ingredients and their proportions for paste, mortar and concrete are presented in Table 1. The proportions were chosen to obtain different paste volume, so that the effect of paste volume on Ultrasonic Pulse Velocity in concrete could be studied. The paste volume selected ranged from 29 – 100%. For each mixture proportion, Portland cement was partially replaced at 15% by weight with silica fume or metakaolin. Water to binder ratio was maintained constant at 0.45 and comparable workability was achieved by varying the amount of superplasticizer. Thus the effect of matrix modification on strength and Ultrasonic Pulse Velocity could be correlated at comparable paste volume and water-to-binder ratio. Mixing was done in a regular laboratory mixer in accordance with ASTM C 192.

Twelve cylinders of 101.6 mm (4 in) diameter and 203.2 mm (8 in) height were cast for each series of cement paste, mortar and concrete. The specimens were demolded after 24 hours and were then moist cured until the age of testing. Minimum of three specimens were tested for any given testing and aging condition.

Table 1 – Test Series and Mixture Proportions

Test Series	Mix Proportion	Superplasticizer : Binder	Silica Fume (%)	Metakaolin (%)	Paste Volume (%)
CP	1:0:0	0.005	0	0	100
CP-SF	1:0:0	0.0125	15	0	100
CP-MK	1:0:0	0.01	0	15	100
M	1:2:0	0.005	0	0	50.7
M-SF	1:2:0	0.0145	15	0	51.2
M-MK	1:2:0	0.012	0	15	51.1
C	1:2:3	0.005	0	0	29.2
C-SF	1:2:3	0.0125	15	0	29.7
C-MK	1:2:3	0.01	0	15	29.7

TEST PROCEDURE

Ultrasonic Pulse Velocity

The Ultrasonic Pulse Velocity (UPV) method was conducted in accordance with ASTM C 597. The Ultrasonic Pulse Velocity test set-up is shown in Figure 1. The instrument used for the Ultrasonic Pulse Velocity method was V-METER MARK II manufactured by James Instruments, Inc. The instrument consists of two transducers, a pulse generator, a receiver amplifier and a digital display. In this method the two transducers were placed in contact with the concrete at two ends of the cylindrical specimen. The receiving transducers received the pulse transmitted from the transmitting transducers, at a distance L. The Ultrasonic Pulse Velocity instrument displayed the time, T, taken by the pulse to travel the distance L. The longitudinal velocity, V, was obtained directly from the instrument was computed from the following equation.

$$V = \frac{L}{T} \tag{1}$$

Where:

V = Pulse velocity
L = Path length in meters
T = effective time in seconds

The velocity of a compressional wave in a homogeneous, isotropic and elastic medium is given by:

$$V = \left[\frac{E_d (1-\mu)}{\rho(1+\mu)(1-2\mu)} \right]^{.5} \qquad (2)$$

Where:

V = Compression wave velocity
ρ = Density of the medium
μ = Poisson's ratio (assumed to be 0.2)
E_d = is the dynamic modulus of elasticity

Fig. 1 Experimental Set-up for Ultrasonic Pulse Velocity Testing

Compressive Strength

A hydraulic testing machine with digital display, Test Mark, was used for the compression testing. The tests were conducted in accordance with ASTM C 39. The breaking load was displayed digitally by the instrument. The specimens were tested for day 1-day, 3-day, 7-day, and 28-day compressive strength and Ultrasonic Pulse Velocity.

EXPERIMENTAL RESULTS AND DATA ANALYSIS

EFFECT OF MATRIX MODIFICATION

The effect of matrix modification on compressive strength of cement paste, mortar and concrete are presented in Table 2. Cement paste, mortar and concrete with metakaolin showed an increase in 28-day compressive strength when compared with pure concrete matrix. The increase in 28-day compressive strength for mortar with metakaolin was 43% while for concrete the increase was 30% over plain concrete. Silica fume however did not have a similar effect over plain concrete. Concrete modified with silica fume showed a marginal increase in compressive strength. It should be noted that higher water-to-cement ratio used in this investigation (0.45) may be partly responsible for poor performance of matrix modified with silica fume.

Table 2 – Compressive Strength Test Results

Test Series	Compressive Strength, MPa Mean (Std. Dev.)							
	1-Day		3-Day		7-Day		28-Day	
CP	13.86	(2.54)	30.61	(2.08)	42.66	(5.03)	60.30	(3.68)
CP-SF	11.65	(6.08)	28.35	(2.80)	37.63	(2.23)	51.42	(6.30)
CP-MK	22.19	(0.53)	36.35	(2.63)	48.35	(4.91)	60.53	(6.29)
M	14.32	(0.13)	29.22	(2.01)	38.59	(1.55)	49.44	(2.54)
M-SF	12.50	(0.73)	21.28	(1.48)	29.41	(1.39)	41.17	(1.50)
M-MK	24.27	(1.83)	37.48	(0.68)	57.36	(3.13)	70.75	(3.61)
C	19.75	(1.09)	35.91	(1.13)	44.49	(1.65)	59.29	(1.85)
C-SF	16.50	(0.59)	31.18	(0.70)	42.25	(0.72)	62.91	(2.18)
C-MK	20.48	(0.33)	36.27	(1.31)	57.72	(2.29)	76.81	(6.71)

(Conversion Factor: 1 MPa = 145 psi)

The effect of matrix modification on Ultrasonic Pulse Velocity in cement paste, mortar and concrete are presented in Table 3. No general trend was observed for both cement paste and mortar. For cement paste, the plain mix showed highest values of pulse velocity at 28-day while cement paste modified with silica fume gave the least value. However for mortar, metakaolin gave higher values when compared to plain mortar. Plain concrete, also like cement paste showed an increase in Ultrasonic Pulse Velocity at 28-day when compared to silica fume and metakaolin.

Table 3 – Ultrasonic Pulse Velocity Test Results

Test Series	Ultrasonic Pulse Velocity, m/s Mean (Std. Dev.)							
	1-Day		3-Day		7-Day		28-Day	
CP	2853	(10.07)	3348	(23.95)	3646	(16.45)	3859	(27.56)
CP-SF	2671	(34.06)	3271	(192.2)	3252	(59.87)	3468	(101.2)
CP-MK	2962	(8.635)	3228	(54.13)	3466	(39.14)	3632	(76.24)
M	3310	(56.65)	3909	(98.25)	4020	(84.85)	4168	(97.13)
M-SF	3492	(18.00)	3623	(44.42)	3982	(43.25)	4178	(38.70)
M-MK	3654	(94.41)	3769	(134.8)	4126	(98.48)	4272	(28.97)
C	4235	(98.11)	4622	(39.62)	4679	(61.58)	4893	(44.82)
C-SF	3976	(110.4)	4214	(73.09)	4453	(29.88)	4760	(69.18)
C-MK	4147	(43.71)	4405	(39.60)	4615	(67.90)	4873	(81.83)

(Conversion Factor: 1 m/s = 3.281 ft/s)

AGE OF TESTING

Figures 2 through 4 shows the variation of compressive strength of cement paste, mortar, and concrete selected in this investigation. It was observed that for all types of concrete there is an increase in compressive strength with increased aging. However, the rate of increase in compressive strength depends on the matrix. Type of pozzolan also has significant influence on strength gain since they react differently. Cement paste modified with metakaolin showed an increase in compressive strength ranging from 60% to 1% than that of pure cement matrix, with maximum increase being at 1 day and comparable strength at 28 days. This was expected since metakaolin contains 20 to 30% Alumina, which is highly reactive. Similar trend was observed for concrete.

Figures 5 through 7 show the rate of increase in Ultrasonic Pulse Velocity with aging for different mix proportions and matrix modification of concrete. Ultrasonic Pulse Velocity also increases with increasing age for cement paste, mortar and concrete. However, the increase in pulse velocity was at a reduced rate. Unlike the compressive strength, by day 1 all pastes and mortars achieve 80% of 28-day Ultrasonic Pulse Velocity values. After 1-day there is only a moderate increase in pulse velocity.

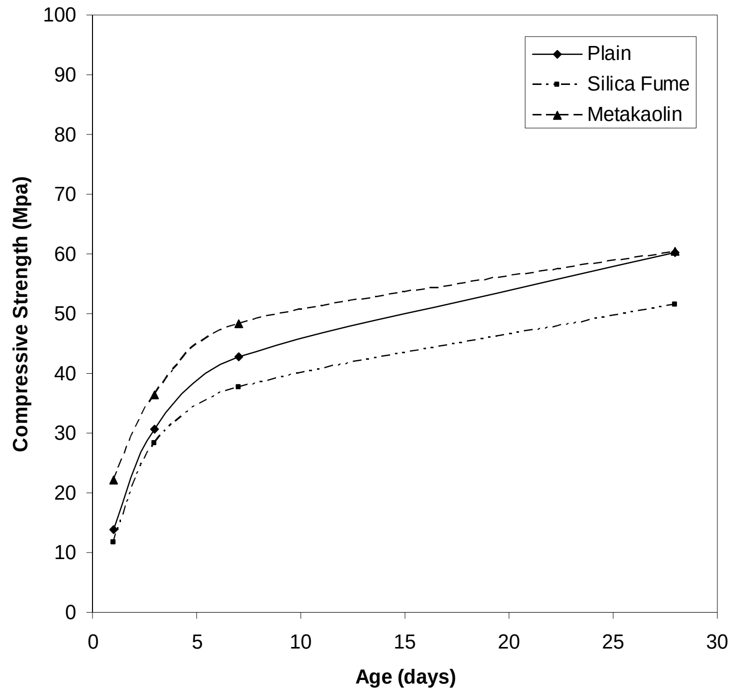

Fig. 2 Variation of Compressive Strength with Age for Paste

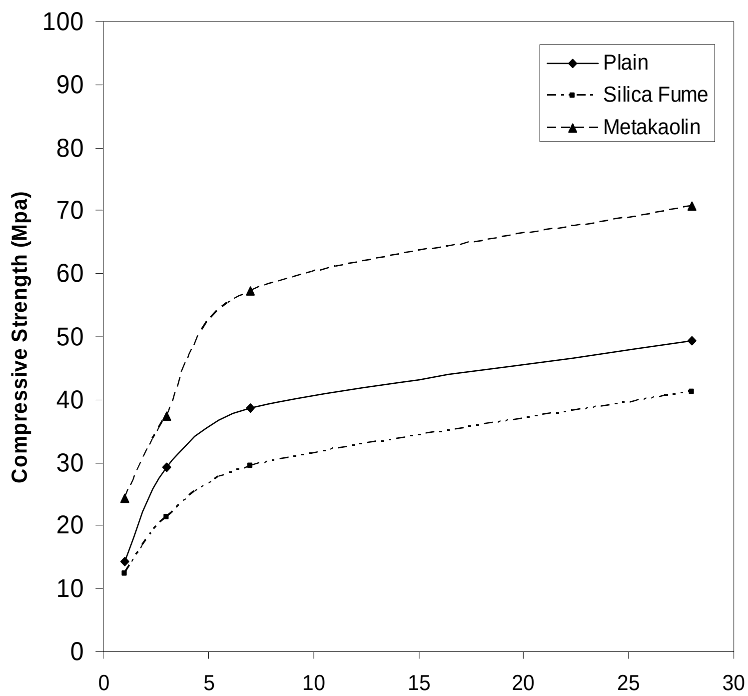

Fig. 3 Variation of Compressive Strength with Age for Mortar

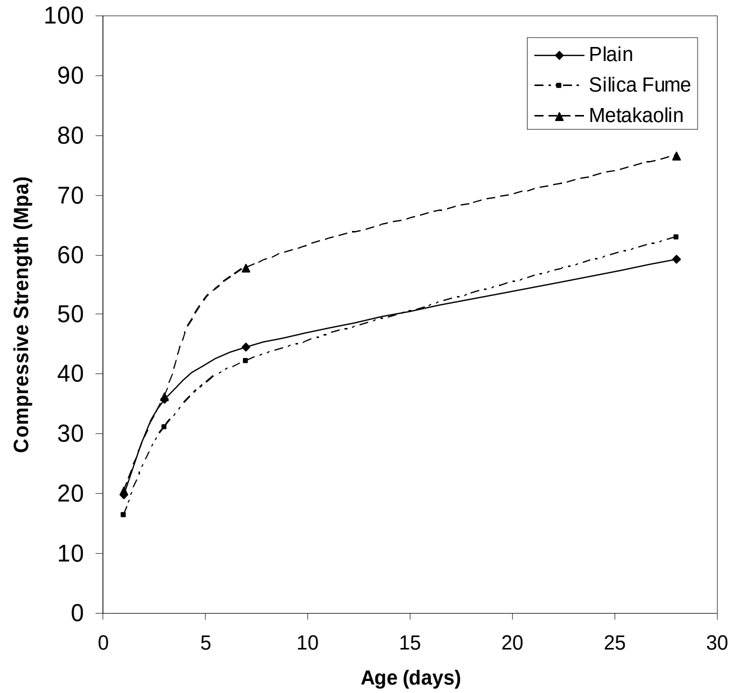

Fig. 4 Variation of Compressive Strength with Age for Concrete

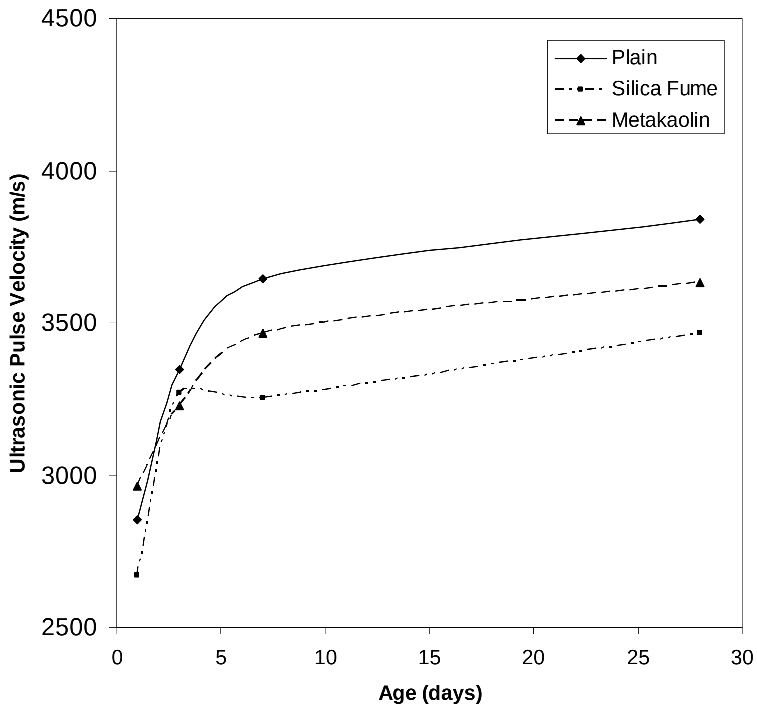

Fig. 5 Variation of Ultrasonic Pulse Velocity with Age for Paste

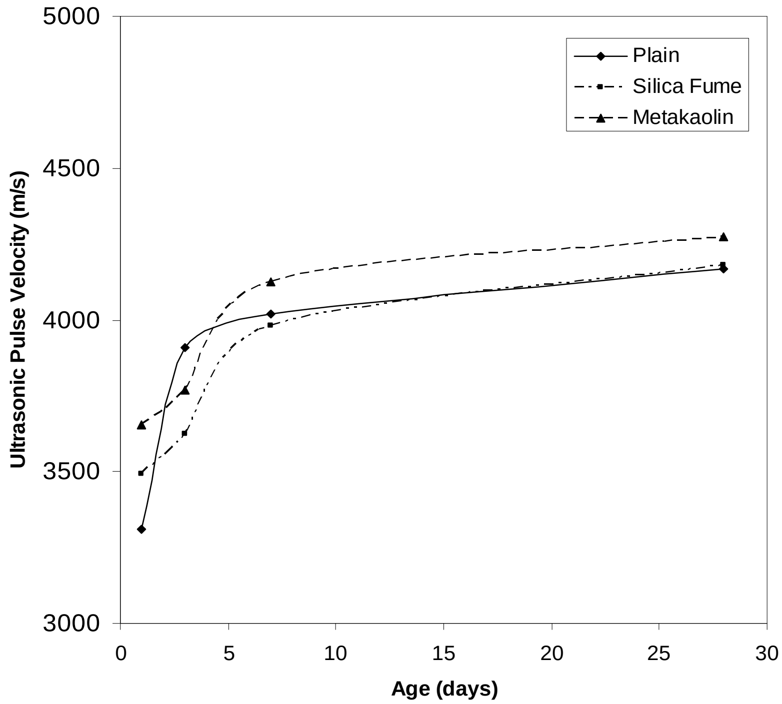

Fig. 6 Variation of Ultrasonic Pulse Velocity with Age for Mortar

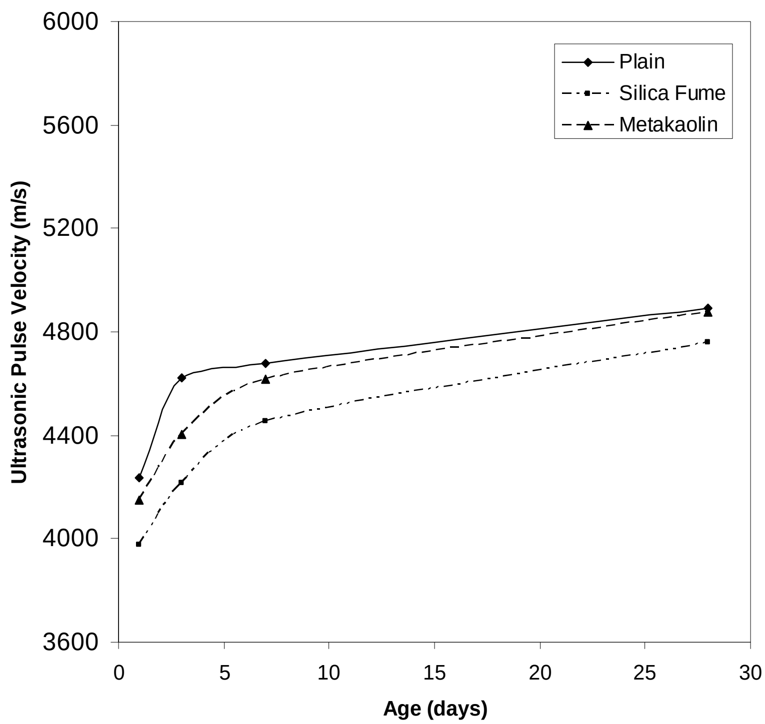

Fig. 7 Variation of Ultrasonic Pulse Velocity with Age for Concrete

EFFECT OF PASTE VOLUME

The variation of compressive strength for a particular age can be compared from the Figures 2 – 4. Comparing 28-day compressive strength one can observe comparable values of strengths for pure cement paste and paste with metakaolin. However, silica fume results in 16% drop in strength. The percentage of paste decrease as aggregate content is increased with higher paste volume achieved with concrete (1:2:3). Metakaolin showed an increasing trend with a decrease in paste volume. Both paste and mortar with silica fume resulted in concrete with reduced strength. However, it should be noted that silica fume is a slow reactive pozzolan. With continued aging there may be an increase in strength. In order to obtain increased compressive strength, paste volume has to be optimized based on the amount and type of pozzolan.

Comparing 28-day ultrasonic pulse values (Figures 5 – 7) one can observe that as the paste volume reduces, the Ultrasonic Pulse Velocity values increases. This observation was true for pure cement as well as silica fume and metakaolin matrix. This was also true at all ages of testing. As the percentage of paste volume increases the density of concrete is reduced. Density has a direct effect on Ultrasonic Pulse Velocity. Thus, Ultrasonic Pulse Velocity values increase with increased aggregate content. It should be noted that the effect of paste volume on strength and Ultrasonic Pulse Velocity are different and thus requires statistical correlation.

CORRELATION OF COMPRESSIVE STRENGTH WITH ULTRASONIC PULSE VELOCITY

Ultrasonic Pulse Velocity does not provide direct measurement of strength. However, correlation between Ultrasonic Pulse Velocity and strength can be established through experimental results and statistical analysis. In earlier investigations exponential model has been observed to provide satisfactory correlation. Hence an exponential model was developed in this investigation to correlate Ultrasonic Pulse Velocity with compressive strength for cement paste, mortar and concrete. The equations for specific mix and the corresponding R^2 value are presented in Table 4. A very good correlation was obtained between pulse velocity and compressive strength for all mixtures selected in this investigation with the R^2 values ranging from 0.9257 to 0.9951. The correlation equations presented in the table can be used for predicting the compressive strength from pulse velocity for a specific type of mix. For reference, Y corresponds to compressive strength and the X corresponds to Ultrasonic Pulse Velocity.

Table 4 – Equations of Correlation between Pulse Velocity and Compressive Strength

Test Series	Exponential Equation	R-Squared Value
CP	$Y = 0.2190e^{1.4958X}$	0.9951
CP-SF	$Y = 0.0900e^{1.8165X}$	0.9554
CP-MK	$Y = 0.2903e^{1.4757X}$	0.9893
M	$Y = 0.0823e^{1.5873X}$	0.9513
M-SF	$Y = 0.7226e^{1.0257X}$	0.9677
M-MK	$Y = 0.0382e^{1.812X}$	0.9731
C	$Y = 0.0155e^{0.0017X}$	0.9919
C-SF	$Y = 0.0257e^{0.0017X}$	0.9623
C-MK	$Y = 0.0059e^{0.0020X}$	0.9949

(Y = Compressive Strength, X = Ultrasonic Pulse Velocity)

Correlation between Compressive Strength, Pulse Velocity, Paste Volume, and Age

Regression analysis using "Data Fit" software was used to correlate compressive strength with Ultrasonic Pulse Velocity, paste volume and age. Here paste volume means volume of cementitious materials in paste and mortar.

The model that best fits the data is a linear regression model:

$$Y= a*X_1+b*X_2+c*X_3+d$$

where:
Y = Compressive strength in MPa
X_1 = Percentage of paste volume
X_2 = Age in days
X_3 = Ultrasonic Pulse Velocity at the age of X_2-day in m/s
a, b, c and d = Regression variables.

Table 5 presents the values of a, b, c and d for plain, silica fume and metakaolin modified concrete along with the co-efficient of multiple determination (R^2) values. While there were significant differences in compressive strength, Ultrasonic Pulse Velocity values were comparable. The correlations established are specific to the mixture proportions and parameters studied in this investigation.

Table 5 – Regression Variables and Co-efficient of Determination for Multiple Regression Models

Concrete Description	a	b	c	d	R^2
Plain Cement Paste and Mortar	0.290393	0.524682	0.023131	-76.5896	0.88217
Silica Fume Modified Cement Paste and Mortar	0.439016	0.547253	0.023404	-91.0931	0.87136
Metakaolin modified Cement Paste and Mortar	0.53915	0.191243	0.047948	-174.77	0.84

SUMMARY AND CONCLUSIONS

The Ultrasonic Pulse Velocity method is an extremely effective method in evaluating the properties of concrete. The Ultrasonic Pulse Velocity gives an indirect measurement of the strength of concrete. In this investigation an effort was made to establish a correlation between the Ultrasonic Pulse Velocity and compressive strength by developing a regression model. Based on the experimental results obtained and analysis performed the following general conclusions could be drawn:

1. Compressive strength increases with age. However, the rate of increase depends upon the type of matrix.
2. The Ultrasonic Pulse Velocity also increases with age for cement paste, mortar and concrete. However, rate of increase in Ultrasonic Pulse Velocity was moderate when compared to compressive strength with most of the Ultrasonic Pulse Velocity being gained by the first day and recording only small increase leading up to the 28th day.
3. Partial replacement of cement with select percentage of metakaolin does have some effect on both Ultrasonic Pulse Velocity and compressive strength. However, silica fume had little effect on the strength and Ultrasonic Pulse Velocity of concrete when compared to plain matrix. Replacement of cement with metakaolin resulted in significantly higher compressive strength and Ultrasonic Pulse Velocity values when compared to that of plain matrix. The replacement of silica fume did not show any improvement in strength or the Ultrasonic Pulse Velocity for either cement paste or mortar, but resulted in increased strength in concrete.
4. Variation of paste volume did not show any particular trend on the compressive strength of concrete. An increase in compressive strength was generally observed with a decrease in paste volume. Concrete with mix proportion 1:2:3, which constituted least paste volume among the selected mixture proportions, provided highest values of compressive strength.

5. The effect of paste volume, however, had a significant effect on the Ultrasonic Pulse Velocity. The Ultrasonic Pulse Velocity increased with a decrease in paste volume. This effect was true for matrix modified with both pozzolans.
6. The exponential model developed for each select mixture can be used to estimate compressive strength from pulse velocity. Linear multiple regression model provides the best correlation between compressive strength, Ultrasonic Pulse Velocity, paste volume and age.

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