Nondestructive testing and structural health monitoring of concrete Using Ultrasonic Pulse Velocity Test

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Abstract

Ultrasonic Pulse Velocity (UPV) is a non-destructive testing method used for testing materials. For concrete, it is used mostly for determination of dynamic elasticity modulus, compressive strength, homogeneity, to determine the depth of cracks or as a supportive method for testing frost resistance. In Concrete structures, sometimes, it is necessary to analyze the concrete quality, when there is a doubt on the concrete compressive strength test results that may not be in compliance with the requested compressive strength according to the design, or when the compressive strength value is not available, in these cases Non-Destructive Tests (NDT) is used to find the compressive strength of concrete. Ultrasonic Pulse Velocity (UPV) test is the common NDTs that used in analyzing the concrete quality and determining concrete compressive strength. In this study, many data collected from literature, for different mix proportion at different ages, to find a relation between ultrasonic pulse velocity and the compressive strength of concrete, in this research a relation for predicting a compressive strength of concrete is obtained between ultrasonic pulse velocity and the compressive strength of concrete from 1 day curing to 120 days curing with different mix proportion. That can predict a compressive strength of concrete at any desired age from the ultrasonic pulse velocity. Also a model equation is obtained to predicting the density of the concrete based on ultrasonic pulse velocity.

Keywords:

Compressive Strength (Fc), Ultrasonic Pulse Velocity (UPV), Non-Destructive Test, Density**.**

1. Introduction

The evaluation of existing steel-reinforced concrete structures has been an important topic for periods. Status assessment of building materials is critical when reassess existing structures since the material condition can affect the performance loss, degradation of safety, and maintenance costs. This could be implemented to regularly monitor the health of old/important concrete structures and/or evaluate damaged concrete structures to keep the structural integrity and for constructional issues i.e. repair and modification. The rehabilitating of concrete structures has become important especially in regions of the world that have been damaged by the wars and military conflict.

Repairing structures instead of demolishing and rebuilding could save time and finance from the one hand and satisfy the aim of sustainable development by conserving the natural resources from the other hand. The structural assessment is mainly/initially carried out by assessing the concrete quality indicated by concrete compressive strength (Fc) which has an exceptional importance in concrete engineering. This importance contributes structural evaluation in addition to the structural design and analysis. Because it provides an indicator for other mechanical properties in addition to its importance in the structural design of the concrete structures.

Destructive test as a core test was previously used to evaluate concrete structures in addition to loading test. Core test requires a large number of cores to be taken from the studied structural concrete member. This cause to decrease the load-bearing capacity of the tested member by decreasing the cross section in addition to its high cost whereas performing loading test needs time and cost. For this two reasons, the use of nondestructive testing (NDT) has become more common to assess the state of existing reinforced concrete structures. The idea of nondestructive testing (NDT) is to evaluate material properties of in place specimens without the destruction of neither the specimen nor the structure from which it is taken. For most cast-in-place concrete structures, construction specifications require that test cylinders or cubes be cast for 28 days for strength determination. Generally, representative test samples are taken from the same concrete mix as the larger structural elements. In most of the time, test specimens are not an exact picture of in-situ concrete and may be affected by variations in specimen type, size, and curing type. One of the common (NDT) is Ultrasonic Pulse Velocity (UPV), that is used to find the compressive strength of the concrete structures.

Many studies in the literature have been performed to find or predict the compressive strength of concrete in the structure with different mix proportions and ages. A set of 9 cubes 150X150X150 mm were cast, with different mix proportions at different age of curing, to predict the compressive strength of concrete, a linear correlation between ultrasonic pulse velocity and compressive strength of concrete was obtained [1]. Another study was performed in literature using different W/C 0.35, 0.37, 0.45, and 0.5 for different ages of curing 7, 28, and 56 days, 288 cubes were casted and tested at different days of curing the result was compared with the previously published paper by Isam H.Nash't, Saeed Hamid in November 2005, using exponential equation that obtained from the Isam H.Nash't and the difference between the actual result from testing machine and the calculated compressive strength from equations was +4.5 % and - 5.83 % [2]. More research was implemented to evaluate the compressive strength of structural lightweight concrete using Ultrasonic Pulse Velocity (UPV), 74 sample were cast using different type of cement and adding different percent of flay ash, silica fume, with using normal and different lightweight aggregate, four exponential model was developed to predict the compressive strength of lightweight aggregate using Ultrasonic Pulse Velocity (UPV) [3].

The performance of ultrasonic pulse velocity in concrete as a non-destructive test, to predict the compressive strength of fiber-reinforced self-compacted concrete with Nanoparticles was performed in this study 40 sample dividing to four different groups A,B,C, and D in which cement was replaced with Nanoparticles 0, 2, 4, and 6 Vole % of nano-Sio2. The different exponential equation was obtained for each contents of nono-Sio2 for predicting the compressive strength of concrete [4].

Total of 225 concrete cubes with different compressive strengths have been tested using two methods of nondestructive tests, namely Rebound Hammer and Ultra Pulse Velocity, then the cubes were tested to destruction for the determination of their compressive strength. The aim of the study was to find a correlation between nondestructive and destructive tests for the practical application. The test program consisted of testing concrete cubes made from five different mixes, their strength ranged from 40 to 60 MPa, they were tested at the ages of 1, 7, 28, and 90 days. The results indicate that obtained equations from a regression analysis on test data for 1 day are more accurate than for 7, 28, and 90 days for all mixes [6].

Single and double-variable regression models (UPV and RN) were used in predicting concrete compressive strength. The suggested models were experimentally evaluated in both laboratory and full scales. It was found that the Indirect Ultrasonic Pulse Velocity (IUPV) test can be used in a combination with RN test to provide a double variable linear regression model (ISonReb). This model was built using analysis of variance (ANOVA) which was found to provide more accurate results than single ones regardless the UPV test arrangements (DUPV or IUPV) [7].

The data collected from literature summarized in Table 1.

1.1. Objectives

The main objective of this study was to find the relation between Ultrasonic Pulse Velocity (UPV) and concrete compressive strength for the different concrete mix at different age of the structure, and find a proper model equation. And finding the correlation between (Density) and (UPV).

- Predicting compressive strength at any desire age from 1 day of curing 120 days.
- Deriving a model equation for each day of curing to predict the compressive strength of concrete based on ultrasonic pulse velocity, 1, 3, 7, 28, 90 and 120 days.
- Predicting density of concrete based on ultrasonic pulse velocity, and finding a model equation.

2. Materials and methods

2.1 Materials

2.1.1 Data Collection

This study was focused on correlations between Ultrasonic Pulse Velocity (UPV) and compressive strength of concrete of different mix proportion at any desired age, Over 502 data was collected from literature for different (mix proportion, W/C, aggregate type, cement type, density, and different admixture), samples were tested at different age of curing of 1, 3, 7, 28, 90, and 120 days, by compressive strength machine and Ultrasonic Pulse Velocity. The mix proportion of the samples that collected from literature summarized in Table 2.

2.2 Methods

2.2.1 Destructive Test (Compressive Strength Machine) According to (BS 1881-116)

To determine the actual compressive strength of cast concrete, destructive tests are the most reliable methods. Typically, test samples were taken from the mixed concrete batch on site and then sent to the laboratory for curing and testing. Then, destructive tests were conducted to obtain the actual concrete compressive strength at different ages [1, 2, 6].

2.2.2 Non-Destructive Test -Ultrasonic Pulse Velocity (UPV) (ASTM-C597-02)

Using (UPV) test for predicting the compressive strength of different concrete mix at different days of curing. This test method is use to measure the uniformity and relative quality of concrete, to indicate the presence of voids and cracks, and to evaluate the effectiveness of crack repairs. It is also applicable to indicate changes in the properties of concrete, and in the survey of structures, to estimate the severity of deterioration or cracking. The ultrasonic pulse velocity method measures the travel time of an ultrasonic pulse (50–54 kHz) passing through the concrete. Comparatively higher velocity is obtained when concrete quality is good in terms of density, uniformity, homogeneity, and strength. The tests begin when an ultrasonic pulse is generated and transmitted from an electro-acoustic transducer, placed in contact with one surface of the concrete. After passing through the concrete, the vibrations are received and converted by the electro-acoustic transducer at the other end of the surface. The elapsed time between input and output of the wave is measured with a precision of at least 0.1 µs. With known traveling distance, D, and the travel time measured, T, the pulse velocity ($V = D/T$) can be calculated. According to different settings of the transducer locations, there are three types of ultrasonic pulse velocity tests, as shown in Fig.12. [8]

3. Modeling:

A nonlinear relationship between Ultrasonic Pulse Velocity (UPV) and compressive strength of concrete was obtained at a different day of curing. Based on the data that collected from literature the following relationship is proposed Eq. (1). Both coefficient of determination (R2) and the root mean square error (RMSE) for the model predictions were used in order to determine the accuracy of the model predictions as defined in Eq. (2) and (3) were quantified.

$$\boldsymbol{Y = Z + A * e^{B*X}} \qquad \textbf{(1)}$$

Where

Y = Compressive strength (MPa) (dependent variable)

X = Ultrasonic Pulse Velocity (UPV) (m/s) (Independent variable)

A, B, and Z = Model parameters

$$R^2 = 1 - \left(\frac{\sum(y_i - y_p)^2}{\sum(y_i - \bar{y})^2}\right) \qquad \textbf{(2)}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \mathrm{yp})^2}{N}} \qquad \textbf{(3)}$$

Where

y_i = actual value;

y_p = calculated value from the model;

$\bar{y}$ = mean of actual values;

N = is the number of data points.

4 Results and Discussion

4.1 Ultrasonic Pulse Velocity (UPV) and Compressive Strength (MPa) model 1 day curing

A nonlinear model was obtained to predict the compressive strength of concrete by measuring (UPV), as shown in Fig.(1). Using 27 different mix proportions, the compressive strength was varied between 3.5 and 24.6 MPa. From the statistical analysis, 29.5% of the compressive strength samples were more than 20 MPa, 7.5% of the samples were between 10 and 20 MPa, and 63% of the samples were less than 10 MPa. The coefficient of determination (R^2) of the model was 0.97, and root mean square error (RMSE) was 1.27, mean and standard deviation was 11.12 and 8.17 respectively. The statistical analyses of the compressive strength and (UPV) is summarized in Table 3 and Table 4 respectively. The model parameters are summarized in Table 5.

4.2 Ultrasonic Pulse Velocity (UPV) and Compressive Strength (MPa) model 3 days curing

Based on the collected data from literature a nonlinear model was obtained to predict the compressive strength of concrete, as shown in Fig.(2). The 10 different mix was tested the value of compressive strength of concrete was varied from 2.4 MPa to 27.9 MPa, from the statistical analysis the compressive strength of 50% of samples were less than 7.5 MPa, 10% of samples were between 7.5 MPa and 22.5 MPa, and 10% were more than 22.5 MPa, with (R^2) 0.96, (RMSE) 1.256, the statistical analyses summarized in Table 3 and Table 4, the model parameters summarized in Table 5.

4.3 Ultrasonic Pulse Velocity (UPV) and Compressive Strength (MPa) model 7 days curing

Based on the collected data from literature a nonlinear model was obtained to predict the compressive strength of concrete at 7 days of curing, as shown in Fig.(3). The 55 Sample was tested the value of compressive strength of concrete was varied between 36 MPa and

79.2 MPa, 33% of sample compressive strength was less than 30 MPa, 45% of sample was between 50 MPa and 70 MPa, 22% of sample compressive strength was more than 70 MPa, with (R^2) 0.93, (RMSE) 3.36, the statistical analyses of compressive strength of concrete and (UPV) summarized in Table 3 and Table 4, respectively the model parameters summarized in Table 5.

4.4 Ultrasonic Pulse Velocity (UPV) and Compressive Strength (MPa) model 28 days curing

Based on the collected data from literature an exponential model was obtained to predict the compressive strength of concrete at 28 days of curing, as shown in Fig.(4). 218 sample of different properties was tested the value of compressive strength of concrete was varied between 27 MPa and 88.7 MPa, the compressive strength 63% of samples were less than 45 MPa, 22.5% of samples were between 45 MPa and 75 MPa, and 14.5% of samples were more than 75 MPa, with (R^2) 0.92, (RMSE) 4.705, the statistical analyses of compressive strength of concrete and (UPV) summarized in Table 3 and Table 4, respectively the model parameters summarized in Table 5.

4.5 Ultrasonic Pulse Velocity (UPV) and Compressive Strength (MPa) model 90 days curing

Based on the collected data from literature an exponential model was obtained to predict the compressive strength of concrete at age 90 days of curing, as shown in Fig.(5). 59 sample has tested the value of compressive strength of concrete was varied from 47 MPa to 91.2 MPa, from the histogram analysis 22% of data was less than 60 MPa, 25% of data was between 60 MPa and 80 MPa, 53% of the data of compressive strength was more than 80 MPa, with (R^2) 0.93, (RMSE) 3.3, the statistical analyses of compressive strength of concrete and (UPV) summarized in Table 3 and Table 4, respectively the model parameters summarized in Table 5.

4.6 Ultrasonic Pulse Velocity (UPV) and Compressive Strength (MPa) model (120) days curing

Based on the collected data from literature an exponential model was obtained to predict the compressive strength of concrete at 90 days of curing, as shown in Fig.(6). 10 sample was tested the value of compressive strength of concrete was varied from 27.4 MPa to 54.6 MPa, From histogram analysis 30% of mix compressive strength less than 35 MPa, 40% of samples compressive strength was between 35 MPa and 45 MPa, 30% of data more than 45 MPa, with (R^2) 0.83, (RMSE) 3.35, the statistical analyses of compressive strength of concrete and (UPV) summarized in Table 3 and Table 4, respectively the model parameters summarized in Table 5.

4.7 Ultrasonic Pulse Velocity (UPV) and Compressive Strength (MPa) model 7, 28, 90, and 120 days curing

Based on the collected data from literature an exponential model was obtained to predict the compressive strength of concrete at different age 7, 28, 90 and 120 days of curing, as shown in Fig.(7). 327 Mix of different properties were tested the value of compressive strength of concrete was varied from 20 MPa to 91.2 MPa, and 47% of the samples compressive strength was less than 45 MPa, 30% of the samples compressive strength were between 45 and 75 MPa, and 23% of samples were more than 75 MPa. with (R^2) 0.93, (RMSE) 4.97, the statistical analyses of compressive strength and (UPV) summarized in Table 3 and Table 4 respectively, the model parameters summarized in Table 5.

4.8 Ultrasonic Pulse Velocity (UPV) and Compressive Strength (MPa) model 7, 28, 90, and 120 days curing

Based on the collected data from literature an exponential model was obtained to predict the compressive strength of concrete at different age 7, 28, 90 and 120 days of curing, as shown in Fig.(8). 198 Mix of different properties was tested the value of compressive strength of concrete was varied from 23 MPa to 91.2 MPa, From the histogram analysis shown that 46% compressive strength of samples were less than 45 MPa, 31% of samples strength were between 45 and 75 MPa, and 23% of compressive strength data were more than 75 MPa. with (R^2) 0.98, (RMSE) 2.76, the statistical analyses of compressive strength and (UPV) summarized in Table 3 and Table 4 respectively, the model parameters summarized in Table 5.

4.9 Ultrasonic Pulse Velocity (UPV) and Compressive Strength (MPa) model 1, 3, 7, 28, 90, and 120 days curing

Based on the collected data from literature an exponential model was obtained to predict the compressive strength of concrete at different age 1, 3, 7, 28, 90and 120 days of curing, as shown in Fig.(9). 502 sample of different mix proportion was tested the value of compressive strength of concrete was varied from 2.4 MPa to 91.2 MPa, 10% of sample compressive strength less than 25 MPa, 75% of the sample compressive strength between 25 and 75 MPa, and 15% was more than 75 MPa. with (R^2) 0.72, (RMSE) 11.13, the statistical analyses of compressive strength and (UPV) summarized in Table 3 and Table 4 respectively, the model parameters summarized in Table 5.

4.10 Ultrasonic Pulse Velocity (UPV) and Compressive Strength (MPa) model 1, 3, 7, 28, 90, and 120 days curing

Based on the collected data from literature an exponential model was derived to assess the compressive strength of concrete at different age 1, 3, 7, 28, 90and 120 days of curing, as shown in Fig.(10). 438 Mix of different properties in term of different (Water/Cement ratio, density, aggregate, cement content) was tested the value of compressive strength of concrete was varied between 2.4 MPa to 91.2 MPa, from the statistical analysis observed that 71% of sample compressive strength between 25 and 75 MPa, and 17% of samples were more than 75 MPa, and 12% were less than 25 MPa. with coefficient of determination (R^2) 0.86, (RMSE) 8.12, the statistical analyses of compressive strength and

(UPV) summarized in Table 3 and Table 4 respectively, the model parameters summarized in Table 5.

4.10 Ultrasonic Pulse Velocity (UPV) and Density (Kg/m^3) model

Based on the collected data from literature an exponential model was derived to predict the density of concrete at age 28 days of curing, as shown in Fig.(11). 90 Mix was tested the value of density was varied from 1458 (Kg/m^3) to 2430 (Kg/m^3), with (R^2) 0.86, (RMSE) 33.98, the statistical analyses of density and (UPV) summarized in Table 7 and Table 8 respectively, the model parameters summarized in Table 6.

Conclusions

This study was done to find a correlation between Ultrasonic Pulse Velocity (UPV) and Compressive Strength of concrete, from the data collection in literature and statistical analyses, the following conclusion can be written.

1- Generally the compressive strength of concrete increased with increasing the value of Ultrasonic Pulse Velocity.

2- The correlation between (UPV) and Compressive Strength for 1 day curing is more accurate (R^2 = 0.975) comparing with the other age of curing 3, 7, 28, 90, and 120 days separately.

3- The correlation for each age of concrete 1, 3, 7, 28, 90, and 120 days of curing derived, with R^2 = 0.975, 0.966, 0.93, 0.922, 0.932, and 0.83 respectively.

4- The correlation for different age of curing 7, 28, 90, and 120 derived with R^2 = 0.981 based on 198 collected data, the result from this mode obtained more accurate.

5- The correlation for different age of curing 7, 28, 90, and 120 derived with R^2 = 0.938 based on 327 collected data from literature.

6- The correlation between (UPV) and compressive strength of concrete derived from 1 day curing to 120 days curing for different (water/cement ratio, aggregate, sand, density). Based on 438 sample with R^2 = 0.863. It can predict the compressive strength of concrete at any age by using this equation.

7- The correlation between (UPV) and compressive strength of concrete derived from (1 day) curing to 120 days curing. Based on 502 sample with R^2 = 0.722. It can predict the compressive strength of concrete at any age by using this equation. But the obtained result from this model was not accurate.

8- More reliable results obtained for certain age of concrete, if equations derived for that age of concrete used.

9- The correlation between the (UPV) and density of concrete at 28 days of curing derived, and from the results show that by increasing the values of (UPV) the density of the sample increase. This model derived based on 90 sample, with $R^2 = 0.86$.

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Table1. Literature review table on Ultrasonic Pulse Velocity (UPV) for predicting compressive strength of concrete

Reference	Fcu (Min-Max) (MPa)	Test UPV (Min-Max) (m/sec)	W/C	Curing (Day)	Equation	R^2	No. of Sample (No.)	Aggregate Maximum Size (mm)	Sand Maximum Size (mm)	Type of cement	Density Kg/m^3	Temperature °C	Remarks
[1] (2008)	25-39.7	2884-4522	--	Different Curing days	Fcu=0.008*UPV+0.928	**Not Available**	6	**Not Available**	**Not Available**	**Not Available**	**Not Available**	**Not Available**	**Linear correlation between (UPV) and (Fcu) obtained with different curing days**
[2] (2013)	23.25-52.65	4510-5080	(0.35 – 0.37-0.45-0.5)	28	$Fcu=1.19*e^{0.715\ UPV}$	**Not Available**	4	2 different type of Agg.	**Not Available**	OPC - PPC	**Not Available**	**Not Available**	**The exponential relation between (UPV) and (fcu) at (28) days curing was obtained using different W/C.**
[3] (2013)	28.1–81.8	3700-5200	0.3-0.65	28	Arlita: $Fcu=1.07*e^{0.92*UPV}$	0.82	74	Normal agg. And light weight agg.	**Not Available**	Different type of cement with (Flay Ash, Silica fume)	1631-2430	**Not Available**	**Three exponential relations were obtained, each one specified to a different content of (Silica fume, Flay Ash)**
					Leca: $Fcu=3*e^{0.63*UPV}$	0.82						**Not Available**	
					Argex: $Fcu=1.65*e^{0.7*UPV}$	0.82						**Not Available**	
					Normal Agg: $Fcu=0.023*e^{1.6*UPV}$	0.88						**Not Available**	
[4] (2013)	59-91.2	4950 - 5610	0.37-0.38-0.39	7–28 - 90	$Fcu = 2.8621* e^{0.6177x}$	0.9675	120	**Not Available**	**Not Available**	OPC (Using Steel Fiber, Polypropylene fiber, Super plasticizer fiber)	**Not Available**	**Not Available**	**Exponential correlation developed with different W/C, and using (steel fiber, polypropylene fiber, super plasticizer fiber) for each percent of these fiber also a relations were developed**
[5] (2015)	2.4-54.6	2720-4470	----	3–7-28-120	**Not Available**	**Not Available**	40	**Not Available**	**Not Available**	OPC- Using (Flay Ash , Slag)	**Not Available**	**Not Available**	
[6] (2016)	3.53-24.6	2650-4110	0.23–0.25–0.45	1	Mix-A: -28.69+10.94U	0.632	108	19-4,75 mm	According to ASTM C33	OPC- (Silica Fume , HRWR)	2309-2461	25	**Twelve linear relations were developed for (3) different type of mix, and with different days of curing (1,7,28, and 90)**
					Mix-C: -5.43+3.49U	0.236							
					Mix-D: -37.85+15.1U	0.872							
	24.75-51.68	2610-4230		7	Mix-A: -134+41.61U	0.568					2484-4410		
					Mix-C: 34.07+2.33U	0.496							
					Mix-D: 45.98+0.45U	0.005							
	36.3-64.48	2730-4350		28	Mix-A: -74.97+27.95U	0.417					2338-2478		
					Mix-C: 67.29-3.78U	0.282							
					Mix-D: 61.97-0.16U	0.00003							
	37.07-66.21	3930-4410		90	Mix-A: -98.28+33.89U	0.687					2325-2484		
					Mix-C: 118-15.08U	0.262							
					Mix-D: 34.74+6.39U	0.076							
[7] (2017)	23-57	3333-5231	Different water/cement ratio	28	Fcu = 0.0136*UPV-21.34	0.7	150	12-14-20	4.75	OPC	**Not Available**	**Not Available**	**Linear relation between UPV and Compressive strength of concrete at (28) days was observed**
Current Study	3.53–24.6	2650-4110	0.23 – 0.25 – 0.45	1	$Fcu = 0.296+ 0.0637* e^{0.00145\ UPV}$	0.975	27	19-4,75 mm	According to ASTM C33	OPC- (Silica Fume , HRWR)	2309-2461	**25**	
Current Study	2.4-27.9	2750-4060	Different water/cement ratio	3	$Fcu = 3.423+ 282E-7* e^{0.00336\ UPV}$	0.966	10						

Current Study	36-79.2	2610-5200	0.23 – 0.25 – 0.45	7	$Fcu = 42.6+ 59E\text{-}8 * e^{0.00344\,UPV}$	0.93	55						
Current Study	27-88.7	3333-5430	Different water/cement ratio	28	$Fcu = 32+ 572E\text{-}6 * e^{0.00213\,UPV}$	0.922	218						
Current Study	47-91.2	4090-5610	Different water/cement ratio	90	$Fcu = 53+ 799E\text{-}6 * e^{0.00192\,UPV}$	0.932	59						
Current Study	27.4-54.6	4070-4470	Different water/cement ratio	120	$Fcu = 0+ 494E\text{-}4 * e^{0.00157\,UPV}$	0.83	10						
Current Study	20-91.2	3333-5610	Different water/cement ratio	7-28-90-120	$Fcu = 13.59+ 691E\text{-}3 * e^{0.000851\,UPV}$	0.938	327						
Current Study	23-91.2	3370-5610	Different water/cement ratio	7-28-90-120	$Fcu = 2.77+ 2.304 * e^{0.00065\,UPV}$	0.981	198						
Current Study	2.4-91.2	2610-5610	Different water/cement ratio	1-3-7-28-90-120	$Fcu = 0.9+ 2.99 * e^{0.000607\,UPV}$	0.722	502						
Current Study	2.4-91.2	2610-5610	Different water/cement ratio	1-3-7-28-90-120	$Fcu = 44E\text{-}5+ 1.9 * e^{0.000688\,UPV}$	0.863	438						
Remarks	**The compressive strength range was between (2.4 – 91.2) MPa**	**Ultrasonic Pulse Velocity measurement varied between (2610 – 5610)**	**Water Cement Ratio Varied Between (0.23 – 0.65)**	**Curing time was between (1-120) days**	**Different type of equation was obtained, dependent value was (Fcu) and independent value was (UPV)**	**The Coefficient of determination of the equation was between (0.00003 – 0.9675)**	**Different number of sample was tested the range (4 – 150)**	**Different aggregate type and size was used**	**Different sand size used**	**Ordinary Portland Cement was used, with adding different percent of (Flay Ash, Silica fume,HRWR, Steel fiber, polypropylene fiber, super plasticizer fiber, slag)**	**The density of mixes was varied between (1631 – 4410) kg/m^3**	**Test was performed at the normal temperature 25 °C**	

Table 2. Summary of the Concrete Mix Properties

Reference	Fcu (Min-Max) (MPa)	Test UPV (Min-Max) (m/sec)	W/C	Curing (Day)	No. of Sample (No.)	Aggregate Maximum Size (mm)	Sand Maximum Size (mm)	Type of cement	Density Kg/m^3
[1]	25-39.7	2884-4522	--	Different Curing days	6	**Not Available**	**Not Available**	**Not Available**	**Not Available**
[2]	23.25-52.65	4510-5080	(0.35 – 0.37-0.45-0.5)	28	4	2 different type of Agg.	**Not Available**	OPC - PPC	**Not Available**
[3]	28.1 – 81.8	3700-5200	0.3-0.65	28	74	Normal Agg. And light weight Agg.	**Not Available**	Different type of cement with (Flay Ash, Silica fume)	1631-2430
[4]	59-91.2	4950 - 5610	0.37-0.38-0.39	7 – 28 - 90	120	**Not Available**	**Not Available**	OPC (Using Steel Fiber, Polypropylene fiber, Super plasticizer fiber)	**Not Available**
[5]	2.4-54.6	2720-4470	**Not Available**	3–7-28-120	40	**Not Available**	**Not Available**	OPC- Using (Flay Ash , Slag)	**Not Available**
[6]	3.53-24.6	2650-4110	0.23 – 0.25 – 0.45	1	108	19-4,75 mm	According to ASTM C33	OPC- (Silica Fume , HRWR)	2309-2461
	24.75-51.68	2610-4230		7					2484-4410

	36.3-64.48	2730-4350		28						2338-2478
	37.07-66.21	3930-4410		90						2325-2484
[7]	23-57	3333-5231	Different proportion water cement ration content	28	150	12-14-20	4.75	OPC	**Not Available**
Remarks	The compressive strength range was between (2.4 – 91.2) MPa	Ultrasonic Pulse Velocity measurement varied between (2610 – 5610)	Water Cement Ratio Varied Between (0.23 – 0.65)	Curing time was between (1-120) days	Different number of sample was tested the range (4 – 150)	Different aggregate type and size was used	Different sand size used	Ordinary Portland Cement was used, with adding different percent of (Flay Ash, Silica fume,HRWR, Steel fiber, polypropylene fiber, super plasticizer fiber, slag)	The density of mixes was varied between (1631 – 4410) kg/m^3

Table 3. Statistical Analysis of Ultrasonic Pulse Velocity for Different Days of Curing

Statistical Parameters	UPV* (1 Day)	UPV (3 Day)	UPV (7 Day)	UPV (28 Day)	UPV (90 Day)	UPV (120 Day)	UPV (7,28,90, and 120) Days	UPV (7,28,90, and 120) Days	UPV (1,3,7,28,90, and 120) Days	UPV (1,3,7,28,90, and 120) Days
No. of Data	27	10	55	218	59	10	327	198	502	438
Range	2650-4110	2720-4060	2610-5200	3333-5430	4090-5610	4070-4470	3333-5610	3370-5610	2610-5610	2610-5610
Mean (μ)	3328	3429	4670	4502	5063	4229	4598	4641	4454	4472
Std. Deviation (σ)	526	372	658	494	567	115	588	606	639	660
COV (%)	15.82	10.84	15.68	11.59	12.42	2.74	12.8	13.06	14.35	14.77

*UPV: Ultrasonic Pulse Velocity (m/s).

Table 4. Statistical Analysis of Compressive Strength for Different Days of Curing

Statistical Parameters	Comp. Strength (MPa) (1 Day)	Comp. Strength (MPa) (3 Day)	Comp. Strength (MPa) (7 Day)	Comp. Strength (MPa) (28 Day)	Comp. Strength (MPa) (90 Day)	Comp. Strength (MPa) (120 Day)	Comp. Strength (MPa) (7,28,90, and 120) Days	Comp. Strength (MPa) (7,28,90, and 120) Days	Comp. Strength (MPa) (1,3,7,28,90, and 120) Days	Comp. Strength (MPa) (1,3,7,28,90, and 120) Days
No. of Data	27	10	55	218	59	10	327	198	502	438
Range	3.53-24.6	2.4-27.9	36-79.2	27-88.7	47-91.2	27.4-54.6	20-91.2	23-91.2	2.4-91.2	2.4-91.2
Mean (μ)	11.12	8.8	59.66	47	73.77	39.32	52.84	54.15	48.136	47.4
Std. Deviation (σ)	8.17	7.13	12.77	16.91	12.9	8.57	19.92	19.94	21.130	22.03
COV (%)	73.48	81.06	38.03	35.96	22.79	21.81	37.7	36.83	43.90	46.47

Table 5. Model Parameters for Compressive Strength for Different Days of Curing

Depended Variable (Y-axis)	In depended Variable (X-axis)	Z	A	B	RMSE	R^2	No. of Data	Fig. No.	Curing (Days)
Compressive Strength (MPa)	Ultrasonic Pulse Velocity (UPV)-(m/s)	0.296	0.0637	145E-5	1.276	0.975	27	1	1
Compressive Strength (MPa)	Ultrasonic Pulse Velocity (UPV)-(m/s)	3.423	282E-5	336E-5	1.256	0.966	10	2	3
Compressive Strength (MPa)	Ultrasonic Pulse Velocity (UPV)-(m/s)	42.646	59E-8	344E-5	3.36	0.93	55	3	7
Compressive Strength (MPa)	Ultrasonic Pulse Velocity (UPV)-(m/s)	32.013	572E-6	213E-5	4.705	0.922	218	4	28
Compressive Strength (MPa)	Ultrasonic Pulse Velocity (UPV)-(m/s)	53.726	799E-6	192E-5	3.3	0.932	59	5	90
Compressive Strength (MPa)	Ultrasonic Pulse Velocity (UPV)-(m/s)	0	0.0494	157E-5	3.353	0.83	10	6	120
Compressive Strength (MPa)	Ultrasonic Pulse Velocity (UPV)-(m/s)	13.59	0.691	851E-6	4.97	0.938	327	7	7, 28, 90, and 120
Compressive Strength (MPa)	Ultrasonic Pulse Velocity (UPV)-(m/s)	2.77	2.304	65E-5	2.763	0.981	198	8	7, 28, 90, and 120

Compressive Strength (MPa)	Ultrasonic Pulse Velocity (UPV)-(m/s)	0.9	2.99	607E-6	11.139	0.722	502	9	1, 3, 7, 28, 90, and 120
Compressive Strength (MPa)	Ultrasonic Pulse Velocity (UPV)-(m/s)	44E-5	1.984	688E-6	8.128	0.863	438	10	1, 3, 7, 28, 90, and 120

Table 6. Model Parameters for Density (Kg/m^3) of Different Mix Proportion

Depended Variable (Y-axis)	In depended Variable (X-axis)	Z	A	B	RMSE	R^2	No. of Data	Fig. No.	Curing (Days)
Density (Kg/m^3)	Ultrasonic Pulse Velocity (UPV)-(m/s)	7.32	599.5	2.7E-4	33.98	0.86	90	11	28

Table 7. Statistical Analysis of Density of Concrete

Statistical Parameters	Density (Kg/m^3)
No. of Data	90
Range	1458-2430
Mean (μ)	1969
Std. Deviation (σ)	222.4
COV (%)	11.29

Table 8. Statistical Analysis of (UPV) for Density

Statistical Parameters	UPV (28 Day)
No. of Data	90
Range	3500-5200
Mean (μ)	4341
Std. Deviation (σ)	380
COV (%)	8.77

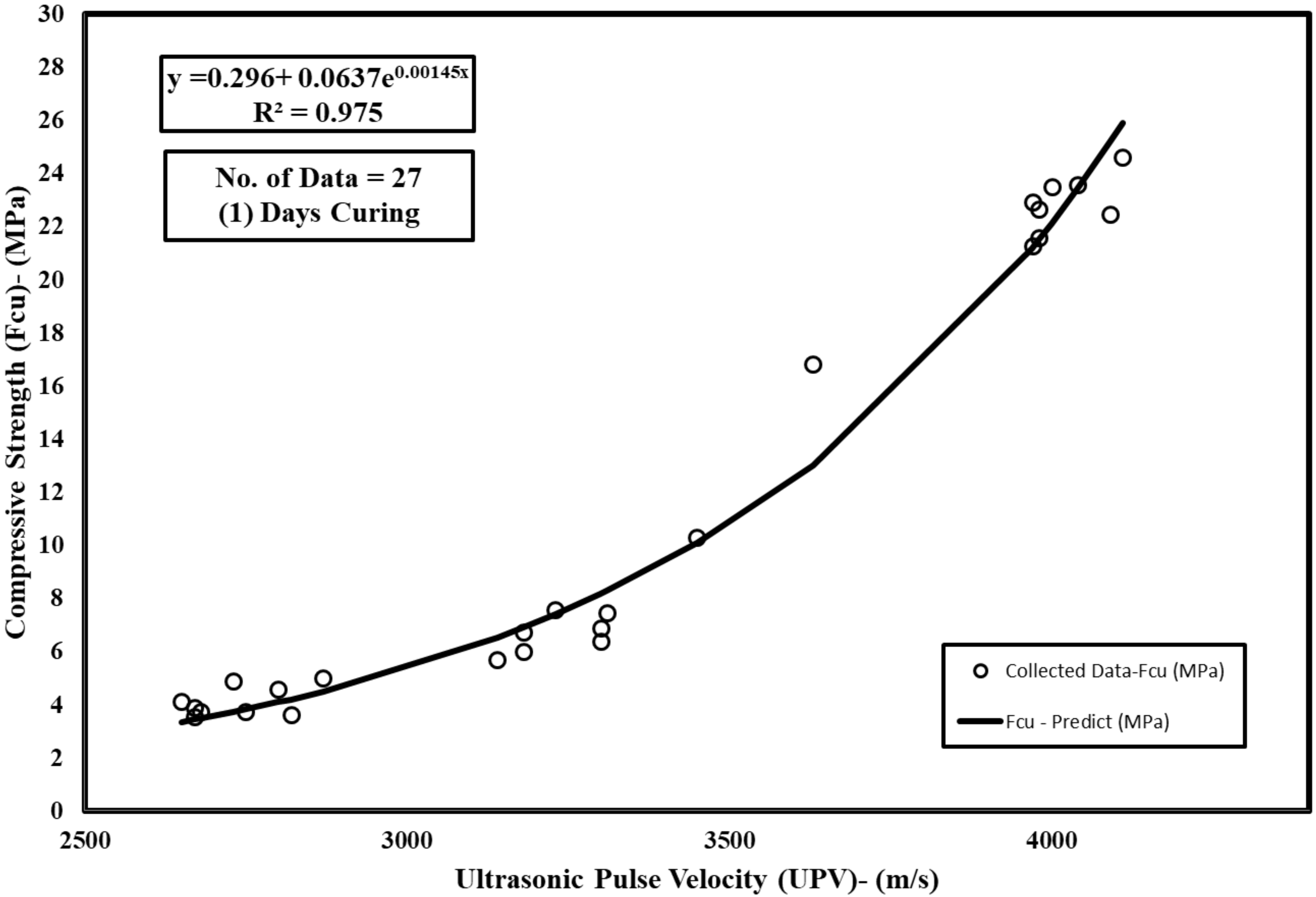

Figure 1- UPV V.S Compressive Strength (1) day curing

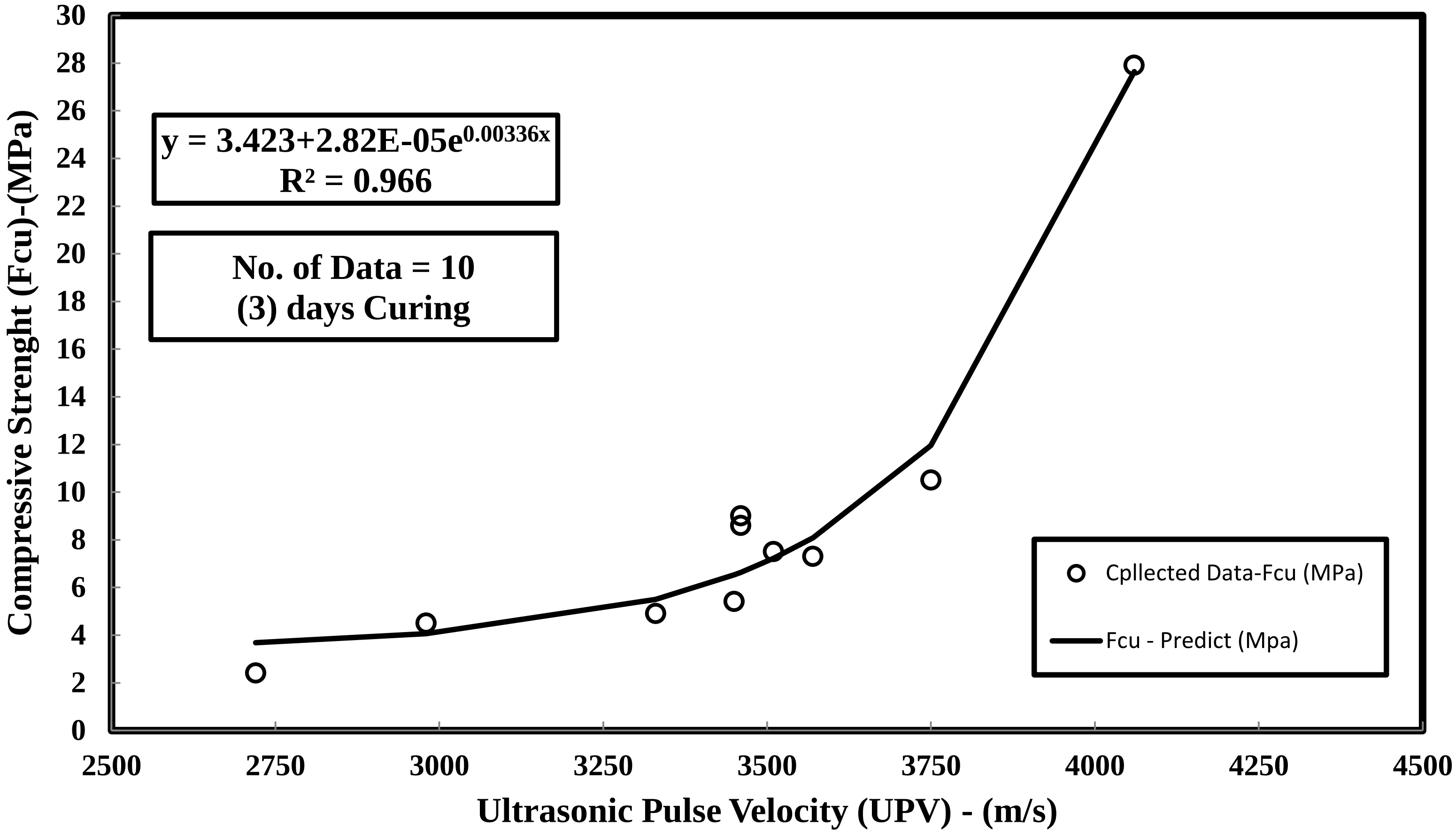

Figure 2- UPV V.S Compressive Strength (3) day curing

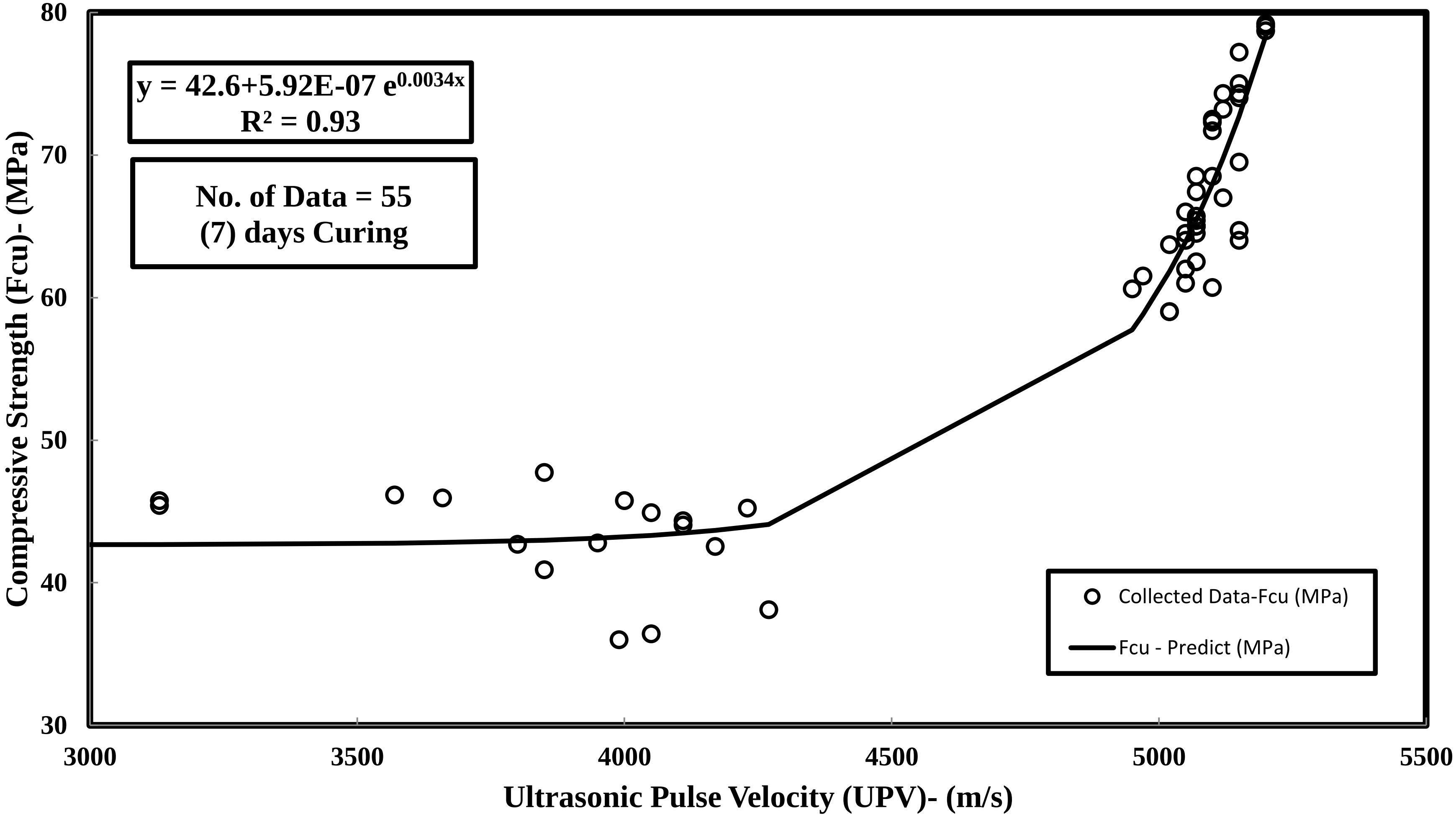

Figure 3- UPV V.S Compressive Strength (7) day curing

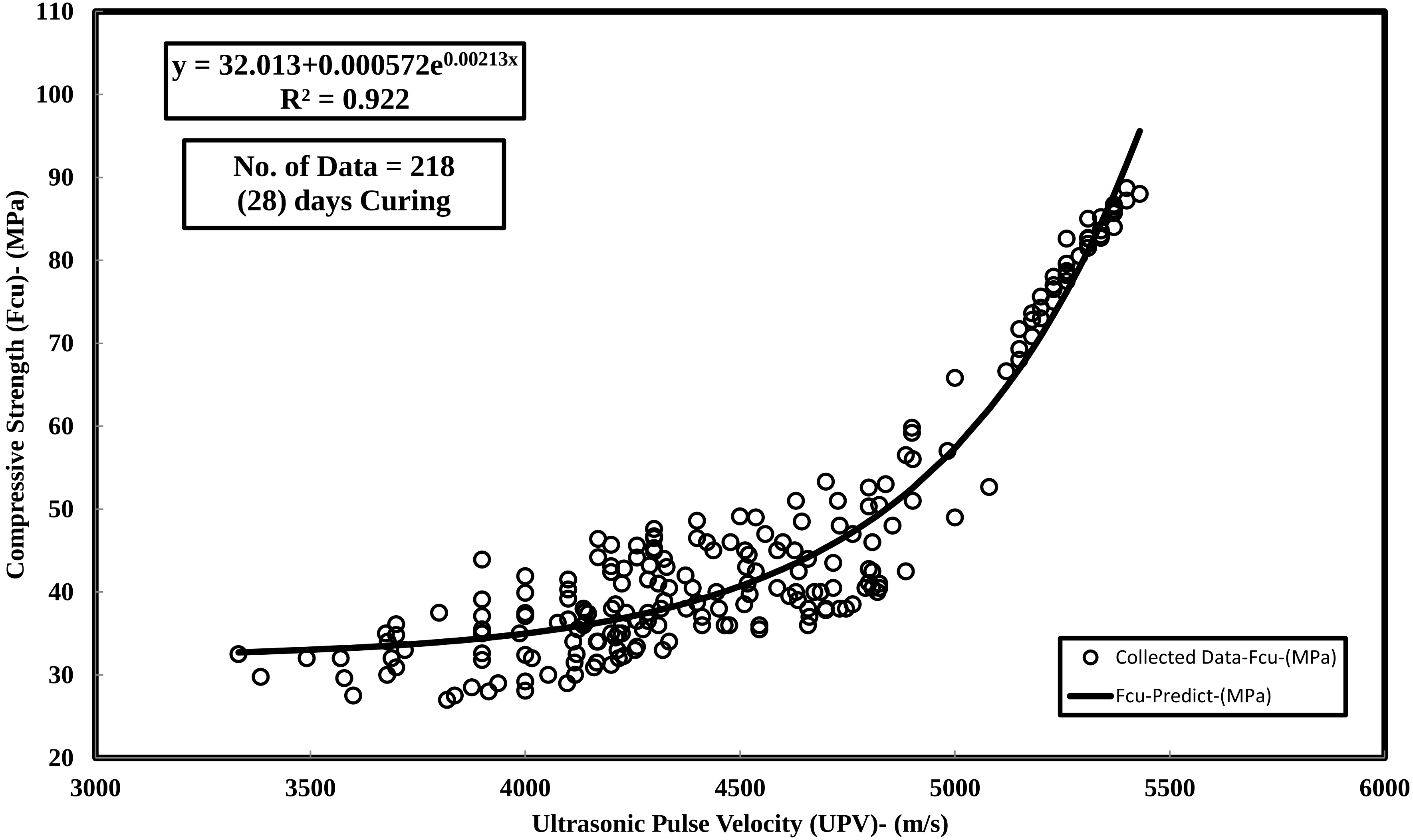

Figure 4- UPV V.S Compressive Strength (28) day curing

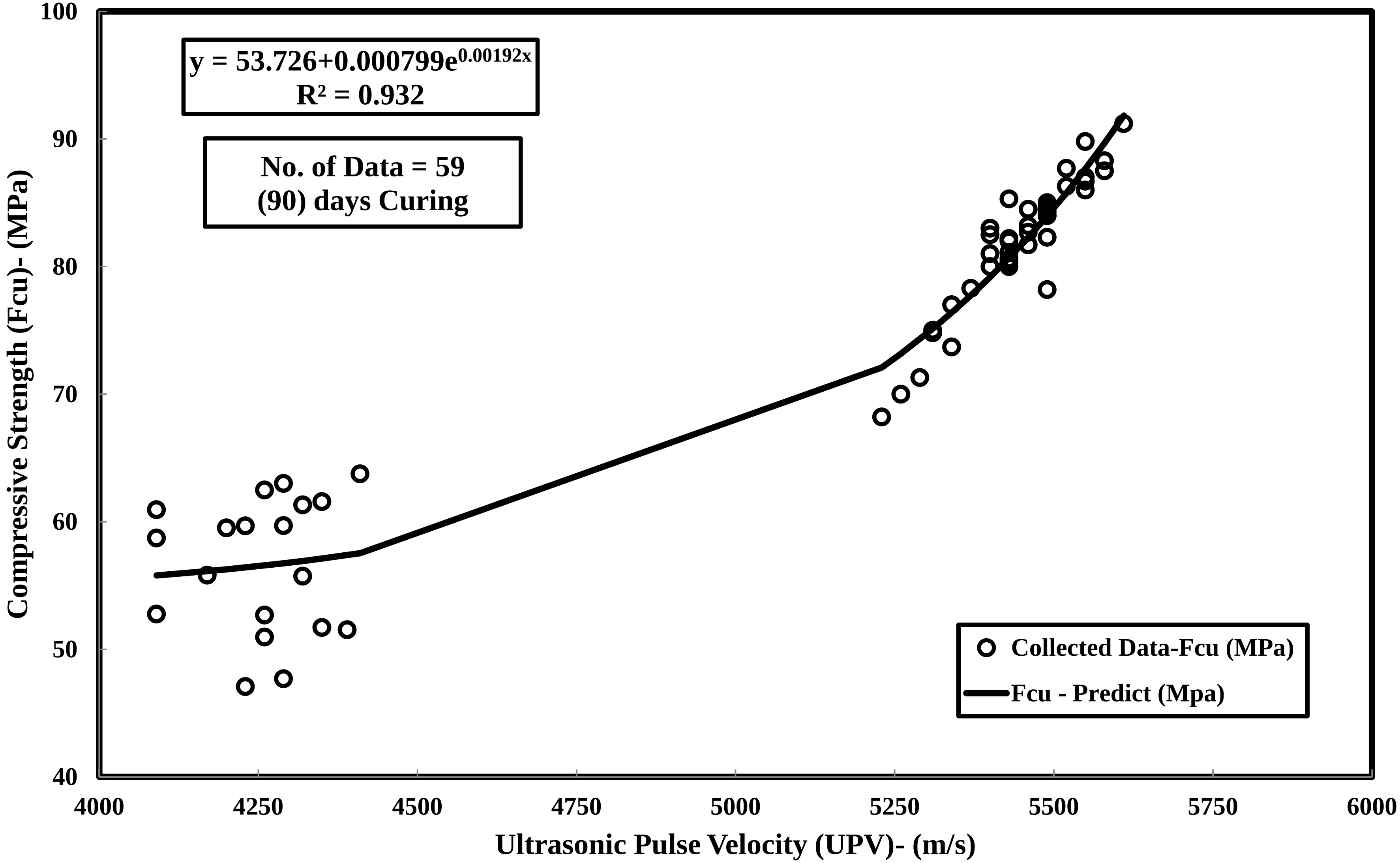

Figure 5- UPV V.S Compressive Strength (90) day curing

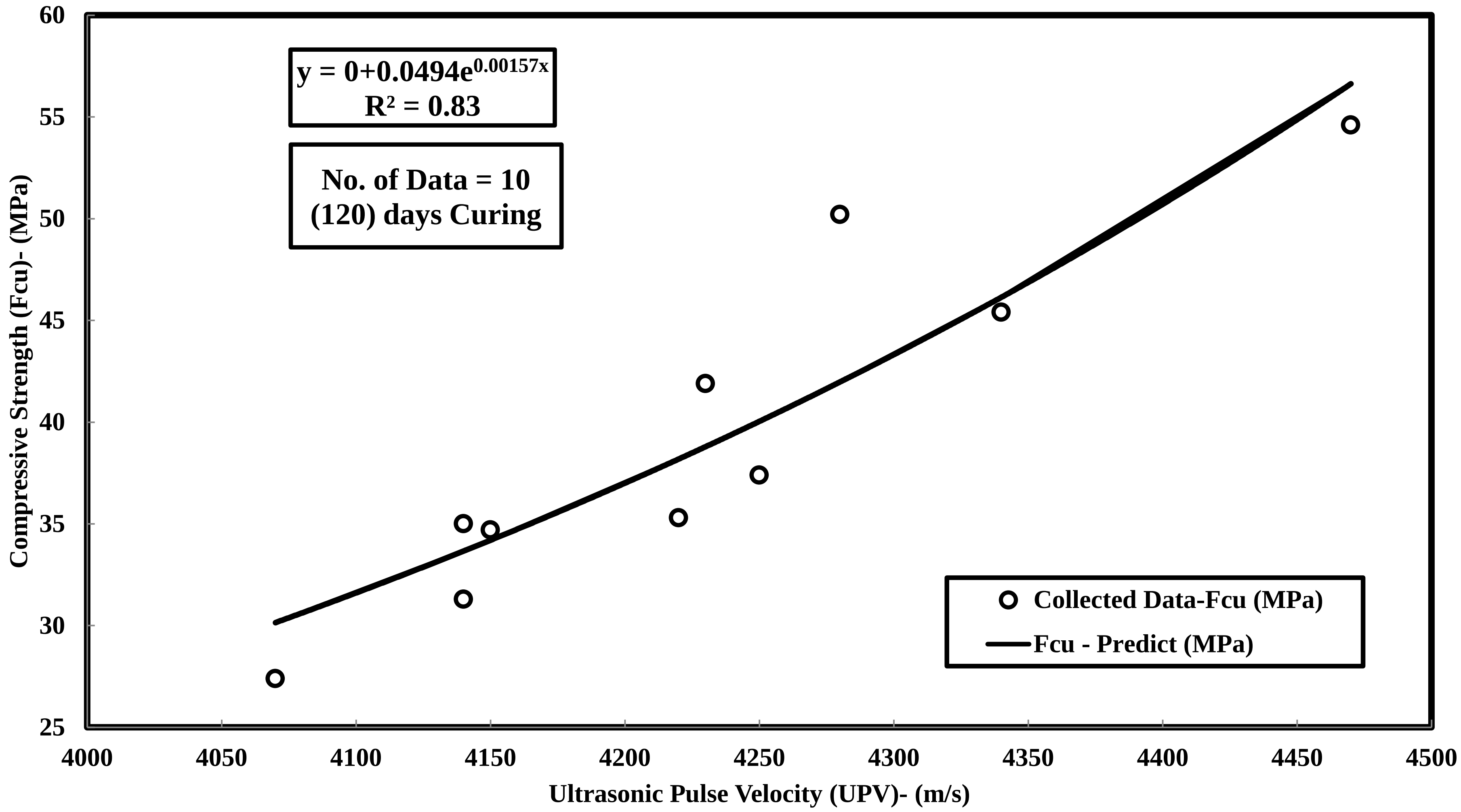

Figure 6-UPV V.S Compressive Strength (120) day curing

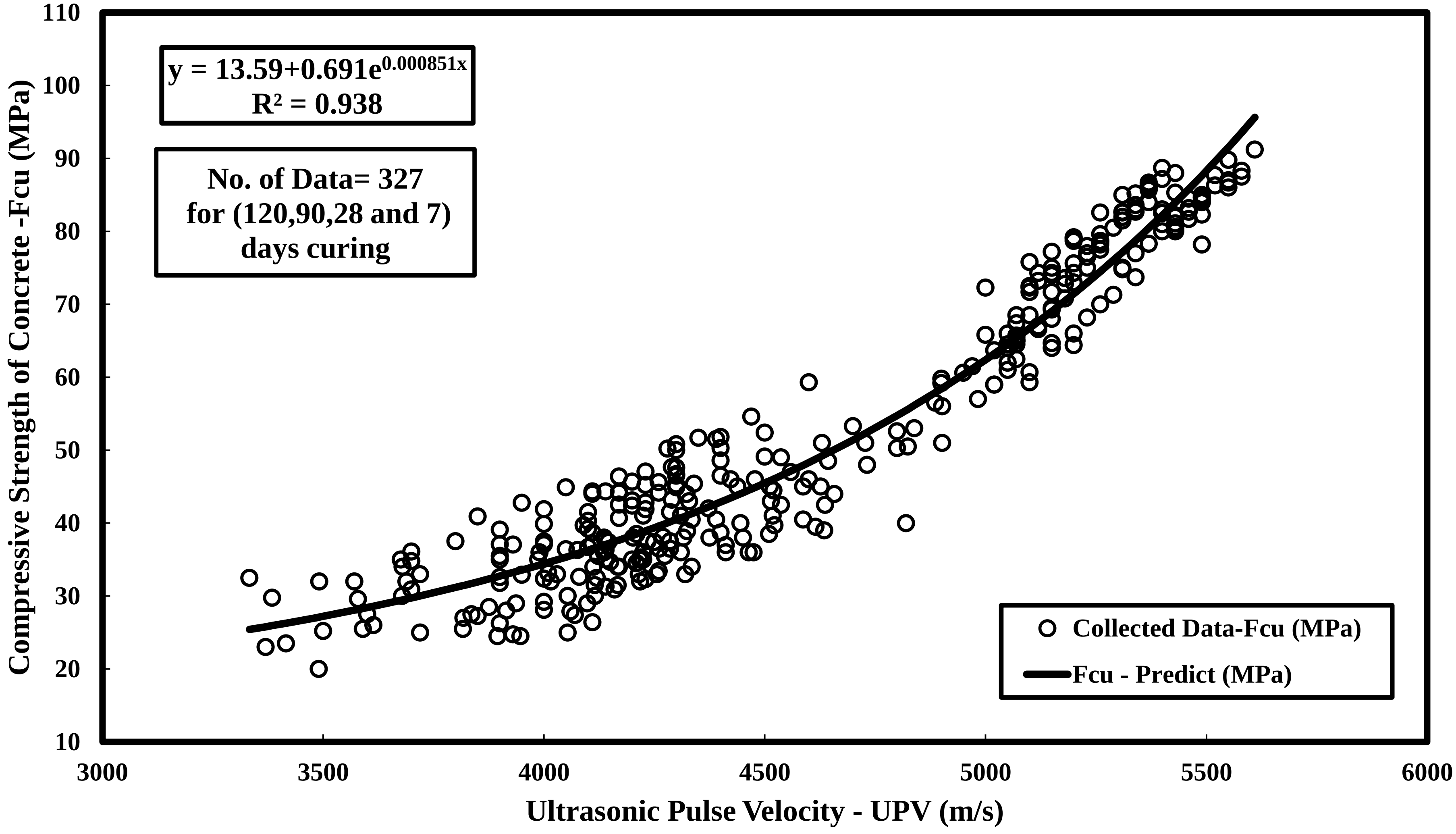

Figure 7-UPV V.S Compressive Strength (7, 28, 90, and 120) days curing

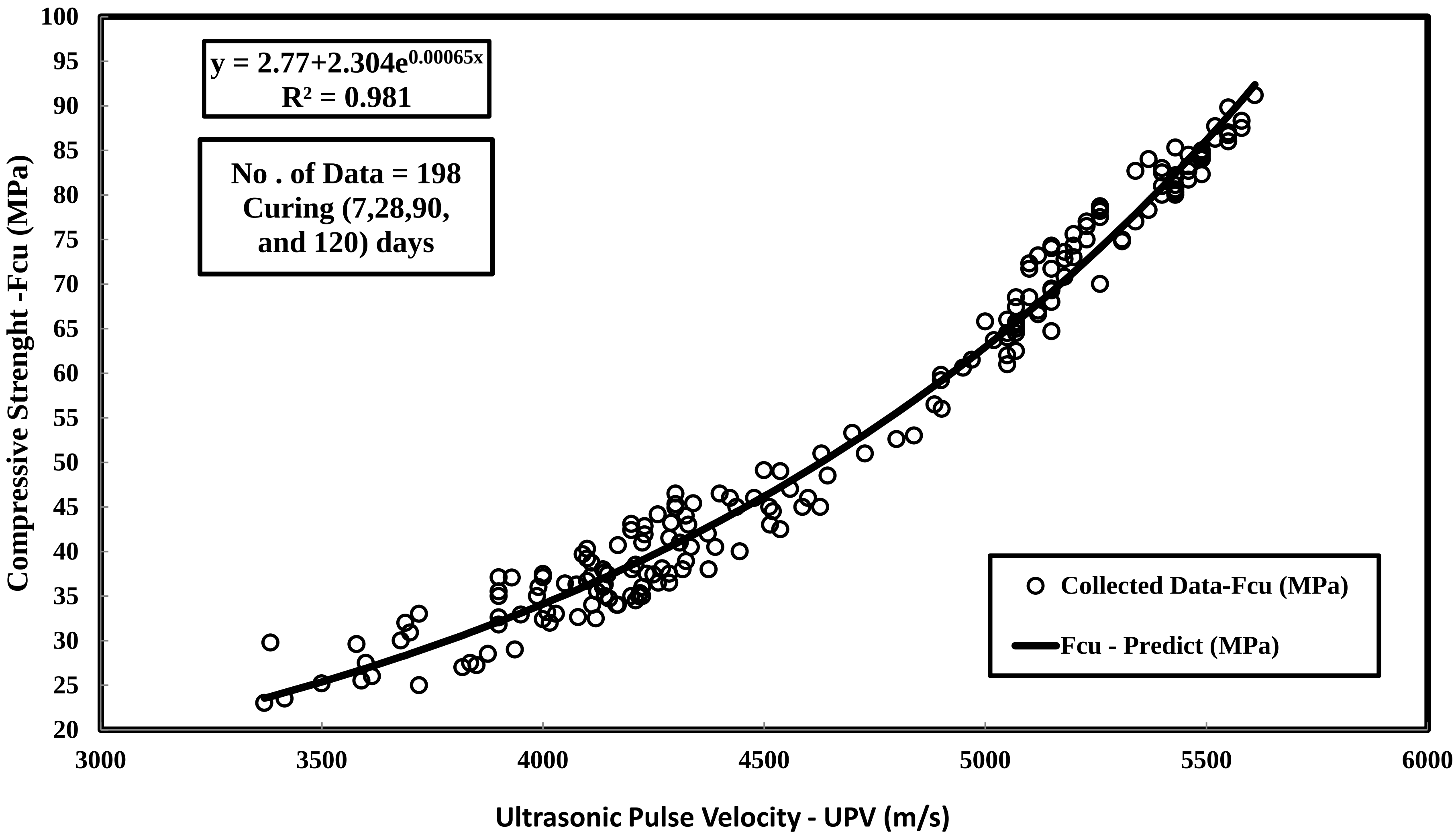

Figure 8-UPV V.S Compressive Strength (7, 28, 90, and 120) days curing

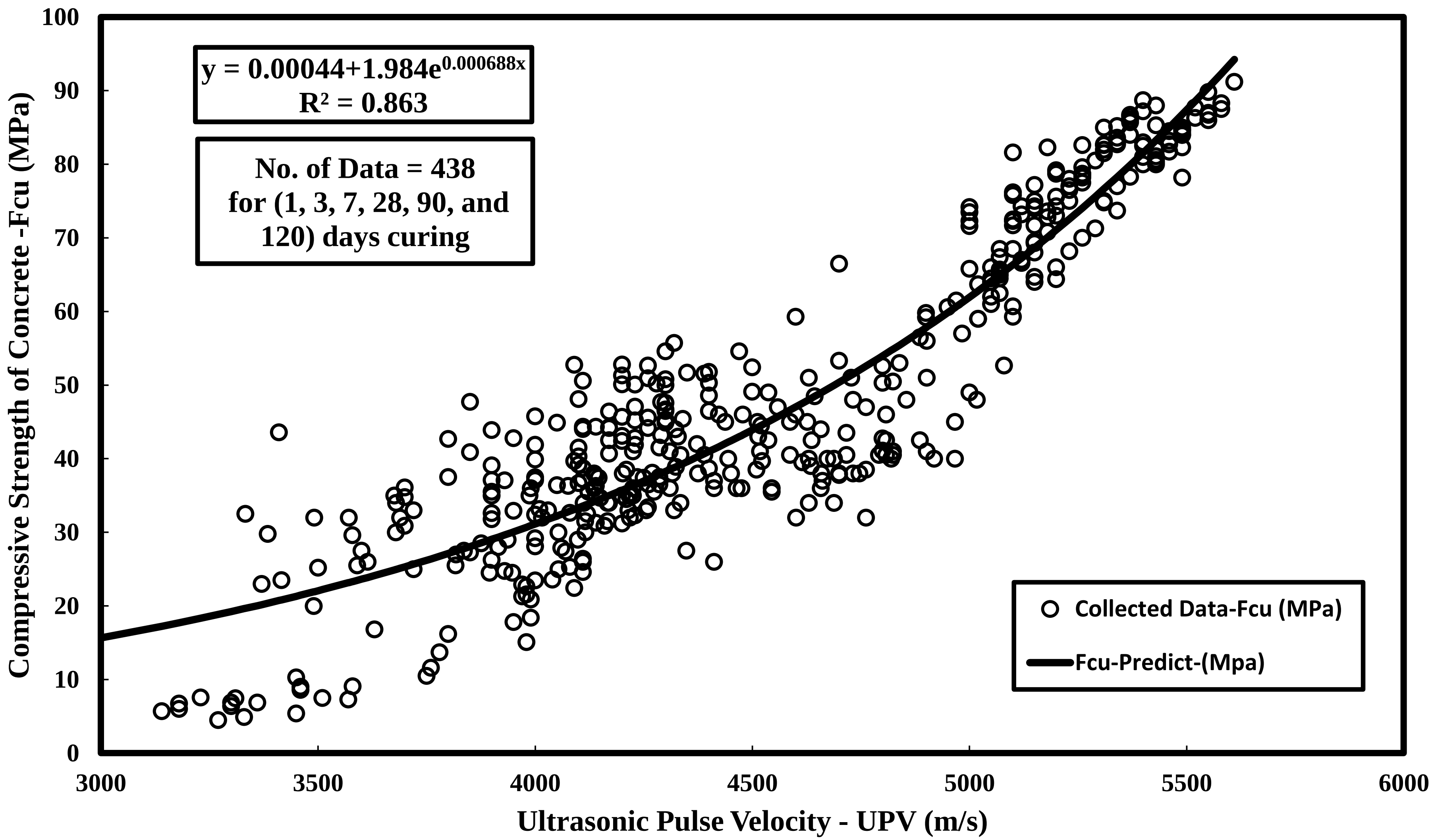

Figure 9- UPV V.S Compressive Strength (1, 3, 7, 28, 90, and 120) days curing

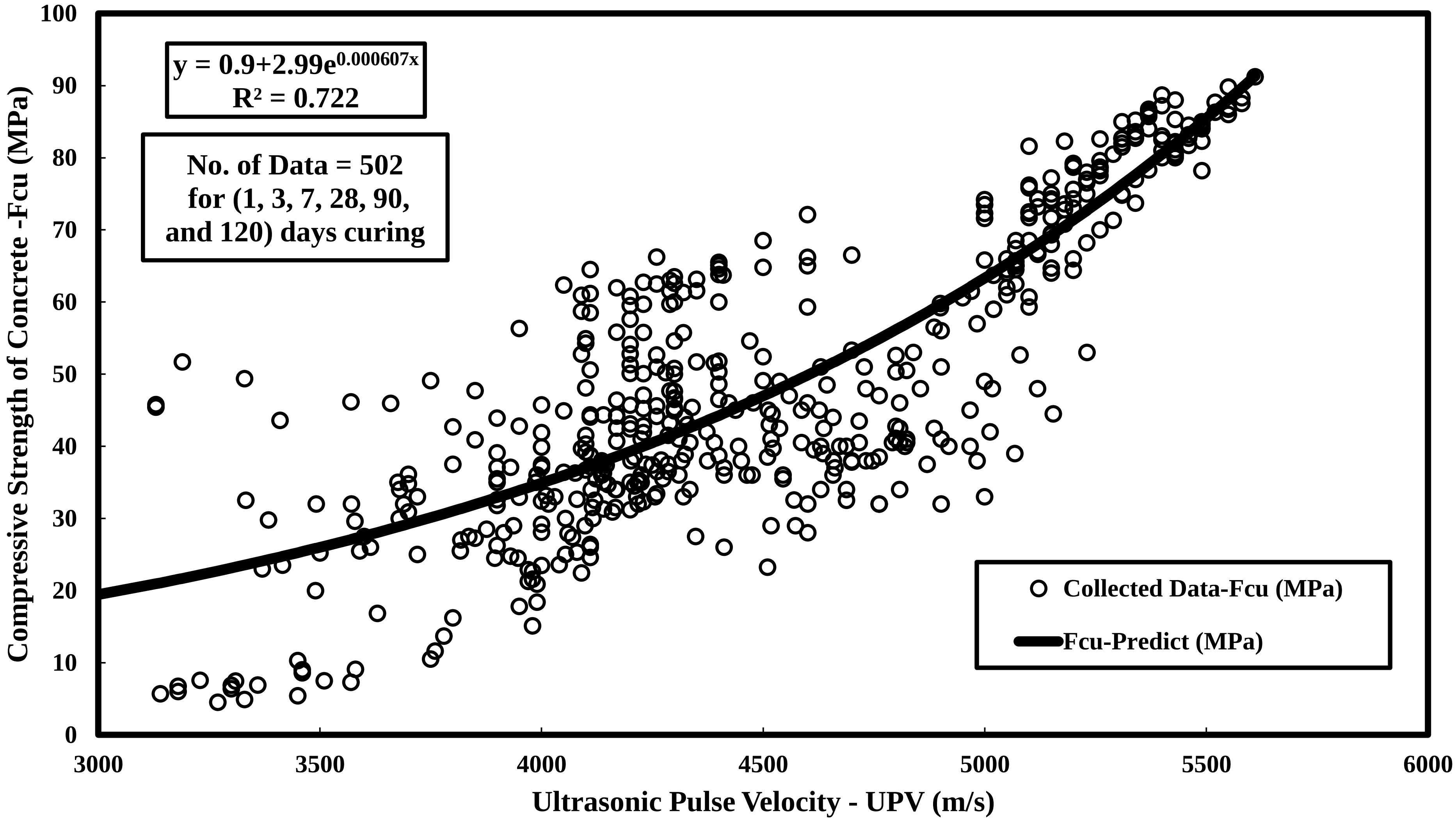

Figure 10-UPV V.S Compressive Strength (1, 3, 7, 28, 90, and 120) days curing

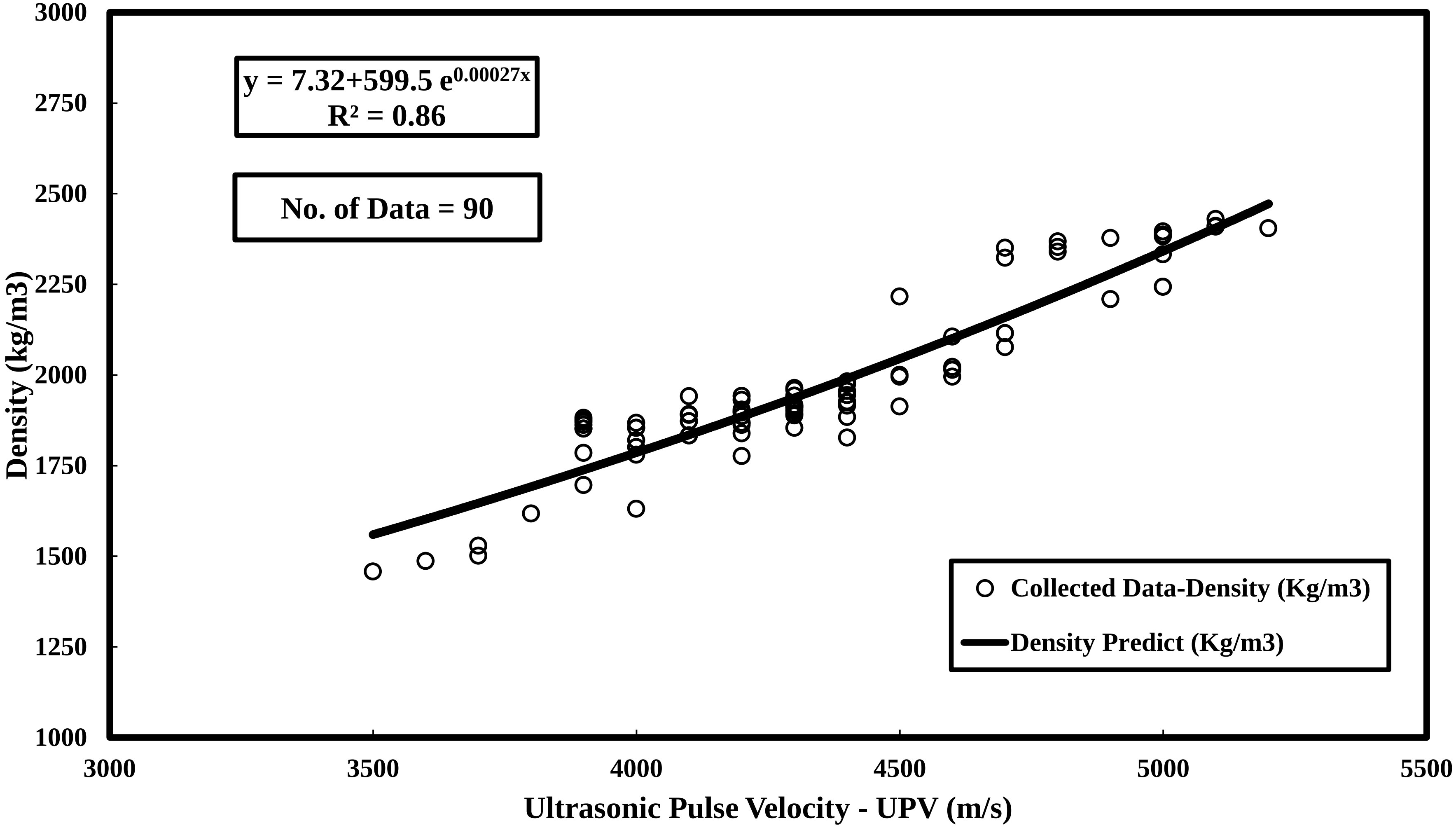

Figure 11- UPV V.S Density (Kg/m3)

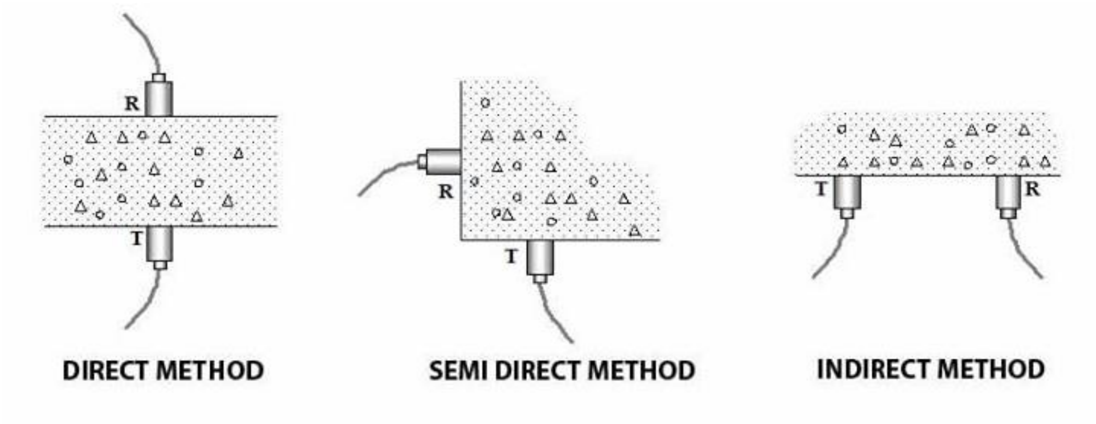

Figure 12- Ultrasonic Pulse Velocity Test – Type of the Test According to the Location