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# Predicting the Compressive Strength of Concrete By Ultrasonic Pulse Velocity

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**Abstract.** The key resolution of non-destructive methods applied to concrete structures is to offer a suitable estimate of the quality of the material. One of the modern methods used in the test of concrete strength is the non-destructive testing applying the ultrasonic pulse velocity (UPV). In this study, the ultrasonic pulse velocity technique as non-destructive testing of concrete was used to distinguish concrete mixture design and show the predictive relationship between compressive strength and UPV. The effect of various grades of concrete (M15, M20, M25, M30, and M35) with water to cement ratio (w/c) of 0.45 and 0.5 were examined. It was observed that grade M15 cubes had the lowest transit time (37.6 – 41.2  $\mu$ s) and grade M35 cubes had the highest transit time (48.7 – 49.9  $\mu$ s) showing that the concrete with short transit time generates the highest pulse velocity than that with low transit time. Grade M15 cubes had the highest pulse velocity (3.6 – 4.0 km/s) and grade M35 cubes had the lowest pulse velocity (3.0 – 3.1 km/s). M15 cubes had the lowest actual compressive strength (18.1 – 19.3 N/mm<sup>2</sup>) and grade M35 cubes have the highest actual compressive strength (34.6 – 36.0 N/mm<sup>2</sup>). There was a good correlation between compressive strength and UPV. The study furthermore revealed that UPV can be used to accurately predict the compressive strength of concrete. For all concrete grades, the percentage variation did not exceed  $\pm 2.5\%$ .

## 1. Introduction

The use, strength and safety of concrete are determined by the characteristic strength [1-4]. Each structural element has its quality strength that determines its life and usage. Compressive strength is one of the valuable factors in concrete construction and it is dependent on other factors. One of the techniques used in assessing the strength of existing structures and durability is non-destructive testing (NDT) [5]. The ultrasonic pulse velocity method is a dynamic method that measures the time of travel of pulse generated by cracks and shock [6].

The development of UPV (ultrasonic pulse velocity) began in England and Canada [7], to the stage of laboratory research where it passed to the application on-site, to become an essential tool for non-destructive testing. Acoustic methods with visual inspection are the oldest form of non-destructive testing [8]. Cracks, voids and delamination are detected through sound. In 1920, Russian scientist Sergi Y. Sokolov Institute of Electrical Leningrad in the USSR was the first who proposed to use the ultrasonic wave velocity. However, until 1942 that the real progress was made NDT Resource Centre (the University of Michigan by Sproule in England). It was in the early 1970s with the improvement of



technology, the onset of the fracture mechanics and development of new law that a real significant change occurs in the field of non-destructive testing [7].

The excitation that is employed in the receiver is shocked by the waves which are generated by piezoelectric crystals as applicable in the case of ultrasonic testing of concrete [9]. The broadcasters encountered in the path of these waves causes diffusion and diversion in that exist as dissipation of heat of heat. This is due to the viscosity of the material. The waves also get modified in speed and this is likely because of the attenuation of the waves through the several processes undergone [10]. The diffusion that take place in the process of this wave propagation is always caused through sand grains, cracks, reinforcement bars or micro-cracks. The principle binding in the emission of these waves frequencies makes the transference of beam energy to coherent waves possible and these include backscattered and incoherent waves. The principle adopted in this process aids the determination of the non-uniform characteristics of the concrete through the measurement of the velocities of the waves. The adoption of this principle also helps in structural crack detection [11]. It can also be used to determine the coefficient of elasticity or Poisson coefficient.

Since there can be no direct measurement of the strength properties and quality of concrete without destructive stress (compressive, flexural and tensile), non-destructive methods have been developed for the assessment [12, 13]. Ultrasonic pulse shows potential for concrete in-situ testing by measuring the speed of ultrasound through materials. It measures the high frequency of ultrasonic pulse through concrete member between the transducers. High pulse reading is the quality of good concrete. Fairly good correlation is obtained between cubes compressive strength and pulse velocity. It enables structural concrete to be predicted within 20% if the aggregate mix is constant [14]. The test can be carried out on both laboratory size specimen and completed concrete structures.

Yılmaz and Ercikdi [15] used UPV to determine the strength in cemented paste in backfill. Wang and Wang [16] reported the use of UPV in self-consolidating waste glass concrete had an increase in strength due to the age and a decrease as the water/binder increases. Al-Nu'man et. al [17] a compressive strength formula for a single grade of concrete using ultrasonic pulse velocity. Shariati et. al [18] utilised UPV and Schmidt rebound hammer as non-destructive tests for evaluating the compressive strength of reinforced concrete. Quite recently, Fatahi and Jafari [19] studied the prediction of compressive strength for lightweight aggregate concrete. Also recently, the effects of the water-to-cement (W/C) ratio, curing conditions and aggregate were experimentally examined by Lee and Lee [20] based on early-stage direct transmission UPV.

This study is a continuation of these lines of investigation. In this study, the ultrasonic pulse velocity technique as non-destructive testing of concrete was used to distinguish concrete mixture design and show the predictive relationship between compressive strength and UPV. Besides the evaluation of cement properties and concrete flow properties, the effect of various grades of concrete with water to cement ratio was examined.

## **2. Materials and Method**

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### *2.1. Materials*

A natural aggregate of both fine and coarse aggregate was used in this study. The fine aggregate used was sharp-sand cleaned, air-dried, sieved with 5 mm sieve and free from waste and larger aggregate. The coarse aggregate used was crushed granite. Sieve analysis was carried out on both aggregates to know their size distribution. The cement used was ordinary Portland cement (Dangote 3x cement) with an initial setting time of 110 minutes, final setting time of 280 minutes, soundness of 0.2, fines of 5% and standard consistency of 37.5%. The water was clean and free from chemical, oil and other impurities.

### *2.2. Concrete Mixes*

The constituent shown in Table 1 were used to make the concrete mix at varying concrete grade as seen in Table 2. The fresh test was carried out on the varying grades and the mix was used to cast 15

concrete cubes specimen which was used in this study. The varying concrete mix proportion was used according to BS EN 206-1. Each strength of cube range from 15 – 35 MPa and UPV ranges from 3 – 4.5 km/s the mixes were cast in wood cube mould of 150 mm by 150 mm by 150 mm for approximately 24 hours then cured for 28 days before the test was carried out.

**Table 1.** Concrete constituent quantity and water-cement ratio

Grade/Constituents	15 MPa	20 MPa	25 MPa	30 MPa	35 MPa
Cement (kg)	2.552	3.003	3.6435	4.641	6.379
Fine Aggregates (kg)	7.656	7.5075	7.287	6.962	6.379
Coarse Aggregates (kg)	15.312	15.015	14.574	13.923	12.76
Water (kg)	1.276	1.5024	1.8218	2.089	2.871
W/C Ratio	0.5	0.5	0.5	0.45	0.45

**Table 2.** Grade designation and velocity criteria

Mix	Concrete Grade	Ratio	Pulse Velocity (km/sec)	Concrete Quality Grade
1	15	1: 3: 6	Above 4.5	<i>Excellent</i>
2	20	1: 2.5: 5	3.5 – 4.5	<i>Good</i>
3	25	1: 2: 4	3.0 – 3.5	<i>Medium</i>
4	30	1: 1.5: 3	Below 3.0	<i>Doubtful</i>
5	35	1: 1: 2	-	-

### 2.3. Fresh and Hardened Concrete Tests

The slump tests (Abrams cone) were conducted on fresh samples of each grade mix respectively according to the EN 12350-2 (2000) [21]. The hardened concrete test was conducted: compressive strength-EN 12390-3 (2003) [22], ultrasonic pulse velocity-BS 1881 (1986): part 203 [23].

### 2.4. Ultrasonic Pulse Velocity Method

The ultrasonic pulse velocity technique as non-destructive testing of concrete was used to distinguish concrete mixture design and show the predictive relationship between compressive strength and UPV. This was done in accordance with BS 1881 (1986): part 203.

## 3. Results and Discussion

### 3.1. Cement Properties

For the fineness of cement, three samples of the same weight (100 g) and was sieved exhaustively with a sieve of size 90 micron. It was observed the % weight of residue of each sample do not exceed 10% which makes the cement fineness for each sample moderate. The results obtained are summarized in Table 3.

**Table 3.** Summary of results for the fineness of cement

Samples	A	B	C
Weight of cement (g)	100	100	100
Size of sieve (micron)	90	90	90
Time (minutes)	15	15	15
Weight of retained sample (g)	70	58	83
% weight of residue	0.7	0.58	0.83

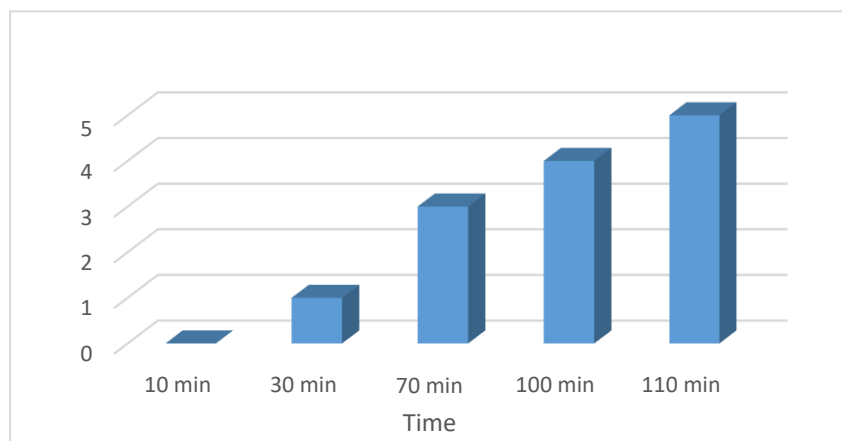
For the soundness of cement, it was observed that the distance of the indicator before submerging to boiling is 45 mm and distance after boiling and cooling is 46.5 mm. The difference in distance between both periods turns out to be moderate (1.5 mm) which does not exceed 10 mm. It was also

observed that the standard consistency of the ordinary Portland cement (OPC) used was in range with normal consistency of OPC which is within the range of 26 – 33% according to IS:4031 (Part 4):1988. And also, the standard consistency result made water content for other tests like initial and final setting time achievable.

Specific gravity defines that the substance is how much heavier than water or reference substance of the same volume [24]. The observation was made that the specific gravity of the cement used is 2.72 times heavier than water, and it is also less than 3.15 g/cc which is the range for specific gravity of Portland cement. It was observed that the weight of cement for grade M35 was the highest and this was due to the mix design specified for the grade. M15 had the highest value in weight for fine aggregate and this was due to the value of the fine aggregate in the mix ratio which supersedes other fine aggregate values. The final weight of the concrete cubes for all grades was all-around 8.1 kg.

### 3.2. Cement Properties

According to the test carried out and result generated from slump test, it was observed that the water-cement ratio used for mixing each grade has an effect on the level of shear that occur in slump test for each concrete grades. The results obtained are summarized in Table 4. The slump of the concrete increased from 15 mm for grade M15 to 40 mm for grade M35. The relationship between the penetration and setting time is shown in Fig. 1. It can be observed that cement penetration increased with increasing setting time.

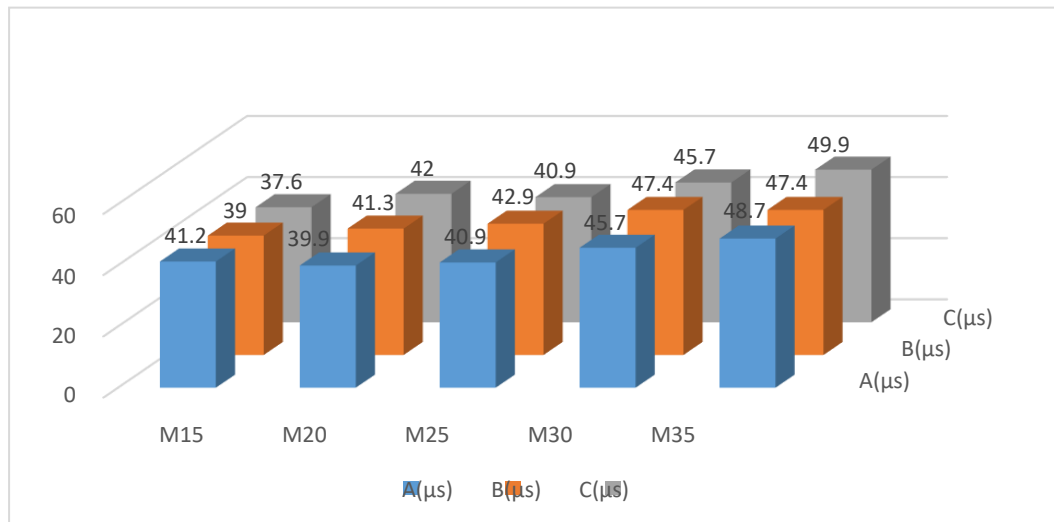


**Figure 1.** Cement penetration against setting time.

**Table 4.** Slump experiment result

Grade (MPa)	Slump Height (mm)	Collapse Height (mm)	Slump (mm)
M15	300	285	15
M20	300	280	20
M25	300	275	25
M30	300	265	35
M35	300	260	40

The observation was made for the transit time recorded from the ultrasonic pulse velocity test that was done using the direct transmission method on a concrete cube. This was implemented three times to achieve accurate transit time on a particular concrete cube. The results obtained are shown in Fig. 2. It was also observed that grade M15 cubes have the lowest transit time (37.6 – 41.2  $\mu$ s) and grade M35 cubes have the highest transit time (48.7 – 49.9  $\mu$ s). It is now understood that materials with short transit time generate the highest pulse velocity than that with low transit time. Reason for high transit is defect in concrete or failure to add enough coupling agent that can eliminate diffraction in wave [25].



**Figure 2.** The transition time of the different concrete grade

Practically, it is known that pulse velocity is a dependent parameter which depends mainly on the ratio between path length and transit time [26]. The results obtained for the pulse velocity and actual compressive strength are summarized in Table 5. It was observed that the value with highest transit time has the lowest pulse velocity and that with the lowest transit time has the highest velocity and that fall on grade M35 and M15 cube C respectively. Grade M15 cubes have the highest pulse velocity (3.6 – 4.0 km/s) and grade M35 cubes have the lowest pulse velocity (3.0 – 3.1 km/s). According to the test carried out using UPV, it was observed that the pulse velocity increases as the grade changes and the velocity generated from the transit time and path length were a good pulse velocity value. Al-Nu'man et. al [17] recommended a UPV >3.5 km/s as the threshold for the concrete to be considered good. Also from the results in Table 5, M15 cubes have the lowest actual compressive strength (18.1 – 19.3 N/mm<sup>2</sup>) and grade M35 cubes has the highest actual compressive strength (34.6 – 36.0 N/mm<sup>2</sup>).

**Table 5.** Result of pulse velocity and compressive test of concrete grades cubes

Grade	Pulse Velocity			Actual Compressive Strength		
	A (km/s)	B (km/s)	C (km/s)	A (N/mm <sup>2</sup> )	B (N/mm <sup>2</sup> )	C (N/mm <sup>2</sup> )
M15	3.6	3.9	4.0	18.1	18.6	19.3
M20	3.8	3.63	3.57	21.3	20.1	20.9
M25	3.67	3.5	3.7	25.9	26.2	25.8
M30	3.3	3.2	3.3	28.7	30	28.8
M35	3.1	3.2	3	34.6	35.1	36

### 3.3. Cement Properties

The prediction of compressive strength is shown in Tables 6 – 10 and the corresponding correlation plots shown in Fig. A – E (in the Appendix) respectively. For the predicted compressive strength of concrete cubes for different grades, it was observed that the strength of each grades cube conformed to the expected strength of a particular grade, except cube A of grade M35 which falls below the estimated strength. The Compressive strength derived from crushing inclines accurately with the grade Strength and also grades having a water-cement ratio of 0.5 has a high pulse velocity than those grades having a water-cement ratio of 0.45, this means that the increase in moisture content in concrete critically affects the ultrasonic pulse velocity of a particular structure, the coefficient of determining R<sub>2</sub> for M15, M25 & M35 seems uniform while that of M20 and M30 falls. For both the actual and

predicted strength it was observed that as the pulse velocity increases the strength of the concrete cube decreases and vice versa. This relationship has also been observed by other researchers [19, 20]. It was also observed that the actual and predicted strength of concrete cubes of M25 are the same and has no percentage variation and also cube B & C of M30 also share from the features. For all concrete grades, the percentage variation did not exceed  $\pm 2.5\%$ . this interval is relatively better than that obtained in an early study [13]. Based on a comparison between the actual and predicted compressive strength it can be concluded that UPV can be used to accurately predict the compressive strength of concrete.

**Table 6.** Result of pulse velocity and compressive test of concrete grades cubes

Samples	Transit Time ( $\mu\text{s}$ )	Pulse Velocity (Km/s)	Actual Compressive Strength ( $\text{N/mm}^2$ )	Predicted Compressive Strength ( $\text{N/mm}^2$ )	Percentage Variation	Linear Regression Equation	$R^2$
A	41.2	3.6	18.1	18.04	-0.33	$C = 2.6923V + 8.3462$	$R^2 = 0.864$
B	39	3.9	18.6	18.8	1.08		
C	37.6	4.0	19.3	19.12	-0.93		

**Table 7.** Concrete grade M20 experiment and prediction results

Samples	Transit Time ( $\mu\text{s}$ )	Pulse Velocity (Km/s)	Actual Compressive Strength ( $\text{N/mm}^2$ )	Predicted Compressive Strength ( $\text{N/mm}^2$ )	Percentage Variation	Linear Regression Equation	$R^2$
A	39.9	3.8	21.3	21.2	-0.45	$C = 2.904V + 10.119$	$R^2 = 0.32$
B	41.3	3.63	20.1	20.6	2.49		
C	42	3.57	20.9	20.5	-1.93		

**Table 8.** Concrete grade M25 experiment and prediction result

Samples	Transit Time ( $\mu\text{s}$ )	Pulse Velocity (Km/s)	Actual Compressive Strength ( $\text{N/mm}^2$ )	Predicted Compressive Strength ( $\text{N/mm}^2$ )	Percentage Variation	Linear Regression Equation	$R^2$
A	40.9	3.67	25.9	25.9	0	$C = -1.9198V + 32.923$	$R^2 = 0.9894$
B	42.9	3.5	26.2	26.2	0		
C	40.5	3.7	25.8	25.8	0		

**Table 9.** Concrete grade M30 experiment and prediction result

Samples	Transit Time ( $\mu\text{s}$ )	Pulse Velocity (Km/s)	Actual Compressive Strength ( $\text{N/mm}^2$ )	Predicted Compressive Strength ( $\text{N/mm}^2$ )	Percentage Variation	Linear Regression Equation	$R^2$
A	45.7	3.3	28.7	28.8	0.35	$C = -12.5V + 70$	$R^2 = 0.9952$
B	47.4	3.2	30	30	0		
C	45.7	3.3	28.8	28.8	0		

**Table 10.** Concrete grade M35 experiment and prediction result

Samples	Transit Time ( $\mu\text{s}$ )	Pulse Velocity (Km/s)	Actual Compressive Strength ( $\text{N}/\text{mm}^2$ )	Predicted Compressive Strength ( $\text{N}/\text{mm}^2$ )	Percentage Variation	Linear Regression Equation	$R^2$
A	48.7	3.1	34.6	35.2	1.73		
B	47.4	3.2	35.1	34.8	-0.85		
C	49.9	3.0	36.0	35.7	-0.83	$C = -4.5V + 49.183$	$R^2 = 0.4023$

#### 4. Conclusion

In this study, the ultrasonic pulse velocity technique as non-destructive testing of concrete was used to distinguish concrete mixture design and show the predictive relationship between compressive strength and UPV. Several conclusions can be drawn from the results of the study. Grade M15 cubes have the lowest transit time (37.6 – 41.2  $\mu\text{s}$ ) and grade M35 cubes have the highest transit time (48.7 – 49.9  $\mu\text{s}$ ) showing that the concrete with short transit time generates the highest pulse velocity than that with low transit time. Grade M15 cubes have the highest pulse velocity (3.6 – 4.0 km/s) and grade M35 cubes have the lowest pulse velocity (3.0 – 3.1 km/s). M15 cubes have the lowest actual compressive strength (18.1 – 19.3  $\text{N}/\text{mm}^2$ ) and grade M35 cubes have the highest actual compressive strength (34.6 – 36.0  $\text{N}/\text{mm}^2$ ). For both the actual and predicted strength it was observed that as the pulse velocity increases the strength of the concrete cube decreases and vice versa. There was a good correlation between compressive strength and UPV. The study revealed that UPV can be used to accurately predict the compressive strength of concrete. For all concrete grades, the percentage variation did not exceed  $\pm 2.5\%$ . From the observations of this study, it is recommended that a non-destructive test should be implemented for the concrete test due to its effectiveness, accuracy and rapidity. Furthermore, this study has also opened up some other areas for future work. Result generated from UPV test if not satisfactory could be modelled with an artificial neural network which can aid in generating more accurate predictions for the properties. For better assurance on concrete strength result, the combined test can be done to make the result more satisfactory.

#### 5. Acknowledgement

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