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Assessment of concrete compressive strength by ultrasonic pulse velocity test

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ABSTRACT

One of the most popular non- destructive techniques is ultrasonic pulse velocity (UPV) which used in assessment of concrete properties. A statistical experimental program was carried out in the present study to establish an accurate relation between the UPV and the concrete compressive strength. The program involved testing of concrete cubes cast with specified test variables. The variables are the age and density of concrete. In this research, all the samples were tested by direct ultrasonic pulse velocity (DUPV) and surface ultrasonic pulse velocity (SUPV) to measure the wave velocity in concrete and the compressive strength for each sample. An experimental study was conducted to compare between the velocities of ultrasonic waves that transmitted along the two paths; direct and indirect. A total of more than 150 cubes having dimensions of 150 mm side were prepared to conduct both non-destructive and the compressive strength (destructive testing). The results from experimental program were used as input data in a statistical program (SPSS) to predict the best equation, which can represent the relation between the UPV (direct, indirect), and compressive strength, a linear equation is proposed for this purpose. The UPV measurement and compressive strength tests were carried out at the concrete age of 7, 28, 56 days. A relationship curves were drawn between DUPV, SUPV, compressive strength and density. The mixes composition in this study consists of ordinary Portland cement, fine sand, gravel, super-plasticizer, and water. All the specimens were under (20) Cº. The statistical analysis revealed that the possibility in evaluating the properties of the concrete by using direct and indirect wave velocities

1. Introduction

Today, great amounts of engineering projects have used concrete as a basic material, which is primarily composed of cement, water, and aggregate. Generally, the aggregate consists of fine aggregate such as sand and coarse aggregate such as gravel or crushed rocks like granite [1]. Ultrasonic Pulse Velocity (UPV) test is a non-destructive test, which is performed by sending high-frequency wave (over 20 kHz) through the media. By following the principle that a wave travels faster in denser media than in provide information on the uniformity of concrete, cavities, cracks, and defects. The pulse velocity in material depends on the density and the elastic properties for material, which in turn are the looser one, the engineer, can determine the quality of material from the velocity of the wave this can be applied to several types of materials such as concrete, wood, etc [2]. Concrete is a material with a very heterogeneous composition. This heterogeneousness is linked up both to the nature of its constituents (cement, sand, gravel, reinforcement) and their dimensions, geometry or/and distribution. Thus, highly possible that defects and damaging should be exist. Non-destructive testing evaluation for these materials have motivated a lot of research work and several syntheses have been proposed [3]. UPV test of concrete is based on the pulse velocity method to provide information on the uniformity of concrete, cavities, cracks, and defects. The pulse velocity in material depends on its density and its elastic properties, which is turn, are related to the quality and the compressive strength of the concrete. It is therefore possible to obtain information about the properties of components by sonic investigations [3.]

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These methods are used to check variations in structure, changes in surface, presence of cracks, or other physical discontinuities, to determine the characteristics of industrial products materials. Non-destructive test (NDT) determination of materials properties is becoming increasingly important in design and life assessment consideration of components and systems. [4]

NDT is conducted by measuring the time taken by ultrasonic wave to pass through concrete. Higher velocities indicate that the quality and continuity of the material is good, while slower velocities indicate that the concrete with many voids and cracks. [5]

Direct transmission is defined as the spread of ultrasonic waves along a straight-line path between the two opposite surfaces of the specimen. Indirect transmission is defined as the spread of ultrasonic waves between points that are located on the same surface of the material.

ASTM C 597 stated that the indirect measurements indicative of properties for the layers that are near the surface, there for this measurements are not recommended except when only one surface of a material is accessible.

Presently, ASTM standards do not exist for indirect UPV measurements. In general, ASTM standards reported that, the direct wave velocities were higher than the indirect wave velocities. To explore the relation between concrete compressive strength and concrete qualities the UPV can be used for main idea that UPV waves are a function of the material density, which are correlated with the compressive strength. [6]

BS (1881): Part 203 (BS, 1881, 1986) test describes the time need for pulse to travel through concrete. Then, the Pulse velocity is measured by a simple formula: - [7]

$$\text{Pulse velocity} = \frac{\text{Width of structure}}{\text{Time taken by pulse to go through}}$$

$V = L/T$ [4]

Where:-

V = velocity of pulse (m/s).

L = length of path (m).

T =effective time (s).

Here the time is equal to the measured time minus the zero-time correction. The zero-time correction is equal to the time takes for pulse travel between the transmitting and receiving transducers when they are pressed firmly together. The quality of concrete in terms of uniformity, incidence or absence of internal flaws, cracks, segregation, etc., indicative of the level of workmanship employed, can thus be assessed using the guidelines given below, which have been evolved for characterizing the quality of concrete in structures in terms of the ultrasonic pulse velocity.

1.1. Methods of testing:-

Depending upon the placement of the transducers, there are three methods of testing the concrete:

1.1.1 Direct Method:-

In this method, the **receiver** is placed at one end and the **transmitter** at the other end throughout the member. (Fig -1-a).

1.1.2 Indirect method:-

In this method, the **receiver** and **transmitter** are place on the same surface of concrete. (Fig -1-b).

1.1.3 Semi-direct method:-

This method is used for corners member of concrete (Fig 1-c).

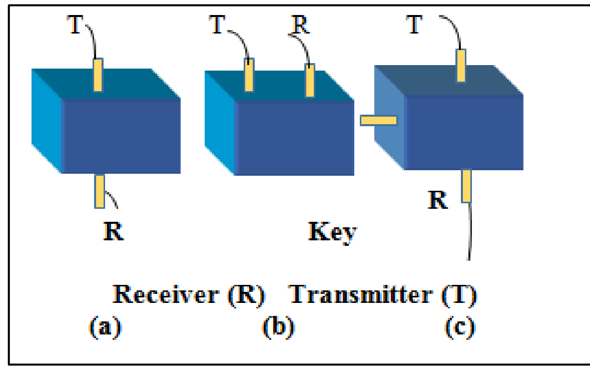

Fig (1) - (a) Direct Transmission (b) Indirect or surface Transmission (c) Semi-direct Transmission

Table -1- Concrete quality given by IS code (B.S, 1881, 1983) as a function of UPV. [9]

Concrete Quality	Pulse Velocity (km/sec)
Excellent	Above 4,5
Good	3.5 – 4.5
Medium	3.0 – 3.5
Doubtful	Below 3.0

The influence of path length will be negligible provided it is not less than 100 mm, when 20 mm size aggregate is used or less than 150mm for 40 mm size aggregate. Pulse velocity will not be influenced by the shape of the specimen. Generally, the velocity of pulses in steel bar is higher than concrete, therefore, pulse velocity measurements may be high and is not representative of the concrete in the vicinity of reinforcing steel.

The influence of the reinforcement small if the bars run at right angles in a direction to the pulse path and the quantity of steel is small to the path length. The influence of the moisture content of the concrete can have a small but significant on the pulse velocity. Generally, when moisture content is increased the velocity is increased, and for lower quality concrete, the influence is more marked.

2- Background

In civil engineering, the NDT application has becoming an interesting testing in various countries. A great number of researches are used, because these tests do not affect the performance and the appearance of the structures analysed. This method can be done at the same place making a determination of possible variations during a period of time and possible continuous monitoring in the structures.[9]

UPV methods can be considered as one of the most promising methods among the available methods of NDT for evaluating the concrete structures. It makes possible an examination of the homogeneity of material.. It makes possible to get a total control of a structure, using the properties variations with the time. It is possible to detect heterogeneous regions in the concrete or verify the capacity by using the analysis of the propagation variations of the ultrasonic velocity wave. [10]

Many studies have been conducted to determine direct pulse velocity and the factors that affect it. ASTM 1999a, b; RILEM 1972; BS 1997) standards are available for measuring direct transmission velocity. There is less information available on indirect transmission. British Standards (BS 1881) made comparison between direct velocity and indirect velocity transmission and state that the indirect velocity is about 5 to 20% lower than the direct velocity.[11]

Generally, indirect pulse velocity transmission can be used when only one face of the concrete structure is accessible as stated in ASTM C 597 (ASTM 1999a; RILEM 1972; BS 1997) stated that indirect measurements are not reliable.

A relationship between pulse velocity of concrete and strength have been proposed presented and presented with numerous experimental data and the correlation relationship. Some figures by Whitehurst[12] suggested some figures for concrete approximately of 2400 kg/m^3 for concrete density are given as very poor , poor, doubtful , good and excellent, for 2000 m/s and below ,3000-3500 , 3500-4500,and 4500 m/s and above, UPV values respectively. Based on experimental results. Tharmaratnam and Tan [13] gave the relationship between the ultrasonic pulse velocity in a concrete (Vc) and concrete compressive strength (fc) as:

$$fc = a\, e^{bv}$$

Where:-

a, b = parameters dependent upon the properties of material.

Keating et al., (1989) [14] investigated the relationship between the cube strength for cement paste and direct ultrasonic longitudinal pulse velocity (DUPV) in the first 24 hours. For concrete cured at room temperature, it is realized that the relative change in the pulse velocity is higher than the observed rate of strength in the first few hours. Anyway, a mutual correlation between these two parameters can be reduced.

2.1. Previous Equations: [15]

The relation between the ultrasonic pulse velocity and the compressive strength was developed by several studies, most important equations were found by following equations:

2.1.1 Raouf, Z and Ali Z.M. Equation:

Raouf and Ali (1983) developed Equation from 650 test results collected from the results of students, the experimental mixes and the other taken from the tested cube, which send to National Centre for Construction Labs.

With confidence, limit equal to (10%) as shown in Equation (1)

$$C = A.e^{B.D} \qquad \text{…..(1)}$$

Where:

C=concrete compressive strength in N/mm^2 (Mpa)

D= direct Ultrasonic velocity (km/s).

A=2.016

B=0.61

2.1.2 Deshpande et al., Equation:

Deshpande et al. (1996) have tested about (200) concrete cube specimens and developed a non-linear equation to relate ultrasonic velocity and compressive strength as shown in equation (2).

$$C = 79.846 + 4.103 \times 10^{-9}\, DE^3 + 0.00217\, A^3 + 4.842 \times 10^{-6}\, D^2 \qquad \text{…..(2)}$$

Where:

C = concrete compressive strength in kg/cm2.

DE = density of concrete in kg/m3.

A= age of concrete in day.

D = ultrasonic velocity in m/sec.

2.1.3- Jones R. Equation:

In 1962, Jones has presented a non-linear equation to relate ultrasonic velocity and compressive strength as shown in equation (3)

$$C = 2.8\ e\ 0.53 \qquad \text{…..(3)}$$

Where:

C= concrete compressive strength in N/mm2 (Mpa)

D= direct Ultrasonic velocity in km/sec

2.1.4 Popovics et al. Equation:

Popovics have used Klieger experimental results in 1957, for a mathematical comparison for use of DUPV and surface ultrasonic waves (SUPV), respectively, for strength estimation. The best-fit formula for the relationship between concrete strength and DUPV for the seventh day experimental results by Klieger is presented by equation (4), (Popovics, 1990).

$$C= 0.0028^{\ 0.0021D} \qquad \text{…..(4)}$$

Where:

C= concrete compressive strength in N/mm2

D= direct Ultrasonic velocity in m/sec

3.1.5. Elvery and lbrahim Equation:

Elvery and lbrahim carried out test to examine the relationship between concrete cube strength and ultrasonic pulse velocity for ages of 3 h over a curing temperature range from 1 to 60C. The authors developed equation below for 28 day age with correlation equal to (0.74) (Elvery and lbrahim, 1976).

3- Experimental Program

3.1. Materials

More than 150 cubes specimens with dimensions of 150x150x150 mm were performed for the goal of the study, which is consisted of the measurement, and comparison of UPV obtained using direct and indirect transducer arrangements on the same specimens at an age of 7, 28, 56 days. Table -2- present the composition of the mix.

Table -2- Concrete Compositions in this study.

Materials	Cement	Fine Sand	Gravel	Water	SP
Quantity (kg/m³)	390	715	1115	180	7.8
% Weight	16.2	29.6	46.3	7.4	0.5

3.1.1. Cement

Ordinary Portland cement (Type 1) satisfy the requirement of Iraqi Specifications No. 5, (1984), [16] was used throughout this work, which has high (C3S) cement compound (49.67%). Tables (3) and (4) show the physical and the chemical test results of the used cement.

Table -3- The physical test results of the used cement.

Physical properties	Test results	Iraqi Specification No.5/1984
Specifics surface area	310	≤230
(Blaine method) m²/kg		
Setting time-vicat apparatus		
Initial setting (minutes)	80	≤45
Final setting (hrs.: min)	5:20	≥10
Compressive strength		
3 day (MPa)	16	≤15
7 day (MPa)	32.9	≤23
Soundness by Autoclave method	0.25	≥0.8

Table-4- Main compounds and chemical composition of the Ordinary Portland cement.

Oxide composition	Content %	Iraqi specification limits No.5/1984
Ca O	61.6	-
Al2O3	5.41	-
SiO2	18.6	-
SO3	2.21	Max 2.8 %
Fe2O3	3.10	-
MgO	1.80	Max % 5.0
K2O	0.38	-
Na2O	0.18	-
L.O.I	1.16	Max % 4.0
I.R	1.10	Max % 1.5
L.S.F	0.92	1.02 – 0.66

3.1.2. Aggregate

Natural sand was brought from AL-Habaniya site and separated by sieving. Its grading satisfies the requirement of B.S specification No.882/1992[17] for fine grading.

Tables (5) and (6) show the physical properties and grading of fine aggregate (natural sand) respectively compared with the requirement of B.S.882/1992

.Natural coarse aggregate was brought from AL-Nibaae site and separated by sieving. Its grading satisfies the requirement of B.S specification No.882/1992. Tables (7) and (8) show the grading of coarse aggregate and the content of sulphate compared with the requirement of B.S.882/1992.

Table -5- Physical properties for the natural sand

Physical properties	Test results	B.S. 882/1992
Specific gravity gm/cm³	2.6	-
Sulfate content	0.41 %	Max 0.5%
Absorption	1.75 %	-
Materials finer than 0.075 mm	0.32 %	5% Max

Table-6-The natural sand gradation compared with the requirement of B.S.882/1992

Sieve size Mm	Cumulative passing%	B.S. 882/1992 Overall grading
9.52	100	100
4.75	95.3	89-100
2.36	84.8	60-100
1.18	74	30-100
0.60	56.6	15-100
0.30	18.7	5-70
0.15	4.5	0-15

Table -7- The grading of coarse aggregate.

Passing % limits of B.S.882/1992	Passing %	Sieve size (mm)
100-90	92.3	20
80-40	59.3	14
60-30	41.8	10
10-0	6.3	5

Tables -8- The Soluble Sulphate Salts (SO3).

Specification Limits of B.S.882/1992	Result
0.1	0.038

3.1.3. Water

In this work, tap water is used for mixing. Table (9) shows the chemical composition of Ramadi City water.

Table -9- Chemical composition of Ramadi City tap water

Tap water	Properties
7.10	Ph.
0.49	Conductivity EC(Ds. M-1)
0.003	Na%+
0.0003	K%+
0.010	Ca+2%
0.007	Mg+2%
0.006	Cl%-
0.001	Bicarbonate%
0.033	SO3%

3.1.4. Superplasticizer

In this study, the super-plasticizer used is Gelunium 51 (super-plasticizer, high range water and reducing agent) which complies with the requirements of ASTM C494–05[18] type F; its properties are shown in table-10.

Table -10- Properties of superplasticizer.

Properties	Description
Main action	Superplasticizer–reducing agent and highly effective water for the production of high quality concrete in hot climates
Type	Polymer
Dosage	0.5% – 2.4% by weight of cement
Color	Brown
Specific gravity	1.1 kg/l
PH value	9 ± 1.0.
Appearance	Liquid

4- Results and discussion

A relationships were established in this study between the results of non-destructive testing (DUPV , SUPV) and those from of mechanical testing of specimens (Table 11). These values are plot in graphs, Matlab is used to extract the curves (regression line), and then coefficients of determination R^2 are obtained for each regression line.

Figures (2), (3), (4), (5) and (6) show the DUPV, SUPV strength development and density, with concrete age for the same mix batches. The DUPV and SUPV strengths of concrete and density appear that an increasing with the age advancement. These five curves of the relationship between (DUPV and SUPV), compressive strength, and density were drown for concrete with the age 7, 28, and 56.

Table (12), shows the relationship between regression curves and the data points for concrete with the ages 7, 28, 56 days. The equations for the curves (Fig 5 and 6) for these three ages as shown in table (13). Where:-

σD = compressive strength (MPa) for (DUPV)

σS = compressive strength (MPa) for (SUPV)

v = the ultrasonic pulse velocity (m/s)

The curves in (Figs 5 and 6) at age (7,28, and 56) show a good relationship between concrete strength and (DUPV, SUPV), with a high coefficient of determination for this particular mixture (R^2) of 0.8113 , 0.7091 , 0.9478 for DUPV and 0.8506, 0.9023, 0.7964 for SUPV respectively as shown in table (12), this indicate the relationship between regression curves and the data points.

Then the compressive strength of the specimen obtained from the destructive tests was compared with the predicted strength. (Table 14). Almost the deviation of the results was about ±10% from the true value between the compressive strength of the specimen and the predicted strength. This verifies the suitability of the proposed relationship curves for prediction of hardened concrete strength with a measured UPV value.

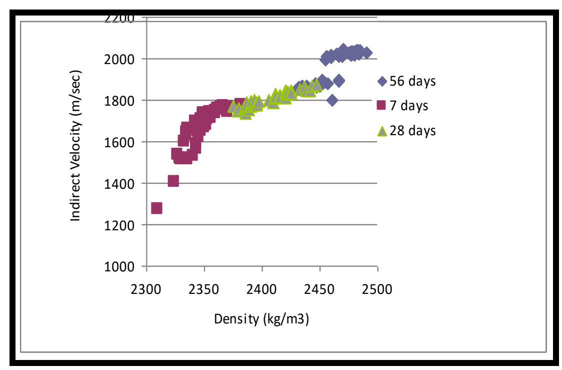

Fig. (2) Relation between density and compressive strength for all samples at 7, 28, and 56 days.

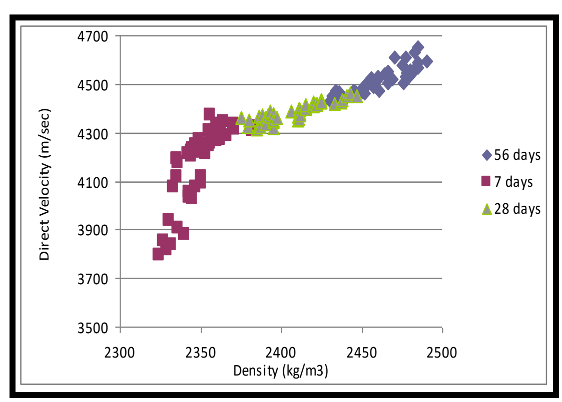

Fig. (3) Relation between density with the indirect velocity for all samples at 7, 28, 56 days

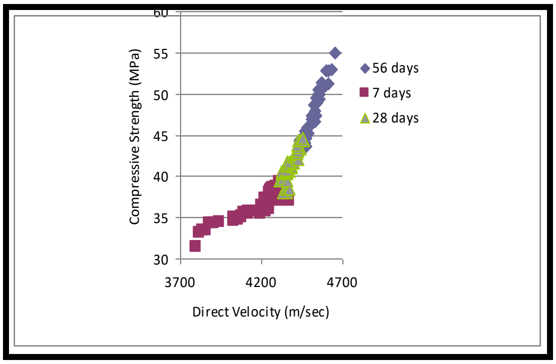

Fig. (4) Relation between density with the direct velocity for all samples at 7, 28, 56 days.

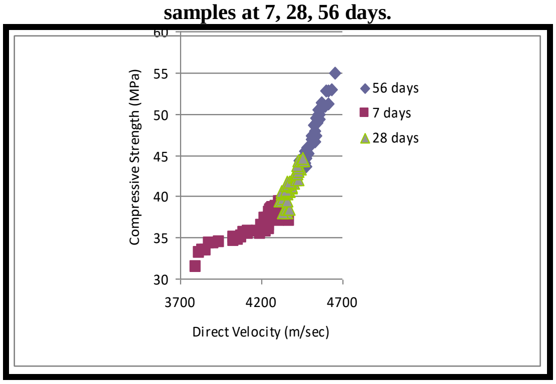

Fig. (5) Relation between (DUPV) with the compressive strength for all samples at 7, 28, 56 days.

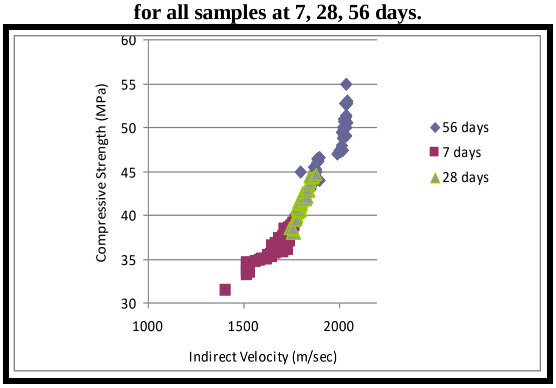

Fig. (6) Relation between (SUPV) with the compressive strength for all samples at 7, 28, 56 days.

5- Conclusions

Most of the reliable and a valuable method of examining the interior of a body of concrete is ultrasonic pulse velocity measurement, which is, describe as non-destructive manner. This method was used to assess the mechanical compressive strength of concrete. The main objective of this paper is to investigate the relationship between compressive strength of concrete and the ultrasonic pulse velocity (UPV) to understand the influence of the age, density of concrete on the relationship between compressive strength and UPV.

Based on a compressive experimental investigation involving more than 150 cubes (15x15x15) cm that came from the same mix butches. Specific conclusions are as follows:-

1- The difference between the values of resistance obtained by destructive and non-destructive tests decreased considerably at the age of 28 days.

2- In this research it is verified that, as shown in Figures (5) and (6), tests on concrete specimens represent that the value of the concrete strength increases as UPV increases.

3- To determine the concrete strengths of the concrete mix proportions at the range of density, the equations obtained from the simulation curves can be used, as shown in table 12.

4-This study indicates that the ultra-pulse velocity tests are very sensitive and Very important data can be provide by used this test about making the decision for concrete conditions.

Table-11- Data tests for specimens

Sample No.	*Comp. Strength 7 days*	*Density kg\m3*	*Direct test m\sec*	*In direct test m\sec*	*Sample No.*	*Comp. Strength 28 days*	*Density kg\m3*	*Direct test m\sec*	*In direct test m\sec*	*Sample No.*	*Comp. Strength 56 days*	*Density kg\m3*	*Direct test m\sec*	*direct test m\sec*
1	35.6	2350	4090	1667	47	41.5	2395	4377	1785	93	46.6	2466	4527	1898
2	38.5	2360	4264	1740	48	42.4	2415	4402	1823	94	47.4	2460	4533	2004
3	30.9	2310	3323	1274	49	38	2375	4360	1769	95	43	2430	4430	1850
4	39.4	2385	4323	1772	50	43.4	2425	4438	1845	96	55	2485	4650	2037
5	31.4	2324	3797	1407	51	38	2379	4327	1750	97	43.6	2432	4451	1861
6	38	2362	4323	1755	52	40.8	2395	4345	1781	98	51	2485	4587	2031
7	38.6	2360	4286	1751	53	42.5	2415	4399	1821	99	48.7	2460	4522	2020
8	33.4	2327	3856	1535	54	38.4	2380	4353	1759	100	44	2447	4464	1865
9	39	2371	4315	1765	55	43	2422	4419	1828	101	51.3	2477	4610	2037
10	34.8	2343	4054	1587	56	40.6	2392	4373	1782	102	45.2	2457	4491	1881
11	38.8	2366	4287	1770	57	43	2422	4412	1840	103	51	2475	4577	2026
12	34.3	2336	3906	1517	58	38.5	2388	4372	1756	104	45.5	2450	4468	1869
13	38.8	2363	4309	1755	59	42.8	2421	4418	1835	105	49.4	2466	4554	2012
14	34.3	2340	3880	1534	60	39.5	2390	4360	1774	106	46	2451	4478	1883
15	38.6	2362	4270	1762	61	42.6	2420	4412	1810	107	49	2464	4539	2023
16	34.6	2343	4032	1566	62	40.4	2390	4355	1790	108	44	2452	4460	1897
17	38.3	2356	4255	1715	63	44.6	2447	4451	1877	109	47.3	2456	4524	2010
18	39.4	2382	4310	1780	64	43	2425	4425	1833	110	53	2483	4633	2041
19	35	2345	4030	1622	65	40.7	2393	4366	1778	111	45	2461	4471	1800
20	38.3	2349	4273	1735	66	44.4	2443	4461	1866	112	47	2455	4505	1993
21	35.2	2347	4076	1650	67	41	2393	4386	1798	113	46.2	2466	4504	1892
22	38	2349	4245	1722	68	44.4	2441	4450	1847	114	46.4	2454	4511	1884
23	33.5	2332	3840	1520	69	38.5	2386	4365	1740	115	44.7	2450	4473	1871
24	38	2370	4335	1744	70	41.3	2397	4360	1792	116	52.8	2490	4595	2030
25	37.5	2347	4249	1710	71	44.3	2438	4438	1848	117	45.4	2450	4481	1871
26	35.7	2352	4225	1680	72	41.6	2411	4399	1811	118	47.4	2476	4505	2022
27	37.3	2345	4237	1685	73	43.8	2433	4420	1850	119	45	2445	4474	1870
28	36	2352	4225	1720	74	41.8	2412	4375	1826	120	48	2477	4530	2015
29	36.7	2344	4225	1670	75	43.5	2425	4425	1836	121	44.6	2445	4453	1869
30	36	2352	4249	1735	76	39.5	2385	4313	1764	122	49	2478	4545	2034
31	36.5	2344	4201	1650	77	42.8	2420	4410	1845	123	44.5	2440	4441	1860
32	33.2	2329	3815	1521	78	41.4	2410	4352	1788	124	52.8	2470	4610	2044
33	36	2353	4215	1709	79	39.5	2386	4323	1769	125	49.5	2479	4533	2022
34	36.3	2342	4213	1700	80	42	2420	4423	1833	126	44.3	2438	4435	1866
35	35.7	2350	4120	1711	81	41.2	2406	4386	1802	127	47.4	2469	4518	2012
36	36.4	2355	4246	1714	82	39.8	2386	4331	1778	128	50	2480	4548	2017
37	35.7	2336	4176	1665	83	42	2415	4412	1816	129	43.8	2436	4468	1859
38	37	2355	4310	1743	84	40.3	2387	4323	1788	130	50	2480	4559	2035
39	35.5	2335	4190	1644	85	42	2412	4395	1831	131	43.7	2435	4453	1867
40	37.3	2346	4221	1690	86	44.3	2437	4425	1861	132	45	2446	4466	1882
41	35	2333	4076	1602	87	41.7	2411	4358	1810	133	43.6	2434	4459	1862
42	37	2356	4371	1735	88	40.5	2390	4335	1797	134	50.5	2482	4550	2041
43	35.4	2335	4121	1627	89	41.8	2412	4373	1817	135	43.6	2434	4471	1852
44	37.7	2360	4333	1740	90	40.6	2395	4322	1791	136	50.7	2484	4573	2024
45	34.5	2330	3937	1517	91	41.5	2410	4366	1790	137	43.6	2432	4441	1858
46	38	2364	4346	1763	92	40.8	2395	4351	1776	138	51.4	2485	4569	2039

Table-12- Equations of existing relationship used for estimation the compressive strength of concrete

	DUPV			SUPV		
Age	V	Compressive strength MPA		V	Compressive strength MPA	
(days)	m/s	Theoretical	Experiment	m/s	Theoretical	Experiment
7	4152	36.1	36.3	1665	36.23	36.3
28	4384	41.48	41.5	1807	41.51	41.5
56	4514	47.54	47.3	1946	47.24	47.3

Table-13- Correlation coefficients and R^2 values for different ages of concrete

The equation	Density Range kg /m^3	R^2
$\sigma D(7) = 0.0105v - 7.5063$	2310-2385	0.8113
$\sigma D(28) = 0.0384v - 126.86$	2386-2447	0.7091
$\sigma D(56) = 0.0546v - 198.92$	2448-2490	0.9478
$\sigma S(7) = 0.0192v + 4.2625$	2310-2385	0.8506
$\sigma S(28) = 0.0507v - 50.105$	2386-2447	0.9023
$\sigma S(56) = 0.0348v - 20.478$	2448-2490	0.7964

Table-14- Comparison results of UPV-strength relationship

UPV type	Age (days)	Correlation Factor	R^2
SUPV	7	0.9264	0.8506
	28	0.9498	0.9023
	56	0.8924	0.7964
DUPV	7	0.8924	0.8113
	28	0.8421	0.7091
	56	0.9735	0.9478

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