IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 13, Issue 5 Ver. VII (Sep. - Oct. 2016), PP 15-22
www.iosrjournals.org

Study of Concrete Quality Assessment of Structural Elements Using Ultrasonic Pulse Velocity Test

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Abstract: *Ultrasonic Pulse Velocity (USPV) test has gained considerable popularity all over the world. Ultrasonic pulse velocity testing 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 a material depends on its density and its elastic properties which in 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. The investigation reported here is to present study of calibration graphs for Non Destructive Testing* (NDT) *Equipment,* which is *ultra sonic pulse velocity test and to study the quality of the concrete in existing structures. These ultra sonic pulse velocity tests were then used to test the quality of the concrete of the various structural elements (columns and beams) of single storied newly under constructed office building. The use of this method produces results that lie close to the true values when compared with other methods. A correlation between ultra sonic pulse velocity test and strength of concrete structure is established, which can be used for strength estimation of concrete structures. The method can be extended to test existing structures by taking direct measurements on concrete elements.*

Keywords: *Calibration, f_{ck}, impact energy, USPV, NDT, SD, IRLOAD*

I. Introduction

To keep a high level of structural safety, durability and performance of the infrastructure in each country, an efficient system for early and regular structural assessment is urgently required. The quality assurance during and after the construction of new structures and after reconstruction processes and the characterization of material properties and damage as a function of time and environmental influences is more and more becoming a serious concern. In recent years, innovative NDT methods, which can be used for the assessment of existing structures, have become available for concrete structures, but are still not established for regular inspections. Therefore, the objective of this investigation is to study the applicability, performance, availability, complexity and restrictions of NDT. The purpose of establishing standard procedures for non destructive testing (NDT) of concrete structures is to qualify and quantify the material properties of in-situ concrete without intrusively examining the material properties. There are many techniques that are currently being research for the NDT of materials today. Present work focuses on the NDT methods relevant for the inspection and monitoring of concrete quality. The NDT being fast, easy to use at site and relatively less expensive can be used for testing any number of points and locations it can assess the structure for various distressed conditions like damage due to fire, chemical attack, impact age. It is also helpful in detecting cracks, voids, fractures, honeycombs, weak location and actual condition of reinforcement. The use of the ultrasonic pulse velocity test is introduced as a tool to monitor basic initial cracking of concrete structures and hence to introduce a threshold limit for possible failure of the structures. Experiments using ultrasonic pulse velocity tester have been carried out, under laboratory conditions, on various concrete specimens and the reference results have been used for the evaluation of the concrete quality of the existing structure (Office Building).

II. Test Methodlogy

Ultrasonic instrument is a handy, battery operated and portable instrument used for assessing elastic properties or concrete quality. The apparatus for ultrasonic pulse velocity measurement consists of the Electrical pulse generator, Transducer (one pair), Amplifier and Electronic timing device. The ultrasonic pulse velocity method could be used to establish homogeneity of the concrete; it can check presence of cracks, voids and other imperfections which is helpful to find values of dynamic elastic modulus of the concrete. USPV is useful to check quality of concrete in relation to standard requirement and relation to another structure.

2.1 Principle Of Uspv Test

The method is based on the principle that the velocity of an ultrasonic pulse through any material depends upon the density, modulus of elasticity and Poisson's ratio of the material. Comparatively higher velocity is obtained when concrete quality is good in terms of density, uniformity, homogeneity etc. The ultrasonic pulse is generated by an electro acoustical transducer. When the pulse is induced into the concrete from a transducer, it undergoes multiple reflections at the boundaries of the different material phases within the concrete. A complex system of stress waves is developed which includes longitudinal (compression), shear (transverse) and surface (Rayleigh) waves. The receiving transducer detects the onset of longitudinal waves which is the fastest. The velocity of the pulses is almost independent of the geometry of the material through which they pass and depends only on its elastic properties. Pulse velocity method is a convenient technique for investigating structural concrete. For good quality concrete, pulse velocity will be higher and for poor quality it will be less. If there is a crack, void or flaw inside the concrete which comes in the way of transmission of the pulses, the pulse strength is attenuated and it passed around the discontinuity, thereby making the path length longer. Consequently, lower velocities are obtained. The actual pulse velocity obtained depends primarily upon the materials and mix proportions of concrete. The principle of the test is that the velocity of sound in a solid material (*V)* is a function of the square root of the ratio of its modulus of elasticity (*E)*, to its density (*d)*, as given by the following equation:

$$V = f\,(gE/d)^{0.5}$$

Where *g* is gravity acceleration

Monitoring modulus of elasticity for concrete through results of pulse velocity is not normally recommended because concrete does not fulfill the physical requirements for the validity of the equation normally used for calculations for homogenous, isotropic and elastic materials.

$$V^2 = E_d\,(1-\mu)/\{\rho(1+\mu)(1-\mu)\}$$

Where *V* is the wave velocity, ρ is the density, μ is Poisson's ratio and E_d is the dynamic modulus of elasticity.

On the other hand, it has been shown that the strength of concrete and its modulus of elasticity are related.

The method starts with the determination of the time required for a pulse of vibrations at an ultrasonic frequency to travel through concrete. Once the velocity is determined, an idea about quality, uniformity, condition and strength of the concrete tested can be attained. In the test, the time the pulses take to travel through concrete is recorded. Then, the velocity is calculated as:

$V = L/T$

Where *V* is pulse velocity, *L* is travel length in meters and *T* is effective time in seconds, which is the measured time minus the zero time correction.

2.2 FACTORS INFLUENCING PULSE VELOCITY MEASUREMENT

The pulse velocity depends on the properties of the concrete under test. Various factors which can influence pulse velocity and its correlation with various physical properties of concrete are as follow:

2.2.1 Moisture Content

1. The moisture content has chemical and physical effects on the pulse velocity.
2. These effects are important to establish the correlation for the estimation of concrete strength.
3. There may be significant difference in pulse velocity between a properly cured standard cube and a structural element made from the same concrete.

2.2.2 Temperature of Concrete

1. No significant changes in pulse velocity, in strength or elastic properties occur due to variations of the concrete temperature between 5° C and 30° C.
2. Corrections to pulse velocity measurements should be made for temperatures outside this range, as given in table 1.

Table 1 : Effect of Temperature on Pulse Transmission. (BS 1881 : Part 203 : 1986)

Temperature (ºC)	Correction to the measured pulse velocity in %	
	Air dried Concrete	Water saturated concrete
60	+5	+4
40	+2	+1.7
20	0	0
0	-0.5	0
-4	-1.5	-7.5

2.2.3 Path Length

1. The path length (the distance between two transducers) should be long enough not to be significantly influenced by the heterogeneous nature of the concrete.
2. It is recommended that the minimum path length should be 100 mm for concrete with 20 mm or less nominal maximum size of aggregate and 150 mm for concrete with 20 mm and 40 mm nominal maximum size of aggregate.

2.2.4 Effect of Reinforcing Bars

1. The pulse velocity in reinforced concrete in vicinity of rebars is usually higher than in plain concrete of the same composition because the pulse velocity in steel is almost twice to that in plain concrete.
2. The apparent increase depends upon the proximity of measurement to rebars, their numbers, diameter and their orientation.

2.2.5 Shape and Size of Specimen

1. The velocity of pulses of vibrations is independent of the size and shape of specimen, unless its least lateral dimension is less than a certain minimum value. Below this value, the pulse velocity may be reduced appreciably.
2. The extent of this reduction depends mainly on the ratio of the wavelength of the pulse vibrations to the least lateral dimension of the specimen but it is insignificant if the ratio is less than unity
3. Table 2 shows the relationship between the pulse velocity in the concrete, the transducer frequency and the minimum permissible lateral dimension of the specimen.

Table 2 : Effect of Specimen Dimension on Pulse Transmission (As Per BS 1881 : Part 203: 1986)

Transducer Frequency (KHz)	Minimum lateral dimension in mm for Pulse specimen velocity in concrete (km/sec)		
	$V_C = 3.5$	$V_C = 4.0$	$V_C = 4.5$
24	146	167	188
54	65	74	83
82	43	49	55
150	23	27	30

2.2.6 Calibration

1. The equipment should be calibrated before starting the observation and at the end of test to ensure accuracy of the measurement and performance of the equipment. It is done by measuring transit time on a standard calibration rod supplied along with the equipment.
2. A platform or staging of suitable height should be erected to have an access to the measuring locations. The location of measurement should be marked and numbered with chalk or similar thing prior to actual measurement (pre decided locations).

2.2.7 Criterion for Concrete Quality Grading

1. The ultrasonic pulse velocity of concrete can be related to its density and modulus of elasticity. It depends upon the materials and mix proportions used in making concrete as well as the method of placing, compacting and curing of concrete.
2. If the concrete is not compacted thoroughly and having segregation, cracks or flaws, the pulse velocity will be lower as compare to good concrete, although the same materials and mix proportions are used.
3. The quality of concrete in terms of uniformity can be assessed using the guidelines given in table 3.

Table 3: Criterion for Concrete Quality Grading [As per IS 13311 (Part 1) : 1992]

S. No.	Pulse velocity by cross probing (km/sec)	Concrete quality grading
1.	Above 4.5	Excellent
2.	3.5 to 4.5	Good
3.	3.0 to 3.5	Medium
4.	Below 3.0	Doubtful

2.3 Mounting Of Transducers

1. The direction in which the maximum energy is propagated is normally at right angles to the face of the transmitting transducer, it is also possible to detect pulses which have traveled through the concrete in some other direction.
2. The receiving transducer detects the arrival of component of the pulse which arrives earliest. This is generally the leading edge of the longitudinal vibration.
3. It is possible, therefore, to make measurements of pulse velocity by placing the two transducers in the following manners:

2.3.1 Direct Transmission (on opposite faces)

1. This arrangement is the most preferred arrangement in which transducers are kept directly opposite to each other on opposite faces of the concrete. The transfer of energy between transducers is maximum in this arrangement.
2. The accuracy of velocity determination is governed by the accuracy of the path length measurement. Utmost care should be taken for accurate measurement of the same
3. The couplant used should be spread as thinly as possible to avoid any end effects resulting from the different velocities of pulse in couplet and concrete.

2.3.2 Semi-direct Transmission

1. This arrangement is used when it is not possible to have direct transmission (may be due to limited access). It is less sensitive as compared to direct transmission arrangement.
2. There may be some reduction in the accuracy of path length measurement, still it is found to be sufficiently accurate. This arrangement is otherwise similar to direct transmission.

2.3.3 Indirect or Surface Transmission

1. Indirect transmission should be used when only one face of the concrete is accessible (when other two arrangements are not possible).
2. It is the least sensitive out of the three arrangements. For a given path length, the receiving transducer get signal of only about 2% or 3% of amplitude that produced by direct transmission.

2.4 DETERMINATION OF PULSE VELOCITY

1. A pulse of longitudinal vibration is produced by an electro acoustical transducer, which is held in contact with one surface of the concrete member under test
2. After traversing a known path length (L) in the concrete, the pulse of vibration is converted into an electrical signal by a second electro-acoustical transducer and electronic timing circuit enable the transit time (T) of the pulse to be measured. The pulse velocity (V) is given by

$$V = L / T$$

Where V is Pulse velocity, L is Path length, T is Time taken by the pulse to traverse the path length.

III. Uspv Test On Specimens

Six cubes samples were cast, targeting at different mean strengths. Further, the cubes samples were cured for different number of days to ensure availability of a wide range of compressive strength attained by these cubes. Size of each cube was 150×150×150 mm.

3.1 TESTING OF SPECIMEN

Three readings of Ultrasonic Pulse Velocity (USPV) were obtained for all surfaces of each cube sample. Then the cubes were then loaded up to their ultimate stress and the Breaking Load was obtained.
Table 4 lists the USPV in each specimen with their mean velocity, breaking load and the actual Compressive Strength as obtained by the Compression Testing Machine.

Table 4 : USPV Testing Results of Various Cubes Samples

Sample No.	V_1 (m/sec)	V_2 (m/sec)	V_3 (m/sec)	V (Average) (m/sec)	Breaking Load (KN)	f_{ck} (N/mm^2) (Actual)
1	2775	2866	2863	2834.67	550	24
2	3400	3635	3268	3434.33	650	29
3	3575	3582	3168	3441.67	720	32

4	4269	4263	4057	4196.33	810	36
5	4361	4394	4067	4274	850	38
6	4675	4575	4467	4572.33	890	40

Figure 1 shows the graph between the Compressive Strength and the Ultrasonic Pulse Velocity. This graph can now also be used to approximately predict the Compressive Strength of Concrete.

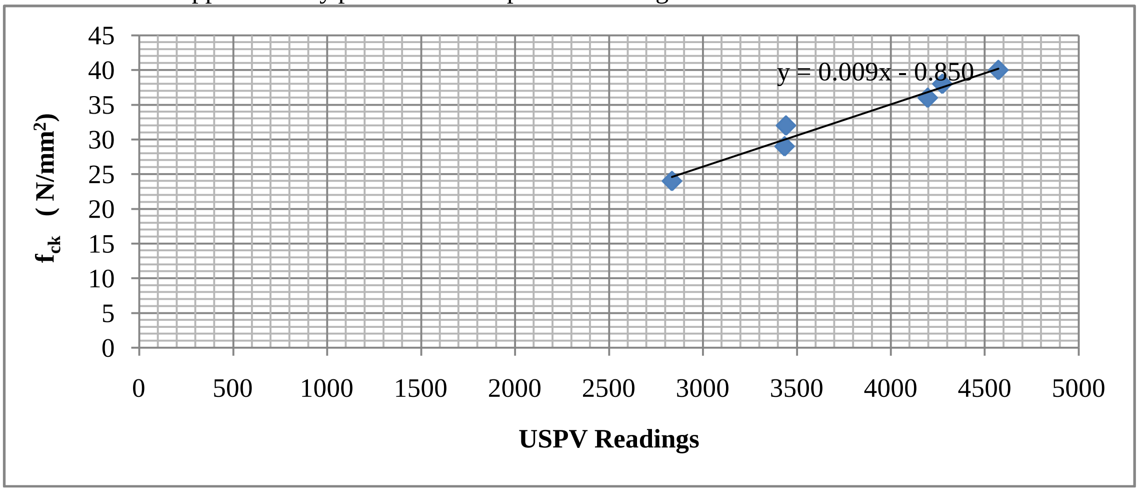

Figure 1: Graph obtained for Compressive Strength and the Ultrasonic Pulse Velocity

3.2 COMPARATIVE STUDY

To Study the effect of reinforcement on the Ultrasonic Pulse Velocities, we have referred the work done by the previous researchers in the Department of Structural Engineering, JNV University, Jodhpur, Rajasthan, India. Those who have establish the correlation between ultra sonic pulse velocity results with reference to the variation of the reinforcement present in the structural elements. The results were used for assessing the quality of the concrete of the newly under construction office building.

Two Beams were casted of the following dimensions:

1. Length = 60 cm , Breadth = 60 cm and Depth = 15 cm
2. Grade of concrete used: M20 and M25

The points where the reinforcements existed were known so the testing was done in two stages:

1. By avoiding the impact of reinforcements or by trying to minimize its impact.
2. By undertaking the effect of reinforcements or by maximizing its impact.

A comparative analysis given in table 5 is then made to know the effect of reinforcement.

Table 5: USPV Tests on Concrete Grades M20 and M25

Locations	Ultrasonic Pulse Velocity (m/sec)			
	Concrete Grade M20		Concrete Grade M25	
	Without Reinforcement	With Reinforcement	Without Reinforcement	With Reinforcement
I	2811	3105	3211	3738
II	2891	3003	3191	3424
III	2941	3025	3141	3438
IV	2850	2958	3272	3728
V	2975	3274	3307	3772

Result of above table : The maximum variation in ultrasonic pulse velocity is 16.1%.

3.3 Ultrasonic Pulse Velocity Test On Strcutural Elemnts (Columns And Beams)

Tests were conducted on some of the Columns and Beams of newly under construction office building for the assessment of their quality. The observations and remarks have been given in tables 6 and 7.

Table 6: USPV Tests on Structural Element (Column) and Remarks on Various Locations

Column Name	Location	USPV (m/s)	Quality f_{ck} N/mm^2	Remarks
A1	Bottom	3263	23	Medium Quality Concrete
	Middle	Over range	13	Voids in concrete, Poor Quality Concrete
	Top	Over range	14	Voids in concrete, Poor Quality Concrete
A6	Bottom	3704	31	Good Quality Concrete
	Middle	3581	30	Good Quality Concrete
	Top	3205	30	Medium Quality Concrete
B3	Bottom	3694	34	Good Quality Concrete
	Middle	3775	33	Good Quality Concrete
	Top	3664	33	Good Quality Concrete
B5	Bottom	3754	31.67	Good Quality Concrete
	Middle	3531	33.76	Good Quality Concrete
	Top	3255	30	Medium Quality Concrete
B8	Bottom	3800	34	Good Quality Concrete
	Middle	3585	30	Good Quality Concrete
	Top	3240	30	Medium Quality Concrete
C2	Bottom	3910	36	Good Quality Concrete
	Middle	3566	30	Good Quality Concrete
	Top	3379	30	Medium Quality Concrete
D4	Bottom	3960	37	Good Quality Concrete
	Middle	3588	30	Good Quality Concrete
	Top	3400	30	Medium Quality Concrete
D7	Bottom	3860	38	Good Quality Concrete
	Middle	3578	31	Good Quality Concrete
	Top	3460	32	Medium Quality Concrete

Table 7 : USPV Tests on Structural Element (Beams) and Remarks on Various Locations

Beam Name	Location	USPV (m/s)	Quality	Remarks
			f_{ck} N/mm^2	
1	1st Support	4418	40	Medium Quality Concrete
	Mid Span	3505	30	Medium Quality Concrete
	2nd Support	3430	31	Medium Quality Concrete
2	1st Support	3605	31	Good Quality Concrete
	Mid Span	3895	32	Good Quality Concrete
	2nd Support	3390	32	Good Quality Concrete
3	1st Support	4455	36	Good Quality Concrete
	Mid Span	4483	36	Excellent Quality Concrete proper compaction may be reason
	2nd Support	4911	41	Excellent Quality Concrete it is the junction of three beams and a column, so heavy reinforcement and proper compaction is indicated
4	1st Support	2570	20	Doubtful Quality Concrete require attention
	Mid Span	2779	20	Doubtful Quality Concrete require attention
	2nd Support	2695	20	Doubtful Quality Concrete require attention
5	1st Support	3372	30	Medium Quality Concrete
	Mid Span	3921	30	Medium Quality Concrete
	2nd Support	3700	31	Good Quality Concrete
6	1st Support	2005	24	USPV is low ,beam or internal voids, require attention
	Mid Span	3283	25	Medium Quality Concrete
	2nd Support	3304	25	Medium Quality Concrete

3.4 INTERPRETATION ON THE BASIS OF USPV TESTS ON STRUCTURAL ELEMENTS

The following interpretation has been drawn on the basis of USPV tests on structural elements:

1. The assessment of compressive strength of concrete from ultrasonic pulse velocity values is not accurate because the correlation between ultrasonic pulse velocity and compressive strength of concrete is not very clear. Because there are large number of parameters involved which influence the pulse velocity and compressive strength of concrete to different extents. However, if details of material and mix proportions adopted in the particular structure are available, then estimate of concrete strength can be made by establishing suitable correlation between the pulse velocity and the compressive strength of concrete specimens made with such material and mix proportions, under environmental conditions similar to that in the structure. The estimated strength may vary from the actual strength by ± 20 percent.
   The correlation so obtained may not be applicable for concrete of another grade or made with different types of material. At some places in columns USPV gave no results or indicated that the velocity was out of range. This place gave a unique sound on striking softly with a hard material like iron which clearly indicated a void in between the concrete. The decrease in the USPV shows the less density of

concrete. On the basis of the correlation of the USPV and f_{ck}, it clearly indicated that the USPV ranging 3500 to 4200 representing the compressive strength from 30 to 40 N/mm^2 but this trend is not shown for lower range of USPV values. The USPV increased in the nearby region of the reinforcement by around 12% to 18%.

2. A general trend was obtained in the columns. The trend was such that towards the base of the column the tests always showed a higher quality of concrete i.e. higher compressive strength. The compressive strength went on decreasing as we go up towards the roof. A graph has been plotted with increasing height against the predicted compressive strength obtained on the basis of the USPV evaluation. It is evident from the graph that the compressive strength goes on decreasing with increase in height of column (Figure 2).

   The reason for this variation is better compaction at the base. Since all the weight of the column acts at the base higher compaction is achieved and also better compaction facilities are available near the base and process compaction becomes difficult as we go up. No such regular trend was observed for beams.

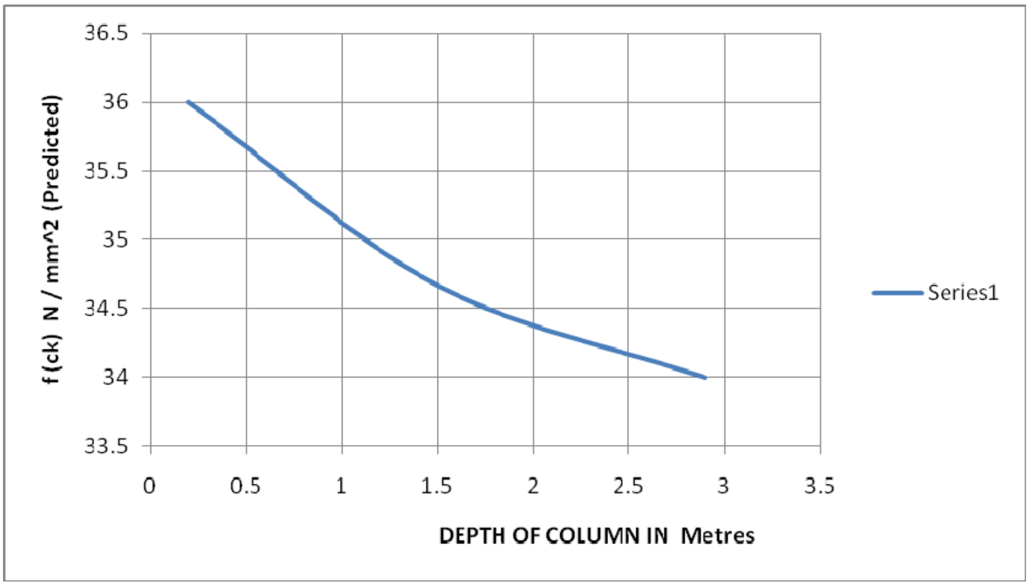

Figure 2 : Variation of Strength with increase in Height of Column

IV. Conclusions

The main conclusions drawn from investigation performed are as follow:

1. The poor quality concrete allows the ingress of moisture and oxygen to the reinforcing bars, and hence corrosion occurs. Presently the system is limited to penetration depths of 1 ft. Research is ongoing to develop a system that can penetrate to a depth of 10 ft or more.
2. The pulse velocity method is an ideal tool for establishing whether concrete is uniform. It can be used on both existing structures and those under construction
3. Usually, if large differences in pulse velocity are found within a structure for no apparent reason, there is strong reason to presume that defective or deteriorated concrete is present.
4. Fairly good correlation can be obtained between cube compressive strength and pulse velocity. These relations enable the strength of structural concrete to be predicted within ±20 percent, provided the types of aggregate and mix proportions are constant
5. Ultrasonic pulse velocity tests have a great potential for concrete control, particularly for establishing uniformity and detecting cracks or defects.
6. Its use for predicting strength is much more limited, owing to the large number of variables affecting the relation between strength and pulse velocity.
7. The deviation between actual results and predicted results may be attributed to the fact that a sample from existing structures was obtained by using various corrections introduced in the specifications.
8. The method presented is simple, quick, reliable, and covers wide ranges of concrete strengths..The method can be easily applied to concrete specimens as well as existing concrete structures by taking direct measurements on concrete elements. The final results were compared with previous ones from literature and also with actual results obtained from samples collected from existing structures. The correlation curves established in the study can be useful for the assessment of the quality of the concrete in an existing nearby structures made with the similar grade of the concrete and the similar sources of the

materials.

9 . Unlike other work, the research ended with important and useful charts that require no previous knowledge of the constituents of the tested concrete.

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