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Influence of Sustained Compressive Stress on Ultrasonic Pulse Velocity in Concrete

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Abstract

Objective of this study is to evaluate the effect of compressive stress over non-destructive assessment of field concrete using ultrasonic pulse velocity (UPV). Influence of compressive stress on UPV for different concrete grades (M25, M30 & M40) tested at laboratory and at field on M40 reinforced concrete (RC) columns of 42 m height of a high bay building is discussed. It is found that there is an increase in pulse velocity for concretes stressed around 5 MPa in addition to the growth in velocity due to water to cement ratio and curing period for cubes tested after 7, 14, and 28 days water curing. In the field study, pulse velocity versus computed stress due to construction loads transmitted at various stages of the RC columns prove that grow in velocity is significant with respect to acting stress and curing age. The results obtained from the study can be used as a reference for concrete ageing programs wherein pulse velocity based assessment is an important tool.

Keywords: Non-destructive testing; pulse velocity; creep compressive stress; field concrete assessment

1. Introduction

Assessment of concrete quality using ultrasonic pulse velocity (UPV) is one of the cost effective non-destructive diagnostic technique in civil engineering. For ensuring concrete quality at the time of construction, procedures are being followed as per IS 1119 [1] and IS 456 [2]. For instant, concrete sampling procedure [1, 3] and acceptance criterion after destructive test [3] are being practiced for ascertaining its intended compressive strength. However non-destructive evaluation (NDE) of concrete strength becomes essential when such samples are (i) not available for destructive testing, (ii) difficulties in obtaining adequate number of distributed samples from the existing structure (iii) functionality while core sampling and (iv) due to economic reasons. Pulse velocity measurement is a widely used method in concrete industry and the results are often correlated with destructive tests [4].

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As per ASTM C597 [5], pulse velocity test method is applicable to assess the uniformity and relative quality of concrete for indicating presence of voids and cracks. Also this method can be used to indicate the changes in the properties of field concrete for estimating severity of deterioration or to distinguish different grades of concretes placed in a specific zone. However, there is no specific mention in ASTM C597 about the influence of nominal stress on pulse velocity used for assessing concretes.

Mixture proportion arrived at laboratory for a particular grade [i.e. based on strength, workability and durability targets] of concrete is the basis for producing at batching plants. Fresh and hardened properties of such design mix concretes at field are affected by various factors at different stages. Probable sources of variations are (i) fluctuation in binder properties, ambient temperature, mixing water quality, variation in grading and moisture content of coarse and fine aggregates- (before mixing) (ii) batch size, accuracy and tolerance achieved in batching plants, control of chemical admixture dosage, mixing speed and duration-(during mixing) (iii) drum insulation of transit mixer, lead distance or concrete transmitting duration, placement temperature, admixture re-dosing -(during transportation) (iv) height / depth of placement [in case of concrete pumping], placement temperature, degree and uniformity in compaction, reinforcement and or any other in-situ congestion, free fall height, - (during placement) (v) moisture loss during setting, initial curing, member size, thermal conductivity of forming material, drying shrinkage, curing method and period, ageing etc. (after placing).

Pulse velocity measurements obtained for the plain concrete specimen prepared at the laboratory need not be an ideal representative of the parent concrete to be tested at field since the homogeneity achieved in casting of in-situ concrete members is differing due to various reasons as cited in the aforementioned section as well as their stressed condition too. This study is aimed to address the influence of sustained compressive stress, field ambience and curing periods in detail.

2. Laboratory Program

UPV measurements are observed at stressed as well as unstressed state for 150mm concrete cube specimens. Three concrete grades (M25, M30 and M40) used widely in construction are planned for UPV assessment. In order to represent field conditions, cube samples of these grades produced at field are used in lab investigation. After initial curing at field (24 hours), samples are arranged for water curing up to 7, 14, and 28 days and then tested for uni-axial compression at saturated surface dry condition.

2.1. Materials and Mix Proportion

Concrete mixtures are prepared using ordinary Portland cement (OPC) of 43 grade conforming to Indian Standard –IS 8112. Blue granite coarse aggregate and river sand fine aggregates are used. The specific gravities of the 20 & 12.5 mm coarse aggregates and fine aggregate are 2.75, 2.7, and 2.62 respectively. Sieve analysis of the aggregates revealed that the gradation is conforming to the requirements of IS 383. The fineness modulus of the sand is found to be 2.37. Sulphonated formaldehyde based water reducing chemical admixture confirming to IS 9103 [6] is used.

Mix proportions for M25, M30 and M40 grades of concretes and their compressive strength are listed in Table 1.

TABLE 1. MIXTURE PROPORTIONS AND COMPRESSIVE STRENGTH.

Grade	Water/ Cement	Cement, kg/m^3	Coarse aggregate, kg/m^3	River sand, kg/m^3	Chemical admixture, kg/m^3	Compressive strength, MPa		
						Curing period, days		
						7	14	28
M25	0.55	340	1149	741	--	21.6	27.8	30.2
M30	0.42	370	1191	765	3.3	31.6	33.7	38.1
M40	0.4	400	1219	751	4.8	38.5	43.2	47.4

2.2. Testing

Figure 1 shows the experimental set up. Initially velocities are measured at five pre-defined locations in the cube specimens when no load is acting on it, as shown in Figure 2. Uni-axial compression load is then applied at the rate of 5.4 kN/sec for first 50 kN, and then the loading is stopped. When the load is maintained at 50 kN, pulse velocity at each location is measured for a wave frequency of 54 kHz. When loading is withheld, load shown by the digital system is noted for all five locations (L1 to L5). Any change in the load at given test location is noted while measuring the pulse velocity, for accuracy. The load is then increased to 100 kN at the same rate and then it is stopped for measuring the velocity at all five locations. This process of measuring direct velocity is continued up to crack propagation stage, beyond that only failure load is noted. Pulse velocity V (m/sec) is then measured from the following relation.

$V = \frac{L}{T}$; where L is distance between pulse generating and receiving transducer (m) and transit time T (sec) measured electronically.

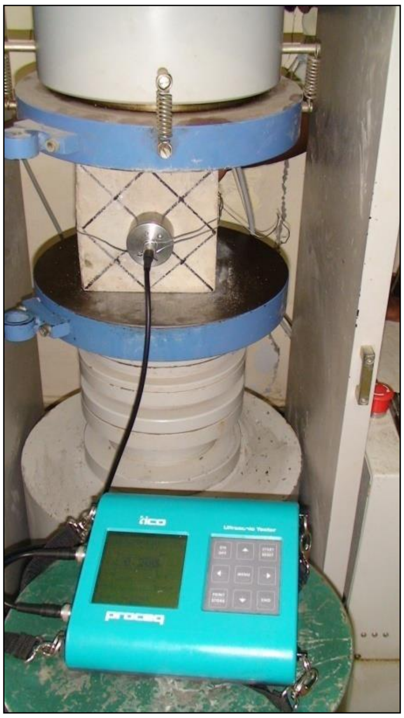

Figure1. Experimental Test set up.

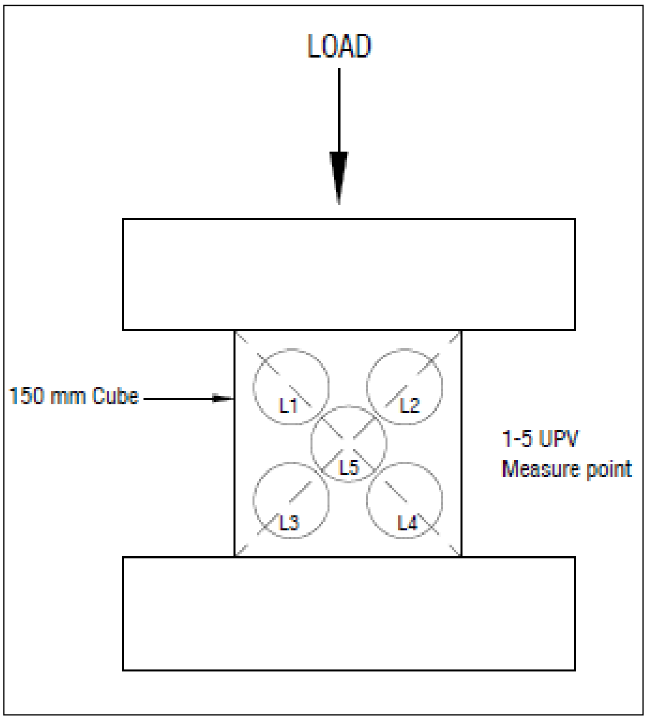

Figure 2. UPV measure locations.

3. Field Investigation

3.1. Influence of Stress

Effect of stress on UPV variations under repeated loading was investigated by T.T.Wu and T.F.Lin [7] and they concluded that compressive-stress induced velocity change of concrete is greater than that of mortar specimen. In case of cyclic loadings, they found that the generation of micro cracks around the coarse aggregate decreases the ultrasonic pulse velocity of concrete. S. Popovics et al. [8] studied the effect of uni-axial compression on pulse velocity and they found that there is increase in direct wave velocity for compressive stress up to 20% of the ultimate strength, from 20% to 70% of the ultimate strength there is no significant change in the velocity. Based on reduction of the apparent modulus of elasticity with increase in stress, especially during initial loading, stresses prevailing in the concrete of a structure do not have to be accounted when UPV is used for assessing the quality [8]. However, in present study, RC column assessed in field using UPV indicates that stressed state of concrete can influence the qualitative assessment as columns are subjected to sustained compressive loads during the intended service life.

3.2. Field Concrete Pulse Velocity Assessment

Pulse velocities are examined in 42 m tall RC concrete columns constructed using M40 grade [mix proportion as listed in Table 1], of a high bay structure. Typical arrangement of various structural elements of the high bay frame is shown in Figure 4. Pulse velocity of plain concrete is assessed in a column at three surrounding locations (one location along short and two locations along long sides of each column) using direct wave traverse. Two significant aspects are considered while selecting ground storey columns for velocity measurements. Firstly, induced moments at middle height of ground storey column is relatively less in magnitude and therefore axial stress variation across the column section is insignificant. Secondly, spacing of column stirrups reinforcement available (250 mm c/c) is twice than that of storey end regions, which is adequate for direct wave transmission through plain concrete, as shown in Figure 3.

Velocity in plain concrete sample measured at laboratory is around 4000 – 4800 m/sec and hence the wave length would be in the range of 74 – 88 mm. And therefore pulse interference through steel reinforcement is ruled out. UPV probes are kept over column concrete surface such that they are within the column stirrup spacing. It is achieved by transferring stirrup levels to a known location before formwork is placed. Alternatively a rebar locator can be used to locate the stirrups. Pulse velocity is assessed at specified three locations of column, as shown in Figure. During eight stages of frame construction and at one stage of entire infill wall construction, velocities are measured at each stage over a period of 426 days.

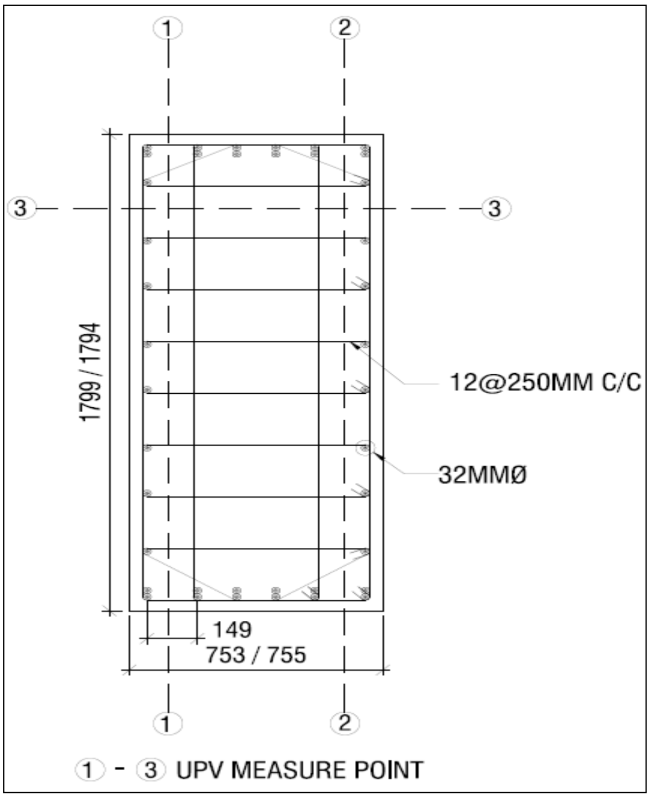

Figure 3. Cross section of RC column and UPV measured points.
(All dimensions in "mm")

3.3 Load Assessment

In present study, influence of axial stress is focused for measuring the relative variation of pulse velocity in columns which are high important structural elements of a tall high bay building. For fixed loads like self-weight and infill loads, columns examined herein are experiencing compressive force with relatively very less moment forces, as listed in Table 2. During construction, effect of fixed loads [self-weight of column, tie beams, infill and roof slab and slenderness effect] acting in the columns at respective stages are considered in this study. Column element forces including P-delta effect for each stage of construction are obtained from analytical models using ETABS 9.1 software. Transmitted loads due to construction of structural and block wall elements up to 42 m height of columns, at UPV measuring point marked in the Figure 2, are listed in Table 2. Compressive stress including creep effect experienced in columns is arrived as per below procedure [2].

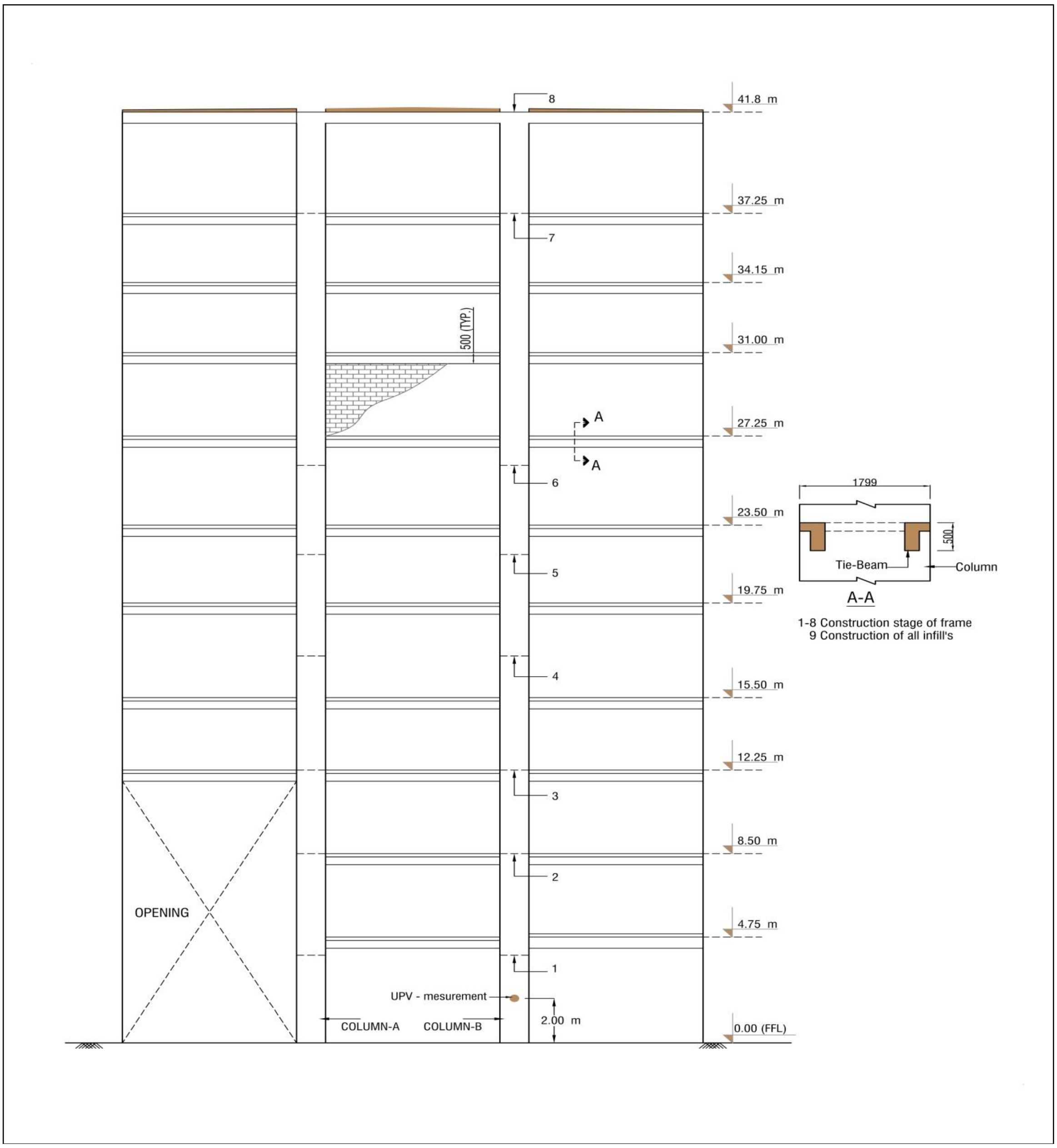

Figure 4. Frame elevation and construction sequence.

$$E_c = 5000 \sqrt{f_{ck}} \tag{1}$$

Where E_c is short term stress-strain modulus of concrete and f_{ck} is the characteristic cube compressive strength at 28 days in Mpa

$$P = \sigma_{cc} A_c + \sigma_{sc} A_{sc} \tag{2}$$

Where P is axial compression load in Newton; σ_{cc} is concrete stress in compression (MPa); A_c and A_s are area of concrete and steel reinforcement respectively (sq.mm). σ_{sc} is reinforcement steel stress in compression (MPa), obtained by multiplying m times σ_{cc} ;. Where m is modular ratio of stress-strain modulus of steel E_s to that of concrete E_{cc} (MPa).

$E_s = 2\times10^5$ MPa and E_{cc} is stress-strain modulus of concrete including creep effect, computed as below.

$$E_{cc} = \frac{E_c}{1+\phi} \tag{3}$$

Age factor ϕ varies like 2.2, 1.6 and 1.0 for 7, 28 and 365 days respectively.

Table 2: CONSTRUCTION SEQUENCE AND COLUMN STRESS WITH CREEP EFFECT

Construction sequence		Column A				Column B			
Stage	Time of construction , (days)	M 1 (kN-m)	M2 (kN-m)	Axial Load (kN)	Concrete stress σ_{cc} (Mpa)	M1 (kN-m)	M2 (kN-m)	Axial Load (kN)	Concrete stress σ_{cc} (MPa)
1	28	-0.11	13.2	117.3	0.07	-0.8	4.3	146.3	0.08
2	84	-0.42	13.28	343.6	0.2	-2.36	6.63	402.3	0.23
3	118	21.3	9.71	723.3	0.42	26.3	3.74	798.8	0.46
4	137	1.83	9.09	1038.9	0.6	7.99	3.02	1117.9	0.65
5	155	-1.17	9.88	1220.4	0.71	1.63	3	1301.4	0.75
6	169	-5.86	9.04	1403.4	0.81	-6.81	3.01	1483.9	0.86
7	200	-17.63	8.8	1812.7	1.05	-21.5	3	1895.6	1.1
8	275	-18.34	8.9	2188.7	1.27	-1.85	1.7	2254.9	1.3
9*	426	-25.83	14.26	2422.3	1.4	-4.62	-5.8	2563	1.48

* All storey solid block infill are constructed in stage 9.
M1& M2 are moment about major a minor axis respectively.

5 Results and Discussion

UPV assessed in concretes at free and stressed state includes (i) effect of water to cement ratio which is directly affects the strength, (ii) curing period and (iii) magnitude of acting stress. These factors were first studied in laboratory specimens and then examined at field column concrete.

5.1. Effect of Strength and Curing conditions on Pulse Velocity

Pulse velocity, measured perpendicular to the loading direction, is increasing when curing period and compressive strength are increased as shown in Figure 5- a to Figure 7c. After 7 days of water curing, velocity is in the range of 4.2- 4.3 km/ sec for M25 grade of concrete and 4.3 – 4.4 km/sec for M30 grade and for M40 grade it is in the range of 4.6 to 4.8 km/sec, when no load is acting as shown in Table 3. The reason for velocity increase in case of higher grade is due to presence of relatively less capillary voids and denser transition zone.

Table 3. CONCRETE PULSE VELOCITY AT NO-LOAD CONDITION.

Concrete grade	Specimen No.	Age of test (days)	Mean Velocity* (m/sec)
M25	1	7	4260
	2		4276
	1	14	4390
	2		4386
	1	28	4430
	2		4377
M30	1	7	4310
	2		4390
	1	14	4517
	2		4585
	1	28	4516
	2		4610
M40	1	7	4680
	2		4710
	1	14	4730
	2		4690
	1	28	4760
	2		4790

*Mean of UPV measured at 5 locations of cube as shown in Figure 2.

Since curing period promotes the hydration process in concrete, 14 days cured concrete shown further increase in velocity but it is insignificant in case of M30 and M40 at 28 days cured samples. From Figure 5-b & Figure 5.c, for unstressed condition, pulse velocity does not vary for M25 grade of concrete cured for 14 and 28 days periods. In case of M40 grade, velocity increase at 28 days is significance than that of 4 days period due to densely packed availability of binder at all ages. Increasing tendency observed with respect to age of concrete is having good agreement with the exponential relation between UPV and curing age proposed by L.M.del Rio[9].

At unstressed state, pulse velocity reduction observed for M25 grade mixes are confirming the effect of water content in concrete on ultrasonic propagation as investigated by Estuzo Ohadaira et.al [10] and S.A Abo-Qudais [11]. Laboratory specimens are tested at saturated surface dry (SSD) condition so that near surface moisture variation within the specimen can be eliminated. However such controlled moisture uniformity is not viable for all in-situ column concrete tests. For example, M40 grade sample cured in immersed water shown 4.7 to 4.8 km/sec which are around 500 m/sec higher velocity than that of observed in column concrete with initial stress as shown in Table 4.

Table 4: Pulse velocity Measured at Field

Column A			Column B		
Concrete Age (Days)	Stress (Mpa)	UPV (m/sec)	Concrete Age (Days)	Stress (Mpa)	UPV (m/sec)
28	0.09	4164	28	0.1	4234
84	0.25	4157	84	0.28	4182
118	0.53	4144	118	0.55	4178
137	0.77	4109	137	0.78	4161
155	0.9	4099	155	0.9	4167
169	1.04	4084	169	1.03	4159
200	1.34	4082	200	1.32	4128
275	1.62	4077	275	1.57	4135
426	1.79	4014	426	1.78	4055

Concrete cubes cured for 28 days and then tested for pulse velocity show velocity increase up to 6, 6.5 and 7% than that of cubes axially loaded around 5-7 Mpa for grades M25, M30 and M40 respectively. Measured velocity changes in cubes loaded at each stage and thereby gradual increase in concrete stress caused reduction in pulse velocity, relation follows second order polynomial as shown in regression plots through Figures 5-a to 5c, Figures 6-a to 6-c and Figures 7-a to 7-c for M25, M30 and M40 grades of cubes respectively. It is to be noted that for stress range up to 5 Mpa there is growth in the velocity and thereafter it is diminishing. This trend is observed irrespective of the curing age and grade of concrete. Reason for velocity increase at initial stress stage is probably due to the consolidation or axial shortening of the specimen prior to significant lateral expansion likely to occur in the direction perpendicular to loading.

However this effect was not sustained for further increase in axial loads due to significant lateral strain and probable growth of micro cracks in concrete. Plots Figure 5.a to Figure 7-c indicate that the UPV measured at location L5 is lower and falls below the regression curve for all grades and curing periods. The influence of shear friction and similar stress field at location L1 to L4 of cube specimen attribute for closely distributed UPV measurements where as it is inconsistence with results obtained at L5 location. This can be inferred from readings which are mostly scattered from the regression line. Therefore location of UPV measurements at stressed condition for a lab specimen becomes essential criteria for correlation.

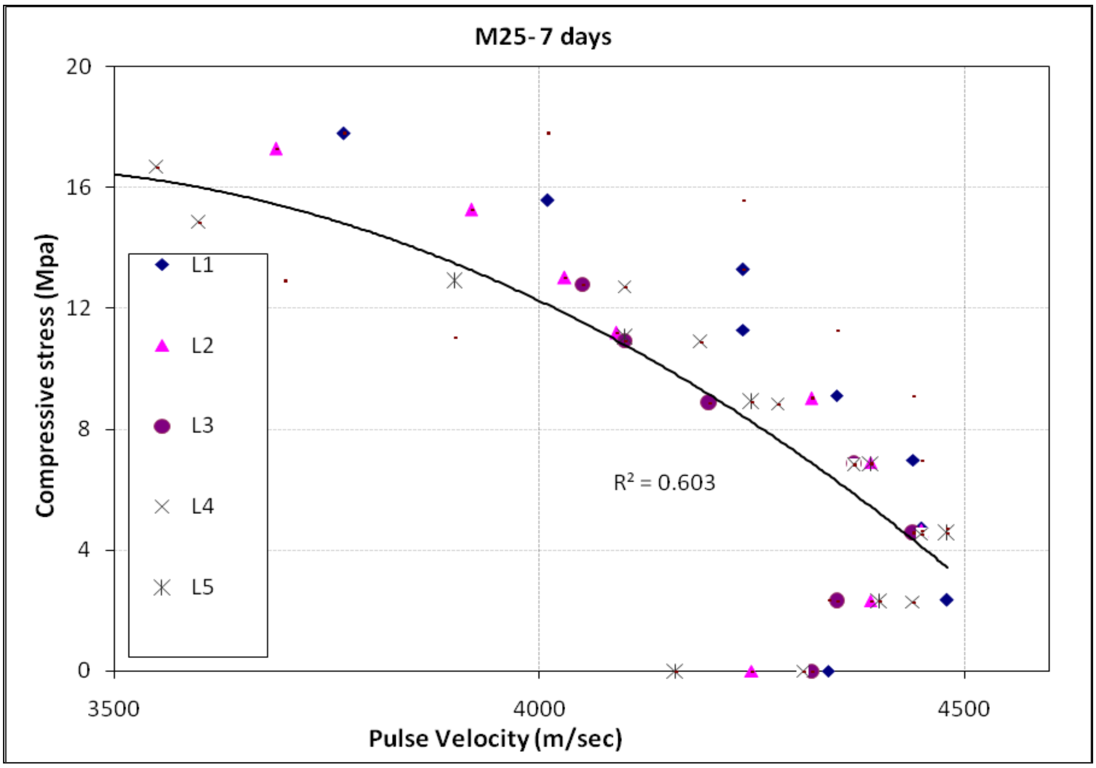

Figure 5-a. Velocity response for M25 grade 7 days cured concrete.

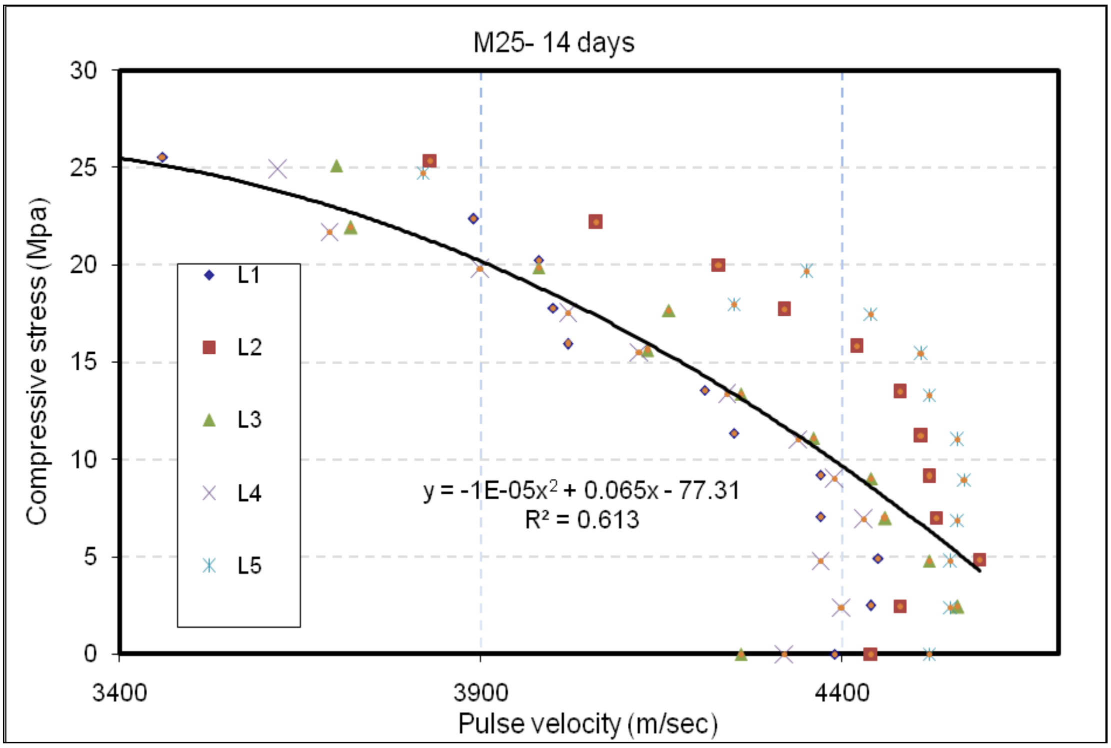

Figure 5-b. Velocity response for M25 grade 14 days cured concrete.

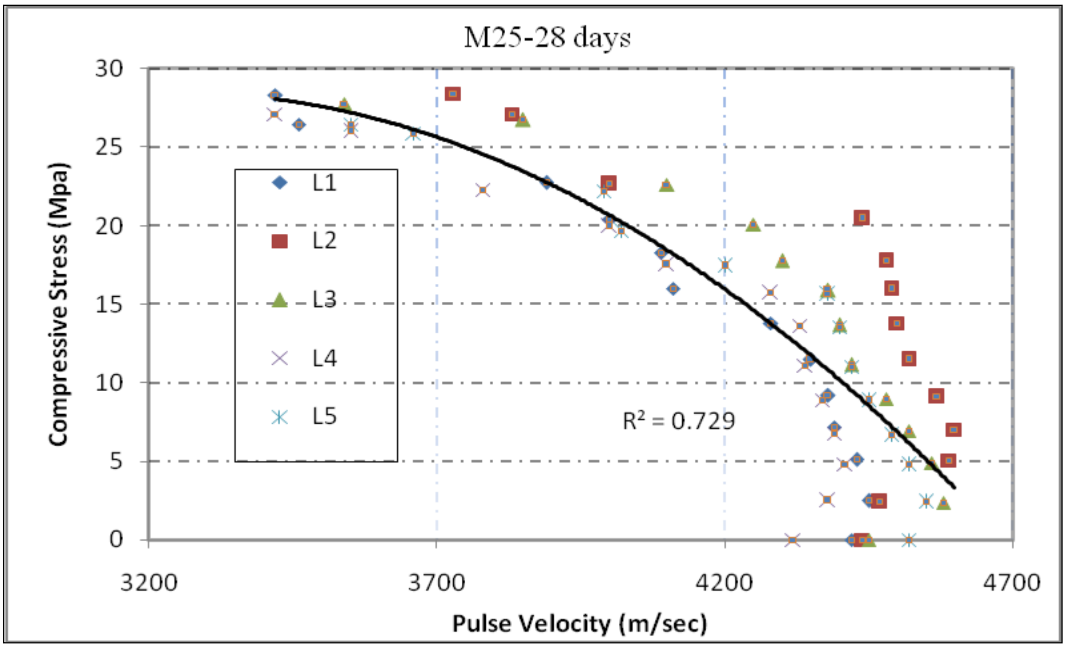

Figure 5-c. Velocity response for M25 grade 28 days cured concrete.

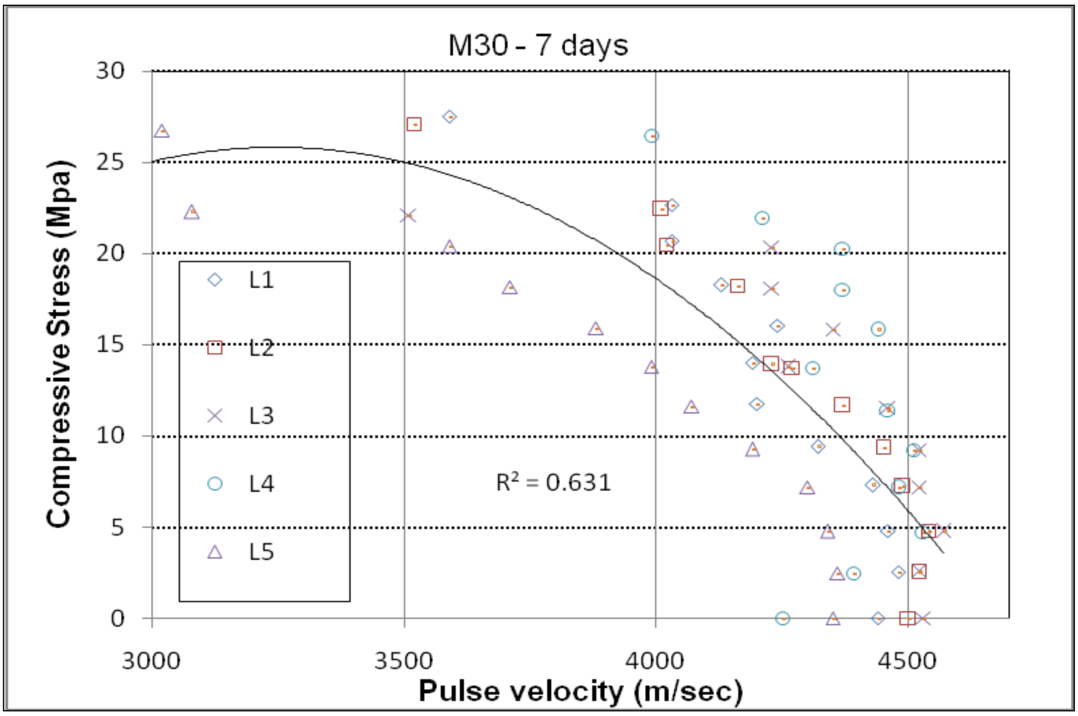

Figure 6 –a. Velocity response for M30 grade 7 days cured concrete.

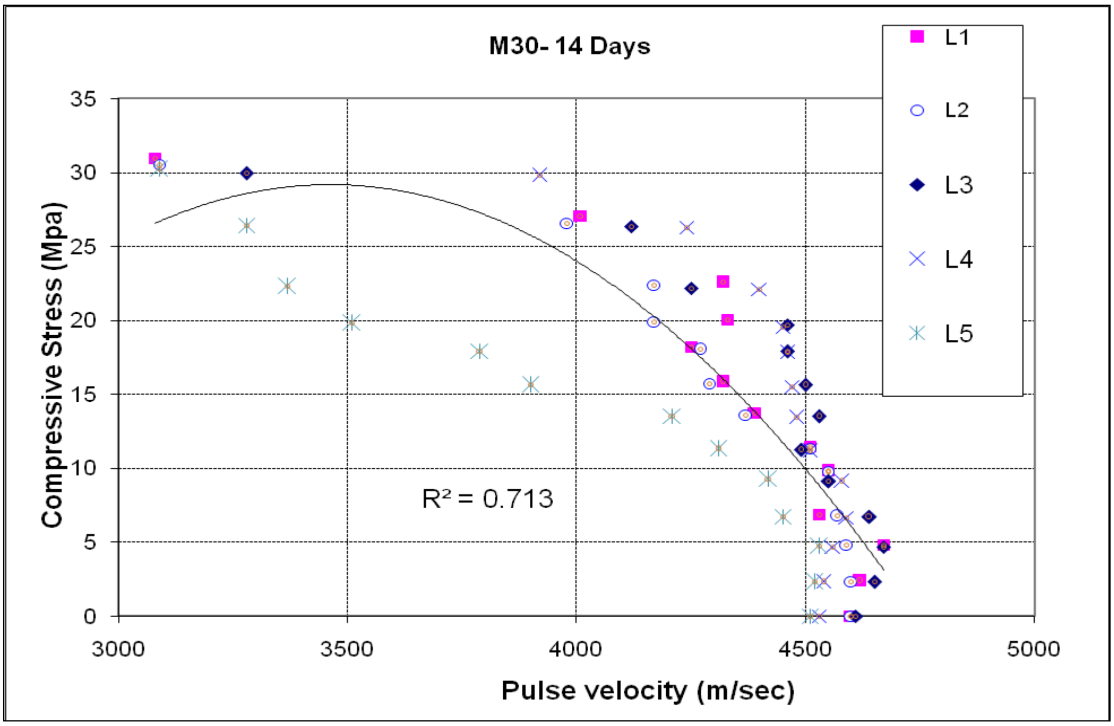

Figure 6-b. Velocity response for M30 grade 14 days cured concrete.

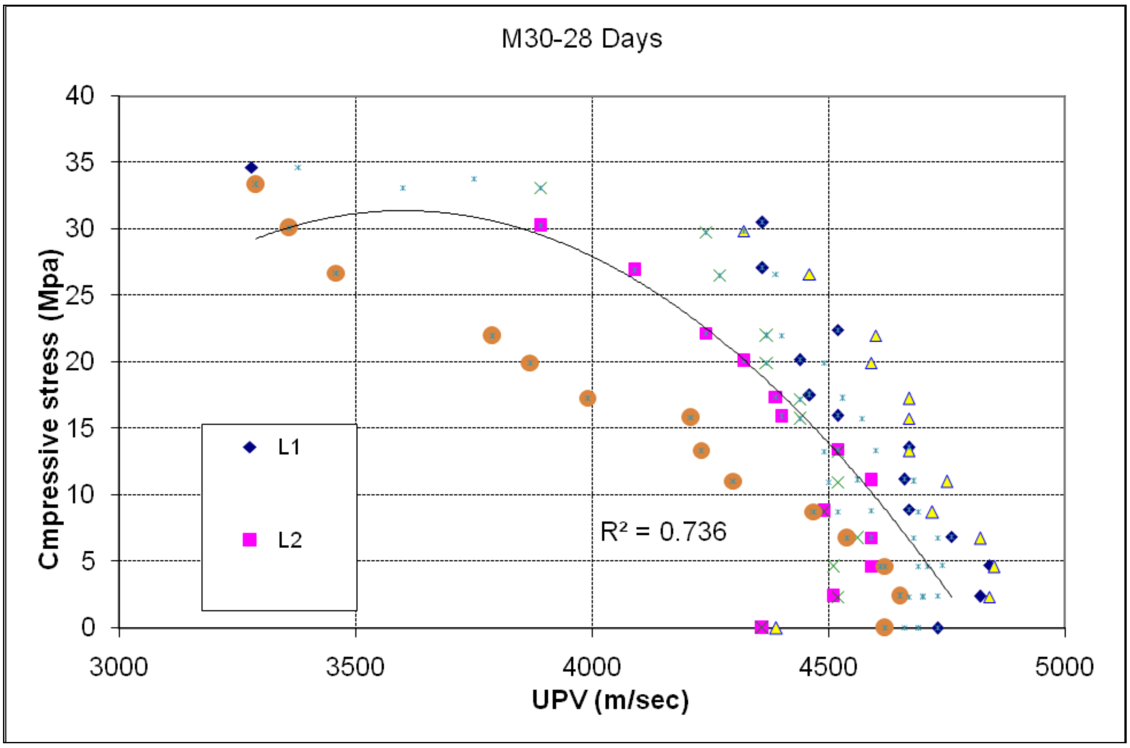

Figure 6-c. Velocity response for M30 grade 28 days cured concrete.

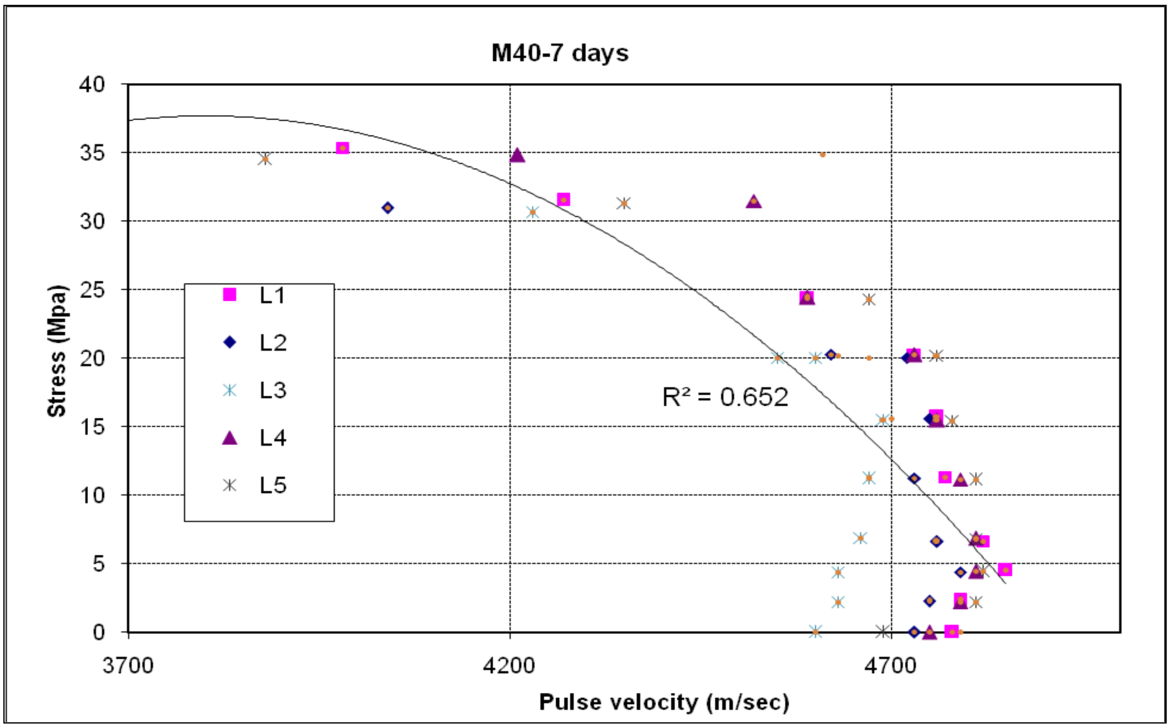

Figure 7-a. Velocity response for M40 grade 7 days cured concrete.

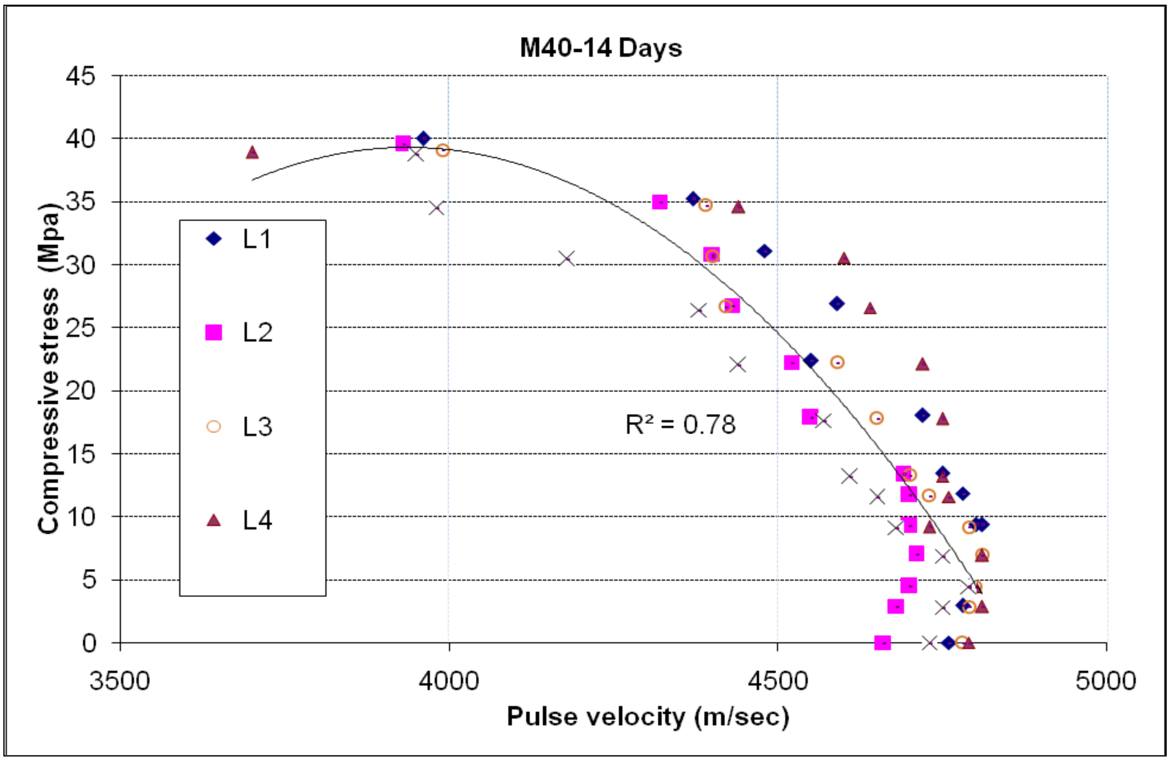

Figure 7-b. Velocity response for M40 grade 14 days cured concrete.

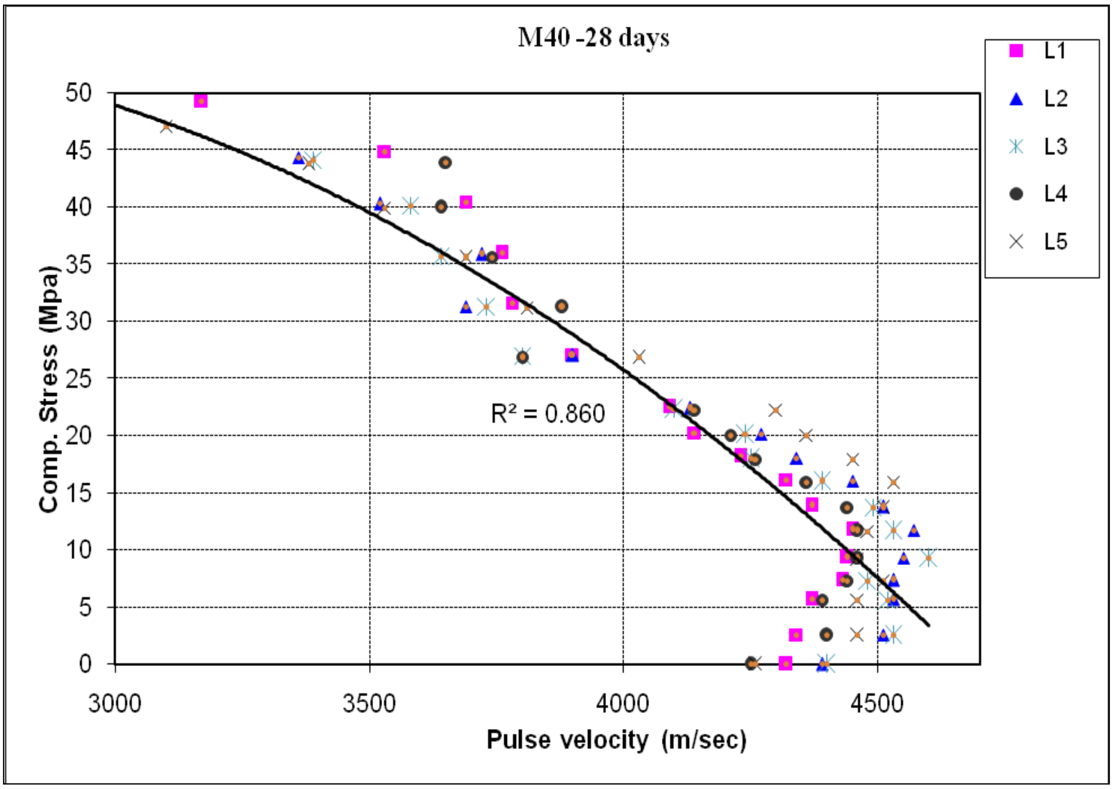

Figure 7-c. Velocity response for M40 grade 28 days cured concrete.

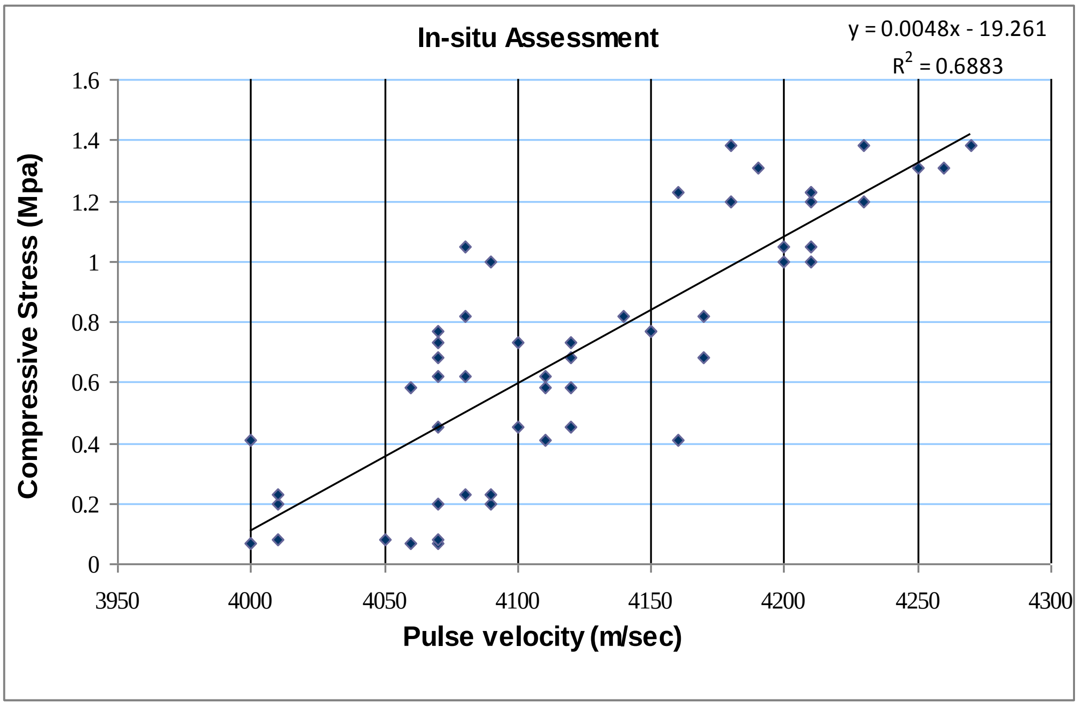

Figure 8. Long term Pulse velocity for Column concrete.

5.2. Field Results

Measured velocity for laboratory based and field concretes are differing due to (i) probable segregation and inadequate or over compaction (ii) surface moisture condition (iii) confinement effect due to stirrup reinforcement (iv) rate of loading (v) shrinkage and creep effects (vi) temperature loads and (vii) age at which concrete is loaded. Concrete shrinkage and presence of voids or honeycombs can reduce the velocity. However when degree of hydration is attaining its maturity, there may be an increase in pulse velocity. Load effects due to creep and temporary loads at the time of construction, nominal service wind loads on tall building are the additional factors which could alter the pulse velocity measured at field when comparing to ideal laboratory tests conditions. Computed stress including creep effect in columns for different stage of construction is listed in Table 2.

Despite the known influencing factors, pulse velocity observed at field was increasing up to 5% when axial stress gets increased due to transmitted loads as shown in Figure.8. Increase in velocity for the stress range of 1.4 Mpa observed in the column concrete is within the influence stress range [i.e 5 Mpa] witnessed in laboratory test specimens. Hence pulse velocities for in-situ concrete is higher than that of their bench-mark data tested in unstressed state measured at elsewhere.

6 Conclusions

The following conclusions are drawn from the laboratory and field investigations:

(i). Increase in pulse velocity was observed when compressive strength of concrete is increasing. Increasing trend was observed for M25 and M30 grades significantly when their moist curing period increased from 7 to 28 days. However velocity difference is insignificant in the same interval for M40 grade.

(ii). Cube specimens subjected uni-axial compression indicates that the pulse velocity measurements are in the order of 5-6% higher than that of unstressed state irrespective of their compressive strength.

(iii). Field UPV measurements indicate that for concrete columns axially compressed around 1.4 MPa can exhibit 2- 5% higher pulse velocity than that of unstressed state.

(iv). Both laboratory and long term field investigations confirm that UPV measured for relative quality of axially stressed concrete in compression should be correlated from the corresponding lab specimens with same state of stress.

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