Prediction of Compressive Strength of Reinforced Concrete Structural Elements by Using Combined Non-Destructive Tests

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ABSTRACT

This research is devoted to investigate relationship between both Ultrasonic Pulse Velocity and Rebound Number (Hammer Test) with cube compressive strength and also to study the effect of steel reinforcement on these relationships.

A study was carried out on 32 scale model reinforced concrete elements. Non destructive testing campaign (mainly ultrasonic and rebound hammer tests) made on the same elements. About 72 concrete cubes (15 X 15 X15) were taken from the concrete mixes to check the compressive strength.. Data analyzed. Include the possible correlations between non destructive testing (NDT) and compressive strength (DT) Statistical approach is used for this purpose. A new relationships obtained from correlations results is given.

Keywords: Non-destructive investigations, concrete, SonReb Methods, Combined Methods

استنباط مقاومة انضغاط الاعضاء الخرسانية المسلحة باستخدام الفحوص اللااتلافية المدمجة

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الخلاصة

ان الغرض من هذا البحث هو ايجاد علاقة رياضية بين كل من سرعة الامواج فوق الصوتية ورقم ريبوند مع مقاومة انضغاط المكعبات الخرسانية وكذلك دراسة تاثير حديد التسليح على مثل هذا النوع من العلاقات

اجريت الدراسة على 32 نموذجا خرسانيا مسلحا بابعاد مختلفة. اخذت مجموعة من الفحوص اللااتلافية على نفس النماذج. تم اخذ 72 مكعبا خرسانيا اثناء عملية الصب للتاكد من المقاومة التصميمية للخلطات الخرسانية بعد ذلك ربطت النتائج المستحصلة من كل من الفحوص اللااتلافية ومقاومة الانضغاط الخاصة بالمكعبات الخرسانية بعلاقة رياضية بواسطة برنامج الاكسل . تم التوصل الى علاقات جديدة خاصة بموضوع استنباط مقاومة انضغاط الخرسانة المسلحة بواسطة دمج عدة من الفحوص اللااتلافية.

الكلمات الرئيسية: الفحوص اللاأتلافية، الخرسانة، طريقة سونرب، الطريقة المشتركة

INTRODUCTION

With good care in the design and production of concrete mixture, many variations may happen in the conditions of mixing, degree of compaction or curing conditions which make affect the final production. Usually, concrete produced have been assessed by standard tests to find the strength of the hardened concrete. Concrete is a non-homogeneous material and even if a uniform distribution of its component is assumed. It is very difficult to develop a model correctly to evaluate its onsite mechanical behaviour. Compressive tests of concrete cores also gives results affected by uncertainty and strongly dependent on reference standard used. Several non-destructive testing methods have been developed in the past for onsite concrete strength assessment. Among them Rebound Hammer and Ultrasonic Pulse Velocity (UPV) tests are the most commonly used in practice though their reliability and usefulness is quite controversial **[Nash't et al., 2005].** A good calibration of the methods is only possible if a good knowledge of the concrete properties is already achieved, i.e. it is necessary to use some destructive tests to obtain such information. When assessing wide non-homogeneous structure such limit can be crucial from an economical and practical point of view. An improvement of the reliability of non-destructive tests could be obtained by their combination as well as in the SONEB method (both ultrasonic pulse velocity and Hammer test). Depending on a wide number of experimental determinations under laboratory condition different regression models have been proposed here. It was evidenced that a preliminary knowledge of concrete characteristics is of great importance to optimize regression model. **[Proverbio and Venturi, 2005].**

The need for systematic assessment of in situ concrete strength usually arises when the safety margin of an existing structure has to be evaluated or if there are concerns about hardened concrete quality of new constructions. The choice among which destructive, semi-destructive (e.g. coring) or non-destructive tests (e.g. ultrasonic pulse velocity, rebound number, should be adopted, has to account for precision requirements, survey extension, available time and cost **[Nash't et al., 2005]**. Briefly, rebound hammer (Schmidt hammer or Swiss hammer, invented in 1948) estimates surface strength as a function of resiliency, measuring the kinetic energy that is not dissipated by hammer impact, on an arbitrary index; ultrasonic pulse velocity, giving an integral measure over length, exploits the relationship between concrete stiffness and strength, since stress waves velocity is also related to concrete Young modulus **[Nash't et al., 2005]**.

The estimate of a single concrete strength value by means of more than one test type, commonly referred to as “combined method **[Mantegazza et al., 2002]**.

1.2 Objective of the Study

The main objectives of this investigation is to find a relationship between ultrasonic pulse velocity and cube compressive strength, Rebound Number and cube compressive strength and both ultrasonic pulse velocity and Rebound Number with cube compressive strength. The main goal of this study is to investigate the effect of reinforcement on these relationships.

EXPERIMENTAL PROGRAM

The details of the experimental program includes details of the materials used, mix proportions, preparations, curing, and testing of specimens.

These experimental works is carried out to find a fitting equation between non-destructive testing and the compressive strength of reinforced concrete in structural member.

Materials

The properties of materials used in any structure are of considerable importance **[Neville 1995, and ACI 211]**. Standard tests according to the American Society for Testing and Materials (ASTM) and Iraqi specifications (I.Q.S.) have conducted to determine the properties of materials.

Cement

Both Ordinary Portland Cement (OPC) and Sulfate Resisting Cement (SRPC) manufactured in Iraq with a commercial name of (Tasluga and Al-jesser) are used for concrete mixes throughout the present work. This cement complied with the Iraqi specification **[IQS, No.5:1984]**. Testing of cement is conducted in the National Center for Construction Laboratories and research. The physical properties and chemical analysis of the cement used are given in the **Table.1**. Also, the compounds of cement calculated according to Bogue equations, **[Neville, 1995]** are listed in **Table (1)**.

Water

Tap Water is used for both mixing and curing of concrete, and the amount of it is based on concrete mix design.

Coarse Aggregate

The coarse aggregate is brought from Al-Nibaii area with a maximum size of (19.5) mm. then recombined to satisfy the **[Iraqi specification No.45/1984]**. The grading and other properties of this type of aggregate are shown in **Table.2**

Fine Aggregate

Natural sand from Al-Akhaider in Iraq is used for mixes. The physical and chemical properties of the sand are listed in **Table.3**; the sand is complying with Zone (2) according to the **[IQS No.45 (1984)].**

Steel Reinforcement

Steel bars are used throughout this work are manufactured in Ukraine. The physical properties are shown in the **Table.4** and the steel bars are grade 75 according to **[ASTM – A615]**.

Mix Design and Proportions

The concrete mix is designed according to **[ACI 211.1-91**] standard as shown in **Table.5.**

Casting Moulds Preparation

Four types of plywood forms are used in this investigation as shown in Plate (3.1). The first type with dimensions (50X30X30) cm is used as beam specimen. The second type with dimension (30X30X50) cm is used as column specimen. The third type with dimension (60X60X40) cm is used as foundation specimen. The fourth type with dimension (60X60X15) cm is used as slab specimen.

Mixing Procedure

Concrete is mixed in a drum rotating laboratory mixer with a capacity of (0.5 m3). The interior surface of the mixer is cleaned before placing the materials. Mixing method is important to obtain the required homogeneity of concrete mix; the mixing was done according **[ASTM C192]**.

Compressive Strength Test

Compressive strength test is carried out according to **[ASTM C-39 -01]**, using a digital testing machine with a capacity of (2000 kN) as shown in Plate 3-5. Three cubes of (150×150×150 mm) and three core specimens of (100 diameter × different high mm) are tested from each mix.

Ultrasonic Pulse Velocity Test (U.P.V)

Ultrasonic Pulse transit times are measured by direct and indirect transmission method as shown in **Plate.1**. This test is carried out according to **[ASTM C597-02]**

Rebound Hammer Test

Schmidt hammer is used to estimate the surface hardness of concrete specimens by recording the rebound number, which can be considered as a measure of the concrete strength and percentage of voids. Schmidt hammer type (Proceq) is used which is shown in **Plate.2**. The test method is prescribed by **[ASTM C 805-02]**.

Obtaining Drilled Cores

The coring process (Hilti Diamond Coring System DD-250EE) is carried out according to **[ASTM C42-03]**, set perpendicular to the laid surface of the specimens as shown in **Plate.3**.

RESULTS AND DISCUSSION

Ultrasonic Test Results

The research covers four groups of each type of elements (Columns, Beams, Foundations & Slabs) which varies with compressive strength (15, 25, 35, and 40) MPa, each group contains two elements which varies with the details of steel reinforcement (S1, S2)
It can be seen from **Table6** that the pulse velocity and the ratio between indirect pulse and direct pulse increase with the increasing of compressive strength that is because the w/c ratio decreases from 0.790 to 0.395, the density increase from 2395 to 2456 kg/m3.

It is clearly seen from **Tables 6, 7 and 8** (case no.1) (the pulse path at the middle of the element) the pulse velocity was approximately similar and there is no significant difference between Columns, Beams and Foundation, that’s because the pulse path is far from the steel reinforcement.

While pulse velocity measured in reinforced concrete in the vicinity of reinforcing bars is usually higher than in plain concrete of the same composition. This is because the pulse velocity in steel may be up to twice the velocity in plain concrete and, under certain conditions, the first pulse to arrive at the receiving transducer travels partly in concrete and partly in steel [BS 1881-Part 203].

So at case No.2 **Tables 6, 7 and 8** (pulse path perpendicular to the steel reinforcement) the pulse velocity increase from 2% for members with 15 MPa compressive strength to 6% for members with 40 MPa compressive strength for both Columns and Beams members, while the increment in Foundations was from 2% for members with 15 MPa compressive strength to 4% for members with 40 MPa compressive strength, the increment at case No.2 for Column and Beams was higher than the increment in Foundation because the ratio Ls/W is equal to (0.160 for S1, 0.167 for S2) for Columns and Beams while its equal to (0.106 for S1, 0.125 for S2) for foundation.

When the pulse path parallel to the steel reinforcement, it indicated from case No.4 [Tables (6) and (7)] that the pulse velocity increase from 3% for members with compressive strength 15 MPa to 8% for members with 40 MPa compressive strength for both columns and beams members [Ls/w)Column =Ls/w)Beam = 0.84].

In spite of Ls/w) Foundation is approximately similar to that ratio in Column and Beam = 0.86, it can indicated from case No.3 **Table.8** that the increment in pulse velocity for Foundation is higher and it start from 4%for members with compressive strength 15 MPa reaching to 10%for members with compressive strength 40 MPa depending on numbers, diameters and the orientation of the steel reinforcement.

The increasing in direct pulse velocity is bigger than the increasing in indirect pulse velocity and that’s clearly appears at **Table.6** this is because the propagation of surface waves is restricted to a region near the boundaries that is to the free external surface of the material.

The linear and non-linear simple regression between compressive strength (dependent) with direct and indirect pulse velocity (independent) was conducted to **[ACI 228.2R-98]** and the equations fixed at the curves on **Figures.1 to 4**.

Hammer Test results

Rebound number was taken for all types of element and illustrated in **Table.10**. It is clearly seen from **Figure.5** that is no significant difference in rebound number between all types of elements. On other hand there is a significant difference between the total proposed Equation and Raouf Equation because Raouf equation was done on concrete cubes samples while the total proposed equation was done on concrete scale model samples.

Combined method

The limitations of a combined method are usually those pertained to the limitation of each component test, except when a variation in the properties of concrete affects the component test results in opposite directions. For example, an increase in moisture content increases pulse velocity but decreases the rebound number. In this case, the errors can be self-correcting. The more information that can be obtained about the concrete ingredients, proportions, age, curing conditions, etc. the more reliable the estimate is likely to be. When testing suspect quality concrete of unknown composition, it is highly desirable to develop a prior correlation relationship.

It is suitable to use the equation which was obtained by linear multi-regression and illustrated in **Table.11**:

CONCLUSION

1- For the pulse path at the middle of the element, the pulse velocity was approximately similar and there is no significant difference between Columns, Beams and Foundation.

2- For the pulse path 3Φ far from the steel reinforcement, the effect of steel reinforcement is approximately disappears for both condition parallel and perpendicular on steel reinforcement.

3- For the pulse path perpendicular on steel reinforcement, the pulse velocity increase from (2% for cubes compressive strength equal to 15 MPa) to (7% for cubes compressive strength equal to 40 MPa) with the increasing of number and the diameter of bars (increasing of the ratio between the length of pulse in steel reinforcement to the total length of pulse in sample) (Ls/W).

4- For the pulse velocity parallel to the steel reinforcement, the pulse velocity also increase from (3% for cubes compressive strength equal to 15 MPa) to (10% for cubes compressive strength equal to 40 MPa) with the increasing of number and diameter of steel reinforcement (increasing of the ration between the length of pulse in steel reinforcement to the total length of pulse in sample) (Ls/W) but the most effecting factor is the distribution of steel reinforcement with respect to the location of the ultrasonic pulse velocity reading.

5- The increasing of pulse velocity for the pulse path parallel to the steel reinforcement is always higher than the increasing of pulse velocity for pulse path perpendicular to the steel reinforcement (Ls/w parallel > Ls/W perpendicular).

6- The ratio between indirect pulse velocity and direct pulse velocity increase from 0.782 to 0.853 when the compressive strength of cubes increases from 15 to 40 MPa

7- R^2 for combined method Equation is higher than R^2 for both Ultrasonic Pulse Velocity Equation and Hammer Equation, so if the evaluation for existing structure is needed, it is better to used the combined method.

REFERENCE

- Proverbio and Venturi, (2005)," **Reliability of nondestructive tests for onsite concrete strength assessment**" 10DBMC International Conférence On Durability of Building Materials and Components LYON [France] 17-20 April 2005.
- Nash't I. H., A'bour S.H. and Sadoon A.A.,(2005)," **Finding an Unified Relationship between Crushing Strength of Concrete and Non-destructive Tests**", www.ndt.net - 3rd MENDT - Middle East Nondestructive Testing Conference & Exhibition - 27-30 Nov., Bahrain, Manama.
- Mantegazza, Chiara N. and Sergio S., (2002),)," **In situ concrete strength testing by non-destructive combined methods with one, two and three variables (rebound number, ultrasonic pulse velocity, Windsor probe)**".
- American Concrete Institute Committee 211.1-21, "**Proportions for Normal, Heavyweight and Mass Concrete**", Reported by ACI committee 211, ACI Manual of Concrete Practice.
- Neville A.M. and Brooks, J.J., "**Concrete Technology**", Second Edition, Longman Group U.K. Limited, 2010.
- Neville A.M., "**Properties of Concrete**", Fourth and Final Edition, Longman Group Limited, England, 1995.
- Newman, J. and Choo, B.S., "**Advanced Concrete Technology: Concrete Properties**", First Edition, Elsevier Ltd., Oxford, 2003.
- Iraqi Organization of Standards, IOS 45: 1984, for **Aggregate**.
- Iraqi Organization of Standards, IOS 5: 1984, for **Portland Cement**.
- ASTM C-617, (2002), "**Standard practice for capping cylindrical concrete specimen**", Annual Book of ASTM Standards American Society for Testing and Materials, vol.04.02.
- ASTM A-615, (2002), "**Standard Specification for Deformed and Plain Billet-Steel Carbon Steel Bars for Concrete Reinforcement**", Annual Book of ASTM Standards American Society for Testing and Materials, vol.04.02.
- ASTM C-192 (2002), "**Making and Curing Concrete Test Specimens in the Laboratory**" Annual Book of ASTM Standards American Society for Testing and Materials, vol.04.02.
- ASTM C-39, (2001), "**Compressive Strength of Concrete Cubes**", Annual Book of ASTM Standards American Society for Testing and Materials, vol.04.02.
- ASTM C-597, (2002), "**Standard Test Method for Pulse Velocity through Concrete**", Annual Book of ASTM Standards American Society for Testing and Materials, vol.04.02.
- ASTM C-805, (2002), "**Standard Test Method for Rebound Number of Hardened Concrete**", Annual Book of ASTM Standards American Society for Testing and Materials, vol.04.02.
- ASTM C-42, (2003), "**Standard Test Method for Obtaining and Testing**

Drilled Cores and Sawed Beams of Concrete", Annual Book of ASTM Standards American Society for Testing and Materials, vol.04.02.

- ACI Committee 228(2003), "**In-Place Methods to Estimate Concrete Strength (ACI 228.1R-03),**" American Concrete Institute, Farmington Hills, MI.

Table (1) Physical and Chemical Properties of Cement

Physical Properties	Test Result		IQS (No.5:1984) limits	
	O.P.C	S.R.P.C	O.P.C	S.R.P.C
Specific Surface area, Blaine method, m^2/Kg	256	259	≥230	≥ 250
Setting time,Vicat's Method				
Initial setting , hr : min	2:30	1:39	≥ 45 minutes	
Final setting , hr : min	4:50	4:20	≤ 10 hours	
Compressive strength MPa				
3-days	16.0	19.3	≥15	
7-days	24.3	23.5	≥23	

Oxides	Percentage (%)		IQS (No.5:1984) limits	
	O.P.C	S.R.P.C	O.P.C	S.R.P.C
CaO	55	60.63	-----	-----
SiO_2	18.33	21.63	-----	-----
Fe_2O_3	3.28	4.76	-----	-----
Al_2O_3	5.88	4.19	-----	-----
MgO	1.93	2.72	≤ 5	≤ 5
SO_3	1.87	2.04	≤ 2.8	≤ 2.5
L.O.I	2.36	1.94	-----	-----
I.R	0.15	0.92	≤ 1.5	≤ 1.5
L.S.F	0.89	0.86	0.66-1.02	0.66-1.022
Compound Composition	Percentage (%)		IQS (No.5:1984) limits	

C_3S	35	32.60	-----	-----
C_2S	26.21	29.95	-----	-----
C_3A	10.03	3.06	-----	3.5
C_4AF	9.97	14.47	-----	-----

Table (2) Physical and Chemical Properties for Coarse Aggregate.

Sieve Size (mm)	% Passing Gravel	% Passing Limits (IQS: No.45) (5-20)
37.5	100	100
19.5	95.1	95-100
9.5	32.6	30-60
4.75	1.02	0-10
IQS (No.45:1984) Limits	Test Results	Properties
≤ 0.1	0.08	Sulphate content SO3 (%)
-----	2.68	Specific gravity
-----	1	Absorption (%)

Table (3) Physical and Chemical Properties for Fine Aggregate.

Sieve Size (mm)	%Passing Sand	%Passing Zone (1) Limits Sand	%Passing Zone (2) Limits Sand	%Passing Zone (3) Limits Sand	%Passing Zone (4) Limits Sand
9.5	100	100	100	100	100
4.75	91.7	90-100	90-100	90-100	95-100
2.36	76.5	60-95	75-100	85-100	95-100
1.18	58.6	30-70	55-90	75-100	90-100
0.60	41.2	15-34	35-59	60-79	80-100
0.3	18.6	5-20	8-30	12-40	15-50
0.15	9.1	0-10	0-10	0-10	0-15

Properties	Test Results	IQS (No.45:1984) Limits
Sulphate content SO3 (%)	0.45	≤ 0.5
Specific gravity	2.62	-----
Absorption (%)	3.31	-----
Fineness Modules (F.M.)	3.0	-----

Table (4) Physical Properties for Steel Reinforcement

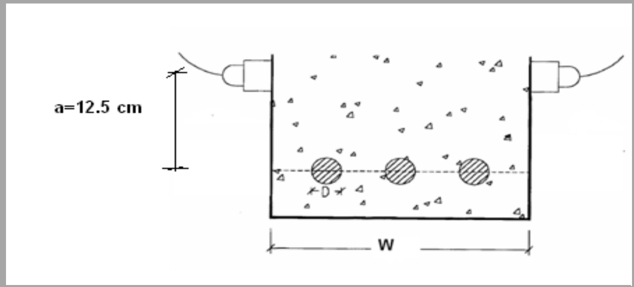
No	Nominal Dia. mm	Weight (kg)/m.l	Dia.(mm)	Yield strength N/mm^2	Tensile strength N/mm^2	Elongation	Bend test
1	12	0.859	11.81	685	795	12.0	Pass
2	12	0.859	11.81	682	792	12.2	Pass
3	12	0.859	11.81	681	792	12.3	Pass
1	16	1.571	15.97	634	714	12.7	Pass
2	16	1.571	15.97	631	712	12.8	Pass
3	16	1.571	15.97	632	713	12.8	Pass
1	25	3.778	24.76	633	737	12.5	Pass
2	25	3.778	24.76	631	735	12.6	Pass
3	25	3.778	24.76	630	736	12.6	Pass

ASTM –A615			
Grade	Min Yield strength N/mm^2	Min Tensile strength N/mm^2	Elongation %
Grade 40	280	420	11 % for Bar 10 mm 12 % for Bar ≥12 mm
Grade 60	420	620	9 % for Bar 10-20 mm 8 % for Bar 22-25 mm 7 % for Bar ≥29 mm
Grade 75	520	690	7 % for Bar 20-25 mm 6 % for Bar ≥29 mm

Table (5) Mix Proportion

Type	Cement kg/M^3	Fine agg. kg/M^3	Coarse agg. kg/M^3	Water kg/M^3	w/c	$\sum$ amount of mix proportion
C15	210	914	1105	166	0.790	2395
C25	300	880	1075	166	0.533	2421
C35	375	832	1067	166	0.422	2440
C40	420	820	1050	166	0.395	2456

Table (6) Ultrasonic Test Results for Beam

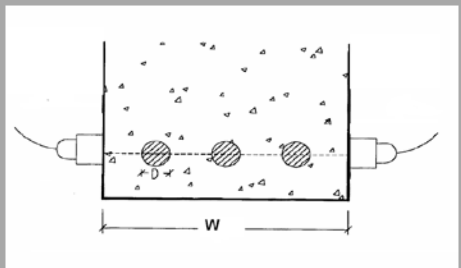


$B_{15}S_1$: Beam class 15 MPa compressive strength series No.1
Ls = length of pulse path in steel
Ls is equal to zero in case No.1
W = concrete element dimension parallel to the pulse path
a= Distance between ultrasonic transducers and steel bars
Ls/W = N/A
a/W= 0.416

Case no.1

pulse path at the middle of the element

Type	Average Direct pulse Km /sec	Average Indirect pulse Km/sec	Average (Indirect/direct) pulse	Average Compressive strength at 28 days (MPa)
$B_{15}S_1$	3.963	3.163	0.798	16.05
$B_{15}S_2$	3.982	3.168	0.796	16.54
$B_{25}S_1$	4.395	3.518	0.801	27.00
$B_{25}S_2$	4.408	3.562	0.808	27.07
$B_{35}S_1$	4.582	3.739	0.816	36.56
$B_{35}S_2$	4.613	3.780	0.819	36.62
$B_{40}S_1$	4.656	3.816	0.820	42.27
$B_{40}S_2$	4.673	3.855	0.825	42.28



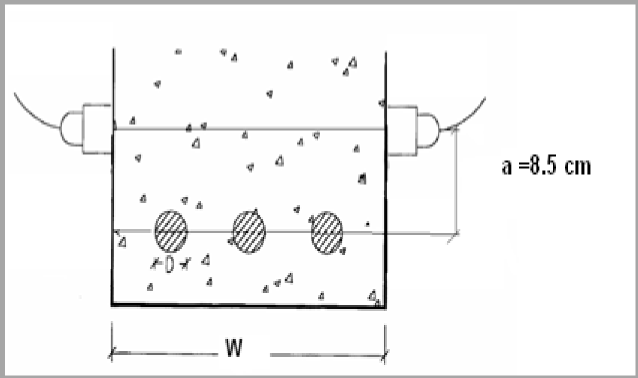
S1=Beam with 3 Φ 16 Top & bottom
S2=Beam with 2 Φ 25 Top & bottom
Ls = ∑ Φ = 3xD = 3x1.6= 4.8 cm for S1
Ls = ∑ Φ = 2xD= 2x2.5 =5.0 cm for S2
W= 30cm
Ls/W= 0.160 for S1
Ls/W= 0.167 for S2

Case no.2

pulse path perpendicular on steel reinforcement

Type	Average Direct pulse	$\frac{case\ No\ 2}{Case\ No\ 1}$ (Direct)	Average Indirect pulse	$\frac{case\ No\ 2}{Case\ No\ 1}$ (Indirect)	Average (Indirect/direct) pulse	Average Compressive strength at 28
$B_{15}S_1$	4.013	1.013	3.215	1.016	0.801	16.05
$B_{15}S_2$	4.063	1.020	3.246	1.025	0.799	16.54
$B_{25}S_1$	4.448	1.012	3.600	1.023	0.809	27.00
$B_{25}S_2$	4.525	1.026	3.647	1.024	0.806	27.07
$B_{35}S_1$	4.789	1.045	3.862	1.033	0.807	36.56
$B_{35}S_2$	4.836	1.048	3.924	1.038	0.811	36.62
$B_{40}S_1$	4.959	1.065	3.977	1.042	0.802	42.27
$B_{40}S_2$	4.984	1.067	4.026	1.044	0.808	42.28

Continuous of Table (6) Ultrasonic Test Results for Beam

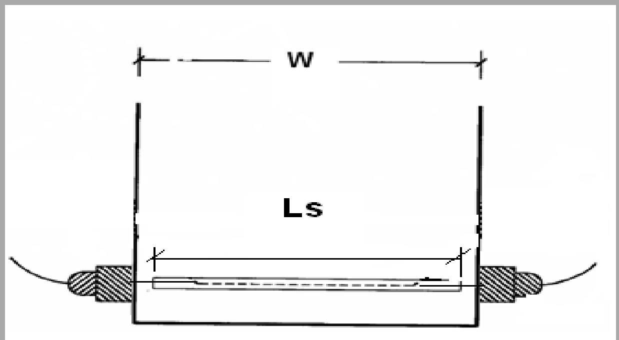


a/W = 0.283

Case no.3

pulse path on 8.5 cm perpendicular on steel reinforcement

Type	Average Direct pulse Km /sec	$\frac{case\ No\ 3}{Case\ No\ 1}$ (Direct)	Average Indirect pulse Km/sec	$\frac{case\ No\ 3}{Case\ No\ 1}$ (Indirect)	Average (Indirect/direct) pulse	Average Compressive strength at 28 days (MPa)
$B_{15}S_1$	3.984	1.005	3.163	0.998	0.794	16.05
$B_{15}S_2$	3.996	1.004	3.168	1.002	0.793	16.54
$B_{25}S_1$	4.427	1.007	3.518	1.004	0.795	27.00
$B_{25}S_2$	4.441	1.008	3.562	1.000	0.802	27.07
$B_{35}S_1$	4.562	0.996	3.706	0.991	0.812	36.56
$B_{35}S_2$	4.579	0.993	3.717	0.983	0.812	36.62
$B_{40}S_1$	4.723	1.014	3.883	1.017	0.822	42.27
$B_{40}S_2$	4.740	1.014	3.922	1.017	0.827	42.28



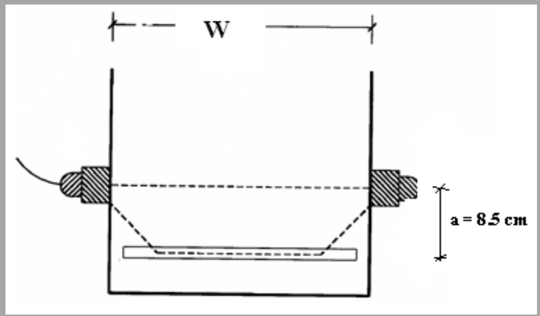
Ls = 42 cm
W= 50 cm
Ls/W= 0.84

Case no.4

pulse path parallel on steel reinforcement

Type	Average Direct pulse	$\frac{case\ No\ 4}{Case\ No\ 1}$ (Direct)	Average Indirect pulse	$\frac{case\ No\ 4}{Case\ No\ 1}$ (Indirect)	Average (Indirect/direct) pulse	Average Compressive strength at 28 days (MPa)
$B_{15}S_1$	4.051	1.022	3.202	1.012	0.791	16.05
$B_{15}S_2$	4.097	1.029	3.212	1.014	0.784	16.54
$B_{25}S_1$	4.539	1.033	3.630	1.032	0.800	27.00
$B_{25}S_2$	4.562	1.035	3.686	1.035	0.808	27.07
$B_{35}S_1$	4.791	1.046	3.867	1.034	0.807	36.56
$B_{35}S_2$	4.834	1.048	3.907	1.034	0.808	36.62
$B_{40}S_1$	5.004	1.075	4.001	1.048	0.800	42.27
$B_{40}S_2$	5.020	1.074	4.030	1.045	0.803	42.28

Continuous of Table (6) Ultrasonic Test Results for Beam



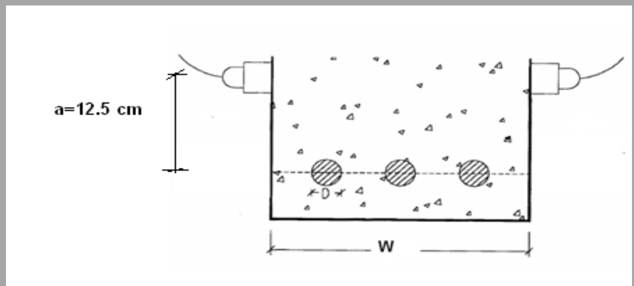
a/W = 0.17

Case no.5

pulse path on 8.5 cm parallel on steel reinforcement

Type	Average Direct pulse Km /sec	case No 5 / Case No 1 (Direct)	Average Indirect pulse Km/sec	case No 5 / Case No 1 (Indirect)	Average (Indirect/direct) pulse	Average Compressive strength at 28 days (MPa)
$B_{15}S_1$	3.996	1.008	3.171	1.002	0.794	16.05
$B_{15}S_2$	4.015	1.008	3.201	1.011	0.797	16.54
$B_{25}S_1$	4.433	1.009	3.508	0.997	0.791	27.00
$B_{25}S_2$	4.462	1.012	3.558	0.999	0.797	27.07
$B_{35}S_1$	4.633	1.011	3.743	1.001	0.808	36.56
$B_{35}S_2$	4.640	1.006	3.780	1.000	0.815	36.62
$B_{40}S_1$	4.735	1.017	3.883	1.017	0.820	42.27
$B_{40}S_2$	4.765	1.020	3.907	1.013	0.820	42.28

Table (7) Ultrasonic Test Results for Column

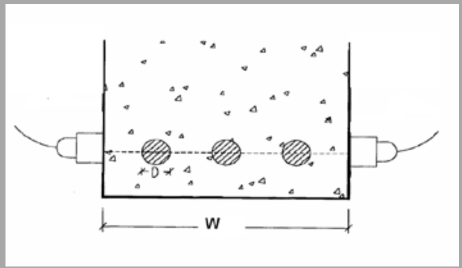


$C_{15}S_1$: Column class 15 MPa compressive strength series No.1
Ls = length of pulse path in steel
Ls is equal to zero in case No.1
W = concrete element dimension parallel to the pulse path
a= Distance between ultrasonic transducers and steel bars
Ls/W = N/A
a/W= 0.416

Case no.1

pulse path at the middle of the element

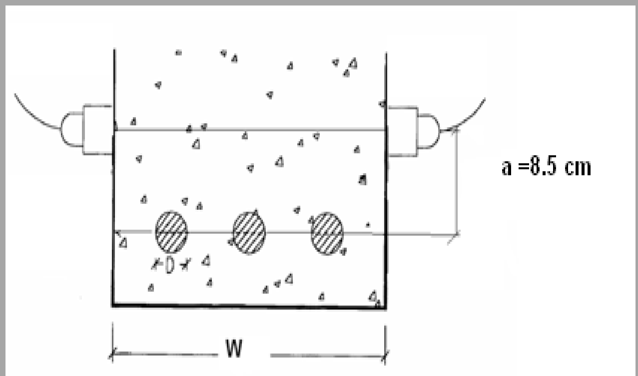
Type	Average Direct pulse Km /sec	Average Indirect pulse Km/sec	Average (Indirect/direct) pulse	Average Compressive strength at 28 days (MPa)
$C_{15}S_1$	3.836	3.022	0.788	16.05
$C_{15}S_2$	3.860	3.080	0.798	16.54
$C_{25}S_1$	4.352	3.531	0.811	27.00
$C_{25}S_2$	4.366	3.554	0.814	27.07
$C_{35}S_1$	4.528	3.747	0.828	36.56
$C_{35}S_2$	4.531	3.776	0.833	36.62
$C_{40}S_1$	4.620	3.815	0.826	42.27
$C_{40}S_2$	4.685	3.892	0.831	42.28



S1=Column with 6 Φ 16
S2=Column with 4 Φ 25
Ls = Σ ⌀ = 3xD = 3x1.6= 4.8 cm for S1
Ls = Σ ⌀ = 2xD= 2x2.5 =5.0 cm for S2
W= 30cm
Ls/W= 0.160 for S1
Ls/W= 0.167 for S2

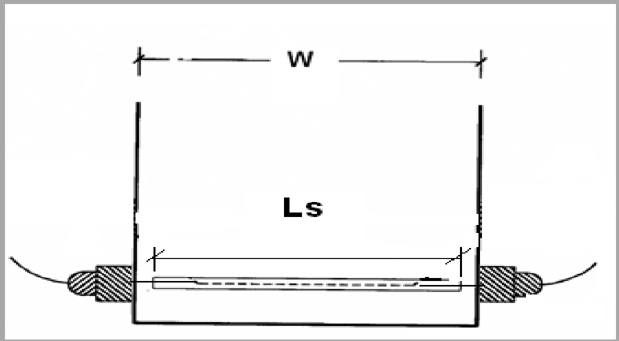
Case	Type	Average Direct pulse	$\frac{case\ No\ 2}{Case\ No\ 1}$ (Direct)	Average Indirect pulse	$\frac{case\ No\ 2}{Case\ No\ 1}$ (Indirect)	Average (Indirect/direct) pulse	Average Compressive strength at 28 days (MPa)
Case no.2 pulse path perpendicular on steel reinforcement	$C_{15}S_1$	3.907	1.0187	3.057	1.0115	0.782	16.05
	$C_{15}S_2$	3.934	1.0192	3.123	1.0140	0.794	16.54
	$C_{25}S_1$	4.489	1.0314	3.620	1.0251	0.807	27.00
	$C_{25}S_2$	4.530	1.0377	3.631	1.0216	0.802	27.07
	$C_{35}S_1$	4.716	1.0414	3.839	1.0246	0.814	36.56
	$C_{35}S_2$	4.723	1.0424	3.877	1.0269	0.821	36.62
	$C_{40}S_1$	4.881	1.0566	3.935	1.0316	0.806	42.27
	$C_{40}S_2$	4.977	1.0622	4.013	1.0313	0.806	42.28

Continuous of Table (7) Ultrasonic Test Results for Colum



a/W = 0.283

Case	Type	Average Direct pulse Km /sec	$\frac{case\ No\ 3}{Case\ No\ 1}$ (Direct)	Average Indirect pulse Km/sec	$\frac{case\ No\ 3}{Case\ No\ 1}$ (Indirect)	Average (Indirect/direct) pulse	Average Compressive strength at 28 days (MPa)
Case no.3 pulse path on 8.5 cm perpendicular on steel reinforcement	$C_{15}S_1$	3.821	0.9963	3.030	1.0025	0.793	16.05
	$C_{15}S_2$	3.814	0.9882	3.063	0.9944	0.803	16.54
	$C_{25}S_1$	4.327	0.9943	3.473	0.9835	0.803	27.00
	$C_{25}S_2$	4.303	0.9856	3.470	0.9764	0.807	27.07
	$C_{35}S_1$	4.535	1.0015	3.702	0.9879	0.816	36.56
	$C_{35}S_2$	4.572	1.0091	3.734	0.9890	0.817	36.62
	$C_{40}S_1$	4.675	1.0119	3.790	0.9936	0.811	42.27
	$C_{40}S_2$	4.784	1.0211	3.881	0.9972	0.812	42.28



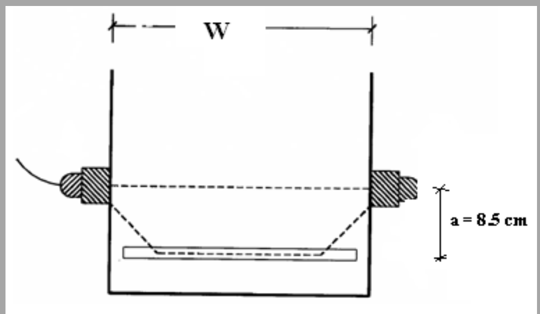
Ls = 42 cm
W= 50 cm
Ls/W= 0.84

Case no.4

pulse path parallel on steel reinforcement

Type	Average Direct pulse	case No 4 / Case No 1 (Direct)	Average Indirect pulse	case No 4 / Case No 1 (Indirect)	Average (Indirect/direct) pulse	Average Compressive strength at 28 days (MPa)
$C_{15}S_1$	3.923	1.0228	3.098	1.0250	0.790	16.05
$C_{15}S_2$	3.930	1.0181	3.177	1.0316	0.808	16.54
$C_{25}S_1$	4.485	1.0306	3.598	1.0189	0.802	27.00
$C_{25}S_2$	4.516	1.0344	3.622	1.0190	0.802	27.07
$C_{35}S_1$	4.772	1.0537	3.819	1.0191	0.800	36.56
$C_{35}S_2$	4.777	1.0543	3.877	1.0268	0.812	36.62
$C_{40}S_1$	5.007	1.0838	4.041	1.0594	0.807	42.27
$C_{40}S_2$	5.063	1.0807	4.133	1.0620	0.816	42.28

Continuous of Table (7) Ultrasonic Test Results for Colum



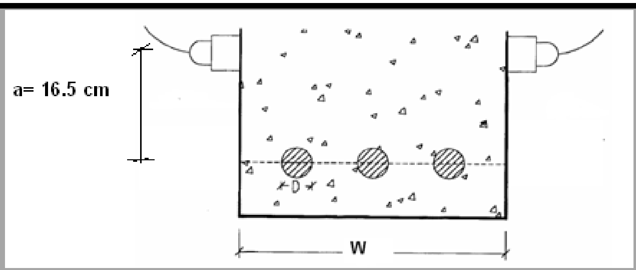
a/W = 0.17

Case no.5

pulse path on 8.5 cm parallel on steel reinforcement

Type	Average Direct pulse Km /sec	case No 5 / Case No 1 (Direct)	Average Indirect pulse Km/sec	case No 5 / Case No 1 (Indirect)	Average (Indirect/direct) pulse	Average Compressive strength at 28 days (MPa)
$C_{15}S_1$	3.930	1.0245	3.081	1.0194	0.784	16.05
$C_{15}S_2$	3.930	1.0181	3.123	1.0140	0.795	16.54
$C_{25}S_1$	4.463	1.0255	3.604	1.0207	0.808	27.00
$C_{25}S_2$	4.453	1.0199	3.604	1.0139	0.810	27.07
$C_{35}S_1$	4.630	1.0225	3.781	1.0091	0.817	36.56
$C_{35}S_2$	4.658	1.0280	3.871	1.0252	0.831	36.62
$C_{40}S_1$	4.717	1.0210	3.956	1.0370	0.839	42.27
$C_{40}S_2$	4.784	1.0211	4.034	1.0366	0.843	42.28

Table (8) Ultrasonic Test Results for Foundation

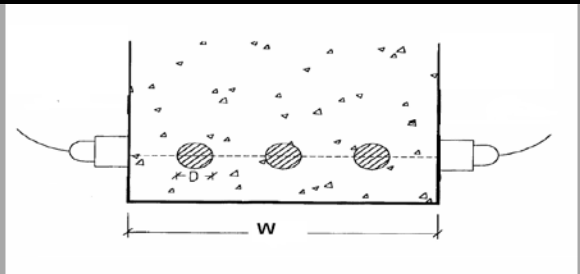


$F_{15}S_1$: Foundation class 15 MPa compressive strength series No.1
Ls = length of pulse path in steel
Ls is equal to zero in case No.1
W = concrete element dimension parallel to the pulse path
a= Distance between ultrasonic transducers and steel bars
Ls/W = N/A
a/W= 0.275

Case no.1

pulse path at the middle of the element

Type	Average Direct pulse Km /sec	Average Indirect pulse Km/sec	Average (Indirect/direct) pulse	Average Compressive strength at 28 days (MPa)
$F_{15}S_1$	3.901	3.137	0.804	16.05
$F_{15}S_2$	3.922	3.148	0.803	16.54
$F_{25}S_1$	4.395	3.689	0.839	27.00
$F_{25}S_2$	4.420	3.706	0.839	27.07
$F_{35}S_1$	4.694	3.932	0.838	36.56
$F_{35}S_2$	4.709	3.960	0.841	36.62
$F_{40}S_1$	4.768	4.053	0.850	42.27
$F_{40}S_2$	4.773	4.071	0.853	42.28



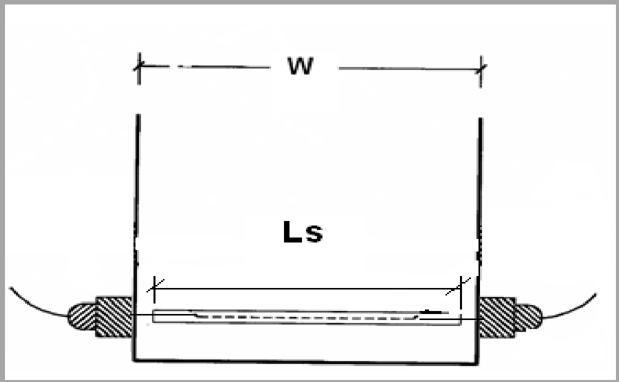
S1=Foundation with 4 Φ 16 Top & bottom
S2=Foundation with 3 Φ 25 Top & bottom
Ls = $\sum \phi$ = 4xD = 4x1.6= 6.4 cm for S1
Ls = $\sum \phi$ = 3xD= 3x2.5 =7.5 cm for S2
W= 60 cm
Ls/W= 0.106 for S1
Ls/W= 0.125 for S2

Case no.2

pulse path perpendicular on steel reinforcement

Type	Average Direct pulse	$\frac{case\ No\ 2}{Case\ No\ 1}$ (Direct)	Average Indirect pulse	$\frac{case\ No\ 2}{Case\ No\ 1}$ (Indirect)	Average (Indirect/direct) pulse	Average Compressive strength at 28 days (MPa)
$F_{15}S_1$	3.994	1.0238	3.188	1.0164	0.798	16.05
$F_{15}S_2$	4.037	1.0294	3.199	1.0160	0.792	16.54
$F_{25}S_1$	4.537	1.0322	3.767	1.0211	0.830	27.00
$F_{25}S_2$	4.575	1.0350	3.780	1.0201	0.826	27.07
$F_{35}S_1$	4.896	1.0431	4.085	1.0388	0.834	36.56
$F_{35}S_2$	4.909	1.0426	4.111	1.0381	0.837	36.62
$F_{40}S_1$	4.993	1.0471	4.225	1.0424	0.846	42.27
$F_{40}S_2$	4.982	1.0439	4.238	1.0409	0.851	42.28

Continuous of Table (8) Ultrasonic Test Results for Foundation



Ls/W= 0.86

Case	Type	Average Direct pulse Km /sec	case No 3 / Case No 1 (Direct)	Average Indirect pulse Km/sec	case No 3 / Case No 1 (Indirect)	Average (Indirect/direct) pulse	Average Compressive strength at 28 days (MPa)
Case no.3 pulse path parallel to the steel reinforcement	$F_{15}S_1$	4.053	1.0389	3.253	1.0372	0.803	16.05
	$F_{15}S_2$	4.060	1.0352	3.246	1.0311	0.800	16.54
	$F_{25}S_1$	4.581	1.0423	3.833	1.0392	0.837	27.00
	$F_{25}S_2$	4.602	1.0412	3.880	1.0470	0.843	27.07
	$F_{35}S_1$	4.985	1.0620	4.111	1.0454	0.825	36.56
	$F_{35}S_2$	4.991	1.0599	4.152	1.0483	0.832	36.62
	$F_{40}S_1$	5.254	1.1019	4.334	1.0692	0.825	42.27
	$F_{40}S_2$	5.245	1.0989	4.370	1.0734	0.833	42.28

Table (9) Ultrasonic Test Results for Slab

Case	Type	Average Direct pulse Km /sec	Average Indirect pulse Km/sec	Average (Indirect/direct) pulse	Average Compressive strength at 28 days (MPa)
Case no.1	$S_{15}S_1$	3.809	3.119	0.819	16.05
	$S_{15}S_2$	3.807	3.119	0.820	16.54
	$S_{25}S_1$	4.333	3.481	0.803	27.00
	$S_{25}S_2$	4.320	3.470	0.803	27.07
	$S_{35}S_1$	4.670	3.845	0.823	36.56
	$S_{35}S_2$	4.685	3.892	0.831	36.62
	$S_{40}S_1$	4.823	4.052	0.840	42.27
	$S_{40}S_2$	4.843	4.052	0.837	42.28

Table 10 Hammer Test Results

Element	Type	Average of three sets of Rebound Hammer	Average Compressive strength (MPa)
Column	$C_{15}S_1$	25	16.05
	$C_{15}S_2$	26	16.54
	$C_{25}S_1$	30	27.00
	$C_{25}S_2$	31	27.07
	$C_{35}S_1$	36	36.56
	$C_{35}S_2$	37	36.62
	$C_{40}S_1$	44	42.27
	$C_{40}S_2$	44	42.28
Beam	$B_{15}S_1$	25	16.05
	$B_{15}S_2$	25	16.54
	$B_{25}S_1$	30	27.00
	$B_{25}S_2$	31	27.07
	$B_{35}S_1$	37	36.56
	$B_{35}S_2$	37	36.62
	$B_{40}S_1$	44	42.27
	$B_{40}S_2$	44	42.28
Foundation	$F_{15}S_1$	25	16.05
	$F_{15}S_2$	26	16.54
	$F_{25}S_1$	30	27.00
	$F_{25}S_2$	31	27.07
	$F_{35}S_1$	37	36.56
	$F_{35}S_2$	38	36.62
	$F_{40}S_1$	44	42.27
	$F_{40}S_2$	44	42.28
Slab	$S_{15}S_1$	25	16.05
	$S_{15}S_2$	25	16.54
	$S_{25}S_1$	30	27.00
	$S_{25}S_2$	30	27.07
	$S_{35}S_1$	37	36.56
	$S_{35}S_2$	37	36.62
	$S_{40}S_1$	44	42.27
	$S_{40}S_2$	44	42.28

Table 11 Summary of Equation of Combined Method

Element	Equation Name	Type of Pulse Velocity	Equation	R^2
Column	Total proposed Column equation	DUPV	y= 10.123 DUPV + 0.913 R - 45.433	0.975
		SUPV	y= 13.502 SUPV + 0.789 R - 45.036	0.981
Beam	Total proposed Beam equation	DUPV	y= 9.166 DUPV + 0.987 R - 44.367	0.981
		SUPV	y= 13.913 SUPV + 0.836 R - 48.447	0.985
Foundation	Total proposed Foundation equation	DUPV	y= 7.293 DUPV + 0.995 R - 37.197	0.980
		SUPV	y= 9.780 SUPV + 0.870 R - 36.654	0.987
Slab	Total proposed Slab equation	DUPV	y= 16.420 DUPV + 0.488 R - 58.495	0.999
		SUPV	y= 26.215 SUPV + 0.056 R - 66.490	0.996
Total	Total combined proposed equation	DUPV	y= 7.666 DUPV + 1.017 R - 38.653	0.974
		SUPV	y= 8.129 SUPV + 1.015 R - 33.877	0.974
-	Raouf equation	DUPV	$y= 0.93R^{0.63}\ e^{0.31DUPV}$	0.978

Table.12 Summary of Proposed Equations

Item	Equation name	Type	Equation	R^2
1.	Proposed Total Plain Concrete Equation	DUPV	$y= 0.173\ e^{1.157\ DUPV}$	0.961
		SUPV	$y= 0.460\ e^{1.150\ SUPV}$	0.944
2.	Proposed Total Effect Equation	DUPV	$y= 0.422\ e^{0.939\ DUPV}$	0.888
		SUPV	$y= 0.747\ e^{0.997\ SUPV}$	0.890
3.	Proposed Total Hammer Equation	R	$y= 5.378\ e^{0.049\ R}$	0.899
4.	Proposed Total Combined Equation	DUPV + R	y= 7.666 DUPV + 1.017 R - 38.653	0.974
		SUPV + R	y= 8.129 SUPV + 1.015 R - 33.877	0.974

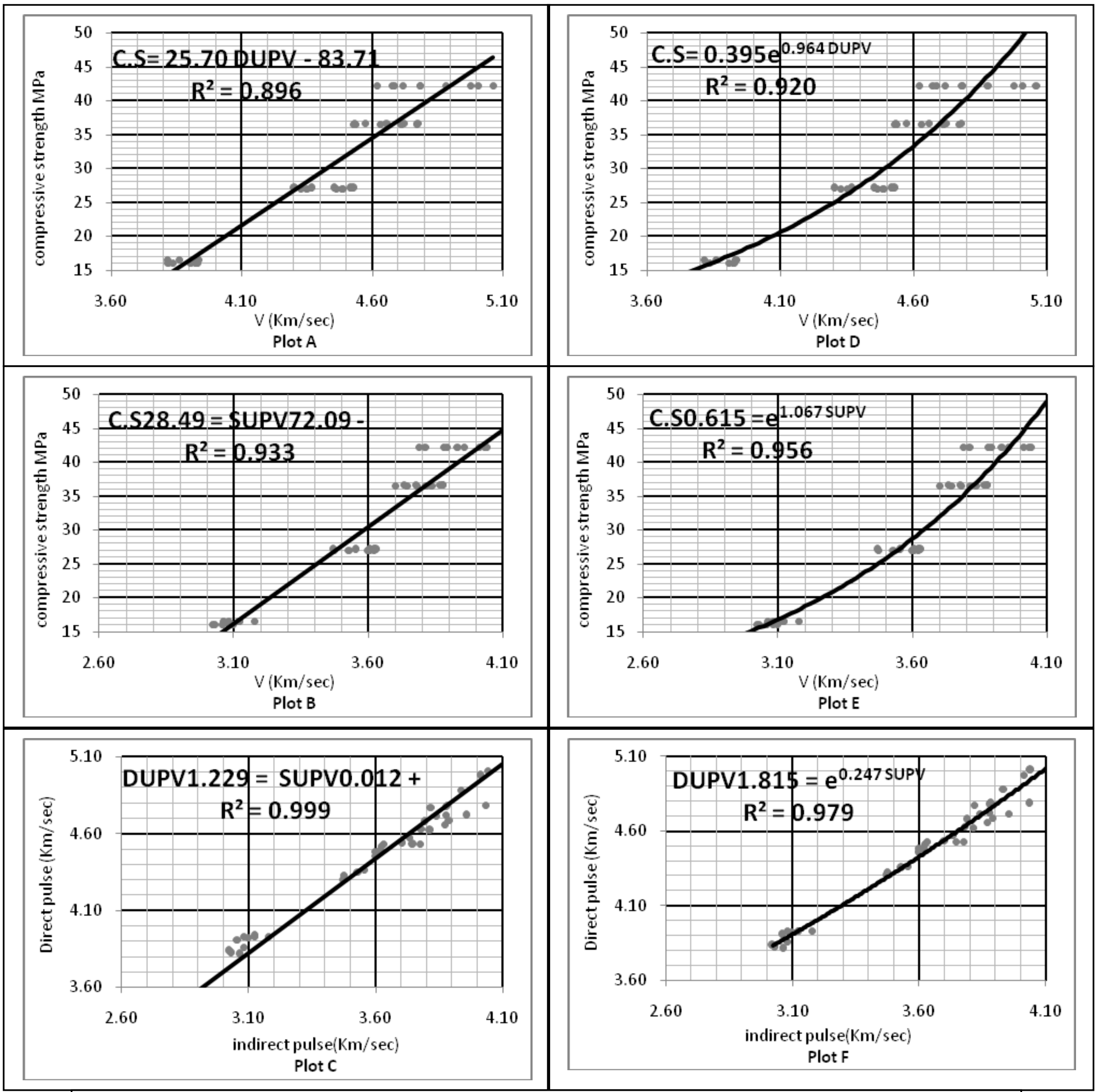


Figure (1) Relationships between Pulse Velocity and Compressive Strength Total Case for Column Element

Plot A Linear relationship between direct pulse and compressive strength

Plot B Linear relationship between indirect pulse and compressive strength

Plot C Linear relationship between indirect pulse and direct pulse

Plot D Non-Linear relationship between direct pulse and compressive strength

Plot E Non-Linear relationship between indirect pulse and compressive strength

Plot F Non-Linear relationship between indirect pulse and direct pulse

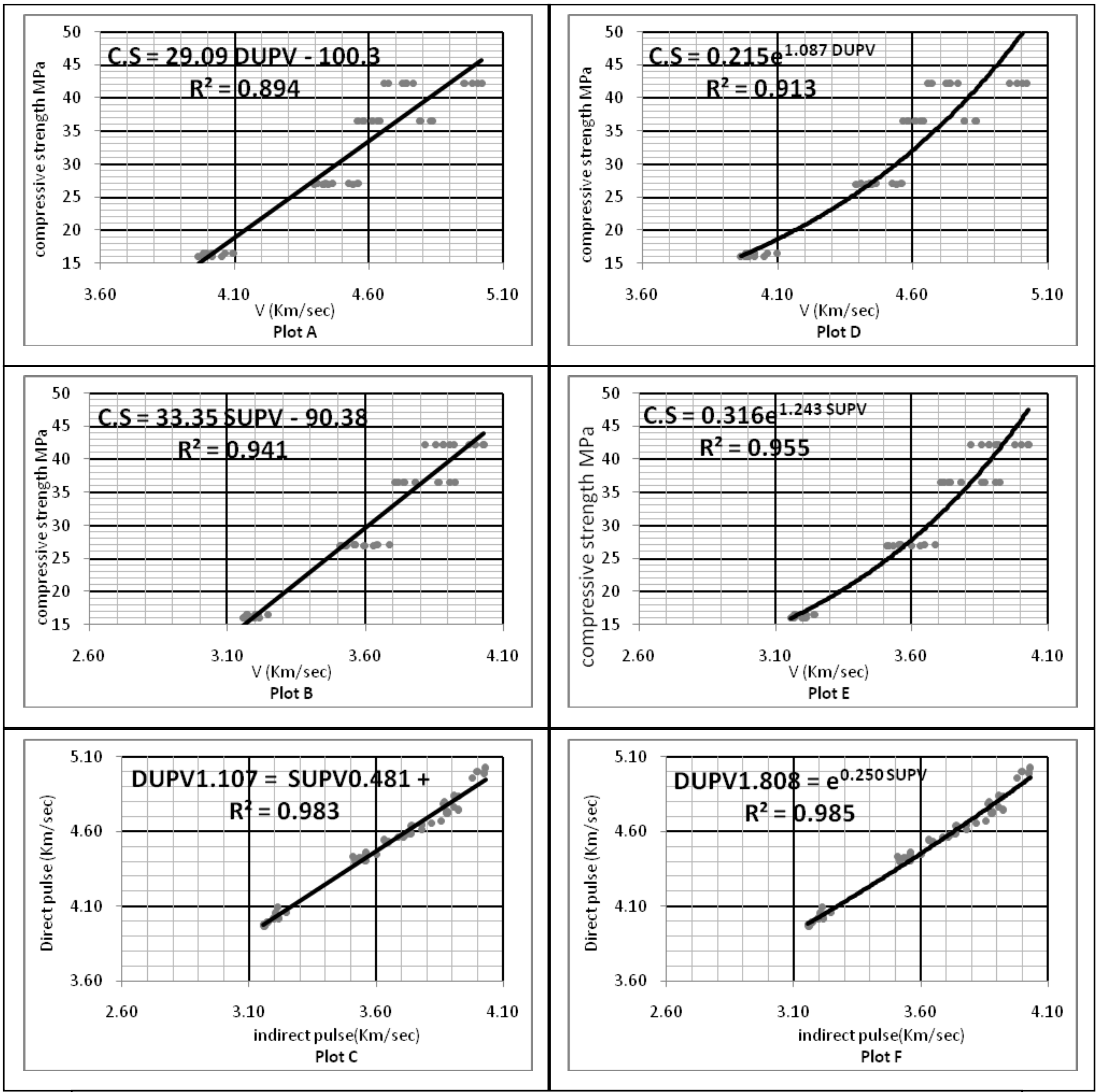


Figure (2) Relationships between Pulse Velocity and Compressive Strength Total Case for Beam Element

Plot A Linear relationship between direct pulse and compressive strength

Plot B Linear relationship between indirect pulse and compressive strength

Plot C Linear relationship between indirect pulse and direct pulse

Plot D Non-Linear relationship between direct pulse and compressive strength

Plot E Non-Linear relationship between indirect pulse and compressive strength

Plot F Non-Linear relationship between indirect pulse and direct pulse

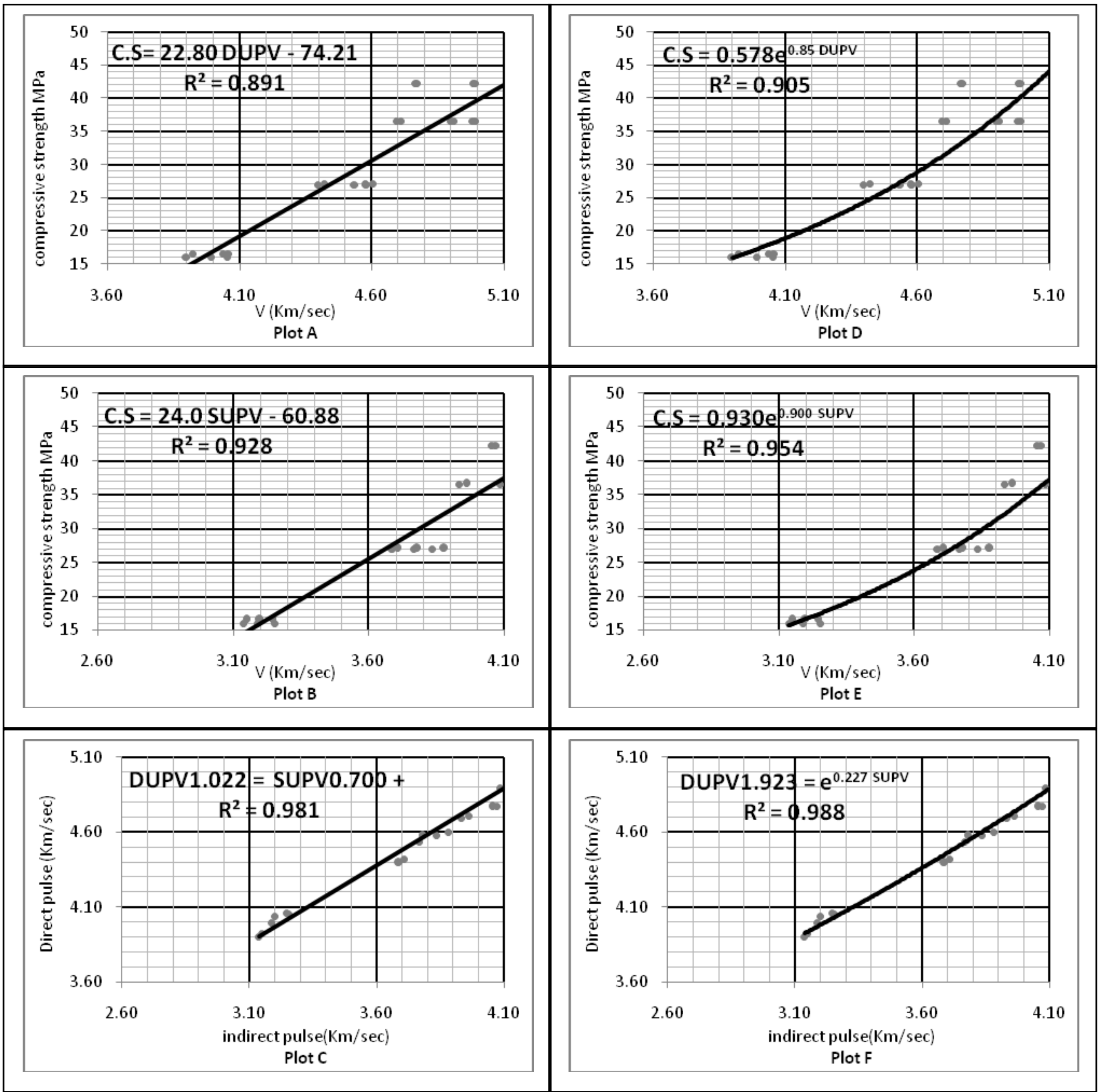


Figure (3) Relationships between Pulse Velocity and Compressive Strength for Total Case for Foundation Element

Plot A Linear relationship between direct pulse and compressive strength

Plot B Linear relationship between indirect pulse and compressive strength

Plot C Linear relationship between indirect pulse and direct pulse

Plot D Non-Linear relationship between direct pulse and compressive strength

Plot E Non-Linear relationship between indirect pulse and compressive strength

Plot F Non-Linear relationship between indirect pulse and direct pulse

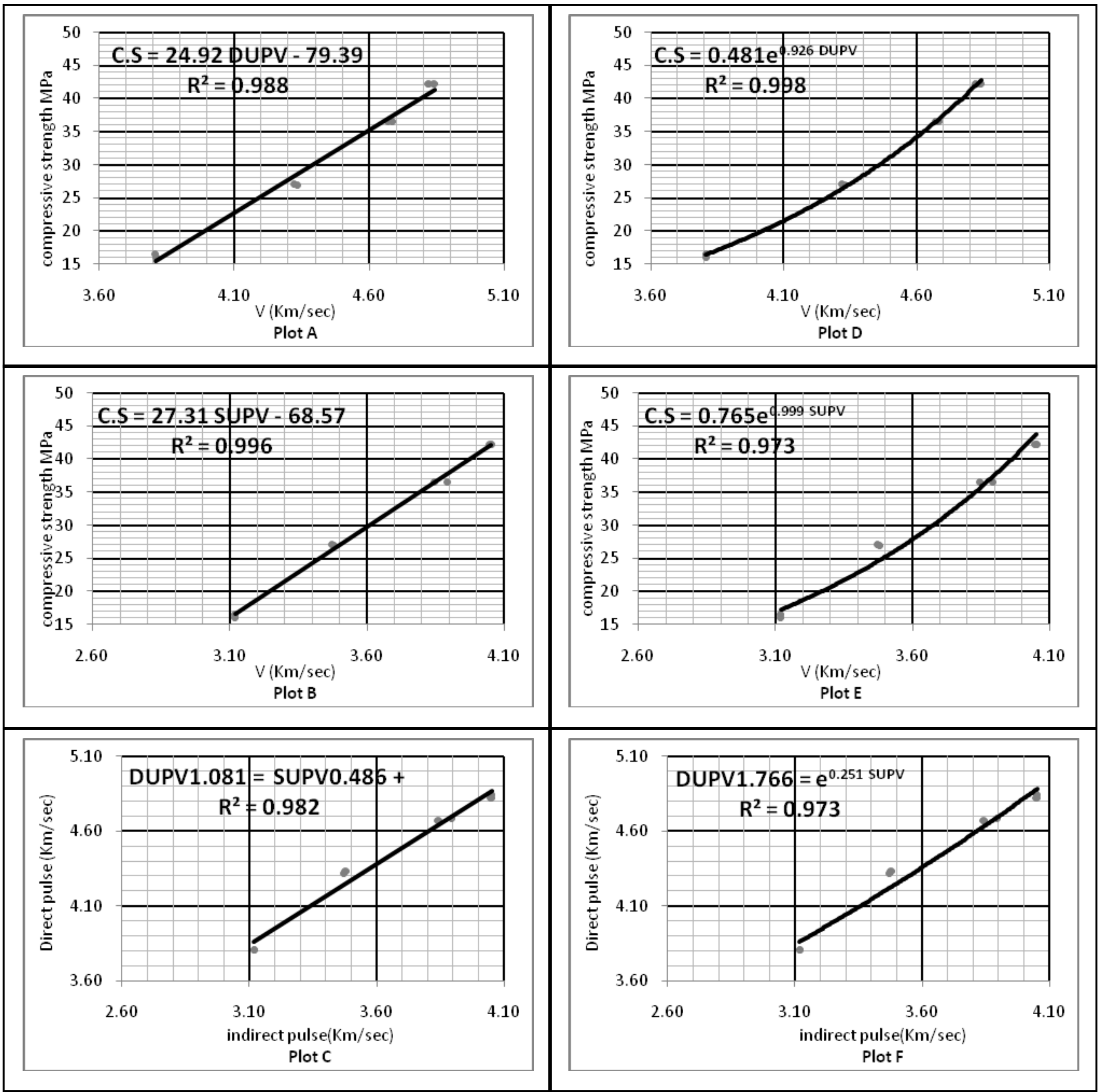


Figure (4) Relationships between Pulse Velocity and Compressive Strength for Slab Element

Plot A Linear relationship between direct pulse and compressive strength

Plot B Linear relationship between indirect pulse and compressive strength

Plot C Linear relationship between indirect pulse and direct pulse

Plot D Non-Linear relationship between direct pulse and compressive strength

Plot E Non-Linear relationship between indirect pulse and compressive strength

Plot F Non-Linear relationship between indirect pulse and direct pulse

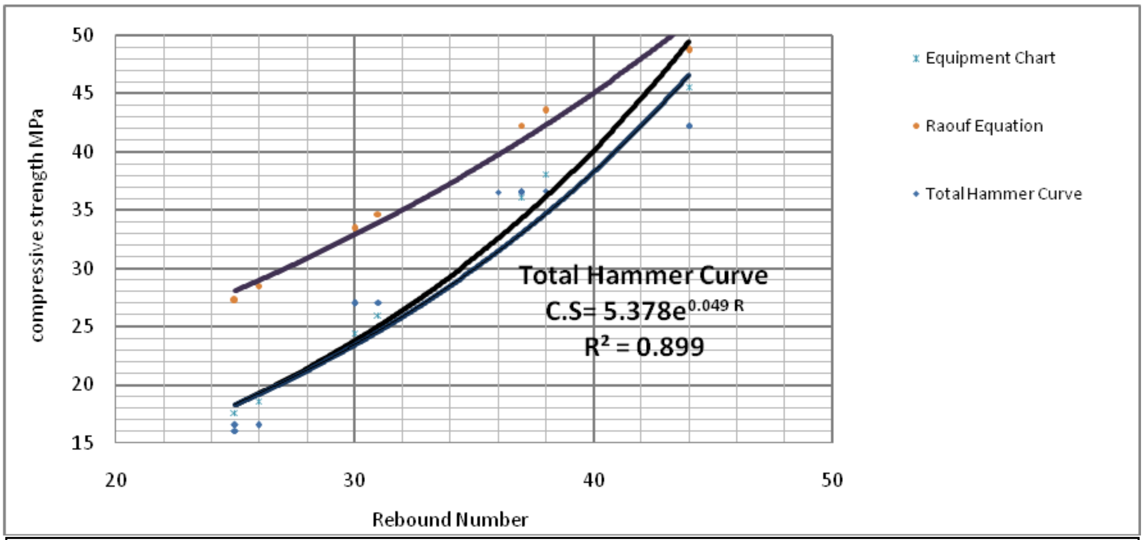


Figure (5) Relationships between Rebound Number and Compressive Strength for All Cases

Plate.1 Direct and Indirect Reading of Ultrasonic Pulse Velocity

Plate.2 Rebound Hammer testers

Plate.3 Cutting core specimens from Beam sample