Estimation of Flexural Strength of Plain Concrete from Ultrasonic Pulse Velocity

Dr. Ala'a Hussein. Alwan Al-Zuhairi
Lecturer, Eng. College-Civil Dept.
Baghdad University
Email: alaalwn@yahoo.com

ABSTRACT

The aim of this study is to propose mathematical expressions for estimation of the flexural strength of plain concrete members from ultrasonic pulse velocity (UPV) measurements. More than two hundred pieces of precast concrete kerb units were subjected to a scheduled test program. The tests were divided into two categories; non-destructive ultrasonic and bending or rupture tests. For each precast unit, direct and indirect (surface) ultrasonic pulses were subjected to the concrete media to measure their travel velocities. The results of the tests were mointered in two graphs so that two mathematical relationships can be drawn. Direct pulse velocity versus the flexural strength was given in the first relationship while the second equation describes the flexural strength as a function of indirect (surface) pulse velocity. The application of these equations may be extended to cover the assessment of flexural strength of constructed concrete kerb units or in-situ concreting kerbstone and any other precast concrete units. Finally, a relation between direct and indirect pulse velocities of the a given concrete was predicted and suggested to be employed in case when one of the velocities is not available can be measured for other ultrasonic pulse test applications

KEY WORDS: Nondestructive tests, ultrasonic, pulse velocity, flexural strength, concrete kerbs.

التنبؤ بمقاومة انحناء الخرسانة من سرعة النبضات فوق السمعية

د.علاء حسين علوان الزهيري
مدرس

الخلاصة

الغرض من اجراء هذه الدراسة هو أقتراح نموذج رياضي لتخمين مقاومة الأنحناء للأعضاء الخرسانية الخالية من حديد التسليح من خلال قياس سرعة النبضات فوق السمعية. تم تعريض أكثر من مائتي قطعة من وحدات الأرصفة الخرسانية السابقة الصب لبرنامج فحص مجدول. انقسمت الفحوص المجراة الى نوعين: فحوص لا إتلافية فوق السمعية وفحوص مقاومة الأنحناء عند الكسر. سلطت النبضات فوق السمعية بنوعيها المباشرة وغير المباشرة وأنفذت خلال الوسط الخرساني لقياس سرعة مرور هذه النبضات. لقد تـم إظهار نتائج الفحص في مخططين منفصلين للحصول على علاقتين رياضيتين. تضمنت المعادلة الأولى العلاقة بين سرعة النبضات المباشرة ومقاومة الأنحناء فيما وصفت المعادلة الثانية مقاومة الأنحناء كدالة من سرعة النبضات غير المباشرة. ومما تجدر الأشارة إليه إنه يمكن توسيع مدى استعمال هاتين المعادلتين ليشمل تخمين مقاومة الأنحناء لوحدات الأرصفة المشيدة أو المنفـذة باسـتعمال الصب الموقعي وكذلك للوحدات الخرسانية السابقة الصب الأخرى. وأخيراً تم إستنباط علاقة بين سـرعتي النبـضات المباشـرة وغيرالمباشرة لنفس الخرسانة يمكن استعمالها في حالة عدم التمكن من قياس احدى السرعتين في تطبيقات فحص النبـضات فـوق السمعية الأخرى.

الكلمات الرئيسية: فحوص لا إتلافية، فوق السمعية، سرعة النبضات، مقاومة الأنحناء، أرصفة خرسانية.

1. INTRODUCTION

The non Destructive Testing (NDT) of concrete has a great technical and useful importance. This testing technique has been grown during the last decads especially in the case of construction quality assessement (Shariati et al.). The main advantage of (NDT) method is to avoid damaging of concrete or impairing the function of consrtucted structural components. Besides, its use is simple, quick and test results are avialble on the site (Hobbs and Tchoketch). Ultrasonic pulse velocity (UPV) and Shmidt rebound hammer (SRH) are so familiar (NDT) methods. The use of (UPV) to non-destructive assessment of concrete quality has been extensively investigated for decads (Solis-Carcano and Moreno). The test is based on measuring the velocity of an ultrasonic pulse passing through the tested solid material. According to the theory of the sound propagation, the pulse velocity depends on the density and elastic properties of that material and independent of the frequency of the pulse (C.N.S. Electronics).

It can be shown that the pulse velocity of longitudinal ultrasonic vibration travelling through an elastic solid is given by: (Krautkramer and Krautkramer)

$$UPV = \sqrt{\frac{E}{\rho}\frac{(1-\nu)}{(1+\nu)(1-2\nu)}} \qquad (1)$$

Where, E = dynamic elastic modulus

ρ = the density

ν = Poisson's ratio.

When ultrasonic testing is applied to metals to detect internal flaws, the former send the echoes back in the direction of the incident beam of pulse. The measurment of time taken for the pulse to travel from a surface to a flaw and back again enables the position of the flaw to be located. Such a technique can not be applied to hetrogeneous materials like concrete since echoes are generated at numerous boundaries of different phases within these materials resulting in a general scattering of pulse energy in all directions. Based on this fact, it is recommended that the pulse frequency used for testing concrete is much lower than that used in metal testing. The higher the frequency, the narrower the incident beam of pulse propagation but the greater the attenuation (or damping out) of the pulse vibration. The frequencies suitable for these materials (metal and concrete) range from about 20kHz to 250kHz with 50kHz being appropriate for the field testing of concrete (C.N.S. Electronics).

1.1 Historical Backgroud

The historical review of development of ultrasonic pulse test shows that the technique is used first in 1946 and 1947 in Canada by engineers at the Hydro-Electric Power Commission of Ontario to investigate the extent of cracking in dams. The developed device is called *Sonicsop*. It was capable of penetrating up to 15m of concrete and measure the travel time with an accuracy of 3%. In early uses of the soniscope on mass concrete, the emphasis was on measuring the pulse velocity rather than estimating strength of concrete.

As stated by Carino (1994), Parker (1953) reported on early attempts at Ontario Hydro to develop relationships between pulse velocity and compressive strength. At the same time when work on the soniscope was in progress in Canada, R.Jones and co-workers at the Road Research Laboratory (RRL) in England were involved to develop an ultrasonic testing apparatus (Jones (1949) stated by Carino (1994)). The apparatus that was developed and called *Ultrasonic Concrete Tester* operated at a higher frequency than the soniscope to produce pulses of shorter path lengths.

Through his wide experience in UPV test, Jones (Carino) established the inherent problems in using the pulse velocity to estimate concrete strength. Despite these early finding, numerous researchers dealed with prediction of concrete compressive strength by measuring the pulse velocity through their media. Most of these works proposed corellations or imperical equations for application to extended ranges of concrete.

1.2 Literature Review

A brief review of some selected works from the avialable literature is shown in Table1. The review was concenterated on works from which the mathematical correlations were proposed.

Through this fair review of literature it was seen that most of researchers (if not all) dealed with the estimation of concrete compressive strength from UPV test. No work was found interested in estimation of flextural strength. For this reason the present study was conducted. On the other hand, flexural strength estimation from UPV helps to control the quality of some precast units that should resist a certain value of flexural stress.

Table 1: Review of some sellected works from literature

No.	Author	Year	Proposed Correlation	Notes
1	Jones	1962	$f_{cu} = 2.8\,exp^{0.53V}$	f_{cu} = compressive strength in MPa. V = direct pulse velocity in km/sec. V_s = indirect (surface) pulse velocity in km/sec.
2	Elvery and Ibrahim	1976	$f_{cu} = 0.0012\,exp^{2.27V}$	
3	Raouf and Ali	1983	$f_{cu} = 2.016\,exp^{0.61V}$	
4	Abdul-Salam	1992	$f_{cu} = -199 + 123V$	
5	Lopes and Neponmuceno	2001	$f_{cu} = 0.00015\,exp^{2.885V}$	
6	Tumendemberel and Baigalimaa	2001	$f_{cu} = 1.356 \times 10^{-5} V^2 - 0.076V + 111.502$	
7	Malhotra and Carino	2004	$f_{cu} = -109.6 + 0.033V$	
8	Nash't et al.	2005	$f_{cu} = 1.19\,exp^{0.715V}$	
9	Ali	2008	$f_{cu} = 0.26\,exp^{V_s} - 0.83$	
10	Lawson et al.	2011	$f_{cu} = 0.053\,exp^{0.001V}$	
11	Shariati et al.	2011	$f_{cu} = 15.533V - 34.358$	
12	Jassim	2012	$f_{cu} = 0.395\,exp^{0.964V}$	

2. EXPERIMENTAL WORKS

203 precast concrete kerb units were used through out this work. The units have different dimensions. The length is ranged between 500-1000mm and width between 100-200mm while 250-300mm is the range of height. Each unit is submitted to the following testing program:

1. Measuring of dimensions and locating the points at which the ultrasonic transducers will be attached for both direct and indirect tests (Fig.1.a).
2. Grease oil is used at located points to be a suitable coplent between transducer and concrete face of the precast units (Fig.1.b).
3. Five direct UPV tests were taken for each unit using 55kHz transducers. The tests were conducted in a mannar so that the travel path of the ultrasonic pulse is across the width of the unit (Fig.1.c). This is done to simulate the future field UPV test on constructed concrete kerb units in the road.
4. Indirect (surface) UPV tests were performed at a constant pulse travel distance of 200mm (Fig.1.d) using the same transducers that used in direct test.
5. Finally, each precast unit was subjected to flextural stress to the failure via utilizing the bending machine shown in Fig.2. The flextural strength is computed from eq.1:

$$f_r = \frac{PLy}{4I} \qquad (1)$$

Where,
f_r = flexural strength in MPa
P = applied force in Newtons
L = span length in mm
y = distance from the neuteral axis of precast unit section to the extreme fiber in mm
I = moment of inertia of precast unit section in mm^4.

3. RESULTS AND DISCUSSION

The results of the direct and indirect tests that were conducted on the precast concrete kerb units were tabulated in Table2. Direct and indirect (or surface) velocities were calculated at five different locations for each precast kerb unit. Then the average velocity of these five readings in both direct and surface tests was determined. To investigate the scattering of the velocities in both direct and indirect tests, the standard deviation was calculated.

In all tests, as it was expected, the average direct velocity was greater than the indirect one.

The increase in the length of pulse insident beam from the measured distance between transducers in the indirect test stand behind this fact.

It was noted that the maximum value of standard deviation was 0.055 km/sec for direct tests and 0.057 km/sec for surface tests. The corresponding coefficients of variation were 1.37% and 1.24% respectively.

Table 2: Ultrasonic pulse velocity test results

No.	Av. V km/sec	SDD km/sec	Av. V_s km/sec	SDS km/sec	f_r MPa	No.	Av. V km/sec	SDD km/sec	Av. V_s km/sec	SDS km/sec	f_r MPa
1	4.70	0.021	4.26	0.042	3.11	53	4.65	0.023	3.75	0.035	3.44
2	4.79	0.024	4.28	0.024	3.15	54	4.59	0.022	3.76	0.049	3.56
3	4.83	0.046	4.29	0.027	3.18	55	4.61	0.022	3.78	0.032	3.36
4	3.48	0.019	3.38	0.013	2.09	56	4.25	0.050	4.13	0.028	3.50
5	3.50	0.041	3.44	0.039	2.13	57	4.32	0.030	4.06	0.017	3.73
6	3.50	0.037	3.48	0.034	2.21	58	4.66	0.043	4.40	0.034	3.45
7	4.13	0.044	3.92	0.022	2.22	59	3.76	0.029	3.15	0.021	2.02
8	4.12	0.045	3.95	0.038	2.29	60	4.32	0.031	3.71	0.014	3.06
9	4.08	0.026	3.97	0.038	2.30	61	4.34	0.044	3.98	0.046	2.96
10	4.33	0.031	3.92	0.055	3.33	62	4.45	0.027	4.38	0.038	3.60
11	4.40	0.053	3.94	0.037	3.77	63	4.46	0.044	4.43	0.024	3.76
12	2.89	0.015	2.56	0.007	1.39	64	4.46	0.030	4.41	0.043	3.98
13	2.89	0.017	2.55	0.012	1.40	65	4.43	0.030	4.38	0.053	3.82
14	2.91	0.018	2.55	0.005	1.42	66	4.42	0.053	4.37	0.051	3.92
15	3.33	0.027	3.10	0.017	2.40	67	4.50	0.035	4.48	0.050	3.71
16	3.33	0.014	3.08	0.016	2.33	68	4.80	0.028	3.86	0.018	3.37
17	3.37	0.036	3.06	0.024	2.33	69	4.39	0.040	3.98	0.024	2.73
18	4.78	0.026	4.46	0.040	3.83	70	4.31	0.051	3.94	0.037	2.73
19	4.89	0.021	4.52	0.026	4.11	71	4.26	0.013	3.95	0.029	2.67
20	4.81	0.033	4.49	0.050	3.99	72	4.18	0.054	3.94	0.047	2.72
21	4.91	0.047	4.51	0.048	3.94	73	4.13	0.032	3.92	0.052	2.81
22	4.79	0.021	4.48	0.040	4.16	74	4.16	0.037	3.90	0.028	2.72
23	4.89	0.026	4.46	0.047	3.83	75	4.91	0.029	4.56	0.023	3.75
24	4.59	0.043	4.37	0.031	3.90	76	3.56	0.035	2.30	0.018	1.77
25	4.74	0.048	4.21	0.029	3.59	77	3.55	0.034	2.29	0.016	1.82
26	4.83	0.016	4.33	0.017	3.82	78	3.60	0.020	2.30	0.035	1.77
27	4.72	0.036	4.28	0.054	3.70	79	5.07	0.041	4.90	0.033	4.61
28	4.79	0.026	4.19	0.033	2.87	80	5.17	0.050	4.89	0.040	4.73
29	4.87	0.017	4.24	0.039	2.93	81	5.15	0.031	4.88	0.045	4.67
30	4.16	0.023	3.85	0.049	2.38	82	4.65	0.052	3.92	0.040	3.25
31	4.28	0.036	3.81	0.045	2.42	83	4.74	0.027	4.16	0.054	3.34
32	4.25	0.046	3.86	0.039	2.44	84	4.79	0.013	4.28	0.031	3.44
33	4.20	0.039	3.64	0.038	2.96	85	4.82	0.033	4.36	0.055	3.34
34	4.29	0.036	3.82	0.031	3.18	86	4.88	0.049	4.34	0.012	3.34
35	4.45	0.032	3.79	0.042	3.35	87	4.82	0.039	4.39	0.046	3.44
36	4.42	0.046	3.76	0.036	3.29	88	4.95	0.029	4.46	0.018	3.54
37	4.59	0.049	4.13	0.028	3.80	89	4.79	0.039	4.32	0.046	3.44
38	4.64	0.050	3.93	0.039	3.59	90	4.86	0.045	4.46	0.048	3.54
39	4.70	0.016	4.03	0.044	3.77	91	4.89	0.053	4.50	0.046	3.58
40	4.79	0.046	4.05	0.024	3.77	92	4.84	0.047	4.51	0.047	3.54
41	4.73	0.040	4.43	0.046	4.10	93	4.82	0.034	4.63	0.037	3.62
42	4.74	0.019	4.59	0.057	4.23	94	5.05	0.046	4.80	0.039	4.30
43	4.81	0.033	4.56	0.054	4.21	95	4.57	0.022	4.23	0.015	3.69
44	4.91	0.013	4.60	0.046	4.29	96	4.52	0.031	4.22	0.025	3.85
45	4.87	0.034	4.61	0.048	4.18	97	4.50	0.029	4.24	0.020	3.79

46	4.87	0.034	4.59	0.052	4.07	98	5.06	0.041	4.88	0.048	4.41
47	4.34	0.033	4.06	0.034	3.81	99	5.06	0.041	4.94	0.049	4.26
48	4.38	0.053	4.17	0.042	3.85	100	5.07	0.021	4.92	0.039	4.62
49	4.35	0.054	4.12	0.031	3.84	101	4.85	0.030	4.46	0.027	3.19
50	4.60	0.024	3.88	0.042	3.33	102	4.75	0.035	4.34	0.018	3.12
51	4.55	0.031	3.80	0.048	3.31	103	3.76	0.025	3.63	0.053	2.43
52	4.58	0.035	3.76	0.037	3.47	104	5.15	0.047	5.02	0.034	4.97

To be continued

Table 2: Ultrasonic pulse velocity test results (continued)

No.	Av. V km/sec	SDD km/sec	Av. V_s km/sec	SDS km/sec	f_r MPa	No.	Av. V km/sec	SDD km/sec	Av. V_s km/sec	SDS km/sec	f_r MPa
105	5.51	0.029	5.13	0.031	5.06	155	3.57	0.019	3.52	0.012	2.51
106	5.66	0.050	5.18	0.038	5.09	156	3.55	0.030	3.52	0.023	2.48
107	5.45	0.036	5.30	0.045	5.06	157	3.61	0.023	3.34	0.024	2.20
108	4.76	0.036	4.20	0.038	3.17	158	3.63	0.034	3.38	0.021	2.06
109	4.90	0.043	4.05	0.031	3.39	159	3.61	0.020	3.36	0.015	2.01
110	4.85	0.051	4.06	0.054	3.22	160	4.86	0.027	4.45	0.045	3.88
111	4.85	0.038	4.05	0.042	3.61	161	4.79	0.045	4.44	0.035	3.61
112	4.84	0.034	3.97	0.040	3.30	162	4.85	0.042	4.38	0.035	3.87
113	4.91	0.042	4.00	0.041	3.69	163	4.64	0.025	3.60	0.032	3.12
114	4.37	0.041	3.94	0.027	3.13	164	4.73	0.040	3.60	0.015	3.17
115	4.36	0.025	3.94	0.043	3.07	165	4.91	0.044	3.94	0.044	3.54
116	4.46	0.030	3.95	0.045	3.07	166	4.38	0.037	3.71	0.013	3.29
117	4.45	0.025	3.96	0.021	3.09	167	4.36	0.032	4.10	0.028	3.37
118	4.36	0.016	3.94	0.041	2.93	168	4.36	0.020	4.09	0.024	3.57
119	4.44	0.041	3.92	0.027	2.98	169	4.33	0.029	4.11	0.029	3.53
120	4.46	0.012	4.02	0.048	3.07	170	3.94	0.037	3.56	0.034	2.86
121	4.35	0.050	3.95	0.050	2.96	171	3.95	0.020	3.56	0.030	2.96
122	4.38	0.035	3.88	0.046	3.02	172	4.04	0.037	3.54	0.027	2.97
123	5.44	0.019	4.85	0.037	4.81	173	4.85	0.054	4.38	0.052	4.07
124	4.41	0.030	3.91	0.035	3.17	174	4.89	0.041	4.28	0.044	3.90
125	4.39	0.023	3.94	0.037	3.39	175	4.90	0.039	4.28	0.047	3.98
126	4.35	0.025	3.99	0.052	3.23	176	4.75	0.039	4.30	0.056	3.82
127	5.20	0.018	5.03	0.025	4.88	177	4.80	0.023	4.34	0.016	3.97
128	5.21	0.031	5.03	0.050	4.98	178	4.95	0.041	4.34	0.013	4.02
129	5.21	0.027	4.95	0.017	4.91	179	4.22	0.040	4.01	0.021	3.03
130	4.90	0.040	4.10	0.040	4.07	180	4.19	0.025	4.01	0.041	3.06
131	4.61	0.035	4.13	0.047	4.18	181	4.19	0.029	4.02	0.018	3.04
132	4.46	0.017	4.10	0.017	4.18	182	3.97	0.017	3.47	0.041	2.35
133	4.93	0.043	4.85	0.044	4.24	183	3.96	0.038	3.54	0.033	2.51
134	4.81	0.042	4.81	0.049	4.30	184	3.96	0.032	3.51	0.038	2.37
135	4.87	0.043	4.95	0.039	4.36	185	4.94	0.050	4.53	0.051	3.53
136	4.66	0.026	4.27	0.042	3.78	186	5.32	0.027	4.73	0.047	4.27
137	4.75	0.049	4.29	0.046	3.62	187	5.49	0.051	4.78	0.041	4.39
138	4.66	0.020	4.30	0.040	3.66	188	4.91	0.026	4.53	0.024	4.29
139	3.09	0.040	2.66	0.057	1.66	189	4.98	0.027	4.52	0.042	4.30
140	2.92	0.023	2.63	0.042	1.61	190	4.99	0.040	4.53	0.027	4.36
141	3.00	0.025	2.63	0.055	1.64	191	4.64	0.014	3.60	0.032	3.23
142	3.65	0.035	2.92	0.026	2.12	192	4.75	0.047	3.60	0.015	3.28
143	3.68	0.027	2.83	0.047	2.17	193	4.91	0.035	3.94	0.044	3.58

144	3.65	0.012	2.70	0.035	2.04	194	4.78	0.031	4.46	0.028	3.77
145	5.05	0.051	4.44	0.032	4.37	195	4.89	0.040	4.52	0.013	4.05
146	5.07	0.036	4.51	0.034	4.46	196	4.81	0.031	4.49	0.032	3.94
147	5.15	0.045	4.48	0.052	4.37	197	4.91	0.033	4.51	0.029	3.88
148	3.93	0.035	3.28	0.021	2.34	198	4.79	0.006	4.48	0.030	4.11
149	4.02	0.055	3.34	0.030	2.46	199	4.89	0.022	4.46	0.038	4.05
150	3.95	0.030	3.54	0.054	2.44	200	5.49	0.044	4.78	0.026	4.43
151	4.99	0.016	4.53	0.024	4.16	201	4.41	0.041	4.09	0.046	3.20
152	5.05	0.038	4.52	0.042	4.18	202	4.41	0.030	4.11	0.037	3.22
153	5.06	0.046	4.53	0.027	4.24	203	4.45	0.023	4.21	0.033	3.29
154	3.47	0.025	3.48	0.030	2.47						

Av. V: average direct ultrasonic pulse velocity in km/sec, Av. V_s: average indirect (surface) ultrasonic pulse velocity in km/sec, SDD: standard deviation for direct velocity in km/sec, SDS: standard deviation for indirect (surface) velocity in km/sec and f_r = concrete flexural strength in MPa.

These acceptable ranges of standard deviation and coefficient of varaition indicate that good control on the use of testing machine was achieved during the testing program.

The results of direct and surface velocities shown in Table2 were plotted againest the flexural strength in two seperated diagrams. One diagram is for direct test method (Fig. 3) and the other for indirect test method (Fig. 4). For each diagram, the data were submitted to a regression process to produce two mathematical correlations for direct and surface ultrasonic pulse test methods. The feature of curve fitting equations was carefully sellected to gain a maximum coefficient of determinaton (R^2). Eq.2 and eq.3 are the correlation results of the above regression process:

1. Direct pulse test method:

$$f_r = 0.439\, exp^{0.447V} \quad (R^2 = 0.881) \qquad (2)$$

2. Indirect (surface) pulse test method:

$$f_r = 0.596\, exp^{0.420V_s} \quad (R^2 = 0.879) \qquad (3)$$

Where,
V: average direct ultrasonic pulse velocity in km/sec,
V_s: average indirect (surface) ultrasonic pulse velocity in km/sec and
f_r = concrete flexural strength in MPa.

It is clear that both equations eq.2 and eq.3 have simillar feature. The differece is in multiplier and the power of expoenential function. Dividing eq.2 by eq.3 produces eq.4 which is a relationship between direct and indirect pulse velocities of the same concrete. This relation was plotted in Fig.(5).

$$\frac{0.439}{0.596}\left(\frac{exp^{0.447V}}{exp^{0.420V_s}}\right) = 1 \qquad (4)$$

$$V = 0.94V_s + 0.685$$

The regression equation of direct UPV (eq.2) was compared with that proposed by Raouf and Ali (1983), the well known correlation used in Iraq although it concerned with prediction of cube compressive strength. This was done by estimating the flexural strength from the vaules computed from Raouf and Ali's equation and converted to cylinder compressive strength using eq.5 that proposed by ACI 209-Committee.

$$f_r = 0.0135\left[wf'_c\right]^{0.5} \qquad (5)$$

Where,
w = unit weight of concrete in kg/m^3 which was assumed 2400 kg/m^3.
f'_c = cylinder compressive strength (MPa) = 0.8 f_{cu}.
f_{cu} = cube compressive strength (MPa).

The comparison was plotted in (Fig. 6) from which a good agrement between the two proposed equations can be indicated.

4. CONCLUSIONS

The following conclusions can be drawn:

1. The proposed two equations (eq.2 and eq.3) can be used in estimating the flexural strength of plain concrete members such as precast kerb units. The method of test may be applied in situ where the units are errected.
2. The application of the proposed method can be extended to cover the other concrete units that should satisfy a specified flexural strength like

concrete roof tiles and terrazo tiles. This extension should be conditioned by using appropriate types of transducers to create suitable ultrasonic pulses for these thin members.
3. The concluded relationship between direct and indirect (surface) pulse velocities (eq.4) may be used in other ultrasonic applications e.g. compressive strength estimation.
4. The two equations (eq.2 and eq.3) cannot be used in estimating the flexural strength of reinforced concrete members because the existance of reinforcement steel has an important role in UPV measurments.

REFERENCES:

ACI Committee 209, "Prediction of creep, shrinkage and temperature effects in concrete structures". (ACI 209R-92). American Concrete Institute, Detroit, 1999.

ASTM C597 (2002). "Standard test method for pulse velocity through concrete". Annual Book of ASTM Standards, vol.04.02. New York, USA.

British Standards Institution (2004). EN12504-4 "Testing concrete determination of ultrasonic pulse velocity".

Abdul-Salam, M.A. (1992). "Ultrasonic pulse velocity versus strength for concrete in Qatar". Engineering Journal of Qatar University, vol.5, pp.87-93.

Ali, B.A. (2008). "Assessment of concrete compressive strength by ultrasonic non-distructive test". MSc. Thesis, Baghdad University.

Carino, N.J. (1994). "Nondestructive testing of concrete: history and challenges". ACI SP-144, Concrete Technology: past, present and future, P.K. Mehta, Ed., American Concrete Institute, Detroit, MI, pp. 623-678.

C.N.S. Electronics ltd. (1979). "PUNDIT manual for use with the portable ultrasonic non-destructive degital indicating tester". London.

Elevery, R.H. and Ibrahim, L.A(1976). "Ultrasonic assessment of concrete strength at early ages". Magazine of Concrete Research, vol. 28 no. 97 pp.181-190.

Hobbs, B.M. and Tchoketch, K. (2007). "Non-destructive testing techniques for the forensic engineering ivestigation of reinforced concrete buildings". Forensic Sci. Int. 167(2-3), pp.167-172.

Jassim, A.K. (2012). " Prediction of Compressive Strength of Reinforced Concrete Structural Members by Using Combined Non-Destructive Tests". MSc. Thesis, Baghdad University.

Jones, R. (1962). " Non-destructive testing of concrete". MSc. Thesis, Cambridge University, London.

Krautkramer, J. and Krautkramer, H. (1969). "Ultrasonic testing of materials". Journal of Sound

Vibration, 11(1), pp.157-158.

Lawson, I., Denso, K.A., Odoi, H.C., Adjei C.A., Quashie, F.K., Mumuni, I.I. and Ibrahim, I.S. (2011). "Non-destructive evaluation of concrete using ultrasonic pulse velocity". Research Journal of Applied Sciences, Engineering and Technology 3(6) pp.499-504. Maxwell scientific organization.

Malhorta, S. and Carino, N. (2004). "Handbook on non-destructive testing", ASTM International, 2nd edition, pp.181-197.

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.ne, 3rd MENDT, Midle East Non-destuctive testing Conference & Exhibition, 27-30Nov., Bahrain, Manama.

Raouf, Z. and Ali, Z.M. (1983). "Assessment of concrete characteristics at an early age by ultrasonic pulse velocity". Journal of Building Reasearch, vol.2 no.1, pp.31-44.

Shariati, M., Sulong, N.H., Arbnejad, M.M., Shafigh, P. and Sinaei, H. (2011). "Assessing the strength of reinforced concrete structures through ultrasonic pulse velocity and Schmidit rebound hammer tests". Scientific Research and Essays vol.6(1), pp.213-220, Kuala Lumpur, Malaysia.

Solis-Carcano, R. and Moreno, E. (2008). "Evaluation of concrete made with crushed limestone aggrgate based on ultrasonic pulse velocity". Construction Building Materials, 22(6), pp.1225-1231.

(a)

(b)

(c)

(d)

Fig. 1: Ultrasonic pulse velocity test method

Fig. 2: Flextural strength test

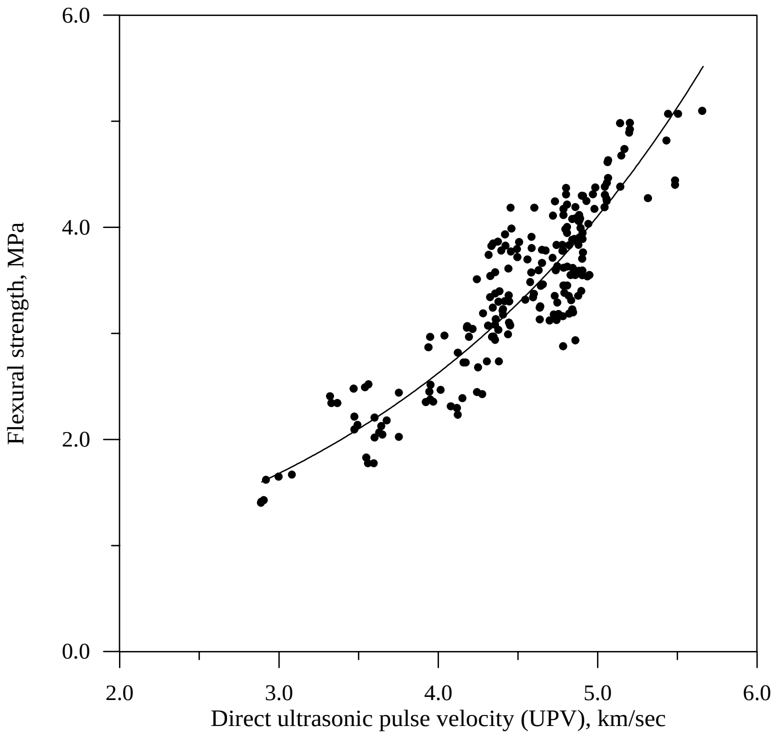

Fig. 3: Direct pulse velocity-flexural strength relationship

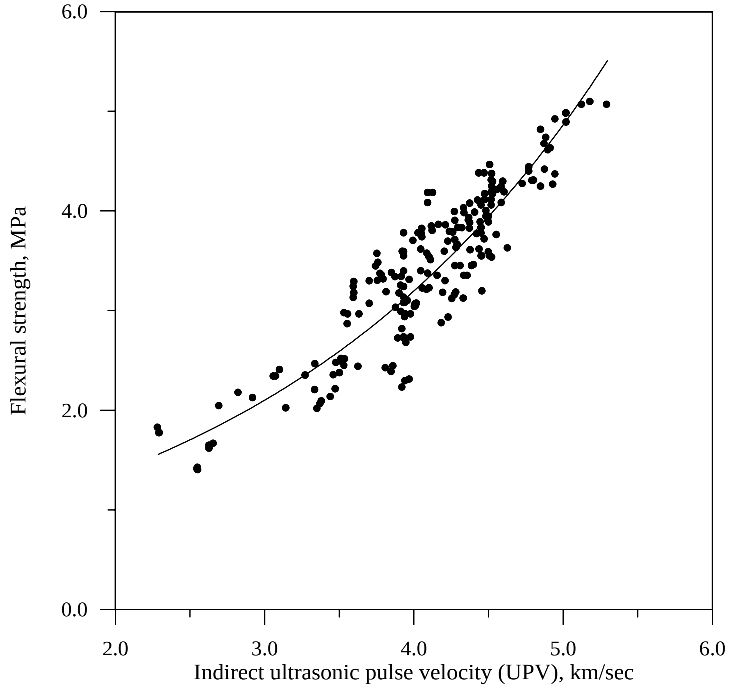

Fig. 4: Indirect (surface) pulse velocity-flexural strength relationship

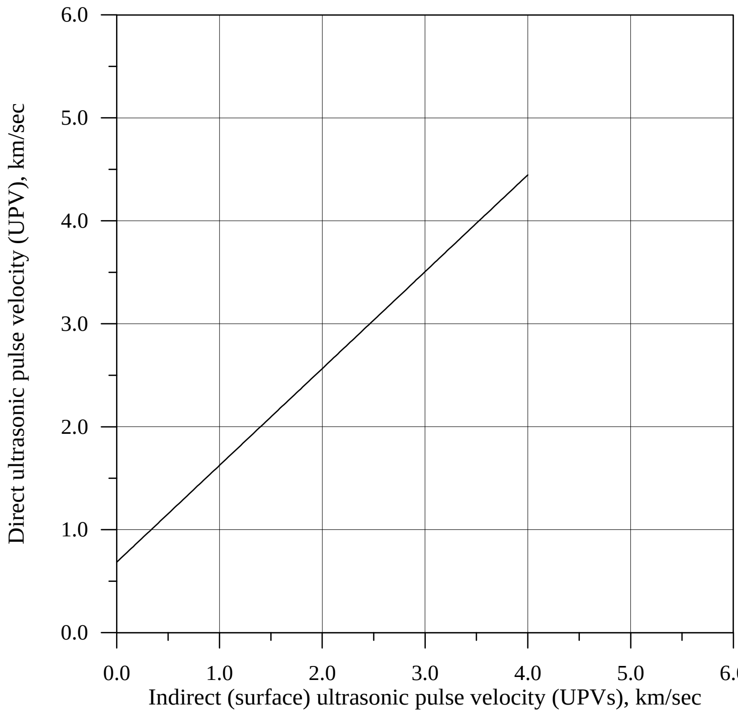

Fig. 5: Direct –indirect ultrasonic pulse velocity relationship

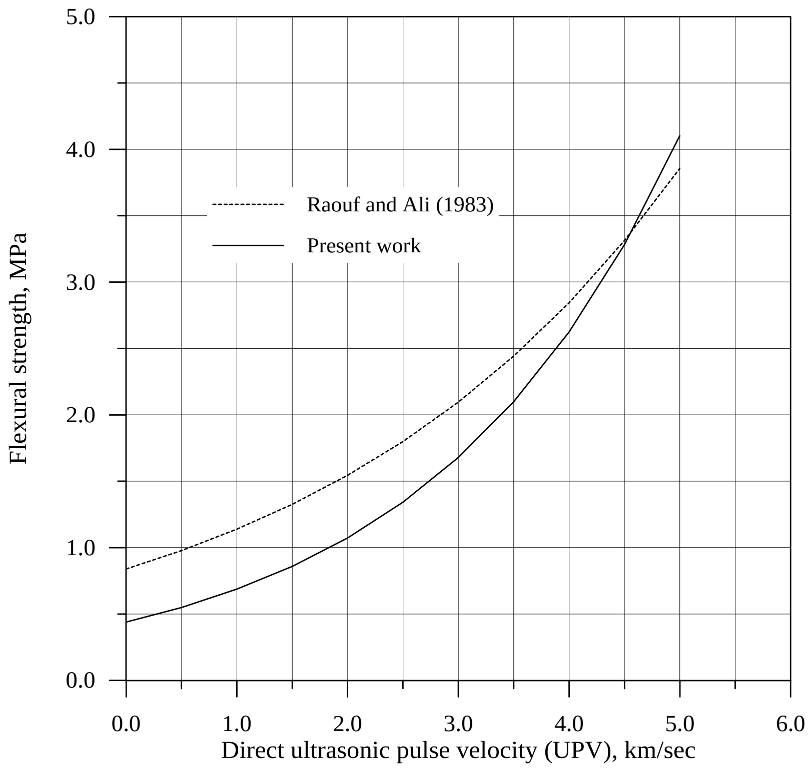

Fig. 6: Comparison between Raouf and Ali (1983) and present work