THE USE OF ULTRASONIC PULSE VELOCITY MEASUREMENTS IN THE ASSESSMENT OF IN SITU CONCRETE STRENGTH

Adel Kurdi
Structural Engineering Department, Faculty of Engineering,
Alexandria University, Alexandria, Egypt.

ABSTRACT

Ultrasonic pulse velocity measurements are a particularly suitable to measure the in situ concrete strength. Cement pastes, mortars, and concretes with water/cement ratio by weight of 0.68, 0.55, 0.52, 0.5, 0.45, 0.4, and 0.35 were used. Several strength grades of concrete were achieved by altering the water/cement ratio and coarse/fine aggregate ratios, while retaining a constant aggregate/cement ratio. The purpose of this paper is to present some of the results obtained in a series of tests that were aimed at relating cube strengths, cured both in air and in water, with structural core strengths. The test specimens were carried out on 100 mm. cubes for cement paste, mortar and concrete, and unreinforced concrete slab 450*450*150 mm. at ages of 1, 2, 5, 7, 14 and 28 days. The cubes and slabs were made from mixes that contained Ordinary Portland Cement (type I). Pink lime stone coarse aggregate was used and the total aggregate to cement ratio was kept constant and equal to 6 for all concrete mixes. From the test results, it can be concluded that the quality of the concrete in a structure may be compared to a properly made and compacted standard specimen by measuring pulse velocity difference in the two concretes. It was also found that the propagation velocity through the cement paste phase gave a good correlation with the crushing concrete strength.

Keywords: Ultrasonic pulse velocity, Core strength, In situ concrete strength, B5 1881 cubes, Air-dried cubes, Pink lime stone, Cement paste, Mortar.

INTRODUCTION

Nondestructive testing of concrete was started in the early 1930 [1]. Within the last three decades, the development of reliable portable instruments such as the PUNDIT for the production, collection and timing of an ultrasonic pulse has brought the technique of the assessment of concrete quality by this means out of the laboratory and on the site.

Ultrasonic pulse velocity measurements are a particularly suitable to measure the quality of concrete structure. One important advantage of the ultrasonic pulse velocity method is that the pulse passes through the full thickness of the unit under inspection. The size and degree of the defects may be estimated with an accuracy suitable for engineering purposes by using simple geometrical principles. The ultrasonic pulse velocity technique may be used to estimate strength with acceptable degree of accuracy by using empirically derived patterns. The determination of the strength of concrete generally implies that representative samples are tested to failure. However, the ultrasonic pulse velocity measures some other property of the hardened concrete and estimates its relative strength from those measurements. The basic theory on which the use of pulse velocity measurements to investigate the quality of concrete has been well stated elsewhere [2] and will not be repeated here. This paper attempts to show the relationships between cube strength, cured both in air and in water and structural core strengths.

The pulse velocity method may be applied to the testing of precast or cast in situ concrete. The measurement of the pulse velocity may be used to determine:

a- The homogeneity of the concrete: may be assessed from the percentage coefficient of variation of the pulse velocity values for a given concrete.

b- The presence of cracks, voids and other imperfections. Once the presence of a defect is suspected, it is important to estimate its size. The center of the void or area of low compaction may be located by finding the minimum transverse velocity from a closely spaced linear set of results in two direction at right angles. Once the approximate center-line of the defect is known, simple geometrical considerations may be used to estimate its size.

c- The changes in the structure of the concrete which occur with time caused by either hydration, which increases strength, or by an aggressive environment, such as sea water attack or sulphate attack. These may be determined by measurements of pulse velocity at different times.

d- The quality of a concrete in relation to standard requirements which generally refer to its strength. It is generally accepted that there is some loss of strength in concrete as placed in the structure compared with the same concrete specimens prepared and cured in a standard manner. By measuring pulse velocity in the perfect and imperfect concrete, the quality of the concrete in the structure may be compared with the properly made and compacted standard specimen.

e- The values of dynamic elastic modulus of the concrete, Since the value of dynamic modulus of elasticity forms part of the basic equation by which the ultrasonic pulse velocity through a material is calculated, the correlation between pulse velocity and dynamic modulus of elasticity is much more satisfactory than that between strength and pulse velocity.

RESEARCH SIGNIFICANCE

The results presented in this paper have been obtained in a laboratory investigation to study the problem of difference between the strength of concrete in a specimen prepared and cured in a standard manner and same concrete placed in a structure.

EXPERIMENTAL PROGRAM

Cement pastes, mortars, and concretes with water/cement ratio by weight of 0.68, 0.55, 0.52, 0.5, 0.45, 0.4, and 0.35 were used. Several strength grades of concrete were achieved by altering the water/cement ratio and coarse/fine aggregate ratios, while retaining a constant aggregate/cement ratio.

MATERIALS

The tests were performed on type I Ordinary Portland Cement. The fine aggregate was a quartzitic sand, zone 2, with a fineness modulus of 2.6, bulk specific gravity (saturated surface dry) = 2.58 and absorption of 0.50 percent. The sand was passed through a No. 4 (4.75 mm.) sieve. The coarse aggregate was a 19 mm. crushed pink lime stone with bulk specific gravity (saturated surface dry) = 2.48 and absorption of 3.50 percent. The coarse aggregate was passed through a 3/4 in. (19 mm.) sieve and retained on a No. 8 (2.36 mm.) sieve. For concrete with water to cement ratio of 0.52, 0.50, 0.45, 0.40, and 0.35, a chloride-free naphthalene sulfonate based superplasticizer at a dosage ranging from .50 to 1.5 percent by weight of cement was used. The values of superplasticizer were obtained by trial and error from preliminary mixes. The superplasticizer produced concretes with slump of 8 cm, with the exception of .35 and .4 concretes, nil slump were achieved. For concrete with water /cement ratios of .68 and .55, the slump were 10 cm and 8 cm respectively without using superplasticizer. Mixes were proportional to limit the number of variables in the study. The cement pastes represented the paste constituents in the mortars, and the mortars represented the mortar constituents in the concrete. The aggregate cement ratio was kept constant and equal to 6 for all concrete mixtures. Details of the mix compositions are given in Table (1).

TEST SPECIMENS

As fabricated, the test specimens were 100 mm. cubes for cement paste, mortar and concrete, and unreinforced concrete slab 450*450*150 mm. Cement paste, mortar and concrete specimens were mixed according to ASTM C305. The molds were filled in three equal layers. For paste and mortar, each layer was hand compacted 25 times using a 19 mm. diameter steel rod. Concrete specimens were filled in three layers, and were consolidated by hand and then reconsolidated on vibrating table. Each layer was vibrated for 1 to 2.5 minutes depending on the water/cement ratio.

Table 1. Mix proportions of concrete, mortar, and cement paste.

	mix No.	w/c	Cement kg	Water kg	Fine kg	Coarse kg
Concrete	C1	0.68	307	209	700	1142
	C2	0.55	319	175	727	1187
	C3	0.52	322	167	734	1198
	C4	0.5	325	163	741	1209
	C5	0.45	330	149	594	1386
	C6	0.40	335	134	603	1407
	C7	0.35	341	119	777	1269
	C8	0.5	325	163	682	1268
	C9	0.55	319	175	957	957
Mortar	M1	0.68	532	362	1213	
	M2	0.55	571	314	1302	
	M3	0.52	581	302	1325	
	M4	0.5	588	294	1340	
	M5	0.45	683	307	1229	
	M6	0.40	707	283	1272	
	M7	0.35	645	226	1470	
	M8	0.5	613	307	1288	
	M9	0.55	493	271	1478	
Paste	P1	0.68	1003	682		
	P2	0.55	1153	634		
	P3	0.52	1195	621		
	P4	0.5	1224	612		
	P5	0.45	1304	587		
	P6	0.40	1395	558		
	P7	0.35	1499	525		

The specimens were covered with plastic sheets immediately after casting, so as to minimize moisture loss. The next day, the specimens were stripped and cured under specified conditions. Half of the concrete cubes were cured in water, while the remaining half were left in the air. The cement pastes, mortars and slabs were cured in the same environment as the air cured concrete cubes. For each slab, four 100 mm. cores were cut at ages of 5,7, 14, 21 and 28 days. Prior to cutting the cores, eight sets of UPV reading were taken on the slab, two each way across the 450 mm. width, and four through the 150 mm. depth at each core position. Prior to concrete compressive cube strength test, UPV readings were taken across each pair of faces.

The ultrasonic pulse velocity test was carried out for cement paste, mortar and concrete cubes at ages of 1, 2, 5, 7, 14, 21 and 28 days. Due to the poor compaction of the two concrete mixes C6 and C7, the slab surface was too rough for UPV reading. The accuracy of the transit time measurement can only be assumed if good acoustic coupling between the transducer face and the concrete can be achieved [3]. Therefore the surface of the slab was covered with a minimum thickness of plaster of paris to obtain suitably smooth surface for the transducer.

TEST RESULTS AND DISCUSSION

Figures (1, 2) and (3) show the results of compressive strength against ultrasonic pulse velocity (UPV) for air-dried cubes, BS 1881 cubes (water-cured cubes) and dry cores respectively. It should be recognized that, in general, each "cube strength point" is the average of three results, and each "core strength point" is the average of four, and also, the core strength is the measured compressive strength as defined in BS 1881 : part 120 : 1989 [4]. From the above test results, it is clear that there is a significant difference between the strength of concrete in a specimen prepared and cured in the standard manner and the same concrete as placed in the structure. It is generally accepted that there is some loss in strength and pulse velocity in the latter. The principle behind this analysis is that the loss in pulse velocity is made up of two parts, as shown in Figure 4. The first is due to strength loss (A), while, the second is due to humidity loss (B). The line joining the BS 1881 cube strength, and the structural strength as judged by concrete society Technical Report 11 [5], may be reasonably called the desiccation line.

The relationship between compressive strength and pulse velocity for water-cured cubes and the structural strength becomes:

$$k = [\log_e (f_{c1}/f_{c2})]/[f_{c1}(V_1-V_2)] \qquad (1)$$

Where:

f_{c1} is the water-cured cube strength.
f_{c2} is the structural strength as measured by "actual strength" and calculated from cores in accordance with BS 1881 : part 120 : 1989.
V_1 is the pulse velocity through the water-cured cube.
V_2 is the pulse velocity through the structure.
k is a constant for water-cured cubes to dry cores.

By measuring the difference in the pulse velocity between the concrete in the structure and the properly made and compacted standard specimen, the structure strength may be compared with that of standard specimen [6,7]. Table (2) shows the constant k for water-cured cubes to dry cores calculated at ages of 5, 7, and 14 days. The estimated core strengths by using the above derived constant k are shown in Table (3) at ages of 21 and 28 days for water-cured to dry cores. The difference between the experimental and estimated core strength values was in the range of -0.50 N/mm^2 to + 1.2 N/mm^2. These results tend to support the contention that accurate strength determination may by obtained by using this principle under controlled conditions.

The relationship between compressive strength and pulse velocity for water-cured to air-dried cubes:

$$k = [\log_e (f_{c1}/f_{c3})]/[f_{c1}(V_1-V_3)] \qquad (2)$$

Where:

f_{c1} is the water-cured cube strength.
f_{c3} is the air-dried cube strength.
V_1 is the pulse velocity through the water-cured cube.
V_2 is the pulse velocity through the air-dried cube.
k is a constant for water-cured to air-dried cubes.

Table (4) shows the constant k for water-cured to air-dried cubes calculated at ages of 2, 5, 7, and 14 days. The estimated air-dried cube strengths by using the above derived constant k are shown in Table (5) at ages of 21 and 28 days for water-cured to air-dried cubes. the difference between the experimental and estimated air-dried cube strength values was in the range of -2.60 N/mm^2 to + 1.0 N/mm^2.

This technique was used for the quality control of concrete slabs, and the value of k was determined for water-cured cubes to dry cores and for water-cured to air-dried cubes. Several strength grades of concrete were achieved by altering the water/cement ratio and coarse/fine aggregate ratios, but retaining a constant aggregate/cement ratio. Values of constant k have been determined empirically for the two following conditions. A value of constant k = 0.018 for water-cured cubes (BS 1881 cubes) to dry cores was derived from 45 results. For the relationship between water-cured to air-dried cubes a constant k= 0.015 has been found from 54 results where strength values were recorded in N/mm^2. The difference between the two constants can be accounted for by a difference in thickness between a standard cube specimen (100 mm.) and each of concrete slab (150 mm.) and the drying effect. In the study carried by Tomsett [7], the value of the constant k′ for water-cured cubes to dry cores was 0.015, while that for water-cured to air-dried cubes was 0.019. It has been demonstrated that, some loss of strength occurs in a concrete structure compared to that in a properly made and compacted standard concrete specimen. From the above test results, it can be concluded that the quality of the concrete in a structure may be compared to a properly made and compacted standard specimen by measuring pulse velocity difference in the two concretes.

Table 2. Constant k for water-cured cubes to dry cores at 5, 7, and 14 days.

Mix		f_{c1} (water-cured cubes) N/mm2	f_{c2} (dry cores) N/mm2	V_1 (water-cured cubes) km/s	V_2 (Dry cores) km/s	k
5 days	C1	13.8	11.3	4.31	3.64	0.022
	C2	15.1	13.3	4.29	3.77	0.016
	C3	16.9	14.9	4.52	3.95	0.013
	C4	22	17.3	4.6	4.11	0.022
	C5	22.9	18.4	4.67	4.1	0.017
	C6	22.6	19.9	4.74	4.17	0.010
	C7	30.7	21.9	4.98	4.19	0.014
	C8	22.4	17.7	4.61	4.06	0.019
	C9	18	14.1	4.46	3.9	0.024
7 days	C1	15.9	12.5	4.35	3.73	0.024
	C2	15.8	13.7	4.65	3.95	0.013
	C3	20.3	15.2	4.65	3.98	0.021
	C4	24.3	18.5	4.74	4.22	0.022
	C5	25.5	19.3	4.83	4.17	0.017
	C6	28.8	21.4	5.02	4.21	0.013
	C7	33.5	23.7	5.08	4.25	0.012
	C8	25.9	18.9	4.81	4.11	0.017
	C9	20.6	15.9	4.63	3.99	0.020
14 days	C1	19.8	13.8	4.63	3.88	0.024
	C2	23.8	16.7	4.75	3.94	0.018
	C3	23.4	16.2	4.8	4	0.020
	C4	28.7	20.3	4.78	4.18	0.020
	C5	30.8	21.3	4.88	4.21	0.018
	C6	37	25.5	5.05	4.27	0.013
	C7	42.4	27.3	5.13	4.3	0.013
	C8	30.4	20.1	4.98	4.18	0.017
	C9	24.7	18.5	4.65	4.06	0.020

Table 3. Estimating core strength by using the derived constant k for water-cured cubes to dry cores.

Mix		f_{c1} (water-cured cubes) N/mm2	V_1 (water-cured cubes) km/s	V_2 (Dry core) km/s	f_{c2} (estimate) N/mm2	f_{c2} (experimental) N/mm2	Error N/mm2
21 days	C1	22.1	4.69	3.89	16.1	15.3	+0.8
	C2	25.1	4.81	4.08	18	16.9	+1.1
	C3	25.2	4.85	4.11	18	18.5	-0.5
	C4	33.4	4.84	4.26	23.6	22.5	+1.1
	C5	35.8	5.05	4.44	24.2	24.4	-0.2
	C6	37.8	5.1	4.63	27.5	26.4	+1.1
	C7	44.1	5.11	4.62	29.9	28.9	+1.0
	C8	32.9	5.05	4.43	22.8	23.1	-0.3
	C9	26.2	4.75	4.15	19.7	18.9	+0.8
28 days	C1	23.3	4.72	3.9	16.5	15.9	+0.6
	C2	27.9	4.83	4.12	19.5	18.9	+0.6
	C3	28.5	4.81	4.13	20.1	19.5	+0.6
	C4	35.2	4.86	4.29	24.5	23.6	+0.6
	C5	36.9	5.08	4.47	24.6	24.9	-0.3
	C6	40.1	5.1	4.65	29	28.2	+0.8
	C7	46.8	5.11	4.66	32	30.8	+1.2
	C8	34.7	5.06	4.44	23.6	23.4	+0.2
	C9	27.9	4.81	4.18	20.3	19.9	+0.4

Table 4. Constant k for water-cured to air-dried cubes at 2, 5, 7, and 14 days.

Mix		f_{c1} (water-cured cubes) N/mm2	f_{c3} (air-dried cubes) N/mm2	V_1 (water-cured cubes) km/s	V_3 (air-dried cube) km/s	k
2 days	C1	9.7	8.9	4.09	3.65	0.020
	C2	10.9	9.8	4.17	3.7	0.021
	C3	12.1	11.5	4.32	4	0.013
	C4	15.2	13.9	4.43	4.05	0.016
	C5	18.1	16.4	4.49	4.09	0.014
	C6	19.4	18.4	4.56	4.15	0.007
	C7	24.9	22.1	4.77	4.27	0.010
	C8	14.8	13.1	4.43	3.97	0.018
	C9	10.7	9.9	4.27	3.89	0.019
5 days	C1	13.8	12.4	4.31	3.97	0.023
	C2	15.1	14.6	4.29	4.12	0.013
	C3	16.9	16	4.52	4.35	0.019
	C4	22	20.2	4.6	4.36	0.016
	C5	22.9	19.8	4.67	4.39	0.023
	C6	22.6	20.2	4.74	4.29	0.011
	C7	30.7	28.1	4.98	4.41	0.005
	C8	22.4	19.8	4.61	4.25	0.015
	C9	18	16.5	4.46	4.2	0.019

7 days	C1	15.9	14.7	4.35	4.03	0.015
	C2	15.8	14.5	4.65	4.25	0.014
	C3	20.3	18	4.65	4.25	0.015
	C4	24.3	23.1	4.74	4.63	0.019
	C5	25.5	21.5	4.83	4.50	0.020
	C6	28.8	25.5	5.02	4.46	0.008
	C7	33.5	30.1	5.08	4.51	0.006
	C8	25.9	21.2	4.81	4.44	0.021
	C9	20.6	18.6	4.63	4.37	0.019
14 days	C1	19.8	17.7	4.63	4.2	0.013
	C2	23.8	20.9	4.75	4.14	0.018
	C3	23.4	20.5	4.8	4.38	0.013
	C4	28.7	26.3	4.78	4.65	0.023
	C5	30.8	27.5	4.88	4.54	0.011
	C6	37	29.8	5.05	4.48	0.010
	C7	42.4	37.8	5.13	4.56	0.005
	C8	30.4	23.6	4.98	4.46	0.016
	C9	24.7	22.6	4.65	4.40	0.014

Table 5. Estimating air dried cube strength by using the derived constant k for water-cured to air-dried cubes.

Mix		f_{c1} (water-cured cubes) N/mm2	V_1 (water-cured cubes) km/s	V_3 (air-dried cube) km/s	f_{c3} (formula estimate) N/mm2	f_{c3} (experimental) N/mm2	Error N/mm2
21 days	C1	22.1	4.69	4.28	19.3	18.9	+0.4
	C2	25.1	4.81	4.50	22.3	22.5	-0.2
	C3	25.2	4.85	4.50	22.1	22.1	0.0
	C4	33.4	4.84	4.69	31	30	+1.0
	C5	35.8	5.05	4.79	31.1	30.1	+1.0
	C6	37.8	5.1	4.64	29.1	30.9	-1.8
	C7	44.1	5.11	4.78	35.5	37.1	-1.6
	C8	32.9	5.05	4.54	25.6	26.8	-1.2
	C9	26.2	4.75	4.47	23.5	24.7	-1.2
28 days	C1	23.3	4.72	4.32	20.3	20	+0.3
	C2	27.9	4.83	4.52	24.5	23.9	+0.6
	C3	28.5	4.81	4.57	25.7	24.9	+0.8
	C4	35.2	4.86	4.71	32.5	32.7	-0.2
	C5	36.9	5.08	4.87	32.9	34.8	-1.9
	C6	40.1	5.1	4.81	33.7	35.3	-1.6
	C7	46.8	5.11	4.85	39	41.6	-2.6
	C8	34.7	5.06	4.62	27.6	28.9	-1.3
	C9	27.9	4.81	4.50	24.5	25.9	-1.4

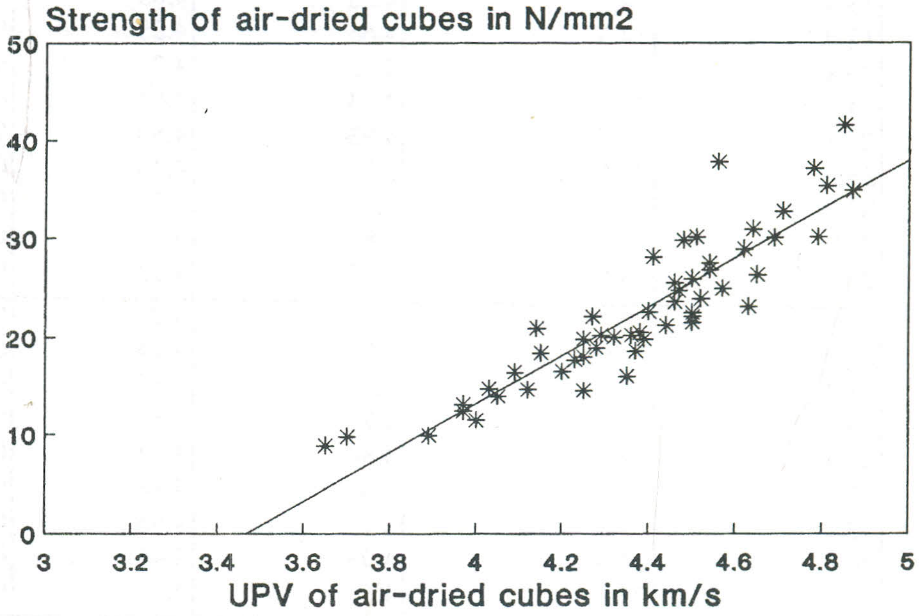

Figure 1. Relationship between ultrasonic pulse velocity and strength of air-dried concrete cubes.

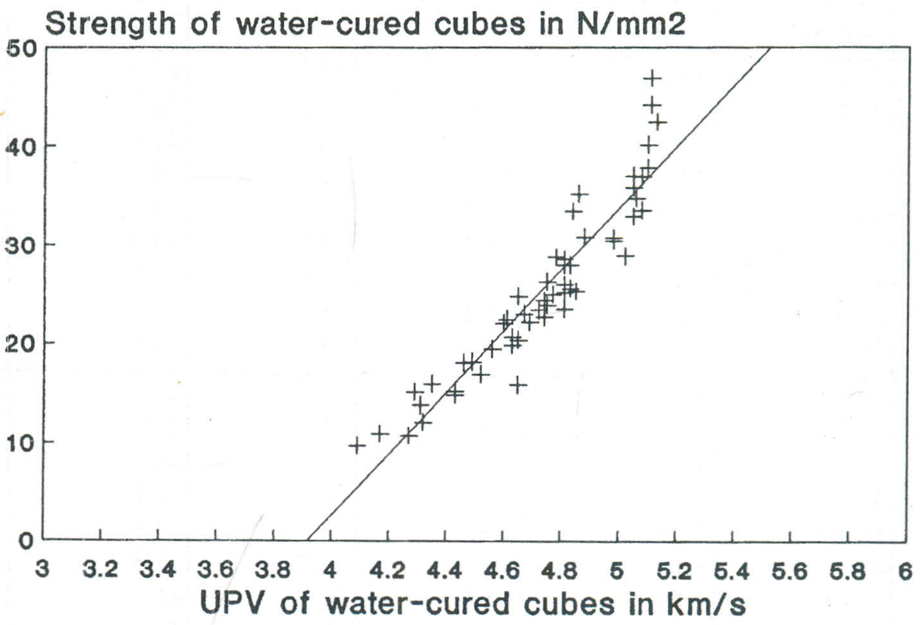

Figure 2. Relationship between ultrasonic pulse velocity and strength of water-cured concrete cubes.

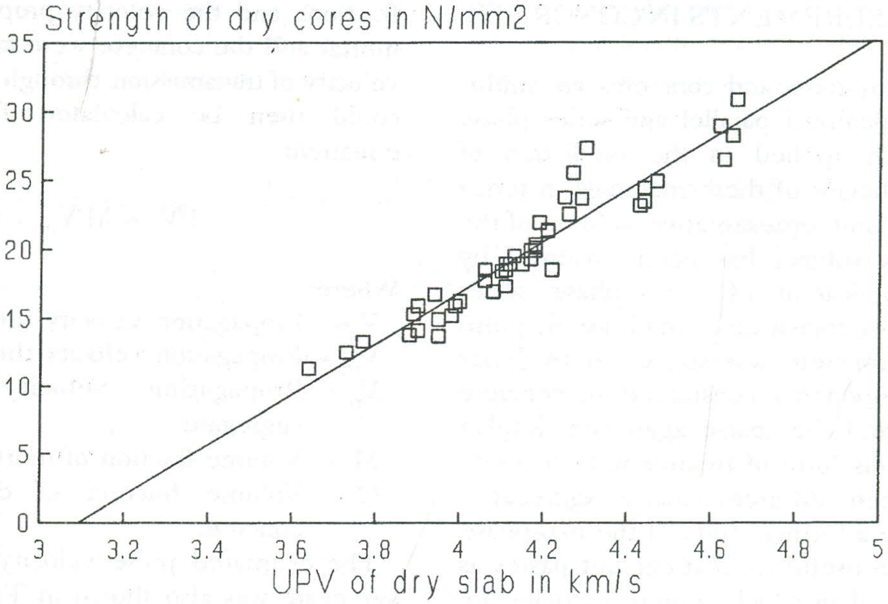

Figure 3. Relationship between ultrasonic pulse velocity of dry slab and strength of dry cores.

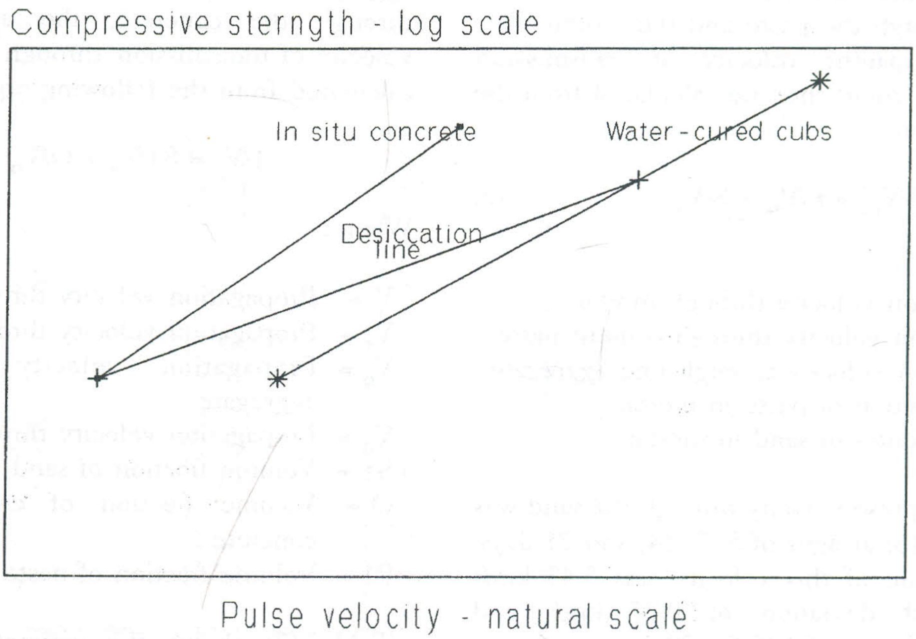

Figure 4. Pulse velocity and strength relationship between standard specomens and the same concrete as placed in the structure.

MULTI-PHASE INTERPRETATION OF PULSE VELOCITY MEASUREMENTS IN CONCRETE.

Cement pastes, mortars, and concretes are multi-phase materials. Idealized parallel and series phase models have been applied in the prediction of average elastic behavior of these materials in terms of elastic property and representative volume of the constituents. This subject has been reviewed by Newman [8]. Application of a two-phase series model for calculating transit times of ultrasonic pulse velocity through concrete was suggested by Jones [9]. The two components considered in concrete were the mortar and the coarse aggregate. Kaplan [10] has applied this form of treatment to concrete made with thirteen different coarse aggregates. Andrew [11] made a further study of the two-phase theory. It has been useful to treat cement pastes as a two-phase material in which cement particles are embedded in water. Besides, the mortars can be treated as a two-phase material in which sand particles are embedded in homogeneous pastes. In this experimental study, the cement paste represented the paste constituents in the mortar, since the volume fractions and the velocity propagation through the paste and the mortar were known. The apparent velocity of transmission through the sand could then be calculated from the following equation:

$$1/V_m = P/V_p + S/V_s \quad (3)$$

Where:

V_m = Propagation velocity through mortar
V_p = Propagation velocity through cement paste
V_s = Propagation velocity through fine aggregate
P = Volume fraction of paste in mortar
S = Volume fraction of sand in mortar

The estimated pulse velocity through the sand was shown in Table (6) at ages of 5, 7, 14, and 21 days. The average value of this velocity was 5.43 km/s with a standard deviation of 0.22 km/s and coefficient of variation of 4 % for 28 results.

Similarly concrete can be treated as a two-phase material in which coarse aggregates particles are embedded in homogeneous mortar. Throughout this experimental study, the mortar represented the mortar constituents in the concrete, and the volume fractions and the velocity propagation through the mortar and the concrete were known. The apparent velocity of transmission through the coarse aggregate could then be calculated from the following equation:

$$1/V = M/V_m + O/V_o \quad (4)$$

Where:

V = Propagation velocity through concrete
V_m = Propagation velocity through mortar
V_o = Propagation velocity through coarse aggregate
M = Volume fraction of mortar in concrete
O = Volume fraction of coarse aggregate in concrete

The estimated pulse velocity through the coarse aggregate was also shown in Table (6) at ages of 5, 7, 14, and 21 days. The average value of this velocity was 5.36 km/s with a standard deviation of 0.32 km/s and coefficient of variation of 6 % for 36 results.

Knowing the volume fractions and the velocity propagation through the sand and the coarse aggregate, and measuring the propagation velocity through the concrete, the apparent estimated velocity of transmission through the paste could be calculated from the following equation:

$$1/V = S1/V_s + O/V_o + P1/V_p \quad (5)$$

Where:

V = Propagation velocity through concrete
V_s = Propagation velocity through fine aggregate
V_o = Propagation velocity through coarse aggregate
V_p = Propagation velocity through cement paste
S1 = Volume fraction of sand in concrete
O = Volume fraction of coarse aggregate in concrete
P1 = Volume fraction of paste in concrete

Table (7) shows the estimated pulse velocity through the cement paste at age of 28 days. In the presented work, the difference between the experimental and estimated values of the apparent velocity of transmission through the paste was found to be less than 10 percent. The curve shown in Figure (5) represents the relationship between the cement paste pulse velocity and compressive strength of dry cores. Using such curve, it is possible to predict the in situ concrete strength after calculating the paste pulse velocity. There was a good correlation between the cement paste pulse velocity and the crushing strength of dry cores.

Table 6. UPV for concrete, mortar, and cement paste cubes (air-dried).

Mix		Experimental			Estimate	
		V km/s	V_m km/s	V_p km/s	V_o km/s	V_s km/s
5 days	C1	3.97	3.22	2.40	5.46	5.23
	C2	4.12	3.52	2.53	5.05	5.64
	C3	4.35	3.58	2.58	5.67	5.7
	C4	4.36	3.79	2.83	5.17	5.52
	C5	4.39	3.73	2.89	5.1	5.44
	C6	4.29	3.76	2.92	4.8	5.37
	C7	4.41	3.93	3.00	5	5.13
	C8	4.25	3.6		5.14	
	C9	4.2	3.69		5.35	
7 days	C1	4.03	3.51	2.65	4.88	5.54
	C2	4.25	3.6	2.67	5.28	5.41
	C3	4.25	3.64	2.73	5.19	5.36
	C4	4.63	3.74	2.95	5.55	4.97
	C5	4.5	3.77	2.99	5.31	5.26
	C6	4.46	3.8	3.01	5.13	5.23
	C7	4.51	3.87	3.03	5.36	4.89
	C8	4.44	3.65		5.61	
	C9	4.37	3.73		5.6	
14 days	C1	4.2	3.63	2.74	5.15	5.73
	C2	4.14	3.7	2.76	4.75	5.5
	C3	4.38	3.79	2.8	5.27	5.74
	C4	4.65	3.85	2.99	5.93	5.24
	C5	4.54	3.89	3.01	5.23	5.69
	C6	4.48	3.94	3.04	5	5.7
	C7	4.56	4.07	3.10	5.16	5.33
	C8	4.46	3.84		5.28	
	C9	4.4	3.86		5.63	
21 days	C1	4.28	3.65	2.78	5.37	5.64
	C2	4.5	3.76	2.81	5.72	5.57
	C3	4.5	3.81	2.89	5.6	5.49
	C4	4.69	3.86	3	6.04	5.25
	C5	4.79	3.94	3.15	5.77	5.41
	C6	4.64	3.98	3.09	5.3	5.68
	C7	4.78	4.11	3.15	5.67	5.34
	C8	4.54	3.88		5.43	
	C9	4.47	3.85		5.97	

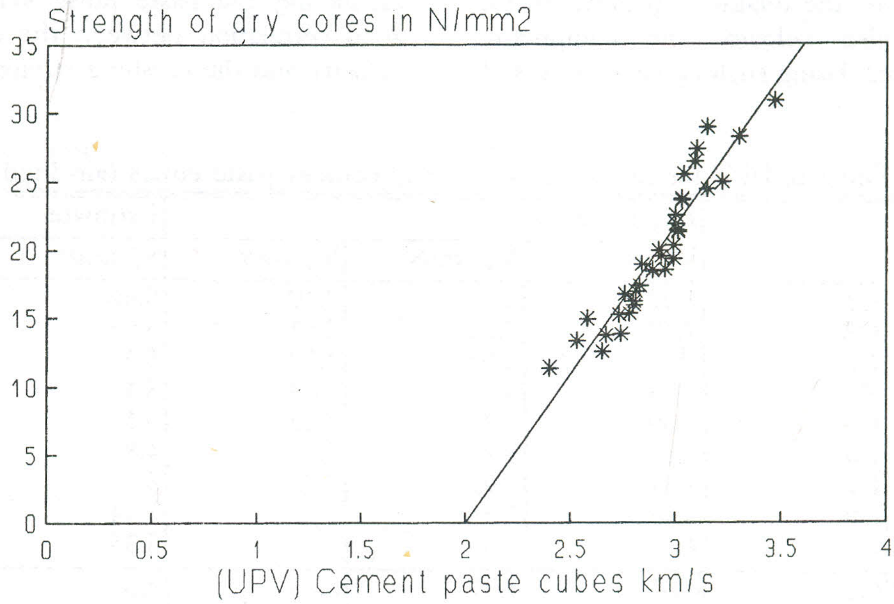

Figure 5. Relationship between ultrasonic pulse velocity of cement paste cubes and strength of dry cores.

Table 7. Estimated pulse velocity through cement paste.

Mix		Experimental			Estimated V_p km/s	Error %
		V km/s	V_m km/s	V_p km/s		
28 days	C1	4.32	3.68	2.8	2.59	-7.5
	C2	4.52	3.77	2.84	2.75	-3
	C3	4.57	3.83	2.93	2.85	-2.7
	C4	4.71	3.91	3.03	3.14	+3.6
	C5	4.87	3.98	3.22	3.53	+9.6
	C6	4.81	4	3.3	3.37	+2.1
	C7	4.85	4.14	3.47	3.34	-3.8
	C8	4.62	3.89			
	C9	4.5	3.91			

CONCLUSION

Ultrasonic pulse velocity technique may be used to estimate the in situ concrete strength with an acceptable degree of accuracy by measuring the difference in the pulse velocity between the concrete in the structure and the properly made and compacted standard specimen. It may be also possible, knowing the volume fractions and the velocity propagation through the sand and the coarse aggregate, and measuring the propagation velocity through the concrete, to calculate the apparent velocity of transmission through the paste. Using the relationship between cement paste pulse velocity and the strength of dry cores, it is possible to predict the strength of concrete. Multi-phase interpretation of pulse velocity measurement could be used to investigate the behaviour and the properties of the different phases in concrete. The calculated propagation velocity through the cement paste gave good correlations with its experimental values, and there was a good correlation between the paste pulse velocity and the crushing concrete strength.

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