Ultrasonic testing of concrete

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The article presents results of a laboratory investigation carried out on 1300 concrete cube specimens using ultrasonic pulse velocity technique. The investigations were carried out to establish correlations between ultrasonic pulse velocity and compressive strength for both undamaged concrete and concrete damaged by chemical attack.

The ultrasonic pulse velocity method is one of the reliable and time-tested methods of non-destructive testing. This technique has been applied for the evaluation of the properties and quality of concrete. Research in laboratory consists of testing small-sized specimens mainly relating the pulse velocity with strength and elastic modulus of concrete for assessing the durability of concrete or its resistance to damage in aggressive environments, studies on setting and hardening of concrete etc. Studies in the field have been mostly conducted to assess the quality of concrete, for estimating deterioration of concrete and for detection of cracks in concrete. It has been established by various investigators that the pulse velocity measurements in concrete are influenced by a number of parameters. The type of cement used, type of aggregate, addition of admixtures, water/cement ratio, aggregate cement ratio, age at test, moisture condition of concrete, smoothness of surface under test, honeycombing in concrete, pulse travel distance, and presence of reinforcing steel are some factors which influence the pulse velocity readings. For the correct assessment of the quality of concrete the influence of some of these parameters was studied in detail in a laboratory and the paper describes the results of the investigation. When concrete gets damaged due to chemical action, its micro-structure undergoes changes, affecting the travel of ultrasonic pulses through it. Correlations between pulse velocity and compressive strength established for undamaged concrete may not be applicable to concrete that has undergone deterioration. Hence, investigations were also carried out to establish correlation between ultrasonic pulse velocity and compressive strength for undamaged concrete and concrete affected by chemical attack.

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Experimental work

Test specimens

Effect of honeycombing

Well compacted and honeycombed cubes of 15-cm size were cast from concrete mix 1:2:4 by weight with a water cement ratio of 0.55. Fine aggregate used was natural sand known as Badarpur sand having a fineness modulus of 2.96. The coarse aggregate was well graded rounded gravel of 20 mm maximum size. Well compacted cubes were consolidated on a vibration table. For this study honey-combed cubes were prepared by incomplete compaction. The moulds were filled with concrete and the top of concrete just levelled. The extent of compaction achieved was due to the pressure of levelling operation and self weight of concrete.

Effect of cracks

Artificial cracks were introduced in the beam while casting, to study the effect of cracks on pulse velocity readings. The beams were cast with the same mix proportion of concrete explained above and the details of the beams are shown in Fig 1. Beam 2 had a single crack, 6 cm deep and 2 mm wide at the centre of the beam. Beam 3 had three cracks, 6 cm deep and 2 mm wide, and beam 4 had a crack having 40.8 cm depth. The cross sectional size of all the beams was 10.5 x 15.5 cm. In beams 2 and 3, the cracks were introduced while casting, with the help of 2 mm thick pieces of G.I. sheet. The oiled G.I. sheet pieces were kept in preplanned crack positions while casting.

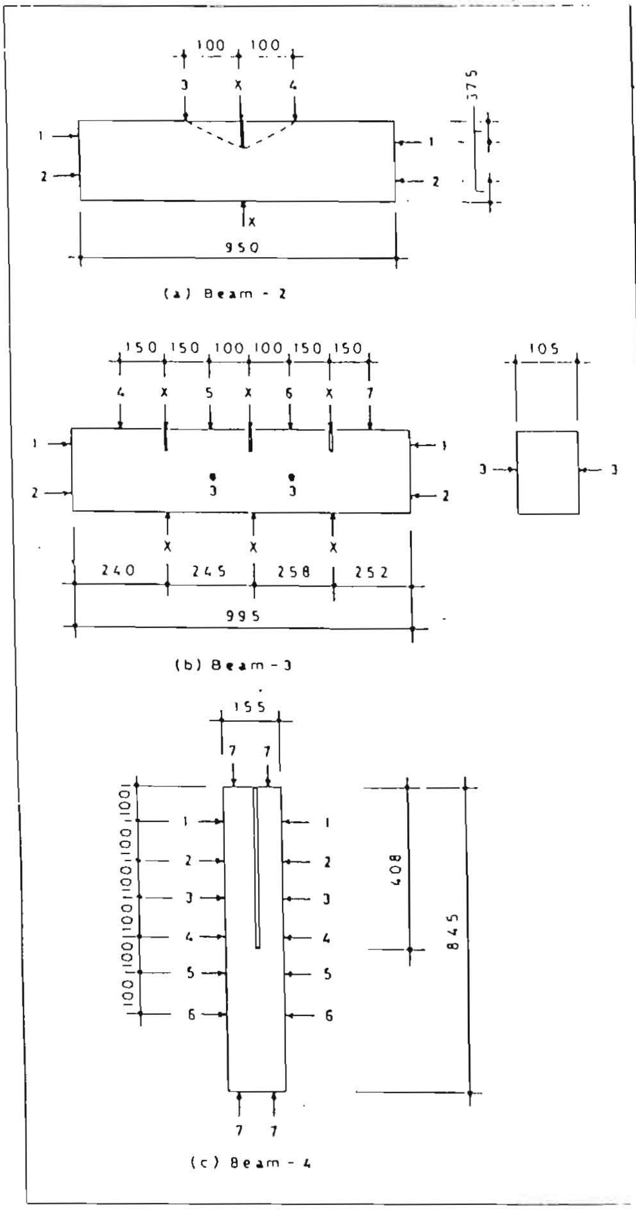


Fig 1 Positions of probes on cracked beams for measurement of path length and crack depth

A day after casting, the G.I. sheet pieces were removed. In beam 4 the crack was introduced by filling sawdust at mid depth of the beam while casting. Concrete was placed, compacted and levelled upto mid depth of the mould. At one end of the mould a polythene sheet of 40.8 cm length and 10.5 cm width was laid over the concrete. Then a layer of sawdust, about 1 cm thick, was put on this sheet. Over this layer of sawdust, another sheet of polythene of 40.8 x 10.5 cm size was again laid. The concrete was now poured and the mould completely filled and levelled. After curing the specimen the sawdust filling was removed with a handsaw. When removed, the sawdust packing gave a well designed crack in the beam.

Table 1 : Materials and mix proportion for specimens

Designation	Mix by volume	Cement	Sand, fineness modulus	Coarse aggregate	No. of cubes
1.1	1:3:6	OPC	3.4	Crushed	36
1.2	1:2:4	OPC	3.4	Crushed	36
1.3	1:1½:3	OPC	3.4	Crushed	36
1.4	1:1:2	OPC	3.4	Crushed	36
2.1	1:3:6	OPC	1.9	Crushed	36
2.2	1:2:4	OPC	1.9	Crushed	36
2.3	1:1½:3	OPC	1.9	Crushed	36
2.4	1:1:2	OPC	1.9	Crushed	36
3.1	1:3:6	OPC	3.4	Natural	36
3.2	1:2:4	OPC	3.4	Natural	36
3.3	1:1½:3	OPC	3.4	Natural	36
3.4	1:1:2	OPC	3.4	Natural	36
4.1	1:3:6	OPC	1.9	Natural	36
4.2	1:2:4	OPC	1.9	Natural	36
4.3	1:1½:3	OPC	1.9	Natural	36
4.4	1:1:2	OPC	1.9	Natural	36
5.1	1:3:6	PPC	3.4	Crushed	36
5.2	1:2:4	PPC	3.4	Crushed	36
5.3	1:1½:3	PPC	3.4	Crushed	36
5.4	1:1:2	PPC	3.4	Crushed	36
6.1	1:3:6	PPC	1.9	Crushed	36
6.2	1:2:4	PPC	1.9	Crushed	36
6.3	1:1½:3	PPC	1.9	Crushed	36
6.4	1:1:2	PPC	1.9	Crushed	36
7.1	1:3:6	PPC	3.4	Natural	36
7.2	1:2:4	PPC	3.4	Natural	36
7.3	1:1½:3	PPC	3.4	Natural	36
7.4	1:1:2	PPC	3.4	Natural	36
8.1	1:3:6	PPC	1.9	Natural	36
8.2	1:2:4	PPC	1.9	Natural	36
8.3	1:1½:3	PPC	1.9	Natural	36
8.4	1:1:2	PPC	1.9	Natural	36

Effect of path length

Beams of cross sectional size 10.5 x 15.5 cm and length 31.5, 63 and 94 cm were cast and from these specimens path length of 10.5, 15.5, 31.5, 63 and 94 cm were available for study. The concrete for all the specimens was mixed at one time in a mixer. The specimens were removed from the mould 48 hours after casting. This much time was given, as casting was done in cold weather. The specimens were then immersed in water for curing. After 28 days they were removed from water and then allowed to dry under room temperature till testing.

Effect of corrosion

1,300 concrete cubes of size 15 x 15 x 15 cm were cast with four different concrete mixes i.e. 1:3:6, 1:2:4, 1:1½:3 and 1:1:2 (cement : sand : coarse aggregate) by volume with water cement ratio of 0.55. Two types of cement, that is, ordinary Portland cement (OPC) and Portland pozzolana cement (PPC), two types of sand i.e. coarse sand and fine sand having fineness modulus of 3.4 and 1.9 respectively and two types of coarse aggregates, that is, crushed aggregate and natural aggregate having fineness modulus of 6.73 and 6.77 respectively were used for making concrete for the test cubes. The materials and

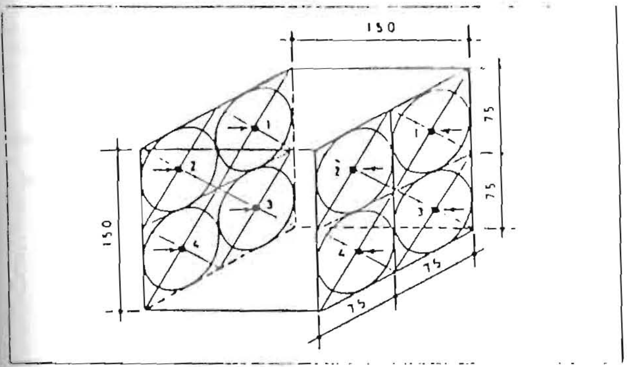


Fig 2 Positions of probes on a pair of opposite faces of a 15 cm cube

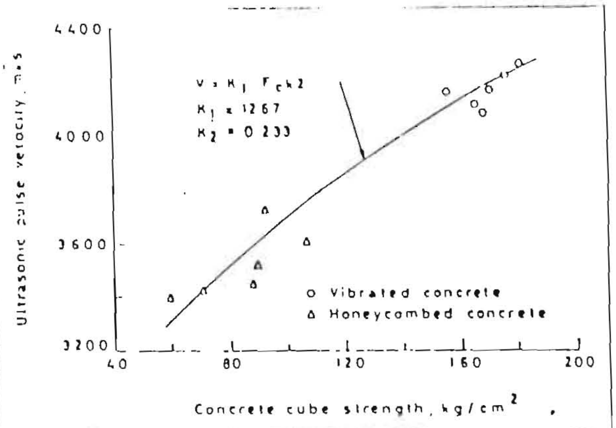


Fig 3 Variation of pulse velocity with strength of concrete

mix proportions for the concrete test specimens are given in *Table* 1.

Thirty six cubes were cast in each set and cured under water for 28 days. Out of each set of 36 cubes, 6 cubes were subjected to non-destructive and destructive tests at 28 days. Twelve cubes were immersed in saturated solution of ammonium sulphate and six cubes in saturated solution of urea. Remaining twelve cubes were kept untreated, to be tested along with treated cubes. Although it is preferable to test the specimens exposed to chemicals for a long period, it is not practicable to prolong the investigation to such a long duration. Hence, in the present study the process of corrosion was accelerated by subjecting the cubes to alternate cycles of immersion in saturated solution of chemicals for a day and drying in sun for 3 days for a period upto 270 days. When dipped in saturated solution of ammonium sulphate/urea, the solution penetrates into the pores and when the cubes are dried, the solution in the pores crystallises. Crystallisation causes swelling, leading to disintegration of concrete. The treated cubes were tested at ages of 90 days, 150 days and 270 days together with untreated cubes of the same age, to establish correlation between destructive and non-destructive tests.

Instrument

Ultrasonic concrete tester of type SEA-690 manufactured indigenously by Saraswathi Engineering Agency, Roorkee, was used for studying the effect of honeycombing, presence of cracks and effect of path length. The frequency of the transducers was approximately 200 kHz and the diameter of the probes was 7.5 cm. The instrument had a measuring range of 1 m and the accuracy of the instrument was $\pm$ 0.1 microsecond. For the study of effect of corrosion the concrete tester used was of type SEA 685 with transducers having a frequency of 50 kHz. The instrument has a measuring range of 2.5m of concrete and an accuracy of $\pm$ 0.1 micro seconds.

Test procedure

For maintaining a proper accoustical contact between the transducers and concrete surface tested, grease was used as a coupling medium. In all the specimens the probe positions were marked prior to testing to ensure proper alignment of probes. Grease was applied on the concrete surface as well as on the probes. The pulse travel time was measured up to 0.1 microsecond. The velocity was calculated from the equation,

$$V = \frac{m}{t}$$

where,

V = longitudinal pulse velocity in m/s

m = travel distance in metres

t = time of travel in microsecond.

Effect of honeycombing

The pulse travel time was measured on a pair of opposite faces of the cubes as shown in *Fig* 2. On each pair of faces four sets of readings were taken and the average is reported as the pulse velocity against each cube. After the pulse velocity measurements the cubes were tested in a compression testing machine.

Effect of cracks

To arrive at the path length and crack depth tests were conducted on beams 2,3 and 4. *Fig* 1 shows the position of probes for pulse readings. In beam 2, 1-1 is a measurement across the crack and 2-2 through uncracked concrete, while 3-4 is a measurement to estimate the crack depth. In this case the probes are on either side of the crack. Similarly in beam 3, 1-1 and 2-2 measurements are as explained for beam 2. Observations 4-5, 5-6 and 6-7 are to measure crack depth. In case of beam 4, the centre of probes are kept at 10 cm centers along the length of the beam to measure crack depth.

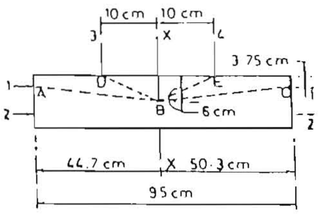
Effect of path length

Velocity measurements were taken on five different path lengths, that is, 10.5, 15.5, 31.5, 63 and 94 cms in beams.

Effect of corrosion

Pulse velocity readings were taken as explained in case (a).

Table 2 : Crack depth and path length

Designation of specimen	Nature of measurements	Readings	Pulse travel time, micro second	Actual path length cm	Pulse velocity through concrete, m/s	Calculated path length, cm	Calculated crack depth, cm	Remarks
Beam 2		1-1	335	95.10	-	98.52	-	Actual path length is ABC. The calculated path length is 3.59 percent more then actual path length
		2-2	323	95.0	2941	95	-	
		3-4	80	23.32	-	23.53	6.198	Actual path length is DBE. Calculated crack depth is 3.3 percent more than actual depth of 6 cm
		X-X	53	15.50	2924.5	-	-	

The cubes were then tested for compressive strength. Tests were conducted at the ages of 28 days, 90days, 150 days and 270 days for both treated and untreated cubes.

Test data and discussion

Effect of honeycombing

The average pulse velocity for vibrated cubes was 4175m/s while the velocity for honeycombed cubes of the same mix was 3525m/s. This gave a reduction of 18.5 percent in the velocity readings due to honeycombing in concrete. It is established that the pulse velocity measurements are influenced by the properties of the basic materials used in concrete, that is, the type of cement, type of aggregate and also the aggregate cement ratio and water cement ratio[1,11]. The constituent materials were kept the same for vibrated and honeycombed concrete in this test as the effect of honeycombing was to be studied. Hence, the reduction in velocity is due to the lower density of the concrete as a result of honeycombing. The approximate density of this concrete from the pulse velocity density relationship[7] is 2075 kg/m^3. From the same relationship the density of well compacted concrete with an average pulse velocity comes out to be 2405 kg/m^3. If this is expressed in density ratio, that is, the ratio of density of honeycombed concrete to density of fully-compacted concrete, it comes out to 0.86. Five percent voids (5 percent of volume of concrete) can lower the strength by 30 percent and 10 percent voids give a highly honeycombed concrete[12]. The strength reduction in the concrete tested is 50 percent and hence this concrete can have voids between 5 and 10 percent and can be rated as fairly high honeycombed concrete.

The pulse velocity readings are plotted against strength as shown in *Fig* 3. A power type relation is established relating pulse velocity and strength as given below :

$$V = K_1 F_c^{K_2}$$

In the above equation V is the ultrasonic pulse velocity in m/s, F_c is the cube compressive strength in kg/cm^2 and K_1 and K_2 are constants. K_1 is 1267 and K_2 is 0.233.

Path length and crack depth

Pulse velocity measurements through different beams for

Table 3 : Crack depth and path length

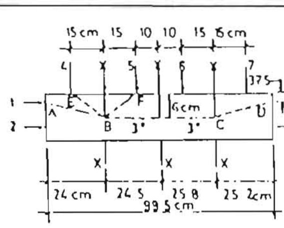
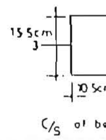
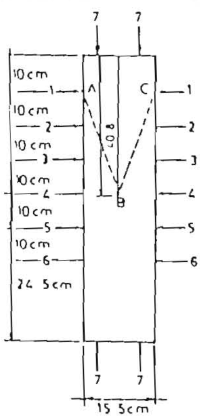
Designation of specimen	Nature of measurements	Readings	Pulse travel time, micro second	Actual path length, cm	Pulse velocity through concrete, m/s	Calculated path length, cm	Calculated crack depth, cm	Remarks
Beam 3		1-1	323	99.7	-	110.82	-	Actual path length is ABCD. The calculated path length is 11.5 percent more than actual path length
		2-2	290	99.5	3431	99.5	-	
		3-3	24	10.5	4375	-	-	
		4-5	95	32.31	-	32.59	6.366	Calculated crack depth is 6.1 percent more
		5-6	69	23.32	-	23.67	6.32	Calculated crack depth is 5.33 percent more
		6-7	99	32.31	-	33.96	7.95	Calculated crack depth is 32.5 percent more
	C/S of beam-3	X-X	61.[illegible]	15.5	2531	-	-	

Table 4 : Crack depth and path length

Designation of specimen	Nature of measurements	Readings	Pulse travel time, micro second	Actual path length, cm	Pulse velocity through concrete, m/s	Calculated path length, cm	Calculated crack depth, cm	Remarks
Beam 4		1-1	240	63.52		82.10	40.31	Actual path length is ABC. Crack depth calculated is 30.87 percent more
		2-2	152	41.4		52.00	24.80	Calculated crack depth is 19.29 percent more
		3-3	87.5	26.58		29.03	12.80	Calculated crack depth is 18.52 percent more
		4-4	40.9	15.5	3789.7			
		5-5	39.9	15.5	3881.72			
		6-6	39.6	15.5	3914.14			
		7-7	247	84.5	3421.05			

path length and crack depth calculations are given in *Tables* 2 to 4. From the pulse velocity measured in a cracked specimen the path length and crack depth can be found out.

$$m = V \times t$$

where,

m = pulse travel distance in m

V = average pulse velocity through uncracked concrete, m/s

t = measured travel time through cracked concrete (microsecond).

For crack depth, if the probes are placed on either side of cracks as 3-4 reading, Beam2

$$t_1^2 = \frac{4(x^2 + h^2)}{V^2}$$

t_1 = travel time

x = horizontal distance of probe from crack

V = pulse velocity of uncracked concrete

h = crack depth.

From *Tables* 2 to 4, it is seen that the calculated path length and crack depth are more than that provided. This is because the pulse path is assumed to be straight lines joining the centre of probes and bottom of crack. But in actual case, the pulses do not travel in straight lines. Hence, the pulse path will be more than what has been assumed, giving a higher travel time than for the straight line path assumed and a higher path length. In case of one crack in beam 3, the variation is 32.5 percent. This much variation may be due to the presence of a microcrack below the crack already provided extending the depth of the crack. In case of beam 4, the cracks are deeper than that in other beams and the crack depth prediction is 18 to 30 percent on higher side. In smaller crack depths, the curved path length will not give a big variation and hence they can be predicted to a better accuracy than in deep cracks.

Effect of path length

The pulse velocity readings recorded for different path lengths are plotted against the path length, *Fig* 4. It is seen that the pulse velocity decreases when the path length increases. But this tendency is found only upto 60 cm path length. After that there is no appreciable change in pulse velocity due to change in path length. The possible reason for this may be that voids in smaller path length will be lesser than what will be detected in a longer path length. Hence, in smaller path length lesser distraction of waves, leading to higher pulse velocity. The pulse velocity in 63 cm path length is 12 percent less than the pulse velocity in 15.5 cm path length.

Effect of corrosion

Figs 5 and 6 show the relation between ultrasonic pulse velocity and cube compressive strength at different ages for untreated concrete and concrete treated with ammonium sulphate/urea[13].

The surfaces of cubes treated by ammonium sulphate at the age of 150 days were white in colour and had become softer and the bond between mortar and aggregates was seen disin-

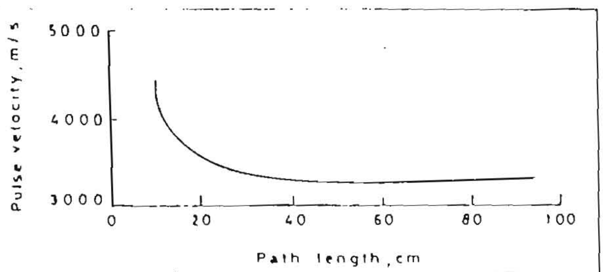


Fig 4 Variation of pulse velocity with path length

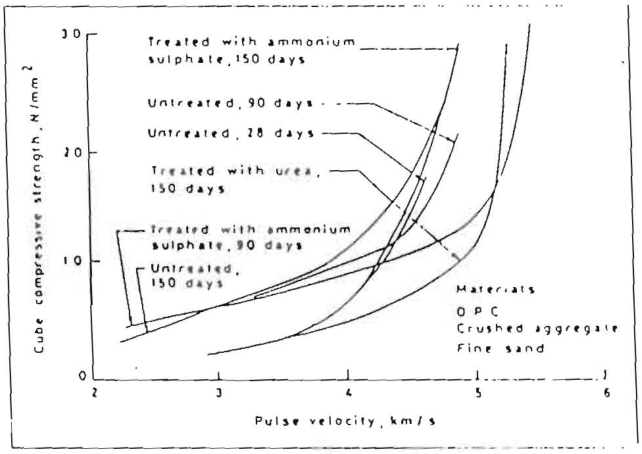


Fig 5 Pulse velocity versus compressive strength

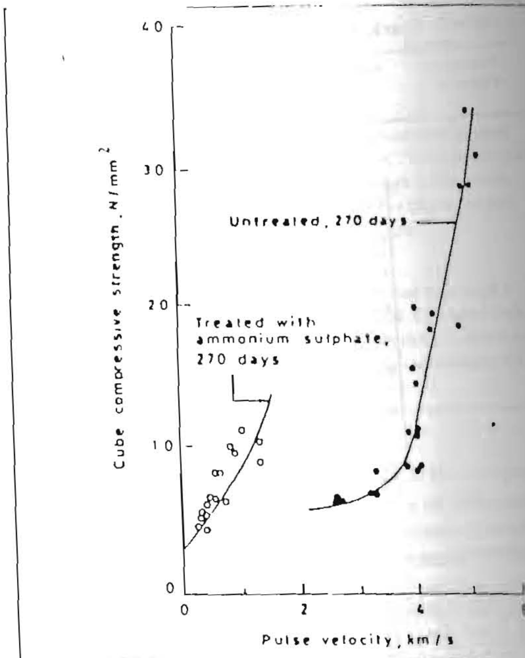


Fig 6 Pulse velocity versus compressive strength

tegrating at the surface. The cubes treated with urea were dark grey in colour and had not shown any disintegration. This is probably because at this age urea is not as corrosive as ammonium sulphate. Needle crystals of urea were visible on the surfaces.

At the age of 90 days, the cubes treated with ammonium sulphate had a strength equal to or slightly higher than that of untreated concrete of same age. Pulse velocity readings were also higher by 2 percent in case of treated concrete. At 150 days, the strength of the cubes treated with ammonium sulphate had gone down by 2 percent, compared to 90-day strength of treated concrete. The strength at 150 days was 30 percent less than that of untreated concrete of the same age. A reduction in pulse velocity of 2 to 6 percent was noticed at 150 days in concrete treated with ammonium sulphate, compared to an untreated sample of same age. At 270 days, the reduction in pulse velocity was 60 percent in concrete treated with ammonium sulphate, compared to untreated cube of same age, while the strength was lower by 35 to 40 percent.

The strength of concrete treated with urea at 150 days was only 2 percent lower than the strength of untreated specimen of same age. Pulse velocity was 6 to 12 percent higher than that of cubes treated with ammonium sulphate and also higher than untreated cubes of the same age.

Reduction in pulse velocity of concrete treated with ammonium sulphate at ages of 150 days and 270 days shows that micro cracks have developed in the cubes. In case of concrete treated with ammonium sulphate, when corrosion started, the continuity of the bond between the mortar and aggregates must have started disintegrating, resulting in higher pulse travel time and lower pulse velocity. In case of concrete treated with urea, no significant reduction in strength was noticed at 150 days, while the pulse velocity was higher. Urea must have crystallised in the pores of the concrete giving an unobstructed path for the pulses to travel and it appears to be the reason for higher pulse velocity. The results also indicate that ammonium sulphate is more corrosive than urea.

Conclusions

(i) The presence of voids in honeycombed concrete causes a decrease in the pulse velocity to an extent of approximately 18 percent for a density ratio of 0.86.

(ii) It is difficult to specify a minimum acceptable pulse velocity for a concrete applicable under all conditions. Based on this study, for a 1:2:4 mix by weight a velocity rating of 3600 to 4200 m/s may represent a good concrete. For concrete having a velocity rating below 3,600 m/s, additional detailed investigations will be needed.

(iii) Based on this study the relationship between the compressive strength of concrete and the pulse velocity may be represented by $V = K_1 F_c^{K_2}$, in which V is the ultrasonic pulse velocity in m/s, F_c is the compressive strength in kg/cm^2, K_1 and K_2 are constants having values of 1267 and 0.233 respectively.

(iv) The calculated path length and crack depth are found to be more than the actual path length and crack depth. The ultrasonic pulse velocity method can be used for estimating shallow crack depth with a better accuracy than for deep cracks. For deep cracks the predicted crack depth were found to be about 30 percent higher than the actual depth.

(v) Pulse velocity is affected by pulse path length if the path length is small. Beyond 60 cm and upto

90 cm no variation in pulse velocity has been noticed. Hence in laboratory where small specimens are used the path length can affect pulse velocity.

The pulse velocity method can give a qualitative estimate of both undamaged concrete and concrete deteriorated due to chemical attack.

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