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The use of USPV to anticipate failure in concrete under compression

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Abstract

The use of the ultrasonic pulse velocity tester is introduced as a tool to monitor basic initial cracking of concrete structures and hence to introduce a threshold limit for possible failure of the structures. Experiments using ultrasonic pulse velocity tester have been carried out, under laboratory conditions, on various concrete specimens loaded in compression up to failure. Special plots, showing the relation between the velocity through concrete and the stress during loading, have been introduced. Also, stress–strain measurements have been carried out in order to obtain the corresponding strains. Results showed that severe cracking occurred at a stress level of about 85% of the rupture load. The average velocity at this critical limit was about 94% of the initial velocity and the corresponding strain was in the range of 0.0015 to 0.0021. The sum of the crack widths has been estimated using special relations and measurements. This value that corresponds to the 94% relative velocity was between 5.2 and 6.8 mm.

Keywords: Concrete; Pulse velocity; Nondestructive testing

1. Introduction

The ultrasonic pulse velocity has been used on concrete for more than 60 years. Powers in 1938 and Obert in 1939 were the first to develop and extensively use the resonance frequency method [1]. Since then, ultrasonic techniques have been used for the measurements of the various properties of concrete [2–31]. Also, many international committees, specifications and standards adopted the ultrasonic pulse velocity methods for evaluation of concrete. Examples are the ASTM C597, BS 1881: Part 203 and ACI 224R, ACI 228.1R, ACI228.2R and ACI228.2R [19–24].

The principle of the test is that the velocity of sound in a solid material, V, is a function of the square root of the ratio of its modulus of elasticity, E, to its density, d, as given by the following equation:

$$V = f\left(\frac{gE}{d}\right) \tag{1}$$

where g is the gravity acceleration. As noted in the previous equation, the velocity is dependent on the modulus of elasticity of concrete. Relationships between pulse velocity and modulus of elasticity of concrete are given in Refs. [4,12,28]. Monitoring modulus of elasticity for concrete through results of pulse velocity is not normally recommended because concrete does not fulfill the physical requirements for the validity of the equation normally used for calculations for homogenous, isotropic and elastic materials (Eq. (2)) [4,28].

$$V^2 = \frac{E_d(1-\mu)}{\rho(1+\mu)(1-\mu)} \tag{2}$$

where V is the wave velocity, ρ is the density, μ is Poisson's ratio and E_d is the dynamic modulus of elasticity.

On the other hand, it has been shown that the strength of concrete and its modulus of elasticity are related [6,29].

The method starts with the determination of the time required for a pulse of vibrations at an ultrasonic frequency to travel through concrete. Once the velocity is determined, an idea about quality, uniformity, condition and strength of the concrete tested can be attained. In the test, the time the pulses take to travel through concrete is recorded. Then, the velocity is calculated as:

$$V = \frac{L}{T} \tag{3}$$

where V = pulse velocity, L = travel length in meters (Fig. 1) and T = effective time in seconds, which is the measured time minus the zero time correction.

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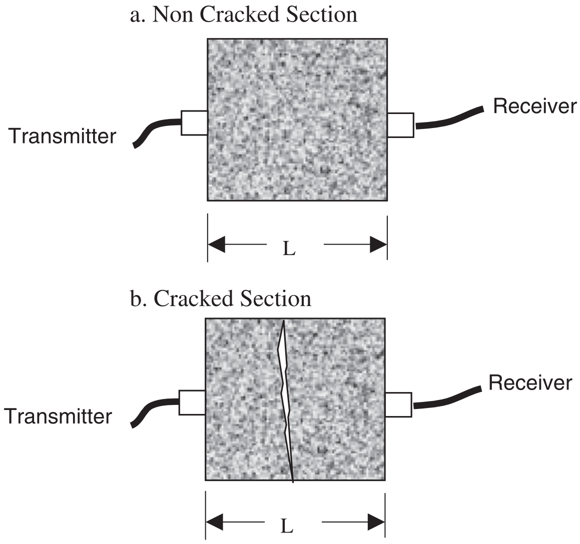

Fig. 1. Test procedure in noncracked and cracked samples.

The zero time correction is equal to the travel time between the transmitting and receiving transducers when they are pressed firmly together. Based on that principle, Whitehurst [3] introduced a relationship between the wave velocity and the quality of concrete as early as 1951.

The variation of the results due to the surface properties, presence of steel reinforcement, presence of voids and cracks, properties of aggregate and mix proportions have been studied and shown in the literature [5,7,9, 10,21–24]. Many attempts have been made to correlate the velocity to the strength of concrete either directly or by the use of combined ultrasonic and rebound hammer [8,14,15,18,21–25].

Special techniques for investigating damage in concrete by the use of wave velocity through cracked concrete have been introduced by Toutanji [1], Selleck et al. [16], Nogueira and Willam [17] and Berthaud [26,27].

From the literature review, it can be concluded that the ultrasonic pulse velocity results can be used to:

(a) check the uniformity of concrete,
(b) detect cracking and voids inside concrete,
(c) control the quality of concrete and concrete products by comparing results to a similarly made concrete,
(d) detect condition and deterioration of concrete,
(e) detect the depth of a surface crack and
(f) determine the strength if previous data is available.

2. Research idea

The determination of the level of failure may be difficult and unreliable without the use of complicated methods and procedures such as the load test. Sometimes, special procedures and methods have to be designed, tried and then applied to the element under consideration. Such methods are usually slow and costly. However, no final conclusions can be drawn without the application of such methods, especially when the engineer has to decide on various remedial measures including the demolition of the structure.

The method presented here is a technique that can be applied to structurally cracked elements in order to obtain a simple conclusion about the tested region.

The basic idea is to measure the velocity through concrete in cracked and uncracked regions. It is obvious that the velocity of concrete is reduced when there is an internal crack as shown in Fig. 1 because velocity through concrete is higher than velocity through air or water (the crack is either filled with air or water). Hence, a reduction in the measured velocity can be noticed when the concrete cracks. However, when the cracks are wide, the sound waves are wholly reflected and no signal is received [20].

Furthermore, a relation between the pulse velocity and the crack width was deduced. The basic idea was that the reduction in the velocity through concrete is basically due to the formation of cracks in concrete as shown in Fig. 1. These cracks are assumed to be filled with water because all samples were saturated surface dry at test. The velocity of waves in water has been calculated using the physical relationship:

$$V_{\mathrm{w}} = \sqrt{\frac{B}{\rho}} \qquad (4)$$

where B is the bulk modulus of water, equals 0.21×10^9, and ρ is the density of water, which equals 1000 kg/m^3 [32]. Using Eq. (4), the value has been found to be 1449.1 m/s and was assumed to be 1450 m/s in calculations. This value was consistent with that appeared in the literature [33,34].

The relationship, in its final form, was as follows:

$$w = \frac{\dfrac{1}{V} - \dfrac{1}{V_0}}{\dfrac{1}{V_{\mathrm{w}}} - \dfrac{1}{V_0}} S \qquad (5)$$

where w is the crack width, V is the velocity in concrete at any stress level, V_0 is the velocity in concrete at zero stress level, V_{w} is the wave velocity in water, taken 1450 m/s, and S is the side length of the cube.

3. Research program

The research consisted of the following steps:

1. Under laboratory conditions, 150-mm concrete cubes were prepared. Various water-to-cement (w/c) ratios were

used. Also 150 × 300 mm cylinders were prepared from the same mixes in order to obtain the stress–strain relationships.

2. All concrete cubes were cured under water according to ASTM C192 [35] and then tested at a predetermined age.
3. Each cube was taken from water at the specified age and then rubbed with a clean dry cloth until a saturated surface dry sample was obtained. The cube was then tested as follows:

   (a) Each of the two opposing surfaces was prepared for the ultra sonic pulse velocity test according to ASTM C597, Section 6.2.3 [19], and then the center of each surface was determined.

   (b) The cube was fitted in the compression-testing machine and a very small load was applied in order to keep the cube in position.

   (c) The transmitter and the receiver of the ultra sonic pulse velocity tester were used on each pair of the opposing surfaces. The time was recorded and the velocity was calculated. Two measurements, each represents one direction, was taken.

   (d) The load was then applied slowly to the tested cube until failure. At each load increment, the time was recorded and the velocity was calculated.
4. The velocity was then plotted against the corresponding stress. Plots similar to that shown in Fig. 2 were obtained.
5. The stress–strain curves of the tested concretes were obtained using the method described in ASTM C469 [30]. A typical plot is shown in Fig. 3.
6. The sum of the crack widths that were formed in the concrete cubes was calculated using Eq. (3). The relative velocity was plotted against the crack width as shown in Fig. 4.
7. In order to eliminate lateral displacements, Poisson's ratio was found using the method described in ASTM C469 [30]. These values were used to estimate the lateral strains and deformation and hence obtain the actual crack width. Fig. 3 shows a typical plot.

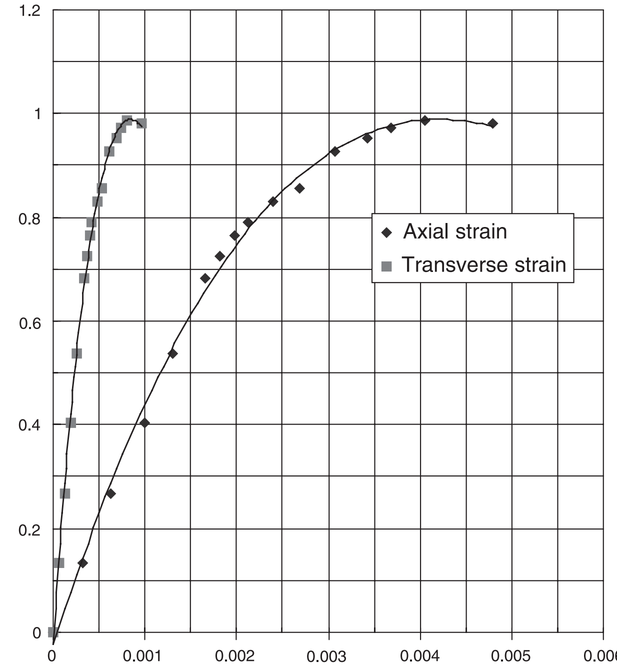

Fig. 3. A typical stress–strain plot (longitudinal and lateral strains).

In order to minimize the effects of the various variables, the following was coped for during tests:

1. The same calibrated equipment and compression-testing machine were used for all the readings.

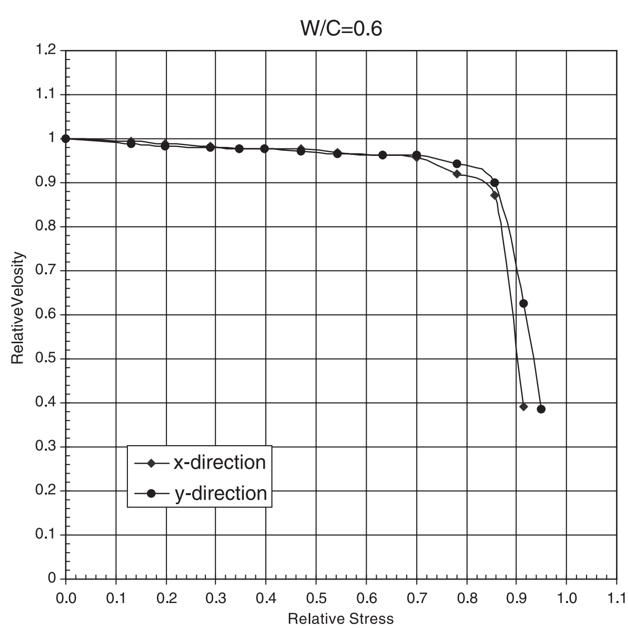

Fig. 2. Relationship between relative velocity and relative stress during loading.

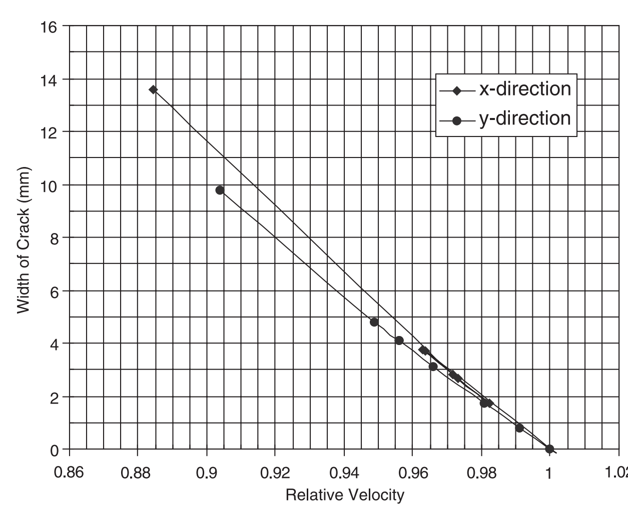

Fig. 4. A typical plot showing relationship between width of crack and relative velocity.

Table 1
Mix proportions and properties

Mix designation	Mix proportions (kg per cubic meter of finished concrete)				Nominal w/c ratio	Slump range (mm)	Strength range (MPa)	Modulus of elasticity (MPa)
	Water (kg)	Cement (kg)	C.A. (kg)	F.A. (kg)				
M1	208	520	993	631	0.40	70–100	38.4–43.8	20.5–26.2
M2	205	410	996	740	0.50	75–105	31.6–36.5	15.7–22.4
M3	200	333	990	805	0.60	80–110	24.9–28.7	12.8–18.8

2. All mixes were proportioned according to the ACI 211.1 method of mix design using w/c ratios of 0.4, 0.5 and 0.6. The mix proportions and their basic properties are shown in Table 1.
3. All mixes were made from the same type of aggregates. Coarse aggregate was crushed limestone and fine aggregate was natural sand, known locally as "Wadi Sand."

4. Results

Plots similar to the one shown in Fig. 2 have been obtained for the different w/c ratios. In the figure, the relative stress, which is the ratio between the stress and the ultimate load, is plotted against the relative velocity, which is the ratio between the measured velocity at a certain load level to the initial velocity. It is clear from the plot that the relative velocity reduces slowly in the first stages until the relative stress reaches a certain level, then a severe reduction in the relative velocity is obtained. Similar trends have been observed by Nogueira and Willam [17] and Spooner and Dougill [31]. The results are shown in Table 2. It is clear from Table 2 that the relative stress at the point where velocity starts to decrease sharply ranges from 82% to 87%. The average was 84.8% with a standard deviation of 2.26%. The sharp decrease was attributed to the formation of cracks inside the cubes. It is also clear from the same figure that the average relative velocity is 94% with a standard deviation of 4.8%.

Stress–strain measurements have been carried out according to ASTM C 469 in order to study the strains at the critical stress level described above. A typical plot of the results is shown in Fig. 3. Stress–strain measurements showed that strains at the critical level of about 85% stress are as shown in Table 3. In order to estimate the effect of lateral elastic strains on the results, ASTM C 469 test was also carried out for transverse strains (Fig. 3). The elastic deformations were estimated using Poisson's ratio. The values obtained were very small (less than 0.10 mm). Therefore, it was concluded that lateral elastic deformations can be neglected and that the measurements are due to the cracks in concrete. The strength and moduli of elasticity of the tested concrete are shown in Table 1.

Fig. 4 shows the relationship between the relative velocity and the corresponding crack width. It was found that the crack widths ranged between 5.2 and 6.8 mm. (about 3.5–4.5% of the initial length of the sample) for a relative velocity of 94%. The results are shown in Table 3. The crack width was too large when compared to the elastic deformation estimated using Poison's' ratio.

It has been found that the sum of the crack widths at the 94% limit of relative velocity is not dependent on the w/c ratio.

Table 2
Results of the tested samples

Sample No.	w/c ratio	Relative stress[a] (%)	Relative velocity[a] (%)	Crack width[b] (mm)
1	0.40	82	90	5.7
2	0.40	82	96	6.7
3	0.40	87	94	6.6
4	0.40	87	96	5.2
5	0.40	86	92	6.0
6	0.50	86	84	6.4
7	0.50	87	94	6.7
8	0.50	87	99	6.0
9	0.50	82	94	6.3
10	0.50	86	99	6.6
11	0.50	82	98	6.5
12	0.60	84	95	6.8
13	0.60	87	99	6.8
14	0.60	86.5	95	6.4
15	0.60	86.5	95	6.1
16	0.60	82	82	6.2
17	0.60	82	96	6.4

[a] Values obtained from plots similar to Fig. 1.
[b] Values obtained from plots similar to Fig. 4.

Table 3
Strains at 85% of stress level

w/c ratios	Strains at 85% stress level
0.40	0.0015
0.50	0.0018
0.60	0.0021

5. Conclusions

From this study, the following can be concluded:

1. The stress level at the point where concrete velocity starts to drop sharply during loading is constant and does not depend on the w/c ratio.
2. At a stress level of about 85%, excessive cracking of concrete under axial compression can be noticed indicating the possibility of failure of the cracked element.
3. The relative velocity through concrete drops slowly up to a stress level of about 85% and then drops sharply. At a relative velocity of about 94%, excessive cracking is expected. The corresponding strains are as shown in Table 3.
4. The lower the w/c ratio, the lower the strain at the 85% stress level. This implies that severe cracking in higher strength concrete starts earlier than cracking in lower strength concrete. Table 3 shows the results.
5. The method may be used for existing structures that are thought to be cracked due to excessive compression loading. Further research is needed in this respect.
6. The crack width at the 94% relative velocity has been found in the range of 5.2 mm to 6.7 mm. This crack width is independent on the w/c ratio.

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