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Full Length Research Paper

Non-destructive evaluation of concrete by the quality factor

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Measurement of the longitudinal P-wave propagation velocity is a commonly used test for the non-destructive evaluation of concrete. However, the pulse velocity is not always a good indicator of the quality of concrete. This paper concerns the application of ultrasonic wave attenuation as a tool for evaluating concrete. A spectral ratio technique is used to determine the quality factor, a non-dimensional parameter that characterizes ultrasonic wave absorption in a material. The experimental study carried out on different types of concrete and described herein shows that this factor is more sensitive to the variation of mechanical properties of concrete as well as to the formation and growth of microcracks in concrete.

Key words: Concrete, nondestructive testing, stress-waves, attenuation, quality factor.

INTRODUCTION

Concrete is the material which is most used for the construction of public utility structures such as bridges, dams, roads, parking garages, etc. Actually, the world's concrete structures are aging and limited resources preclude the replacement of all structures that are in need of repairs or have exceeded their life times. Therefore, the assessment of the state of health of these structures is crucial to implementing a systematic and cost effective approach to repair and/or replace the deteriorated structures. Unfortunately, the evaluation of the condition of concrete structures is complex. Indeed, unlike metals, concrete is a highly inhomogeneous material composed of various ingredients (water, sand, cement, aggregates and chemical agents). It contains from the outset a great number of defects, in the shape of small cavities, pores, interstices, and is also a material recorded signals whose properties are not rigorously reproducible, even under the best situations. In addition, environmental effects (e.g. freezing-thawing) as well as increasing service loads lead to the growth of microcracks during the working life of the structures.

The compressive strength of concrete had been initially used by civil engineers to evaluate the condition of structures in service. This property is determined by mechanical tests on cylindrical samples extracted from the structures by coring. This procedure is however destructive, costly and the information given by the samples is punctual and does not permit adequate evaluation of the structures.

To overcome these problems, the concept of non-destructive testing (NDT) has been in use since early 1940's in the construction industry. One of the principal needs of the engineers was *in situ* monitoring of the gain of the compressive strength of concrete at early age to determine when the formworks could be removed or when to apply the post-tensioning in the case of stressed concrete.

Measurement of ultrasonic wave propagation velocity through concrete is one of the first NDT techniques used worldwide to help answer these problems. Since the propagation velocity is related to the modulus and density, and indirectly to the strength of concrete (Neville, 1991), the longitudinal P-wave propagation velocity

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Abbreviations: Q, quality factor; **Vp,** longitudinal wave velocity; **f'c,** compressive strength; **E,** elastic energy stored in the material; **ΔE,** energy dissipated per cycle of the periodic oscillation; **A,** wave amplitude; **dx,** infinitesimal distance along the direction of propagation; **λ,** wavelength; **α,** coefficient of attenuation; **F,** frequency; **A(f),** Fourier transform of the two method had been established as a standard NDT technique for concrete (Komloš et al., 1996). Many studies (Rajagopalan et al., 1973; Ben-Zeitun, 1986) showed however that the correlation between the compressive strength of concrete (f'_c) and the P-wave propagation velocity (V_p) is not unique; it depends on the properties of the individual components of the concrete, on the mix proportion, the curing history, etc. Nevertheless, some typical correlations can be used as a general guideline.

Because the relationship between V_p and f'c is typically exponential, the sensitivity of the P-wave propagation velocity to the variations of material properties decreases significantly at higher strengths. When f'_c goes from 5 to 15 MPa, the corresponding increase of the P-wave velocity is approximately 600 m/s. However, the increase of V_p is only 100 m/s when f'_c passes from 25 to 35 MPa. Knowing that the concrete used in the construction industry has generally a compressive strength higher than 25 MPa, the P-wave propagation velocity proves thus very restrictive when concrete of similar characteristics have to be compared.

Another limitation of the ultrasonic testing of concrete is that the P-wave propagation velocity is not a good indicator of the presence of microcracks (Shah and Chandra, 1970; Raju, 1970). The reason is that concrete is so heterogeneous in its composition that the scatter of ultrasonic waves preclude the use of frequencies as high as those used in the metallurgical industry. In fact, the range of frequencies used in laboratory studies is generally lower than 500 kHz and, for *in situ* works, frequencies greater than 20 kHz are rarely used. These low frequencies cannot provide sufficient resolution for the detection of microcracks in concrete.

Faced with the restrictions of the pulse velocity test, it is important to identify an alternative solution that allows better evaluation of concrete. The approach used in the field of rock mechanics is to consider the attenuation of the ultrasonic waves rather than the propagation velocity. Geophysicists and seismologists often use the quality factor Q (Q-factor) or its inverse the dissipation factor Q^{-1} to study this attenuation in rocks (Knopoff, 1964; Tarif, 1986). An infinite Q means that there is no attenuation. This factor is a function of the mineral composition of rocks (ex. Q = 250 for granite and 58 for sandstone) as well as of their mechanical performances (Ilyas, 2010).

There are several methods for evaluating the Q-factor of a material (Rainer, 1989), the best known is the spectral ratio technique (Tarif and Bourbié, 1987; Kharrat, 1997). This procedure, which seems to be particularly relevant for the analysis of microcracks in rocks (Tarif, 1986) is, however, not yet applied to concrete. In this study, the assessment of the concrete condition using the Q-factor is investigated. The ability of this factor to characterize concrete of different properties is highlighted as well as its sensitivity to the formation and growth of microcracks.

The spectral ratio technique

As an ultrasonic wave propagates through concrete, it undergoes attenuation characterized by a decrease in amplitude and a preferential loss of the high frequencies components. This attenuation is a function of three processes: Spreading, scattering and absorption. Spreading is related to the geometry of the material and wave source characteristics; the ultrasonic energy is redistributed over an increasing area. Scattering and absorption are material properties and results from the interaction between the wave and the various components of concrete (sand, aggregates, pores, microcracks). In this work, only the energy loss due to material properties, simply called attenuation hereafter, is discussed.

Up to now, the investigations of ultrasonic wave attenuation in cement based materials mainly focused on the dependence of this attenuation upon frequency (Landis and Shah, 1995; Gaydecki et al., 1992). These investigations have been carried out according to some measurement techniques more or less in common use. These techniques can be related to the energy loss during the propagation of an acoustic wave. In the field of rock mechanics, this loss is often described by the expression (Knopoff, 1964):

$$\frac{\Delta E}{E} = \frac{-2\pi}{Q} \tag{1}$$

In this equation, ∆E is the energy dissipated per cycle of the periodic oscillation in a certain volume of the material, E is the peak elastic energy stored in the same volume and Q, the quality factor, is a dimensionless quantity that is proportional to the absence of attenuation, that is, higher the attenuation, lower the value of Q.

In terms of the wave amplitude, Equation (1) can be expressed by the formula:

$$\frac{\Delta A}{A} = \frac{-\pi \, dx}{Q \, \lambda} \tag{2}$$

where A is the wave amplitude, dx is infinitesimal distance along the direction of propagation and λ is the wavelength. For a periodic disturbance of constant wavelength, Equation (2) can be integrated to give the usual exponential decay relation for amplitude with travel distance:

$$A = A_0 \exp\left(-\pi \, x/_{Q \, \lambda}\right) = A_0 \exp(-\alpha \, x) \tag{3}$$

$$\alpha = \pi/_{Q \, \lambda} \tag{4}$$

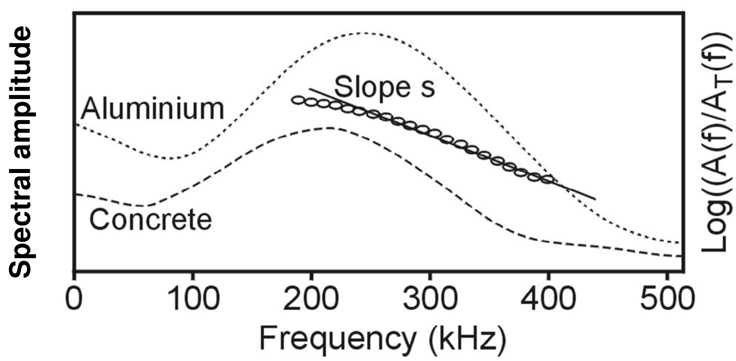

Figure 1. Example of a spectral ratio result.

The parameter α, is the coefficient of attenuation. In solids, this parameter varies as the first power of the frequency. On the contrary, laboratory experiments had shown that, up to moderately high frequencies, Q is independent of frequency (Knopoff, 1964).

A variety of physical processes can explain the attenuation of ultrasonic waves measured by Q (Johnson et al., 1979). In dry materials, friction at grain and crack boundaries turns out to be the dominant mechanism. For partially or totally-saturated materials, relative movement between fluid and solid induced by the wave propagation seems to provide the most plausible explanation for attenuation.

The spectral ratio technique (Tarif and Bourbié, 1987; Kharrat, 1997) consists of comparing the spectral amplitude of two signals traversing two geometrically identical samples, one of which is a reference sample, and the other is a sample of the material investigated. Assuming that the experimental condition (coupling condition, transducers) are identical and remain the same during the measurements, the logarithm of the spectral amplitude ratio of the two signals can be expressed as a function of the Q-factor:

$$\mathrm{Log}\left(\frac{A(f)}{A_r(f)}\right) = -\pi\ X\ f\left((QV)^{-1} - (Q_r V_r)^{-1}\right) + K \qquad (5)$$

where the subscript r denotes the reference sample, K is a constant which is independent of frequency, V is P-wave propagation velocity, X is the common length of the samples and A(f) is the Fourier transform of the two recorded signals.

Plotting $\mathrm{Log}(A(f)/A_r(f))$ as a function of frequency gives the Q-factor if Q_r is known. In our experiments, the reference sample was an aluminium test bar, whose the Q-factor is in the order of 150,000 (Tarif and Bourbié, 1987). Hence, the term $(Q_r V_r)^{-1}$ in Equation (5) can be neglected. Figure 1 shows a typical example of the spectral amplitudes of signals obtained on the reference sample and on a concrete sample. The logarithmic plot of the spectral ratio versus the frequency, also shown in this figure, presents a straight line over a given frequency interval. The slope (s) of this curve is then used to compute the Q- factor by the simple equation:

$$Q = -\pi X / sV \qquad (6)$$

Experimental program

An experimental study of the Q-factor of concrete was carried out using the spectral ratio technique. The goal of the investigation was to evaluate the material attenuation characteristics as a function of the mechanical properties as well as a function of the formation and growth of microcracks induced by mechanical cyclic loadings.

Four types of concrete (A, B, C and D) was casted and cured in 100% moisture room during 28 days. Table 1 summarizes the mix proportions of the specimens. To avoid the influence of the mineral nature of aggregates on the variation of the Q-factor, all concretes studied were cast with the same aggregates. Concrete type A was first manufactured, and then the other three concretes of lower mechanical properties were fabricated by progressively increasing the porosity level in the concrete, that is increasing water/cement ratio and the sand/aggregate ratio in the mixes. It was necessary to design and test several concrete mixes to obtain four concrete types of not only different mechanical properties but also of high and low P-wave propagation velocities similar to those measured on structures in service.

The average values, at 28 days, of density, compressive strength (f'_c), Young's modulus (E) and the P-wave propagation velocity of all the concrete are indicated in Table 1. The concrete studied can be classified in point of view of the mechanical properties as good (type A, E = 28 GPa, f'_c = 38 MPa), questionable (type B, E = 24 GPa, f'_c = 17 MPa), poor (type C, E= 14 GPa, f'_c = 6 MPa) and very poor (type D, E = 11 GPa, f'_c = 4 MPa).

To have low P-wave propagation velocities, it was necessary to produce concrete with high water/cement ratio (>0.8) and high sand/aggregate ratio (> 1.4). This explains why the compressive strengths of concrete C and D are much lower than those measured on concrete of structures.

For each concrete type, three cylindrical samples of 10 cm diameter and 20 cm of length were fabricated. The measurement of the Q-factor was carried out on the samples three months after casting. To collect the ultrasonic data, a sample of the material

Table 1. Characteristics of the concrete investigated.

	Concrete designation			
Mix proportions (for 100 kg)	**A**	**B**	**C**	**D**
Water (kg)	7.4	6	8	7
Cement (kg)	14.7	9	9.6	8
Water/cement	0.5	0.67	0.83	0.88
Sand (kg)	34.7	49	48.4	54.5
Aggregates[1] (kg)	43.2	36	34	30.5
A.E.A.[2] (ml)	---	---	20	20
Properties of hardened concrete (at 28 days)				
Density (kg/m^3)	2400	2280	2050	1925
f'_c (MPa)[3]	38	17	6	4
E (GPa)[4]	28	25	14	11
V_P (m/s)[5]	4628	4520	3703	3025

[1]Diameter of 10 mm;[2]air entraining agent; [3]compressive strength;[4] Young's modulus; [5] P-wave velocity.

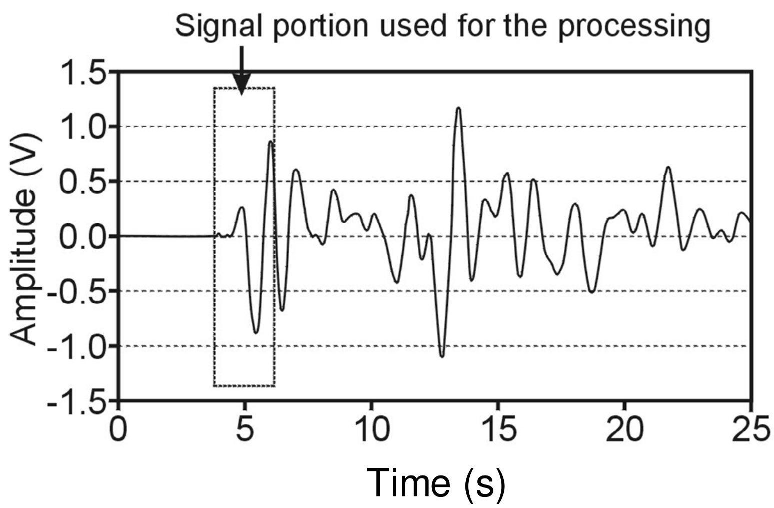

Figure 2. Typical ultrasonic signal recorded in time domain.

investigated was mounted between two identical piezoelectric transducers (Panametric Model 5052) characterized by a resonant frequency of 250 kHz. The sensivity of these transducers has no effect on the measurement of Q-factor since the spectral ratio technique use reference sample to determine this factor.

The transducers were coupled to the smoothed surfaces of the samples using a petroleum-based gel. The transmitter was excited to resonance by a pulser unit (Analogic, 2020). The receiving transducer was connected to a wide band conditioning amplifier that was in turn connected to the input of a Kikusui 7061A digital oscilloscope. The oscilloscope was triggered to sample the data at a rate of 20 MHz over 1024 points by a synchronization with the signal generated by the pulser. Data was then transferred via an IEEE interface to an IBM compatible PC computer for storage and processing.

For all concrete types, the measurements of the Q-factor were carried out on three samples of 5 cm length. This length proved to be sufficiently low to allow recording of signals having a good signal/noise ratio, even in the case of concrete type C and D which were particularly porous. On the other hand, this length was high enough to reach the far field zone of the transducers used. Finally, only the first three half-cycles of the collected signals were considered for the processing (Figure 2). It was found that this first 1.5 wavelength of the ultrasonic signals is free from any lateral reflections in the studied samples.

RESULTS AND DISCUSSION

Concrete properties – quality factor relationship

Figure 3a shows typical examples of the spectral amplitude of the ultrasonic signals collected on the concrete studied. It can be easily observed that the

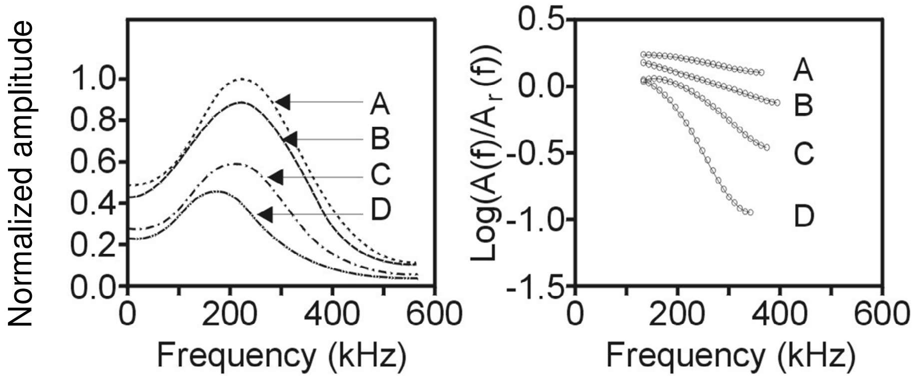

Figure 3. Example of (a) spectral amplitudes and (b) spectral ratios.

Table 2. Variation of Q with mechanical properties of concrete.

Concrete	Q1	Q2	σQ1	Q1	σQ2
Type A	42	44.5	9.8	9.8	6.7
Type B	23	33	5.8	5.8	4.7
Type C	14	15	2.1	2.1	3.1
Type D	9	8	0.7	0.7	0.5

quality of the concrete has an effect on both the amplitude and the central frequency of the spectrums. Indeed, when the quality of the concrete decreases, the amplitude of the spectrums decrease and the central frequency is shifted toward lower frequencies. This result shows however that the attenuation characteristics of concrete type A and B are similar and are better than those of concrete type C and D. The plots of the logarithmic ratio $Log(A(f)/A_r(f))$ as a function of frequency for the four types of concrete investigated are shown in Figure 3b. Note that when the quality of the concrete decrease, the slope of the curve increase and hence the Q-factor decreases.

Table 2 gives the average values of the Q-factors corresponding to the materials studied. Two cases are considered: (a) Where the transducers are in direct contact with the sample (Q1), and (b) Where a PMMA (plexiglas) discs of 1 mm thickness are introduced between transducers and the sample (Q2) to assure that the transfer function of the transducers remain the same for all the samples. Preliminary investigation showed that the Q value relative to the PMMA is equal to 47. This value is comparable to the one reported by Tarif (1986) and estimated to 50.

Table 2 indicates that different values of Q are associated with different types of concrete. For example, the average values of Q2 are 45.5, 33, 15 and 8 for concrete type A, B, C and D respectively. In general, these values are higher than those obtained without the PMMA discs (Q1). The PMMA reduce the acoustical contrast between the transducers and the samples, and hence the loss of energy by diffraction at the interfaces. Therefore, the Q2 values are more representative of the Q-factor of the different materials investigated.

Table 2 also gives the standard deviation σ_{Q1} and σ_{Q2} corresponding to Q1 and Q2 respectively. First, it can be noted that the values of σ_{Q1} and σ_{Q2} increases when the mechanical properties of the material increases. This can be explained by the fact that the slopes of the curves $Log(A(f)/A_r(f))$ versus frequency (Figure 3b) decrease when the mechanical properties of the materials increase. Since a lower value of the slope leads to a lower precision on its determination, the uncertainty on the corresponding value of the Q-factor will be higher. On the other hand, the values of σ_{Q2} were generally lower than those of σ_{Q1}. Hence, the PMMA discs not only allow the reduction of energy loss by diffraction at the transducer-sample interfaces, but also minimize the dispersion of the data and consequently improve the repeatability of the tests.

The relationship between the Q-factor (Table 2) and the P-wave propagation velocity for sound concrete (Table 1) is reported in Figure 4. This relation, which is well described by an exponential function, show that the sensitivity of the Q-factor to the variation of the mechanical properties of concrete is higher than the sensitivity of the P-wave propagation velocity (V_p). In addition, the difference between ΔQ and ΔV_p increases with the quality of concrete. For example, in the case of concrete C and D, ΔQ is in the order 46% whereas the

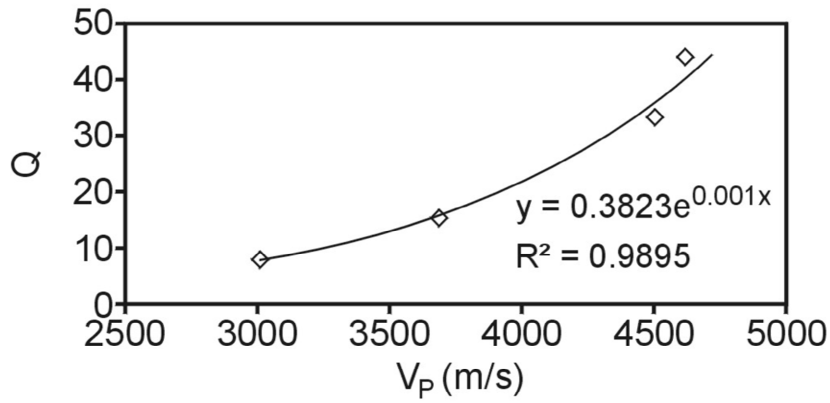

Figure 4. Relationship between Q-factor and V_p.

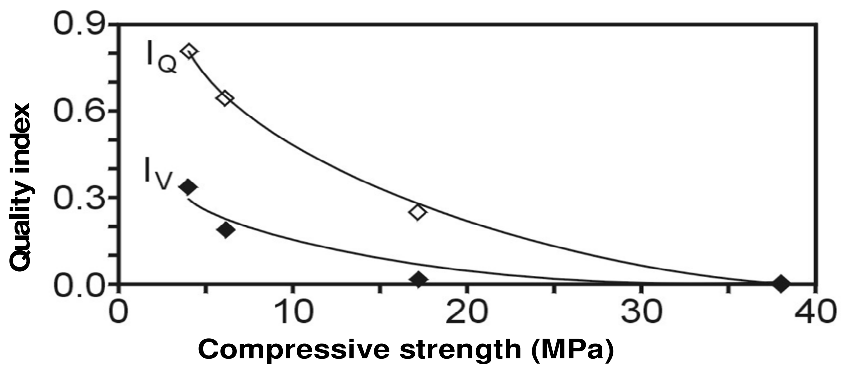

Figure 5. Variation of the quality index as a function of the compressive strength.

corresponding ΔV_p is only 18%. For concretes A and B of higher mechanical properties, ΔQ is 25% while ΔV_p is very small, about 0.23%.

Also, for concrete specimens C and D, the velocity value is not so low (respectively 3703 and 3025 m/s). Regarding to this velocity value, it is possible to say that the quality of the concrete C is good and perhaps just questionable for concrete D (Bungey, 1980). However, the compressive strengths of these concretes (respectively 6 and 4 MPa) indicate clearly that they are very poor, and this is also demonstrated by the very low value of the Q-factor.

Another way to characterize concrete by the Q-factor is to consider the quality index (I) (Mouza et al., 1983). This parameter can be defined as the ratio of the Q-factor of the material investigated (Qi) to the Q-factor of a reference sample of the same material:

$$I_Q = 1 - Qi/Qr \tag{7}$$

The quality index is equal to zero for the reference sample and evolves toward 1 as the quality of the damage material. Figure 5 shows the evolution of this parameter as a function of the compressive strength of the concrete studied. The reference sample used herein is the concrete with the highest mechanical properties (type A). For comparison purposes, the variation of the quality index I_V determined from the P-wave propagation velocity is also indicated in this figure. It is apparent that, from the resolution point of view, the value of I_Q based on the Q-factor allows better differentiation between the four types of concrete studied. In the case of concrete A and D, the variation of I_Q is 80% for Q, which is more than two times the variation of I_V determined using V_p (35%).

Effect of cracks on the quality factor

Cyclic loading tests were also carried out on concrete type A and B to study the effect of the formation and progressive growth of cracks on the Q- factor. For each concrete type, the tests were conducted until the complete rupture of two cylindrical samples 10 cm in length and 10 cm diameter. A function generator was

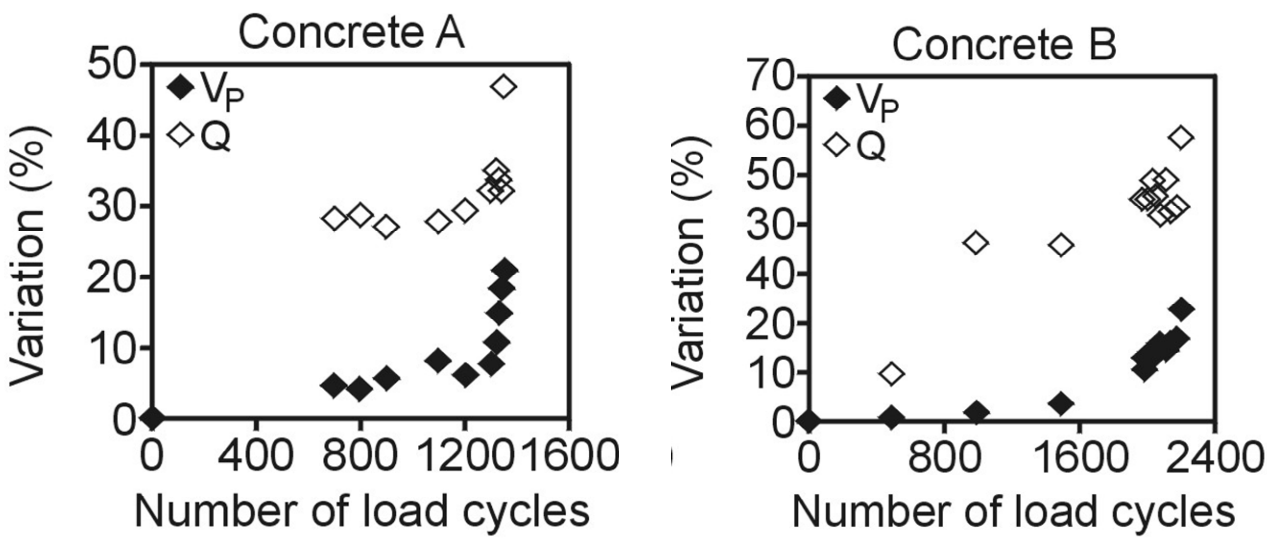

Figure 6. Variation of Q-factor and V_p during cyclic loading tests – concrete A and B.

used to cycle the load sinusoidally (frequency: 1 Hz) between preset limits. The minimum stress was adjusted to 0.1 times the compressive strength and the maximum stress was fixed to 70 and 95% of the compressive strength for concrete type B and A, respectively. The ultrasonic measurements were done at different stages of the tests and along the direction parallel to the direction of loading. The decrease in percent of Q and V_p from the original state of the samples are given in Figure 6a for concrete A and in Figure 6b for concrete B.

Failure of sample A occurred at a number of cycles lower than for the sample B because the maximum stress for A was higher than for B. It can also be noticed that the behaviour of Q and V_p reflects the different mechanical behaviour observed between the two samples during the tests. The values of Q and V_p measured during the last load cycles of sample A (Figure 6a) does not really change and shows a stabilization right before the sudden rupture of this sample. However, for sample B, the rupture was more ductile and the values of Q and V_p undergo a gradual decrease until the end of the tests (Figure 6b).

The difference observed between Q-fator and V_p for sample A as well as for sample B concern the fact that the decrease of the Q-factor values begun much earlier than for V_p. In the case of sample A and for a number of load cycles of 700, the reduction of Q is 27% whereas this reduction is only about 5% for V_p (Figure 6a). For sample B, the decrease of Q and V_p are 10 and 0% respectively when the number of load cycles is 600 (Figure 6b). In fact, the decrease of V_p becomes significant only when the samples are close to the rupture, although while the damage appear much earlier. This result is in agreement with the conclusions of a study reported by Suaris and Fernando (1987) which deals with ultrasonic monitoring of concrete during cyclic loading tests. These authors indicated that V_p did not change appreciably until a number of load cycles of about 90% the number of cycles to failure. The change is found to be about 22% at the end of the tests. In our experiments, the total decrease of V_p reach 25% of the initial value while the decrease of Q-factor is 47% for sample A and 55% for sample B. These results clearly indicate that Q-factor is more sensitive to the formation and growth of crack in concrete than V_p.

Conclusions

The results of the investigations reported in this paper show that different values of Q-factor are associated with different qualities of concrete in an analogous manner that different pulse velocities are usually associated with different concrete qualities. Because of its higher sensitivity to the variation of mechanical properties, the Q-factor appears more suitable for the evaluation of concrete. This factor also appears more sensitive to the formation of microcracks in concrete and more appropriate for monitoring of crack growth than the P-wave velocity. Taking into account these interesting results, this technique can be applied to large structures (e.g. concrete dams) according to the methodologies developed in geophysics (Gusmerol et al., 2000).

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