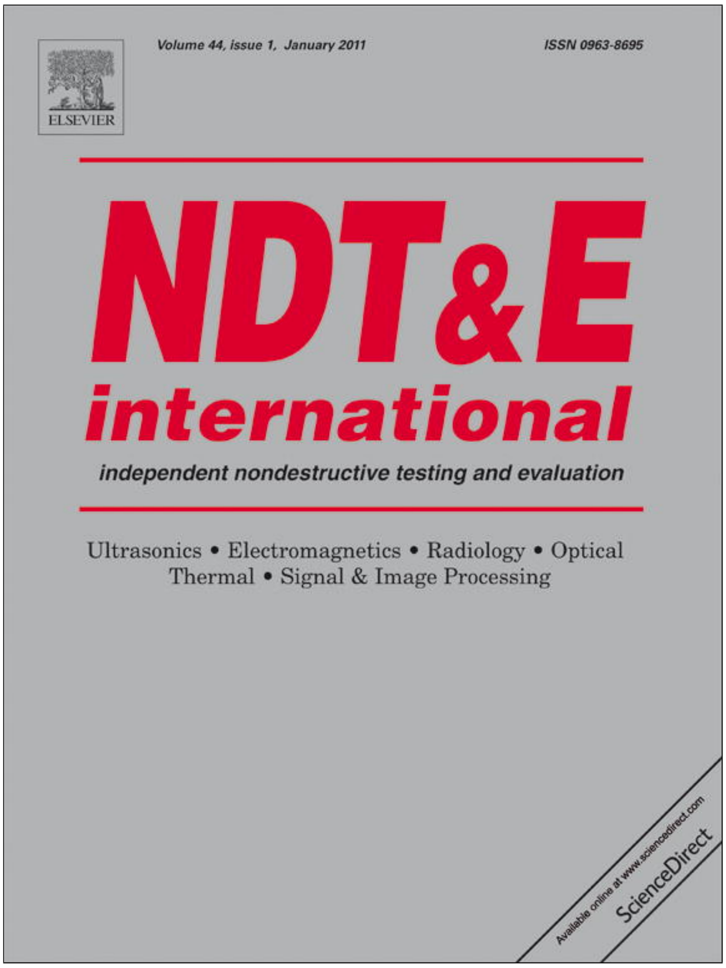
Volume 44, issue 1, January 2011
ISSN 0963-8695
ELSEVIER
NDT&E
international
independent nondestructive testing and evaluation
Ultrasonics • Electromagnetics • Radiology • Optical
Thermal • Signal & Image Processing
Available online at www.sciencedirect.com
ScienceDirect

NDT&E International 44 (2011) 61–66

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Longitudinal waves for evaluation of large concrete blocks after repair

D.G. Aggelis [a,*], S. Hadjiyiangou [a,b], H.K. Chai [c], S. Momoki [c], T. Shiotani [d]

[a] Department of Materials Science and Engineering, University of Ioannina, Ioannina 45110, Greece
[b] Nemesis Construction PLC, Strovolos, Nicosia 2015, Cyprus
[c] Research Institute of Technology, Tobishima Corporation, 5472 Kimagase, Noda-shi, Chiba 270-0222, Japan
[d] Graduate School of Engineering, Kyoto University, Nishikyo-ku, Kyoto 615-8540, Japan

ARTICLE INFO

Article history:
Received 18 March 2010
Received in revised form
3 September 2010
Accepted 16 September 2010
Available online 21 September 2010

Keywords:
Concrete
Cracks
Dispersion
Nondestructive testing
P-wave velocity
Repair

ABSTRACT

The present paper discusses the repair characterization of large concrete blocks based on the propagation of low-frequency elastic waves. A common repair method applied in damaged structures is cement injection. As a result, cracks and voids are eliminated; however, due to the poor initial mechanical properties of fresh cement, pulse velocity does not recover immediately, complicating the assessment. Results of *P*-wave velocity measured through the thickness of a large structure show that only after a suitable hydration period wave parameters increase. Laboratory tests were also conducted in order to extract information under more controlled conditions. It is concluded that velocity, frequency and amplitude of the ultrasonic waves are sensitive to the repair condition and the hardening of the injection material, while slight dispersion trends are eliminated after proper repair.

1. Introduction

Nondestructive evaluation of the structural condition of large concrete blocks can be conducted by means of elastic waves. Due to application of the ultrasonic method in concrete for many decades, various empirical correlations between velocity and material condition have been established [1,2]. These correlations offer a first estimation for the interior concerning concrete strength, distributed damage or specific large defects [3–6] and delaminations [7]. Wave propagation is also influenced by inhomogeneity in the form of porosity and aggregates [8,9]. In case repair is considered necessary, it may be conducted by cement injection through boreholes opened on the surface of the concrete structure [10,11]. The evaluation of repair effectiveness is again conducted by similar methods, comparing the initial elastic wave velocity of the damaged to the measured velocity of the structure after repair [10–12]. However, as has been shown in a number of cases, the estimation of the repair effect is not straightforward due to the time dependent nature of the mechanical properties of the cement materials used for injection. Immediately after injection, the cementitious material replaces a number of interconnected voids offering extra strength and reducing the permeability of the concrete block. However, this is not immediately reflected in the measured wave velocities [11,13], therefore casting doubts on the efficiency of repair. This is attributed to wave scattering on the pockets of fresh grout, which exhibits quite a strong mechanical impedance mismatch with that of the hardened concrete matrix, especially in cold environments, which could further delay cement hydration. Scattering generally induces additional attenuation and dispersion or renders the velocity dependent on frequency. Due to scattering, velocity initially decreases after cement injection and starts to recover towards the initial level or even higher, after a period of time, which is necessary for cement hardening, depending on the type of cement and temperature. The wave application in such conditions has been treated using the scattering theory recently [11], as well as experimentally using concrete impregnated with fresh cement paste [14]. Experiments on porous cylindrical concrete specimens showed that immediately after impregnation, pulse velocity decreased by approximately 10%. Thereafter, depending on the type of concrete and temperature there was an eventual increase in velocity to the initial or slightly higher level except for the case of a specimen maintained at low temperature (5 °C), of which the velocity did not increase even after three months [14]. Therefore, this phenomenon that complicates the assessment of the structural condition should be studied further.

In this paper, through the thickness wave propagation measurements in large concrete piers of a water intake facility (dam) are presented. The first assessment of the structural condition by visual inspection of the concrete surface and *P*-wave velocity measurement led to repair by cement injection. These

* Corresponding author. Tel.: +30 26510 08006; fax: +30 26510 08054.
E-mail addresses: daggelis@cc.uoi.gr, aggelis_d@yahoo.com (D.G. Aggelis).

0963-8695/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ndteint.2010.09.007

piers support large metal gates, which control the water flow. Although the application of wide frequency band was hindered by the large dimensions of concrete (thickness over 4 m), the correlations between propagation velocity of the pulses and their corresponding central frequency enabled the examination of dispersion in a small but indicative frequency band up to 20 kHz. The examination took place both before and after repair in order to estimate the effect of freshly injected grout. Additionally, laboratory ultrasonic experiments took place on a concrete cube, which was drilled in order to simulate damage. The drilled holes were then filled with fresh cement paste (corresponding to cement injection) and the wave velocity was measured immediately, as well as 7 days later to allow the paste to obtain some rigidity. Results confirm that the velocity should not be expected to rise immediately after cement injection in a concrete structure.

2. Measurements on large structure

2.1. In situ measurements

Measurements of *P*-wave velocities were conducted at several cross sections of the concrete piers. Fifteen piezoelectric accelerometers of flat response up to 30 kHz (SAF51, Fuji Ceramics Corp.) were placed in a straight line at intervals of 0.5 m along one side of a 7 m × 4.1 m section (see Fig. 1(a)). The excitation was driven consecutively at different heights using an impact hammer of 35 mm diameter. The accelerometer adjacent to the impact hammer was used to record each impact and trigger the acquisition of the other 15 receivers attached to the opposite side. Considering all the possible combinations of pulsers' and receivers' positions a total of 450 wave paths were examined and the corresponding times-of-flight were processed to produce *P*-wave velocity tomograms [11]. In this study, in order to examine the frequency of the pulses as well, only the horizontal paths were considered, see Fig. 1(a). The signals were recorded by a 16-channel TEAC GX-1 system at a sampling frequency of 200 kHz. In most cases 200 distinct signals were stacked in order to enhance the signal-to-noise ratio, while pulse velocity was measured based on a threshold crossing algorithm, where the threshold was equal to the maximum level of noise exhibited in a pre-trigger period of 500 μs. After fast Fourier transformation (FFT), the central frequency, *C*, of the pulses was calculated as

$$C = \frac{\int_0^{40} f M(f) df}{\int_0^{40} M(f) df} \qquad (1)$$

where f is the frequency, $M(f)$ the magnitude of the FFT and the maximum frequency considered was 40 kHz.

2.2. Results

In Fig. 1 (b)–(d), three cases of different cross sections are presented. The graphs show the pulse velocity and the central frequency measured at each respective height of the structure both before and after cement injection. Each point stands for the pulse velocity and central frequency of one measurement (one horizontal path), and data are presented in this way in order to examine any potential correlation between the two measured parameters, as well as to observe the experimental scatter of the measurements. The level of wave velocity of the old structure in all three cross sections can be considered quite satisfactory, considering the age of more than 60 years. Velocity before repair ranges around or slightly lower than 4000 m/s. The frequency is calculated at an average of approximately 10 kHz. In all three cases of Fig. 1, the cloud of points is translated to lower velocities

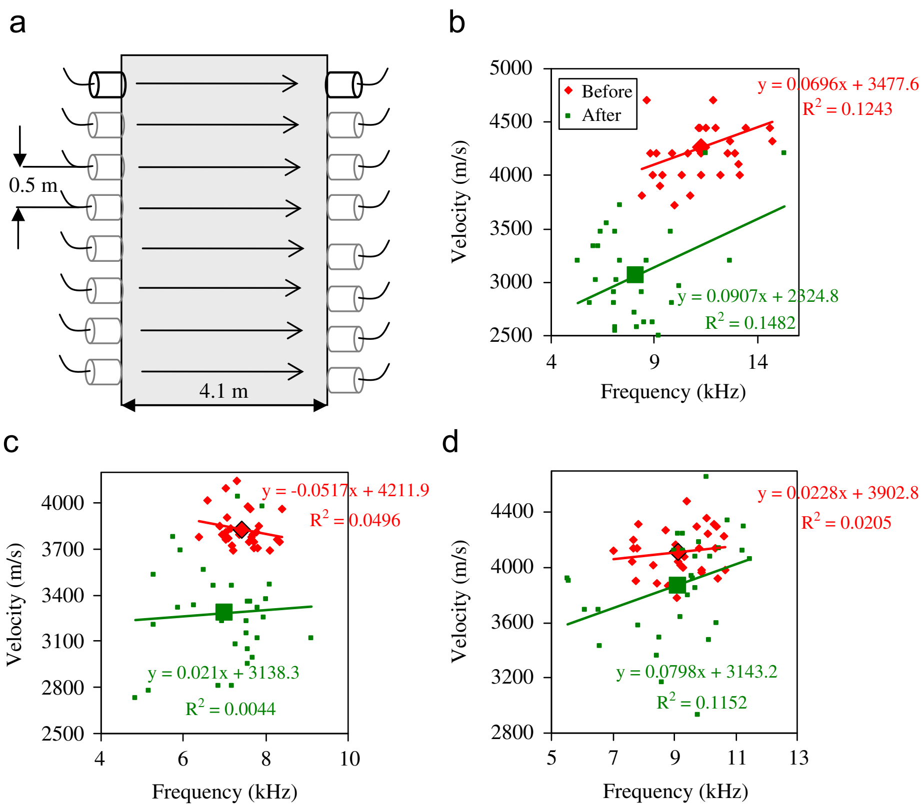

Fig. 1. (a) Schematic representation of the wave measurements, (b)–(d) Correlation plots of pulse velocity vs. central frequency for three different cross sections. Large symbols stand for the average of the populations.

and frequencies after injection with fresh grout. This is in accordance with recently observed results [11], and is attributed to scattering on the pockets of fresh grout, which break the wave front and redirect part of the energy away from the original forward direction. In average, pulse velocity was reduced from 4028 to 3477 m/s one week after grouting (reduction of 13.6%), while the frequency was reduced from 8.9 to 7.1 kHz (20.5%). It is worth mentioning that apart from the decrease in velocity and frequency, the experimental scatter (expressed as the standard deviation divided by the average of each population) of the measurements was considerably increased after injection: from 6.5% to 14.7% for pulse velocity and from 20% to 30.5% for central frequency. This is again an indication of the increased degree of heterogeneity after application of cement grout.

Based on the literature, velocities of less than 3500 m/s are connected to troublesome concrete status [15]. However, as discussed in this study, this decrease could be attributed to the effect of fresh cement injection. Allowing adequate time to pass, the material inside the cracked volumes gains rigidity and is supposed that the velocity rises eventually. Measurements are not always easy in situ due to logistics and service of the structure. However, in this case, indicative measurements on one side of one pier were conducted after a period of two years, which successfully confirmed the increase in pulse velocity as a result of the repair. These are shown in Fig. 2, in which the total initial (damaged stage, before repair) and intermediate (1 week after grouting) population of data are also given. The initial group of measurements (before repair) averages at 3970 m/s and 8.3 kHz, while just after grouting, it was reduced to 3577 m/s and 8 kHz. Measured much later when hydration development would have certainly stopped (specifically two years later), pulse velocity and frequency increased higher than the original state (4366 m/s and 11.8 kHz, respectively). It is worth mentioning that in most cases of Figs. 1 and 2, a weak positive correlation is observed between pulse velocity and frequency. Since this trend is seen in the vast majority of cases, it should not be disregarded. It is in accordance with the positive dispersion at the low band of frequencies, which has been measured in laboratory concrete specimens due to heterogeneity [16,17]. Due to the limited bandwidth of the measurements at the site, it is not easy to draw reliable dispersion curves; however, the weak positive correlation implies that when higher frequency components survive, the velocities tend to be higher. This common trend for the damaged or freshly injected structure is not followed for the final measurements after two years, see Fig. 2, where the correlation has almost been eliminated. This should be attributed to the decrease in heterogeneity after the injection material is adequately hydrated and obtains properties similar to matrix concrete.

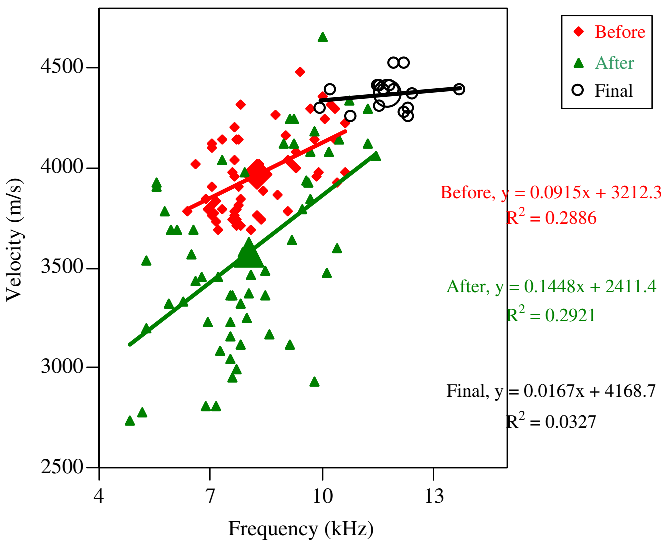

Fig. 2. Correlation plot of pulse velocity vs. central frequency for a cross section of a concrete pier for different times relative to repair. Large symbols stand for the average of the populations.

Certainly the number of data for the age two years after repair (16 measurements) cannot be considered adequate for establishing any engineering trend concerning frequency dependence of velocity and repair. However, this trend has also been observed on numerous surface measurements on the same major structure [18]. One-sided measurements taken at similar time periods after treating of surface cracks with injection cement resulted in an increase in velocity and frequency and elimination of the correlation between them [18]. In that case the changes in wave propagation were apparent much earlier, just one week after the surface cracks repair had taken place. This earlier action however, can be explained by the mechanics of propagation, which are certainly different in the two cases (surface as opposed to through the thickness propagation). In surface measurements, the wave is either transmitted through, or is reflected by the surface cracks, which are roughly vertical to the surface. In this way, if the cracks are empty most of the energy is reflected. On the other hand, if the cracks are filled with a material, even as soft as freshly injected grout, longitudinal waves can propagate through the crack and therefore the wave parameters such as velocity and amplitude are increased quite early after cement injection. On the other hand, through transmission propagation is more complicated in that it is not a simple matter of transmission or reflection, due to the scattering on all possible angles. As has been shown by the solution of the problem of scattering on soft elastic scatterer (Young's modulus approximately 10 GPa or lower) in a much stiffer matrix (modulus of 40 GPa), it produces stronger scattering interactions (and consequently lower velocity and wave amplitude) than the solution of scattering on a cavity inside the same stiff matrix for the low frequency range examined (below 20 kHz) [11]. Therefore, until the grout pockets obtain a certain level of rigidity, which could take several months in cold environments, the velocity and central frequency are not expected to recover. This is by no means an indication that the structure's condition has been deteriorated; it is a reasonable wave phenomenon caused by wave scattering.

3. Laboratory confirmation

In order to experimentally examine this trend under more controlled conditions, simple laboratory experiments were conducted. One cube of concrete (150 mm side, water to cement 0.50, maximum aggregate size 10 mm) was drilled from one surface, and a number of 14 holes of 6 mm diameter were opened, see Fig. 3(a). Consequently, the holes were filled with fresh cement paste to simulate repair by cement injection (Fig. 3(b)). The velocity and central frequency were measured both before and just after application of fresh paste, as well as 7 days later in order to allow some time for the paste to harden inside the holes.

Due to the limited size of the specimen, the experiments were conducted by the small and sensitive acoustic emission transducers (Pico, PAC), which exhibit a quite wide frequency band. A Tektronix AFG3102 function generator was used to produce an electric pulse of one cycle of 200 kHz, which was fed to the transducer acting as pulser. The received signal was pre-amplified by 40 dB and digitized at a sampling rate of 5 MHz in a PAC PCI-2 board. Noise level was low and therefore pulse velocity was measured by the first detectable disturbance of the waveform (onset). The typical signal-to-noise ratio (S/N) was higher than 700. Indicatively, Fig. 4(a)–(c) shows typical received waveforms,

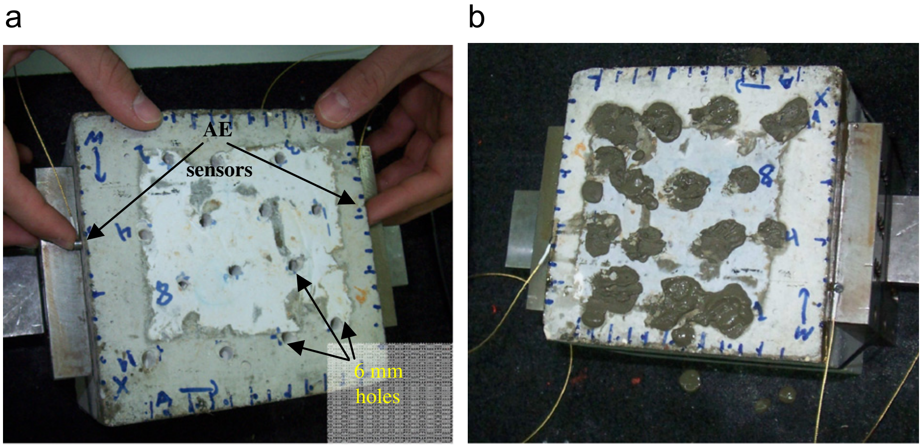

Fig. 3. Measurement of pulse velocity on a concrete cube (a) with drilled holes and (b) the holes were filled with fresh paste.

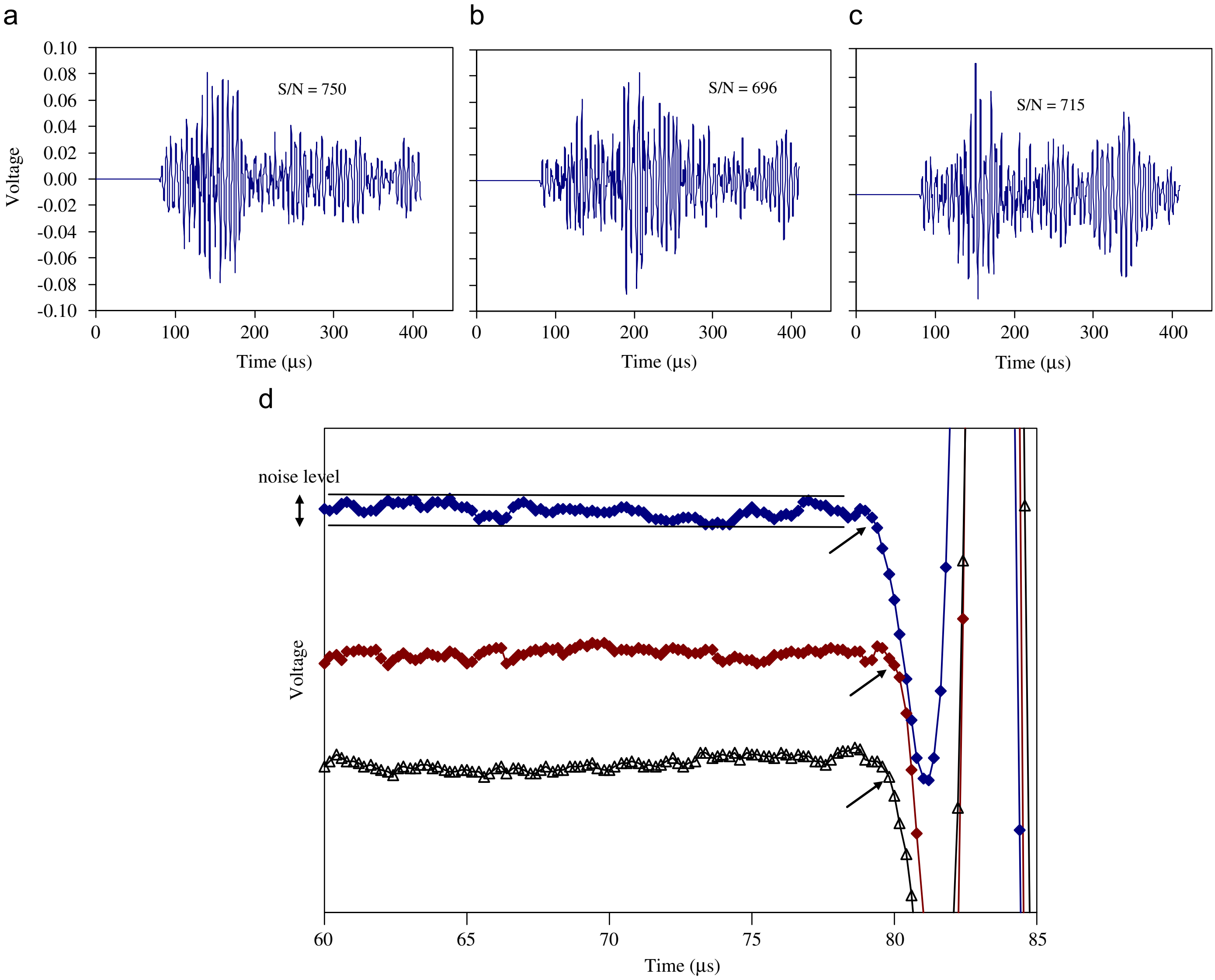

Fig. 4. (a)–(c) Typical received waveforms with their signal-to-noise ratio and (d) zoom at the onset of the waveforms.

while Fig. 4d shows more clearly the start of the waveforms. The noise level is low enough to allow comfortable picking of the correct point with a minimum error of one or two points. The resulting wavelength is approximately 25 mm (considering the pulse velocity of 5000 m/s and the frequency of 200 kHz), which is considerably shorter than the specimen's side of

150 mm. Therefore, no interactions are expected due to other wave or vibrational modes. Additionally, although experience shows that in similar concrete cubes, strong reflections from other sides are not expected (more likely due to extensive attenuation), even if they were visible, still they would not influence the pulse velocity measurements due to their late arrival. It is mentioned that the electric signal was also led to the second channel of the acquisition board and was used as a trigger for acquisition. The time of flight was specifically calculated by the delay between the received signal through concrete and the electric signal after excluding the sensor delay effects, which were measured separately at 0.6 μs. Measurements were conducted in several paths (12 horizontal and 12 vertical) in order to have an indicative population due to the irregular pattern of boreholes.

In Fig. 5(a) one can see the correlation plot between the velocity and frequency for the three different sets of measurements: before impregnation designated as "holes", a few minutes after impregnation (fresh paste), and 7 days later. Immediately after impregnation, the velocity reduced by 1% and central frequency by 6.7%. These changes are not similar to the corresponding decreases in the real structure; however, the large dimensions of the concrete structure contain an infinite number of cracks as opposed to the finite number of the drilled holes on the laboratory specimen. Although the changes in the laboratory are smaller, they can be readily captured due to the more sensitive equipment and the carefully controlled conditions. Seven days after cement application, the velocity increased even higher than the initial "damaged" condition, while the frequency was still at the same level as the freshly repaired specimen. Measuring the amplitude also showed similar trends, as can be seen in Fig. 5(b). The amplitude was measured by the maximum peak to peak voltage of the received waveform. Immediately after impregnation, the amplitude decreased by 22% (from 0.123 to 0.095 V) and did not a show clear increase even at the age of 7 days. This large decrease in amplitude (compared to the decrease in velocity) is a result of the higher sensitivity of attenuation mechanisms to the presence of inhomogeneity [16,17]. For reasons of consistency, Fig. 5(c) includes the graph of frequency vs. amplitude.

It is worth mentioning that in all cases, the correlation coefficient is quite low ($R^2 < 0.18$) but specifically for the case of the 7 days hardened paste, the correlations are generally the weakest ($R^2 < 0.018$), possibly due to the reduced inhomogeneity after the paste had been placed and hardened. This made scattering interactions weaker and reduced the trends of scattering dispersion.

4. Conclusions

The present paper deals with the assessment of the condition of cement injected structures by *P*-wave velocity. Due to the impedance mismatch of fresh cement inside the cracks, the velocity of the structure does not immediately rise after repair, as would be normally expected. In fact for the particular structure discussed herein it decreased by more than 6%, while the central frequency of the transmitted pulses decreased by 20%. This simultaneous decrease implies that inhomogeneity and cement injection impose a sort of wave dispersion, which is eliminated after a period of time necessary for the cement to be hydrated. This phenomenon was also examined in the laboratory, where damage was simulated by drilling holes in a concrete cube, and cement injection by filling the drilled holes with fresh paste. Results confirmed that application of cement causes initially a decrease in all measured wave parameters like velocity, frequency and amplitude, which was confirmed in situ. It is suggested that apart from pulse velocity, the central frequency of the pulses should also be studied in order to enhance characterization of structures, since it is sensitive to the repair condition. This study intends to enlighten wave propagation in complicated structures such as damaged/repaired concrete blocks and explain trends that were not adequately addressed so far.

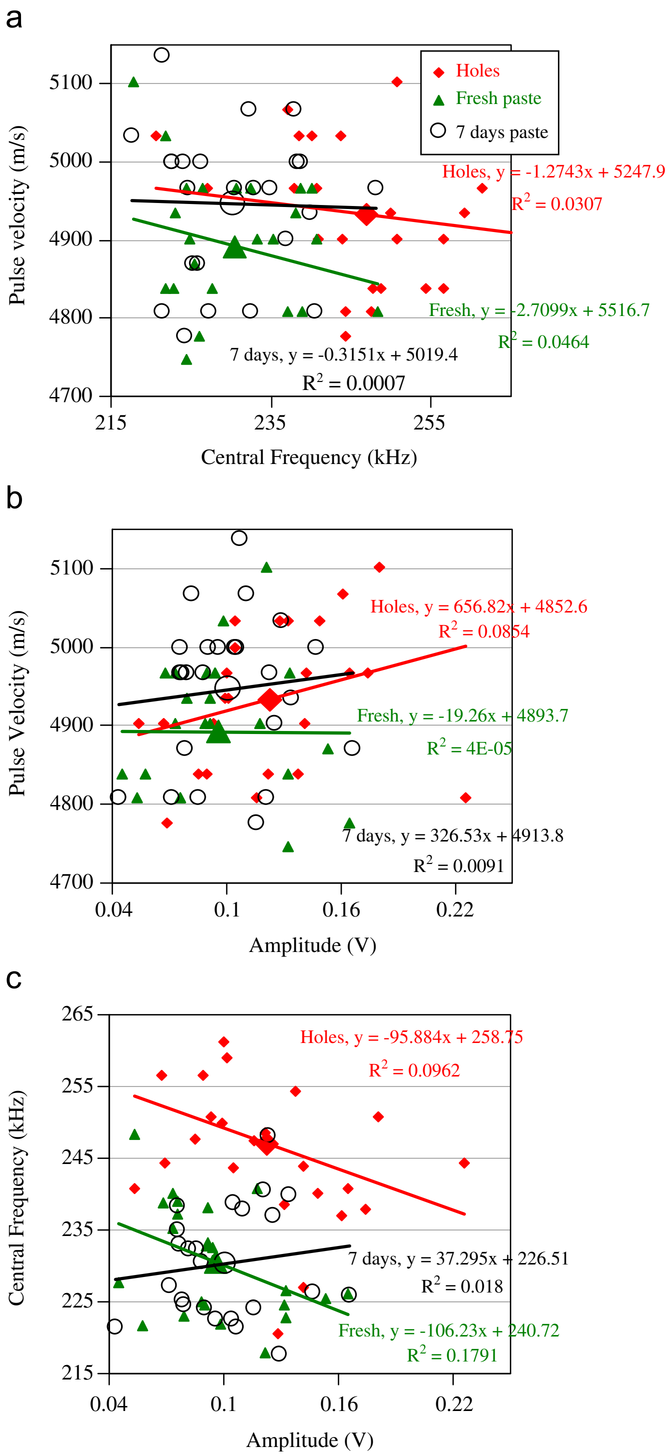

Fig. 5. Correlation plots of (a) pulse velocity vs. central frequency, (b) pulse velocity vs. wave amplitude and (c) central frequency vs. amplitude for the laboratory specimen at three times relative to the application of cement.

Acknowledgement

The authors thank Dipl. Engineers Nikos Zoides of Geotest S.A. and Charis Orfanidou for the preparation of the concrete specimen.

References

[1] Kaplan MF. The effects of age and water/cement ratio upon the relation between ultrasonic pulse velocity and compressive strength. Mag Con Res 1959;11(32):85–92.
[2] Anderson DA, Seals RK. Pulse velocity as a predictor of 28- and 90-day strength. ACI J 1981;78–79:116–22.
[3] Gudra T, Stawinski B. Non-destructive characterization of concrete using surface waves. NDT & E Int 2000;33:1–6.
[4] Aggelis DG, Shiotani T. Surface wave dispersion in cement-based media: inclusion size effect. NDT&E Int 2008;41(5):319–25.
[5] Ohtsu M, Alver N. Development of non-contact SIBIE procedure for identifying ungrouted tendon duct. NDT&E Int 2009;42:120–7.
[6] Aggelis DG, Shiotani T. Repair evaluation of concrete cracks using surface and through-transmission wave measurements. Cem Concr Compos 2007;29:700–11.
[7] Cheng C, Sansalone M. The impact-echo response of concrete plates containing delaminations: numerical, experimental and field studies. Mater Struct 1993;26:274–85.
[8] Vergara L, Miralles R, Gosalbez J, Juanes FJ, Ullate LG, Anaya JJ, et al. NDE ultrasonic methods to characterise the porosity of mortar. NDT&E Int 2001;34:557–62.
[9] Tong JH, Chiang CH, Jung WL. The numerical investigation into the influence of the scattering effect from the aggregates of concrete on the transient-elastic-wave-based NDT technologies. In: Proceedings of the 17th world conference on nondestructive testing (WCNDT), Shanghai, China, October 25–28, 2008. 〈http://www.ndt.net/article/wcndt2008/papers/474.pdf〉.
[10] Shiotani T, Nakanishi Y, Iwaki K, Luo X, Haya H. Evaluation of reinforcement in damaged railway concrete piers by means of acoustic emission. Acoust. Emission 2005;23:260–71.
[11] Shiotani T, Momoki S, Chai H, Aggelis DG. Elastic wave validation of large concrete structures repaired by means of cement grouting. Constr Build Mater 2009;23(7):2647–52.
[12] Kase EJ, Ross TA Quality assurance of deep foundation elements, Florida Department of Transportation. In: Proceedings of the 3rd international conference on applied geophysics–geophysics 2003, Orlando, FL, December 8–12, 2003.
[13] Shiotani T, Aggelis DG. Evaluation of repair effect for deteriorated concrete piers of intake dam using AE activity. Acoust. Emission 2007;25:69–79.
[14] Aggelis DG, Shiotani T. Experimental study of wave propagation through grouted concrete. ACI Mater J 2009;106(1):19–24.
[15] Naik TR, Malhotra VM, Popovics JS. The ultrasonic pulse velocity method. In: Malhotra VM, Carino NJ. editors. CRC Handbook on nondestructive testing of concrete. Boca Raton: CRC Press; 2004.
[16] Chaix JF, Garnier V, Corneloup G. Ultrasonic wave propagation in heterogeneous solid media: theoretical analysis and experimental validation. Ultrasonics 2006;44:200–10.
[17] Philippidis TP, Aggelis DG. Experimental study of wave dispersion and attenuation in concrete. Ultrasonics 2005;43:584–95.
[18] Aggelis DG, Momoki S, Chai HK. Surface wave dispersion in large concrete Structures. NDT&E Int. 2009;42:304–7.