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Experimental study of wave dispersion and attenuation in concrete

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Abstract

Results from an experimental study concerning wave propagation in cementitious materials are presented in this paper. Narrow band pulses at several frequencies were introduced into specimens of cement paste, mortar and concrete allowing direct measurement of longitudinal wave velocities and amplitude for each frequency. It is shown that aggregate content play an important role in wave propagation increasing considerably the wave velocity, while the aggregate size seems to control the attenuation observed. Slight velocity variations observed with frequency are discussed in relation to the degree of inhomogeneity of the materials.

Keywords: Concrete; Dispersion; Attenuation

1. Introduction

Stress wave propagation methods have been systematically used in non-destructive testing (NDT) of concrete. Features concerning strength, porosity and damage of concrete can be adequately revealed by analyzing ultrasonic signals [1,2]. Due to the highly inhomogeneous nature of the material though, consisting of cement, sand, fine and coarse aggregates, water and air bubbles, results are usually valid for qualitative only conclusions, without direct correlation with structural integrity parameters. The way ultrasound interacts with the different phases of the material should be thoroughly understood in order to establish any robust relation between propagation characteristics and material properties.

In this paper, results from an experimental study of through transmission ultrasonic measurements on cementitious material specimens is described revealing interesting features concerning the influence of mix design parameters (such as water and aggregate content and aggregate size) on the propagating wave.

The initial motivation of this work, undertaken in the framework of a national research project was the quality evaluation and more specifically the water content (water to cement ratio by mass, w/c) determination of fresh and hardened concrete which definitely affects strength and durability of the material. As to the hardened material the outcome was quite successful as wave propagation parameters treated in an adequate manner resulted in successful determination of w/c of most specimens [3]. The ultrasonic examination concerned low frequencies (below 200 kHz) and concrete ages from 2 to 90 days. These specimens were maintained and tested after a period of about 3 years, aiming this time not at the w/c estimation at this age but focusing more on the dispersive and attenuative effects the inhomogeneous nature of the material may impose, thus, addressing the possibility of enhancing NDT capabilities by the use of higher frequencies.

Studies have shown that concrete, which can be considered a particulate composite of aggregates embedded

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in the paste matrix exhibits dispersive behavior, examined through the analysis of Rayleigh waves acquired on different points on the surface of a mortar specimen [4]. Dispersion has also been related to the aggregate size [5], since phase velocity calculated up to frequencies of 10 MHz, exhibited larger deviation from the velocity measured experimentally using a 500 kHz excitation in concrete than in mortar or paste. Additionally, pulse velocity in concrete has been shown to increase considerably from 54 to 120 kHz while this was not mentioned in paste specimens, an attitude mainly attributed to the "compositeness" of concrete in contradiction to the homogeneous nature of paste [6]. As to frequency dependent attenuation, the increasing size of aggregates has resulted in higher attenuation in the range up to 1 MHz attributed mainly to scattering [7]. However, in a number of other works [5,8,9] attenuation does not seem to increase with aggregate size. This behavior is attributed to the air bubbles present in cement paste [5], or to the existence of aggregates that act as "larger homogeneous structures embedded in the matrix that facilitate the propagation of high frequencies" [8]. Also in [9], after examination of concrete with different aggregate size it is concluded that scattering losses are negligible compared to absorption ones. Therefore a relationship between wave attenuation and aggregate fineness in concrete has not been generally accepted. It has also been shown that an increase in the aggregate content results in higher wave velocity and decreases the high frequency content of the transmitted signal in concrete containing aggregates with higher acoustic impedance than cement paste while the inclusion diameter does not seem to crucially affect velocity [10].

In all above cited studies, the frequency dependent nature of attenuation was evaluated by comparing the spectrum of the through transmission acquired signal as a response to a wide band excitation with a reference spectrum taken normally from a material considered non-attenuative. Specifically, the spectrum of the acquired waveform was divided by the reference spectrum showing which frequency bands survive through the examination material and which bands are being cut off. In the present work wave velocity and attenuation variations with respect to frequency were obtained directly from experimental measurements exciting the specimens with narrow band tone bursts of different central frequencies. The results show the effect of sand and aggregate content, in terms of aggregate to cement ratio by mass, a/c, on wave parameters i.e. wave velocity and amplitude, while the contribution of the elasticity of the matrix, controlled mainly by w/c, is also detectable. Besides, comparison of data acquired from concrete, mortar and paste specimens highlights the substantial role aggregates play in wave propagation in such materials.

2. Experimental procedure

2.1. Test methodology and equipment

The experimental setup is a simple through-transmission ultrasonic configuration and exhibits similarities with the one described in [3]. It consists of a waveform generator board (Physical Acoustics Corporation, PAC, Wavegen 1410, Version 2.0), two broadband transducers (Panametrics V413) of center frequency 500 kHz, a PAC 1220A pre-amp and a PAC MISTRAS 4 channel data acquisition system. For some indicative investigation measurements the acoustic emission sensors PAC R6 were also used concerning frequencies below 200 kHz, since this is the region of their maximum sensitivity, providing similar results with the V413 as will be seen.

The driving transducer was excited with a sine wave in a sine envelope introducing a relatively narrow band excitation into the material, see Fig. 1(a) and (b) where a typical input waveform of 25 kHz and its corresponding FFT is depicted. Tests at various frequencies were performed from 15 kHz up to 1 MHz as at higher frequencies the signal is severely attenuated and not appropriate for reliable feature extraction. The sensors are mounted directly on the specimen surface and acoustic coupling is enhanced by a layer of roller bearing grease, which has been found more appropriate than other commercial ultrasonic couplants.

2.2. Materials and specimen geometry

The specimens tested were cubic of 150 mm edge and were prepared according to the New Greek standard of concrete technology 97 (ΣK 303), which is in accordance

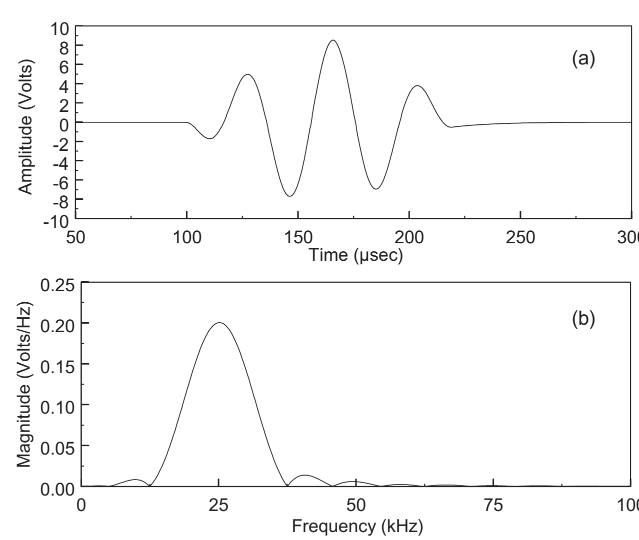

Fig. 1. Input electric signal of 3 cycles at 25 kHz in sinusoidal envelope, (a) in time domain and (b) in frequency domain.

with ASTM C192, at the Greek Center for Cement Research (EKET), where compressive tests on specimens of the same compositions took place. High strength Portland cement was used while the aggregates were of limestone origin. Several different compositions of mortar and concrete were manufactured and are summarized in Table 1 along with their corresponding water to cement ratio by mass, w/c and aggregate to cement ratio by mass, a/c. In total, 24 specimens (one of each composition) were examined. Mortar specimens contain only cement, sand and water, while concrete ones contain also fine and coarse aggregates. Sand grains size is up to 4.75 mm, fine aggregates range from 1.18 to 25 mm and coarse from 4.75 to 37.5 mm. The exact grading of all aggregates used is indicated in Table 2, while the proportion between coarse, fine and sand in concrete is 39:11:50 by weight [11]. In addition to the above compositions, five cement paste specimens of dimensions $50 \times 30 \times 40\ mm^3$ and w/c ratios 0.375, 0.425, 0.45, 0.50 and 0.55 were produced for evaluation of the dispersive behavior of the matrix material alone. At the time of test all mortar and concrete cubes were between 2.5 and 4 years of age, old enough to consider hydration variations of no importance. Paste specimens had all the age of 10 months. Although, this is in any case an age that development of elasticity in any cementitious material due to hydration has theoretically almost stopped, the effect of age is the same for all paste specimens compared.

Table 1
Mix parameters of tested specimens

a/c	w/c 0.375	0.40	0.425	0.50	0.55	0.60	0.65
Mortar							
1.5	♦		♦				
3		♦	♦	♦	♦	♦	♦
4				♦	♦	♦	♦

a/c	0.375	0.40	0.425	0.45	0.475	0.50	0.525	0.55
Concrete								
3	♦	♦	♦	♦	♦	♦		
4			♦	♦	♦	♦	♦	♦

♦ denotes manufactured and tested compositions.

Table 2
Aggregates grading table (% cumulative percentage passing sieve opening)

ASTME 11-87	Sieve size (mm)	Sand	Fine aggregates	Coarse aggregates
1 1/2″	37.5	100.0	100.0	100.0
1″	25.0	100.0	100.0	98.5
1/2″	12.5	100.0	93.3	8.9
3/8″	9.5	100.0	69.4	1.4
No. 4	4.75	99.9	8.0	0.7
No. 8	2.36	83.2	1.3	0.0
No. 16	1.18	56.1	1.1	0.0
No. 30	0.6	38.5	0.0	0.0
No. 50	0.3	27.6	0.0	0.0
No. 60	0.25	25.1	0.0	0.0
No. 200	0.075	14.2	0.0	0.0

3. Attenuation measurements

The examination of the amplitude of the signals at different frequencies revealed interesting features related to the aggregate content and size. Since the same transducers were used and the amplitude of the electric input signal was held constant throughout the experimental series, changes in the amplitude can be attributed directly to the attenuative behavior of the material. This implies both, intrinsic (absorption) and extrinsic (scattering) mechanisms, which cannot be directly separated. Geometric attenuation, attributed to the spreading of the wavefront over a wider volume has always the same effect as mortar and concrete specimens, used for amplitude observation, are all of the same dimensions. The attenuation coefficient is determined by measuring the reduction in amplitude of an ultrasonic wave, which has traveled a known distance through a material and is given by

$$\alpha = -\frac{20}{x}\log\left(\frac{A_X}{A_0}\right) \tag{1}$$

where A_0 is the initial amplitude of the wave and A_X is the amplitude after it has traveled a distance X.

The output wave amplitude (A_X) is the absolute peak voltage of the received signal, while the amplitude of the pulse entering the specimen was measured separately on a face to face configuration of the transducers. The difference of amplitudes of the sent and received pulse signals although cannot provide an absolute measure of signal transmission, gives an indication of the signal attenuation through the thickness of concrete and has been used for evaluation of concrete deterioration after freezing-thawing cycles in an immersion through transmission configuration [12]. A certain cause of energy loss is due to coupling [13]. However, in [13] the losses are considered frequency independent and excluded from the calculation of attenuation coefficient, while in [14] coupling loss factor varies with the roughness of the specimen surface. Although coupling can never be identical in all cases, in the frame of this work, the measurements were all conducted by the same operator following the same procedure throughout the whole experimental series, minimizing random effects. Therefore, differences in measured signal of different materials were attributed in the nature of the material itself, since the preparation procedure using cubic metal matrices for the forming of specimens resulted in the same good quality of surface finishing. Apart from this, it was ensured that, when sensors were mounted to the specimen surface and before the test commences, the lowest frequencies, furthest apart from the broadband sensors' sensitivity, were transmitted clearly. This guaranteed that the coupling was appropriate and that all other frequencies used in the test are transmitted in a reliable way.

Paste amplitude cannot be unambiguously compared to concrete and mortar due to reduced specimen size, that leads also to reduced wavefront spreading and therefore it is presented separately.

3.1. Results

Examination of paste, mortar and concrete waveforms revealed considerable differences between these materials. The degree of inhomogeneity increases from paste to mortar due to the presence of sand while it is further increased in concrete as aggregates in the order of some centimeters are embedded in the paste. Therefore the way the structure of the material interacts with the propagating wave is of major interest. Comparison between concrete and mortar sharing the same parameters w/c and a/c revealed that concrete is more attenuative, behavior more clear above 100 kHz, as can be seen in Fig. 2. In both cases of this figure specimens contain the same total amount of aggregates and water, e.g. a/c = 3 and w/c = 0.425 for Fig. 2(a) and a/c = 3 and w/c = 0.40 for Fig. 2(b). Therefore this difference in attenuation can be attributed to the different degree of aggregate fineness, the maximum sand grain in mortar being 4.75 mm while the maximum aggregate size in concrete is 37.5 mm. Apart from this, the known increasing trend of the coefficient of attenuation with

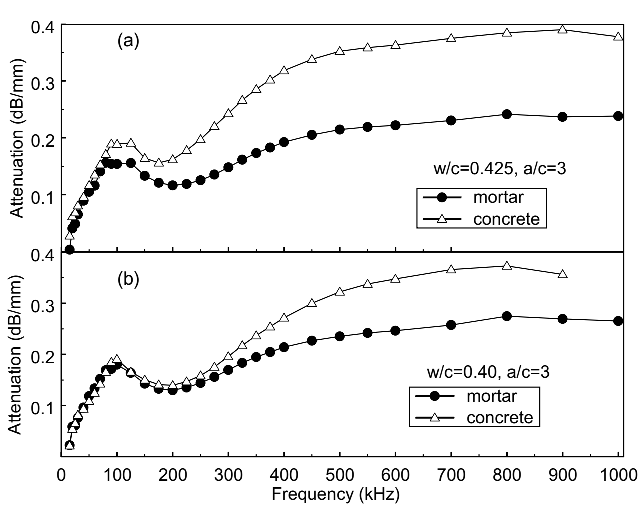

Fig. 2. Effect of aggregate size on attenuation variation with respect to frequency of material with (a) w/c = 0.425 and (b) w/c = 0.40.

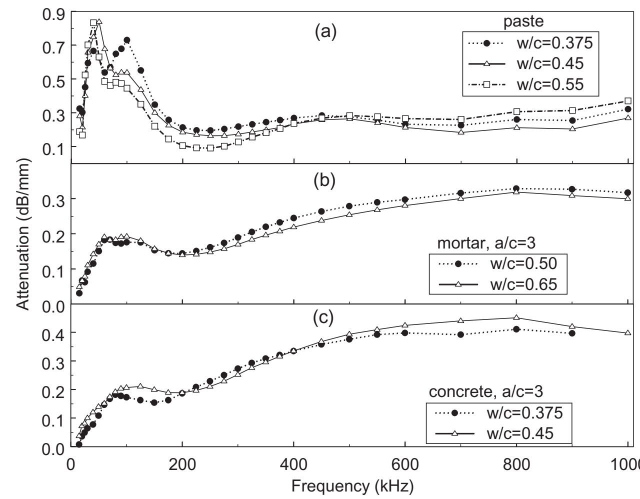

Fig. 3. Effect of w/c on attenuation variation with respect to frequency of (a) paste (b) mortar with a/c = 3, (c) concrete with a/c = 3.

frequency for such materials [5,7–9,15] can also be mentioned here for the range of 200–700 kHz.

In addition, the attenuation of paste can also be observed in Fig. 3(a). Paste seems to facilitate the propagation of frequencies above about 200 kHz while it exhibits strong attenuation at low frequencies. It is indicative that despite the reduced specimen size, for a number of frequencies below 100 kHz paste specimens exhibit lower amplitude than mortar or concrete cubes with wavepath five times that of paste. The higher attenuation of paste for low frequencies however, with respect to material containing aggregates, has been reported in other studies [5,8] as well. Another striking difference concerning paste and mortar or concrete behavior is the approximately constant value of attenuation for the frequency band above 200 kHz, in contrast to mortar and concrete whose attenuation rises until at least 800 kHz, as can be seen in Fig. 3(b) and (c) respectively.

Therefore, the presence and size of inclusions exercises certain influence on wave attenuation. The influence of water content, on the other hand, seems not so clear in all three different types of material, thus, making the amplitude a weak wave characteristic when used to distinguish between mortar and concrete specimens of different w/c ratio. Despite the fact that, as will be seen later, the w/c = 0.5 mortar specimen exhibited higher velocities in all frequency bands than the one with w/c = 0.65, the attenuation coefficient is not influenced much following more or less the same trend with respect to frequency, see Fig. 3(b).

The same behavior holds for concrete as well. Fig. 3(c) depicts the attenuation curves of two different w/c concretes. Concrete with w/c = 0.45 does not seem to be constantly more attenuative than 0.375, although at most frequencies it exhibits slightly lower amplitudes. The w/c difference of these two classes of material was most evident during the compressive tests as for example the 2-day strength of w/c = 0.375 concrete was measured at 39.2 MPa, 8 MPa higher than w/c = 0.45.

Testing of mortar material with different sand content revealed that the increase of a/c from 1.5 to 3 (corresponding to sand volume contents approx. 43.4% and 60.6% respectively for w/c = 0.425) facilitates wave propagation more likely due to increase of the effective elastic constants of the material, see Fig. 4(a). Further increase of a/c from 3 to 4 (in mortar with w/c = 0.50 corresponding sand vol% 57.7 and 64.5) seems not to crucially affect the received amplitude, although above 150 kHz a/c = 4 mortar seems more attenuative, see Fig. 4(b). This trend is not observed for concrete, see Fig. 5, as specimens with a/c = 3 and 4 do not show systematic discrepancy in attenuation. In this case, concrete of a/c = 3 contains approximately 60% aggregates while concrete of a/c = 4 about 66.5% per volume.

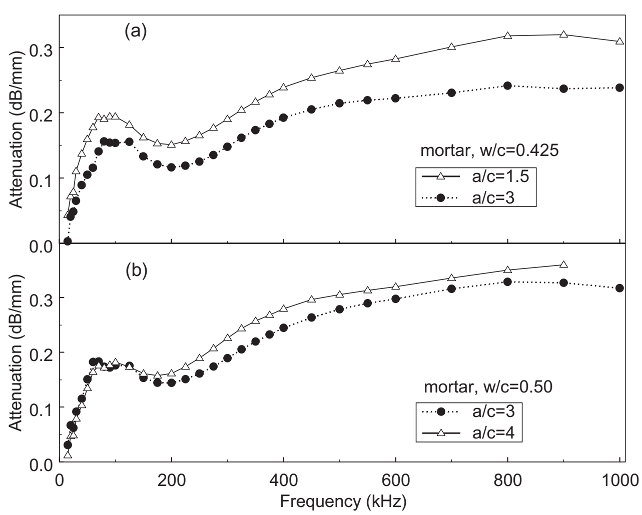

Fig. 4. Effect of a/c on attenuation variation with respect to frequency of mortar with (a) w/c = 0.425 and (b) w/c = 0.50.

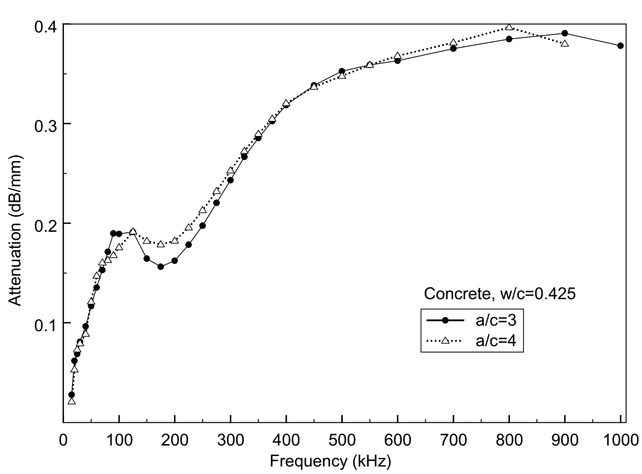

Fig. 5. Effect of a/c on attenuation variation with respect to frequency of concrete with w/c = 0.425.

An interesting outcome of the above measurements is the different level of attenuation between paste, mortar and concrete related to their inhomogeneity. Apart from this, attenuation for mortar and concrete increases with frequency exhibiting a local minimum at around 200 kHz. Similar concrete attenuation behavior for the band 200–1100 kHz concerning surface waves has also been observed in [4,9] while in [16] the attenuation coefficient obtained through a reflection setup on a mortar slab seems to linearly increase for the band of approximately 340–760 kHz. Also in [17] the attenuation of mortar probes measured in a through transmission immersion setup, increases up to frequencies above 1.5 MHz.

The aggregate size seems to influence the overall attenuation; however the exact mechanism is not obvious. One explanation is through scattering. Another potential relation of aggregate size with attenuation is through the absorption losses that take place in the interfacial zone between the aggregate and the mix. This relation although not clear has been considered responsible for the discrepancy of attenuation curves obtained from different aggregate size concretes [9].

4. Dispersion characterization

Concrete being a porous composite of sand and coarse aggregates embedded into the cement paste matrix cannot a priori be assumed non-dispersive as any homogeneous and isotropic material. Its behavior was examined through both the phase velocity and the time difference between the input and received waveforms. In a non-dispersive medium since phase and group velocities are equal these two features are expected to exhibit identical values. In cementitious materials employed in this experimental series however, they exhibit slight difference.

The pulse used in this experimental series is of the form of Fig. 1(a) for several different central frequencies. While traveling in a non-dispersive medium this envelope will experience no shape distortion. For dispersive wave propagation however, the individual peaks within the wave packet will move relative to the centroid as the wave propagates through the medium [18].

To avoid wave propagation terminology confusion, discrimination between pulse velocity and phase velocity should be done. Pulse velocity is generally defined as the specimen thickness divided by the transit time t, see Fig. 6. This transit time is dependent on an amplitude threshold, which in this case was defined as the highest noise amplitude recorded before each individual measurement. Phase velocity on the other hand, is determined from the position of reference "phase" points of the

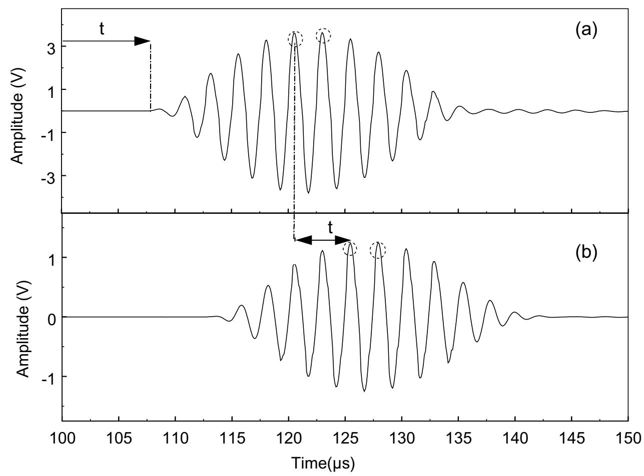

Fig. 6. Tone bursts collected after propagation through different wavepaths in the material.

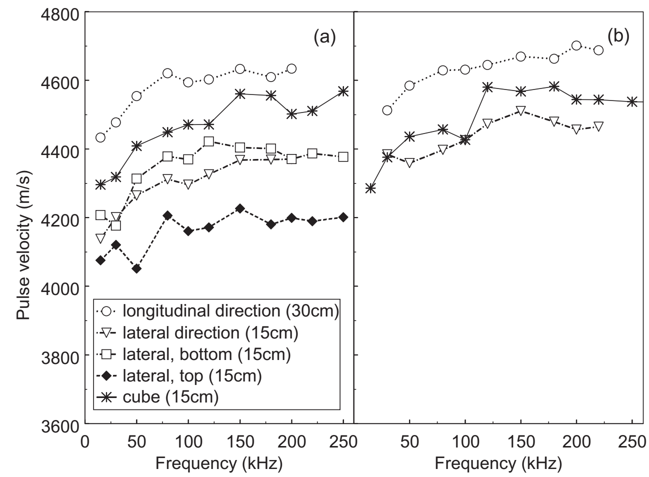

Fig. 7. Effect of specimen geometry on pulse velocity vs. frequency curve obtained using (a) resonant and (b) broadband sensor.

waveforms on signals recorded using different wavepaths, see Fig. 6, or the phase difference between the received and input waveforms, as will be mentioned later [19].

4.1. Geometry effect on velocity measurements

Earlier studies [6] have shown that concrete and paste specimens exhibit dispersive pulse velocities for the range of 24–120 kHz. This is expected due to the inhomogeneous nature of the material. However, dispersion has been attributed also to geometric effects since pulse velocities in concrete cylinders measured in the lateral and longitudinal direction were not equal especially at low frequencies, implying that the limited wavepath compared to the long wavelength of low frequencies sets up a ‘‘guided wave situation’’ that affects velocity readings [6].

Apart from this, the common rule for accurate velocity measurements mentioned in ASTM C457, suggests that the wavepath must be higher than the wavelength of the applied ultrasound. Since for paste specimens in this work, of thickness 30 mm, the wavelengths up to about 80 kHz are higher, as is also the case for frequencies below 30 kHz for concrete and mortar cubes (size 150 mm) it was deemed necessary to measure pulse velocities of the same material over different geometric configurations, in order to examine whether specimen geometry has an influence on pulse velocity and any dispersion observed.

Therefore, measurements were conducted along the axial and lateral direction of standard concrete cylinders ($150 \times 300\ mm^2$) as well as on concrete cubes of side 150 mm, all of the same composition. These measurements were conducted using the resonant sensors, PAC R6, which are very sensitive below 200 kHz. In Fig. 7(a) the pulse velocities of different tone bursts from 15 kHz central frequency to 250 kHz are depicted. It is clear that the axial direction (wavepath = 300 mm) of the cylinder results in the highest velocity values for all frequencies. The velocity curve obtained from cube measurement (150 mm wavepath) is approximately 150 m/s lower, while the cylinder lateral dimension results in even lower values. The height of the cylinder at which the measurement is conducted influences the velocity due to the internal segregation, meaning that aggregates tend to move downwards during placing and compaction because of density discrepancies with paste [6], and also to the air bubble amount that rises to the free surface. Nevertheless, even for the measurement at the bottom of the cylinder, lateral pulse velocity is lower than the one, measured at the center of the cube surface, indicating that other ‘‘boundary conditions’’ besides wavepath are also relevant with respect to the transmitted wavelength.

In order to confirm that velocity readings are not strongly dependent on the resonance of the specific sensors, the same specimens were interrogated with the broadband Panametrics V413 sensor of center frequency 500 kHz. The results are shown in Fig. 7(b) without exhibiting different trends except for somehow higher velocities. These sensors were used throughout the whole experimental series and for all results displayed hereafter. In Fig. 8(a) two indicative signals through the concrete cylinder axial direction with central frequencies 30 kHz and 50 kHz are depicted along with their corresponding FFTs, Fig. 8(b), showing that the propagating pulses actually carry the intentionally introduced frequency component even for ranges away from the maximum sensor sensitivity (500 kHz).

From the above it is obvious that different geometries result in different velocity vs. frequency curves, sharing however the same dispersion, since the increase in pulse velocity is approximately 5% from 15 kHz to the maximum value for all cases.

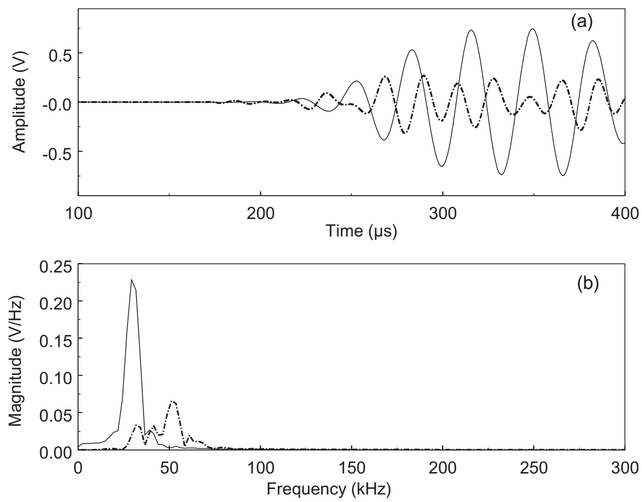

Fig. 8. Tone bursts of 30 (solid) and 50 kHz (dash-dot) after propagation through the cylinder longitudinal direction in (a) time and (b) frequency domain.

Regarding the consideration about the wavelength compared to the specimen size, it is noted that even for 15 kHz, the cylinder height is greater than the wavelength, fulfilling the ASTM rule as to measurements in the longitudinal direction. However, the relation between velocity and λ/D (ratio of wavelength to wavepath) is not unique as can be seen in Fig. 9. For the three different configurations, even if the λ/D is equal, the velocities differ substantially implying that other parameters of the geometry or the volume of the specimen play an important role, with the thickness alone being very important since for example for $\lambda/D \approx 0.3$ in the lateral dimension of the cylinder the velocity is measured 4370 m/s (corresponding frequency 100 kHz) while for the axial direction and frequency 50 kHz, the velocity is measured 4554 m/s The geometry effect is emphasized since the lateral measurements at the bottom are used in Fig. 9, which due to segregation concern material with higher aggregate content and higher elastic constants. However, the velocity is still lower than the longitudinal direction where the pulse propagates through all "layers" of concrete.

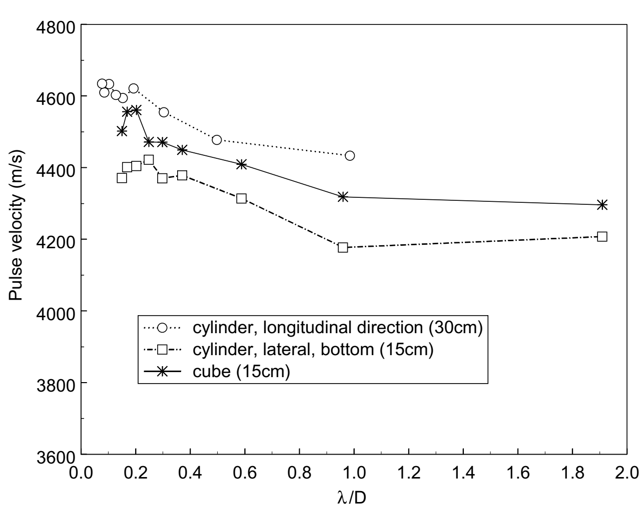

Fig. 9. Effect of specimen geometry on concrete pulse velocity dispersion curves.

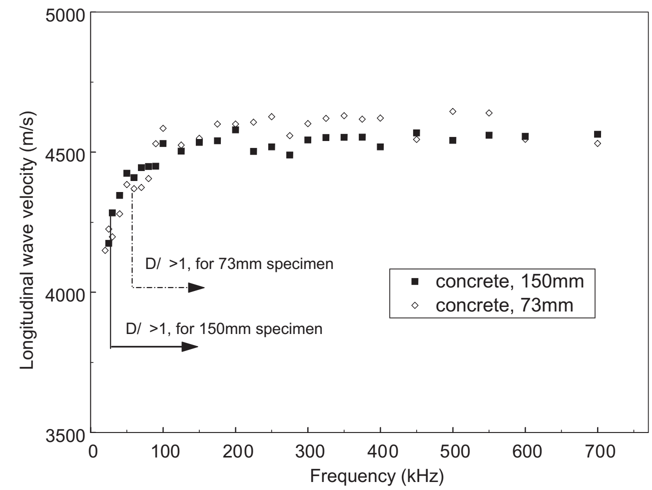

Fig. 10. Effect of specimen size on pulse velocity of concrete.

Another case of investigation concerns the pulse velocity measurement, through the thickness of a concrete cube before and after it was cut in two parts corresponding to wavepaths of 150 mm and 73 mm. As seen in Fig. 10, the velocities differ for about 1% for frequencies above 200 kHz, while the dispersive behavior is not much affected, although the λ/D ratio for each frequency is about twice for the half cube configuration compared to the initial one.

From the above investigation two general assumptions can be drawn concerning velocity measurements on cementitious material; first that, as has been seen earlier [6], comparison between velocities of different materials is valid only when the tests are conducted on specimens of the same geometry. Else, differences of even 5% have been noticed concerning the axial and lateral direction of concrete cylinders at any frequency. Another outcome is that the dispersive trend observed at the lower end of the applied frequency range holds no matter the wavepath, the wavelength to wavepath ratio or the geometry of the specimen. Therefore, it is reasonable to assume it originates from the inhomogeneous nature of concrete and mortar.

4.2. Pulse velocity

Prior to presenting results for different compositions of cementitious materials a few points concerning the measurements should be discussed.

Leading both the electric signal from the wave generator and the received signal from the transducer to separate, synchronized data acquisition channels the wave velocity can be obtained from the time shift between the waveforms acquired by the two channels, excluding sensor delay times, a procedure that will be explained below. The onset of each signal was set as the first threshold crossing. In order to evaluate the noise level a pre-trigger time of 100 μs was recorded before each signal. The threshold was set equal to the maximum amplitude exhibited in this period. Since the onset of the wave is characteristic of the pulse, without however being necessarily characteristic of the phase or group velocity, this feature will be called "pulse velocity" hereafter.

The sensor delay time is attributed to the propagation of the wave through the sensor's wearplate as well as any electronic switching time or cable delays and should be taken into account for enhanced accuracy [20]. In order to determine this delay time, δt, tone burst calibration measurements where conducted in reference media. The distance between the sensors was different for each measurement. However, due to the fact that the velocity of the reference medium (C_{ref}) is constant regardless of the wavepath, δt can be calculated as follows. For two different configurations (wavepaths S_1 and S_2) and any specific pulse the time difference between the introduction of the electric signal and the arrival of the received was measured t_1 and t_2 respectively. These values contain the delay δt which is therefore calculated by

$$\delta t = \frac{S_2 t_1 - S_1 t_2}{S_2 - S_1} \tag{2}$$

For further accuracy in the present case the delay was measured using different media namely water, fresh cement paste, a steel calibration block and concrete specimens of different sizes. The results were quite close, while not exhibiting any noticeable dependence on the central frequency of the tone burst. Therefore, the delay was calculated as the average of the delay exhibited in all different calibration measurements, namely 1.575 μs. This value was subtracted thereafter from the time shift between the received and the electric input signal. Typical pulse transit times through the concrete specimens are approximately 30–35 μs, therefore considering no delay effects would lead to an about 5% underestimation of velocity measurement. Indicatively it should be mentioned that subtracting the value of $\delta t = 1.575$ μs from measurements in water, sound velocity calculated from all different tone bursts results in an almost constant value of 1501 m/s regardless of the frequency with a standard deviation of 7.8 m/s.

Concrete and mortar have been reported previously to exhibit dispersive behavior in through transmission [5,6] and one side Rayleigh wave measurements [4]. Results of this work reveal such a trend at low frequencies.

In Fig. 11 the velocity of the individual wave packets from 15 kHz to 1 MHz concerning cement paste specimens is depicted. It is worth noting that the different

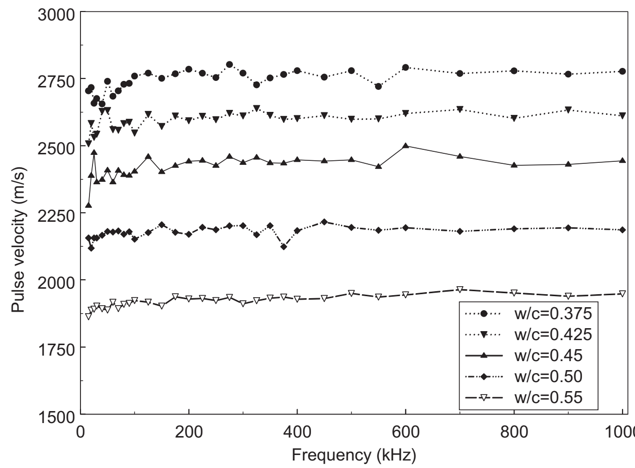

Fig. 11. Effect of w/c on pulse velocity curves of paste.

curves are clearly distinguishable, showing the net influence of w/c on the propagating wave mainly through the control of porosity. This decreasing trend of longitudinal wave velocity with w/c is well known and holds not only for hardened paste but also mortar [21] and concrete [22]. The results do not show appreciable dispersion, since all values for each specimen do not generally differ more than ±50 m/s from its average. The reduced size of specimen is expected to have a negative impact on the velocity values according to the investigation of Section 4.1; however, this geometry allows for the discrimination between different composition pastes.

A slightly different trend of velocity vs. frequency is observed for mortar, see Fig. 12(a) and concrete, Fig. 12(b). It seems that pulse velocity experiences a rise up to about 200 kHz, obtaining an approximately constant value up to the highest frequency tested. The water content influence is clearly shown especially in the mortar case. The mortar curves are smoother, probably because the larger size of inhomogeneities in concrete results in

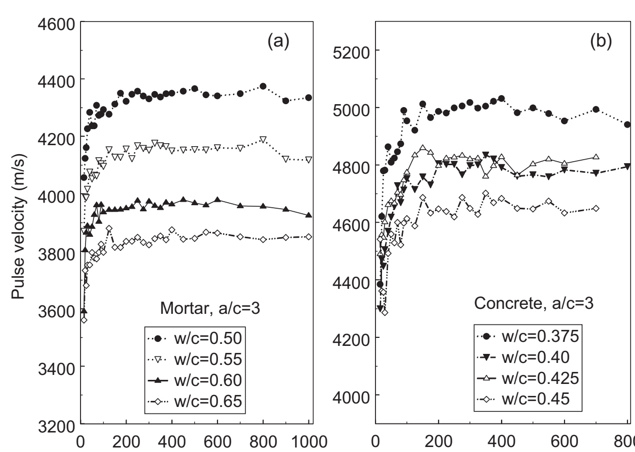

Fig. 12. Effect of w/c on pulse velocity of (a) mortar and (b) concrete.

increased experimental scatter. Although generally w/c affects concrete velocity too, specimens of neighboring classes and specifically of w/c = 0.40 and 0.425 are not well separated as seen in Fig. 12(b). This is the reason velocity has been considered, a weak characterization parameter as to the w/c ratio of concrete while it seems more powerful descriptor in mortar [3]. Anyway any differences should be sought above 100 kHz.

It is noted that in certain cases high frequency signals were severely attenuated and not liable to any analysis. This is why some curves are truncated before 1 MHz and while the acquired signal is still clear.

The reinforcement of the matrix with more stiff inclusions (aggregates) seems also to have a more pronounced effect on velocity probably due to the improvement of elastic constants. Fig. 13(a) shows the difference an increase of about 17% in volume content of sand, i.e. increase of the a/c ratio from 1.5 to 3, makes in the longitudinal wave velocities mortar. A velocity rise is clearly observed in concrete too with an increase of a/c from 3 to 4, corresponding to volume contents 60.5% and 67.2% respectively, see Fig. 13(b). Close examination of the curves, reveals that the increase of inclusions embedded in the matrix seems to influence the discrepancy between the lower and maximum values, since a/c = 1.5 mortar exhibits an increase of about 6% in velocity from 15 kHz to the maximum velocity observed while the velocity increase for a/c = 3 mortar is 9%. Similarly, pulse velocity of a/c = 3 concrete undergoes an increase of 7.5% while for concrete of a/c = 4 the increase is 11%.

A general remark from examination of all available specimens is that the increase of velocity throughout the band 15–200 kHz is approximately 5% for paste, 8.5% for mortar and 11% for concrete being in accordance with the increasing level of inhomogeneity of these materials.

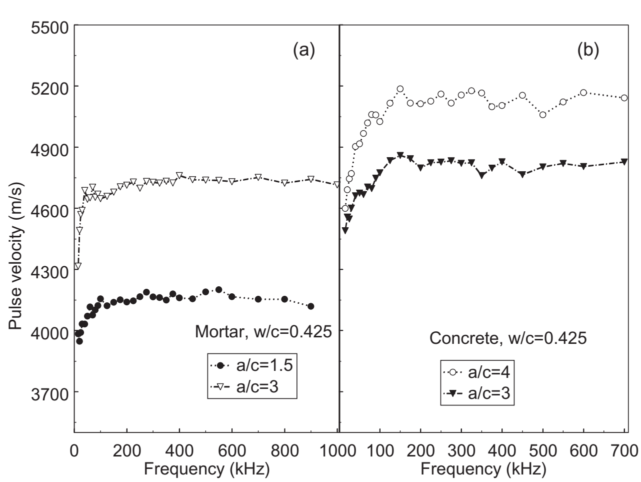

Fig. 13. Effect of a/c on pulse velocity of (a) mortar and (b) concrete.

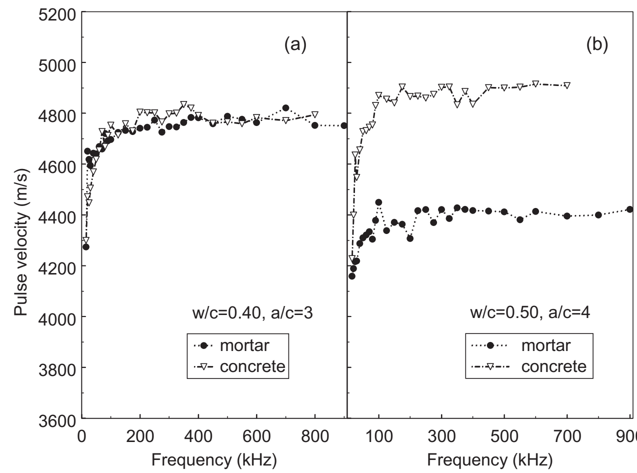

Fig. 14. Effect of aggregate size on pulse velocity of material with (a) w/c = 0.40 and a/c = 3 and (b) w/c = 0.50 and a/c = 4.

Another interesting comparison is the one between curves obtained from mortar and concrete, which however share common design parameters, i.e. a/c and w/c. Therefore, the effective elastic constants and density are considered similar and any discrepancy could be attributed to the different inclusion size. It should be reminded that the maximum aggregate size for mortar is 4.75 mm while 37.5 mm for concrete. Although the aggregate size cannot be considered a key factor for wave velocity in concrete, its increase has been reported to yield slightly higher velocity values in through transmission measurements [10]. From the obtained results no clear tendency as to wave velocity is established, since in certain cases mortar velocity is comparable to concrete one, see Fig. 14(a), while in others, Fig. 14(b) velocity in concrete seems to be favored. This difference has been attributed to the "interfacial transition zone" around the aggregates, which is characterized by increased porosity [10]. Since the specific surface of the aggregate rises inversely proportional to the diameter it is reasonable to assume that the total volume of material contained in this zone is increased for mortar, resulting in overall poorer elasticity and velocity.

4.3. Phase velocity

Although it is a common practice to measure pulse velocity in concrete, phase velocity can be of certain importance especially when elastic properties are estimated or theoretical modeling is undertaken.

The phase velocity measurement is based on the phase difference of two signals, the one entering the specimen and the received after propagation through the examination material, as calculated through the Fourier transform. The pulse used is broadband in order to excite a wide frequency range. With the specific equipment, material attenuation limits frequency range to values no higher than 1 MHz.

Specifically, the pulse used was 1 cycle of 450 kHz, or of duration 2.22 μs with a FFT spectrum covering adequately the first MHz, as seen in Fig. 15. The face to face response of the V413 transducer and the response of a concrete specimen can be seen in Fig. 16(a) and (b) respectively. Although the driving electric signal consists of one cycle, it is clear that both the face to face and specimen response exhibit longer duration, fact that effectively reduces the bandwidth. Application of the calculation scheme introduced in [19] to the entire signals, results in phase velocity curve as seen in Fig. 17.

For the specific concrete specimen that was cut in two parts, phase velocities at the different frequencies were also measured from the time delay between a specific peak of the waveform collected from the intact and the one collected from the cut specimen with difference in wavepath 77 mm, see Fig. 6. The phase velocities measured for different central frequencies are also depicted in Fig. 17. It has been observed that isolating parts of the signals and specifically using the second cycle of both the face to face and specimen response, see bold lines of Fig. 16(a) and (b), provides a dispersion curve quite close to the phase velocity points measured. This was verified with other materials as metals and water, which are generally considered non-dispersive. Applying the phase measurement technique on the entire signal resulted in strongly dispersive curve while isolating one cycle, resulted in non-dispersive curves and velocity values close to the theoretical stress wave velocities for metal and water. Therefore, phase velocities presented herein were calculated using the second cycle of the waveforms after all other points are zeroed, as seen in Fig. 16. The unwrapping of the phase spectrum, which is involved in the calculation scheme, and corresponding group and phase velocity calculations were performed using standard built-in functions in MATLAB environment as well as with a simple code in Visual Basic indicating no discrepancies.

Phase velocity curves vs. frequency calculated as mentioned earlier for all examined materials do not exhibit qualitative differences with the above presented pulse wave velocities. Indicatively, the phase velocity of cement paste specimens show the same decreasing trend with the w/c ratio, while it seems frequency independent above 100 kHz as can be seen in Fig. 18. The same trend holds again for mortar and concrete as seen in Fig. 19(a) and (b) respectively. However, concrete phase velocity seems to undergo greater increase than mortar, starting at values between 3000 and 4000 m/s implying that it is a dispersive feature observed by means of this experimental setup that can be attributed to the increased inhomogeneity large aggregates impose. It is worth noting that the w/c = 0.40 and 0.425 classes

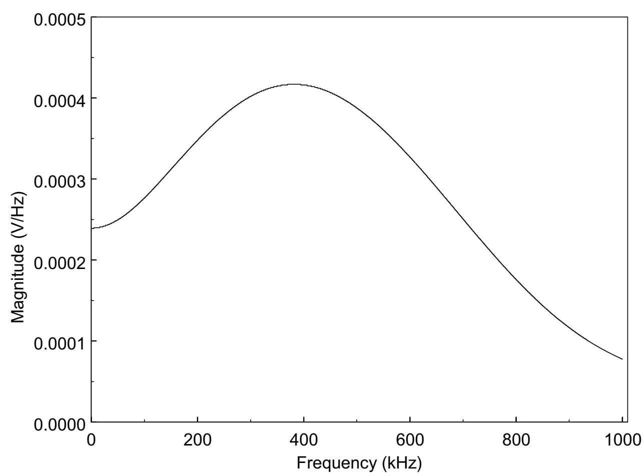

Fig. 15. FFT of 1 cycle of 450 kHz, used for phase velocity calculation.

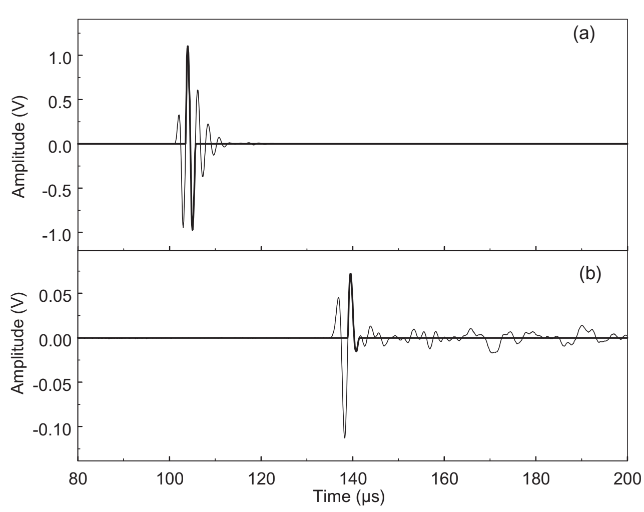

Fig. 16. (a) Sensor face to face and (b) concrete specimen response on the excitation of 1 cycle of 450 kHz. Bold line stands for the part of the signals selected for phase velocity measurements.

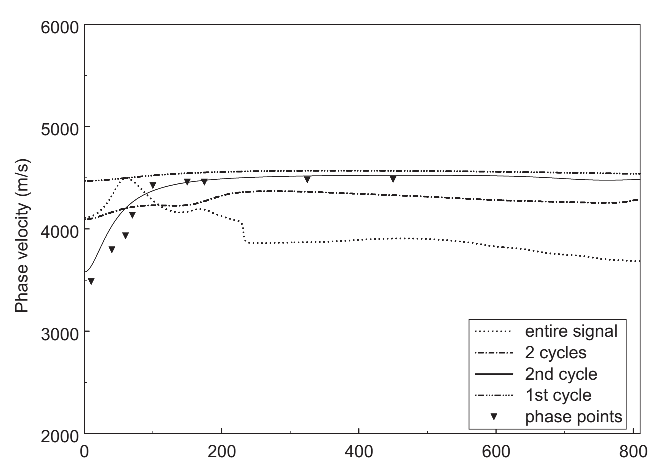

Fig. 17. Concrete phase velocity calculated using different parts of the signal.

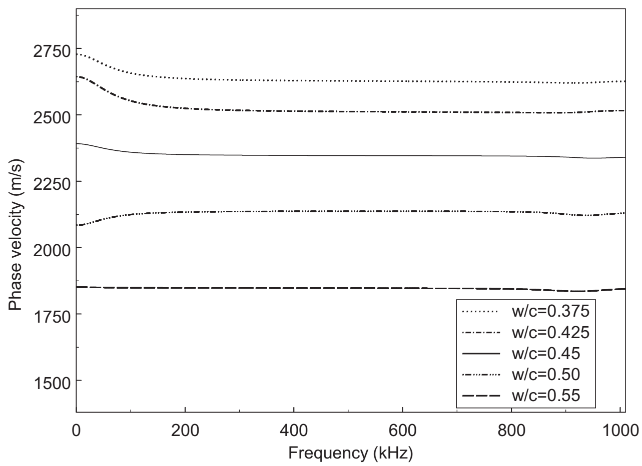

Fig. 18. Effect of w/c on phase velocity of paste.

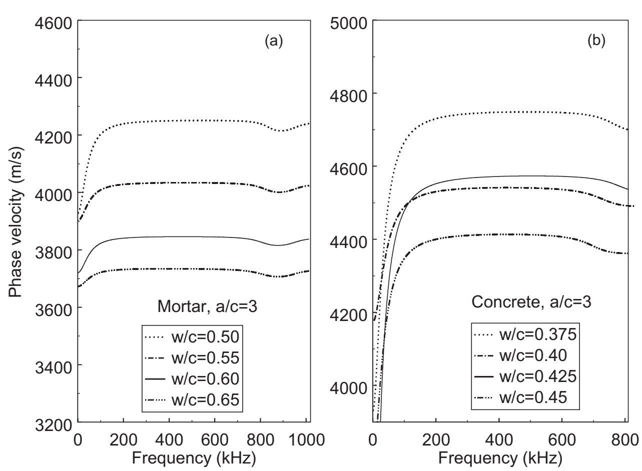

Fig. 19. Effect of w/c on phase velocity of (a) mortar and (b) concrete.

of concrete yield similar phase velocities also as was the case with their pulse velocities, indicating the correspondence between the pulse velocity measured through several different tone-bursts and phase velocity calculated using one cycle of one excitation pulse of 450 kHz as explained above. For most frequencies the calculated phase velocities exhibit lower values than the pulse. Specifically for paste the difference is generally somewhat lower than 100 m/s, for mortar it is about 150 m/s and for concrete the discrepancy is greater reaching 250 m/s. This discrepancy in phase and pulse velocity could also be interpreted as a sign of dispersion imposed by the increased level of inhomogeneity mortar and concrete contain.

5. Conclusions

In the present paper results from an experimental study of ultrasonic through-transmission measurements on cementitious materials are described. Narrow band pulses of different frequencies up to about 1 MHz are introduced into paste, mortar and concrete specimens allowing for direct measurement of pulse wave velocity and attenuation for each frequency while phase velocity was also calculated according to the technique introduced by Sachse and Pao [19]. Experimental investigations have shown that although specimen geometry influences velocity measurements, it is not the reason for the observed dispersion which is therefore attributed to the material itself. The results highlight the w/c influence being mostly evident on paste and mortar while the aggregate content is a decisive parameter in the propagation behavior of mortar and concrete. Following the comparison between mortar and concrete, the aggregate size seems to have a more definite impact on the attenuative behavior than on the pulse velocity while the observed slight dispersion at low frequencies seems to be originating from the inhomogeneous nature of mortar and especially concrete. Nevertheless, any difference in propagation parameters due to different design parameters of concrete, i.e. w/c, a/c and aggregate fineness, should be sought at frequencies above 100 kHz.

Acknowledgments

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