# Frequency Dependency of Elastic Wave in Cement-Based Materials with Artificial Damages

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**1. Introduction**: Stress wave has been used for many decades for the evaluation of concrete properties. Certain correlations have been observed between the wave parameters; especially pulse velocity and strength[1)] or damage[2)]. The energy or the amplitude of the waveform is reported to be more sensitive to inhomogeneity than velocity, in the form of specific macroscopic cracks[3)] or distributed inclusions and flaws in laboratory conditions[4)]. However, all observed correlations are only qualitative. Any characterization as for the general condition of concrete is based on empirical formulas and does not hold for any type of material[5)]. Incidentally, the inhomogeneity is enhanced by damage properties as well. Such parameters as the size, number and orientation of cracks complicate the interpretation of stress wave parameters, and they do not have the same interaction with any propagating wavelength. Study with different frequencies has thus been carried out, leading that cement-based materials behave in a more dispersive manner than metals. In the present paper, results of an experimental series on cement-based materials with distributed vinyl inclusions are described, namely the inhomogeneity is provided by small plate vinyl inclusions simulating distributed cracks. The wave propagation is discussed in terms of velocity dependence on inclusion content and frequency. Energy-related parameters are also examined since they are expected to be more sensitive to damage than velocity.

**2. Experimental Condition**: Wave measurements were conducted in through the thickness mode. As shown in **Fig. 1**, the experimental setup is a simple ultrasonic configuration. To cover the lower frequency band, AE sensors of 60 kHz resonance were used, whereas wideband sensors (1045S, Fuji Ceramics Corp) were employed for higher frequency. Artificial excitation ranging from 10 to 500 kHz was made with a function synthesizer (1910, NF Corp.), where the frequencies of 10, 30, 50, 80, 100, 150 and 200 kHz were used. The received signal was pre-amplified by 40dB, digitized with a sampling rate of 10MHz and stored in an AE acquisition system (Mistras 2001, PAC). The mortar specimens used were cubic of 150mm side. The W/C and S/C were set at 0.5 and 3 by weight, respectively. The grains size was chosen as smaller than 2mm to restrict the inhomogeneity of the matrix. Simulating cracks, small vinyl plates of size 30 x 30 x 0.2mm$^3$, were embedded in the mortar, where four different contents, namely 0%, 1%, 5% and 10% were examined.

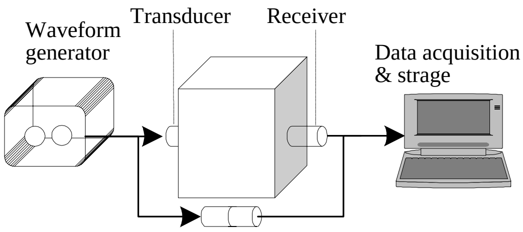


Fig. 1. Representation of experimental set up.

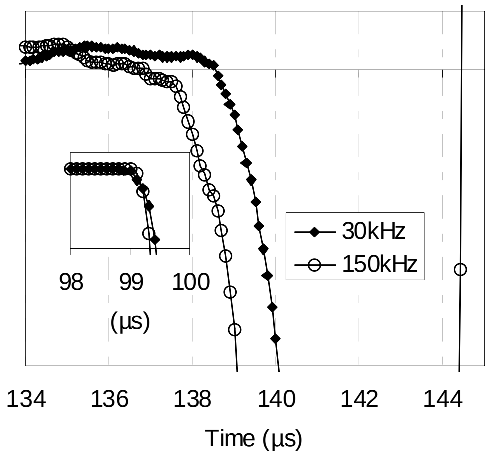


Fig. 2. Waveform onset for 10% inclusion.

**3. Results**: In **Fig. 2** an example of the onset of two waveforms is depicted. The onset of the 150kHz waveform obviously arrives earlier than of 30kHz. **Fig. 3** shows the pulse velocity for different types of material with excited frequency. Plain mortar shows a slight increase of velocity from less than 4100m/s to about 4200m/s up to 200kHz. The velocity becomes even higher values with the 500kHz excitation (approximately 4300m/s). Results with 5% and 10% inclusions show a clear decrease in velocity for any frequency examined. Surprisingly the velocity at low frequencies is very much influenced since for 10% inclusions it stands at 3300m/s, 800m/s lower than sound material. As the frequency increases though, the velocity increases, and at 500kHz, it is only 350m/s lower than sound material. This implies that cementitious material is expected to behave in a similar

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frequency-dependent way when actually damaged. In a cementitious material, aggregates, voids or cracks typically range in the order of mm up to cm, and provided that a velocity is 4000m/s, the wavelength of 10kHz is about 400mm, while for 500kHz the wavelength is less than 10mm. This suggests a common idea that shorter wavelengths (high frequencies) should be more critically influenced by the inhomogeneity in contrast to low frequencies. However, the above measurements show the opposite trend that is also met in the general field of particulate composites and are attributed to scattering mechanisms. **Fig. 4** shows a simple illustration of the displacement field for a long wavelength (a) and for a short wavelength propagation (b) through an inhomogeneous medium. The volume of the material vibrating under the transient excitation is large, containing a great number of inclusions (see a). Since the plastic inclusions (or cracks) have mechanical properties inferior to those of mortar, this decreases the "effective" modulus of elasticity, leading to lower velocity. As the frequency gets higher though, the wave interaction with inclusions is stronger, as can be seen in **Fig. 4**(b). A large part of energy is multiply reflected and redirected causing higher attenuation, and possibly delay in the transit time. However, a small part of energy is scattered in the forward direction or travels through the matrix alone. This part reaches the receiver earlier, resulting in higher velocity measurement. The amplitude of all different frequency pulses propagated through the materials is depicted in **Fig. 5**. The relative amplitude decreases for higher frequencies, specifically for each frequency, the order of amplitudes follows the inverse order of inclusion content. This decrease is much larger than that of velocity. As shown previously, the velocity of 10% inclusion specimen is decreased up to a percentage of 20% compared to the plain material; however, the amplitude decreases by orders of magnitude, being typically 30 times smaller than the sound mortar's amplitude. Furthermore, it is obvious that even 1% of inclusions can be distinguished from intact for any frequency, while that was not clear from the velocity measurements (see **Fig. 3**).

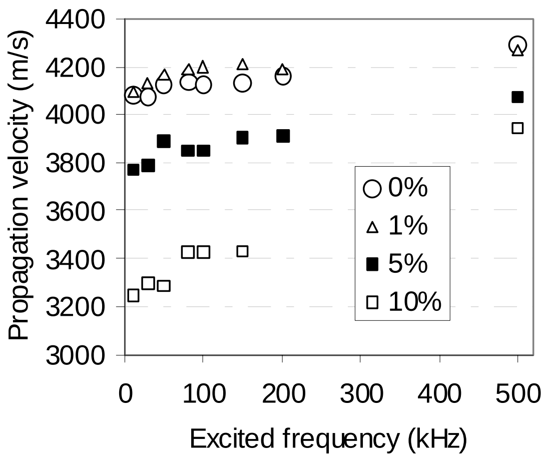


Fig. 3. Pulse velocity with excited frequencies.

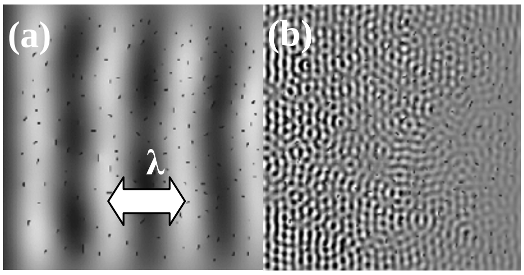


Fig. 4. Illustration of stress wave propagation.

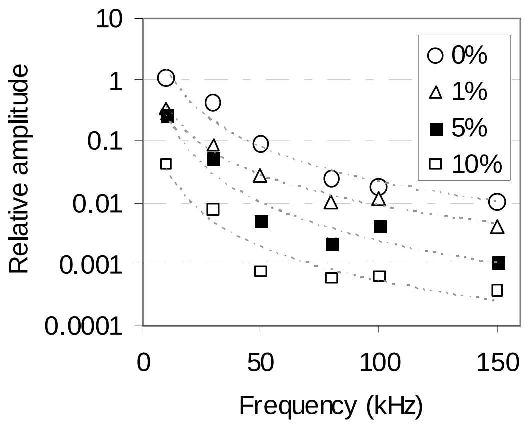


Fig. 5. Relative amplitude with frequency. Amplitude is normalized according to the face to face response of the sensors.

**4. Conclusion**: Measurement of velocity at different frequencies should be studied as an additional criterion to characterize the material damage. The same material may exhibit different velocity for pulses of different frequency even in the low frequency band that is applied for the actual tests. Energy-related parameters are more sensitive to the presence of damage. However, in actual monitoring such conditions as concrete surface, sensor-couplant and the applied pressure on the sensor can influence the received amplitude to a great extent, and therefore only when these parameters are adequately controlled in situ, energy related parameters would lead to enhanced characterization of damage.

**References**: **1)** Anderson, D. A. et al.: Pulse velocity as a predictor of 28- and 90- day strength, ACI J, Vol. 78-9, No. 2, pp. 116-122, 1981. **2)** Selleck, S. F. et al.: Ultrasonic investigation of concrete with distributed damage, ACI Mater J, Vol. 95, No. 1, pp. 27-36, 1998. **3)** Van Hauwaert, A. et al.: Use of ultrasonics to follow crack growth, Ultrasonics, Vol. 36, pp. 209-217, 1998. **4)** Otsuki, N. et al.: Influence of aggregates on ultrasonic elastic wave propagation in concrete, Non-Destructive Testing in Civil Engineering, Elsevier Science, pp. 313-322, 2000. **5)** Popovics, S.: Analysis of the concrete strength versus ultrasonic pulse velocity relationship, Materials Evaluation, Vol. 59, No. 2, pp. 123-130, 2001.