Experimental study of surface wave propagation in strongly heterogeneous media

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Abstract: In the present paper, the propagation of Rayleigh waves in a strongly heterogeneous medium is discussed. Scattering of stress waves is a difficult scientific problem. Specifically, the interaction of surface waves with distributed inhomogeneity seems highly complicated due to the existence of two displacement components. Rayleigh waves undergo significant attenuation and velocity change depending on the frequency and the inhomogeneity content. The aim of this study is to highlight the dispersive behavior of concrete, especially when damaged, and increase the experimental data in an area where the work is limited.

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1. Introduction

Stress wave propagation has long been used for characterization of cement-based materials. Although correlations between wave parameters like velocity or attenuation and strength or distributed damage have been observed, the results are always qualitative, based mainly on empirical formulas. One reason is certainly wave scattering due to the extremely inhomogeneous nature of the material that contains pores, air bubbles, sand grains, and aggregates as well as distributed cracks. The length scale of the above phases varies from micrometers to several centimeters, influencing the propagation of practically any frequency and complicating the interpretation of the results. In order to understand the mechanics of propagation in cementitious materials, stress wave dispersion in mortar and concrete has been studied.[1–3]

Focusing on Rayleigh waves, propagation has been studied for multilayered media,[4] or material with surface opening cracks and slots.[5] However, the propagation of Rayleigh waves in a medium with distributed scatterers has not been treated adequately for concrete or other materials, while the body wave scattering has been extensively studied.[6–8]

This paper presents experimental results of surface wave propagation in cement-based materials with randomly distributed and oriented thin inclusions. The aims are: To highlight the dispersive nature of cementitious materials, to make suggestions for more accurate material characterization, and to increase the experimental data of dispersion and attenuation in a specific area where the work is limited so far. The results show that wave propagation velocity depends on inclusion content and frequency while the effects of dispersion are even visible in the raw waveforms. Rayleigh wave parameters are much more influenced by inhomogeneities than longitudinal ones.

2. Experimental details

The experimental setup consists of three wide band piezoelectric transducers with high sensitivity up to 1 MHz. They were placed on the same surface of the specimen (cube of 150 mm side), in a straight line, with a center-to-center distance of 20 mm. The excitation was conducted 20 mm away from the first receiver by pencil lead break, which introduces frequencies up to at least 300 kHz. The small distances were selected due to the severe attenuation, which

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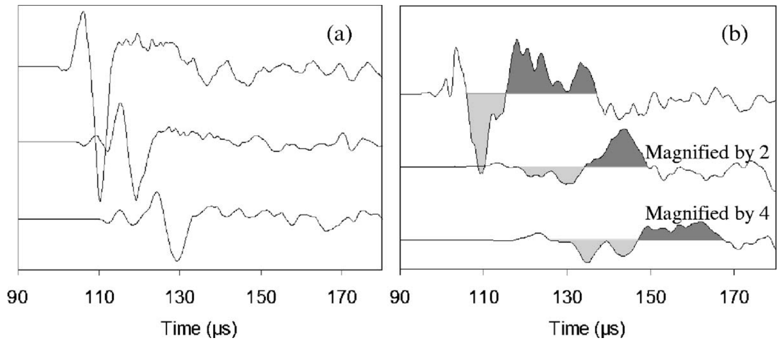

Fig. 1. Average of waveforms collected at 20 mm increments relative to the excitation source on the surface of mortar with inclusion content, (a) 0%, (b) 10%.

made signal acquisition troublesome for longer distances. The material was mortar with fine sand, and small vinyl plates were embedded during mixing at volume contents of 1%, 5%, and 10%. The presented results concern inclusions of dimensions $15\times 15\times 0.2$ mm. This shape resembles actual cracks more closely than the spherical inclusions used previously.[2] The acoustic impedance of mortar is approximately eight times higher than the impedance of the inclusions. Additionally, the major wavelength of approximately 20 mm (calculated using the major frequency peak and wave velocity) is comparable to the inclusion dimensions, potentially leading to strong scattering phenomena. The coupling between the sensors and the mortar surface was enhanced by roller bearing grease and no pressure was applied on the sensors in order to minimize any influence on the propagating wave.

3. Inhomogeneity effect on time domain waveforms

Before discussing propagation velocity and attenuation, it is interesting to note the remarkable degree of distortion visible in the time domain signals. Waveforms collected at different locations of a strongly heterogeneous medium are certain to exhibit discrepancies. However, averaging of individual waveforms reveals the common pattern (coherent field). In Fig. 1(a), the averages of waveforms collected by each receiver on a plain mortar specimen are depicted. A strong Rayleigh cycle follows after the initial longitudinal arrivals. Due to the inhomogeneous nature of mortar itself, the Rayleigh cycle becomes more rounded as the wave travels across the surface. Nevertheless, it is clearly visible in all three waveforms.

In the case of mortar with 10% inclusions, which is depicted in Fig. 1(b), the first receiver (20 mm from the source) reveals a highly distorted Rayleigh cycle, while for longer distances multiple peaks are observed. The distortion is likely the result of the distribution of energy in multiple paths. In a homogeneous medium the wave energy travels in a straight line [see Fig. 2(a)] and a reference Rayleigh point [e.g., the strong negative peak in Fig. 1(a)] is visible in all the waveforms. However, as the inhomogeneity increases, the presence of the scatterers distributes the energy to various paths with different length [see Fig. 2(b)]. Therefore, the waveform distorts and a single transit time cannot be easily identified. This can be discussed in terms of the wavelength to inclusion size ratio. Using the major frequency peak and wave velocity, the wavelength, λ, is calculated to be approximately 20 mm, and the sand grains of size less than 3 mm are not expected to strongly influence the wave. On the other hand, the plastic inclusions, which are 15 mm long in two dimensions, seem to cause strong interactions. Note that the central frequency (calculated as the centroid of the fast Fourier transform) is 108 kHz for plain mortar, while for mortar with 10% inclusions it is reduced to 88 kHz for the same propagation distance of 60 mm.

Although the inclusion content of each specimen was strictly controlled in total, it is reasonable that the small volume examined at each individual measurement exhibits variations in the number of inclusions and their orientation. The different arrangement of the scatterers

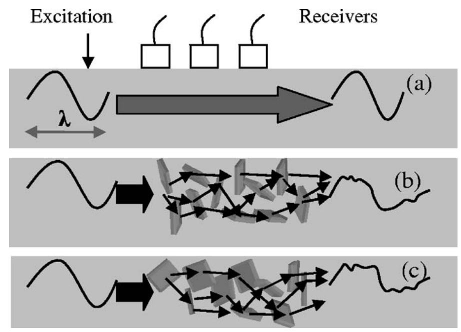

Fig. 2. Propagation in a medium with (a) no scatterers, (b) distributed scatterers, (c) different arrangement of distributed scatterers.

results in different waveforms [see Fig. 2(c)]. To highlight the effect of local variation, a number of individual waveforms for each material are shown in Figs. 3(a) and 3(b). Each waveform was recorded at a different point on the surface, but at the same distance from the excitation. In the case of Fig. 3(a), the waveforms come from plain mortar. It is seen that the change in measurement position causes no serious distortion. The Rayleigh cycle is always identified at the same time. This is a result of the limited local variations in the structure of mortar. In Fig. 3(b), where the case of material with 10% inclusions is concerned, the waveforms exhibit almost no similarities. This is due to strong local variations of the material structure that make any travel path unique. However, averaging the waveforms reveals a weak coherent field, as presented earlier in Fig. 1(b).

The above results are a manifestation of the dispersion induced by the inclusions. They imply that as damage is accumulated in concrete, the material behaves increasingly like an inhomogeneous medium. Therefore, interpretation of ultrasonic data based on homogeneous assumptions should be enhanced or modified in order to provide a wealth of new information in the field of concrete damage characterization.

4. Velocity results

Measuring the transit time of the leading edge of a waveform as it propagates between different receivers leads to the calculation of "pulse velocity". This parameter is widely used in nondestructive testing of concrete, being indicative of the velocity that the energy propagates, although it cannot be defined either as phase or group velocity. However, it is commonly accepted that it corresponds to longitudinal waves. Calculation of this parameter reveals that the increase of plastic inclusions has a decreasing effect on pulse velocity [see Fig. 4(a)]. The longitudinal

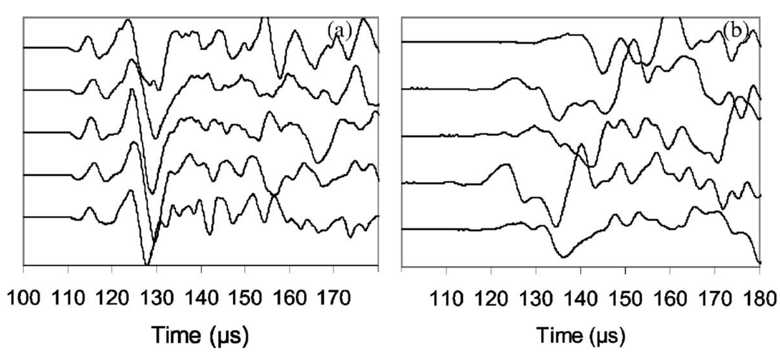

Fig. 3. Waveforms collected at different positions on the surface of mortar with inclusion content, (a) 0%, (b) 10%. The distance from the source is 60 mm.

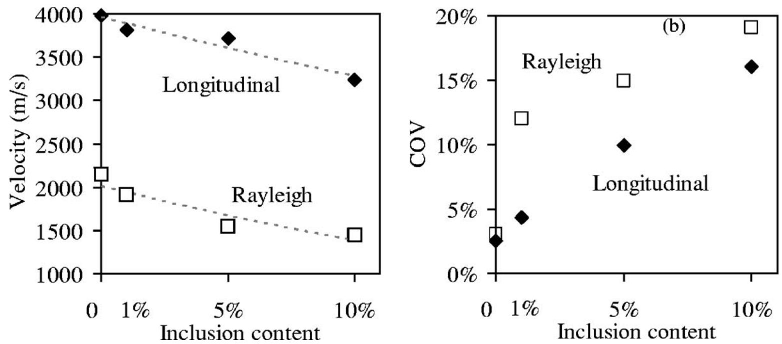

Fig. 4. Influence of vinyl inclusion content on (a) wave velocity and (b) experimental scatter of velocity measurements on mortar.

velocity decreases from almost 4000 m/s, in the case of plain mortar, to 3239 m/s for mortar with 10% inclusions, or suffers a decrease of approximately 18%. This is the average value calculated from 20 individual measurements on the surface of each specimen. It is worth noting that the experimental scatter clearly increases with the inclusion content. In Fig. 4(b) the coefficient of variation, COV (the standard deviation of the twenty measurements divided by the average value) is depicted vs the inclusion content. For the case of plain mortar the variation is quite low (approximately 2.5%), as a result of the uniformity of the material. The addition of inclusions increases COV up to 16%. This trend is another manifestation of the local variations in the composition and arrangement of the material.

Concerning Rayleigh waves, for no or low inclusion content a reference point can be identified in all cases, as mentioned earlier. However, there is no common reference in the signals from the 5% and 10% specimens, complicating velocity measurements. Therefore, cross-correlation between the signals collected from the first and third receiver was used. The resulting time lag can be considered as a measure of the transit time of the major part of the energy between the two transducer positions. This way, although a specific Rayleigh cycle is not always identified, a measure of energy velocity is available. The results again show a decreasing trend as the inclusion content increases. Inhomogeneity clearly diminishes the velocity from 2141 m/s for plain mortar to 1450 m/s for 10% of inclusions, as seen in Fig. 4(a). The decrease of 32% shows that Rayleigh wave propagation is more influenced by inhomogeneity than longitudinal waves.

The difference in the behaviors of longitudinal and Rayleigh wave velocities seems peculiar for an elastic material. According to well-established relations used for concrete,[4] this change of longitudinal to Rayleigh velocity ratio could be explained by a dramatic increase of Poisson's ratio from 0.24 for plain to 0.35 for "damaged" mortar, that is highly unlikely. The greater decrease of Rayleigh velocity is more likely the result of its propagation mechanics, including displacement components in two directions, which make it more sensitive to the existence of scatterers.

The experimental scatter of Rayleigh velocity values increases with inhomogeneity and is certainly higher than that of longitudinal waves. It is worth mentioning that, although for plain mortar the Rayleigh velocity COV is similar to the longitudinal waves' one, for material with just 1% of inclusions it becomes 12.3%, increasing up to almost 20% for high inclusion content.

5. Rayleigh phase velocity

The above-mentioned results concern the propagation velocity of the whole pulse. Since the medium is strongly inhomogeneous, each frequency component could be influenced in a different way, imposed by the content and size of the scatterers. The pulse used contains energy up to 300 kHz and it is interesting to examine how each frequency component behaves. Therefore,

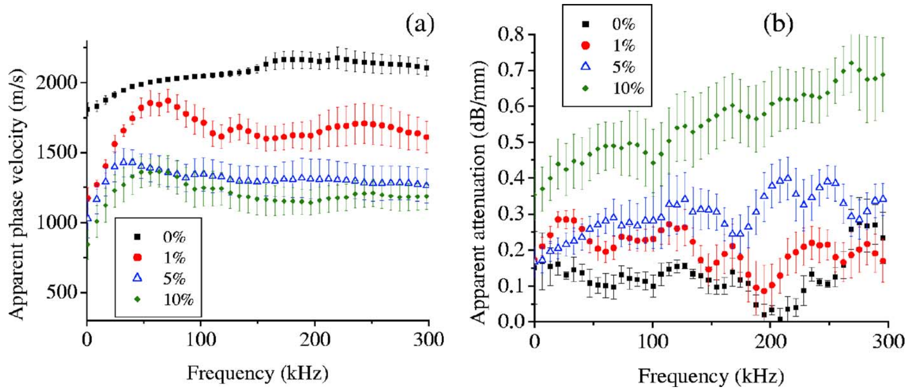

Fig. 5. (Color online) (a) Rayleigh dispersion curves and (b) attenuation curves for different inclusion content of mortar. The error bars stand for the standard deviation.

the frequency dependent phase velocity should be calculated. This is not trivial, since dispersion hinders the identification of a particular portion of the wave, such as the Rayleigh contribution.[9]

However, the energy of the Rayleigh waves is much higher than the other contributions and, therefore, isolating a part of the signal where the Rayleigh is expected, can yield information about this wave type with very little influence from other types. In this case, a window of 30 μs around the major Rayleigh arrivals was isolated and the rest of the waveform was zero-padded, as presented in other cases.[9] Using fast Fourier transform, the phase of the waveform was calculated and unwrapped. Therefore, the phase difference between waveforms collected at different distances from the excitation (i.e., the first and third receiver) leads to the calculation of phase velocity versus frequency curve.[10] The results are depicted in Fig. 5(a) for different materials. Each curve is the average of 20 individual curves, while the error bars stand for the standard deviation and increase with inclusion content, as expected. It is seen that plain mortar exhibits dispersive behavior, with velocity increasing up to about 200 kHz, as has been observed recently for the longitudinal velocity of cementitious materials.[1,2] The increased inhomogeneity induced by the plastic inclusions influences the velocity behavior more strongly. Material with 10% inclusions exhibits the lowest curve, but even 1% of vinyl lowers the curve considerably, compared to plain mortar.

Focusing on the shape of the curves, one detail is worth mentioning. At lower frequencies, the curves exhibit high gradients. However, above 100 kHz the changes are not as abrupt. This is a trend mentioned in many different multi-phase systems. Composites of solids in solids, or suspensions of solids in liquids exhibit similar trends.[7,8,11] At lower frequency bands the velocity exhibits changes, and possibly many resonance peaks. However, at higher frequencies phase velocity seems to converge to a value closer to the velocity of the matrix material. This trend is explained by scattering theory when body waves are concerned. However, in the present case a theoretical treatment is more complicated.

6. Attenuation

In order to obtain information concerning material damage, the attenuation behavior is studied complementary to the velocity. The presence of inhomogeneities increases the attenuation, mainly due to the redistribution of the energy to directions different from the receiver direction. Strongly inhomogeneous media are known to exhibit more dramatic variations in attenuation than in velocity. As seen earlier, inhomogeneity may result in velocity decrease of 30% compared to the velocity of the matrix [see Fig. 4(a)]. However, attenuation may increase even by orders of magnitude, as has been observed for many composite systems[8] and concrete.[12] The material attenuation is the combination of different mechanisms. In the present study the total attenuation $\alpha(f)$ was calculated by

$$\alpha(f) = -\frac{20}{x}\log\left(\frac{A_1(f)}{A_3(f)}\right), \tag{1}$$

where f is the frequency, $A_1(f)$ and $A_3(f)$ are the spectra from the first and third sensor respectively, with a separation distance $x=40$ mm.

As seen in Fig. 5(b), plain mortar exhibits the lowest attenuation while material with inclusion content 10% is more attenuative for the entire band.

It is noted that the attenuation of "damaged" is many times higher than the one of sound material. Even for material with only 1% inclusions the attenuation is certainly increased, making this feature suitable for characterization of slight damage in cases where the velocity exhibits small or no sensitivity.[12] This discrepancy increases with frequency. Therefore, higher frequencies are more powerful for characterization, but only in laboratory conditions so far. In large structures attenuation makes the acquisition and interpretation of stress wave data troublesome.

Another worth mentioning detail concerns the compatibility of dispersion and attenuation curves. Considering the Kramers–Kronig relations, a rapid increase of phase velocity [e.g., as in the lowest 50 kHz of Fig. 5(a)], should be accompanied by a clear attenuation peak within the same frequency bandwidth.[13,14] However, this is not observed for all the attenuation curves of Fig. 5(b). This can be partially attributed to the errors bars, which could mask an attenuation peak, especially for material with 10% inclusions. Another reasonable explanation though, is that the material does not behave linearly (the response is not proportional to its stimulus). Linearity is a condition for the validity of the Kramers–Kronig relations,[13,14] but cementitious materials have been reported to exhibit strongly non-linear behavior.[15] Of course, the Fourier spectroscopy approach assumes linearity, so if nonlinearity is a major issue, the attenuation coefficient and phase velocity determinations may not be perfectly valid. Hence, we have labeled these as the "effective velocity and attenuation spectra".

7. Conclusion

This paper presents experimental results of surface wave propagation through a strongly inhomogeneous medium with randomly distributed and oriented thin inclusions. The main observations concern the strong Rayleigh velocity dependence on frequency and inclusion content, the waveform distortion, and the frequency downshift which results in higher attenuation with increasing frequency. Additionally, the inclusions obstruct Rayleigh waves more strongly than longitudinal. This dispersive behavior is due to contributions from scattering, visco-elastic and microstructure mechanisms, making the theoretical investigation highly complicated. However, the experimental study of scattered waves' characteristics can provide additional correlations with damage, since the crack content leaves its signature on the propagating waveforms, dispersion, and attenuation curves. A next step of particular interest is to compare the influence of different shape and size of inclusions on the Rayleigh parameters.

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