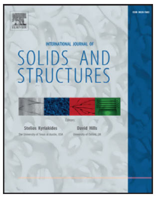
International Journal of Solids and Structures 78-79 (2016) 149–159

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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



Wave dispersion in fresh and hardened concrete through the prism of gradient elasticity

Sokratis N. Iliopoulos[a,*], Dimitrios G. Aggelis[a], Demosthenes Polyzos[b]

[a] *Department of Mechanics of Materials and Constructions, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium*
[b] *Department of Mechanical Engineering and Aeronautics, University of Patras, 265 04 Rio, Patras, Greece*

ARTICLE INFO

Article history:
Received 17 June 2015
Revised 25 August 2015
Available online 19 October 2015

Keywords:
Concrete
Fresh
Hardened
Acoustic Emission
Ultrasonic testing
Wave dispersion
Phase velocity
Strain gradient elastic theory
Non-local lattice model
Micro-stiffness
Micro-inertia

ABSTRACT

The determination of the early age concrete properties and the monitoring of their evolution is the key point for an optimized construction with assured high quality. To this direction, the ultrasonic nondestructive testing technique is highly promising since it gives feedback on the mechanical properties and damage condition, allowing for the continuous interrogation of the material. It has experimentally been observed that concrete at both its fresh and hardened state exhibits a significant dispersive behavior concerning longitudinal ultrasonic pulses. Analytically, only few attempts have been made to explain this low-frequency change of phase velocity through the development of enhanced elastic theories. The most commonly used higher order theory is the simple strain gradient elastic theory which takes into account the microstructural effects in heterogeneous media like concrete. These microstructural effects are described by two internal length scale parameters g and h which correspond to the micro-stiffness and micro-inertia, respectively. In the present paper, it is shown that this simplest possible version of the general gradient elastic theory proposed by Mindlin can effectively describe the velocity dispersion of fresh and hardened concrete specimens with various water and sand contents. Moreover, it is here found that micro-inertia is dominant in fresh concrete while, on the other hand, micro-stiffness dominates the hardened concrete, which suggests that gradient elasticity can be successfully applied for the monitoring of the setting process of the above mentioned material. To overcome the fact that the considered strain gradient elastic model cannot attribute geometrical and mechanical properties of the microstructure to the microstiffness and microinertia terms, a non-local lattice model is adopted. Using that model, which reproduces the same differential wave equation as the one dimensional strain gradient elastic model, the derived Mindlin's microstructural coefficients are directly linked to the characteristic size of the microstructure. Finally, using the lattice model, it is made clear that prior knowledge of the dominant microstructural coefficient values accompanied by the mechanical and physical properties of the concrete matrix and aggregates, explicitly provides, among others, the interparticle distance l, the mean diameter of the inclusion as well as a measure of the intensity of nonlocal effects.

1. Introduction

Among the existing nondestructive testing methods, which exploit wave propagation for inspection purposes, it can be said that ultrasonic testing (UT) and acoustic emission (AE) are the most widely used techniques for quality characterization of concrete at its fresh and hardened states (Malhotra and Carino 1991; Uomoto, 2000; Shiotani et al., 2004; Mpalaskas et al., 2014; Trtnik and Gams, 2014). Concrete can be considered as a composite material where large aggregates (5 to 30 mm) are embedded in a mortar matrix, while the mortar consists of small aggregates (0.1 to 5 mm) dispersed in a cement paste medium. This description reveals that concrete is a highly non-homogeneous material with a complex microstructure containing random inhomogeneities over a wide range of length scales. Therefore, ultrasonic wave propagation in cement-based materials is a complicated process and understanding of how a stress wave propagates through such a medium is of paramount importance for the aforementioned non-destructive testing techniques.

Many studies have been published concerning ultrasonic wave velocity measurements in concrete materials and structures. However, quite a small number of them are occupied with experimental evidence of the dispersive nature of the material. It has been shown that concrete exhibits more dispersive behavior compared to cement paste, mortar and steel (Kim et al., 1991) since its phase velocity varies more around the average value for frequencies 0–10 MHz. Also, Owino and Jacobs (1999) have shown that surface wave pulses

---

* Corresponding author.: Tel.: +32 26292983; fax: +32 26292928.
E-mail address: Sokratis.Iliopoulos@vub.ac.be, sociil069@hotmail.com (S.N. Iliopoulos).

http://dx.doi.org/10.1016/j.ijsolstr.2015.09.005
0020-7683/

recorded at different distances from the source on mortar specimens are different in time and frequency domain, constituting a dispersive feature attributed to the inhomogeneous nature of the material, since similar aluminum specimen do not exhibit the same behavior. Apart from that, concrete pulse velocity has been found frequency dependent for the range of 24–120 kHz (Popovics et al., 1990). Experiments performed in Philippidis and Aggelis (2005) show that traveling longitudinal waves in concrete as well as in mortar undergo dispersion only at low frequencies where the material microstructure is much smaller than the wavelength of the incident wave. On the contrary, longitudinal pulses propagating in cement paste do not exhibit significant dispersive behavior. Similar trends as to low frequency dispersion of concrete have also been noticed for longitudinal (Chaix et al., 2006) and Rayleigh waves (Aggelis and Shiotani, 2007). The dependence of velocity on frequency at low ranges (below 200 kHz) bears extreme practical interest since in situ tests usually employ sensors from 24 kHz to 120 kHz. The mainly experience-based correlation of concrete strength with wave velocity (ASTM C597) does not include frequency correction features meaning that deviations in measurements due to different sensor used could be wrongly attributed to the state of the material.

Several theories dealing with continuum and discrete models have been used so far for the dynamic behavior of concrete. The simplest one treats concrete as a macroscopically homogeneous linear elastic material: (Reynolds et al., 1978; Hernandez et al., 2000; Wu and Liu, 1998; Landis and Shah, 1995; Popovics et al., 1998; Rhazi et al., 2002; Malhotra and Carino, 1991; Otsuki et al., 2000). Although simple and practical, it is not able to capture the aforementioned dispersion and attenuation phenomena in concrete.

Since concrete structures undergo creep deformations, many investigators considered concrete as isotropic viscoelastic material with Lame constants being frequency dependent. Another manifestation of concrete viscoelastic behavior is the higher values of the dynamic modulus of elasticity, obtained by pulse velocity or vibration techniques compared to the static one (Malhotra and Carino, 1991; Neville, 1995; Mehta and Monteiro, 2001). Fan et al. (2013) conclude that concrete under dynamic loading behaves as viscoelastic material, while it is nonlinear viscoelastic under quasi-static conditions. Experiments on similar materials like asphalt concrete or rubber concrete have also shown that the dynamic modulus of elasticity rises with frequency (Hernandez-Olivares et al., 2002; Hochuli et al., 2001). Different visco-elastic models have been used (Mehta and Monteiro, 2001; Hildebrand, 2002; Panneerselvam and Panoskaltsis, 2002) in order to fit experimental data mainly concerning the creep behavior. However, the problem with viscoelastic models is that most of them predict phase velocities increasing with frequency, which is true only for the case of hardened concrete. Besides, they do not provide internal length scale parameters that correlate the microstructure with the macro-structural behavior of cement-based materials.

Another possible explanation of wave dispersion in concrete is the multiple wave scattering phenomena. When a stress wave propagates through a non-homogeneous material undergoes both dispersion and attenuation due to its multiple scattering by the randomly distributed inhomogeneities (Tsinopoulos et al., 2000; Verbis et al., 2001; Aggelis et al., 2004b). In many works appearing so far in the literature for cementitious materials, scattering has been considered as the basic mechanism affecting wave propagation (Jacobs and Owino, 2000; Anugonda et al., 2001; Kim et al., 1991; Landis and Shah, 1995; Chaix et al., 2012; Aggelis et al., 2005; Otsuki et al., 2000). Although wave scattering theories provide in many cases good predictions for wave dispersion and attenuation in cement-based materials, they introduce many material and geometric parameters which render any inversion process a very difficult and time consuming task. Nevertheless, different types of scatterers are active exercising influence at different wavelengths. Aggregates, considered “tenuous” scatterers do not seem sufficient to explain the dispersive trends exhibited at the low frequency regime, while scattering on voids (entrapped air bubbles or light inclusions) seem to closer explain the ultrasonic behavior of hardened or fresh concrete (Mpalaskas et al., 2014; Punurai et al., 2006; Aggelis et al., 2005).

Ten years ago, Ulm et al. (2004) published a paper where they reached to the conclusion that cementitious materials can be considered as poroelastic materials and utilizing advanced homogenization techniques they provided estimations for stiffness, Biot and Skempton coefficients of cement paste, mortar and concrete without providing any information on the dynamic behavior of those materials. Sayers and Dahlin (1993) observed that as the cement paste hydrates forming interconnected solid phase the material behaves as saturated porous medium and the propagation of ultrasonic waves can be facilitated through Biot’s theory. However, there is not so far (to authors’ best knowledge) any experimental evidence that renders Biot theory adequate to explain wave dispersion in all types of cementitious materials.

The failure of the aforementioned theories to establish internal length scale parameters that correlate explicitly the macro-structural dynamic behavior of a non-homogeneous material with its microstructure, gave the impetus to many investigators to turn their attention to generalized continuum theories such that of Cosserat elasticity (Cosserat and Cosserat, 1909), couple stresses (Toupin, 1964; Koiter, 1964), multipolar elasticity (Green and Rivlin, 1964), strain gradient elasticity (Mindlin, 1964, 1965), micromorphic, microstretch and micropolar elasticity (Eringen, 1999) and non-local elasticity (Eringen, 1992). Historical reviews as well as comments on those theories can be found in Tiersten and Bleustein (1974), Eringen (1992), Vardoulakis and Sulem (1995), Tsepoura et al. (2002), Exadaktylos and Vardoulakis (2001) and Askes and Aifantis (2011) while some examples where generalized elastic theories are utilized for cement-based and granular materials are those of Monteiro and Lubliner (1989), Metrikine (2006), Aggelis et al. (2005), Papargyri-Beskou and Mylonakis (2009), Oliver et al. (2012), Triantafyllou and Giannakopoulos (2013) and Polyzos et al. (2015).

In the present work, the strain gradient elastic theory introduced by Mindlin (1964) is employed in order to explain the dispersion of longitudinal ultrasonic pulses in fresh and hardened concrete. Mindlin’s theory, in its simplest form, describes linear elastic behavior with microstructural effects by introducing two intrinsic lengths, one for stiffness and one for inertia, that give a measure of the area of microstructure that influences macrostructure and is responsible for the dispersive behavior of longitudinal and transverse waves propagating in nonhomogeneous materials. Many works dealing with wave propagation phenomena in gradient elastic materials have appeared in the literature. Representatives are those of Vardoulakis and Georgiadis (1997), Fish and Chen (2004), Georgiadis et al. (2004), Papargyri-Beskou et al. (2009), Vavva et al. (2009), Dontsov et al. (2013), Berezovski et al. (2013), Greene et al. (2012), Gonella et al. (2011), Salupere and Tamm (2013), Lim et al. (2015) and Hui and Oskay (2014). The key idea of the present study is that a proper determination of the two microstructural material constants enables one to explain remarkably well the observed low frequency dispersive nature of both fresh and hardened concrete.

The Mindlin’s strain gradient elastic theory as well as almost all the aforementioned enhanced theories have been developed via elastic continuum considerations by adding new terms either in the expressions of potential and kinetic energy or in the constitutive equations. Thus, although the dimensions of the new intrinsic parameters are defined, their correlation with the size of the micro-structure is not explicitly provided. This is made possible using discrete lattice models (Metrikine and Askes, 2002; Polyzos and Fotiadis, 2012; Iliopoulos et al., 2015) as it is also presented in this paper. Lattice models compared to continuum ones have the advantage of taking into account microstructural effects more accurately by combining all the geometric and material characteristics of the micro-structure