ULTRASONIC PROPERTIES OF ANCIENT CERAMIC MATERIALS WITH POROUS STRUCTURE

LUMINITA MORARU, FLORICA SZENDREI

"Dunarea de Jos" University of Galati, Faculty of Science, 800201, Galati, Romania

Abstract. *This paper reports a new method of estimating mechanical properties of ancient ceramic materials from the ultrasonic properties. The methodology is based on the observation that the ratio of normalized value of Young's modulus is a function of porosity only and varies with longitudinal velocity. The ultrasonic velocity measurements have been used as a non-destructive means to determine the moduli of materials. It may be mentioned here that sometimes the measurement of ultrasonic properties of ceramic fragments creates difficulties due to fragility of the compact. The applicability of the method has been evaluated in terms of experimental data reported in the literature.*

Keywords**:** *ultrasound, ancient pottery, porosity, mechanical properties.*

1. INTRODUCTION

It is well known [1] that ultrasonic velocity variation in porous material is dependent both on the amount of porosity and pore geometry. Thus porosity dependence of ultrasonic velocities and elastic properties of porous material have been the subject of extensive research over the last few decades leading to a large number of theoretical and empirical relations correlating porosity with ultrasonic velocities or moduli.

Theoretical relations are usually derived from the theories of two-phase materials by considering the stiffness of the included phase to be zero. The multiple scattering theories of Waterman and Truell [2] and Ying and Truell [3] have been widely used to treat the ultrasonic propagation characteristics of two-phase materials consisting of spherical scatterers. Sayers and Smith [4] have solved these equations numerically for porous solid but found that they give unphysical results for high porosity. They proposed a self-consistent theory which could be solved analytically and it gave reasonable behavior at high porosity. The self-consistent [5–8] and differential methods [9] have also been widely used in developing elastic moduli-porosity relations in porous solids. They essentially provide a method of approximately extending the exact analytical solution for small fraction of spherical or ellipsoidal pores to higher porosities.

We used this method that correlates the ultrasound velocity and mechanical properties to analysis the ancient pottery. This non-destructive analysis offers a way to get information on the process and even sometimes on the date of ancient artifacts. These relations can only be useful in analyzing post-product behavior when the microstructural details are known. We used previous SEM data for image analysis, digital scaling and measurement of the pores dimensions. For this analysis, at each sample have been made 50 digital measurements on a scattered randomly distribution in the sample picture field [11].

2. MODEL OF ULTRASONIC WAVE PROPAGATION

An ultrasonic wave propagation model in porous ceramics body was proposed by Ishihara *et al.* taking account of wave-pore interaction process [10]. The following assumptions are made in deriving the analytical procedure:

a. Pores are uniformly distributed and oriented so that the material can be considered isotropic on a macroscopic scale.

b. Spherical pores with a radius *r*

c. Pores are filled with air whose bulk modulus is negligible.

d. Fine, relative homogenous and oriented texture of the ceramic fragments with uniform pore distribution.

In the model, ultrasonic waves are propagated in a porous body through interactions with pores. If a wave comes into collision with a pore, it will go forward creeping through the pore edge with some probability. The creeping wave has a time delay in comparison with a direct wave without collision. Ultrasonic waves are propagated into the body through interactions with a great number of pores. The propagated waveform through a great number of pores in the body can be calculated by a statistical method with cumulating of the time delay and the collision probability for the pores. The waveform, as a result, can be expressed in the Gaussian function as a function of propagation time [11]. The ultrasonic wave characteristics must be effective to evaluate inner stress condition of the ancient ceramic by considering the wave-pore interaction process. As a result of this propagation analysis, the Young's modulus *E* of the porous body is evaluated as a normalized value by that of the ideal polycrystals E_i [10].

$$\frac{E}{E_i} = \frac{1-f}{\left[1+\frac{3f(\pi\beta/\alpha-2)}{8}\right]^2}$$

3. EXPERIMENTAL DATA

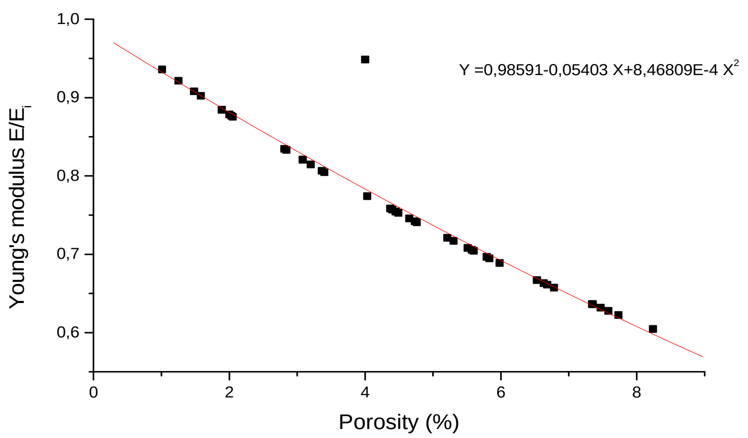

Fig. 1. Young's modulus E of the porous body as a normalized value by that of the ideal polycrystals E_i versus porosity.

Table 1 shows the measured values of ultrasonic velocity, density and porosity for the ceramic samples.

Table 1. The ultrasonic porosity, velocity and density for the ceramic samples

Sample no.	d [mm]	f [%]	c [m/s]	ρ [g/cm^3]
3	6,10	5,52	5332	1,82
4	9,70	4,01	5415	2,73
5	7,46	4,74	5370	1,82
6	10,00	5,84	5303	2,13
8	12,06	4,50	5385	2,33
10	10,26	3,41	5451	2,60
11	8,00	8,25	5165	1,66
12	9,12	3,37	5454	2,57
13	5,58	7,36	5210	2,43
15	5,80	7,59	5196	1,84
16	5,58	6,69	5251	1,71
19	5,50	2,04	5535	2,38
20	4,02	4,38	5392	1,54
21	7,00	1,49	5569	1,67
22	5,12	7,74	5187	2,00
23	13,00	6,54	5260	2,31
24	9,80	1,90	5544	3,19
25	9,02	4,04	5413	1,83
26	10,70	4,46	5390	2,29
27	11,04	5,31	5335	1,49
28	8,54	1,90	5548	1,71
29	10,28	2,06	5530	1,47
30	8,58	2,82	5487	2,32
31	9,50	4,41	5393	2,41
33	4,80	5,99	5294	1,65
34	4,72	5,22	5339	2,42
35	5,00	1,59	5570	2,31
36	12,66	6,64	5260	1,65
37	9,58	3,09	5470	1,64
38	10,66	1,26	5585	1,75
39	8,14	1,02	5599	1,80
40	6,82	5,61	5315	4,78
41	6,50	7,35	5211	2,00
43	11,22	4,77	5369	1,77
44	3,54	7,48	5190	2,35
45	8,00	4,66	5382	1,74
46	8,14	5,80	5300	1,63
47	12,80	3,21	5473	2,88
48	8,20	3,09	5460	1,87
50	4,88	6,79	5255	2,60
51	5,18	5,58	5336	3,06
52	9,00	4,46	5392	1,64
53	7,00	2,01	5531	2,09
54	6,50	2,85	5488	2,66

The sample density ρ(= 2148 ± 1005 kg·m^{-3}) was measured by Archimedes' method using distilled water as a flotation fluid. Based on the analytical procedure described here ultrasonic velocity variation with porosity (relative density = 1-*f*). The density of the sample is 95% and porosity around 5%. SEM analyses showed that the pores are irregularly shaped with a maximum size less than about 5.90 μm and randomly distributed in the ceramic. It is used $4Lp = 2\pi r$ a perimeter of the pore and $\alpha = V_c / V_p = 0.65$.

The relation between the Young's modulus E of the porous body, evaluated as a normalized value by that of the ideal polycrystals E_i and the porosity, is presented in Fig. 1.

4. CONCLUSIONS

This paper presents a semi-analytical procedure based on the theories of physical acoustics and predicts mechanical characteristics from ultrasonic velocity variation. The ultrasonic velocity variation in porous material is dependent both on the amount of porosity and pore geometry and it correlating porosity with Young's modulus E. However, the ultrasonic properties of the theoretically dense or pore-free material must be known. The study shows that the normalized value of Young's modulus is a function of porosity. This non-destructive analysis offers a way to get information on the process and even sometimes on the date of ancient artifacts.

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