Marble ageing characterization by acoustic waves

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Abstract

In cultural heritage, statue marble characterization by acoustic waves is a well-known non-destructive method. Such investigations through the statues by time of flight method (TOF) point out sound speeds decrease with ageing. However for outdoor stored statues as the ones in the gardens of Chateau de Versailles, ageing affects mainly the surface of the Carrara marble. The present paper proposes an experimental study of the marble acoustic properties variations during accelerated laboratory ageing.

The surface degradation of the marble is reproduced in laboratory for 29mm thick marble samples by using heating/cooling thermal cycles on one face of a marble plate. Acoustic waves are generated by 1 MHz central frequency contact transducers excited by a voltage pulse placed on both sides of the plate. During the ageing and by using ad hoc transducers, the marble samples are characterized in transmission, along their volume by shear, compressional TOF measurements and along their surface by Rayleigh waves measurements. For Rayleigh waves, both TOF by transducers and laser vibrometry methods are used to detect the Rayleigh wave. The transmission measurements point out a deep decrease of the waves speeds in conjunction with a dramatic decrease of the maximum frequency transmitted. The marble acts as a low pass filter whose characteristic frequency cut decreases with ageing. This pattern occurs also for the Rayleigh wave surface measurements. The speed change in conjunction with the bandwidth translation is shown to be correlated to the material de-structuring during ageing. With a similar behavior but reversed in time, the same kind of phenomena have been observed through sol-gel materials during their structuration from liquid to solid state (Martinez, L. et all (2004). “Chirp-Z analysis for sol–gel transition monitoring”. Ultrasonics, 42(1), 507-510.). A model is proposed to interpret the acoustical measurements.

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1. Introduction

To evaluate the degradation degree of historical construction materials, knowledge of their physical and mechanical properties can be a solution. This is done in a non-destructive method because of the high cultural value of historical constructions. Within the view to apply such methods to the Carrara marble statues of the garden of the château de Versailles, the present paper investigates the potential of acoustics waves. The estimation of the alteration degree of marble can be done by measuring mechanical properties such as elasticity moduli (E), shear moduli (G) and Poisson ratio (ν) through its ageing (Sklodowski et al, 2011). In order to reduce in terms of the days the secular ageing resulting from outdoor exposition an accelerated artificial ageing protocol was used to prepare aged samples by using heating/freezing cycles.

As Rayleigh wave discovered by Lord Rayleigh (1885) has been widely applied in rock examination for measurement of elastic constants of stones by Pinińska (1986), its behavior with aged marbles is studied in parallel with compressional and shear wave propagation.

2. Theory and experiment:

The study is focused on a white ordinary marble. A non-degraded sample (I1) and an artificial aged sample (G1) are investigated with acoustical methods.

Table 1. Samples description

| Sample | I1                  | G1                  |
|--------|---------------------|---------------------|
| Dimension (mm) | 100*100*30   | 50*50*30            |
| Density (kg/m³) | 2777.5        | 2520                |
| State    | Non-degraded sample | Artificial aged sample |
| Ageing process | None            | 100 heating/freezing cycles (450°C/0°C, 1 hour period) |

In an infinite elastic media, two types of waves that can propagate: these are longitudinal (P) and transversal (S) waves. However, when the media is a half-space with a boundary, a third type of waves may exist whose effects are limited closely to the surface. These surface waves, first described by Lord Rayleigh in 1885, have been investigated in detail in seismology before finding applications in the ultrasonic frequency range for non-destructive evaluation of materials by Masserey (2006), Graff (1975) and Viktorov (1967).

The ultrasonic equipment used for generating P-wave (Resp. S-wave) is an impulse generator (DPR 300 from JSR ultrasonics) and high power compressional transducers pair (Resp. shear transducer) of 1MHz central frequency (figure 1).

Fig 1. P and S waves measurement principle. (1) emitter transducer; (2) oscilloscope; (3) impulse generator; (4) receiver transducer; (5) marble sample

P-wave and S-wave group velocities values are estimated using equation [1]:

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Equation [1]
Where \( v_{LT} \) is the wave velocity (m/s), \( d \) is the distance between transmitter and receiver (m), and \( t \) is the time of flight that the wave takes to travel the distance \( d \) (s).

The measured \( v_{LT} \) velocities are used to calculate the elasticity moduli (E), the shear moduli (G) and Poisson ratio (\( \nu \)):

\[
E = \rho v_L^2 \frac{3v_T^2 - 4v_L^2}{v_T^2 - v_L^2} \quad G = \rho v_T^2 \quad \nu = \frac{\left(\frac{v_L}{v_T}\right)^2 - 2}{2\left(\frac{v_L}{v_T}\right)^2 - 1} \tag{2}
\]

Where \( \rho \) is density (kg/m\(^3\)).

For Rayleigh wave, the equipment used (figure 2a) is the impulse generator, a shear emitter transducer of 1 MHz and a laser for detection (OFV-505 from Polytec). The transducer is carefully placed to generate only the Rayleigh wave. For the altered sample G1, we scan the side that was exposed to the ageing process in x direction, as we can see in the figure (2b).

By using the expressions of stress components in a semi-infinite half space, and by introducing boundary conditions on waves propagation in a solid material, a relationship can be introduced between longitudinal (P) and transversal (S) waves:

\[
R = \begin{pmatrix} k^2 + p_T^2 & -2ikp_T \\ 2ikp_L & k^2 + p_L^2 \end{pmatrix} \tag{3}
\]

\( R \) is the so-called Rayleigh matrix of wave propagation in isotropic solid materials. In order to have non-trivial solutions for this system of equations, the determinant of the Rayleigh matrix should be equal to zero. \( p_T \) and \( p_L \) are depending in \( k \) and \( v_{LT} \): 

\[
k^4 + 2k^2p_T^2 + p_T^4 + 4k^2p_Lp_T = 0 \tag{4}
\]

We replace \( \frac{\omega}{k} \) by \( v_R \), we find:

\[
v_R^4 - 4v_R^2v_T^2 - 4v_T^4\sqrt{1 - \frac{v_T^2}{v_R^2}} - 1 - \frac{v_T^2}{v_R^2} + 4v_T^4 = 0 \tag{5}
\]

This equation for the unknown phase velocity \( v_R \) has to be solved numerically. The resulting solution for \( v_R \) is known as the Rayleigh velocity of the material and depends only on \( v_L \) and \( v_T \).

3. Results and discussion:

Experimental measurements of bulk wave propagation (P and S waves) in the healthy and aged material points out a great sensitivity of both waves. As observed in figures (4a, 4b, 4c), P-wave is attenuated in the altered sample G1 and its travel time is higher than I1 and its maximal frequency transmitter is lower than I1 figures (4d, 4e).
pointing out a great decrease of the corresponding speed (Table 2). For S-wave, we could not to measure it for G1 using the 1 MHz transducer, this could be explained by the state of degradation and the intergranular porosity caused by the ageing process.

Figure 4: (a) P wave propagation in I1, (b) P wave propagation in G1 (b), (c) S wave propagation in I1. Time-frequency domain of P wave in (d) I1, (f) G1, (e) Time-frequency domain of S wave in G1.

For Rayleigh wave propagation on the healthy sample (I1), attenuation is low enough to authorize its reflection when the wave arrives at the limit boundary of the sample I1 (figure 5a), after 100mm propagation distance. However on the aged sample (G1) the behavior of the Rayleigh wave is quite different: both dispersion and attenuation are high enough to prevent the wave to reach the plate border, only 50mm from the source (figure 5b).

The Fast Fourier Transform in 2 dimensions (figure 5c and 5d) is used to get the experimental Rayleigh waves velocities presented in Table 2. One can note that for the I1 sample, the experimental results are very close to the predicted ones. The Rayleigh wave is observed in the 10 KHz-600 KHz bandwidth. On the aged sample (G1), the Rayleigh wave is observed only under 200 KHz; with a velocity 5 times lower than for the healthy sample. The S-wave velocity value that fits the Rayleigh equation for the corresponding measured Rayleigh wave is about 5 times lower for the aged marble than for the healthy one.

Table 2. Samples description

| Sample | \( v_L \) (m/s) | \( v_T \) (m/s) | \( E \) (GPa) | \( G \) (GPa) | \( v \) | \( v_R \) (m/s) | \( v_R \) (m/s) |
|--------|----------------|----------------|--------------|--------------|------|---------------|---------------|
| I1     | 5128.2         | 3125           | 65.35        | 27.12        | 0.51 | 2850          | 2849.4        |
| G1     | 1960 (estimated)| 634            | 29.2         | 10.12        | 0.85 | 600           | 600.93        |
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5. Conclusion

Both bulk waves and Rayleigh waves properties have been investigated for characterizing marble ageing. Both methods are sensitive to the material evolution. However, the Rayleigh wave potential is higher, as it can be used on the surface of the material, which is well adapted to sub-surface degradation estimation for highly degraded materials.

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