Coupling ultrasonics, nanoindentation, and homogenization theory; for identification of porous ceramics in biomedical and civil engineering materials

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Porous polycrystals play an important role in many engineering applications, including biomedicine and construction materials. Thorough understanding of their mechanical nature is key to various design challenges, and recent years have attested the quest of understanding the microstructure underlying the materials' mechanical properties, at ever increasing detail. While this has led to significant surge of experimental data having been created over a little more than the last decade, the understanding of the mutual dependencies of different experimental methods such as nanoindentation or high-frequency ultrasonic tests are not always clear. The present contribution wishes to improve this situation, by coupling nanoindention and ultrasonics tests with a profound micro-poromechanical theory of porous polycrystals; showing recently obtained results for highly porous baghdadite ($Ca_3ZrSi_2O_9$) bone tissue engineering scaffolds, and discussing the wider application of these new results, e.g. in the field of brick design and optimization.

Our coupled analysis starts with a very large campaign of nanoindentation results, so as to distinguish, by means of statistical de-convolution following [1], the elastic intact dense ceramic phase from pore phases, or ceramic being damaged during the indentation process. These intact elastic properties then enter a poro-micromechanics model which has been validated across a wide variety of different porous polycrystals [2] in order to predict elastic properties of differently dense porous ceramics. The latter are then compared to ultrasonic measurements [3] performed on the aforementioned ceramics. The corresponding very satisfactory agreement qualifies our method as the first one to solve the puzzle why average nanoindentation-derived elastic properties are normally lower than those measured by ultrasonics: It is not a "dynamic-versus-static tests" issue, but simply an "artifact" stemming from partial damaging of the material during the nanoindentation method itself.

REFERENCES

[1] F.-J. Ulm, M. Vandamme, C. Bobko, J.A. Ortega, K. Tai and C. Ortiz, "Statistical Indentation Techniques for Hydrated Nanocomposites: Concrete, Bone, and Shale", *J. Am. Ceram. Soc.*, Vol. 90(9), pp. 2677-2692, (2007).

[2] A. Fritsch, C. Hellmich and P. Young, "Micromechanics-derived scaling relations for poroelasticity and strength of brittle porous polycrystals", *J. Appl. Mech.*, Vol. 80(2), pp. 020905, (2013).

[3] J.M. Carcione, *Wave fields in real media: wave propagation in anisotropic, anelastic, and porous media*, 1st Edition, Elsevier, 2001.