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PAPER

Nutshells' mechanical response: from nanoindentation and structure to bionics models

Gerd Kaupp*[a] and Mohammad Reza Naimi-Jamal[b]

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Nut or seed hardshells' mechanical response is studied by vertical nanoindentation in the untreated surface with pyramidal tips. As in uniform materials the exponent of the loading curves is also determined to be 3/2 (but not 2 as Hertzian theory would predict) in all of the nanocomposites with correlation coefficients $r > 0.999$ (except two cases with $r > 0.996$ due to minor distortions) for the linear plots with slope k (μN nm$^{-3/2}$). Unlike hardness H and reduced elastic modulus E_r, the pyramidal nanoindentation coefficient k reflects the total mechanical response. It allows for depth calculations according to $F_N = kh^{3/2}$. Thus, the k-values represent the penetration resistance, and k^{-1} represents the penetratability. Importantly, the penetration depth h follows $F_N^{2/3}$ but not $F_N^{1/2}$ what Hertzian theory had been claiming, despite the importance for wear, mar, mechanical treatments, and tribology. A quantitative mechanical rating is now possible for the first time. The values of k can be converted to different tip tapers. Reliable and repeatable vertical indentations with sharp cube corner were achieved by approaching sufficiently flat summit sites on the rough surfaces under AFM control. The surfaces were not previously destroyed by microtome cutting or abrading and polishing. Detailed knowledge of the architectures of the shells' sclerenchyma was obtained by 3D optical microscopy in color of clean natural surfaces and on fresh fracture surfaces in different directions. Multiple layers, fibrous structures in various alignments and several types of almost isodiametric cells were differentiated. The linearity of the F_N *versus* $h^{3/2}$ plots secures uniformity of the thick-walled cells notwithstanding initial minor deviations due to nanoroughness and surface layers. Comparison with published bone and nacre data is added and discussed. The nanomechanical response of unidirectional indentation at the cellular level influences the cracking resistance of the whole nuts/seeds, but the higher level of wood hierarchy has often the higher weight. The various stabilization tools governing the elastic and brittle responses towards the bending forces that apply upon cracking of the nuts/seeds with their different sizes and shapes are discussed on the basis of the structural data. Importantly, the combination of the mechanical and structural results reveals four new bionics models. These are possible improvements of Yacoe-Davis type dome constructions by stiffeners between the polygons, hedgehog effect for highly elastic materials by efficient interlocking, ellipsoidal cell effect for highly inelastic products, and vertical nanofiber arrays for highly light absorbing very dark surfaces.

1 Introduction

Wood is a hierarchically structured organic composite material that provides stability and elasticity. The cellulose framework (45–50%) is embedded in pectin that consists of lignin (25–30%), hemicelluloses (15–20%), and various further wood-ingredients. The cellulose and the pectin are synergistically increasing the mechanical properties, similar to the related synergies in other biomimetic biological materials such as for example bone, nacre, *etc.* Trees build up highly anisotropic cellular structures by growing annual rings of very long fibers of thick-walled hollow cells leaving channels for adhesive water transport. On the other hand nuts and seeds are one-year three-dimensional (3D) closed products. Their wooden hardshells with largely corresponding chemical composition lack the need for far reaching water transport. They exhibit stability and elasticity by the same synergy as in tree-woods though with much shorter fibrous or elliptical or spherical cells in various arrangements. The result depends on the particular levels of hierarchy. For example, for the cracking resistance the geometry of the full nuts or seeds might supersede the influence of the cellular architecture, or it is known that the water content of ripe nuts and seeds has only marginal influence. However, the cellular architecture of various hardshells and its relation to the mechanical

[a]*Faculty V, Organic Chemistry I, University of Oldenburg, Diekweg 15, D-26188 Edewecht, Germany. E-mail: gerd.kaupp@uni-oldenburg.de; Fax: +49 4486 920704*
[b]*Department of Chemistry, Iran University of Science and Technology, Tehran, Iran. E-mail: naimi@iust.ac.ir; Fax: +9821 77240289*