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Keratin: Structure, mechanical properties, occurrence in biological organisms, and efforts at bioinspiration

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ABSTRACT

A ubiquitous biological material, keratin represents a group of insoluble, usually high-sulfur content and filament-forming proteins, constituting the bulk of epidermal appendages such as hair, nails, claws, turtle scutes, horns, whale baleen, beaks, and feathers. These keratinous materials are formed by cells filled with keratin and are considered 'dead tissues'. Nevertheless, they are among the toughest biological materials, serving as a wide variety of interesting functions, e.g. scales to armor body, horns to combat aggressors, hagfish slime as defense against predators, nails and claws to increase prehension, hair and fur to protect against the environment. The vivid inspiring examples can offer useful solutions to design new structural and functional materials.

Keratins can be classified as α- and β-types. Both show a characteristic filament-matrix structure: 7 nm diameter intermediate filaments for α-keratin, and 3 nm diameter filaments for β-keratin. Both are embedded in an amorphous keratin matrix. The molecular unit of intermediate filaments is a coiled-coil heterodimer and that of β-keratin filament is a pleated sheet. The mechanical response of α-keratin has been extensively studied and shows linear Hookean, yield and post-yield regions, and in some cases, a high reversible elastic deformation. Thus, they can be also be considered 'biopolymers'. On the other hand, β-keratin has not been investigated as comprehensively. Keratinous materials are strain-rate sensitive, and the effect of hydration is significant.

Keratinous materials exhibit a complex hierarchical structure: polypeptide chains and filament-matrix structures at the nanoscale,

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organization of keratinized cells into lamellar, tubular–intertubular, fiber or layered structures at the microscale, and solid, compact sheaths over porous core, sandwich or threads at the macroscale. These produce a wide range of mechanical properties: the Young's modulus ranges from 10 MPa in stratum corneum to about 2.5 GPa in feathers, and the tensile strength varies from 2 MPa in stratum corneum to 530 MPa in dry hagfish slime threads. Therefore, they are able to serve various functions including diffusion barrier, buffering external attack, energy-absorption, impact-resistance, piercing opponents, withstanding repeated stress and aerodynamic forces, and resisting buckling and penetration.

A fascinating part of the new frontier of materials study is the development of bioinspired materials and designs. A comprehensive understanding of the biochemistry, structure and mechanical properties of keratins and keratinous materials is of great importance for keratin-based bioinspired materials and designs. Current bioinspired efforts including the manufacturing of quill-inspired aluminum composites, animal horn-inspired SiC composites, and feather-inspired interlayered composites are presented and novel avenues for research are discussed. The first inroads into molecular-based biomimicry are being currently made, and it is hoped that this approach will yield novel biopolymers through recombinant DNA and self-assembly. We also identify areas of research where knowledge development is still needed to elucidate structures and deformation/failure mechanisms.

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