63

Thermal Tuning of Magneto-Elasticity in pNIPAM-Alginate IPN Hydrogels

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The integration of stimuli-responsive polymers with magnetic fillers enables the development of multifunctional soft matter with programmable physical states. In this work, we design and characterize hybrid hydrogels based on dual-network architectures, combining the thermo-responsive properties of poly(N-isopropylacrylamide) (pNIPAM) with the tunable elasticity of sodium alginate. By synthesizing both Interpenetrating (IPN) and Semi-Interpenetrating (SIPN) networks, we create a platform capable of undergoing a discrete volume phase transition (VPT) triggered by temperature, while exhibiting remote magnetic actuation. Magnetic microparticles were incorporated into the dual-network matrix using an optimized synthesis protocol to ensure colloidal stability and prevent large-scale aggregation. We focus on the interplay between the cross-linking density of the alginate network and the external magnetic field in governing the material's viscoelasticity. Mechanical characterization through oscillatory rheology reveals that the viscoelasticity can be tuned by both the magnetic field and the cross-linking density of the alginate network. A key physical feature of these systems is the massive deswelling observed during the VPT, where the thermal collapse of the pNIPAM chains drives the expulsion of approximately 75% of the total mass. ESEM imaging and swelling kinetics experiments confirm that the internal pore morphology and the resulting water release profiles are sensitive to the network topology (IPN vs. SIPN). These results demonstrate that the volume phase transition acts as a structural switch, effectively modulating the magnetic responsiveness of the dual-network system. This multi-responsive platform provides a basis for the design of smart magnetic hydrogels with programmable, stimulus-selective responses for active soft matter and targeted remote actuation.

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