Multi-Responsive Magnetic pNIPAM-Alginate Colloidal Hydrogels

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Smart hydrogels are hybrid materials capable of modifying their properties in response to external stimuli such as temperature, pH, magnetic fields, or electromagnetic radiation [1]. When embedded with functional nanoparticles, these materials can exhibit optical responses that emerge from the interfacial interplay between the chemical composition of the particles and their geometric arrangement — a fundamental coupling that poses challenges for rational design [2]. These characteristics make them of particular interest for active soft matter and remote actuation systems.

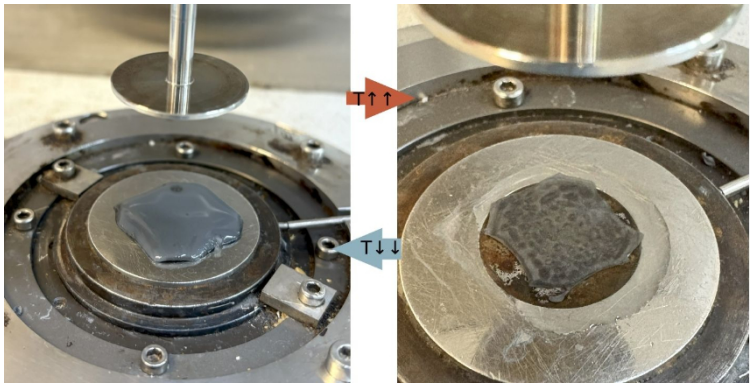
In this work, dual-network hydrogels with a polymeric composition of pNIPAM and alginate were designed, forming both Interpenetrating Polymer Networks (IPN) and Semi-Interpenetrating Polymer Networks (SIPN). The pNIPAM component confers thermos-responsiveness, while alginate enables fine tuning of the network elasticity. Magnetic microparticles were incorporated to introduce sensitivity to external magnetic fields. An optimized synthesis procedure was developed to ensure colloidal stability within both network architectures.

A full mechanical characterization was carried out, revealing that the application of a magnetic field and the variation of alginate cross-linking density drastically tune the viscoelastic properties of the hydrogel. ESEM imaging provided complementary structural insight, showing how these factors alter the internal pore morphology. These observations were consistent with swelling experiments, in which the hydrogels underwent a volume phase transition (VPT), expelling approximately 75% of their mass as the thermally collapsed pNIPAM network drove water release.

Electromagnetic simulations were conducted to investigate the infrared absorption behavior of the core-shell colloidal inclusions. By modeling a core-shell architecture — a 668 nm iron core with a 32–100 nm silica shell — we demonstrate a non-additive optical coupling between composition and geometry that produces highly selective absorption at 8 μm, sharper than that of either constituent material alone.

These results establish the multi-responsive character of the synthesized IPN and SIPN hydrogels, integrating thermal and magnetic actuation within a single soft matter platform. The combination of tunable mechanical properties characterized network topology, and optically engineered particle inclusions provides a basis for the rational design of colloidal hydrogels with programmable, stimulus-selective responses. Future work will explore the exploitation of these properties in targeted applications, including magnetically guided soft actuators.

Keywords:
Magnetism, Soft Matter, Nanoparticles



Example of swelling and de-swelling of the magnetic hydrogel.

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