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Highly Deformable Magnetic SIPN Hydrogels for Soft Actuation

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The development of smart materials for remote actuation requires a delicate balance between robust magnetic responsiveness and structural integrity. Traditional magnetic hydrogels often suffer from mechanical weakening when loaded with the high particle concentrations necessary for effective displacement. This work presents a versatile strategy to overcome these limitations by using semi-interpenetrating polymer networks (SIPNs) to create high-performance, magneto-active soft materials.

We first report the synthesis of Mag-SIPNs based on a cross-linked acrylamide/bisacrylamide matrix intertwined with natural carbohydrate biopolymers (alginate and various cellulose derivatives) [1]. These systems accommodate high loadings of silica-coated iron microparticles (up to 26.2% w/w) while maintaining exceptional mechanical properties, including tensile strains at break up to 220% and high water content. This structural robustness is a significant advancement over conventional biopolymer hydrogels, enabling their use in demanding environments.

Furthermore, we extend this SIPN architecture to the design of advanced soft actuators by incorporating high-remanence neodymium-iron-boron (NdFeB) microparticles. A key feature of these devices is the synergistic control of sedimentation kinetics and magnetic field alignment during the in situ polymerization process. This enables the generation of a prescribed particle density gradient, yielding a functionally graded material with a biomimetic bilayer-like architecture. We analyze how this structural asymmetry, coupled with the pH-dependent swelling of the network, governs the mechanics and the resulting macroscopic bending. Under low-frequency alternating magnetic fields, the actuator exhibits large-amplitude oscillatory motion. We demonstrate that this programmed asymmetry breaks symmetry, generating a directional net-pumping effect that offers a scalable solution for fluid manipulation in microfluidics and biomimetic devices.

By bridging the gap between fine biopolymer design and macroscopic magneto-mechanical functionality, these Mag-SIPNs represent a significant step toward sustainable, high-performance active magnetic matter for medical and industrial technologies.

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References

[1] Leon-Cecilla, et al. Int. J. Biol. Macromol., 260, 129368 (2024).

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