Supporting Information

Magnetic manipulation of liquid-wrapped hydrogels

Utsab Banerjee, Sirshendu Misra, Sushanta K. Mitra*

Micro & Nano-scale Transport Laboratory, Waterloo Institute for Nanotechnology, Department of Mechanical and Mechatronics Engineering, University of Waterloo, 200 University Avenue West, Waterloo, Ontario N2L 3G1, Canada

*Corresponding author: skmitra@uwaterloo.ca

S1. Variation of magnetic field (H-field) in the y-direction

As stated in the main text, if the strength of the magnetic field at a particular magnet height is known, it can be used to calculate the magnetic Bond number Bo_m. For this, we performed simulations of the magnetic field (H, in $A\,m^{-1}$) using commercial finite element solver COMSOL multiphysics 5.2a. We first create a geometry of the magnet that we used in the experiments. The magnet size is $a = b = c = 12.7\ mm$, which is kept inside an air box with size $p = q = r = 12.7\ cm$. The computational domain is meshed using tetrahedral elements of a maximum mesh size of $0.69\ cm$ and minimum mesh size of $0.05\ cm$. The mesh growth rate is $3.55\ cm$. The input parameters used in the simulation are the relative permeability of air $\mu_r = 1$ and relative permeability of the neodymium iron boron magnet $\mu_m = 1.05$. The following governing equations are used to solve the system.

$$\nabla \cdot B = 0 \quad (1)$$

$$B = \mu\mu_r H + B_r \quad (2)$$

$$H = -\nabla V_m \quad (3)$$

Where, B is the magnetic flux density, B_r is the remnant flux density and V_m is the magnetic scalar potential. The above equations are subject to the following boundary conditions.

$B_r = 0$ in air and $B_r = 1.32\ T$ inside the magnet.

At the air-box boundary, the insulation boundary condition is imposed $n \cdot B = 0$. The results are presented in Figure S1 in terms of variation of H vs y.

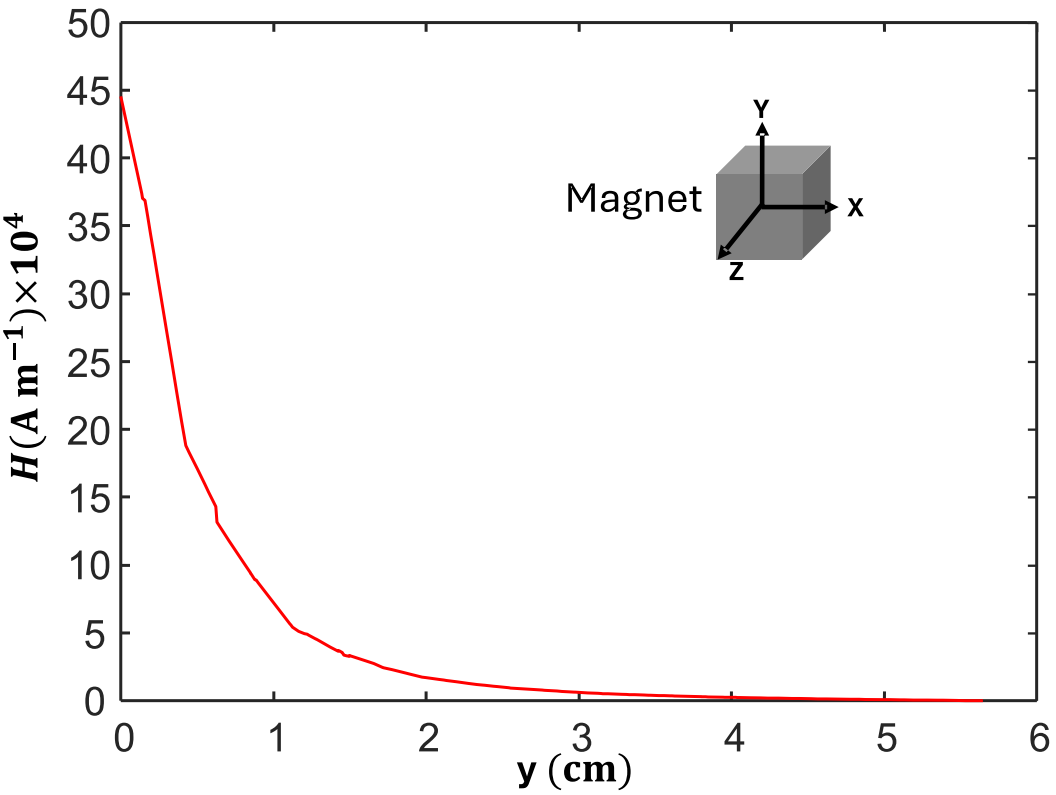

Figure S1. Variation of the magnetic field H along the distance y from the surface of the neodymium iron boron magnet used in the experiments.

S2. Rheological characterization of non-magnetic and magnetic hydrogel

We analyzed the dependence of the viscoelastic moduli ($G^{'}$ and $G^{''}$) as a function of frequency for the magnetic and the non-magnetic hydrogel. The rheological characterization is performed using a rheometer (Kinexus, Malvern ultra+). For this, we placed the hydrogel samples (3.5 mm disk) on the lower plate of the measuring system.[1] It can be seen that the incorporation of the magnetic nanoparticles inside the hydrogel matrix enhances the viscoelastic moduli. The presence of magnetic nanoparticles (MNPs) significantly influences the rheological properties of hydrogels, leading to distinct differences between magnetic and non-magnetic hydrogels. In magnetic hydrogels, the storage modulus ($G^{'}$) is higher due to the reinforcing effect of MNPs, which act as additional crosslinking points within the hydrogel network, enhancing its elasticity. In contrast, non-magnetic hydrogels rely solely on polymer crosslinking, often resulting in a lower $G^{'}$. Similarly,

the loss modulus (G'') is higher in magnetic hydrogels because of increased energy dissipation from MNP interactions, whereas non-magnetic hydrogels exhibit lower G'', indicating a more stable viscoelastic balance. Additionally, magnetic hydrogels offer tunable mechanical properties, as their G' and G'' can be dynamically adjusted by an external magnetic field, a feature absent in non-magnetic hydrogels. These differences highlight the enhanced adaptability of magnetic hydrogels, making them suitable for applications requiring external control, such as soft robotics and targeted drug delivery.

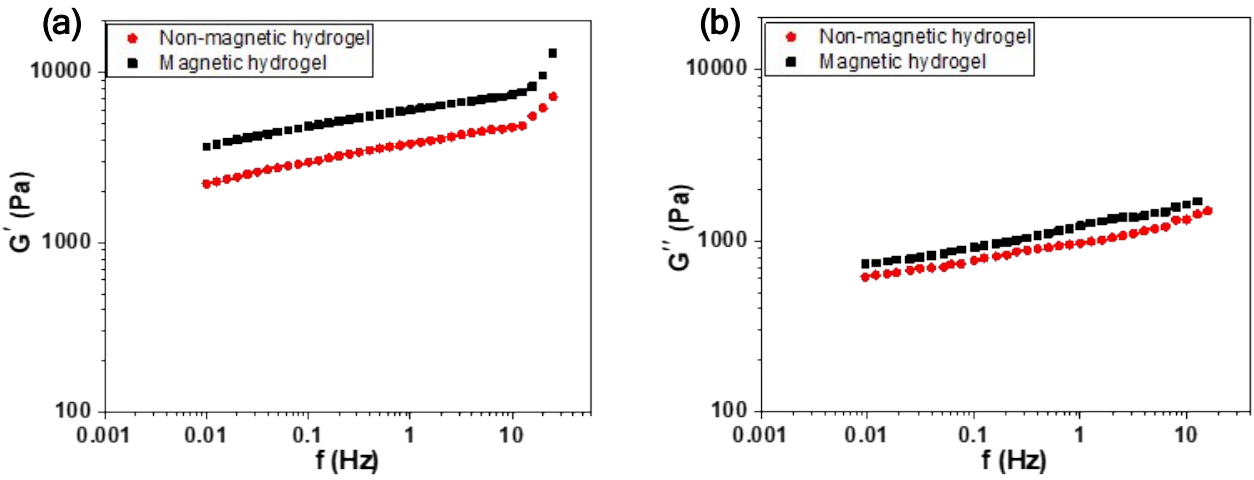

Figure S2. **(a)** Storage modulus (G') and **(b)** loss modulus (G'') as a function of the frequency (f) of oscillatory measurements for the non-magnetic and magnetic hydrogels.

References

1 C. Gila-Vilchez, A. B. Bonhome-Espinosa, P. Kuzhir, A. Zubarev, J. D. G. Duran and M. T. Lopez-Lopez, *J Rheol (N Y N Y)*, 2018, 62, 1083–1096.