Electronic Supplementary Information

Switching shape of hollow layer-by-layer hydrogel microcontainers

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Experimental

Materials. Ammonium hydrogen carbonate and manganese(II) sulfate monohydrate, 2-propanol, poly(N-vinylpyrrolidone) (PVPON, average M_w=55,000 Da), poly(methacrylic acid) (PMAA, average M_w=150,000 Da), 1-ethyl-3-(3-(dimethylamino)propyl)-carbodiimide hydrochloride (EDC) were from Sigma-Aldrich. Alexa Fluor 488 was from Invitrogen, Inc. Ultrapure de-ionized water with the resistivity of 0.055 μS/cm (18.2 Ω cm) was used in all experiments (Siemens). To control pH, buffer solutions of NaH_2PO_4 and Na_2HPO_4 (Sigma-Aldrich) of ACS grade were used. To control ionic strength, sodium chloride was utilized (Alfa Aesar).

Synthesis of cubical manganese carbonate particles

Manganese carbonate particles were synthesized using a modified procedure for spherical manganese carbonate particles as described elsewhere.[1] Cubical manganese carbonate microparticles were produced by mixing 0.06 M NH_4HCO_3 and 6 mM $MnSO_4$ solutions. Using fresh nano-seed solution containing nanoseeds for crystal growth, the size of the manganese carbonate particles is controlled to be close to a monodisperse distribution. In a typical experiment, for $MnCO_3$ microparticles of ~ 3 μm, a nano-seed solution was first prepared by mixing 20 mg of NH_4HCO_3 and 1 mg of $MnSO_4$ in 100 mL of de-ionized water under stirring for several seconds. Next, 75 mL of the nano-seed solution was added to 500 mL of 6 mM aqueous $MnSO_4$ solution containing 0.5% of 2-propanol and rapidly stirred for several seconds (target solution). Then, 500 mL of 0.06 M ammonium bicarbonate solution with 0.5% of 2-propanol were poured into the target solution. The mixture was immediately heated at 80°C for 40 minutes without stirring. After the precipitate was formed, the supernatant was discarded. The precipitate was filtered through 0.45 μm filters (Whatman), followed by six washings with de-ionized water. Then the microparticles were dried at 60°C in the oven for 3 hours. Finally, manganese carbonate microparticles were transferred into the test-tubes and kept at room temperature until needed. The procedure was similar for the synthesis of the spherical manganese carbonate microparticles used in control experiments, except that the mixture was heated under vigorous stirring (~2000 rpm). The inset in Fig.S1a shows the size dependence of the cubical manganese carbonate particles on the $MnSO_4$ concentration (in the nano-seed solution).

Fluorescent labeling of PMAA

The fluorescent labeling reaction of PMAA was performed in methanol. PMAA (200 mg) was dissolved in 10 mL of methanol and 1-ethyl-3-(3-(dimethylamino)propyl)-carbodiimide hydrochloride (132 mg) were added and incubated for 30 min with occasional shaking. The activation step was followed by an addition of 5 mg of Alexa Fluor 488 dihydrazide sodium salt (Invitrogen). During 24 hours allowed for completing the reaction, the mixture was constantly stirred in darkness. After that, the reaction mixture was dialyzed exhaustively against de-ionized water using Spectra/Por float-A-lyzer (Spectrum Laboratories) with the molecular weight cutoff of 50 000 Da. The dialysis was interrupted after no traces of fluorescence could be detected in the dialysis water. Solution of the fluorescently tagged PMAA-Alexa was freeze-dried and 0.5 mg/mL polymer solutions were prepared and used. Preparation of cubic $(PMAA)_n$ hydrogel capsules

For all deposition steps, 0.5 mg/mL polymer solutions were used to reach saturated adsorption within 15 min deposition time. Hydrogen-bonded multilayers of $(PMAA/PVPON)_n$, where *n* denotes a number of bilayers were deposited on PEI-coated $MnCO_3$ particles. PEI precursor was allowed to adsorb at pH=6 from 0.5 mg/mL aqueous solution. Assembly of (PMAA/PVPON) hydrogen-bonded layers was then performed at pH 3.6, starting from PMAA. Each deposition cycle was followed by rinsing three times with a buffer solution at pH=3.6 to remove excess polymer, followed by centrifugation of suspensions at 5000 rpm for 3 min to remove supernatant. Deposition and rinsing steps were performed in a shaker (Fisher Scientific). After a desired number of layers were deposited, chemical cross-linking of polyacid layers was performed. For that, the core-shell particles were exposed to carbodiimide solution (5 mg/mL) at pH=5 for 30 min, followed by reaction with ethylene diamine (5 mg/mL; pH=5.8). The carbonate cores coated with PEI(PMAA/PVPON)$_7$ or PEI(PMAA/PVPON)$_{14}$ were transferred into a Lab-Tek chambered coverglass (Electron Microscopy Sciences) for analysis using confocal microscopy and then dissolved using 1 M HCl solution to yield hollow polymeric capsules.

Measurements

Scanning electron microscopy (SEM) analysis was performed using a Phillips 515 filament-emission microscope at 20 kV. Manganese carbonate particle samples were prepared by placing a drop of a particle suspension on a carbon film and allowing it to dry at room temperature.

Confocal images of capsules were obtained with Zeiss LSM 710 confocal microscope equipped with a 63x oil immersion objective. Capsules were visualized through deposition of the fluorescently tagged polyacid, PMAA-Alexa, within the last two bilayers of PMAA capsules. The excitation wavelength was 488 nm. To observe pH-dependent changes, a drop of a hollow capsule dispersion was added to Lab-Tek chambered coverglass (Electron Microscopy Sciences), which were filled with buffer solutions at certain pH. Capsules were allowed to settle down and then analyzed.

The zeta-potentials of the cubical cross-linked (PMAA)$_7$ capsules were measured at different pH values on Nano Zetasizer (Malvern). The pH values of aqueous capsule solutions were adjusted using 0.01 M HCl or NaOH solutions. Each value was obtained by averaging three independent measurements. The capsules were produced by dissolution of $MnCO_3$ cores in HCl and dialyzed in water and followed by dialysis in 0.1M EDTA and DI water (EDTA-treated).

Film thickness measurements were performed using a M2000U spectroscopic ellipsometer (J.A. Woollam) on Si wafers (University Wafers). To enhance surface adhesion of the subsequently grown multilayer to a silicon wafer, precursor $(PAH/PMAA)_2$ bilayers were deposited first.[2] The precursor layers were heated to 175°C for 1 h in an oven for thermal cross-linking of $(PAH/PMAA)_2$ layers and their enhanced adhesion to the silicon wafer surfaces. Hydrogen-bonded PMAA/PVPON films were then deposited from 0.5 mg/mL polymer solutions at pH 3.6. After depositing 14 bilayers, the films were cross-linked as described for capsules. Wafers containing cross-linked multilayers were then exposed to pH 8.0 for 2 hours to remove the remains of poly(N-vinylpyrrolidone), transferred to pH 5 to de-swell the films, and dried. For dry film measurements, surface-tethered films were dried under a stream of nitrogen. Studies of film swelling were performed using a liquid flow-through cell (Woollam).

X-Ray Photoelectron Spectroscopy (XPS) was carried out using PHI 5000 VersaProbe XPS Microprobe (with the resolution depth of 4 nm). For that, manganese particles coated with $PEI(PMAA)_{14}$ were dissolved in 1 M HCl and dialyzed in DI water for 24 hours. After that, one half of the capsule suspension was dialyzed against 0.1 M EDTA at pH 6 for 1 hour followed by dialysis of both parts against de-ionized water for 1 hour. Samples for XPS were prepared by placing a drop from each of the $PEI(PMAA)_{14}$ capsule suspensions on separate silicon wafers, dried for several hours and used for the analysis of manganese ions.

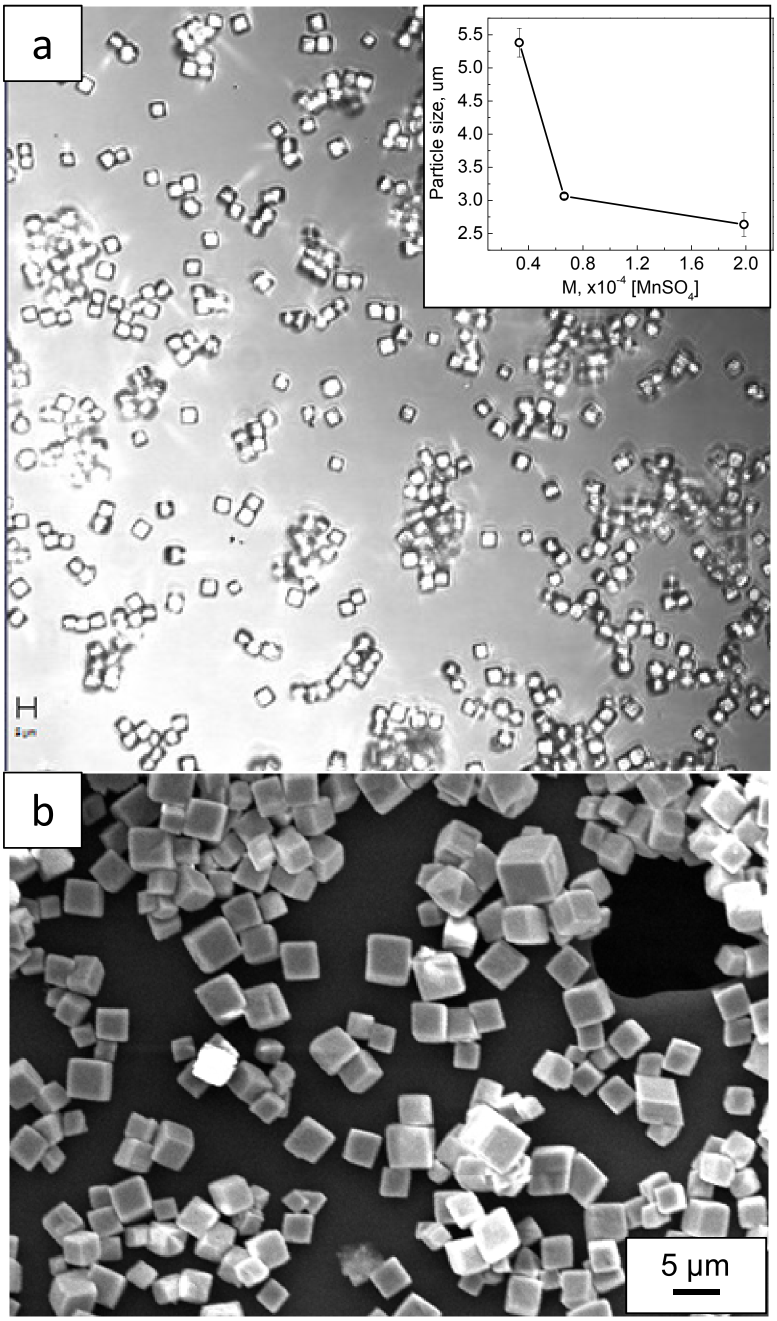

Figure S1. (a) A large area CLSM image (transmitted light mode) of $MnCO_3$ particles. The scale bar is 5 µm. The insert shows the dependence of the size of manganese carbonate cubic particles on the concentration of manganese sulfate in a nano-seed solution. (b) A SEM image of $MnCO_3$ particles.

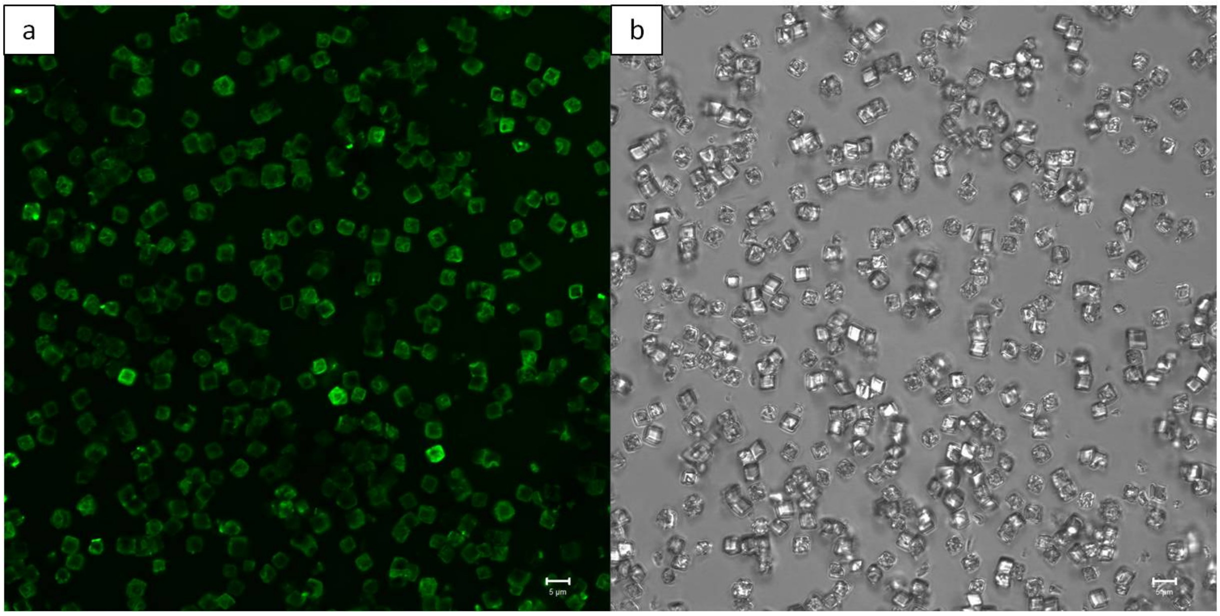

Figure S2. A large-area CLSM image of $(PMAA)_{14}$-coated $MnCO_3$ particles before manganese carbonate core dissolution. The left image is taken in the fluorescence mode and the right image is in the transmitted light mode. The scale bar is 5 µm.

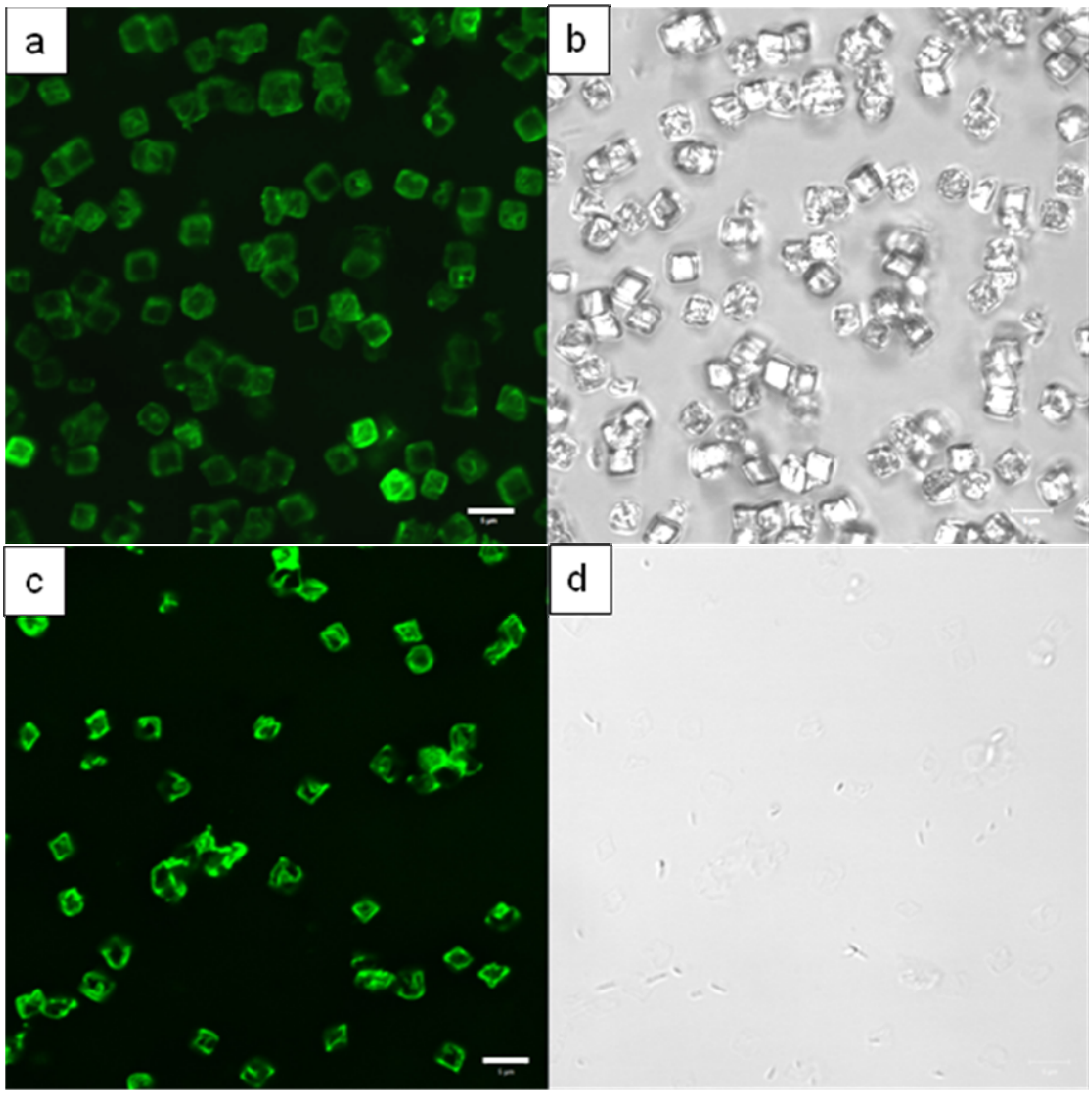

Fig. S3. CLSM images of (PMAA)$_{14}$-coated $MnCO_3$ particles before (a, b) and after manganese carbonate core dissolution (c, d). Left images are in a fluorescence mode (a, c) and right images are in a transmitted light mode (b, d). Scale bar is 5 μm.

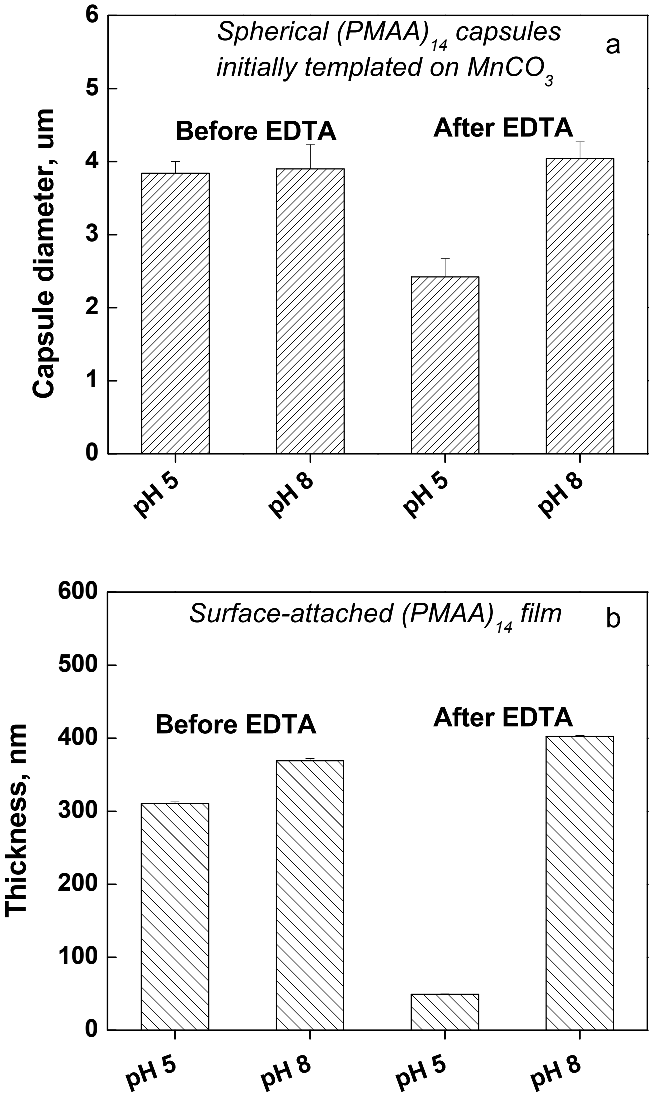

Figure S4. (A) Dependence of the capsule diameter on pH measured with CLSM. Spherical PEI(PMAA)$_{14}$ capsules were produced by dissolution of spherical manganese carbonate cores coated with PEI(PMAA)$_{14}$ in 1 M HCl, and subsequently washed with 0.01 M phosphate buffers at appropriate pH. Experiments were performed in Lab-Tek chambered coverglass. (B) Thickness variations with pH of surface-tethered (PMAA)$_{14}$ LbL hydrogel films measured by ellipsometry in a liquid cell. Before measurements, the films were exposed to a solution produced by dissolution of 160 mg of $MnCO_3$ in 2 mL of 1 M HCl followed by rinsing with a buffer solution at pH=5 to mimic the core dissolution conditions when hollow hydrogel capsules are produced.

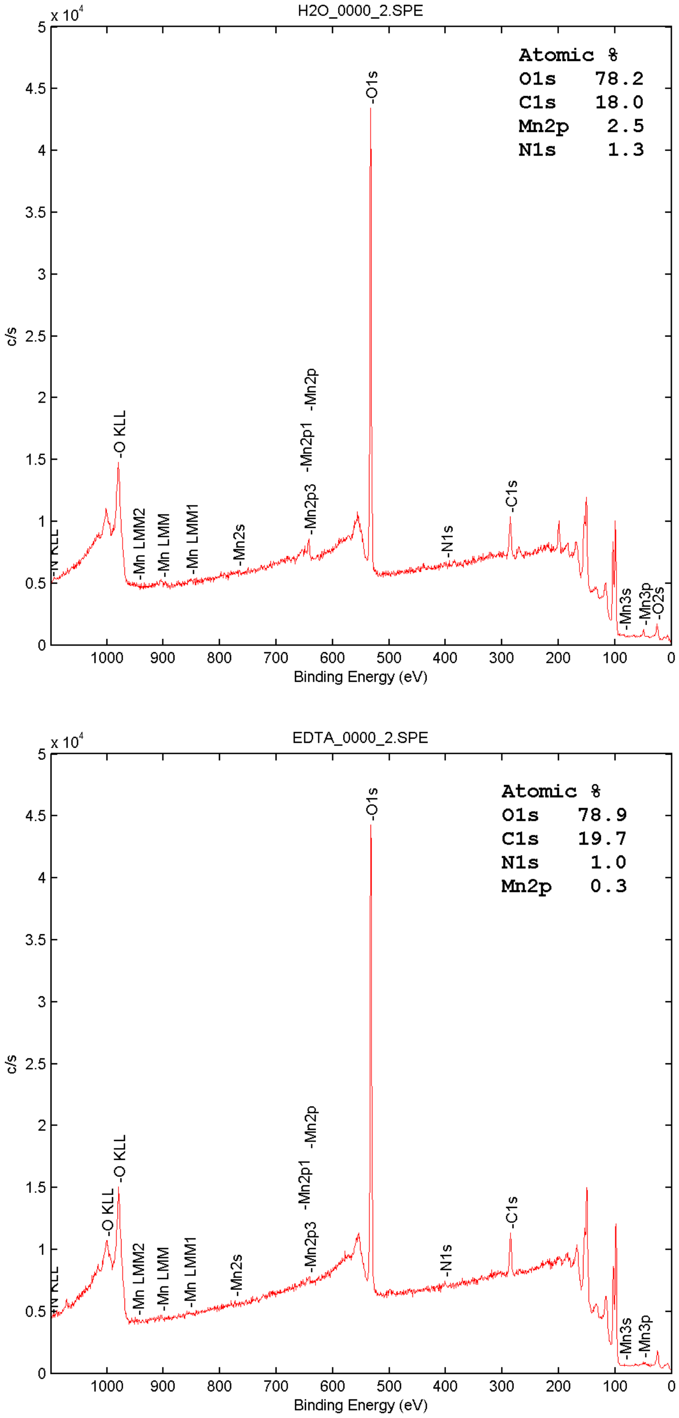

Figure S5. Survey XPS spectra of PEI(PMAA)$_{14}$ capsules dialyzed in DI water after $MnCO_3$ cores dissolution (top) and of the (PMAA)$_{14}$ capsules dialyzed in EDTA for 1 hour followed by dialysis in DI water to remove EDTA (bottom).

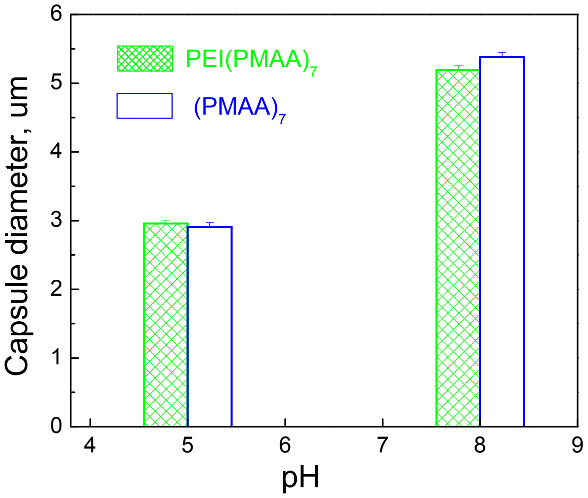

Figure S6. Variations of a $(PMAA)_7$ capsule diameter in response to pH changes. Hydrogel capsules were initially built up either on bare silica (clear bars) particles or on silica with the pre-adsorbed PEI layer (patterned bars).

The PEI priming layer has a negligible effect on the topping (PMAA) hydrogel swelling at higher pH. Figure S6 shows variations of a diameter of sphericlal $(PMAA)_7$ hydrogel capsules, initially template on spherical silica particles, in response to pH changes. Both types of capsules, $PEI(PMAA)_7$ and $(PMAA)_7$ increased their diameters by ~77% and ~85%, respectively, when pH was increased from pH=5 to pH=8. The observed 8% larger swelling for $(PMAA)_7$ capsules under these conditions demonstrates no significant effect of PEI on the swelling of the outmost layered PMAA hydrogel.

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1 H. Zhu, E. W. Stein, Z. Lu, Y. M. Lvov and M. McShane, *J. Chem. Mater.*, 2005, **17**, 2323.

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[2] V. Kozlovskaya, E. Kharlampieva, M. L. Mansfield, S. A. Sukhishvili, *Chem. Mater.*, 2006, **18**, 328.