Supplementary Information (SI) for Polymer Chemistry.

Supporting Information

Base-Assisted Degradable Methacrylic Microcapsules Synthesized via Interfacial Radical Polymerization Using 4,4-Dimethyl-2-methylene-1,3-dioxolan-5-one (DMDL)

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1. Experimental Section

Materials. Methyl methacrylate (MMA) (>99.8% Tokyo Chemical Industry (TCI), Japan), methacrylic acid (MAA) (>95%, TCI), allyl methacrylate (AMA) (98%, Sigma Aldrich, USA), 2-acetoxyisobutyryl chloride (95%, Fluorochem, UK), triethylamine (>99%, TCI), sodium dodecyl sulphate (SDS) (>97%, TCI), 1,1,3,3-tetramethylbutyl peroxyneodecanoate (OND-70) (70%, NOF, Japan), trimethylsilyl diazomethane ($TMSCHN_2$) ($TMSCHN_2$ solution in hexane (0.6 mol/L), TCI), sodium hydroxide (NaOH) (>97%, VWR Chemicals, USA), anhydrous magnesium sulfate ($MgSO_4$) (>98%, TCI), Rhodamine-B (>95%, TCI), dichloromethane (≥99.5%, VWR, USA), chloroform ($CHCl_3$) (≥99.8%, Fisher Scientific, UK), chlorobenzene (99%, Sigma Aldrich), tetrahydrofuran (THF) (99.8%, J.T.Baker, USA), and acetone (100%, VWR) were used as received.

Synthesis of 4,4-Dimethyl-2-Methylene-1,3-Dioxolan-5-One (DMDL). 4,4-Dimethyl-2-methylene-1,3-dioxolan-5-one (DMDL) was synthesized, as previously reported.[1] A solution of 2-acetoxyisobutyryl chloride (100 g, 0.607 mol), triethylamine (67.5 g, 0.667 mol), and dichloromethane (600 mL) was heated under reflux for 3 h with magnetic stirring. The reaction mixture was filtered, and the filtrate (solution) was concentrated using a rotary evaporator. The concentrated mixture was further filtered (the second time) to remove the triethylamine salt. The residual liquid was subjected to distillation at 15 Torr and at 40 ^{o}C to give DMDL. Yield: 76.5 g (83% yield). ^{1}H NMR (400 MHz, $CDCl_3$): 3.69 (d, J = 1 Hz, 1H), 3.61 (d, J = 1 Hz, 1H), 1.54 (s, 6H).

Interfacial Polymerization. In a typical run (**Table 1**, entry 1), a mixture of MMA, AMA, DMDL, and OND-70 in an organic solvent ($CHCl_3$ or chlorobenzene) (6.8 g of the monomers in total and 9.2 g of the organic solvent) and a separate mixture of MAA and SDS in water (6.0 g of MAA and 21.5 g of water) were added together in a round-bottomed flask (250 mL flask), which was subsequently bubbled with argon, and stirred at 800 rpm at 45 ^{o}C for 4 h under argon flow. In **Table 1** (entry 5), a fluorescent dye (Rhodamine B) was added to the organic phase. After the polymerization, an aliquot was used for microcapsule size analysis in the swollen state using a particle size analyzer. The rest of the polymerization mixture (resultant microcapsule) was washed thrice with water, twice with acetone, and once with dichloromethane. The microcapsule was then dried overnight at 70 ^{o}C and analyzed using scanning electron microscopy (SEM).

Methylation of Non-crosslinked Polymer. The non-crosslinked polymer (**Table 1**, entry C2) (the MAA units in the polymer) was methylated before gel permeation chromatogram (GPC) analysis. The polymerization mixture (0.1 g) was diluted with THF (3 mL). To this mixture, 0.04 g of $TMSCHN_2$ (0.6 mL of a $TMSCHN_2$ solution in hexane (0.6 mol/L)) was added. The mixture was stirred overnight at room temperature. The mixture was dehydrated using $MgSO_4$ and filtrated. The filtrated solution was used for the GPC analysis.

Degradation of Microcapsules. The Rhodamine B-encapsulated microcapsule (**Table 1**, entry 5) was used for degradation. The purified and dried microcapsule (0.05 g) was suspended in aqueous neutral and basic solutions (2 mL) and stirred for 24 h at room temperature, after which they were washed thrice with water, twice with acetone, and once with dichloromethane. The microcapsule was then dried overnight at 70 ^{o}C and analyzed using scanning electron microscopy. The degradation in the basic (NaOH) solution was also studied in the swollen state using a confocal laser scanning microscope.

NMR. The ^{1}H NMR spectra were recorded on a Bruker (Germany) Avance III 400 BBFO400 spectrometer (400 MHz) at room temperature. The determination of the monomer conversion and characterization of the polymer in the non-crosslinked system (**Table 1**, entry C2) were carried out using DMSO-d_6 (Cambridge Isotope Laboratories, USA) as an NMR solvent. The characterization of the synthesized DMDL monomer (after the monomer synthesis) was carried out using chloroform-*d* ($CDCl_3$) (Cambridge Isotope Laboratories) as an NMR solvent. The chemical shift was calibrated with the residual non-deuterated solvent as the internal standard.

GPC. The GPC analysis using DMF as an eluent was performed on a Shimadzu i-Series Plus liquid chromatograph LC-2030C Plus (Kyoto, Japan) equipped with two Shodex LF-804 columns (300 × 8.0 mm; bead size = 6 μm; pore size = 3000 Å) and one Shodex KD-802 column (300 × 8.0 mm; bead size = 6 μm; pore size = 150 Å). The DMF eluent contained 10 mM of LiBr, and the flow rate was 0.34 mL/min (40 °C). Sample detection was conducted using a Shimadzu differential refractometer detector RID-20A, and the column system was calibrated with standard poly(methyl methacrylate)s (PMMAs).

Scanning Electron Microscopy (SEM). Scanning electron microscopy (SEM) images were taken on Schottky Field Emission JSM-7600F Scanning Electron Microscope (JEOL, Japan) via low-energy secondary electron imaging (LEI). The sample (microcapsule) was sputtered with platinum for 30-60 s, forming a 10-20 nm thick layer.

Transmission Electron Microscopy (TEM). Transmission electron microscopy (TEM) images were taken using a JEOL JEM-1400 Transmission Electron Microscope (Tokyo, Japan), operating at 100 kV. The TEM grid used was a carbon-coated 200 copper mesh (Ted Pella, Redding, USA). The microcapsule synthesized using chloroform as an organic solvent (**Table 1**, entry 3)) was suspended in acetone. The suspension was dropped onto the grid. The microcapsule was mechanically ruptured by instant evaporation of solvents under vacuum (chloroform inside the capsule was instantly evaporated) and analyzed with TEM. (The microcapsule was gradually dried at 70 ^{o}C under ambient pressure for the SEM sample, which was not ruptured.)

Particle Size Analyzer. The size (Dv50) and its distribution of the microcapsule were determined using a Mastersizer 3000 particle analyser (Malvern Panalytical, UK) coupled with a large volume wet sample dispersion unit (Hydro LV) (Malvern Panalytical). The polymerization mixture (microcapsule) was diluted (dispersed) with water in the Hydro LV unit and magnetically stirred at 2250 rpm.

Confocal Microscopy. Confocal laser scanning microscope images were taken with the Carl Zeiss LSM 800 confocal laser microscope (Germany). The excitation wavelength of the laser was 561 nm with the pinhole size of 50 µm, and the emission wavelength was 568 nm (± 20 nm).

2. Supplementary Images

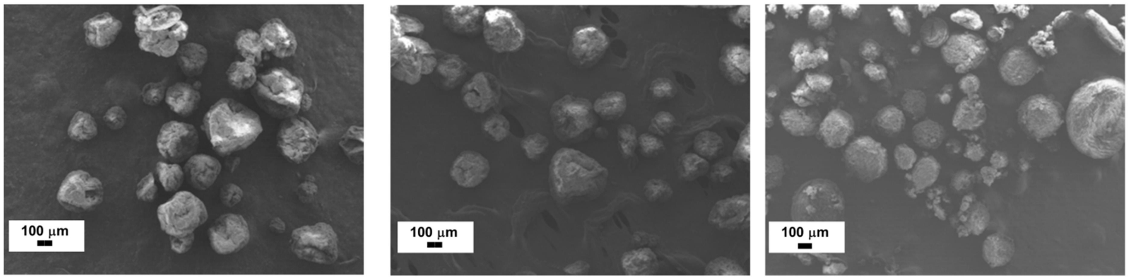
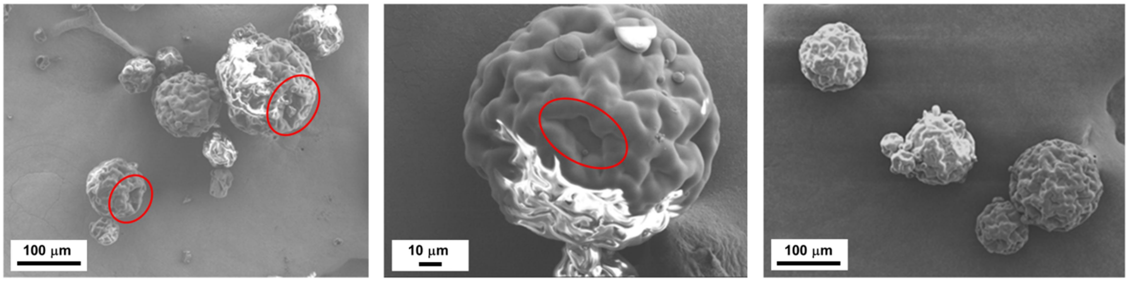


Figure S1. SEM images of the microcapsules synthesized in **Table** 1, entry 1. The left image is the same as **Figure 2** in the manuscript. The average microcapsule size was calculated form 10 capsules per image and across 3 images given in **Figure S1**.


(a) SEM image of microcapsules after treatment at pH = 12 for 24 h. (Holes are indicated by red circles.)

(b) Magnified SEM image of microcapsule after treatment at pH = 12 for 24 h. (A hole is indicated by red circle.)

(c) SEM image of microcapsules after treatment at pH = 10 for 24 h.

Figure S2. SEM images of the microcapsules synthesized in **Table 1**, entry 5 after treatment at pH = 12 and 10 for 24 h. (a) SEM image and (b) magnified SEM image of microcapsules after treatment at pH = 12 and (c) SEM image of microcapsules after treatment at pH = 10. In (a) and (b), holes were observed, which were generated during the treatment at pH = 12 or in the drying process for the SEM sample preparation because the microcapsule shells became mechanically weak via degradation.

Reference

(1) Oh, X. Y.; Ge, Y.; Goto, A. Synthesis of degradable and chemically recyclable polymers using 4,4-disubstituted five-membered cyclic ketene hemiacetal ester (CKHE) monomers. *Chemical Science* **2021,** *12* (40), 13546-13556.