

Self-assembled Shells Composed of Colloidal Particles: Fabrication and Characterization

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We construct shells with tunable morphology and mechanical response with colloidal particles that self-assemble at the interface of emulsion droplets. Particles self-assemble to minimize the total interfacial energy, spontaneously forming a particle layer that encapsulates the droplets. We stabilize these layers to form solid shells at the droplet interface by aggregating the particles, connecting the particles with adsorbed polymer, or fusing the particles. These techniques reproducibly yield shells with controllable properties such as elastic moduli and breaking forces. To enable diffusive exchange through the particle shells, we transfer them into solvents that are miscible with the encapsulant. We characterize the mechanical properties of the shells by measuring the response to deformation by calibrated microcantilevers.

1. Introduction

The encapsulation and controlled release of drugs, fragrances, and other active agents are of increasing importance to the biomedical, pharmaceutical, and food industries.^{1–8} Well-characterized, hollow shells possess characteristics that are attractive for these applications. For example, polymer shells that encapsulate cells not only permit exchange of nutrients and active agents with the exterior environment but also offer cellular immunoisolation against organisms that cannot fit through the pores.⁹ Capsules of silicon made with microfabrication technology enable even finer control of pore size for applications requiring selective permeability and slow release.¹⁰ Alternatively, shells that break in response to

a specified range of external stresses are also desirable for controlled release. Moreover, use of materials that are naturally available enables large-scale manufacture at low cost. Colloidal particles are attractive materials for building capsules because particles with a vast array of material properties are readily available. Interstices of packed layers of colloidal particles have a characteristic cross-sectional area that is determined by the particle size, enabling construction of shells of tunable permeability.

Self-assembly is a simple and robust approach to spontaneously create shells with desired properties that encapsulate active agents. Polymer films that are assembled onto solid enzyme crystals have demonstrated protection from protease degradation and controlled release that is pH-triggered.¹¹ Layer-by-layer assembly¹² of charged polymers and particles onto charged templates of colloidal particles has enabled the controlled formation of composite structures.¹³ Indeed, colloidal particles are attractive materials as templates for assembled shells because particles with a broad range of surface properties are readily available. Moreover, many of these surfaces are easily modified, facilitating assembly onto an array of chemically distinct surfaces. For these same reasons, colloidal particles are also suitable as components of assembled shells.

Assembly of shells at the interface of emulsion droplets enables efficient encapsulation with minimal disturbance of active agents that are suspended or solubilized in liquids. Assembly of colloidal particles onto emulsion droplet interfaces^{14–19} is a simple and straightforward way to make shells with a wide range of interesting properties.

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The mobility of the particles at the droplet interface can allow formation of equilibrium structures, and the interface itself can modify the interactions among particles, thus influencing the final structure. The interactions^{20–22} and ordering²³ of particles adsorbed at interfaces have been studied. Recent experiments have investigated long-ranged interparticle attraction^{24–26} and defects in the packing of spheres on curved 2D surfaces.²⁷ The suitability of these structures for encapsulation and delivery via selective permeability has recently been demonstrated. The pore size is a well-defined fraction of the size of the particles that comprise the shell, as determined by the geometry of packed spheres. Particles that are smaller than this threshold size can permeate through the shell, while larger ones cannot.¹⁸ Systematic studies of the efficacy of colloidal particles in stabilizing emulsion droplets as a function of colloidal surface properties²⁸ and emulsion composition²⁹ reflect the flexibility in surface and chemical properties that can be exploited to create self-assembled shells with distinct structural properties. However, only a few of the many possibilities for modifying the morphology and mechanical properties of these shells have been explored and fully exploited.

We self-assemble layers of colloidal particles at the interface of emulsion droplets and employ several different techniques to stabilize them before transferring them into solvents that are miscible with the droplet phase. Following the assembly of particle layers, we tune the morphology and mechanical properties by employing several distinct methods of stabilization to create solid shells. We accomplish this by modifying the particle interactions at or near the emulsion droplet interface, adsorbing polymer to reinforce the shell,^{12–13} and fusing the particles together through sintering.^{30–31} These shells are characterized by interstices between the packed spherical particles. We facilitate selective exchange through these pores through addition of co-solvent^{15–17} and centrifugation, thus replacing the continuous phase with a fresh solvent that is miscible with the droplet phase. We examine shell morphology with optical and electron microscopy and investigate mechanical response by deformation with calibrated microcantilevers.^{32–38}

2. Experimental Methods

Aqueous suspensions of polystyrene particles are purchased from Interfacial Dynamics Corporation (IDC). We use divinylbenzene cross-linked particles 1.3 and 0.5 μm in diameter with carboxyl surface charge groups (DVB carboxyl particles) and 1.1 μm -diameter particles with aldehyde sulfate surface charge groups (aldehyde sulfate particles). The latter particles are biotin-coated, but this is unlikely to play a role in these experiments. 1-Octanol, toluene, dodecane, glycerol (all 99% pure), TWEEN20, and SPAN80 are purchased from Aldrich and not subject to further purification before use. Silicone oil (Fluka, 10836), ethanol (200 proof, Pharmco), and poly-L-lysine 0.1% w/v aqueous solution (Sigma, P8920) are also used as obtained from the manufacturers. The deionized water used for the experiments is purified by a Millipore Milli-Q system. Wesson vegetable oil is filtered with a 0.45 μm -pore hydrophobic syringe filter prior to use.

We prepare aqueous suspensions of particles by cleaning the original suspensions from the manufacturer to minimize any impurities that may persist from particle synthesis. We clean by performing several cycles of dilution and concentration; in each cycle, we dilute the suspension with deionized water to volumes of about 4 mL, sonicate for 10 min to homogenize the suspension, centrifuge for 30 min at 800g, and remove of the supernatant. We then add deionized water to attain the desired volume fraction of about 0.1%.

We use these same polystyrene particles in our nonaqueous suspensions. To transfer the particles from aqueous to organic solvents, we first clean the particles with deionized water and then transfer the particles to the organic solvents. Because many organic solvents are not miscible with water, we perform successive steps of solvent exchange. We first exchange water in the original suspension with ethanol through several cycles of dilution and concentration; in each cycle, we dilute the particle suspension with ethanol, sonicate, centrifuge, and remove the supernatant. We then repeat the process of dilution and concentration with octanol to exchange ethanol for octanol. To suspend the particles in nonpolar solvents such as dodecane or toluene, we dilute suspensions of about 1 vol% of particles by volume in octanol by a ratio of 1:10 with the desired nonpolar solvent. This yields final suspensions with volume fractions of about 0.1%. We prepare suspensions in vials with Teflon-lined caps; the rubber coatings that commonly line caps can dissolve in some solvents, contaminating the suspension.

We employ these aqueous and nonaqueous suspensions of particles to encapsulate both oil and water droplets. In these experiments, particles always originate from the exterior of the droplets. To create shells that encapsulate oil droplets, we add droplets of oil or other organic solvents to aqueous particle suspensions to form an oil-in-water (o/w) emulsion, as shown in Figure 1a. Particles self-assemble at the interface of the oil droplet to minimize total interfacial energy, forming a coating of polystyrene particles, as illustrated in Figure 1b. We stabilize the particle coating to form a solid shell before transferring the shells into oil, as shown in Figure 1c. Correspondingly, to encapsulate water droplets, we add droplets of water and other aqueous solutions to nonaqueous particle suspensions. Following self-assembly of a particle layer at the interface of the water droplets, we stabilize the particle layer by locking the particles together to form a solid shell. We then transfer these shells into water.

The morphologies of layers and shells of particle are examined by optical microscopy (Leica DMIRB, transmitted illumination) and scanning electron microscopy (LEO 982). Optical microscopy samples are imaged in glass sample chambers. Most images are obtained with 63 \times /0.70 air and 100 \times /1.40 oil objectives. To prepare samples for scanning electron microscopy, we first immerse the shells in ethanol and then allow them to dry in air for about 1 day. Before imaging, we sputter-coat the dry shells with a layer of gold that is 2–3 nm in thickness.

Deformation by calibrated microcantilevers enables quantitative characterization of the mechanical properties of shells.

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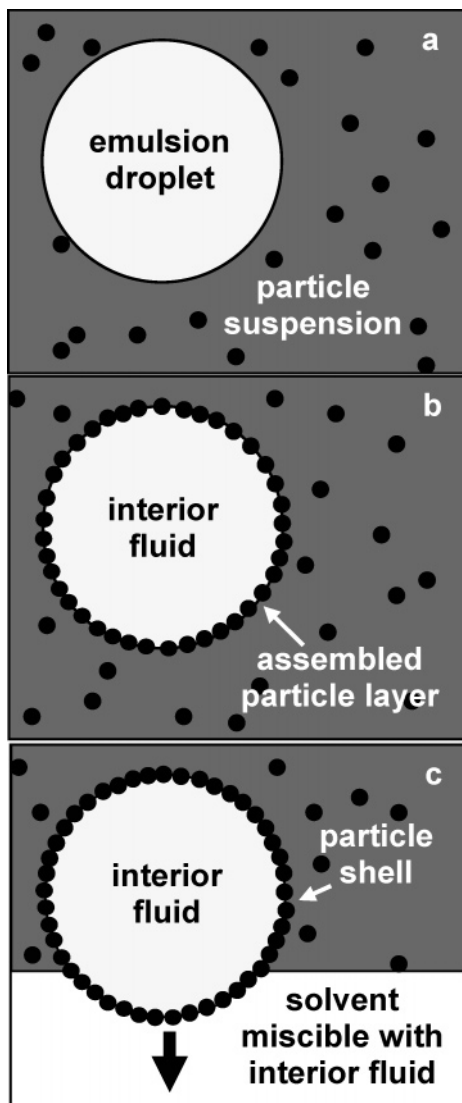


Figure 1. Schematic illustration of the shell fabrication process. (a) Emulsion droplets are formed in a suspension of particles. (b) Particles adsorb at the interface of emulsion droplets to minimize total interfacial energy, forming a layer of particles that encapsulates the droplets. Following self-assembly, we stabilize the layers to form solid shells. (c) Shells are transferred to a solvent miscible with the fluid inside the shell, thereby removing the droplet interface to create a porous capsule. Shell stabilization enhances the probability that capsules remain intact.

Microcantilevers are made by pulling glass capillaries or rods in a micropipet puller (Flaming/Brown Micropipet Puller P-97, Sutter Instruments). We calibrate the spring constant of each reference microcantilever by positioning the pulled tip just above a rigid straightedge mounted onto an analytical balance and then moving the microcantilever base down; the deflection of the tip of the microcantilever from its base is linear in applied force, allowing us to determine its spring constant. The tips of secondary microcantilevers are bent at right angles to their bases and shaped to define indenter geometries; these indenter tips are hemispherical and small compared to particle shells. Secondary microcantilevers are calibrated by pressing against reference microcantilevers and used to deform capsules axisymmetrically. Microcantilevers are controlled by a hydraulic micromanipulator while observed by optical microscopy.

3. Results and Discussion

Self-Assembly of Particle Layers. Self-assembly is a simple and effective method of encapsulating emulsion droplets with a layer of colloidal particles. Particles

assemble spontaneously at the interface of emulsion droplets to minimize the total interfacial energy.^{18–20} The assembly of particles eliminates interfacial area between the droplet phase and the continuous phase, thereby reducing interfacial energy. However, assembled particles become partially immersed in a different solvent, a change of interface that may result in a net increase in interfacial energy. Self-assembly proceeds when the total interfacial energy decreases; thus, adsorption is energetically favorable if $\sigma_{d,c} > |\sigma_{p,d} - \sigma_{p,c}|$, where $\sigma_{d,c}$, $\sigma_{p,d}$, and $\sigma_{p,c}$ are the interfacial energies between the droplet and continuous phases, the particle and the droplet phase, and the particle and continuous phase, respectively.³⁹ With our polystyrene particles, this criterion for self-assembly is satisfied by many chemically distinct emulsions. Moreover, particles assemble from water onto oil droplets, as well as from organic solvents onto water droplets.

To assemble particle layers that encapsulate water droplets in oil or other organic solvents, we add 1 μL of water to 200 μL of particles suspended in organic solvent. We emulsify the water in a glass vial by agitating with a vortex for several seconds, forming about 10^3 emulsion droplets that are about 10–200 μm in radius. When we add water to suspensions of DVB carboxyl particles in toluene or chlorobenzene and agitate, the particles assemble at the interface of the water droplets in monolayer coatings with nearly perfect local crystalline order,²⁷ as shown in Figure 2a. Most of the emulsion droplets are completely covered by a layer of particles. Furthermore, once particles self-assemble at the interface of the droplet, they never thermally desorb from the interface. This indicates that the adsorption energy is much larger than $k_B T$, as expected.²⁰ Particles at the interface are disperse and undergo thermal motion. Absence of aggregation enables particles to rearrange into arrays with a high degree of order.

We employ a similar process to assemble particle layers that encapsulate oil or other organic solvents in water. We add organic solvent to aqueous suspensions of particles and emulsify with gentle shearing to form thousands of smaller droplets of organic solvent. When we add droplets of toluene or chlorobenzene to aqueous suspensions of DVB carboxyl particles and agitate, the particles also assemble at the interface of the droplets of organic solvent, but with substantially lower surface coverage. Nevertheless, assembled particles never thermally desorb, undergoing thermal fluctuations at the interface.

Stabilization of Particle Layers for Shell Formation. Although emulsion droplets can be efficiently covered by a layer of self-assembled particles, it is desirable to stabilize these particle layers. Stabilization transforms layers of disconnected particles into solid shells, enabling the mechanical properties of the shells to be tuned. We reinforce the particle layers by adsorbing polymer to lock the particles together. By sintering, we increase the cross-sectional area of the connections between the particles, thereby strengthening the shell. Alternatively, if the particles in the layer become unstable, they can spontaneously aggregate to form a solid shell.

We stabilize particle layers that encapsulate water droplets in oil by polymer adsorption and by controlling the particle interactions near the droplet interface. We adsorb polymer by adding polymer to the water droplets, thereby stabilizing the particle layer from within the droplets. We control the particle interactions by suspending the particles in a solvent in which the particles

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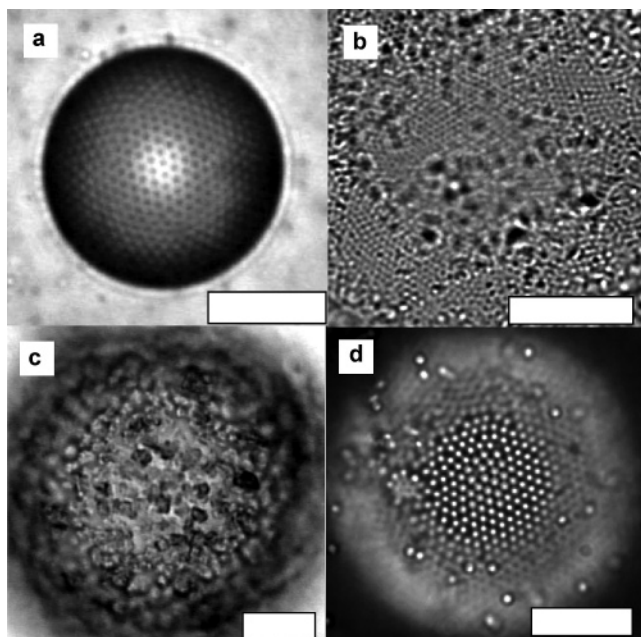


Figure 2. Optical micrographs of particle shells created with different droplet and continuous phases. Although particles always originate from the continuous phase, the stability of particles when suspended in each of the fluid phases impacts the morphology of the particle layer. (a) Particles assembled onto water droplets from toluene form monolayers of unfixed, diffusing particles with a high degree of local crystalline order. Particles are stable in both fluid phases. Particles assembled onto (b) droplets of aqueous polymer solution in toluene and (d) droplets of vegetable oil in water form monolayered shells of fixed particles that exhibit a lower degree of crystalline order. In each of these two cases, particles aggregate in the droplet phase but are disperse in the continuous phase. (c) Particles assembled onto water droplets in dodecane form disordered, multilayered shells of fixed particles. Particles aggregate in the continuous phase. Shells are composed of either 1.0 μm DVB carboxyl (a), 0.5 μm DVB carboxyl (b and c), or 1.1 μm aldehyde sulfate (d) polystyrene particles. White scale bars that are 10 μm in length appear at the bottom right of each image.

aggregate. The multilayered shells that form from particle aggregates begin at the droplet interface and extend into the continuous phase, deriving shell stability from particle interactions outside of the droplet.

To reinforce the shells via polymer adsorption, we add aqueous poly-L-lysine solution to suspensions of DVB carboxyl particles in toluene. After waiting for about an hour after shearing to allow the polymer to adsorb, we observe that assembled monolayers of particles are locked into shells. The particles are immobilized and exhibit a lower degree of crystalline order, as shown in Figure 2b. Poly-L-lysine fixes particles in place and prevents crystalline ordering, impacting both the morphology and the mechanical properties of the layer of assembled particles.

We can assemble particle layers onto droplets of water and other aqueous solutions from particles that are suspended in a number of oils and organic solvents. The stability of the particles in the oil influences the structure of the resulting particle layer, enabling tuning of the morphology and mechanical properties of the particle layer. By dispersing the particles in an organic solvent in which particles are unstable, particles aggregate in solution and near the interface of the water droplet, thereby locking the particles into a solid shell.

Particle stability is determined by interactions between the particles, the sum of electrostatic, steric, and van der

Waals interactions within a specific solvent.^{40,41} Polystyrene particles are stable in water because of electrostatic repulsion.⁴² Although charge stabilization is eliminated in pure, nonaqueous solvents, polystyrene particles that are cross-linked remain stable in good solvents such as toluene and chlorobenzene because of reduced van der Waals attraction and steric repulsion.⁴³ However, polystyrene particles aggregate in nonaqueous solvents such as dodecane and vegetable oil because van der Waals attraction dominates.

By assembling DVB carboxyl particles suspended in dodecane onto water droplets, we obtain multilayered shells of immobilized particles that are disordered, as shown in Figure 2c. Because particles aggregate in dodecane, they either adsorb at the droplet interface as aggregates or adhere to particles already at the interface. This precludes ordering via rearrangement, accounting for the disordered morphology. We also observe nonspherical shells encapsulating nonspherical water droplets when we agitate with greater intensity during fabrication, evidence of sufficient shell elasticity to counterbalance surface tension stresses from the water droplet. Therefore, particle stability in the continuous phase can significantly impact both the morphology and the mechanical properties of the shell.

Similarly, we stabilize particle layers that encapsulate oil droplets in water by controlling the particle interactions at the droplet interface. We control these interactions by using oils and organic solvents in which the particles aggregate, resulting in the stabilization of particle layers at the droplet interface. Additionally, we stabilize these particle layers by sintering, heating them above their glass transition temperature. By forming necks at the points of contact between particles, we impart additional strength to the particle shells and tune their structural properties.

We can assemble particle layers onto droplets of a number of oils and organic solvents from particles suspended in water. Even though the particles originate from the water phase in these systems, the stability of the particles in the oil influences the structure of the layer of assembled particles, enabling tuning of the morphology and mechanical properties of the layer. By assembling the particles onto droplets of an oil in which the particles are unstable, particles can become unstable at the interface as well, thereby locking the particles into a solid shell.

The stability of particles at the interface of an emulsion droplet can be influenced by the stability of particles in each phase of the emulsion. For emulsions of oil droplets in water, we expect that particles partially immersed in an oil such as vegetable oil in which the particles are unstable would be more likely to aggregate than particles partially immersed in an organic solvent such as toluene in which the particles are stable. However, additional interactions among particles at fluid interfaces may also be important. For example, the mismatch in dielectric constants of adjacent fluids can result in asymmetric particle charging, creating an electrostatic repulsion between effective dipoles.^{20,23,44} Moreover, there may be an additional capillary attraction induced by deformation of the fluid interface near the particles.^{24–26} However, capillary attraction induced by gravity is not relevant here

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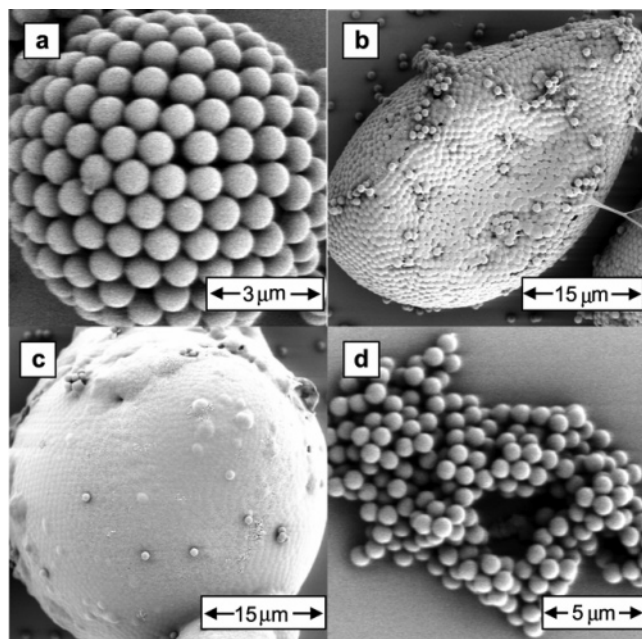


Figure 3. SEM images of shells after various stages of sintering. Shells composed of $1.1\ \mu\text{m}$ aldehyde sulfate particles are formed on droplets of vegetable oil in water, sintered at $105\ ^\circ\text{C}$, and immersed in ethanol to remove the interface of the emulsion droplets. The resulting shells are then dried to enable imaging with the SEM. After 5 min of sintering (a), the capsules exhibit well-defined, interstitial pores. These pores gradually disappear as capsules are sintered for longer times: 20 min (b) and 2 h (c). In contrast, unsintered capsules collapse upon drying (d).

because of the small size of the particles and the presence of solvents of similar mass density.²¹

Aldehyde sulfate particles that adsorb from water onto vegetable oil or silicone oil droplets aggregate at the droplet interface, resulting in shells of immobilized particles. Although these shells exhibit some degree of order, as illustrated in Figure 2d, aggregation prevents rearrangement into arrays with a greater degree of crystalline order. When we fabricate these shells by vigorous shaking instead of gentle shearing, we observe that the resulting shells are nonspherical, encapsulating oil droplets that are correspondingly nonspherical. This demonstrates that the shells are not only rigid but are also strong enough to counterbalance oil–water surface tension stresses of the emulsion droplets.

Alternatively, we sinter the particle shells not only to impart additional stability but also to tune the porosity and permeability. Sintering entails heating in an oven to $105\ ^\circ\text{C}$, slightly above the glass transition temperature of the polystyrene particles. Since this temperature exceeds the boiling point of water, we add 70 wt% of glycerol to the water to elevate its boiling point. By heating these shells, we enable the particles to fuse together at points of contact. When necks begin to form at these contact points, the shell becomes stronger and the interstitial pores become smaller. Shells of aldehyde sulfate particles become less porous with increasing sintering time, as shown in Figure 3. Pores are open in most shells sintered for 5 min (Figure 3a) and some shells sintered for 10 min. However, pores of almost all shells sintered for 20 min are closed (Figure 3b). Individual particles are essentially indistinguishable after 2 h of sintering (Figure 3c), indicating completion of the sintering process.

These methods of shell stabilization can be employed both in systems where particle layers encapsulate water

in oil and in systems where particle layers encapsulate oil in water. We explicitly demonstrate in each case that shells can be stabilized by controlling the particle interactions at or near the interface of the emulsion droplet. Although we demonstrate polymer stabilization only for particle layers that encapsulate water droplets in oil, it is also possible to stabilize particle layers that encapsulate oil droplets in water by adsorbing the same polymer from the exterior phase. Similarly, it is also possible to sinter particle layers that encapsulate water in oil.

Shell Permeability. To allow our particle shells to function as permeable capsules and to fully exploit our control over shell morphology, we remove the interface of the emulsion droplets. Interface removal enables diffusive exchange and selective permeability through the interstitial pores between particles that comprise the shells; this allows shell morphology to regulate selective exchange across the shell, rather than the interface of the emulsion droplet. We remove the interface of emulsion droplets by centrifugation and by addition of co-solvent. During centrifugation, shells are drawn into a solvent that is miscible with the encapsulated droplet phase, as illustrated schematically in Figure 1c. When a co-solvent is added to the fluid outside the shell, the encapsulant becomes soluble in the exterior fluid. We then verify selective permeability of these shells by measuring the flux of particles that are small enough to fit through the pores and by demonstrating that particles that are larger than the pores size cannot permeate through the shell.¹⁸

To remove the interface of emulsion droplets from shells that encapsulate water droplets in organic solvent via centrifugation, we first place a column organic solvent that contains shells of particles on top of a column of aqueous surfactant solution in a container. The surfactant facilitates the transfer by lowering the surface tension of the interface through which the shells traverse. The density of water is greater than that of the organic solvent but less than that of the particles. When a downward force is applied during centrifugation, the shells are drawn from the organic solvent into the water.

Stabilization of assembled particle layers is essential to survive centrifugation. Monolayers of DVB carboxyl particles are first assembled in toluene on water droplets and then transferred to octanol, which has a lower surface tension with water. To further decrease the surface tension, we add 10 mg/mL of Tween 20 to the aqueous phase beneath the octanol. We place approximately 1 mL of this aqueous surfactant solution in a 1.4 mL centrifuge tube and then add about $100\ \mu\text{L}$ of octanol solution containing particle shells on top. After centrifugation at $9300g$ for 10–15 min, these unstabilized particle layers disintegrate at the interface between octanol and the aqueous surfactant solution. In contrast, these same particle layers survive centrifugation when stabilized by polymer adsorption. In a typical batch, about 1–10% of these shells maintain their mechanical integrity. The remainder consists of shells that are slightly deformed, punctured, or ripped. Thus, stabilized shells can maintain their structural integrity when the droplet interface is removed. The survival of different types of shells against different methods of interface removal is summarized in Table 1. For particle layers encapsulating water droplets in organic solvent, we also remove the droplet interface by means of co-solvent addition. To accomplish this, we add large volumes of ethanol, in which all solvents used in this experiment are at least partially soluble. For these monolayers of DVB carboxyl particles that encapsulate water droplets in toluene, we add a few milliliters of ethanol to about $100\ \mu\text{L}$ of toluene with particle-stabilized

Table 1. Effect of Interface Removal on the Mechanical Integrity of Particle Shells^a

	unfixed layer of particles	polymer stabilized	van der Waals stabilized	sintered
centrifugation	disintegrates	remains intact	remains intact	not tested
addition of co-solvent	disintegrates	remains intact	remains intact	remains intact
drying	not applicable	flattens	flattens	remains intact

^a Removal of the emulsion droplet interface enables particle shells to function as selectively permeable capsules. This table summarizes the typical impact of interface removal on the mechanical integrity of particle shells. Stabilized shells maintain structural integrity following centrifugation and the addition of co-solvent, enabling them to function as selectively permeable capsules. Images of typical shells of unfixed particles and of particles stabilized with polymer, van der Waals bonds, and sintering appear in Figures 2a, 2b, 2d, and 3a, respectively. For comparison, the effect of drying on the mechanical integrity of these shells is also tabulated

water droplets. The encapsulated water droplets then become soluble in the exterior fluid. As expected, shells of unfixed particles disintegrate. In contrast, most shells stabilized by polymer adsorption survive this process. Unlike in centrifugation, the appearance of most of these shells does not change substantially after interface removal.

We also centrifuge shells that encapsulate oil droplets in water, as with shells that encapsulate water droplets in oil. To remove the interface of emulsion droplets in these systems, we centrifuge the shells from water to an organic solvent that is miscible with the encapsulant. Shells of aldehyde sulfate particles stabilized by van der Waals forces that encapsulate silicone oil in water survive interface removal via centrifugation. We facilitate the transfer of shells from water to silicone oil by adding 1 mg/mL of Span 80 to the silicone oil to lower the surface tension with water. We place approximately 1 mL of this oil/surfactant solution in a 1.4 mL centrifuge tube and add about 100 μ L of aqueous solution that contain particle shells on top. Because the density of this oil/surfactant solution is greater than that of water but less than that of the particles, the shells are drawn from the water into the oil/surfactant solution during centrifugation. After centrifuging at 9300g for 10–15 min, a few of these shells maintain their mechanical integrity in a typical batch. The remainder consists of shells that are slightly deformed, punctured, or ripped.

These shells also survive interface removal by addition of co-solvent. To accomplish this, we add a few milliliters of ethanol to about 100 μ L of shell-stabilized droplets of silicone oil in water. This enables the silicone oil to become soluble in the exterior fluid. Unlike in centrifugation, the appearance of most of these shells does not change substantially after interface removal. Similarly, shells that encapsulate vegetable oil in water also survive this process, both before and after sintering.

Each method of removing the interface of emulsion droplets imposes a stress on the particle shells. Thus, observations of how various types of shells maintain mechanical integrity against different methods of interface removal provide a qualitative characterization of the mechanical properties of the shells. Stabilized particle shells generally survive removal of the emulsion droplet interface, while unstabilized particle layers do not, as summarized in Table 1.

Mechanical Response of Shells. To quantitatively measure the mechanical properties of the particle shells, we observe the mechanical response to deformation by a calibrated microcantilever. Controlling shell properties such as breaking force is important in ensuring a desired response to specific mechanical stimuli. Before characterization, we transfer the shells to a solvent that is miscible with the encapsulant. This allows us to measure the properties of the shell, independent of the interface of the emulsion droplet used for self-assembly. We then incrementally indent, deform, and break the shells axially with calibrated microcantilevers. By ob-

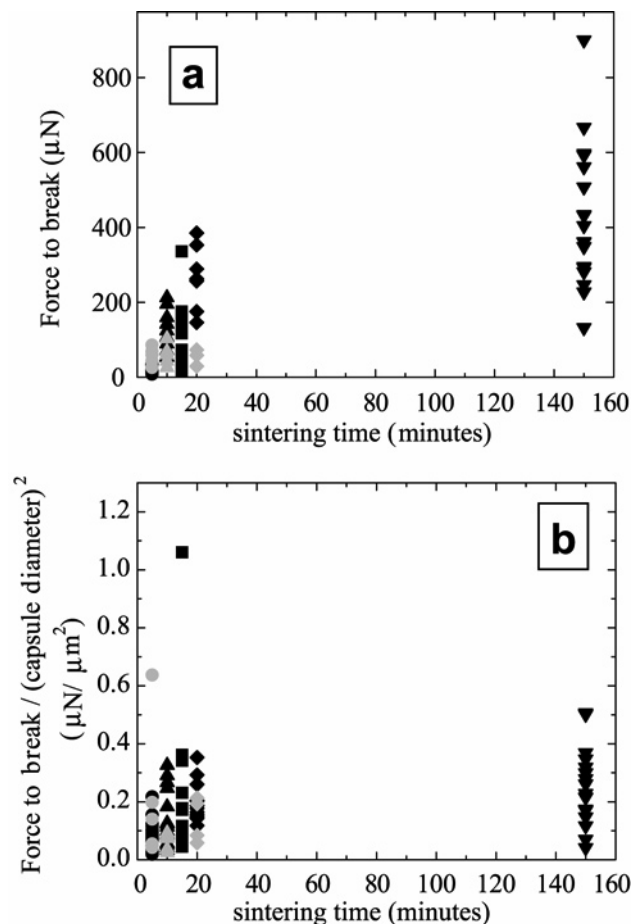


Figure 4. (a) The typical force required to break or puncture sintered shells increases with sintering time. The range in breaking force also increases with sintering time but (b) decreases significantly at longer sintering times when breaking force is normalized by the square of the capsule diameter. This indicates size-dependent behavior, suggesting the onset of continuum shell deformation behavior with long sintering times. Grey symbols designate trials on a second batch of shells with a different microcantilever. Some shells sintered for 150 min cannot be broken with any of our microcantilevers and are omitted.

serving the deflection of the microcantilever, we determine the applied stress. Measuring the strain response from shell deformation yields measurements of mechanical properties.

Shell stabilization can impact not only shell morphology but also the mechanical properties of capsules following interface removal. After centrifugation, polymer-stabilized shells show remarkable elastic resilience to deformation. Shell mechanical response is dominated by adsorbed and free interior poly-L-lysine, with structural spring constants from point indentations of $\sim 10^{-2}$ N/m and critical indentation values greater than 0.7 shell diameters.³⁸ In contrast, sintered shells are more stiff and brittle than those stabilized with polymer. Moreover, mechanical

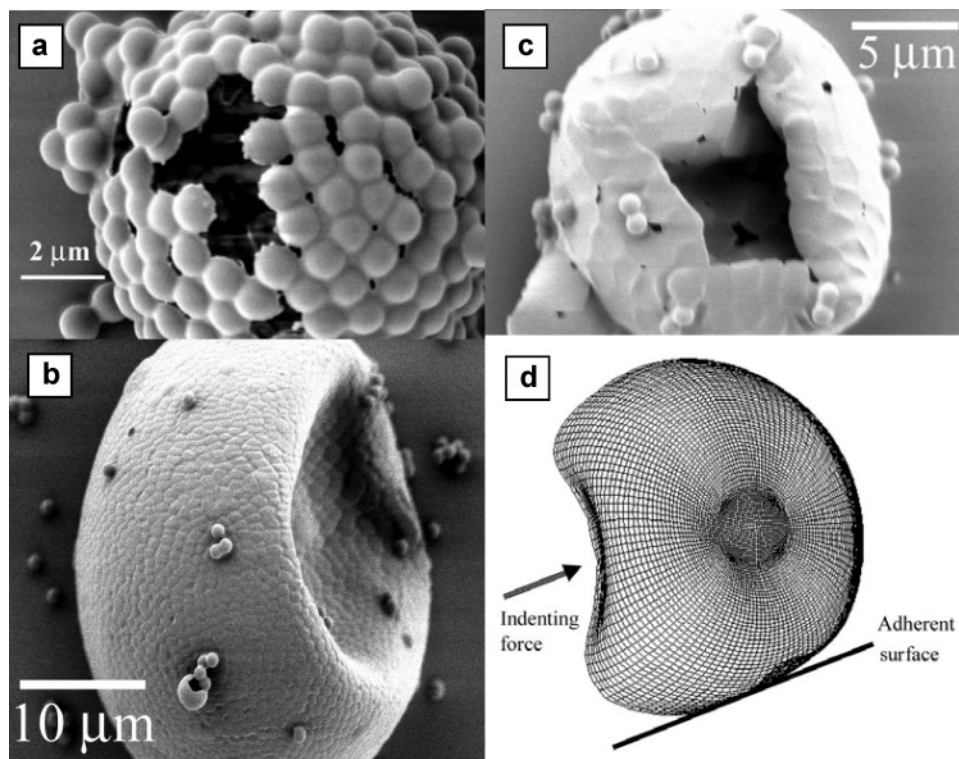


Figure 5. Shells sintered for varying amounts of time exhibit distinct breaking modes, as shown in SEM images. Typically, with lightly sintered shells (20 min shown), microcantilevers punch out discrete particles along perforated connections with minimal impact on shell regions away from the puncture site (a). In contrast, well-sintered shells (150 min shown) exhibit continuum deformation (b) and failure (c). Simulations of the deformed shape of a substrate-adhering shell with a uniform thickness of $1 \mu\text{m}$ and the bulk elastic modulus of polystyrene (3 GPa) (d) agree well with experimentally observed point deformation on sintered shells (b).

properties such as shell modulus and breaking force can be modified by varying sintering time. As we increase sintering time from 5 to 150 min, typical shell moduli increase from 5 to 100 N/m. Data from microcantilever measurements show that for comparable shell size distributions, both the typical force needed to break shells and the range of breaking forces increase with sintering time, as plotted in Figure 4a. Sintering causes the contacts between particles to thicken and form necks. Because we expect structural strength to increase with the cross-sectional area of these necks, it is not surprising that progressively longer sintering times result in stronger capsules. The variation in breaking forces also increases with sintering time. This reflects the variability of mechanical properties among sintered shells. Nevertheless, there is still an upward trend in breaking force as a function of sintering time, demonstrating that we can tune the mechanical properties of these capsules through sintering, as well as by polymer adsorption.

In addition to strengthening the capsules, sintering also transforms the mode of failure. Failure of capsules sintered for shorter times is discrete and localized; individual particles detach from the shell along connections between particles, as shown in Figure 5a. In contrast, well-sintered shells exhibit continuum deformation and failure that impacts regions far from the indentation point, as demonstrated in Figure 5b and c. Furthermore, normalization of breaking force by shell diameter significantly narrows the breaking force range for longer sintering times, as plotted in Figure 4b. This indicates size-dependent indentation behavior and suggests the onset of continuum shell deformation. Simulations of deformation provide additional confirmation that well-sintered shells behave approximately as continuum shells. Our model shell has a uniform thickness of $1 \mu\text{m}$ and a bulk

elastic modulus of 3 GPa; these material parameters correspond to those of well-sintered shells made with polystyrene particles used in our experiments. Simulation by finite element analysis⁴⁵ yields an indentation load–displacement relationship that is essentially linear and consistent with measurements.³⁸ The similarity between images of shells deformed in experiment and simulation is illustrated in Figure 5b and d.

In addition to increasing the breaking force and transforming the mode of failure, sintering also enables these shells to maintain structural integrity when dried. Because drying imposes stresses on the shells, mechanical response to drying is another method of shell characterization. These stresses are highly relevant in applications such as powder processing for which drying is necessary. Shells of aldehyde sulfate particles are stabilized by van der Waals forces and remain intact when transferred to ethanol. However, when we dry these shells by allowing the ethanol to evaporate away, they flatten into disordered clusters of particles, as shown in Figure 3d. Results are similar for polymer-stabilized shells. In contrast, sintering the shells of aldehyde sulfate particles before removal of the emulsion droplet interface allows them to survive drying stresses. For comparison, these results of response to drying are summarized in Table 1 along with response to interface removal.

4. Outlook

The process of constructing permeable shells by means of self-assembly of colloidal particles is not only simple and robust but also versatile. By selecting from distinct techniques at each point of the fabrication process, we

(45) ABAQUS; ABAQUS Inc.: Pawtucket, RI, 1999.

demonstrate that there are many options through which to create and tune the properties of permeable shells in different experimental systems for numerous applications. During self-assembly, the first step of shell fabrication, we coat both aqueous and oil droplets with a layer of colloidal particles. This enables encapsulation of active agents that are both hydrophilic and hydrophobic. Thus, this method for encapsulation can be used for applications ranging from biological materials and other aqueous solutions to fragrances and other organic compounds. In the next step, we stabilize these layers of colloidal particles to create a solid shell either by polymer adsorption or by sintering to form solid capsules. Through polymer adsorption, we impart the elasticity and permeability of polymer shells to the shell of colloidal particles.³⁸ Through sintering, we can enhance the strength and reduce the permeability of the shell as the interstices between particles gradually shrink and ultimately disappear with longer sintering times. Control of these mechanical properties is essential for applications requiring controlled release in response to mechanical stresses and by diffusion. Finally, because the shell is solid, we can transfer the structures to a new continuous fluid, thereby removing the interface between the internal and continuous fluids. This enables diffusive exchange through the walls of these capsules. Though co-solvent addition is the simpler method of interface removal, centrifugation can be essential if encapsulants include biological cells, for which common co-solvents such as ethanol are toxic. Drying the capsules can also be of interest in powder processing or applications where rehydration after extended periods of storage time is desirable. Thus, flexibility in the composition of the encapsulant, the type of shell stabilization, and the method of interface removal underscores the versatility of this technique for the self-assembly of permeable shells.

In these experiments, we employ only polystyrene particles to construct shells of colloidal particles. Even though we use particles of only one material, we can still control of shell morphology and mechanical properties through a number of different methods. This latitude underscores the vast number of possibilities for self-assembling capsules with specific, well-characterized properties. Colloidal particles of many different compositions are readily available, and many of their surface properties are easily modified so that particles can assemble on a number of chemically distinct fluid–fluid interfaces. In addition, colloidal particles with a large range of glass transitions are available, facilitating sintering to solidify the shell and adjust the permeability. We expect that the assembled layer of particles can be stabilized with the proper choice of solvent and further

tuned with a number of shell-stabilization techniques. This versatile approach enables the construction of self-assembled shells with tunable properties in applications with significant material constraints on the colloidal particles and the solvents. On the basis of our success in constructing shells via self-assembly with a benchmark colloidal particle, we expect that a similarly broad array of shells can be self-assembled with particles of many other compositions.

5. Summary

We present a method of fabricating self-assembled shells of polystyrene particles whose morphology and mechanical properties can be tuned through selection of the appropriate solvents. When the particles do not aggregate in the exterior fluid, the particles can self-assemble to form monolayer shells. When particles aggregate in neither exterior nor interior fluids, they form a monolayer of unfixed particles at the interface of emulsion droplets. In contrast, when particles aggregate in the interior fluid, the particles form shells that are relatively rigid. Furthermore, when particles aggregate in the exterior fluid, the particles form shells that are multilayered and disordered. With this latitude, we make shells for applications ranging from the study of particle interactions and ordering at spherical interfaces to the fabrication of selectively permeable membranes for encapsulation.

To explore the viability of these shells as capsules, we remove the emulsion droplet interface by transferring the capsule into a continuous fluid phase that is miscible with the internal fluid of the droplet. This requires particle shells with sufficient structural strength to withstand the change in surface tension; thus, we investigate the structural integrity of the shells. By removing the interface, we enable diffusive exchange of small particles through the interstices of the particles that comprise the shell. Qualitatively, we demonstrate that van der Waals- and polymer-stabilized shells remain intact against interface removal via centrifugation and addition of co-solvent. Quantitatively, measurements of deformation by calibrated microcantilevers show that polycations dominate the mechanical properties of polycation-stabilized shells³⁸ and that sintering strengthens and stiffens the shells as expected by gradually transforming discrete and porous particle shells into continuum shells.

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