Supplementary information

Definition of mechanics terms:

Stress – Force per unit area in a material. As first recognized by Galileo in a study of the bending of a beam, the description of forces in a material always begins with recognition that it is the stress distribution that is most significant.

Strain – Change in length per unit length. Usually, this can be estimated by measuring the change in length following deformation and dividing by the original length of the material.

Elastic – An elastic material deforms a finite amount under a given load or applied stress. When the stress is removed, the material recovers its initial shape and configuration. A plot of stress versus strain is generally linear and the slope of the stress-strain curve, or elastic modulus, characterizes the material.

Plastic – A plastic response refers to deformations, or strains, that are large enough that the stress-strain curve is no longer linear and the material does not completely recover its initial configuration following removal of the applied loading.

Perfectly plastic – A perfectly plastic material deforms continually under a constant applied stress. The stress versus strain diagram in this case is a horizontal line.

Hoop Stress: Stress acting perpendicular to the radius of an object.

Shear flow experiment for verification of bubble rigidity

The armoured bubbles were transferred to a continuous medium of pure glycerol to achieve higher shear stresses when subjected to flow. The flow chamber employed was a custom made quartz parallelepiped with a height of 1.0 mm, width 10 mm and length of 10 mm. Shear rates of up to 4 s^{-1} were applied by controlling the flow rate with a syringe pump. Application of the flow results in an increase in the fluid pressure, which causes the bubble to crumple, prior to undergoing a tumbling motion.

A fluid-like response of a particle covered membrane requires ε_{micro} over most of the surface, as discussed in the main text, the particles must be free to slide relative to one another to achieve a liquid-like response. Since the interfacial solid is elastic in tension and compression, the effective elasticity[2] of the membrane is $E=4.92\gamma/r$ where γ is the interfacial tension and *r* is the particle radius.

So a strain ε_{micro} requires a stress: $4.92(\gamma/r)\varepsilon_{micro}$.

For shear flow of shear rate $\dot{\gamma}$ and a fluid of shear viscosity, μ, a balance of viscous stresses and elastic stresses yields

$$\mu\dot{\gamma} \cong 5\frac{\gamma}{r}\varepsilon_{micro}$$

or

$$\dot{\gamma} \cong 5\frac{\gamma}{\mu r}\varepsilon_{micro}$$

The approximate shear rate required to trigger the transition from tumbling to tank-treading for the above experimental setup is $3.2\text{x}10^3$ s^{-1} for bubbles armored with 2.0 μm radius beads in glycerol, or a fluid velocity of 3.2 m/s.

References:

1. Gere, J.M. & Timoshenko, S. P. *Mechanics of Materials*, (PWS Publishers, Boston, ed. 2, 1987).
2. Vella, D., Aussillous, P. & Mahadevan, L. Elasticity of an interfacial particle raft. *Europhys. Letts.* **68**, 212-218 (2004).

Caption for Supplementary Movie 1:

A bubble armored with 4.0 μm diameter polystyrene particles subjected to a shear flow in pure glycerol. Note that the bubble crumples when the flow is started and tumbles like a solid even for a high shear rate. The tumbling motion of a smaller out of focus crumpled bubble on the left hand side of the movie can also be observed.

Caption for Supplementary Movie 1:

An ellipsoidal bubble armored with polydisperse ground zirconium oxide particles, with an average diameter of 200 microns. The movie was treated with ImageJ image processing software to highlight the edges of the particles. The bubble is compressed with a pair of tweezers. Note that the bubble transitions from a prolate to oblate elliposoid. The particles move in shear bands in response to the applied stress.