

Climbing Colloidal Suspension

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Abstract: Mixtures of powder and liquid are ubiquitous in nature as well as industries and exhibit complex flowing and deforming behaviors, including sol to gel transition under shear stress. In order to better understand the characteristic features of this type of mixture, we observed the behavior of a mixture of colloidal silica particles and water as a model system under vibration. The mixture showed different states, from powder-like to viscous fluid-like, with increasing content of water. At certain concentrations of silica particles (around 70 wt. %) and under relatively faster vibration (over 17 Hz), we observed that the colloidal suspension of silica particles and water climbed up the wall of a container against gravity. The main purpose of this paper is to report how we can observe the climbing suspension of colloidal silica. The rheological measurements of the climbing suspension demonstrated that the climbing suspension showed shear-thickening behavior, where force chain networks and normal stress differences are considered to develop. Therefore, we speculate that the transient formation and breaking of force networks and normal stress differences under vibration contribute to the occurrence of the climbing suspension. The tunable nature of colloidal suspensions may help to elucidate the climbing mechanism in the future.

Keywords: dense suspension; rheology; vibration; shear thickening; dilatant fluid



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1. Introduction

In many industrial and environmental processes, it is of great importance to understand and control the flowing properties of powder, liquids, and their mixtures [1–7]. The states of mixtures of liquid and particles can be flowing liquid-like, elastoplastic solid or gel-like, granule-like, or powder-like depending on liquid content, particle shape, surface properties, solution chemistry, applied stress, etc. [8–14]. Rheological measurements using well-defined flow and deformation fields with theoretical considerations can allow us a mechanistic understanding of fluidic and elastoplastic behaviors of the mixtures of particles and liquid [2,15–18]. Meanwhile, primitive tests such as direct observations of the behavior of mixtures of particles and liquid under repeated impacts, the vibration of fresh concrete, and rolling clay by hand are still useful methods to characterize the behavior and states of the mixtures and particles [8,19]. Therefore, direct observations of fluid, powder, and their mixture under mechanical stimulation could somehow give us important information.

It has been imperative to understand the transition of the states of mixtures composed of particles and liquid from powder-like to liquid-like from scientific and engineering points of view [8,14,19]. To obtain better insight into the transition of states, the authors have observed the behavior of a mixture of water and spherical colloidal silica particles as a model system in a container vibrated by a test tube mixer. On a certain occasion, rather surprisingly and interestingly, the authors could observe that the liquid-like colloidal suspension climbed along the wall of the container against gravity at least in centimeter-scale flow (Movies S1 and S2 in Supplementary Materials). This strange phenomenon

was easily and repeatedly reproducible from the preparation of the suspension to direct observation of climbing by each of the authors.

At the moment, it has been known that polymer solutions, powders, and colloids show peculiar and interesting phenomena, and such phenomena are introduced in textbooks and research papers as fascinating examples of these fields for beginners and researchers. For example, polymeric liquids climb along a spinning rod, known as the Weissenberg effect, where it is considered that normal stress differences play a significant role in climbing [7,20]. Dry powder can be solid-like and liquid-like and make various patterns under vibration, and the physics behind it has been discussed [6]. Rheological behaviors of concentrated suspensions such as jamming and solidification at high shear have attracted attention [21,22]. Such concentrated suspensions show dancing-like behavior under vibration, and controlling suspension viscosity by vibration was successfully demonstrated [23,24]. Recently, soft active matter has been reported to climb a wall, and theoretical consideration for this climbing using a constitutive model was made [25,26]. Very similar phenomena of the climbing of suspension droplets, Faraday wave, holes, and fingers were observed for granular cornstarch–water suspension under vertical vibration by Hou and Peterson [27], who introduce the concept of effective negative viscosity of discontinuous shear-thickening fluid to explain the climbing qualitatively. A new concept of viscosity metamaterial for dense suspensions was introduced [28]. All these phenomena are very intriguing examples of liquids, powder, and suspensions. Nevertheless, to the best of the authors' knowledge, the phenomenon of simple and typical colloidal suspensions discernibly climbing against gravity under simple horizontal or vertical vibration in an easy manner as introduced in this paper has not been reported so far. Properties of colloidal suspensions can be tuned with the particle shape, the particle size, the particle size distribution, the surface chemistry of particles, the wettability, the medium type, and the ionic composition of the medium. Due to this tuning possibility and stability, the climbing colloidal silica suspensions could be good model systems to deepen the understanding of the climbing phenomenon. Thus, we have investigated the conditions for the climbing suspension of colloidal silica to appear.

Here, in this paper, we report the climbing colloidal suspension of a mixture composed of spherical colloidal silica particles and deionized water. The effect of water content and particle size on the occurrence of the climbing suspension are shown below. Furthermore, the rheological properties, non-Newtonian viscosity, and storage modulus and loss modulus of the climbing suspension are given and discussed. While a lot of things are not known about the mechanism of the climbing suspension at this moment, we believe that these experiments on the climbing of mixtures of colloidal silica particles and water by simple horizontal and vertical vibration can offer a better example for the climbing phenomenon than granular cornstarch suspension and stimulate the research communities that have been dealing with liquids and suspensions.

2. Materials and Method

2.1. Materials

Commercially available silica particles in a dried powder state (Seahoster KE-P series, Nippon Shokubai, Japan) were used as received. Three different diameters adopted in this study were 0.5, 1, and 2.5 μm . The manufacturer has been providing nearly monodispersed and spherical silica particles, which are well dispersed in water at low salt concentrations and at neutral to high pH because of the negative surface charge of silica particles [13,29–32]. About 10 g of total mixtures of silica and water was prepared by placing the silica powder and deionized water produced by the Elix 5 system (Millipore, Tokyo, Japan) in a sealed A-6 polypropylene ointment container with a container size of 48 mm for the inner diameter and 66 mm for the height (MI Chemical, Itami, Japan). The mixture in the container was mixed by using the compact planetary mixer AR-100 (Thinky, Tokyo, Japan) for at least 5 min. The planetary mixer can apply a revolution speed of 2000 rpm and a rotation speed of 800 rpm to the container, which ensure the sufficient mixing of viscous samples. After the mixing, we noted that powder-like states remained at lower water contents, while rather

viscous flowing suspensions were visually confirmed at higher water contents. Any further treatments of the suspensions were not carried out without the vibration described below.

2.2. Vibration Experiments

The silica suspensions in the containers were subjected to vibration by using a test tube mixer (TTM-1, Sibata, Tokyo, Japan), which provides eccentric rotational motion of a cylindrical disc head. Horizontal vibration was applied to the mixture of the silica particles and the deionized water in the container by attaching the container bottom to the head surface of the test tube mixer. This attaching of the container bottom to the disc head was executed by using a piece of double-sided adhesive tape. Vertical vibration was also tested by laying down the test tube mixer and tapping the container bottom by the side of the disc head of the test tube mixer under different frequencies with a vibration amplitude of 1.7 mm. The container was supported by a hand during the vibration applied by the laid test tube mixer. The amplitude and frequency of vibration were determined from the video images taken by a high-speed video camera (EXLIM PRO EX-F1, Casio, Tokyo, Japan). We have observed that viscous liquid-like suspensions at proper water contents were able to climb up along the wall inside the container at higher frequencies (see Figure 1 and Movies S1 and S2 in Supplementary Materials). This state was categorized as “climbing suspension”. In some cases, whole suspensions could reach the lid. We did not vary the height of the container. Therefore, the maximum height was equal to the container height. Examining the maximum reachable height would be a future work. At lower water content, the mixtures of silica particles and water were dry-powder-like, wet-powder-like, or solid-like, and thus, this state was judged as an undispersed state. Undispersed ones did not climb along the wall. The suspensions with higher water contents were flowing liquid-like, but the mixture showed an agitated surface and did not climb up when subjected to vibration. This state was simply classified as dispersed suspension. The dispersed one was liquid-like and less viscous than the climbing suspension and did not climb. Our preliminary test results confirmed that the vertical vibration was more effective in inducing the climbing suspension. Therefore, we report the results of the states diagram obtained by vertical vibration below. We judged the “climbing suspension” state at different diameters of particles and frequencies when the entire suspension left the bottom. The jumping of particles seen for dry powder was not found for the suspensions in this study due to the confinement of particles by water [22]. Typically, in the case of the climbing suspension, this climbing happened in 30 s at the maximum frequency. Some suspensions showed a symptom of climbing, but a part of the suspension remained on the bottom. Such suspensions were nonclimbing and classified as dispersed suspensions. There would be a possibility that some nonclimbing suspensions would climb after a very long time of vibration. The vibration experiment was started just after the sample mixing.



Figure 1. Pictures of the climbing colloidal suspension of 70 wt. % silica particles of 1.0 μm diameter with water under horizontal vibration. The corresponding movie is given in Supplementary Materials. The left picture shows the suspension at rest, and the middle (~8 s in the movie) and right (~12 s in the movie) ones are under vibration.

2.3. Rheological Experiments

A rheological experiment was carried out for the suspension, showing the behavior of the climbing suspension. Measurements of shear-rate-dependent steady shear viscosity and dynamic viscoelastic properties as a function of frequency at 1 Hz and as a function of strain amplitude at 1% [32] were carried out by using a rheometer equipped with two concentric cylinders (ONRH-1, Ohna Tech, Tsukuba, Japan). The choice of the frequency of 1 Hz and the strain amplitude of 1% was to follow a previous research study on the rheology of silica suspension [32]. The diameters of the inner and outer cylinders were 19.36 mm and 21.00 mm, respectively. The suspension set in the gap between the two cylinders was sheared by rotating the outer glass cylinder. The rheological measurement was started just after the sample mixing. The pH of suspensions was around pH = 6, which was measured by using a compact pH meter (Laqua twin pH-22B, Horiba, Kyoto, Japan). All the experiments were carried out at room temperature around 20 °C.

3. Results and Discussion

After the sufficient mixing of the silica powder and deionized water, the mixture state in the container was observed under the highest vibration frequency around 42 Hz. This observation was carried out for the mixtures with different particle concentrations and diameters of silica particles. The obtained diagram of the states is shown in Figure 2, where the vertical and horizontal axes are the diameter of silica particles and the solid concentration of silica particles, respectively. In this figure, the red-filled circles, the black crosses, and the green open triangles stand for the climbing suspension state, the undispersed state, and the dispersed suspension, respectively. As shown in Figure 2, our results demonstrated that the climbing suspension appeared for all the examined particles with different diameters in a very limited range of particle concentrations; that is, 70 weight (wt.) % for silica particles with 0.5 and 1.0 μm diameters and 72.5 wt. % for silica particles with a diameter of 2.5 μm were observed. With the density of silica particles by the manufacture of 1.9 Mg/m^3 and the density of water of 1.0 Mg/m^3 , the corresponding volume fractions of the climbing suspensions are 0.55 and 0.58 for 70 wt. % and 72.5 wt. %, respectively. At these concentrations, the climbing suspensions were found to occur at vibration frequencies higher than 17 Hz. We also confirmed that the climbing suspensions, which climbed up to the upper part of the container during the vibration, flowed down due to gravity once the vibration was stopped (see Movie S2 in Supplementary Materials). These results based on direct observation demonstrated that precisely controlling the content of water and applying a reasonably high vibration frequency are necessary for the climbing colloidal suspension to be observable by the naked eye.

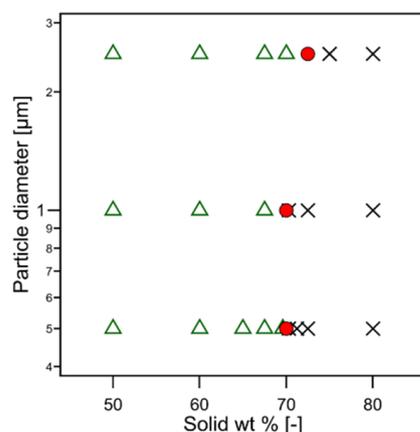


Figure 2. States diagram of the mixtures of silica particles with different diameters of 0.5, 1.0, and 2.5 μm and deionized water: dispersed suspension (Δ), climbing suspension (\bullet), and undispersed (\times).

It should be mentioned here that the climbing suspension was found for a freshly prepared concentrated mixture (61 wt. %) of cornstarch powder (Starch, Corn, Guaranteed Reagent, Fujifilm Wako Pure Chemical Corporation, Osaka, Japan) and deionized water as well. The concentrated mixture of cornstarch and water is a widely known example of shear thickening or, in other words, dilatant fluid. Thus, the climbing suspension is a potentially universally observable phenomenon for concentrated suspensions showing shear thickening at appropriate particle concentrations and vibration speeds.

In order to obtain further insight into the climbing suspension phenomenon, we have carried out rheological measurements. The results of the rheological measurements for the climbing suspension of water and silica particles with 1.0 μm diameter are shown in Figure 3, where the viscosity of the suspension against the shear rate (a), the storage modulus and the loss modulus against frequency (b), and the storage modulus and the loss modulus against strain amplitude (c) are plotted. Figure 3a shows that the climbing suspension was a non-Newtonian fluid. We measured the viscosity from low shear rates to higher shear rates twice successively. The first and second relationships between viscosity and shear rate differed probably due to sedimentation. In the figure, we see shear thinning at low shear rates and shear thickening at shear rates higher than 20 s^{-1} . Shear thickening was also observed for the climbing suspensions of water and silica particles with 0.5 and 2.5 μm diameters. Figure 3b,c indicate that the storage modulus is smaller than the loss modulus in the whole range, but the storage modulus becomes higher than the loss modulus at high frequencies. While gelled suspensions generally show a trend that storage moduli at low frequencies are almost constant within small strain amplitudes, the present silica suspension did not show such a trend, indicating that the present silica suspension is liquid-like or weak-gel-like. These results imply that the present silica suspension is liquid-like at low shear rates or low frequencies and can become more elastic and gel-like at high shear rates or high frequencies.

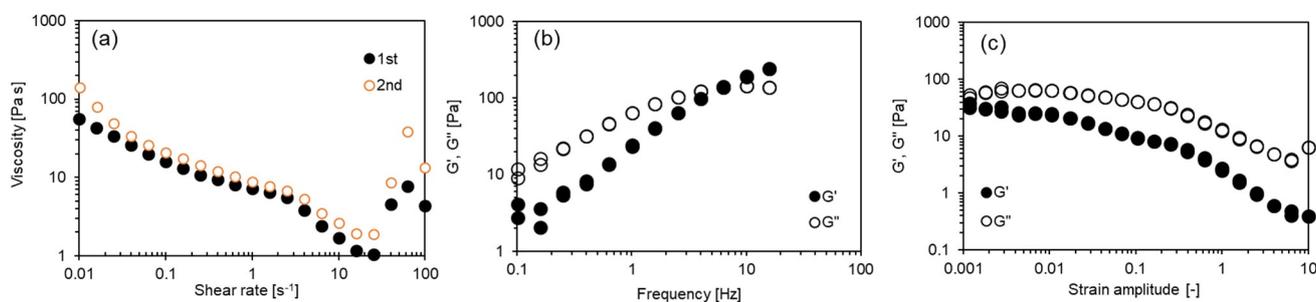


Figure 3. Viscosity, storage modulus (G'), and loss modulus (G'') of climbing colloidal suspension of 70 wt. % silica particles of 1.0 μm diameter and water: (a) viscosity against shear rate, (b) G' and G'' against frequency at a strain amplitude of 0.01, and (c) G' and G'' against strain amplitude at a frequency of 1 Hz.

The viscosity of the climbing suspension was much higher than the medium viscosity of water of 1 mPa·s. For this suspension, the volumetric concentration of solid particles was 55 vol. % and was significantly high, and moreover, the concentration of ions was expected to be low because of the absence of additional electrolytes except ions released from the particles. In such a case, the viscosity at a low shear rate is high because of the high effective volume fraction due to the overlapped electric double layer in addition to the volume of silica particles themselves. The resulting colloid crystal-like structure and electroviscous effects are possible reasons for higher viscosity at a low shear rate and shear thinning because the addition of salt reduces the viscosity of silica suspensions [13,15,18,32]. Increasing the shear rate reorganizes such structure and reduces viscosity, and thus, we see shear thinning. At shear rates higher than 20 s^{-1} , the viscosity increased, that is, shear thickening clearly happened. Dense suspensions of solid particles with a volumetric concentration of particles higher than around 50 vol. % often show such a shear-thickening behavior, and many studies have been carried out on this topic. While there are several

debates on the mechanisms of shear thickening, shear thickening in the case of charge-stabilized colloidal suspensions is mainly considered to be initiated by hydroclustering, which is determined by the balance between the force by shear stress working on particles and the force by the overlapped electric double layer [19,33]. Then, a further increase in the viscosity of shear-thickened suspensions is influenced by the friction between contacting particles and the development of force chain networks [17,21]. Additionally, Brownian motion and particle softness are key factors in shear thickening [34].

The climbing suspension is a concentrated suspension of solid particles and shows shear thickening, which is often observed for concentrated suspensions. In such shear-thickening concentrated suspensions, normal stress differences and force chain networks could appear in general [21,33]. It is also known that normal stress differences are key parameters to explain the Weissenberg effect, that is, polymer solutions can climb along a rotating rod against gravity [20]. On the basis of these considerations, normal stress differences and the transient appearance and disappearance of force chain networks under vibration can probably contribute to the occurrence of the climbing suspension. To make suspensions climb up the wall against gravity, the upward force during climbing and the elastic and adhesive forces for staying on a wall are considered necessary to develop in the climbing suspension during the vibration. We would have to somehow make a connection between these upward forces as well as the staying force, normal stress differences, and the transient force chain network to deepen our understanding of the climbing suspension. At the moment, however, the distinct mechanism explaining the climbing suspension is not clear, and numerical modeling of the climbing suspension is not successful. The arrangement of constitutive models for the climbing active matter in references [26] and applying the concept of negative viscosity used for the qualitative explanation of the climbing suspension droplet [27] could be useful starting points to model the climbing phenomena of suspensions in the future.

Future studies under well-defined fields and detailed observation might help to elucidate the mechanism of the climbing suspension phenomena. Characterizing elongational viscosities might be useful. These challenging points remain for future works. Additionally, it could be a similarly interesting topic to find climbing suspensions for different systems in different fields such as food technology, concrete engineering, soil engineering, and so on, where mixtures of particles, powder, and liquids are often handled in many situations. The main contribution of this work is the fact that colloidal suspensions can climb with a centimeter unit of scale and motion. The rheological behaviors of suspensions of colloidal particles strongly depend on particle shape, medium types, ion types and concentration, and surface charge of the particles through the electric double-layer interaction between suspended particles. The shear jamming of dense suspensions is elicited by hydrogen bonding [35]. Our preliminary results showed that the rheological properties of aqueous colloidal silica suspension were affected by pH and salt concentration, and the climbing speed was slowed down by the addition of salt. Therefore, under different solutions and surface chemistry, the climbing behavior of colloidal suspensions can probably be much richer. This possibility of tuning the rheology of colloidal suspensions can also be important in the quantitative verification of proposed models for climbing suspensions. Examining the effect of colloidal and surface properties on the climbing suspension might provide intriguing outcomes. The effect of possible sedimentation on the occurrence of the climbing suspension should be further examined by using density-matching fluids with consideration for the changes in colloidal interaction, solvent viscosity, etc.

4. Conclusions

We report climbing of colloidal silica suspensions. That is, concentrated aqueous suspensions of colloidal silica particles with different diameters of 0.5, 1.0, and 2.5 μm at 70, 70, and 72.5 wt. %, respectively, climbed up the wall of a container against gravity under vibrations higher than 17 Hz. The climbing colloidal silica suspension showed shear-thickening behavior. Therefore, we presume that normal stress differences and the

appearance and disappearance of force networks under vibration can explain the occurrence of the climbing suspension, while a quantitative discussion has not been attained. Future studies are needed to quantify the climbing suspension behavior and to find climbing suspensions for different systems. To this end, the climbing colloidal suspension reported in this paper can be a good candidate because the rheology of colloidal suspensions is tunable with particle shape, solution chemistry, surface chemistry, and so on.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/liquids3010004/s1>, Movie S1: Climbing suspension under horizontal vibration, Movie S2: Climbing suspension under vertical vibration.

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References

1. Ohshima, H.; Furusawa, K. *Electrical Phenomena at Interfaces: Fundamentals: Measurements, and Applications*, 2nd ed.; Taylor & Francis: Abingdon, UK, 1998; ISBN 9780824790394.
2. Wagner, N.J.; Mewis, J. *Theory and Applications of Colloidal Suspension Rheology*; Cambridge University Press: Cambridge, UK, 2021.
3. Groarke, R.; Danilenkoff, C.; Karam, S.; McCarthy, E.; Michel, B.; Mussatto, A.; Sloane, J.; O' Neill, A.; Raghavendra, R.; Brabazon, D. 316L Stainless Steel Powders for Additive Manufacturing: Relationships of Powder Rheology, Size, Size Distribution to Part Properties. *Materials* **2020**, *13*, 5537. [[CrossRef](#)] [[PubMed](#)]
4. Zhou, K.; Wu, D.; An, Z. Experimental Study on Matched Particle Size and Elastic Modulus of Preformed Particle Gel for Oil Reservoirs. *Gels* **2022**, *8*, 506. [[CrossRef](#)] [[PubMed](#)]
5. Yu, H.; Ma, Z.; Tang, L.; Li, Y.; Shao, X.; Tian, Y.; Qian, J.; Fu, J.; Li, D.; Wang, L.; et al. The Effect of Shear Rate on Dynamic Gelation of Phenol Formaldehyde Resin Gel in Porous Media. *Gels* **2022**, *8*, 185. [[CrossRef](#)] [[PubMed](#)]
6. Duran, J. *Sands, Powders, and Grains*; Springer: New York, NY, USA, 2012; ISBN 9781461267904.
7. Lodge, A.S. *Elastic Liquids*; Academic Press: San Diego, CA, USA, 1964; ISBN 9780124548503.
8. Hunger, M.; Brouwers, H.J.H. Flow Analysis of Water–Powder Mixtures: Application to Specific Surface Area and Shape Factor. *Cem. Concr. Compos.* **2009**, *31*, 39–59. [[CrossRef](#)]
9. Kobayashi, M.; Sato, Y.; Sugimoto, T. Effect of pH and Electrolyte Concentration on Sol–Gel State of Semi-Dilute Aqueous Cellulose Nanofiber Suspension: An Interpretation Based on Angle-Dependent DLVO Theory. *Colloid Polym. Sci.* **2022**, *300*, 953–960. [[CrossRef](#)]
10. Kawasaki, S.; Kobayashi, M. Affirmation of the Effect of pH on Shake-Gel and Shear Thickening of a Mixed Suspension of Polyethylene Oxide and Silica Nanoparticles. *Colloids Surf. A Physicochem. Eng. Asp.* **2018**, *537*, 236–242. [[CrossRef](#)]
11. Huang, Y.; Kobayashi, M. Direct Observation of Relaxation of Aqueous Shake-Gel Consisting of Silica Nanoparticles and Polyethylene Oxide. *Polymers* **2020**, *12*, 1141. [[CrossRef](#)]
12. Yamagata, Y.; Miyamoto, K. Gel Formation and Its Relaxation Mechanism of Shear-Induced Aqueous Suspensions Comprised of Bentonite and Heptaethylene Oleyl Ether. *Colloids Surf. A Physicochem. Eng. Asp.* **2021**, *624*, 126786. [[CrossRef](#)]
13. Nakamura, H.; Makino, S.; Ishii, M. Effects of Electrostatic Interaction on Rheological Behavior and Microstructure of Concentrated Colloidal Suspensions. *Colloids Surf. A Physicochem. Eng. Asp.* **2021**, *623*, 126576. [[CrossRef](#)]
14. Hodgson, D.J.M.; Hermes, M.; Blanco, E.; Poon, W.C.K. Granulation and Suspension Rheology: A Unified Treatment. *J. Rheol.* **2022**, *66*, 853–858. [[CrossRef](#)]
15. Russel, W.B.; Saville, D.A.; Schowalter, W.R. *Cambridge Monographs on Mechanics: Colloidal Dispersions*; Cambridge University Press: Cambridge, UK, 2012; ISBN 9780511608810.

16. Kobayashi, M.; Adachi, Y.; Ooi, S. On the Steady Shear Viscosity of Coagulated Suspensions. *Nihon Reoroji Gakkaishi* **2000**, *283*, 143–144. [[CrossRef](#)]
17. Mari, R.; Seto, R.; Morris, J.F.; Denn, M.M. Discontinuous Shear Thickening in Brownian Suspensions by Dynamic Simulation. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 15326–15330. [[CrossRef](#)] [[PubMed](#)]
18. Mewis, J.; Wagner, N.J. *Colloidal Suspension Rheology*; Cambridge University Press: Cambridge, UK, 2012; ISBN 9780521515993.
19. O’Kelly, B.C. Review of Recent Developments and Understanding of Atterberg Limits Determinations. *Geotechnics* **2021**, *1*, 59–75. [[CrossRef](#)]
20. Barthès-Biesel, D. *Microhydrodynamics and Complex Fluids*; CRC Press: Boca Raton, FL, USA, 2012; ISBN 9781138072404.
21. Morris, J.F. Shear Thickening of Concentrated Suspensions: Recent Developments and Relation to Other Phenomena. *Annu. Rev. Fluid Mech.* **2020**, *52*, 121–144. [[CrossRef](#)]
22. Brown, E.; Jaeger, H.M. Shear thickening in concentrated suspensions: Phenomenology, mechanisms and relations to jamming. *Rep. Prog. Phys.* **2014**, *77*, 046602. [[CrossRef](#)]
23. McDonald, L. Tune Shear-Thickening Fluid Viscosity with Acoustics. Available online: <https://ceramics.org/ceramic-tech-today/basic-science/tune-shear-thickening-fluid-viscosity-with-acoustics> (accessed on 31 December 2022).
24. Sehgal, P.; Ramaswamy, M.; Cohen, I.; Kirby, B.J. Using Acoustic Perturbations to Dynamically Tune Shear Thickening in Colloidal Suspensions. *Phys. Rev. Lett.* **2019**, *123*, 128001. [[CrossRef](#)]
25. Palacci, J. A Soft Active Matter That Can Climb Walls. *Science* **2022**, *377*, 710–711. [[CrossRef](#)]
26. Adkins, R.; Kolvin, I.; You, Z.; Witthaus, S.; Marchetti, M.C.; Dogic, Z. Dynamics of Active Liquid Interfaces. *Science* **2022**, *377*, 768–772. [[CrossRef](#)]
27. Hou, X.; Peterson, J.D. A study of dense suspensions climbing against gravity. *J. Non-Newton. Fluid Mech.* **2022**, *317*, 104868. [[CrossRef](#)]
28. Sehgal, P.; Ramaswamy, M.; Ong, E.Y.X.; Ness, C.; Cohen, I.; Kirby, B.J. Viscosity Metamaterials. *arXiv*, 2022. [[CrossRef](#)]
29. Kobayashi, M.; Skarba, M.; Galletto, P.; Cakara, D.; Borkovec, M. Effects of Heat Treatment on the Aggregation and Charging of Stöber-Type Silica. *J. Colloid Interface Sci.* **2005**, *292*, 139–147. [[CrossRef](#)] [[PubMed](#)]
30. Yamaguchi, A.; Kobayashi, M.; Adachi, Y. Yield Stress of Mixed Suspension of Silica Particles and Lysozymes: The Effect of Zeta Potential and Adsorbed Amount. *Colloids Surf. A Physicochem. Eng. Asp.* **2019**, *578*, 123575. [[CrossRef](#)]
31. Huang, Y.; Yamaguchi, A.; Pham, T.D.; Kobayashi, M. Charging and Aggregation Behavior of Silica Particles in the Presence of Lysozymes. *Colloid Polym. Sci.* **2018**, *296*, 145–155. [[CrossRef](#)]
32. Nakamura, H.; Ishii, M. Rheological Behavior of Concentrated Monodispersed Colloidal Suspensions. *Nihon Reoroji Gakkaishi* **2019**, *47*, 1–7. [[CrossRef](#)]
33. Lee, Y.-F.; Luo, Y.; Bai, T.; Brown, S.C.; Wagner, N.J. Microstructure of Continuous Shear Thickening Colloidal Suspensions Determined by Rheo-VSANS and Rheo-USANS. *Soft Matter* **2022**, *18*, 4325–4337. [[CrossRef](#)]
34. Kawasaki, T.; Berthier, L. Discontinuous shear thickening in Brownian suspensions. *Phys. Rev. E* **2018**, *98*, 012609. [[CrossRef](#)]
35. James, N.M.; Han, E.; de la Cruz, R.A.L.; Jureller, J.; Jaeger, H.M. Interparticle hydrogen bonding can elicit shear jamming in dense suspensions. *Nat. Mater.* **2018**, *17*, 965–970. [[CrossRef](#)]

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