Applied Rheology | DOI: 10.3933/APPLRHEOL-25-12466 | WWW.APPLIEDRHEOLOGY.ORG

Shear-Thickening Behavior of Precipitated Calcium Carbonate Particles Suspensions in Glycerine

Yi Chen[1]*, Weijian Xu[2], Guangsheng Zeng[1], and Wenyong Liu[1]

[1] Key Laboratory of Advanced Materials and Technology for Packaging of Hunan,
Hunan University of Technology, Zhuzhou 412008, P. R. China
[2] Institute of Polymer Research, College of Chemistry and Chemical Engineering,
Hunan University, Changsha 410082, P. R. China

* Corresponding author: yiyue514@aliyun.com

Received: 30.1.2014, Final version: 16.9.2014

Abstract:
For developing a new composite material owning shear-thickening characteristic, the rheological behaviors of nano-sized precipitated calcium carbonate (PCC) particles with irregular sharp in glycerine were investigated systematically by means of steady and dynamic rheometry. The results showed that the concentrated PCC suspensions exhibit a strong shear-thickening behavior under both steady and dynamic oscillatory shear when the volume fraction of PCC above the threshold (about 41 %). In steady shear tests, the critical shear rate decreases and the maximum viscosity in shear thickening region increases dynamically with the increase of volume fraction. While, for suspensions with different volume fractions, the similar critical stress for the onset of shear thickening is found. In dynamic strain sweep at different fixed frequencies, with the increase of fixed frequency, the complex viscosity of suspensions decreases slightly, while the critical strain for shear-thickening shifts to lower value. The dynamic oscillatory rheological behavior of suspensions at low frequency ($\omega < 100$ rad/s) could be reasonably interpreted in terms of the steady shear behavior. For the suspensions with same volume fraction, it was interestingly found that the critical dynamic shear rate equaled to the product of critical strain and frequency could agree well with the critical shear rate in steady shear. Moreover, the rheological behavior of PCC suspensions shows excellent reversibility and reproducibility.

Key words:
precipitated calcium carbonate, glycerine, shear-thickening, rheological behavior, steady shear, dynamic oscillation

1 INTRODUCTION

In recent decades, the rheological behavior of suspensions was researched deeply [1–4]. Among all of researches, a special rheological phenomenon, shear thickening behavior, as a significant, continuous or discontinuous steep increase in viscosity, is found to exist in concentrated colloidal suspensions. Most of shear thickening fluids (STFs) with nano size particles undergo a weak shear thinning at a low shear rate, but once a critical shear rate, or a critical strain is reached, the viscosity increases sharply.

In parallel to the analysis regarding the shear-thickening behavior, the mechanism is also under debate and two main models were developed to explain it. Firstly, Hoffman, in his pioneering studies, used a combination of rheology with in situ light diffraction to elucidate microstructural changes that occur during shear-thickening. He concluded that the incipience of shear-thickening at a critical shear rate corresponds to a transition from an easy flowing state where the particles are ordered into layers to a disordered state where this ordering is absent. This mechanism is generally called an order-disorder transition [5]. After that, Bender and Wagner noted that although order-disorder transitions may accompany the shear thickening transition, the underlying order-disorder transition is neither necessary nor sufficient to trigger shear thickening. They have shown that reversible shear thickening results from the formation of hydroclusters, or transient stress bearing particle aggregates that form as a consequence of short range hydrodynamic lubrication forces overcoming the interparticle repulsive forces during flow. Percolation of these hydroclusters with increasing shear results in the formation of larger aggregates that can jam the flow, leading to discontinuous shear thickening behavior. The formation of jamming clusters bound together by hydrodynamic lubri-

This is an extract of the complete reprint-pdf, available at the Applied Rheology website
http://www.appliedrheology.org

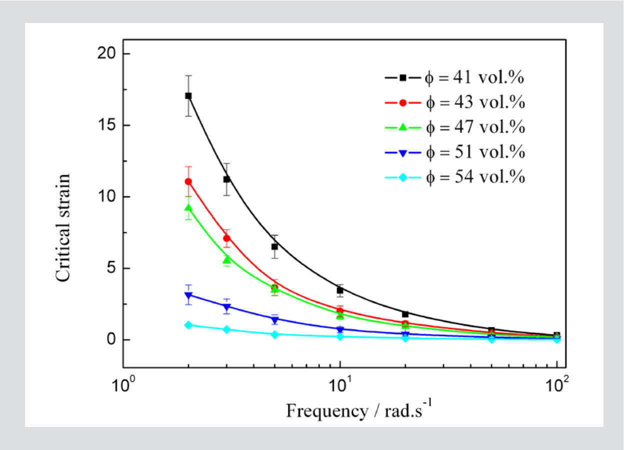

Figure 8: Critical strain versus frequency under dynamic strain sweep for suspensions of PCC with different volume fractions.

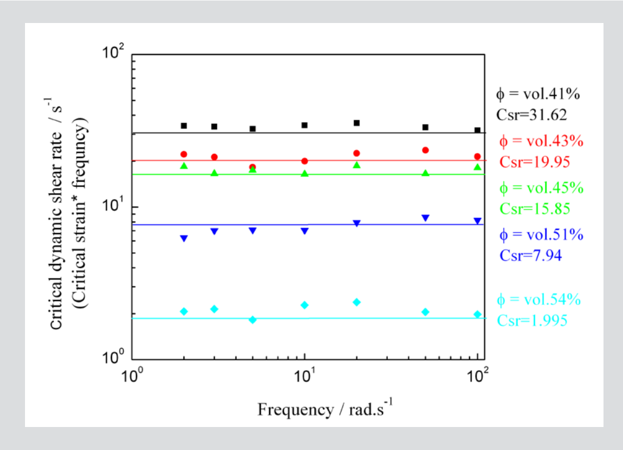

Figure 9: Critical dynamic shear rate (noted by point) under dynamic sweep tests fitted by the product of critical strain and frequency as a function of frequency and the critical steady shear rate (noted by line) under steady sweep for suspensions with different volume fractions. (Csr in figure is the short of Critical shear rate).

that the dynamic oscillatory behavior under low frequency for this PCC suspensions could be approximatively interpreted in terms of the steady shear behavior. The error may be due to the irregular shape of PCC particles in this work. Moreover, it was found that the critical steady shear rate is well agreed to the critical dynamic shear rate calculated by critical strain*frequency.

In order to figure out the validity of this found (critical steady shear rate = critical dynamic shear rate = critical strain times frequency) to all PCC suspensions with volume fraction which is big enough for shear thickening, the dynamic oscillatory tests were conducted on PCC suspensions with different volume fractions. Figure 8 showed the critical strains for shear-thickening at different fixed frequencies. The suspensions with higher volume fraction exhibit a lower critical strain, and the critical strain decreases with the increase of frequency. Critical dynamic shear rate in dynamic oscillatory tests calculated by the product of critical strain and frequency as a function of frequency were all shown in Figure 9, and the critical steady shear rate in steady sweep was also noted by line. Obviously, for the suspensions with same volume fraction, the value of critical dynamic shear rates is closed with the critical steady shear rate. The result further reveals that the dynamic rheological behavior of the PCC suspensions in low frequency could be interpreted in terms of the steady shear behavior.

4 CONCLUSIONS

In this work, the rheological behavior of suspensions consisting of glycerine and nano-sized PCC with irregular sharp was investigated by a stress controlled rheometer under both steady shear and dynamic oscillatory shear for developing a new material applied in protection region and enrich the practice and theory of STFs, three main conclusions have been obtained.

Firstly, the rheological behavior of PCC/glycerine suspensions exhibit obvious dependency on the volume fraction of PCC in suspensions. In steady shear, a discontinuous jump of viscosity, corresponding to shear-thickening behavior happens when the volume fraction of PCC is higher than 41 %. The critical shear rate decreases with the increase of volume fraction. However, it was also found that the onset of shear thickening happen under the similar stress, which meets the model developed by Maranzano and Wagner for hard square systems well. It indicates that the model is also suitable to the particles with irregular shape. Meantime, the maximum viscosity increase drastically with the increase of volume fraction due to the formation of bigger “hydroclusters” jamming the flow.

Secondly, in dynamic oscillatory shear tests including strain sweep and frequency sweep, the volume fraction of PCC also affects the rheological behavior significantly. The critical frequency and critical strain decreases and the discontinuous jump of complex viscosity becomes more drastic with the increase of volume fraction. More importantly, it was found that the suspensions corresponds to the Cox-Merz rule, the critical steady shear rate is equal to the critical dynamic shear rate defined as critical strain*frequency basically. Meantime, the modified Cox-Merz rule, the dynamic oscillatory rheological behavior of suspensions at low frequency ($\omega <$ 100 rad/s) could be reasonably interpreted in terms of the steady shear behavior, is also effective in this suspensions. Finally, the rheological behaviors of the PCC suspensions are reversible and reproducible, the viscosity of suspensions is only dependent on the shear rate, but independent of the shear process, which is conducive to the application.

ACKNOWLEDGEMENTS

This work was supported in part by the Hunan provincial Science and technology project (2012FJ4369), and the National Natural Science Foundation of China (21104017, 61174100).

This is an extract of the complete reprint-pdf, available at the Applied Rheology website
http://www.appliedrheology.org

REFERENCES

[1] Ouari N, Kaci A, Tahakourt A, Chaouche M: Rheological behaviour of fibre suspensions in non-Newtonian fluids, Appl. Rheol. 21 (2011) 54801.

[2] Metin C, Bonnecaze R, Nguyen O: Shear rheology of silica nanoparticle dispersions, Appl. Rheol. 21 (2011) 13146.

[3] Thomas SP, De SK, Hussein IA: Impact of Aspect ratio of carbon nanotubes on shear and extensional rheology of polyethylene nanocomposites, Appl. Rheol. 23 (2013) 23635.

[4] Sato ACK, Perrechil FA, Cunha RL: Rheological behavior of suspensions dispersed in non-Newtonian matrix, Appl. Rheol. 23 (2013) 45397.

[5] Hoffman RLJ: Discontinuous and dilatant viscosity behavior in concentrated suspensions. II. Theory and experimental tests, J. Colloid. Interface Sci. 46 (1974) 491 – 506.

[6] Fischer C, Braun SA, Bourban P-E, Michaud V, Plummer CJG,Månson JE: Dynamic properties of sandwich structures with integrated shear-thickening fluids, Smart Mater. Struct. 15 (2006) 1467 – 1475.

[7] Foss DR, Brady JF: Structure, diffusion and rheology of Brownian suspensions by Stokesian dynamics Simulation, J. Fluid Mech. 407 (2000) 167 – 200

[8] D’Haene PD, Mewis J, Fuller GG: Scattering dichroism measurements of flow-induced structure of a shear thickening suspension, J. Colloid. Interface Sci. 156 (1993) 350 – 358.

[9] Bender JW, Wagner NJ: Reversible shear thickening in monodisperse and bidisperse colloidal dispersion, J. Rheol. 40 (1996) 899 – 916.

[10] Farr RS, Melrose JR, Ball RC: Kinetic theory of jamming in hard-sphere startup flows, Phys. Rev. E 55 (1997).7203 – 7211.

[11] O’Brien VT, Mackay ME: Stress components and shear thickening of concentrated hard sphere suspensions, Langmuir 16 (2000) 7931 – 7938.

[12] Laun HM, Bung R, Hess S, Loose W, Hess O, Hahn K, Hädicke E, Hingmann R, Schmidt F, Lindner P: Rheological and small angle neutron scattering investigation of shear-induced particle structures of concentrated polymer dispersions submitted to plane poiseuille and couette flow, J. Rheol. 36 (1992) 743 – 787.

[13] Bender JW, Wagner NJ: Reversible shear thickening in monodisperse and bidisperse colloidal dispersion, J. Rheol. 40 (1996) 899 – 916.

[14] Maranzano BJ, Wagner NJ: Flow-small angle neutron scattering measurements of colloidal dispersion microstructure evolution through the shear thickening transition, J. Chem. Phys. 117 (2002) 10291 – 10302.

[15] Foss DR, Brady JF: Structure, diffusion and rheology of Brownian suspensions by Stokesian dynamics simulation, J. Fluid Mech. 407 (2000) 167 – 200.

[16] Kaldasch J, Senge B, Laven J: Shear thickening in electrically stabilized non-aqueous colloidal suspensions, Appl. Rheol. 19 (2009) 23493.

[17] Osuji CO, Kim C Weitz DA: Shear thickening and gel elasticity in a colloidal system with attractive interactions, Phys. Rev. E. 7 (2008) 060402.

[18] Lee YS, Wagner NJ: Rheological properties and small-angle neutron scattering of a shear thickening nanoparticle dispersion at high shear rates, Ind. Eng. Chem. Res. 45 (2006) 7015 – 7024.

[19] Kirkwood K, Kirkwood J, Wetzel ED, Lee YS, Wagner NJ: Yarn pull-out as a mechanism for dissipating ballistic impact energy in Kevlar KM-2 fabric. Part I: Quasi-static characterization of yarn pull-out, Tex. Res. J. 74 (2004) 920 – 928.

[20] Decker MJ, Halbach CJ, Nam CH, Wagner NJ, Wetzel ED: Stab resistance of shear thickening fluid (STF)-treated fabrics, Comp. Sci. Technol. 67 (2007) 565 – 578.

[21] Lee YS, Wagner,NJ: Dynamic properties of shear thickening colloidal suspensions, Rheol. Acta 42 (2003) 199 – 208.

[22] Srinivasa RR, Saad A K: Shear-thickening response of fumed silica suspensions under steady and oscillatory shear, J. Colloid. Interface Sci. 185 (1997) 57 – 67.

[23] Jiang WQ, Sun YQ, Xu YL, Peng C, Gong XL, Zhang Z: Shear-thickening behavior of polymethylmethacrylate particles suspensions in glycerine-water mixtures, Rheol. Acta 49 (2010) 1157 – 1163.

[24] Metin C, Bonnecaze R, Nguyen Q: Shear rheology of silica nanoparticle dispersions, Appl. Rheol. 21 (2011) 13146.

[25] Shenoy SS, Wagner NJ: Influence of medium viscosity and adsorbed polymer on the reversible shear thic kening transition in concentrated colloidal dispersions, Rheol. Acta 44 (2005) 360 – 371.

[26] Galindo-Rosales FJ, Rubio-Hernández FJ, Velázquez-Navarro JF: Shear-thickening behavior of Aerosil® R816 nanoparticles suspensions in polar organic liquids, Rheol. Acta 48 (2009) 699 – 708.

[27] Galindo-Rosales FJ, Rubio-Hernández FJ: Static and dynamic yield stresses of Aerosil(R) 200 suspension in polypropylene glycol, Appl. Rheol. 20 (2010) 22787.

[28] Egres RG, Wanger NJ: The rheology and microstructure of acicular precipitated calcium carbonate colloidal suspensions through the shear thickening transition, J. Rheol. 49(2005) 719 – 746.

[29] Yang HL, Ruan JM, Zhou ZC, Zou JP, Wu QM, Qiu M, Xie YY: Rheological responses of fumed silica suspensions steady and oscillatory shear, J. Cent. South Univ. Technol. 16 (2009) 900 – 915.

[30] Yang HL, Ruan JM, Zou JP, Wu QM, Zhou ZC, Xie YY: Nonlinear viscoelastic rheological properties of PCC/PEG suspensions, Chin. J. Chem. Phys. 22 (2009) 46 – 50.

[31] Maranzano BJ, Wagner NJ: The effects of particle size on reversible shear thickening of concentrated colloidal dispersions, J. Chem. Phys. 114 (2001) 10514 – 10527.

[32] Li C, Friedrich K, Schlarb AK, Tanner R, Lin Y: Shear-thickening behaviour of concentrated polymer dispersions under steady and oscillatory shear, J. Mater. Sci. 46 (2011) 339 – 346.

[33] Raghavan SR, Khan SA: Shear-thickening response of fumed silica suspensions under steady and oscillatory shear, J. Colloid. Interface Sci. 185 (1997) 57 – 67.

This is an extract of the complete reprint-pdf, available at the Applied Rheology website
http://www.appliedrheology.org