Programme

Day 1

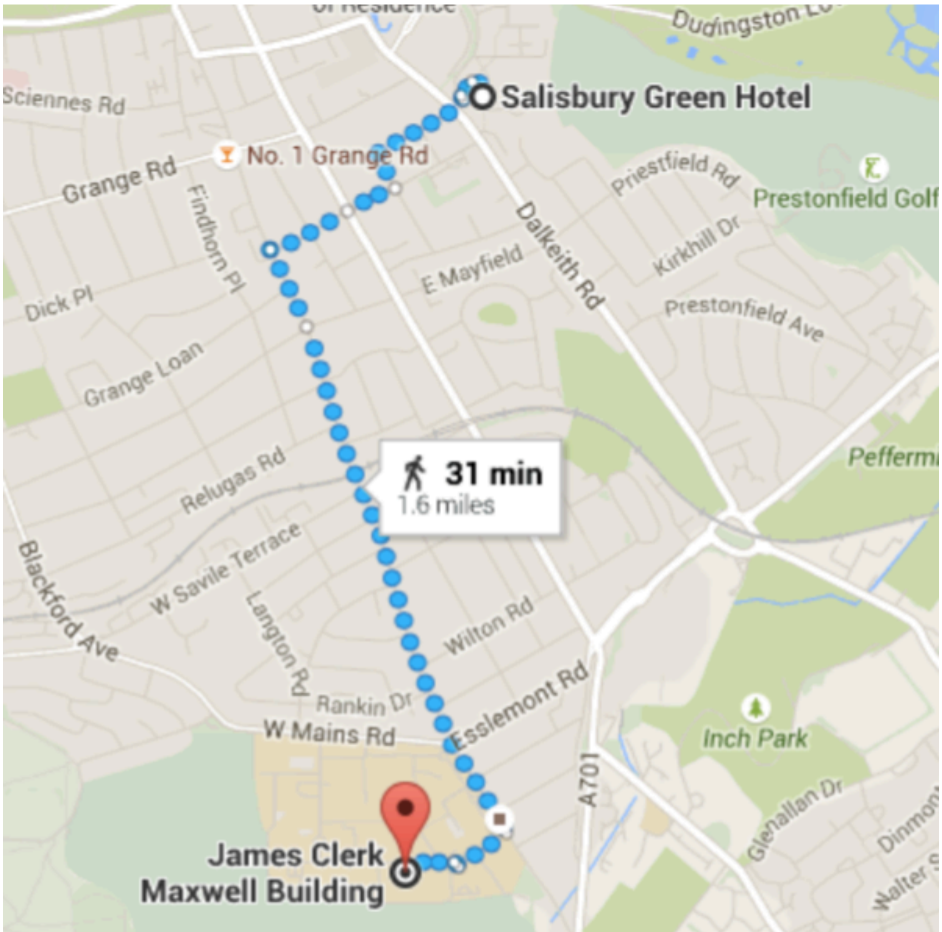
12:30	Registration/Lunch	
14:00	Introduction	Wilson Poon (Edinburgh)
14:15	Talk 1	Jeff Morris (NY City College)
14:45	Talk 2	Lucio Isa (ETH Zürich) [RSC 2015 *Soft Matter* lecture]
15:15	Discussion 1	Wilson Poon (Edinburgh)
15:45	Tea/Coffee	
16:15	Talk 3	Shomeek Mukhopadhyay (Yale)
16:45	Talk 4	Michiel Hermes (Edinburgh)
17:15	Discussion 2	Eric Weeks (Emory)
17:45	End of day 1	

Day 2

09:30	Talk 5	Mark Haw (Strathclyde)
10:00	Talk 6	Ludovic Berthier (Montpellier)
10:30	Discussion 3	Emanuela del Gado (Georgetown)
11:00	Tea/Coffee	
11:30	Talk 7	Daniel Bonn (Amsterdam)
12:00	Talk 8	Itai Cohen (Cornell)
12:30	Discussion 4	Dimitris Vlassopoulos (Crete)
13:00	Lunch	
14:00	Talk 9	François Peters (Nice)
14:30	Talk 10	Jin Sun (Edinburgh)
15:00	Discussion 5	Suzanne Fielding
15:30	Tea/Coffee	
16:00	Talk 11	Philippe Coussot (Paris)
16:30	Talk 12	Simon Davies (AkzoNobel)
17:00	Discussion 6	Richard Buscall (Melbourne)
17:30	End of day 2	
19:00	Conference Dinner	Rainy Hall, Mound Place

Day 3

09:00	Talk 13	Annette Zippelius (Göttingen)
09:30	Talk 14	Olivier Pouliquen (Marseilles)
10:00	Discussion 7	Morton Denn (NY City College)
10:30	Tea/Coffee	
11:00	Talk 15	George Petekidis (Crete)
11:30	Talk 16	Michel Cloitre (Paris)
12:00	Discussion 8	Bill Russel (Princeton)
12:30	General discussion	Mike Cates (Edinburgh)
13:00	Lunch	
14:00	End of day 3	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1. Discontinuous shear thickening and flow-induced jamming

Jeffrey F. Morris, Romain Mari, Ryohei Seto & Morton M. Denn

Levich Institute and Dept. of Chemical Engineering
City University of New York, City College

In recent work [1, 2], we have considered through a simulation study the minimum set of components to reproduce experimentally observed shear thickening behaviors in concentrated suspensions, including the extremely abrupt or "discontinuous shear thickening" (DST). A combination of viscous lubrication and frictional contact forces is found to be essential.

Features of the behavior of viscous suspensions in which particles make frictional contact will be described. Frictional interactions shift the maximum packing fraction f_m (at which the effective viscosity diverges) to smaller values, so that a frictional suspension has a higher effective viscosity than an otherwise equivalent frictionless (or lubricated) suspension. Upon introducing a short-ranged repulsive force between particles, a transition from the lubricated to frictional branch of the flow curve with increasing shear rate or shear stress is observed, implying shear thickening. This transition becomes progressively steeper as f increases, until a discontinuous shear thickening and strongly dilatant normal stress is observed. The basis for the material response is found in the frictional contact network: as the shear rate increases, friction is increasingly mobilized as more such contacts form.

An overview of the predictions of the frictional-viscous simulational model for a suspension in simple shear will be given for non-Brownian, charge-stabilized suspensions under both *shear rate* and *shear stress* control, and for Brownian suspensions under rate control. The stress-controlled simulations exhibit an S-shaped flow curve for sufficiently concentrated conditions in a frictional suspension, such that with increase of stress, the viscosity increases while the shear rate declines. Under stress control, shear-induced jamming occurs at sufficiently high solid fraction.

1] R. Seto, R. Mari, J. F. Morris & M. M. Denn 2013 Discontinuous shear thickening of frictional hard-sphere suspensions.Phys. Rev. Lett., 111:218301.
[2] R. Mari, R. Seto, J. F. Morris & M. M. Denn 2014 Shear thickening, frictionless and frictional rheologies. J. Rheol. 58, 1693.
[3] R. Mari, R. Seto, J. F. Morris & M. M. Denn 2015. Non-monotonic flow curves of shear thickening suspensions. In press *Phys Rev. E.*

Session and Discussion Chair: Wilson Poon

2. Microscopic mechanism for the shear-thickening of non-Brownian suspensions : linking friction and rheology

N.Fernandez[1], R.Mani[2], D.Rinaldi[3], D.Kadau[2], M.Mosquet[3], H.Lombois-Burger[3], J.Cayer-Barrioz[4], HJ. Herrmann[2], ND. Spencer[1], **L.Isa[5]**

[1]LSST, ETH Zurich; [2]CPEM, ETH Zurich; [3]Lafarge LCR,St Quentin-Fallavier, France; [4]LTDS - UMR 5513 CNRS, Ecully, France; [5]ISA, ETH Zurich

Shear-thickening can lead to large-scale processing problems of dense pastes in a host of practical applications [1]. Despite extensive efforts to describe its microscopic origin [1-4], current explanations fail to address the mechanism behind the shear-thickening of dense granular pastes. In such systems, networks of contacting particles can develop and transmit positive normal stresses [5]. Moreover, viscosity can suddenly diverge under flow (discontinuous shear-thickening [6-7]) with dramatic effects. Previous experiments have demonstrated that the features of the viscosity increase (slope, critical stress) can be controlled by tuning particle surface properties such as roughness[8] and/or by adsorbing polymers[9]. These findings suggest that inter-particle contacts play a crucial role in the macroscopic flow at high volume fractions and that a precise description of these contacts is essential to interpret the rheological behavior. We propose a simple model, supported by contact-dynamics simulations as well as rheology and friction measurements, which links the transition from continuous to discontinuous shear-thickening in dense granular pastes to distinct lubrication regimes in the particle contacts. In particular, we identify a local characteristic number (Sommerfeld number) that determines the transition from Newtonian to shear-thickening flows, and then show that the suspension's volume fraction and the boundary lubrication friction coefficient control the nature of the shear-thickening transition, both in simulations and experiments. The generality and consistency of our data and of the proposed model sets a global framework in which the tribological (friction) and rheological properties of dense non-colloidal systems are intimately connected.

References:

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[7] E. Brown et al., Nat. Mater. 9, 220 (2010).
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[9] F. Toussaint, C. Roy, and P. H. Jézéquel, Rheol. Acta 48, 883 (2009).

Session and Discussion Chair: Wilson Poon

3. Impact Activated Dynamic Jamming in Shear Thickening suspensions

Shomeek Mukhopadhyay[1] , Eric Brown [1,2]

[1] Department of Mechanical Engineering and Materials Science
[2] Department of Physics, Yale University , New Haven, CT- 06520.

Shear Thickening fluids such as cornstarch and water show remarkable response under impact, which allows, for example, a person to run on the surface of the suspension. We perform constant velocity impact experiments along with imaging and particle tracking in a shear thickening fluid at velocities lower than 500 mm/s and suspension heights of a few cm. In this regime, where inertial effects are insignificant, we find that a solid-like dynamically jammed region with a propagating front is generated under impact. The suspension is able to support large stresses like a solid only when the front reaches the opposite boundary. These stresses are sufficient to support the weight of a running person. These impact-activated fronts are generated only above a critical velocity. We construct a model by taking into account that sufficiently large stresses are generated when this solid like region spans to the opposite boundary and the work necessary to deform this solid like material dissipates the kinetic energy of the impacting object. The model shows quantitative agreement of the measured penetration depth using high speed video of a person running on cornstarch and water suspensions.

Session and Discussion Chair: Eric Weeks

4. S-shaped flow curves in a model shear thickening suspension.

Michiel Hermes[1], Ben Guy[1], Guilhem Poy[1,2], Wilson Poon[1]

[1] School of Physics & Astronomy, The University Edinburgh
[2] Univ Lyon, École Normale Super Lyon, Phys Lab, 46 Alle Italie, F-69364 Lyon 07, France

Recent simulations [1] and theory [2] attribute shear thickening in suspensions to the formation of frictional contacts. Based in these results we formulate an analytical expression for the flow curve. Three kinds of shear thickening are possible within this framework: continuous shear thickening (CST), discontinuous thickening to a jammed state (DST) and discontinuous thickening between two stable flowing states. The latter occurs when there is an underlying flow curve is S-shaped [1]. CST and DST have been readily observed in a wide range of systems [3], but discontinuous thickening between flowing states has proved more elusive, with only limited experiment evidence [4].

Our analytical expression quantitatively predicts the flow behaviour of our model shear thickening suspensions and accurately predicts the onset of DST. Unstable flow precludes direct observation of the S-shaped flow curves, but our observations are consistent with the formation of two vorticity bands coexisting at different stresses. However, the banded state seems to be unstable and the rheology has a non-trivial time-dependence in this regime.

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Session and Discussion Chair: Eric Weeks

5. Force fluctuations in shear thickening colloidal suspensions

Mark Haw, Claire Forsyth, Calum Williams and Leo Lue

Department of Chemical & Process Engineering, University of Strathclyde, Glasgow G1 1XJ, UK.

Using a simple piezo sensor technique analogous to an old-fashioned record player needle, we measure the statistics of macroscopic intermittent forces during shear of concentrated colloidal suspensions. In the shear-thickening regime, intermittent jamming/dilation events are observed with an exponential magnitude distribution and a power-law time distribution, demonstrating similarity to diverse other systems such as clogging in granular, pedestrian and animal flows. At a given applied stress, the volume-fraction dependence of the sum of event magnitudes per unit strain follows that of the effective viscosity (obtained from the ratio of stress to time-averaged shear rate), demonstrating that the bulk system rheology in the shear-thickening regime is determined directly by the statistics of intermittent jamming/dilation events. The observed force fluctuations, and the fact that the system is able to shear at all in the thickening regime, are related to dilation: when a closed cell (fixed total volume) is used, fewer dilation events are observed, and at high enough volume fraction the system becomes completely jammed.

Session and Discussion Chair: Emanula Del Gado

6. Thinning or thickening? Multiple rheological regimes in dense suspensions of soft particles

Ludovic Berthier

Laboratoire Charles Coulomb, UMR 5221 CNRS-Université de Montpellier, Montpellier, France

The shear rheology of dense colloidal and granular suspensions is strongly nonlinear, as these materials exhibit shear-thinning and shear-thickening, depending on multiple physical parameters. I will present results from computer simulations of the rheological behaviour of a simple model of soft repulsive particles at large densities, showing that nonlinear flow curves reminiscent of experiments on real suspensions are obtained. By using dimensional analysis and basic elements of kinetic theory, we can rationalize these multiple rheological regimes and disentangle the relative impact of thermal fluctuations, glass and jamming transitions, inertia particle softness, and frictional contacts on the nonlinear flow curves.

Session and Discussion Chair: Emanula Del Gado

7. S-Shaped Flow Curves of Shear Thickening suspensions: Direct Observation of Frictional Rheology

Daniel Bonn
Institute of Physics, University of Amsterdam, Science Park 904, Amsterdam, Netherlands

We study the rheological behavior of concentrated granular suspensions of simple spherical particles. Under controlled stress, the system exhibits an S-shaped flow curve (stress vs. shear rate) with a negative slope in between the low-viscosity Newtonian regime and the shear thickened regime. Under controlled shear rate, a discontinuous transition between the two states is observed. Stress visualization experiments with a novel fluorescent probe suggest that friction is at the origin of shear thickening. Stress visualization shows that the stress in the system remains homogeneous (no shear banding) if a stress is imposed that is intermediate between the high and low-stress branches. The S-shaped shear thickening is then due to the discontinuous formation of a frictional force network between particles upon increasing the stress.

Session and Discussion Chair: Dimitris Vlassopoulos

8. Disentangling the role of hydrodynamic and frictional forces in a shear-thickening suspension

Lin, Neil (Cornell University, Department of Physics) Hermes, Michiel (The University of Edinburgh, School of Physics and Astronomy) Guy, Ben (The University of Edinburgh, School of Physics and Astronomy) Poon, Wilson (The University of Edinburgh, School of Physics and Astronomy) **Cohen**, **Itai** (Cornell University, Department of Physics)

Who among us has not spent countless hours squeezing, rubbing, and smushing gooey substances like, tooth paste, silly putty, corn starch, and even bodily fluids between our fingers? If we could magnify our view and look deep within the substances we are handling what structures would we find? How, do these structures lead to the fascinating mechanical properties that we experience on the scale of our fingers. In this talk I will address the phenomenon of shear thickening in which the viscosity of a suspension increases with increasing shear rate. I will describe recent measurements we have made using a newly developed confocal rheoscope that, for the first time, experimentally visualize the hydrodynamically induced particle clusters. Such clusters have been implicated in continuous shear thickening. It remains controversial as to whether thickening in such suspensions also arises from frictional interactions between particles. The distinct contributions of frictional and hydrodynamic forces are typically difficult to measure independently using conventional techniques. Here, I will describe our approach for using both bulk rheometry techniques and our confocal rheoscope to disentangle their contributions to the total stress response.

Session and Discussion Chair: Dimitris Vlassopoulos

9. Shear-reversal in non-Brownian suspensions: experiments and simulations

François Peters

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Suspensions of non-Brownian particles display a complex rheology that originates in a subtle balance between hydrodynamic interactions and direct forces between particles, together with the so-called shear- induced microstructure. In particular, the influence of the microstructure has been qualitatively evidenced years ago in shear-reversal experiments. At the particle scale, experimental studies pointed the role played by the surface roughness of the particles in promoting direct contact between particles, and recent numerical computations suggest that contact friction between particles could be part of the explanation for the large viscosity of non-Brownian suspensions.
In recent shear-reversal experiments, we have shown that the viscosity transient allows to quantitatively identify the contribution of the shear induced microstructure to the suspensions viscosity. As the volume increases, this contribution is increasingly predominant.
To get a deeper insight on each step of the transient, we have performed numerical simulations of suspensions submitted to shear-reversal. The simulations account for short range lubrication interactions together with direct contact forces between particles, including surface roughness, contact elasticity and solid friction. The separated contributions of hydrodynamics and contact forces to the stress are identified during the transient and the influence of the contact law parameters are evaluated. In particular, we show that the contribution of the shear-induced microstructure to the viscosity that was determined in experiments provides an approximate measurement of the contribution of contact forces to the steady viscosity. In addition, at shear reversal, besides a short time contact force relaxation , the viscosity undergoes a finite jump at a more larger strain scale. This jump depends both on the roughness of the particle surface and on the friction coefficient between particles. A physical picture of this jump can be given from simple low Reynolds number hydrodynamics principles.

Session and Discussion Chair: Suzanne Fielding

10. Shear thickening and reversal in dense granular suspensions

Christopher Ness and **Jin Sun**
School of Engineering, University of Edinburgh

We investigate shear thickening and unsteady rheology of dense granular suspensions using discrete element simulations, modelling hydrodynamic interactions (HI) as pairwise lubrication forces and particle contacts as linear springs.

We show that a thickening mechanism due to particle interactions switching from being frictionless to frictional upon exceeding a critical load, discovered by others for Stokes flow, is also applicable to inertial flows. We further demonstrate abrupt changes in microstructure (coordination number and fabric anisotropy) and dynamics (diffusion coefficient and velocity correlation length) upon shear thickening at constant volume fractions. Such analyses evidence collective motion at thickened states correlated through frictional contacts, but not purely by HI. The changes can also be understood from the distinct divergence behaviour of these microscopic quantities against volume fractions at the non-thickened and thickened states, similar to that of the suspension viscosity. We thus extend the viscous number based model with particle-friction-dependent critical volume fraction and stress ratio, successfully capturing the shear thickening rheology.

We also probe the unsteady rheology of flows in and out of the thickening state with or without a reversal of the flow direction. Transient evolution of stress and microstructure is found if the thickening state or the direction is changed, though the steady state is history independent. The mechanism for the stress evolution involves configurational changes at very small strains and microstructural re-orientation at large strains. The transition starting from a non-thickened state is always slower than its counter cases.

Session and Discussion Chair: Suzanne Fielding

11. Concentrated dispersed systems: a variety of time-dependent solid-liquid transitions and time-dependent behavior types

P. Coussot

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At first sight it seems that concentrated systems can be ranged in two classes according to the way their solid-liquid transition occurs. Systems in which the interactions between elements are mainly repulsive interactions exhibit a simple yield stress fluid behaviour with a smooth transition from the solid to the liquid regime, i.e. with homogenous deformation in both phases. In contrast concentrated systems with mainly attractive interactions tend to develop shear-banding around the solid-liquid transition. The smooth solid-liquid transition for repulsive systems can be associated with a short relaxation time for restructuring process while the abrupt transition is associated with a sufficiently long relaxation time. As a consequence the latter fluids are thixotropic, in particular their apparent viscosity decreases in time during flow and this process is reversible. Unfortunately this simple scheme is unable to encompass the diversity of behaviour of non-model systems. For example Carbon black suspensions appear at first sight as simple yield stress fluids but their rheological behavior is much more subtle. As for thixotropic fluids they exhibit a viscosity bifurcation, but the apparent yield stress does not at all depend on the time they have been left at rest: this yield stress is tunable, it entirely depends on the previous flow history, which sets up the material in a specific state of structure. Thus these materials can flow steadily for any stress value as long as they have been previously submitted to an appropriate flow history. Another example is waxy crude oils which exhibit an abrupt solid-liquid transition associated with an irreversible destructuring process, so that their apparent behaviour depends on the highest shear level imposed during the flow history of the system.

Session and Discussion chair: Richar Buscall

12. Simulational exploration of frictional interactions in viscous suspensions: Relating paint rheology to application behaviour

Simon Davies

Material Science Group, AkzoNobel Decorative Coatings, Wexham Rd, Slough

Many rheological text books use paint as an example of a shear thinning dispersion whose application behaviour may be explained by simple rheological measurements. It is claimed that roller pick up, sagging, flow and levelling etc. correlate with the viscosity of the paint at a certain shear rate. In reality this is far from the truth. The constraints placed on current paint formulations results in many of them being highly thixotropic, often showing shear thickening behaviour and having significant extensional viscosity. In this talk I will describe our attempts to develop appropriate rheological methods to allow the prediction of paint performance. I will also cover current challenges in controlling paint rheology and how the new insights being discussed in this meeting may help tackle them.

Session and Discussion chair: Richard Buscall

13. Dense Granular Flow of Frictional Particles

Matthias Grob, Claus Heussinger and **Annette Zippelius**

Institut für Theoretische Physik, Georg-August-Universität Göttingen, Friedrich-Hund-Platz 1, D-37077 Göttingen, Germany

A jamming scenario of frictional particles is discussed and interpreted in terms of a nonequilibrium first order phase transition [1]. Results of numerical simulations will be presented and analyzed in the framework of a simple model which can account for both, the continuous frictionless case and the discontinuous frictional case. The most important features of the frictional phase diagram are reentrant behaviour and a critical jamming point at finite stress. In the simulations, we observe that small systems settle into a stationary state, whereas large systems do not relax to a stationary state on the timescale of observation, but rather display chaotic time dependence. We propose a hydrodynamic model which couples stress relaxation to a scalar variable accounting for the microstructure of the packing. Linear stability analysis reveals an extended phase diagram which in addition to regions of stationary flow and jammed states displays chaotic states.

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Session and Discussion Chair: Morton Denn

14. Suspensions of non-colloidal particles in yield-stress fluids.

Simon Dagois-Bohy[1], Sarah Hormozi[2], Elisabeth Guazzelli[1] & **Olivier Pouliquen**[1]

[1]Aix-Marseille University, CNRS, IUSTI UMR 7343, 13453 Marseille, France
[2]Department of Mechanical Engineering, Ohio University, Athens, Ohio 45701-2979, USA

The rheology of dense suspensions of rigid particles in a visco-plastic fluid is experimentally investigated. An original home made pressure imposed rheometer is used, which consists in an annular shear cell with a top plate which is porous to the fluid but not to the particles. This alternative way of studying at suspensions enabled to circumvent the divergence observed in volume-imposed rheometry and provided examination of the rheology close to the jamming transition. By carrying out systematic experiments with different yield stress fluids, accurate measurements for both the shear stress and particle normal stress are obtained and constitutive laws can be proposed for viscoelastic suspensions.

Session and Discussion Chair: Morton Denn

15. Structure and Dynamics in Sheared Colloidal Glasses

George Petekidis

Department of Materials Science and Technology, University of Crete
and IESL-FORTH, Heraklion, Crete, Greece

The relation of the microscopic structure and dynamics with the mechanical response of model hard-sphere colloidal glasses under shear is discussed. We probe the interplay between Brownian motion and shear-induced rearrangements and follow the stress, micro-structure and particle dynamics by experimental rheology, microscopy and Browian Dynamics simulations under steady[1] and oscillatory[2] shear. We find that Brownian motion assisted cage escape dominates at low frequencies or shear rates while escape through shear-induced collisions are dominant at high ones. Under large amplitude oscillatory shear both mechanisms are related with a yielding peak in G''. At intermediate frequencies a novel, for HS glasses, double peak in G'' is revealed reflecting both mechanisms. At high frequencies and strain amplitudes a persistent structural anisotropy causes a stress drop within the cycle after strain reversal, while higher stress harmonics are minimized at certain strain amplitudes indicating an apparent harmonic response[2]. In steady shear we probe similar shear-induced structural anisotropy which builds up during a start-up shear and is related with a stress overshoot.

We also utilize orthogonal superposition rheometry were a small strain oscillatory motion orthogonal onto a steady state shearing motion, probes viscoelastic spectra of a sheared colloidal glass. Near the crossover frequency, a strain rate-orthogonal frequency superposition (SROFS) is obtained, due to a convective cage release that introduces a structural relaxation linearly dependent on shear rate. Comparison between experiments and simulations suggest that low frequencies deviations from a simple terminal flow response in SROFS are caused by hydrodynamic interactions.

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3. A. R. Jacob, A. S. Poulos, S. Kim, J. Vermant and G. Petekidis**,** submitted (2015)\

Session and Discussion Chair: Bill Russel

16. Non linear rheology of soft amorphous solids: a microscopic perspective

Michel Cloitre
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Soft amorphous solids are made of soft and deformable particles jammed into a glass-like structure like concentrated emulsions, microgel suspensions, vesicles, star polymers, copolymer micelles and laponite suspensions. In spite of their great variability in composition and architecture, these materials exhibit generic dynamical properties intermediate between those of solids and liquids. They behave like weak elastic solids at rest but yield and flow with complex shear-rate dependence at large stresses. Although such materials are ubiquitous and relevant in applications, a theory connecting macroscopic flow behaviour to microstructure and particle properties remains a formidable challenge.

In this talk we present a micromechanical three-dimensional model that provides microscopic insights into the nonlinear rheology of soft amorphous solids. Our model deals with suspensions of athermal, frictionless, elastic spheres, which are dispersed at volume fractions well above the random close-packing of hard spheres in a solvent. The particles are in contact and interact via elastohydrodynamic repulsive forces [1]. We use a combination of rheological and real space microscopy experiments on well-defined microgel suspensions and concentrated emulsions, particle scale 3D simulations, and theory. We describe and analyze the microscopic mechanisms which are at the origin of yielding [2], flow [1], and aging [3]. Our results provide constitutive equations for the shear stress and normal stress differences as well as quantitative predictions of the microstructure in terms of particle scale properties. We discuss the generality of our results in relation with the behavior of various glassy materials.

Acknowledgments: this work was done in close collaboration with R. T. Bonnecaze and L. Mohan from the Department of Chemical Engineering at the University of Texas at Austin, USA.

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Session and Discussion Chair: Bill Russel