Flocculated Suspensions: From Microstructure to Macroscopic Behavior

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This workshop on flocculated suspensions was held on the campus of Université Paris-Est, at École des Ponts ParisTech, in the eastern suburbs of Paris, on June 28-29 2012. It was funded by the Lafarge-École des Ponts ParisTech Chair "Materials Science for Sustainable Construction", and organized by people from University Paris-Est Navier (Xavier Chateau and Guillaume Ovarlez) and people from Lafarge (Paul Acker and Fabrice Toussaint).

The focus of the workshop was on colloidal suspensions such as cementitious suspensions, sewage, muds, paints, ... These are yield stress fluids which display a time-dependent behavior. Their peculiar behavior comes from the ability of the particles to flocculate at rest and under shear. The flocculated particles can also be redispersed, at least partly, by shearing or by agitation. Knowledge of the structure of flocculated materials and of the physical processes which govern this structure is necessary for understanding their flow behavior. Such knowledge is also a key for developing models and for industrial applications.

The central idea of the conference was to bring researchers and engineers together so as to combine the skills of both fundamental research and technical matters solving in the field of flocculated suspensions, with a focus on presenting recent developments obtained with complementary advanced tools (direct visualization of 2D model systems; confocal microscopy; neutron scattering; MRI; microrheology; numerical simulations...). Studying the mechanical behavior of individual flocs and measuring the structural properties of sheared flocculated suspensions are indeed key elements that should be used to

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to promote gelation and lead to lower critical volume fraction to generate gels than what is found with argument based on diffusion only. Peter Schall, from University of Amsterdam, showed that large scale convective flows due to gravity may also play an important role in accelerating gelation: this was revealed by comparing gelation in space, without gravity, with gelation on Earth. Gelation in space may thus be the only real case where diffusion limited aggregation occurs. Stephane Rodts, from University Paris-Est Navier, has presented recent developments in the field of Nuclear Magnetic Resonance to get information on the structure of flocculated suspensions. NMR techniques specifically provide information that are related to Brownian motion of Hydrogen atoms (and thus water); this motion being affected by the interaction with surfaces, information on the size distribution of voids/flocs can be obtained. Typical fractal dimensions are here shown to differ from those obtained with classical light scattering techniques; this opens the question of the relevant structural description of the fractal-like structure of flocs. Emanuela Del Gado, from ETH Zürich, has reviewed recent progress concerning the local processes and physical mechanisms underlying colloidal gelation and its interplay with flocculation. Using numerical simulations she has detailed the phase diagram of colloidal systems and shown how gel networks form due to the branching of elongated aggregates produced by the kinetic arrest of a separation between a dense and a dilute phase. She also studied in detail the system dynamics. The numerical simulations provide evidence that different dynamics exist at particle/meso/structure scales.

Yielding of flocculated suspensions has also been addressed. Robert Flatt, from ETH Zürich, has presented a model to predict the yield stress of particulate suspensions, which proves to be in very good agreement with experimental data of the literature. This model incorporates known microscopic properties of the material such as the particle size, their volume fraction, and the interparticle forces; the possibility of steric hindrance is also accounted for, which make it possible to predict the impact of superplasticizers used to deflocculate suspensions. At this stage, homogeneous structure is assumed: the model may thus be applicable only to very dense systems; the case of strongly heterogeneous flocculated structures remains to be investigated. Eric Furst, from University of Delaware, has shown experiments in which chains of colloids are manipulated with optical tweezers; such model aggregate mimics the stress-bearing backbone in a gel. He showed that upon shear, slip occurs between particles for forces much smaller than the critical force that would be necessary to separate them; this points to the existence of a critical bending torque that may play a crucial role in the yielding of flocculated suspensions. Jean-Noël Roux, from University Paris-Est Navier has presented recent numerical simulation results on adhesive non-Brownian particles. He first studied in detail quasistatic isotropic consolidation of loose samples. He shown that the material exhibits plastic behavior ruled by a dimensionless pressure, accounting for the relative importance of confining pressure and cohesion, sliding friction and rolling resistance. Simulation results reveal that the materials behave as a dense packing of tenuously connected blobs which average size is correlated to the overall material properties.

Several talks have dealt with flows of flocculated suspensions. Jan Vermant, from Katholieke Universiteit Leuven, has presented investigation of the behavior of 2D model systems. These systems are very convenient to study as optical techniques allows full characterization of their structure, and 2D rheometrical tools are in constant progress. J. Vermant has questioned in detail the 2D nature of these systems and their relevance to 3D systems; he showed in particular that the full 3D interaction of particles has to be taken into account to properly describe these systems, and that some specificities may exist such as the hysteresis of interparticle interaction. Many information can be get from these experiments; first, the aggregated structure formed at rest can be characterized and used to test fractal-based model of their mechanical properties; these models are here shown to work pretty well, although systems are rather dense and fractal concepts were not obviously expected to be applicable in such cases. The experiments also provide much information on the structure formed under shear. P. Schall has presented an investigation of the flow of dense suspensions of colloidal particles in a simple shear geometry with a confocal microscope, which allows getting information on the motion of all particles. In this system, he showed that, at very low shear rates, a transition from homogeneous

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flow to shear-banding occurs; from the temporally resolved 3D images, 3D maps of the local strain can be obtained. These last show that the behavior is mostly that of an elastic material in the case of homogeneous flow, whereas strongly correlated plastic motions are observed in direction of flow in the shear band. J.-N. Roux has presented first results of steady uniform shear flow simulation; the state of the flowing material is ruled by both the classical granular inertial number accounting for the relative importance of confining and inertial forces and the dimensionless pressure. Constitutive laws allowing to evaluate effective friction and solid fraction as a function of the two dimensionless numbers have been proposed and validated. At the microscopic scale, important collective effects observed suggest that simplified models relying on “typical particle’ or “typical force” can be developed, even if inclusion of hydrodynamic interaction in such a model is still a challenging task. Frédéric Pignon, from Université de Grenoble, has presented investigations of 3D flows of colloidal suspensions with scattering techniques. He first showed that various scattering information can be combined to get information on the various relevant sizes in a flocculated suspensions. E.g, in a laponite gel, it is shown that dense regions of agglomerated particles exist and that loose fractal percolated structures are formed by aggregation of these dense regions. Under simple shear, these techniques allow to get the characteristics of disaggregation and shear-induced orientation of the aggregates. F. Pignon has shown that they can now be used to study complex problems; e.g. they allow understanding what the characteristics (aggregates size volume fraction, orientation) of the material formed under filtration are, which is crucial for practical applications.

This workshop has been a unique opportunity to review recent advances from model systems to cementitious materials. Stimulating discussions took place during the presentations and the breaks, and allowed people from different communities to share their knowledge. Even if a lot of work remains to be done, it is expected that the results presented during this meeting provide most of the pieces of the puzzle of a micro-macro approach of the behavior of flocculated suspensions.

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