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RPPR Final Report
as of 01-Sep-2021

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Proposal Number: 67524MS **Agreement Number: W911NF-16-1-0078**

INVESTIGATOR(S):

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DUNS Number: 005421136 EIN: 362177139
Report Date: 14-Mar-2020 Date Received: 30-Aug-2021
Final Report for Period Beginning 15-Mar-2016 and Ending 14-Dec-2019
Title: Dynamic Jamming in Concentrated Particle Suspensions
Begin Performance Period: 15-Mar-2016 **End Performance Period:** 14-Dec-2019
Report Term: 0-Other
Submitted By: Heinrich Jaeger Email: jaeger@uchicago.edu
Phone: (773) 702-6074
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 5 **STEM Participants:** 9

Major Goals: The project is a systematic investigation of dynamic jamming phenomena in suspensions, focusing on fully three-dimensional (3D) systems in the non-Brownian regime. This investigation combines state-of-the-art experimental techniques, including high-speed imaging using video and several modalities of ultrasound. It breaks new ground by probing non-invasively the transient reconfigurations associated with dynamic jamming.

The overall scientific aim of the project is to provide a better fundamental understanding of dynamic jamming in concentrated particle suspensions, in order to enable the design of smart materials with adaptive stress response.

Major goals of the project are to:
1. Provide detailed experimental data on 3D dynamic jamming phenomena under different modes of excitation. Currently only limited data of this type exists, primarily for normal impact.
2. Map out the state diagram for dynamic jamming. None of the models for steady-state shear thickening currently available in the literature can provide an appropriate framework, and neither can the original jamming phase diagram for frictionless particles. Our hypothesis is that shear jamming forms a good basis for such framework.
3. Develop suspensions with tailored frictional as well as liquid-mediated interactions to optimize dynamic jamming properties.
4. Apply dynamic jamming concepts to develop predictive capabilities for new types of ‘smart’ suspensions that exhibit stress adaptive properties.

The project is delineated into two closely coupled efforts:

A. Exploring the Properties of the Dynamically Jammed State
This first effort investigates key aspects concerning the basic properties of the dynamically jammed state that are still unresolved, thereby addressing Major Goals 1&2, above. This includes the relative importance of frictional (granular) and viscous (hydrodynamic) particle interactions in controlling how this state is established during loading and central properties such as the effective mechanical moduli. It also includes how this state reverts back to the liquid-like state once the applied stress is removed.

B. Using Dynamic Jamming to Design the Impact Response
The second effort develops the basis for a systematic approach to optimizing the energy dissipating properties, thereby addressing Major Goals 3&4, above. We are particularly interested in establishing how particle-level properties such as particle shape can be used to tailor dynamic jamming, especially the front propagation speed and the properties of the jammed solid. By tuning the particles’ properties and their frictional interactions in concert

with the viscosity of the suspending liquid, we can control not only the onset stress and tailor the upper stress limit, but also the manner in which the jammed solid fails when the upper stress limit is exceeded.

Accomplishments: Overall, the project developed the experimental basis for a new framework for the understanding, predicting and controlling of strong shear thickening and shear jamming in concentrated suspensions of particles in a liquid.

As part of the project, a total of 11 papers were published, including one in Nature Communications, one in Nature Materials and two in Physical Review Letters.

Key accomplishments were as follows:

- We introduced a novel method based on high-speed ultrasound imaging to track rapidly propagating shear jamming fronts inside dense suspensions. These measurements were the first of their kind and helped establish the conditions for dynamic shear jamming. E. Han, I. R. Peters, and H. M. Jaeger, High-speed ultrasound imaging in dense suspensions reveals impact-activated solidification due to dynamic shear jamming, Nature Communications 7, 12243 (2016). http://dx.doi.org/10.1038/ncomms12243

- We showed that shear jamming fronts are generated in dense suspension both by impact and also by extension. S. Majumdar, I. R. Peters, E. Han, and H. M. Jaeger, Dynamic shear jamming in dense granular suspensions under extension, Physical Review E 95, 012603 (2017). http://dx.doi.org/10.1103/PhysRevE.95.012603

- Combining experiments with theory we showed how shear stress applied at a boundary of a dense suspension generates jamming fronts that propagate into the interior. E. Han, M. Wyart, I. R. Peters, and H. M. Jaeger, Shear fronts in shear-thickening suspensions, Phys. Rev. Fluids 3, 073301 (2018). http://dx.doi.org/10.1103/PhysRevFluids.3.073301

- Our discovery of how hydrogen bonding can control shear jamming in dense aqueous suspensions was published in Nature Materials (N. M. James, E. D. Han, R. A. L. de la Cruz, J. Jureller, and H. M. Jaeger, Interparticle hydrogen bonding can elicit shear jamming in dense suspensions, Nature Materials 17, 965 (2018). http://dx.doi.org/10.1038/s41563-018-0175-5

- We performed the first direct measurements of how hydrogen bonding controls the frictional interactions between individual micron-size particles in a sheared suspension. N. M. James, C.-P. Hsu, N. D. Spencer, H. M. Jaeger, and L. Isa, Tuning Interparticle Hydrogen Bonding in Shear-Jamming Suspensions: Kinetic Effects and Consequences for Tribology and Rheology, Journal of Physical Chemistry Letters 10, 1663-1668 (2019). http://dx.doi.org/10.1021/acs.jpclett.9b00135

- We developed a method for quasi-3D ultrasound imaging, for example to extract the flow field during oblique impact. E. Han, L. Zhao, N. Van Ha, S. T. Hsieh, D. B. Szyld, and H. M. Jaeger, Dynamic jamming of dense suspensions under tilted impact, Physical Review Fluids 4, 063304 (2019). http://dx.doi.org/10.1103/PhysRevFluids.4.063304.

- We mapped out the first state diagrams delineating discontinuous shear thickening and shear jamming of rod-shaped particles. N. M. James, H. Xue, M. Goyal, and H. M. Jaeger, Controlling shear jamming in dense suspensions via the particle aspect ratio, Soft Matter 15, 3649 - 3654 (2019). http://dx.doi.org/10.1039/c9sm00335e

- We demonstrated how shear jamming fronts can be used to establish locally stress-controlled conditions for measurements inside a dense suspension under shear, something that cannot be done with traditional rheology approaches. E. Han, N. M. James, and H. M. Jaeger, Stress Controlled Rheology of Dense Suspensions Using Transient Flows, Physical Review Letters 123, 248002 (2019). http://dx.doi.org/10.1103/PhysRevLett.123.248002

- Using state-of-the-art simulations we showed how shear thickening and shear jamming are controlled by the constraints on relative particle movement due to different types of contact friction (sliding and rolling). A. Singh, C. Ness, R. Seto, J. J. de Pablo, and H. M. Jaeger, Shear thickening and jamming of dense suspensions: the roll of friction, Physical Review Letters 124, 248005 (2020). http://dx.doi.org/10.1103/PhysRevLett.124.248005

In addition, graduate students Endao Han and Nicole James defended their PhD theses, based on results from work under this grant. Endao Han's thesis subsequently was published by Springer as a book, as part of their Outstanding PhD Theses series:

Endo Han, Transient Dynamics of Concentrated Particulate Suspensions Under Shear, Springer Nature Switzerland AG, Cham, Switzerland, 2020. ISBN 978-3-030-38348-0

Training Opportunities: Postdoc Abhinendra Singh was hired in summer 2018 and was co-mentored by the PI and Prof. Juan de Pablo (Pritzker School of Molecular Engineering). He participated in grant writing with the PI and co-mentored all graduate and undergrad students on the project.

Graduate students Endao Han, Nicole James and Michael van der Naald were trained in state-of-the art measurement and analysis techniques, including particle imaging velocimetry (PIV), advanced rheometry, and high-speed ultrasound and optical imaging.

Undergraduate students Medha Goyal and Huayue Xue worked in the PI’s lab from summer 2018 until Winter 2019. Medha Goyal was trained in taking advanced measurements with our rheometers, while Huayue Xue was trained in chemical synthesis of particles for suspensions as well as in using scanning electron microscopy (SEM) and image analysis for particle characterization. Both undergrads were mentored extensively by graduate student Nicole James.

Undergraduate student Liang Zhao worked in the PI’s lab until 2020 before moving on to graduate school. He was trained in ultrasound imaging techniques, particle imaging velocimetry (PIV), and in taking advanced measurements with our rheometers. He was mentored by graduate student Michael van der Naald.

During summers 2019 and 2020, undergraduate student Margot Young and high-school student Ionnis Nikas participated in project-related research in the PI’s lab. Both were trained on the rheometers to measure flow curves of suspensions and were mentored by graduate student Michael van der Naald.

Results Dissemination: Besides the publications in journals, mentioned above, the PI, postdoc and graduate students disseminated results from this project through seminars and talks at conferences. Postdoc Abhinendra Singh attended the Society of Rheology meeting to present a talk on his simulation results and grad student Nicole James participated in APS and ACS Meetings and gave contributed talks on her work on hydrogen bonding. The PI gave invited seminars and colloquia at universities throughout the country.

Honors and Awards: During the project the PI was elected member of the American Academy of Arts & Sciences.

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Heinrich Jaeger
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Endao Han
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Nicole James
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Michael van der Naald
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Abhinendra Singh
Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Research Experience for Undergraduates (REU) Participant
Participant: Nigel van Ha
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Undergraduate Student
Participant: Margot Young
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Research Experience for Undergraduates (REU) Participant
Participant: Ionnis Nikas
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Undergraduate Student
Participant: Liang Zhao
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Undergraduate Student

Participant: Medha Goyal
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Undergraduate Student
Participant: Huayue Xue
Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: High School Student
Participant: Nigel van Ha
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

ARTICLES:

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Journal: Nature
Publication Identifier Type: DOI Publication Identifier: 10.1038/nature17167
Volume: 532 Issue: 7598 First Page #: 214
Date Submitted: 8/29/16 12:00AM Date Published: 4/1/16 5:00AM
Publication Location:
Article Title: Direct observation of dynamic shear jamming in dense suspensions
Authors: Ivo R. Peters, Sayantan Majumdar, Heinrich M. Jaeger
Keywords: shear thickening, shear jamming, solidification, phase diagram
Abstract: Liquid-like at rest, dense suspensions of hard particles can undergo striking transformations in behaviour when agitated or sheared. These phenomena include solidification during rapid impact, as well as strong shear thickening characterized by discontinuous, orders-of-magnitude increases in suspension viscosity. Much of this highly non-Newtonian behaviour has been interpreted within the framework of a jamming transition. However, although jamming indeed induces solid-like rigidity, even a strongly shear-thickened state still flows and thus cannot be fully jammed. Furthermore, although suspensions are incompressible, the onset of rigidity in the standard jamming scenario requires an increase in particle density. As a result, it has remained unclear how these dense suspension phenomena are connected to jamming. Here we demonstrate that a fully jammed, solid-like state can be reached without compression and instead purely with shear, as recently proposed for dry granular systems.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nature Communications
Publication Identifier Type: DOI Publication Identifier: 10.1038/ncomms12243
Volume: 7 Issue: First Page #: 12243
Date Submitted: 8/29/16 12:00AM Date Published: 7/1/16 12:00AM
Publication Location:
Article Title: High-speed ultrasound imaging in dense suspensions reveals impact-activated solidification due to dynamic shear jamming
Authors: Endao Han, Ivo R. Peters, Heinrich M. Jaeger
Keywords: ultrasound imaging, shear thickening, shear jamming, solidification
Abstract: A remarkable property of dense suspensions is that they can transform from liquid-like at rest to solid-like under sudden impact. Previous work showed that this impact-induced solidifi- cation involves rapidly moving jamming fronts; however, details of this process have remained unresolved. Here we use high-speed ultrasound imaging to probe non-invasively how the interior of a dense suspension responds to impact. Measuring the speed of sound we demonstrate that the solidification proceeds without a detectable increase in packing fraction, and imaging the evolving flow field we find that the shear intensity is maximized right at the jamming front. Taken together, this provides direct experimental evidence for jamming by shear, rather than densification, as driving the transformation to solid-like behaviour. On the basis of these findings we propose a new model to explain the anisotropy in the propagation speed of the fronts and delineate the onset conditions for dynamic shear jamming.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Soft Matter
Publication Identifier Type: DOI Publication Identifier: 10.1039/C7SM00182G
Volume: 13 Issue: 19 First Page #: 3506
Date Submitted: 8/28/17 12:00AM Date Published:
Publication Location:
Article Title: Measuring the porosity and compressibility of liquid-suspended porous particles using ultrasound
Authors: Endao Han, Nigel Van Ha, Heinrich M. Jaeger
Keywords: ultrasound, time of flight, packing fraction
Abstract: A key parameter describing the behavior of suspensions is the volume fraction f of the solid particles that are dispersed in the liquid. Obtaining accurate values for f becomes difficult for porous particles, because they can absorb some of the liquid. A prime example are the widely used cornstarch suspensions, for which f usually is only estimated from the mass fraction of particles. Here we present a method to measure the effective porosity and compressibility of porous particles with ultrasound. We obtain the speed of sound in dilute cornstarch suspensions at multiple particle concentrations and with different solvent compressibilities. With the measured particle porosity of 0.31 we are able to calculate the volume fraction of the saturated particles reliably.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review E
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevE.95.012603
Volume: 95 Issue: 1 First Page #:
Date Submitted: 8/28/17 12:00AM Date Published: 1/1/17 6:00AM
Publication Location:
Article Title: Dynamic shear jamming in dense granular suspensions under extension
Authors: Sayantan Majumdar, Ivo R. Peters, Endao Han, Heinrich M. Jaeger
Keywords: extensional rheology, suspensions, impact, fronts
Abstract: Unlike dry granular materials, a dense granular suspension like cornstarch in water can strongly resist extensional flows. At low extension rates, such a suspension behaves like a viscous fluid, but rapid extension results in a response where stresses far exceed the predictions of lubrication hydrodynamics and capillarity. To understand this remarkable mechanical response, we experimentally measure the normal force imparted by a large bulk of the suspension on a plate moving vertically upward at a controlled velocity. We observe that, above a velocity threshold, the peak force increases by orders of magnitude. Using fast ultrasound imaging we map out the local velocity profiles inside the suspension, which reveal the formation of a growing jammed region under rapid extension. This region interacts with the rigid boundaries of the container through strong velocity gradients, suggesting a direct connection to the recently proposed shear-jamming mechanism.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

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Journal: Physical Review Fluids
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Date Submitted: 9/1/18 12:00AM Date Published: 7/1/18 12:00AM
Publication Location:
Article Title: Shear fronts in shear-thickening suspensions
Authors: Endao Han, Matthieu Wyart, Ivo R. Peters, Heinrich M. Jaeger
Keywords: non-Newtonian fluids, jamming, dynamics
Abstract: We study the fronts that appear when a shear-thickening suspension is submitted to a sudden driving force at a boundary. Using a quasi-one-dimensional experimental geometry, we extract the front shape and the propagation speed from the suspension flow field and map out their dependence on applied shear. We find that the relation between stress and velocity is quadratic, as is generally true for inertial effects in liquids, but with a prefactor that can be much larger than the material density.We show that these experimental findings can be explained by an extension of a phenomenological model originally developed to describe steady-state shear thickening. This is achieved by introducing a sole additional parameter: the characteristic strain scale that controls the crossover from startup response to steady-state behavior. The theoretical framework we obtain points out a linkage between transient and steady-state properties of shear-thickening materials.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

BOOKS:

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Publication Identifier Type: ISBN Publication Identifier: 978-3-030-38348-0
Book Edition: Volume: Publication Year: 2020 Date Received:
Publication Location: Cham, Switzerland, 2020
Publisher: Springer Nature Switzerland AG
Book Title: Transient Dynamics of Concentrated Particulate Suspensions Under Shear
Authors: Endao Han
Editor:
Acknowledged Federal Support: N

Publication Type: Book Peer Reviewed: N **Publication Status:** 0-Other

Publication Identifier Type: ISBN Publication Identifier: 978-3-030-38348-0
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Publication Location: Cham, Switzerland, 2020
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Book Title: Transient Dynamics of Concentrated Particulate Suspensions Under Shear
Authors: Endao Han
Editor:
Acknowledged Federal Support: N

Publication Type: Book Peer Reviewed: N **Publication Status:** 0-Other
Publication Identifier Type: ISBN Publication Identifier: 978-3-030-38348-0
Book Edition: Volume: Publication Year: 2020 Date Received:
Publication Location: Cham, Switzerland, 2020
Publisher: Springer Nature Switzerland AG
Book Title: Transient Dynamics of Concentrated Particulate Suspensions Under Shear
Authors: Endao Han
Editor:
Acknowledged Federal Support: N

Publication Type: Book Peer Reviewed: N **Publication Status:** 0-Other
Publication Identifier Type: ISBN Publication Identifier: 978-3-030-38348-0
Book Edition: Volume: Publication Year: 2020 Date Received:
Publication Location: Cham, Switzerland, 2020
Publisher: Springer Nature Switzerland AG
Book Title: Transient Dynamics of Concentrated Particulate Suspensions Under Shear
Authors: Endao Han
Editor:
Acknowledged Federal Support: N

Publication Type: Book Peer Reviewed: N **Publication Status:** 1-Published
Publication Identifier Type: ISBN Publication Identifier: 978-3-030-38348-0
Book Edition: Volume: Publication Year: 2020 Date Received:
Publication Location: Cham, Switzerland, 2020
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Book Title: Transient Dynamics of Concentrated Particulate Suspensions Under Shear
Authors: Endao Han
Editor:
Acknowledged Federal Support: Y

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: University of Chicago
Date Received: 01-Sep-2018 Completion Date: 7/27/18 10:28AM
Title: TRANSIENT DYNAMICS OF CONCENTRATED PARTICULATE SUSPENSIONS UNDER SHEAR
Authors: Endao, Han
Acknowledged Federal Support: **N**

RPPR Final Report
as of 01-Sep-2021

Publication Type: Thesis or Dissertation
Institution: University of Chicago
Date Received: 30-Aug-2021 Completion Date: 3/29/19 10:59AM
Title: The Role of Surface Chemistry in the Shear Jamming of Dense Suspensions
Authors: Nicole James
Acknowledged Federal Support: **N**

Partners

,

Juan J. de Pablo, Professor, Pritzker School of Molecular Engineering, Univ of ChicagoStuart Rowan, Professor, Pri

I certify that the information in the report is complete and accurate:
Signature: Heinrich Jaeger
Signature Date: 8/30/21 4:31PM

Major Goals
The project is a systematic investigation of dynamic jamming phenomena in suspensions, focusing on fully three-dimensional (3D) systems in the non-Brownian regime. This investigation combines state-of-the-art experimental techniques, including high-speed imaging using video and several modalities of ultrasound. It breaks new ground by probing non-invasively the transient reconfigurations associated with dynamic jamming.

The overall scientific aim of the research has been to provide a better fundamental understanding of dynamic jamming in concentrated particle suspensions, in order to enable the design of smart materials with adaptive stress response.

Major goals of the project are to:

1. Provide detailed experimental data on 3D dynamic jamming phenomena under different modes of excitation. Currently only limited data of this type exists, primarily for normal impact.
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Accomplishments Under Goals
Overall, the project developed the experimental basis for a new framework for the understanding, predicting and controlling of strong shear thickening and shear jamming in concentrated suspensions of particles in a liquid.

As part of the project, a total of 11 papers were published, including one in Nature Communications, one in Nature Materials and two in Physical Review Letters.

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- We performed the first direct measurements of how hydrogen bonding controls the frictional interactions between individual micron-size particles in a sheared suspension. N. M. James, C.-P. Hsu, N. D. Spencer, H. M. Jaeger, and L. Isa, Tuning Interparticle Hydrogen Bonding in Shear-Jamming Suspensions: Kinetic Effects and Consequences for Tribology and Rheology, Journal of Physical Chemistry Letters 10, 1663-1668 (2019). http://dx.doi.org/10.1021/acs.jpclett.9b00135

- We developed a method for quasi-3D ultrasound imaging, for example to extract the flow field during oblique impact. E. Han, L. Zhao, N. Van Ha, S. T. Hsieh, D. B. Szyld, and H. M. Jaeger, Dynamic jamming of dense suspensions under tilted impact, Physical Review Fluids 4, 063304 (2019). http://dx.doi.org/10.1103/PhysRevFluids.4.063304.

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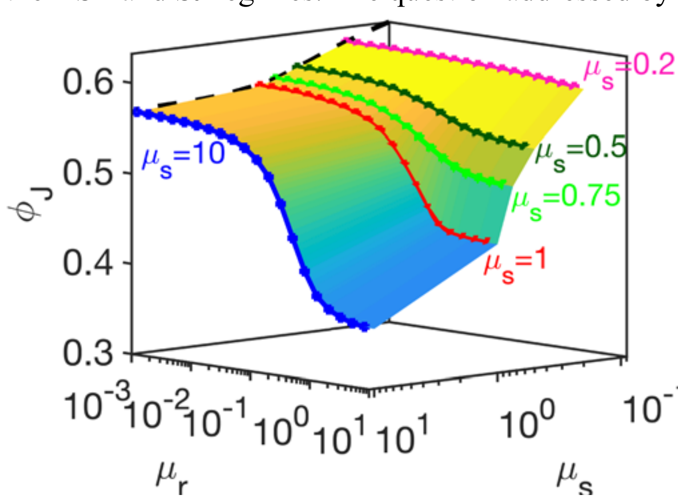
- We demonstrated how shear jamming fronts can be used to establish locally stress-controlled conditions for measurements inside a dense suspension under shear, something that cannot be done with traditional rheology approaches. E. Han, N. M. James, and H. M. Jaeger, Stress Controlled Rheology of Dense Suspensions Using Transient Flows, Physical Review Letters 123, 248002 (2019). http://dx.doi.org/10.1103/PhysRevLett.123.248002

- Using state-of-the-art simulations we showed how shear thickening and shear jamming are controlled by the constraints on relative particle movement due to different types of contact friction (sliding and rolling). A. Singh, C. Ness, R. Seto, J. J. de Pablo, and H. M. Jaeger, Shear thickening and jamming of dense suspensions: the roll of friction, Physical Review Letters 124, 248005 (2020). http://dx.doi.org/10.1103/PhysRevLett.124.248005

In addition, graduate students Endao Han and Nicole James defended their PhD theses, based on results from work under this grant. Endao Han's thesis subsequently was published by Springer as a book, as part of their Outstanding PhD Theses series:

Endo Han, Transient Dynamics of Concentrated Particulate Suspensions Under Shear, Springer Nature Switzerland AG, Cham, Switzerland, 2020. ISBN 978-3-030-38348-0

Major Activities not already discussed in prior reports for this project focused on mapping out how the state diagram for dense suspensions can be tailored by controlling frictional particle-particle interactions to optimize dynamic jamming properties. This effort addressed **Major Goals 2 & 3** and was led by postdoc Abhinendra Singh. Prior simulations by Singh and colleagues at had shown how the interparticle sliding friction coefficient μ controls the extent of the SJ regime in the (σ, ϕ) state diagram as well as the extent of DST. The key message that emerged from these simulations is that friction needs to be maximized in order to make the interval $[\phi_J^{\mu}, \phi_J^{0}]$ as large as possible, i.e., in order to optimize access to the DST and SJ regimes. The question addressed by Singh in the PI's group now became how this is modified by the presence of additional constraints on the relative movement of contacting particles, such as rolling friction in addition to sliding friction. This required a careful extension of the simulation code and extensive calibration against experimental results. For the latter, Singh used data published by grad student Nicole James in her 2018 Nature Materials paper. The idea here being that hydrogen bonding introduces a



strong constraint against rolling. The upshot of these simulations was that the short-range attractive forces due to hydrogen bonding, with range on the molecular scale and thus much less than λ, do not produce a yield stress, but instead shift the onset of DST to lower stress levels and furthermore increase the viscosity in the high-stress limit. Acting like molecular-scale 'sticky pads', hydrogen bonds strongly enhance sliding friction by snapping contacting surface patches together, and they *also introduce a certain degree of stickiness*. Our simulations indicate that the overall effect of this stickiness is similar to introducing rolling friction in addition to sliding friction.

A central result from these simulations was the development of a state diagram that shows how the onset packing fraction for shear jamming, ϕ_J^μ, is controlled by the strengths of sliding (μ_s) and rolling (μ_r) friction. This is shown in the picture above. Very interestingly, rolling friction only appears to have a significant effect beyond a minimum of sliding friction, around $\mu_s = 0.2$. However, for physically reasonable values of the order of $\mu_s = 0.5 \ldots 0.8$ already small amounts of rolling friction, perhaps one order of magnitude smaller than μ_s, can dramatically lower the onset threshold ϕ_J^μ for jamming in the state diagram. These results were published in Physical Review Letters 124, 248005 (2020).

Training Opportunities:
Postdoc Abhinendra Singh was hired in summer 2018 and was co-mentored by the PI and Prof. Juan de Pablo (Pritzker School of Molecular Engineering). He participated in grant writing with the PI and co-mentored all graduate and undergrad students on the project.

Graduate students Endao Han, Nicole James and Michael van der Naald were trained in state-of-the art measurement and analysis techniques, including particle imaging velocimetry (PIV), advanced rheometry, and high-speed ultrasound and optical imaging.

Undergraduate students Medha Goyal and Huayue Xue worked in the PI's lab from summer 2018 until Winter 2019. Medha Goyal was trained in taking advanced measurements with our rheometers, while Huayue Xue was trained in chemical synthesis of particles for suspensions as well as in using scanning electron microscopy (SEM) and image analysis for particle characterization. Both undergrads were mentored extensively by graduate student Nicole James.

Undergraduate student Liang Zhao worked in the PI's lab until 2020 before moving on to graduate school. He was trained in ultrasound imaging techniques, particle imaging velocimetry (PIV), and in taking advanced measurements with our rheometers. He was mentored by graduate student Michael van der Naald.

During summer 2019 undergraduate student Margot Young and high-school student Ionnis Nikas participated in project-related research in the PI's lab. Both were trained on the rheometers to measure flow curves of suspensions and were mentored by graduate student Michael van der Naald.