

PAPER • OPEN ACCESS

Experimental Study of Granular Materials Composed of Platonic Polipods: Exploring Geometric Cohesion and Solid Fraction

To cite this article: D. Aponte *et al* 2025 *IOP Conf. Ser.: Earth Environ. Sci.* **1480** 012118

View the [article online](#) for updates and enhancements.

You may also like

- [Cosmic microwave background radiation in an inhomogeneous spherical space](#)
R Aurich, P Kramer and S Lustig
- [Higher multipoles of highly symmetric charge distributions over Platonic solids](#)
Orest Hryhorchak and Andrij Rovenchak
- [Optical properties of Platonic clusters of plasmonic nanoparticles](#)
V.V. Klimov and G.V. Sharonov

EXPERIMENTAL STUDY OF GRANULAR MATERIALS COMPOSED OF PLATONIC POLIPODS: EXPLORING GEOMETRIC COHESION AND SOLID FRACTION

D. Aponte^{1,2} N. Estrada¹ J. Barès² M. Renouf² E. Azéma^{2,3,4}✉

¹ *Universidad de los Andes, Dept. Civil and Environmental Engineering, Bogotá, Colombia*

² *LMGC, Université de Montpellier, CNRS, Montpellier, France*

³ *Institut Universitaire de France, Paris, France*

⁴ *Department of Civil, Geological and Mining Engineering, Polytech. Montréal, Montréal, Canada.*

✉ emilien.azema@umontpellier.fr

Abstract: In this study, we explored the stability and compactness of columns formed from highly irregular particles. These particles, known as Platonic polypods, are fashioned by extruding arms onto the faces of Platonic solids, for which we systematically varied the number and thickness of these arms. We investigated the emergence and vanishing of geometric cohesion (i.e., solid-like characteristics, in the absence of adhesive forces among particles). We first built columns by depositing particles within a cylindrical container, which was then removed to assess the structure's stability. Experiments employing three different materials discerned the impact of the friction coefficient between grains. Our results show that specific granular systems manifest geometric cohesion, depending upon their geometric and contact attributes. Furthermore, we measured the initial solid fraction of the columns, illustrating their capacity to attain stability even in markedly loose configurations.

1. Introduction

Research on the shape of particles in granular materials has been extensive. Recent studies have focused on understanding how angularity, elongation, and platyness affect the geometrical and mechanical properties of granular materials. There's a growing interest in materials with highly non-convex particles, which represent an extreme in particle morphology. These materials are notable for their unique behaviors, such as remarkably low solid fractions and solid-like behavior resulting solely from particle geometry and friction. This phenomenon, known as geometric cohesion, was initially described by S.V. Franklin in 2012 [1]. Geometric cohesion has been observed in various types of granular materials, including those composed of bars, staples, Z-shaped particles, star-shaped particles, and polypods. For some recent examples, see Refs. [2, 3, 4, 5, 6], and for a more complete list see the references in [5]. However, many of these studies lack a comprehensive analysis of the characteristics enabling or hindering its emergence. This knowledge gap presents challenges in interpreting new findings and limits the practical utilization of these materials.

This study aimed to systematically investigate granular materials displaying geometric cohesion. Over 3000 experiments were conducted using highly non-convex particles, known as Platonic polypods, fabricated by adding arms onto Platonic solids' faces. We varied the number and thickness of these arms and the friction coefficient between particles using three materials: HDPE, EPDM, and PA12. HDPE and EPDM were used to create hexapods with different arm thicknesses relative to particle size, while PA12 was employed for 3D-printing polypods with 4 to 20 arms. These particles were then assembled into granular columns of various diameters for stability testing. This setup enabled us to observe the emergence and disappearance of geometric cohesion while quantifying the solid fraction in the initial arrangements.

2. Methods

We employed three different materials in particle fabrication to explore the impact of the friction coefficient at particle contacts. (i) The first material, High Density Polyethylene (HDPE), was



liquefied and injected into metal molds to produce hexapod-shaped particles with varying arm thickness relative to particle size. This material has the lowest friction coefficient μ between particles. We introduced a dimensionless parameter, η , to quantify the aspect ratio of the arms, defined as $(d - \delta)/d$, where d represents the particle diameter and δ denotes the arm thickness. Particle size was standardized at $d = 1.2$ cm, and η values ranged from 0.33 to 0.87. Figure 1(a) shows two HDPE particles with η values of 0.33 and 0.87, along with their respective d and η values. (ii) The second material, Ethylene Propylene Diene Monomer (EPDM), underwent a similar manufacturing process as HDPE, involving liquefaction and injection into metal molds. This material has an intermediate μ . (iii) To examine particles with various arm numbers N_a , we utilized Polyamide 12 (PA12) as a third material. Using a 3D printer, particles with N_a values ranging from 4 to 20 were produced, corresponding to the number of faces of Platonic polyhedra. This material and fabrication procedure produce the largest μ . All PA12 particles had $\eta = 0.87$. Figure 1(b) shows the five types of particles constructed with PA12.

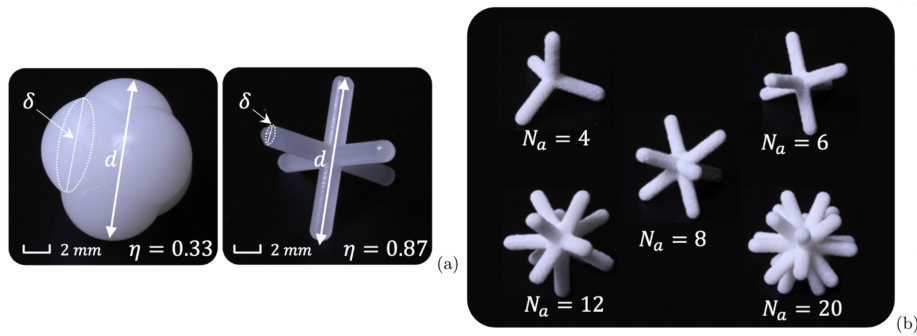


Figure 1. Particle description: All particles had a diameter d of 1.2 cm. (a) Particles made of PEHD and EPDM had varying arm thickness δ , quantified by the aspect ratio η of the arms. The figure shows examples with the lowest and highest η values used. (b) Polypods made of PA12 had different arm numbers ($N_a \in (4, 6, 8, 12, 20)$), all with $\eta = 0.87$.

To evaluate the stability of the particle arrangements described earlier, we conducted column collapse tests, a method proven effective in previous studies [7, 5]. Initially, two halves of a plexi-glass cylinder were placed on a flat, rough surface covered with 40-grit sandpaper. A predetermined quantity of particles was then carefully poured into the cylinder before slowly separating the halves. Consistent with prior literature [7, 5], a significant number of repetitions were performed to ensure the statistical significance of the results. After cylinder removal, two distinct behaviors were observed: (i) Some experiments resulted in material collapse, forming a pile with an approximately conical shape, referred to as a "frictional response" in this paper. (ii) In contrast, other experiments retained their initial shape, forming a free-standing column resembling a solid, termed a "cohesive response" throughout the paper. To explore the impact of column size, we used three cylinders with diameters D that were 2.75, 5.16, and 8.08 times the size of the particles d . Figure 2(a) shows these cylinders, while Fig. 2(b) shows both frictional and cohesive responses in the experiment. To quantitatively evaluate column stability, we utilized the collapse ratio r , defined in Ref. [7], given by $r = N_{\text{out}}/N_p$, where N_{out} is the number of particles outside the initial column volume, and N_p is the total number of particles used. For columns with cohesive responses, r tends towards zero, while for those with frictional responses, r tends to be closer to one. Additionally, to assess sample compactness, we computed the initial solid fraction $\phi = V_p/V$, where V_p is the volume occupied by the particles, and V is the total volume.

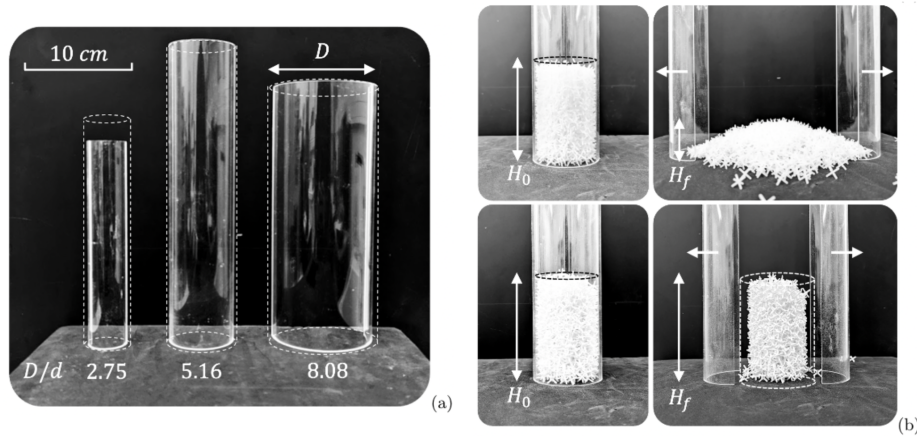


Figure 2. Experimental setup: (a) Three cylinders of varying internal diameters D relative to particle size d were used to construct the columns. (b) Initial (left) and final (right) states of the experiment are shown for systems exhibiting frictional (top) and cohesive (bottom) responses. Graphical representations of initial and final column heights (H_0 and H_f , respectively) are provided.

3. Results

Figure 3 displays the collapse ratio r against the normalized initial height H_0/d . Rows represent different container diameters D/d , while columns represent the three materials used: HDPE, EPDM, and PA12. For HDPE and EPDM, the series represent particles with varying arm aspect ratios η , all hexapods ($N_a = 6$). Conversely, for PA12, the series represent polypods with different N_a , each having $\eta = 0.87$. Each series corresponds to a “system,” comprising experiments with columns containing different numbers of particles N_p and thus varying initial heights H_0 . In systems exhibiting a frictional response (e.g., all systems in the first row and first column of the figure), the collapse ratio r increases rapidly with H_0/d , indicating that even the shortest columns eventually collapse, approaching unity as column height increases. However, a distinct behavior is observed in certain systems within larger containers, thinner arms, and more frictional materials. These systems demonstrate geometric cohesion, transitioning from a cohesive to a frictional response. For shorter columns, r remains small, sometimes approaching zero, but beyond a critical column height, r gradually increases before asymptotically approaching unity, resembling the behavior of systems with a frictional response. This transition is notably observed in EPDM particles with an aspect ratio $\eta = 0.87$, as well as in PA12 particles with N_a values of 8, 12, and 20. Clearly, wider containers and higher local friction coefficients facilitate the emergence of geometric cohesion.

Finally, we measured the initial solid fraction ϕ of the systems as a function of arm aspect ratio η , arm number N_a , and particle friction coefficient μ . Firstly, we observed that ϕ decreases with increasing η , transitioning from typical granular material values (e.g., 0.6) to much lower values (0.2, meaning that only 20% of the volume is occupied by the particles!). Secondly, ϕ notably decreases with increasing μ , especially for higher N_a . Thin containers also reduce ϕ , as wall influence becomes more pronounced.

4. Conclusions

In conclusion, our findings reveal that certain granular systems exhibit geometric cohesion, depending upon their geometric and contact properties. Notably, the emergence of this property was observed in EPDM particles with an aspect ratio of $\eta = 0.87$, as well as in PA12 particles with N_a

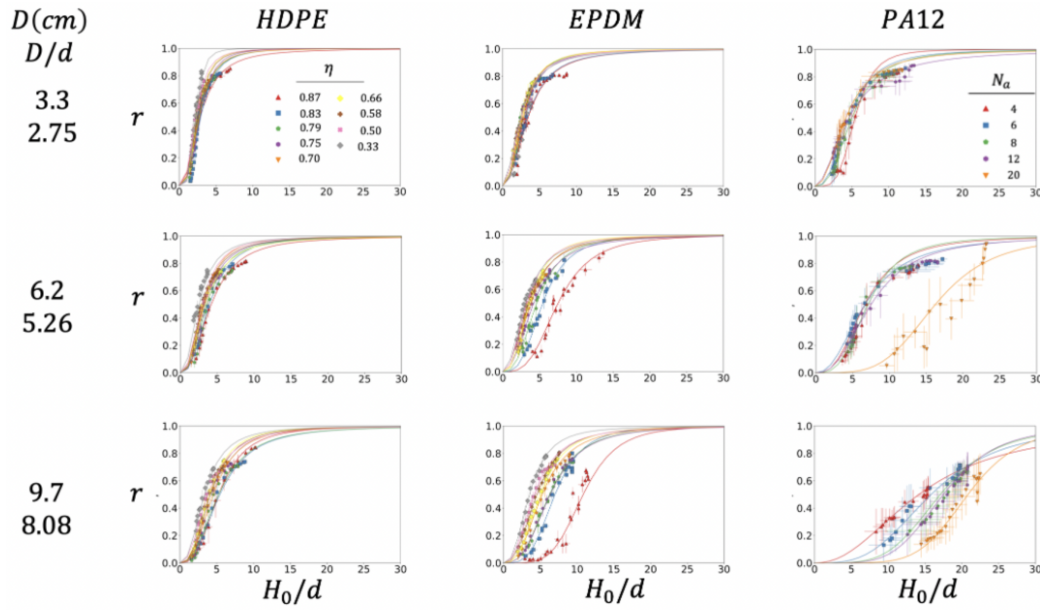


Figure 3. Collapse ratio r plotted against normalized initial height H_0/d . Rows represent container diameter D ratios ($D/d \in (2.75, 5.16, 8.08)$), while columns depict the materials used (HDPE, EPDM, and PA12). For HDPE and EPDM, series represent different arm aspect ratios η ; all particles for these materials were hexapods ($N_a = 6$). For PA12, series represent polypods with varying arm numbers N_a , all having an aspect ratio $\eta = 0.87$. Each series corresponds to columns constructed with different particle numbers N_p and thus different H_0 values.

values of 8, 12, and 20. Moreover, wider containers were found to facilitate geometric cohesion. These results highlight the critical interplay between particle shape and contact friction, both of which are essential conditions for the manifestation of geometric cohesion. Additionally, our study reaffirms the significance of container size, as systematically explored in Ref. [7]. Furthermore, we measured the initial solid fraction of the columns, finding that these systems can achieve stability even in highly loose states, contrasting with traditional granular materials.

References

- [1] Franklin, S. V. (2012). Geometric cohesion in granular materials. *Phys. Today*, **65**.
- [2] Trepanier, M. and Franklin, S. V. (2010). Column collapse of granular rods. *Phys. Rev. E*, **82**, 011308.
- [3] Savoie, W., Tuazon, H., Bhamla, M. S., and Goldman, D. I. (2023). Amorphous entangled active matter. *Soft Matter*, **19**, 1952–1965.
- [4] Karapiperis, K., Monfared, S., Buarque de Macedo, R., Richardson, S., and Andrade, J. E. (2022). Stress transmission in entangled granular structures. *Granular Matter*, **24**, 1–15.
- [5] Aponte, D., Estrada, N., Barés, J., Renouf, M., and Azéma, E. (2024). Geometric cohesion in two-dimensional systems composed of star-shaped particles. *Accepted to Phys. Rev. E*.
- [6] Tran, T. D., Nezamabadi, S., Bayle, J. P., Amarsid, L., and Radjai, F. (2024). Contact networks and force transmission in aggregates of hexapod-shaped particles. *Soft Matter*, **20**, 3411–3424.
- [7] Barés, J., Zhao, Y., Renouf, M., Dierichs, K., and Behringer, R. (2016). Structure of hexapod 3d packings: understanding the global stability from the local organization. *Powders and Grains 2017*.