Time-Dependent Response of Coke-Glycerin Mixtures to Mechanical Vibration

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Abstract

Carbon anodes, made by compacting anode paste in a mold through vibro-compaction, play a crucial role in the Hall-Héroult process. The response of the anode paste to mechanical vibration highly depends on the rheological characteristics of the pitch and the properties of coke particles. Given the variations in the properties of raw materials, such as coke density and shape and pitch viscosity, the dynamic behavior of the anode paste differs from time to time in the vibro-compaction stage. This variability in anode paste composition leads to different flowability and compaction capabilities; each needs a specific vibration frequency, acceleration, and time to ensure optimal compaction and rearrangement of the coke aggregates. This study aims to show how different sizes of coke particles behave regarding flowability and compaction under vibration when combined with a specific amount of a viscous fluid. To do so, we designed an experimental apparatus comprising a vibration table, a transparent vessel, and an ultra-high-speed camera to track the time-dependent motion of different materials subjected to vertical vibrations. We used a mixture of calcined petroleum coke particles and glycerin as a representative material to simulate the anode paste. Preliminary results show that the vibration rearranges the coke aggregates, minimizes the space between the particles, and compacts the bulk through time. Moreover, the particle size distribution significantly affects the compaction dynamics, with the bidisperse mixture of fine and coarse particles exhibiting the highest packing density and uniformity among the studied cases. The results are expected to apply to the industrial vibro-compaction of anode paste, and the setup can be utilized to refine vibration parameters for various simulated anode paste recipes with different flowabilities.

Keywords: Aluminium production, Carbon anodes, Vibration, Angle of repose, Flowability.

1. Introduction

The study of granular materials is essential in various industrial applications, from enhancing powder packing in pharmaceutical manufacturing to producing high-quality anodes in aluminum production [1, 2]. In particular, pre-baked carbon anodes, commonly used in the electrolysis reaction that extracts aluminum from alumina, are manufactured through vibro-compacting a mixture of 85 wt % different sizes of coke particles and butts and 15 wt % coal-tar pitch. The pitch acts as the binder agent between the coke aggregates to cement the fine particles into the interstices of the coarse particle matrix [3].

The mixture is first poured into the vibro-compaction chamber, creating a semi-conical heap. This initial pouring stage shows inherent heterogeneities within the pile, with minimal porosity at the center and increasing porosity towards the edges [4]. In addition, the interaction of fine and coarse particles during this process leads to a preferential distribution, with finer particles accumulating in the central region and coarser ones migrating farther [5]. A descending flat plate acts as a mold and exerts pressure on the bulk of granular materials in the vibro-compaction chamber. At the same time, a vertical vibration is employed to facilitate the rearrangement of the particles. This process enables coke particles to migrate from the pile center to the sides, forming a more uniform distribution [6–8]. Given that the density and homogeneity of the produced anodes affect the overall performance of the aluminum production, an optimized vibration with specific amplitude and frequency should be applied to the system to minimize porosity variation and preferential distribution after the pouring stage. This optimized vibration setting differs from time to time, as different raw materials with varying flowabilities respond differently to vertical vibration.

The angle of repose (AoR) or slope is a key parameter that quantifies the flowability of granular materials, defined as the steepest slope of a stable conical heap formed after pouring the material onto a horizontal surface or into a confined box [1, 9–11]. The AoR is an indicator of the packing capability of a material, making it a crucial factor in many industrial applications, especially in grain storage systems where a lower AoR is desirable as it reduces the cost and complexity of filling silos and maintaining heap surfaces [12, 13].

Several factors affect the AoR and flowability of granular materials, including surface texture, sphericity, and moisture content. More textured and less spherical particles slide over each other less easily and exhibit a higher AoR due to increased interlocking and inter-particle friction [1, 5, 13]. Moreover, increasing the moisture content promotes liquid bridge formation between the particles, further increasing the AoR [14].

Additionally, particle size is another parameter that alters the AoR. Coarse particles typically exhibit a higher initial angle of repose, as they tend to interlock more and have greater friction at the contact points, reducing their flowability. Smaller particles, on the other hand, tend to flow more easily, leading to a lower angle of repose post-pouring [15–17].

In addition to the shape of the particle bed and the angle of repose, the packing characteristics of the material also play a crucial role in determining its response to mechanical vibration and final density post-vibration. The maximum packing fraction, which is the highest possible proportion of a vessel that particles can fill, is affected by the particle size distribution of a mixture. When uniform-sized spherical particles are poured into a container and vibrated, they can occupy a maximum of 64 % of the container's volume. A wider range of particle size classes, however, leads to higher packing density as smaller particles can fill the space between the larger ones, highlighting the importance of having different sizes of particles to reach the highest-packed mixture [18, 19].

In the anode production process, the paste recipe requires an optimal proportion of coarse, medium, and fine coke particles to obtain the highest anode density and mechanical strength. Sarkar et al. showed that reducing the medium-sized particles while adjusting the amount of fine and coarse aggregates can increase the green and baked anode densities and minimize the electrical resistivity. However, completely eliminating the medium-sized particles leads to a significant reduction in anode density [20]. In addition, it is shown that the particle size distribution affects the compaction behavior by determining the amount of pitch required for effective compaction. Mixtures with higher proportions of coarse particles need lower pressure to temperature is similar to that of pitch at vibro-compaction temperature. An experimental setup comprising a vibration table, a transparent vessel, a material feed tube, and an ultra-high-speed camera is used to analyze the response of different materials to vertical vibration. Three cases were studied: coarse particles (2.3–4.7 mm) with glycerin, mixed (50 % coarse, 50 % fine) particles with glycerin, and fine particles (0.3–0.6 mm) with glycerin. In general, the preliminary results are summarized as follows:

- Granular materials form a heap after being poured into a box. The vibration makes the heap collapse and compact. The results show that the particle bed compacts more at the first two seconds of vibration and becomes more stable from this time onward. This is true for both fine and coarse coke aggregates.
- The maximum possible packing fraction increases by increasing the number of particle size classes. Therefore, the bidisperse mixture of fine and coarse particles shows the highest density among the three cases over the given period of vibration.
- Glycerin acts as a binder, increasing the cohesive forces between the particles. The increased cohesiveness caused by glycerin seems to be more pronounced for fine particles, possibly due to their higher surface area to volume ratio, which increases the contact points with the glycerin and, consequently, strengthens inter-particle cohesion.
- The height uniformity of the mixed particles is initially higher than that of the other two cases and remains higher throughout the vibration.
- The angle of repose for the mixture of fine and coarse particles is initially minimal and remains the lowest throughout the ten-second vibration. This behavior can be governed by reduced mechanical interlocking, probably because when fine and coarse particles are mixed, the fine particles fill the porosities of larger coarse particles, which mitigates the mechanical interlocking between the irregular-shaped coarse aggregates, reducing the angle of repose.

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6. References

1. Bei-Bing Dai, Jun Yang, and Cui-Ying Zhou, Micromechanical origin of angle of repose in granular materials, *Granular Matter*, May 2017, 19: 24.
2. Zahraa Kansoun et al., Strain rate and stress amplitude effects on the mechanical behavior of carbon paste used in the Hall–Héroult process and subjected to cyclic loadings, Materials, February 2022, 15: 1263.
3. Roozbeh Mollaabbasi et al., Effect of fine coke particles on rheological properties of the binder matrix of carbon anodes in aluminium production process, *Canadian Journal of Chemical Engineering*, April 2022, 100: S58–71.
4. Han Wei et al., Numerical and experimental studies of the effect of iron ore particle shape on repose angle and porosity of a heap, *Powder Technology*, July 2019, 353: 526–534.
5. Chengzhi Li et al., The angle of repose and size segregation of iron ore granules: DEM analysis and experimental investigation, *Powder Technology*, October 2017, 320: 257–272.
6. Bazoumana Sanogo et al., Determination of optimum vibro-compaction time using sound analysis, *Journal of Manufacturing Processes*, August 2021, 68: 118–125.
7. Fatma Rebaïne et al., 2-DOF dynamic model of vibro-compactor used for the carbon anodes block production, *CIRP Journal of Manufacturing Science and Technology*, August 2017, 18: 45–52.

8. Fatma Rebaïne, et al., Development of an analytical dynamic model of a vibro-compactor used in carbon anode production, *Light Metals 2013*, February 2013: 1111–1115.
9. LA Chacon and JC Baret, Microfluidic angle of repose test for Pickering emulsions, *Journal of Physics D: Applied Physics*, October 2017, 50: 39LT04.
10. Feng-guang Yang et al., Study on the Angle of Repose of Nonuniform Sediment, *Journal of Hydrodynamics*, October 2009, 21: 685–691.
11. Michael Rackl, Florian E Grötsch, and Willibald A Günthner, Angle of repose revisited: When is a heap a cone?, *EPJ Web of Conferences*, June 2017, 140: 02002.
12. Paulo C Corrêa et al., Preservation of roasted and ground coffee during storage Part 1: Moisture content and repose angle, *Revista Brasileira de Engenharia Agrícola e Ambiental*, June 2016, 20: 581–587.
13. R.N. Cunha et al., Repose angle of monoparticles and binary mixture: An experimental and simulation study, *Powder Technology*, December 2016, 303: 203–211.
14. Y Guo et al., Discrete element simulation studies of angles of repose and shear flow of wet, flexible fibers, *Soft Matter*, 2018, 14: 2923–2937.
15. Ahmed Hafez et al., The effect of particle shape on discharge and clogging, *Scientific Reports*, February 2021, 11: 3309.
16. Jian-Jun Fu et al., Effect of Particle Shape on Repose Angle Based on Hopper Flow Test and Discrete Element Method, *Advances in Civil Engineering*, August 2020, 2020: 1–10.
17. Azadeh Samadani and A Kudrolli, Angle of repose and segregation in cohesive granular matter, *Physical Review E*, October 2001, 64: 051301.
18. Alessandro Averardi et al., Effect of particle size distribution on the packing of powder beds: A critical discussion relevant to additive manufacturing, *Materials Today Communications*, September 2020, 24: 100964.
19. Patrick Mutabaruka et al., Effects of size polydispersity on random close-packed configurations of spherical particles, *Physical Review E*, October 2019, 100: 042906.
20. Arunima Sarkar et al., Effect of Coke Granulometry on the Properties of Carbon Anodes based on Experimental Study and ANN Analysis, *Journal of Materials Science Research*, September 2016, 5: 63.
21. Kamran Azari et al., Compaction properties of carbon materials used for prebaked anodes in aluminum production plants, *Powder Technology*, September 2013, 246: 650–657.
22. Amir Kafaei et al., Effect of Vibration on the Bulk Flow of Coke Particle-Glycerin Mixtures Using Image Analysis Techniques, *Proceedings of the Canadian Society for Mechanical Engineering International Congress*. 2024.
23. Abel GM Ferreira, et al., The viscosity of glycerol, *The Journal of Chemical Thermodynamics*, October 2017, 113: 162–182.
24. Salah Amrani et al., Study on the cracking of carbon anodes used in aluminium industry, *The Canadian Journal of Chemical Engineering*, December 2021, 99: 2635–2646.
25. Aaron Dörr, Amsini Sadiki, and Amirfarhang Mehdizadeh, A discrete model for the apparent viscosity of polydisperse suspensions including maximum packing fraction, *Journal of Rheology*, February 2012, 57: 743–765.