Fracture Mechanics of Pelleted Feces Within Mammals

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1 abstract

In this combined experimental and theoretical study, we test the hypothesis that feces length is set by the dynamics of drying within the intestine. With previous measurements of the water contents of both pelleted and cylindrical feces at Zoo Atlanta collected, we find a transition from cylindrical to pelleted feces when the fecal water content drops below 65%. We thus focus our study on the drier pellet feces, whose length is dictated by crack formation. Using previous measurements for feces length, food intake and intestinal dimensions, we find that pellet length scales inversely with the flux of water absorbed during digestion. This relationship suggests that the drying is similar to the formation of hexagonal columnar jointing, found in cooling lava beds. We build a mimic of the intestine using drying corn starch cakes in open troughs and confirm that feces length scales with water flux$^{-0.61}$, giving us qualitative confirmation of the scaling of feces length in mammals. Our study shows new similarities between geological rock formations and the formation of pellet feces within the intestine. The physical picture shown here may be of use to physiologists and veterinarians interested in using feces length as a marker of intestinal health.

2 Introduction

Comparative bio-mechanics is an important field that allows us to analyze mechanisms that underlie a specific functionality within an organism. The insights from such a comparative analysis allow for several applications in engineering and chemistry such as antennae modeled after the parasitic fly *Ormia Ochracea* or the invention of Velcro which was inspired by burdock seeds [1, 2]. We assessed what mechanisms physiologically influenced the formation of pelleted versus cylindrical fecal matter. Our current focus is working to understand how a particular animal, the bare nosed wombat, *Vombatus ursinus*, has the ability to excrete cube-shaped fecal matter,through said physiological differences in its intestinal tract.. This is a rather unique phenomenon in comparison to all other mammals. By understanding what dictates fecal matter geometry within the colon we can identify and characterize key processes in digestion. From preliminary research, we have determined fecal geometry is largely in part determined by fecal water concentration,and that a geophysics phenomenon referred to as columnar jointing, is an event that similarly occurs within mammalian intestines that allow for segmentation of their fecal matter.

3 Literature Review

3.1 Comparative Analysis of Fecal Matter

To understand how wombats create cube-like feces, we first considered what influences fecal matter formation within the intestines. The bowel movement is a process that most mammals perform as a part of waste excrement,so we looked to those to understand the phenomenon more generally. For humans, stool is thought to be a general indicator of health [3]. Stool that results from a bowel movement has a variety of characteristics that show what potential sicknesses a person may have, with water content being an immediate quantitative relationship. The Bristol stool chart translates this in effect, by having 7 different qualitative descriptions of feces with one side of its spectrum showing constipation which is shown as small hard pellet formation (1), and the other side diarrhea which is shown as liquid (7). In humans, somewhere between these two extremes is considered to be healthy, however in animals this is not entirely the case with the same qualitatively observed pellet formation being a normal occurrence in many species [3].

3.2 Water Concentration Determines Fecal Geometry

Our lab sought to explain what determines the formation of pelleted versus cylindrical feces within animals. Based on our understanding from the existing literature on several mammalian species, we proposed that below 65% of fecal water content pelleted feces forms, and above this value cylindrical feces take form as shown by Fig 2A. **Figure ??A**. [4–24].

This relationship led us to believe that drying is an integral part in pelleted feces formation. As a pellet dries, similar to a rock formation cooling, it forms an outer "dry" layer, and an inner "wet" layer [25]. This difference in water content causes a volumetric change between the two layers, which leads to internal stresses forming that crack the outer layer (see Fig 1A).

We hypothesized the dehydration process causes crack propagation eventually segmenting the stool into pellets (see Fig 1C, 1D). Research on crack formation due to drying, such as the geophysics phenomenon columnar jointing, had been conducted already, and is typically observed when lava is cooling. A similar delta between an outer, colder more brittle area forms against the more malleable, warmer layer. This difference in temperature allows for a materialistic change in elasticity in the layers. As a result, when internal stresses build to a certain point, the outer material fractures [25]. In laboratory settings columnar jointing can be observed within cornstarch cakes (mixtures of equal parts in mass water and cornstarch) drying and cracking when under a constant heat source. The cornstarch shares similar material properties with feces as well. They are both visco-poro-plastic in nature, meaning when saturated with water, they behave like a viscous liquid, however, when dry, they become porous, brittle solid. In terms of shared properties that have been extensively studied, they are most similar to wet soil [26–28]. The mechanism for this dichotomy in water concentration is diffusion driven for visco-poro-plastic materials as well.

Drying creates non-homogeneity in the media, in which the aforementioned dry outer layer contracts against the inner wet layer. These layers are created by a concentration-dependent diffusivity $D(c)$ where c is the local water concentration. At high water concentration, liquid water fills the pores, so diffusion transport of molecules occurs in this liquid state. In this regime, diffusion decreases with decreasing concentration as shown in **1b**. As the water concentration decreases, liquid no longer spans all of the pores, and the molecules diffuse as vapor. In this regime, diffusion increases with decreasing concentration [29]. At a critical water concentration between these two regimes, c_m, diffusivity is at a minimum D_m **Figure ??B**. This minimum diffusivity D_m maintains a sharp transition between the dry outer layer in the vapor transport regime, and the wet inner layer in the liquid transport regime.

3.3 Relationship between flux and pellet size

We believe that fecal matter dries and fractures in a similar manner within the mammalian intestinal tract, with the diffusion of water into the lumen, rather than due to flux of heat into the environment. Columnar jointing research predicts that the spacing between cracks is inversely proportional to the flux of water (or heat) out of the system [25].

In order to show that the process of feces pellet generation is similar to that of columnar jointing, we use previous literature measurements to derive a scaling law for the average flux J of water through the intestinal wall.

To maintain equilibrium, we require that all water intake is either absorbed through the intestines or excreted in feces. This relationship can be written:

$$\dot{m}_{w,in} = \dot{m}_{intestine} + \dot{m}_{w,out} \tag{1}$$

where $\dot{m}_{w,in}$ is the water intake, $\dot{m}_{intestine}$ is the water flux through intestinal walls, and $\dot{m}_{w,out}$ is the water ejected through feces. Note that the water flux through the intestinal wall can then be ejected from the body through urine, sweat, or evaporation, but tracking that pathway is not necessary to understand feces shape.

The water intake $\dot{m}_{w,in} = \dot{m}_{in} - \dot{m}_{dry}$ can be written as the the difference between the total mass intake and the dry mass intake. The total mass intake in (kg/day) [30] is

$$\dot{m}_{in} = 0.097M^{0.97} \tag{2}$$

where from hereon, M is body mass (kg). The dry mass intake (kg/day) [31] was found to be

$$\dot{m}_{dry} = 0.0004M^{0.75}. \tag{3}$$

The excreted water $\dot{m}_{w,out} = w\dot{m}_{out}$ may be written as the product of the water content and the defecation rate. We start with the rate at which they excrete feces (kg/day) [30]

$$\dot{m}_{out} = 0.01M^{0.83}. \tag{4}$$

The water flux $J = \dot{m}_{intestine}/A$ may be written as the ratio of $\dot{m}_{intestine}$ and the surface area $A = \pi L_{colon} D_{colon}$ of the intestinal wall, where the colon is the shape of a cylinder. We only consider the colon because this is where the feces goes from a watery content to its final shape, as shown in **1C**. The length (cm) and diameter (cm) of the colon [30] are given by

$$L_{colon} = 28M^{0.71} \tag{5}$$

and

$$D_{colon} = 0.83M^{0.36}. \tag{6}$$

In all, we can write

$$J = \frac{\dot{m}_{in} - \dot{m}_{dry} - w\dot{m}_{out}}{\pi L_{colon} D_{colon}} \tag{7}$$

This gives a scaling of flux as $J \sim M^{-0.12}$. If columnar jointing is the mechanism that cracks the feces, we would expect $L \sim J^{-1}$. According to a scat recognition field guide, among mammals that form pelleted feces in North America, the pellet length scales with animal body mass M according to $L \sim M^{0.17}$, $R^2 = 0.69$, very similar to the inverse of the flux scaling (See **2b**) [32]. [25,33].

This inverse correlation suggests larger animals, particularly those with larger gastro-intestinal tracts, will have less water removed from their fecal matter during the duration of digestion.

Further research is needed on more accurately identifying whether the internal environment gives rise to high enough stresses and diffusion rates of water to cause fractures indicative of columnar jointing. Since columnar jointing has only been analyzed in 2-D infinite planar scenarios, such as the lava beds, determining its effects in a narrow system similar to the mammalian intestines will be integral to understanding the mechanisms causing fracture in pelleted feces.

4 Goals

We aim to create a model that encompasses the cracking that occurs within the intestines of mammals that influences fecal matter shape. To that end, We plan to address this by assessing columnar jointing as a mechanism for pellet formation in a pseudo 1-D system. In addition, we also will observe differences columnar jointing in confined spaces such as the intestinal tract of mammals.

5 Methods and Techniques

To illustrate the effects of columnar jointing in a lab setting, a cornstarch cake mixture containing equal parts cornstarch and water was dried under a heat lamp with adjustable temperature settings [25] (see **Figure ??A**). To analyze columnar jointing in other geometric settings, we adapted the cornstarch cake experiment, imitating intestinal walls in a 1-D system, by adding aluminum foil wrapped wooden spacers to make "troughs" that span the dish. 300 grams of water and 300 grams of cornstarch were added into a 7.5cm H x 15cm inner W x 21cm inner L glass Pyrex™dish. They were mixed for 5-10 minutes or until the fluid did not have any visible clumps. Then, 5 spacers sized at 3.5cm H x 1.5cm W x 19cm L were added and spaced at approximately 1cm apart into the dish from edge to edge. In order to maintain stability in the beginning for the spacers, a small weight (55g) was added on top of the dish. Afterwards an Exo-Terra™120v 100w intense baking lamp light was placed over the dish a certain distance vertically away (30cm to 75cm above). To direct the light's beams, a 15cm diameter lamp shade was placed over the light. The mass was recorded periodically (every 5-15 hours) to observe the change in water concentration. This was done by putting the dish over a weight scale, by which to measure the mass change over time. The experiments' duration were roughly 60-72 hours depending on lamp light height. The cake was filmed drying to determine when major crack formation occurred, whereas an image was recorded every time the experiment was completed, and used for analysis in MATLAB, by which the crack lengths were digitally measured, and a graphical representation was created for comparison with the mass transfer rate from the dish..

6 Results

With the addition of the spacers, cracks formed perpendicular to the aluminum troughs, which is suggestive of what might occur internally within mammals (see fig 3B). we show that with consideration to different flux rates, the length of the crack spacing for the cornstarch slurry scales according to $L_{spacing} \sim J^{-0.64}$, $R^2 = 0.92$. (see fig 3B). A total of 6 experiments were ran, with flux of water being affected by said lamp height (see fig 4A). since the flux rate was not a constant value, but followed an exponential decay, this rate was linearized around the 10 hour mark, as that is when fracturing of the cornstarch occured.

7 Discussion

In this study, we provide evidence that feces break up within the intestine due to the removal of moisture during digestion and that this process is similar to that of columnar jointing. Break up into pellets occurs when the water content drops below 65%. Above this water content, feces maintains an elongated cylindrical shape, suggesting that no dry outer layer forms within the feces. Based upon past drying research, this leads to a prediction for future investigation. The diffusivity of water within feces must have a minimal diffusivity when the water content is 65%. That is to say, the system transitions between a liquid transport regime to a vapor transport regime at a water content of 65%.

Our observation that pelleted feces form when the water content is below 65% is further supported when compared to studies of human feces. Referring back to The Bristol Stool Chart, it maps qualitative descriptions of human feces to quantitative values from 1-7, with 1 indicating constipation and 7 indicating diarrhea. Of note, a Bristol number of 1 describes the feces as hard nuts that are difficult to pass. The physical description of the feces is similar to that of pelleted feces. In fact, feces characterized as a Bristol number 1 had a water content of 65%, very similar to the threshold water content for pelleted feces found in this study, and much lower than a typical human water content of 0.80 [34].

Future work and applications may focus on the appearance of pelleted feces during human constipation. It is intriguing that pelleted feces are normal for some animals, but are difficult to expel for humans. Future comparative studies could investigate the evolutionary trade-offs of pelleted feces as well as adaptations allowing for pelleted feces to be dispelled. By understanding how pelleted feces form, we may gain a better understanding of how to prevent and treat human constipation.

Our flux scaling along with observed pellet length scaling continue to support the hypothesis that columnar jointing leads to pellet formation. Prior columnar jointing work finds that the flux is inversely proportional to the spacing between cracks. Similarly, we find that the scaling of flux with respect to body mass have approximately inverse powers. Furthermore, from the analysis on Cornstarch drying in a 1D environment, we show that the inverse relationship between flux and crack spacing or pellet segmentation within animals is upheld. the the power law exponential ratio is similar to the pre-evaluated scaling relationship determined by considering mass-flux and mass-pellet length relationships.

Using body mass as an intermediate variable as we have done has its downsides because it does not capture outliers among the scaling laws. The pellet length scaling comes from only North American mammals. Meanwhile, the Australian bare-nosed wombat has feces of length 4 cm, longer than most pelleted feces used to calculate the scaling law. The wombat also has an exceptionally long colon, causing the flux to be much lower that that of most mammals, potentially explaining the exceptionally long feces, but also illustrating the need for one-to-one measurements of pellet length and water flux to more strongly establish the trends found here.

Another potential caveat is related through the experimental methods. Throughout experimentation we observed relationships between the overall length scale and flux of water leaving the cornstarch medium. The relationship proposed from literature review suggested that the two characteristics would share an inverse relationship, but from experimentation, this more closely approximated a -0.6 correlative value. a potential reasoning for this is due to how the flux of water from the medium was not held constant through out the experiment(see **Figure ??A**. It had an roughly inverse relationship with time. As compared to Goehring and Morris, who had suggested that this occurs assuming constant flux the relationship is seemingly not upheld when in a dynamic system [35]. This suggests that as the water left the medium, the rate at which it did would decrease, meaning the amount of water at any given time point in the cornstarch cake was deterministic to the out-flux from the cake. Being that columnar jointing is the phenomenon we suggest this occurs in, the type of flux is not entirely unrealistic. This type of flow is indicative of a low Peclet number (0.3) meaning it has a diffusive dominant flow as compared to an advective one [35]. Further investigation remains to be done as to the effects of this changing flux on cornstarch drying and columnar jointing as its mechanism for fragmentation.

8 Conclusion

To observe and determine the mechanisms that allow for the bare nosed wombat to excrete cubes, we assessed phenomena in other natural formations in which polygonal fracturing occurs, such as rock-faces or cooling lava. The effects of columnar jointing, which is the underlying mechanism that dictates crack formations in the aforementioned environments has also been evaluated in systems with similar physical properties to fecal matter. By adapting them to more closely resemble the intestinal environment, we simulated the drying that drives the cracking process. We present a relationship between flux through this said material and the crack formation geometry in Pseudo 1-D. While it is not fully understood the effect of a changing flux on the crack behavior in columnar jointing, We believe that this relationship is applicable in the intestines of mammals as well.

9 Figures

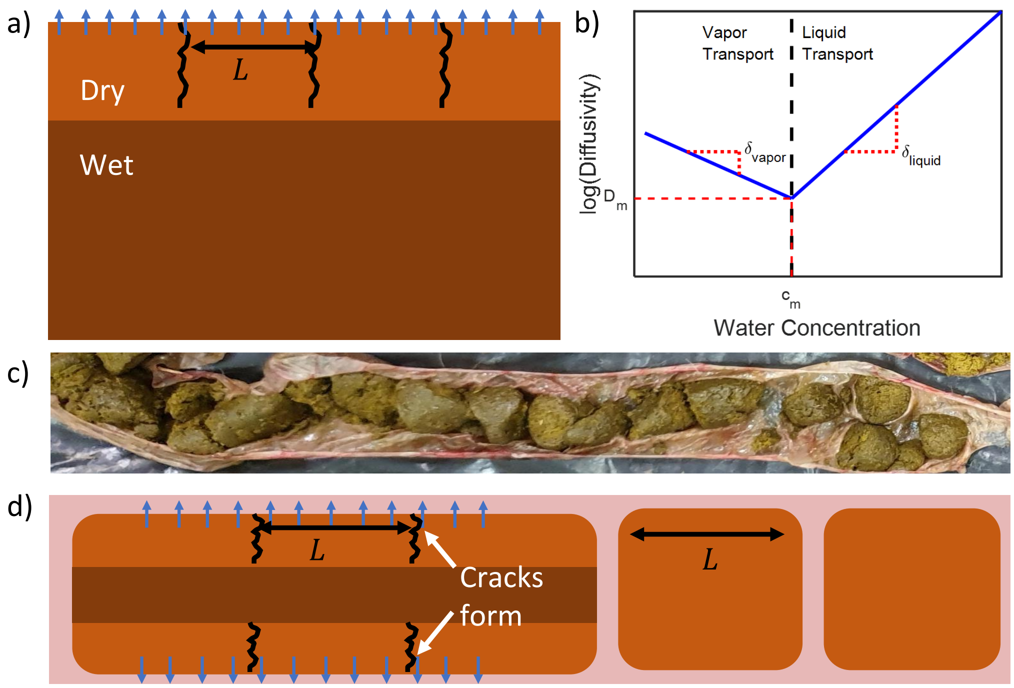

Figure 1: We hypothesize that drying leads to pellets forming in the intestines. (a) As a porous medium dries, it forms a dry surface layer and a wet lower layer. Regular patterns of cracks form in the dry layer. (b) These distinct layers are facilitated by a water concentration dependent diffusivity, in which the minimal diffusivity is found in the transition between the wet and dry layers. (c) A similar regular break-up of feces is observed in wombat intestines. (d) We hypothesize that as water is removed from the feces, a dry layer forms with a wet inner core, leading to cracking into pellets.

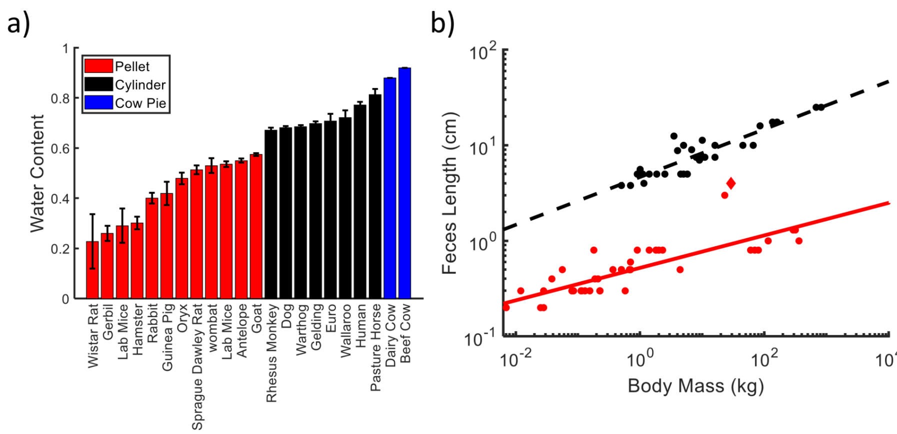

Figure 2: Pellet data collected from literature search. (a) Pellets are drier than other feces, having a water content less than 65%. (b) The length of the pellet tends to increase with the size of the mammal according to the scaling $L \sim M^{0.17}$

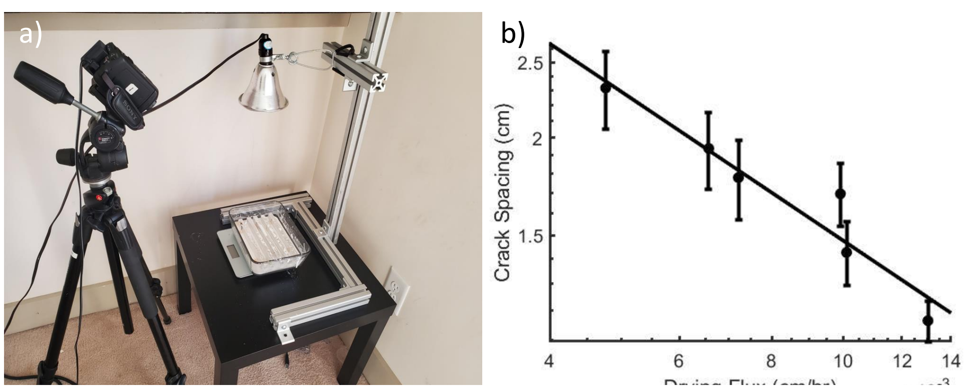

Figure 3: Classic columnar jointing experiment to investigate drying in confined environments. (a) Cornstarch slurry drying in pseudo 1D troughs. Primary cracks form perpendicular to the barriers. (b) relationship between flux and Crack Spacing.

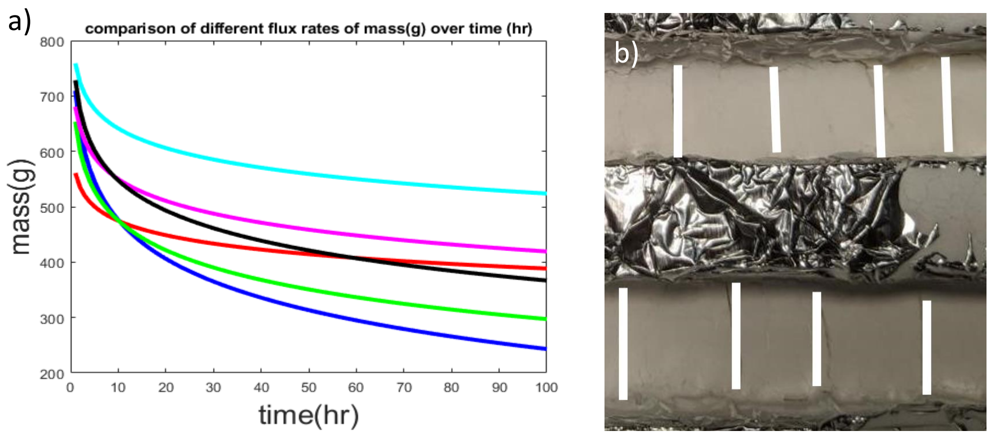

Figure 4: Classic columnar jointing experiment to investigate drying in confined environments. (a) with varying lamp heights and slightly varying starting points, the flux tends rates tend to differ. In addition,the rates at which exponential decay occurs are also different. (b) closer look at spacing between cracks of columnar jointing cornstarch experiment.

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