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Fabric and Structure of Potter Wasp Nests

Shweta Mukundan, Ph.D.,[1] Bhupendra Chand,[2] Shruti Pandey, Ph.D.,[3] Tejas G. Murthy, Ph.D.,[4] Renee M. Borges, Ph.D.[5]

[1]Centre for Ecological Sciences, Indian Institute of Science, Bengaluru-560012; E-mail: shwetam@iisc.ac.in
[2]Department of Civil Engineering, Indian Institute of Science, Bengaluru-560012; E-mail: bhupendrac@iisc.ac.in
[3]Department of Civil Engineering, Indian Institute of Science, Bengaluru-560012; E-mail: shrutip@iisc.ac.in
[4]Department of Civil Engineering, Indian Institute of Science, Bengaluru-560012; E-mail: tejas@iisc.ac.in
[5]Centre for Ecological Sciences, Indian Institute of Science, Bengaluru-560012; E-mail: renee@iisc.ac.in

ABSTRACT

Potter wasps are one of the few insects capable of building durable mud nests on different surfaces. Potter wasp nests (n=101) were collected and categorized based on their shape and size. Tests for understanding the physical properties such as grain size distribution, Atterberg limits, specific gravity, organic content of the nest soil and control soil were performed in addition to estimating the shear strength. The soil fabric/structure of the nest was acquired using X-ray computed tomography for a typical ellipsoidal shaped nest which revealed varying wall thicknesses. This 3- D structure was imported into the finite element software ABAQUS for stress analysis. The study evaluates the influence of the nest orientation on the stability of nest and highlights the vulnerable regions of high stress concentration. Insights from the composition, geometry and construction techniques of potter wasp nests can inspire advancement in civil engineering, for light weight, durable and efficient material design.

INTRODUCTION

The field of engineering often relies on animal-built structures for many of its innovations. Bio-inspired engineering takes advantage of mechanics observed in nature to create sustainable, eco-nomical, and eco-friendly structures. Soil stabilization by plant roots, microbial-induced carbonate precipitation (MICP) for soil enhancement (Mondal & Ghosh 2019) (Rahman et al. 2020), study of termite nests to provide efficient ventilation (Singh et al. 2019) (Zachariah et al. 2020), and ant colony optimization for logistics (Gambardella et al. 2003) (Dorigo et al. 2006) are few examples where engineering problems are tackled from the bioinspiration perspective. Many insects build nests which fulfill diverse functions including facilitating reproduction, providing shelter, and aiding in social cohesion (Dawkins 1982). Mud nests built by social insects like termites

(Kandasami et al. 2016), (Jouquet et al. 2003) and ants (Belachew et al. 2024) are better studied, compared to those of solitary insects (Bogusch 2022). Park et al. (Park et al. 2022)(Park et al. 2023) worked on mud nests built by mud dauber wasps (*Sceliphron* spp.) focusing on the material properties and structural design of the nests. Even though Segoli et al. (Segoli et al. 2020) and Udayakumar et al. (Udayakumar et al. 2022) have explored potter wasp nesting behaviour, detailed investigations into the structure and mechanical property relation are few and far between.

Figure 1: *Delta pyriforme*, *Delta conoideum* and *Phimenes flavopictus* on their respective nests

Potter wasps (Subfamily: Eumeninae) are solitary, predatory wasps showing remarkable diversity in their nesting habits ranging from nesting in soil, in pre-existing cavities or build free-standing mud nests which are provisioned with paralyzed lepidopteran or coleopteran larvae (Kumar et al. 2019). The mud nests vary in shapes and sizes, and can be single- or multi-chambered.

The wasps are capable of building durable mud nests on a wide range of surfaces such as plant leaves and branches, glass windows, concrete and stone, in shaded and unshaded conditions using natural resources of soil and water. The soil properties modulated during the mound construction by the wasps have not been clearly elucidated. Cursory examination of the material properties of the soils used by the potter wasps have been made, however, the interface strength and a detailed look at the structure of the mound have not been achieved. This paper examines the microstructural characteristics and stability of potter wasp nests through a suite of experiments and FE analysis.

EXPERIMENTAL

Over 100 potter wasp nests built by *Delta pyriforme*, *Delta conoideum* and *Phimenes flavopictus* species (Figure 1) were collected from different parts of Bengaluru city (India). Physical properties such as the specific gravity, liquid limit, plastic limit, organic content, and particle size distribution of the nest soil and control soil available in the surrounding areas were determined prior to the finite element analysis. After the basic soil classification, unconfined compression tests were conducted on a table top micro universal testing machine (UTM) to estimate a reasonable value of “unconined compressive strength”. Advanced X-ray computed tomography was used to capture the 3D geometry of an ellipsoid-shaped nest since we have observed that size of the nest is dependent on the number of levels in the nest and an ellipsoid shape is the repetitive unit of other multichambered nests. Nest scans were captured at a high resolution of 17 μm with 100 keV energy. Over 600 images of the nest were captured while the sample rotates from 0 to 180°. Nest volume, thickness of wall, network of pores, and porosity were calculated using MATLAB. 3D structures were imported into a finite element software ABAQUS for stability analysis. The mechanical responses of the nest were evaluated at different orientations and their stability was compared on the basis of their displacement and stress distribution profiles.

Finite Element Analysis of Potter Wasp Nests.

A finite element analysis was carried out using ABAQUS, a general purpose finite element analysis software program that can simulate highly nonlinear situations and analyze intricate solid and structural mechanics systems.

The Potter Wasp Nest Structure: Cad Model.

The μCT images were stacked together to form a structure containing triangular elements employing 3D slicer software. The stl file was imported in freeCAD, a shape was created using the mesh and then finally converted to a solid part. The part is exported as a STEP file.

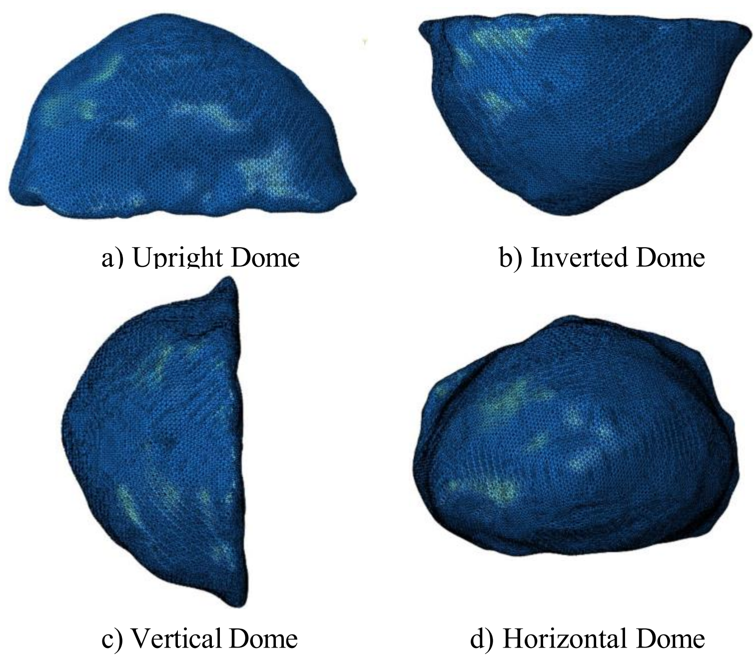

Figure 2: Different orientations of the potter wasp nests

Abaqus Model.

The structure was meshed using second order tetragonal elements C3D10M. The mesh consists of a total of 276526 elements. The nodes at the boundary were fixed by applying zero displacements. To study the stability of the structure, only the self-weight of the mound was considered in the analysis. The analysis was carried out for different orientations of the nest, see Figure 2. In nature, potter wasp nests are found in different orientations. To accurately simulate and analyze these scenarios the simulations were carried out over a range of configurations: upright dome, inverted dome, vertical dome and horizontal dome (Figure 2). These orientations were chosen to reflect the potential natural positions a nest may adopt allowing us to explore how the nest's structure may respond to different forces.

The Mohr–Coulomb failure criterion (Labuz & Zang 2014) was used in the model. The parameters employed in the simulation were obtained from literature (Rao & Revanasiddappa 2002; Georgian- nou et al. 2017; Lai et al. 2021) and from the uniaxial compressive test performed in this study. The parameters are listed in Table 2.

Table 1: Parameters used in FE analysis of the potter wasp nest

Density ρ	Elastic modulus E	Poisson's ratio	Friction angle	Cohesion c
1.65 g/cm^3	19.5 MPa	0.3	30^o	5 kPa

RESULTS AND DISCUSSION

The collected nests were categorized based on their external morphologies into the following broad shapes: Ellipsoid, Ovoid, Spherocylindrical and Globular as shown in Figure 3 (a). In Figure 3 (b), the frequency distribution of the nests based on their measured dimensions (L× W × H) is shown.

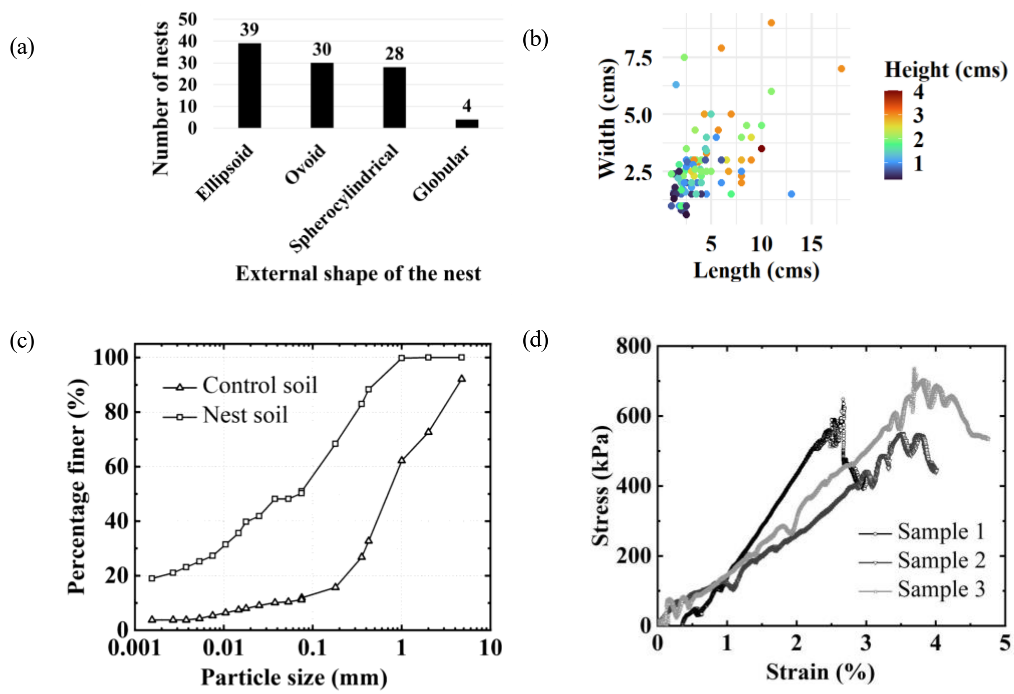

Figure 3: (a) Categories of shapes of the nests, (b) L× W × H dimension of the nests indicating the aspect ratio in cms, (c) Grain Size Distribution (GSD) of the control soil and potter wasp nest soil, (d) Stress–strain curve for the different orientations of the potter wasp nest.

Figure 3 (b) indicates that the aspect ratio for the majority of the nests is constant, except some of the large nests. Mechanical properties of the mound soil and the control soil were estimated through a battery of tests conducted on nest soils (Table 1). All tests were conducted as per protocols provided by IS-2720. To determine amount of external material, the organic content in soil was measured, and similar values were obtained for nest soil and control soils.(Kandasami et al. 2016) have previously shown that physical properties, including p^H, do not change drastically between nest soil and control soil for soil samples collected from Bengaluru. On the basis of particle size analysis carried out (Figure 3(c)), nest soil is classified as lean clay whereas control soil is silty sand. Overall, the nest soil has more fines content than the control soil. The mean particle size for nest soil (D50) is 0.075 mm whereas mean particle size of control soil is 0.7 mm, which is nearly ten times that of nest soil. Unconfined compression tests were also performed on small cylindrical samples (5 mm diameter and 10 mm height) of the nest walls in a micro UTM machine (Figure 3(d)) and the average compressive strength of the nest samples was 600 kPa. The initial slope of the stress-strain curve was used to determine the elastic modulus of the soil which was used for the FE analysis.

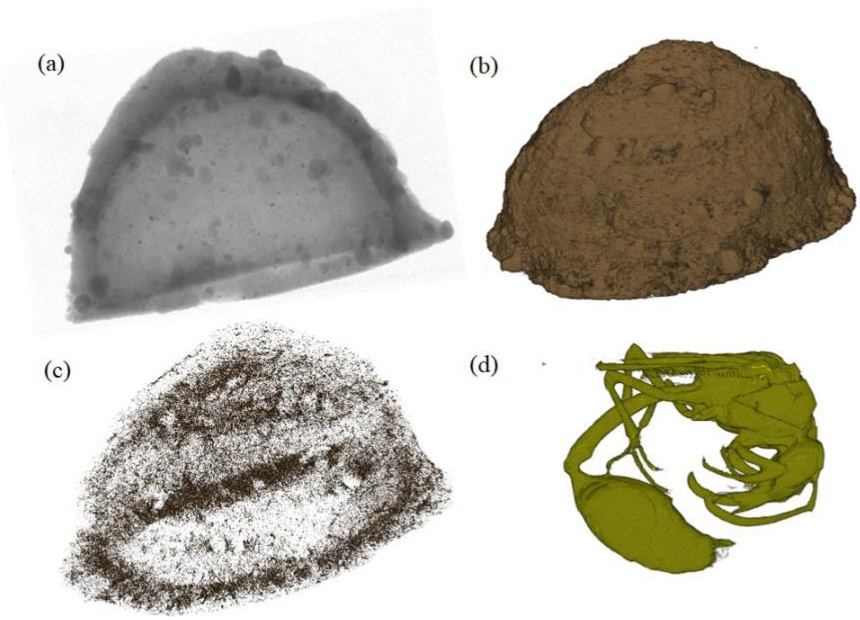

Figure 4: Images from XRCT analysis: (a) Raw image of the nest scan, (b) Reconstructed 3D image of the potter wasp nest, (c) Network of voids on the wall of potter wasp nest, and (d) Scan of potter wasp body.

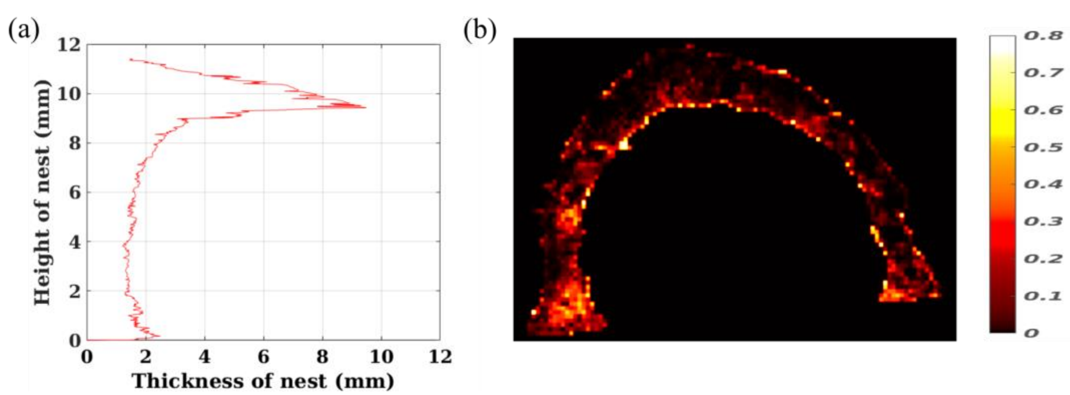

Figure 5: (a) Average thickness of walls along the height of the potter wasp nest and (b) Distribution of porosity on a medial plane section.

X-Ray Computed Tomography (XRCT).

An example ellipsoid shaped nest was scanned and the projections of nest tomographs were stitched together to obtain the overall geometry. The 3D images were later segmented into solid and void phases by the Otsu thresholding method (Figure 4(c)). The volume of the nest wall was 0.85 cc whereas volume of the nest's cavity was 1.13 cc. The cavity volume was compared with the adult wasp body volume. For this purpose, an adult potter wasp was also scanned (Figure 4(d)) and its volume was 0.38 cc. The volume of the nest cavity is nearly three times of an adult wasp. This extra space must be required to store the paralyzed caterpillars on which developing wasp larvae feed.

The thickness of the walls plays an important role in maintaining the stability of the structure and gas exchange. The average thickness of the nest wall was determined from the images and its distribution is presented in Figure 5(a). The lower regions of the nest had greater thickness than the middle sections and the maximum thickness of the walls was at the crest. A thick base is necessary to provide sufficient contact area to generate sufficient adhesion between the two surfaces. These walls are porous and the pore network is seen in Figure 4(c). The pore ratio of the walls is quantified by the void network and is the ratio of voxels occupied by voids to the total voxels occupied by the nest walls (Figure 5 (b)). The top surface of the nest wall has fewer pores than the lower sections. The average porosity of the entire nest is around 10%.

Table 2: Physical properties of the control soil and the nest soil

Properties	Liquid Limit (%)	Plastic Limit (%)	Specific Gravity	Organic Content (%)
Nest Soil	35.85	19.83	2.62	4.33
Control Soil	30.38	19.17	2.65	4.96

FE Analysis Results.

The deformation contour maps for four different orientations of the nests are presented in Figure 6. The overall deformation when the orientation of the nest is in the horizontal direction is maximum, followed by the vertically hanging dome. The deformations in the upright dome and inverted dome nests are similar. The maximum deformation is observed near the center of the dome for all cases.

The stress contour plots for the four different orientations of the potter wasp nest are presented in Figure 7. The grey coloured zone representing a higher value of stress is absent in the upright dome. For the inverted dome, the stress maps are nearly symmetric with higher stresses near the boundaries. For case (c), the vertically hanging dome, the stresses near the bottom are higher. Similarly for the horizontal dome, the stresses in the areas below the major axis of the structure are higher. Therefore, from the stress and deformation contour maps it is evident that an upright dome has the lowest deformation and consequently lowest stresses in the loading direction and is the most stable orientation.

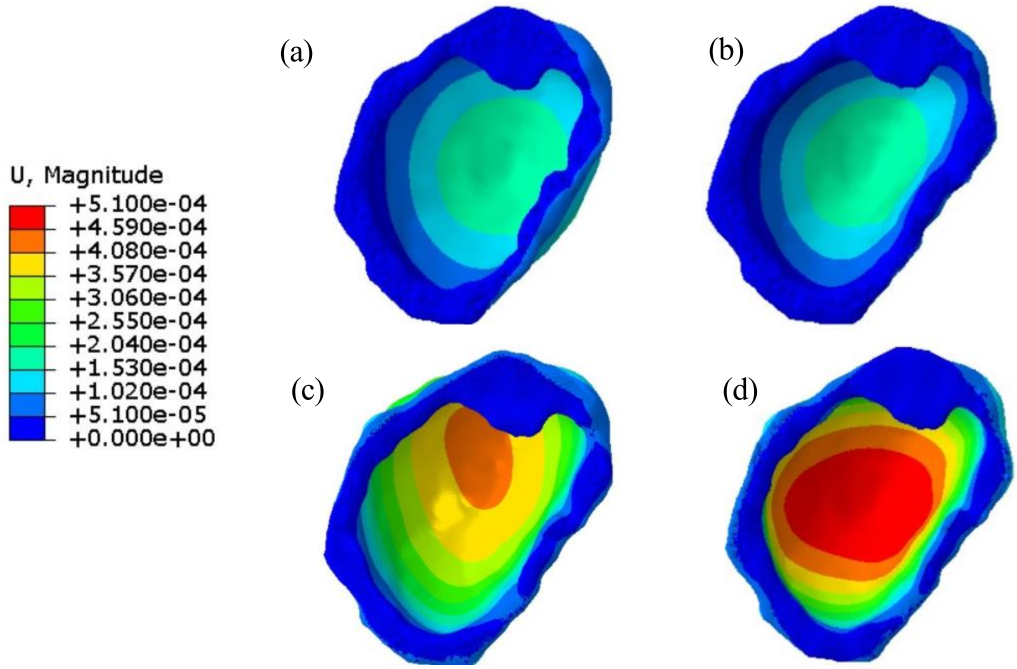

Figure 6: Deformation contour maps for (a) upright dome, (b) inverted dome, (c) vertical dome and (d) horizontal dome potter wasp nest. The deformation (U) is in mm.

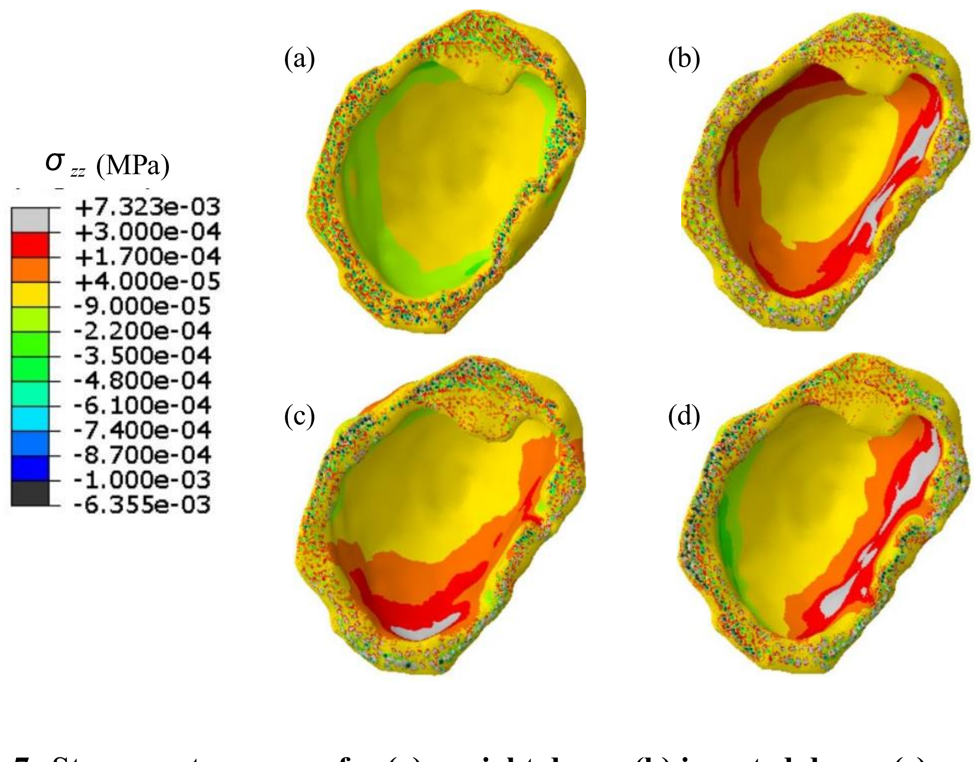

Figure 7: Stress contour maps for (a) upright dome, (b) inverted dome, (c) vertical dome

and (d) horizontal dome potter wasp nest.

Biological Implication of the Structural Analysis.

The results from these experiments and analysis suggest that in addition to material selection, the orientation of the nest is critical for the survival of the wasps. A single nest chamber can be packed with anywhere between three to eight paralyzed caterpillars, each of nearly half the size of the adult wasp, in addition to a single egg that is suspended from the roof of the nest before it is sealed by the female parent wasp. The substantial volume of a single potter wasp nest chamber, roughly three times that of an adult wasp, is likely an adaptive feature designed to accommodate the multiple stored paralyzed prey and the egg; the larva starts active feeding within hours of hatching, increasing in size and volume drastically over a span of 48 hours. The thicker base of the nest with thinner edges and thickest roof reflects an optimization of material distribution to enhance stability, load bearing and protection. The wider base enhances stability and thinner walls provide a shell- like structure to the nest. With an average porosity of 10% the potter wasp nest exhibits a porosity comparable to that of high-quality fired clay bricks, which typically range from 10-20% (Čáchová et al. 2014), indicating a balance between structural strength and permeability. The porous walls are necessary to ensure gas exchange and maintain uniform temperature and moisture inside the nest which is essential for the survival and growth of the larva as well as the paralysed caterpillars. The variation in deformation observed in different orientations of potter wasp nest can be attributed to differences in how the orientation changes the stress profile due to self-weight. Understanding these variations provide insights into the structural mechanics of the nest improving our knowledge on the factors that influence its stability and design.

CONCLUSION

Through careful choice of building material (soil) and active selection of appropriate-sized soil particles, potter wasps build nests of appropriate shape and size for the survival and development of its inhabitants. The meticulous nature in which the solitary female wasp decides the surface to build the nest, its orientation, taking into account the gamut of external forces likely to act on it, building stable structures with least exposure to stress and deformation is awe-inspiring.

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