A new numerical simulation model for high pressure squeezing moulding

***Li Hua[1], Wu Junjiao[1], Huang Tianyou[1] and Makino Hiroyasu[2]**

(1. Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China; 2. SINTOKOGIO, Ltd., Toyokawa, Aichi Pref. 4430021, Japan)

Abstract: High pressure squeeze is the most popular moulding process applied in modern moulding machines. Because of the unique characters of moulding sand and nonlinearity of squeezing process, the mechanical model is of key importance for computer simulation. Drucker-Prager/Cap is a typical soil mechanical theory model and it was used to simulate the squeezing process in this study, while ABAQUS software is used to simulate dynamic stress/strain evolution during the process. The simulation agrees well with the experimental results. We conclude that Drucker-Prager/Cap is an appropriate model for the squeezing compaction of moulding sand, and that the associated nonlinearity can be solved well with ABAQUS software.

Key words: high pressure squeeze; Drucker-Prager/Cap; ABAQUS; numerical simulation; green sand moulding
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With the increasing demand for near net shape castings, intensive attention has been paid to mould quality. As a popular moulding method, high pressure squeeze has been applied in modern molding machines of both flask tight and flaskless. More recently, numerical simulation has been introduced into the field of green sand compaction in order to optimize the moulding process. A successful numerical simulation usually consists of an accurate modeling and a well-developed algorithm. Therefore, the key problem is to build an accurate mechanical/material model. In this paper, Drucker-Prager/Cap was used for high pressure squeezing simulation.

The main working sequence of aeration sand filling and squeeze flaskless moulding machine is shown schematically in Fig.1. It can be seen from Fig. 1 that moulding sand is filled into the flask with compressed air, then the squeezing force is applied through the squeeze plates to compact the moulding sand.

1 The constitutive relationship

1.1 The characters of green sand and the moulding process

The mechanical characters of green sand are as follows[1]:

(1) The stiffness varies with applied pressure.

(2) The volumetric deformation is plastic under static pressure, thus, green sand cannot be treated as a continuous material.

***Li Hua**

Female, born in 1983. Ph.D candidate. Research interests: molding technology and equipment.

E-mail: lihua02@mails.tsinghua.edu.cn
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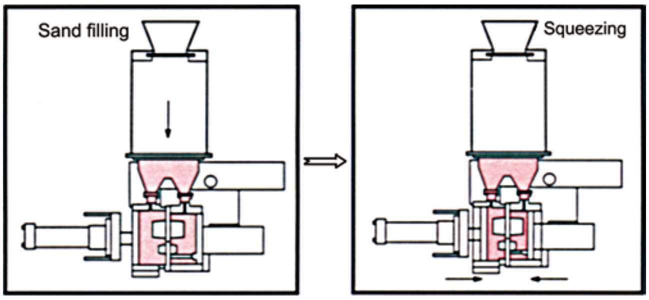

Fig.1: Schematic of main working sequence in a high pressure squeeze process

(3) The volumetric deformation is determined by both static pressure stress and Mises equivalent stress.

Nonlinearity of green sand has to be considered during a squeezing process. There are three types of nonlinearity working simultaneously in a normal compaction process.

(1) Mechanical response nonlinearity: the strain-stress curves obtained experimentally for four green sands (with different density) are shown in Fig. 2. It seems that the stress increases exponentially with strain, and a large deformation of 30%–40% can be obtained upon the completion of a compact process.

(2) Structural nonlinearity: moulding sand is composed of discrete silica sand grains covered with bentonite/water layer and air voids, as schematically shown in Fig.3. For such material, the internal friction angle and cohesion are two major factors, which are usually used to represent the features of material. When subject to an external force, the air voids existing among moulding sand are squeezed out. Consequently, the deformation of moulding sand is plastic.

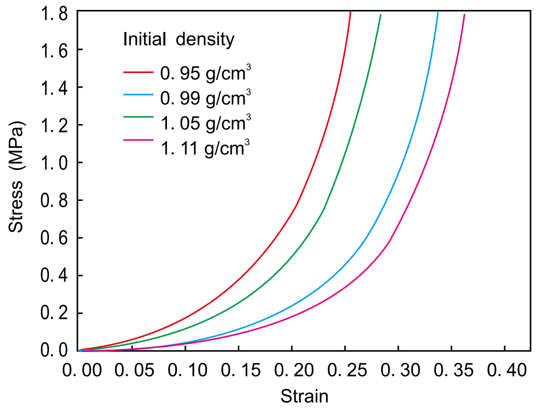

Fig.2: Stress-strain curves of squeezing process

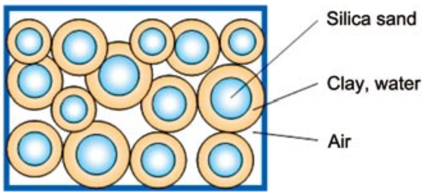

Fig.3: Composition of molding sand

(c) Contact nonlinearity: external friction which exists between sand and flask wall as well as between sand and mold influences the compaction effect significantly.

1.2 Two numerical simulation methods

There are two main methods for numerical simulation in sand compaction: (1) discrete element analysis (DEA) and (2) finite element analysis (FEA).

1.2.1 DEA method

For discrete element analysis, sand is treated as an individual grain. The spring and damper models are used to describe the relations between sand grains. Although such simulation represents the closest physical model, it requires enormously large computer capacity. Usually, it is assumed that a "sand grain" is composed of hundreds of actual sand grains for less computation in simulation process. Inevitably, the calculation error would be large, especially when a complicated pattern is involved.

Till now, some meaningful simulation results have been achieved with DEA method. For example, Maeda Yasuhiro and Maruoka Yosuk, et al [2] applied DEA method to simulate high pressure squeeze process. Sand is filled into a cylinder tank layer by layer, it is then pressed downward from the top (Fig.4). It can be seen from Fig. 4 that the general tendency of squeezing process can be clearly resolved and the calculation results represent the actual experimental data fairly well.

1.2.2 FEA method

(1) Traditional model

For finite element analysis, sand is treated as continuous material. Such assumption simplifies the situation and makes such calculation possible with a personal computer. In most of the initial researches, strain-stress curve has been employed as the main mechanical model for calculation. However, since the model assumes the sand as completely continuous material (refer to section 1.1) and some significant features of the material and process are also neglected, the simulation result will be adversely influenced. Leone and R. L. Lewis [3] are the pioneers who developed the procedure based on FEM to solve green sand molding problem. In their research, the displacement field, stress field, and hardness field were calculated. Regina Lenz [4] also applied some commercial FEM software to simulate green sand molding process, however the compact stress obtained was far too low compared with the practical result.

(2) A newly developed model based on Drucker-Prager/Cap

The mechanical computation method – Drucker-Prager/Cap is mainly used in solving deformation problem of discrete material (such as soil, sand, rock). This model not only contains the process feature but also considers the characters of material. It can be illustrated with a failure curve (Fig. 5).

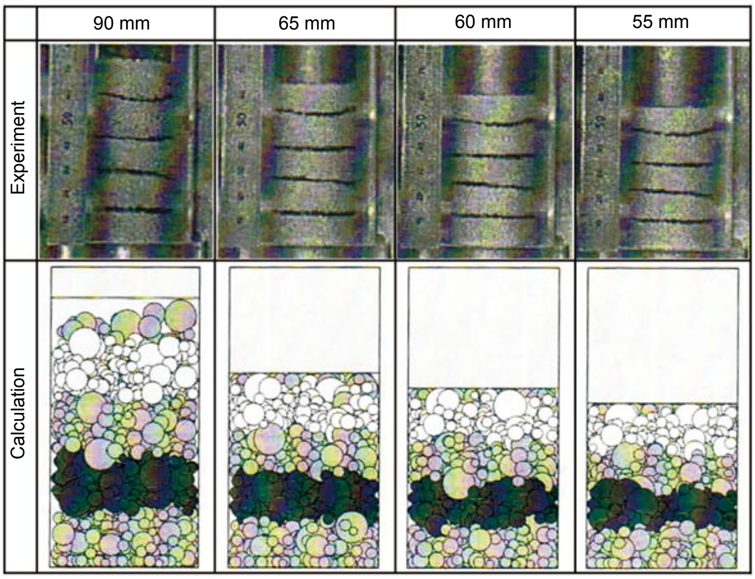

Fig.4: Calculation results of Maeda Yasuhiro, et al using DEA [2]

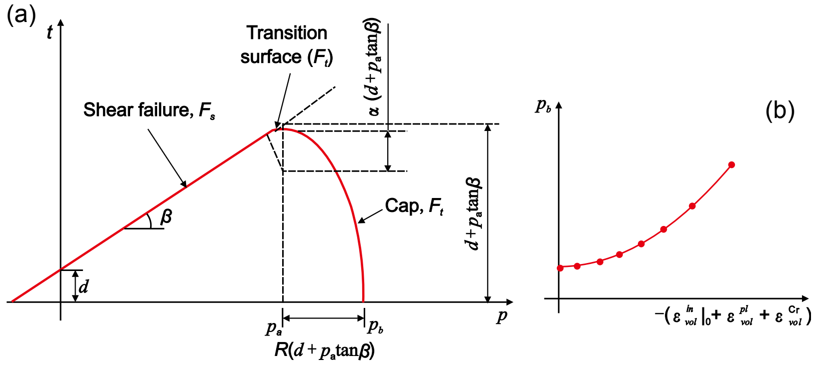

Fig.5: Drucker-Prager/Cap [5]

In this model, the close curve is composed of shear failure part and volume failure part. There are two variables in Fig.5(b): p is static pressure and t represents Mises equivalent stress. While p is related to volume distortion, t causes shear distortion. The area below the shear failure line belongs to elastic deformation region, while the rest of area corresponds to plastic deformation.

The curve in Fig. 5(b) shows the relationship between static yield stress and volumetric inelastic strain.

$\varepsilon^{in}_{vol}|_0$ – the initial state of the material when analysis begins

ε^{pl}_{vol} – volumetric plastic strain

ε^{cr}_{vol} – volumetric creep strain.

Shear failure caused by stressing is defined as:

$$F_s = t - p \cdot \tan\beta - d = 0 \tag{1}$$

where, β is the angle of internal friction of material and d is the cohesion of material. Both β and d are temperature θ and field varient f_i (i=1, 2, ……) dependent.

The Mises equivalent stress t can be calculated as following:

$$t = \frac{1}{2} \cdot q \cdot \left[1 + \frac{1}{K} - (1 - \frac{1}{K}) \cdot (\frac{r}{q})^3\right] \tag{2}$$

where, $q = \sqrt{\frac{3}{2} S : S}$ (Mises equivalent stress) (3)

$$r = (\frac{9}{2} S : S \cdot S)^{\frac{1}{3}} \text{ (the third invariant stress)} \tag{4}$$

$$S = \sigma + p \cdot I \text{ (the deviatoric stress tensor)} \tag{5}$$

$K(\theta, f_i)$ is the material parameter (ranging from 0.778 to 1.0) depending on the shape of failure curve; σ is stress tensor and I is unit tensor.

$$p = -\frac{1}{3} \cdot trace(\sigma) \text{ (static pressure)} \tag{6}$$

Volumetric (Cap) yield face

$$F_c = \sqrt{[p - p_a]^2 + \left[\frac{Rt}{(1 + \alpha - \alpha / \cos\beta)}\right]^2} - R(d + p_a \tan\beta) = 0 \tag{7}$$

where $R(\theta, f_i)$ is a material parameter determining the shape of Cap and α is a small number used to define a transition yield surface (the range of the value is 0.01–0.05)

$$P_a = \frac{p_b - Rd}{(1 + R\tan\beta)} \tag{8}$$

Transition face

$$F_t = \sqrt{[p - p_a]^2 + \left[t - (1 - \frac{\alpha}{\cos\beta})\right]^2} - \alpha(d + p_a \tan\beta) = 0 \tag{9}$$

2 Case study of FEA – Drucker-Prager/ Cap model

In this paper, ABAQUS was employed to directly simulate the nonlinear problem involved in a moulding sand squeezing process. Drucker-Prager/Cap was integrated into the model database.

2.1 The physical and geometrical model

Figure 6 shows the geometrical features of the moulding sand squeezing process used for the current study. The dimension of the flask is 608 mm × 510 mm × 260 mm. There are nine sleeve

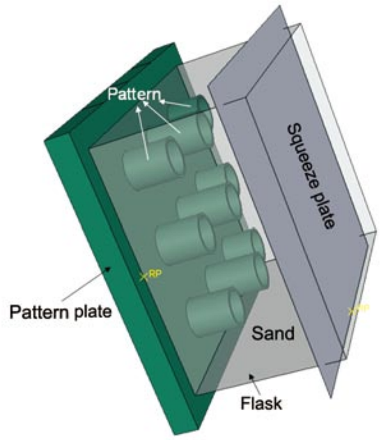

Fig.6: Geometrical model of squeezing process

patterns (with outer diameter 80 mm and inner diameter 70 mm with the height of 70 mm, 90 mm and 110 mm, respectively) located on the pattern plate. All three sleeve patterns lined in the same row have the same height.

The material of the pattern plate is cast iron. In order to simplify the computational model, both the flask and the squeeze plate are treated as rigid body.

2.2 The property of materials

Material properties of the pattern plate (i.e. cast iron) are shown in Table 1.

Parameters for molding sand used in Drucker-Prager/Cap model are listed in Table 2. It is noted that the parameters values shown in Table 2 correspond to the initial bulk density of molding sand, which is 0.95 g/cm^3.

Table 1: the material properties of the pattern plate

Density	Young's modulus	Poisson ratio
7,800 kg/m^3	2.1×10^{11} Pa	0.3

Table 2: The parameters of Drucker-Prager/Cap model

d	β	R	ε	α	K	Yong's modulus	Poisson ratio
25 kPa	29°	0.1	0.00041	0.01	1	3×10^7 Pa	0.35

Depending on the mixing technique, chemistry of sand structure and the filling method, the initial bulk density of moulding sand in the flask is in the range of 0.8–1.2 g/cm^3. Stress-strain relationship can be calculated based on equation 10 [6], from which Cap hardening data could also be obtained.

$$\sigma_{yield} = (0.624 - 0.735\rho) + \frac{-0.223 + 0.297\rho}{4 \times (\varepsilon_v - (0.903 - 0.493\rho))^2 + 0.0118\rho} \tag{10}$$

where σ_{yield} is yield stress (MPa); ε_v is volumetric plastic strain and ρ is sand bulk density (g/cm^3).

Other parameters used in the ABAQUS simulation include: the applied squeeze pressure of 1.0 MPa; the squeezing distance of 8 cm; and the coefficient of friction of 0.5 between flask wall/squeeze plate/pattern plate and sand.

In the case that sand is filled into moulding chamber with compressed air, the sand bulk density is not spatially even. In the current simulation (with reference to the experiment data), we divided the whole sand bulk in the molding chamber into several regions and assigned different density for each individual region.

2.3 Simulation results

2.3.1 A special case without pattern inserts

In this case, all patterns on the pattern plate are removed. The mould is divided into several parts for density evaluation purpose. The simulation result is converted from the calculated stress field to strength field according to equation 11[6].

$$M_s = -77.2553 \times \exp(-\frac{\sigma_{equ}}{1.8989}) + 79.9389 \quad (11)$$

where, σ_{equ} is the equivalent stress (MPa) and M_s is mould strength (N/cm^2).

Figure 7 shows the mould strength distribution contour of the simulation results, the experimental results are also included for reference. It can be seen clearly from Fig. 7 that the mould strength distribution and mould strength range are close between simulated and experimental data. Due to the external friction effect, the maximum value and the minimum value exist at the corners of the mould. Mould strength decreases from the squeeze plane to the parting plane. For parting plane, the majority of mould strength values are about 30 N/cm^2 which is hard enough for mould handling and pouring.

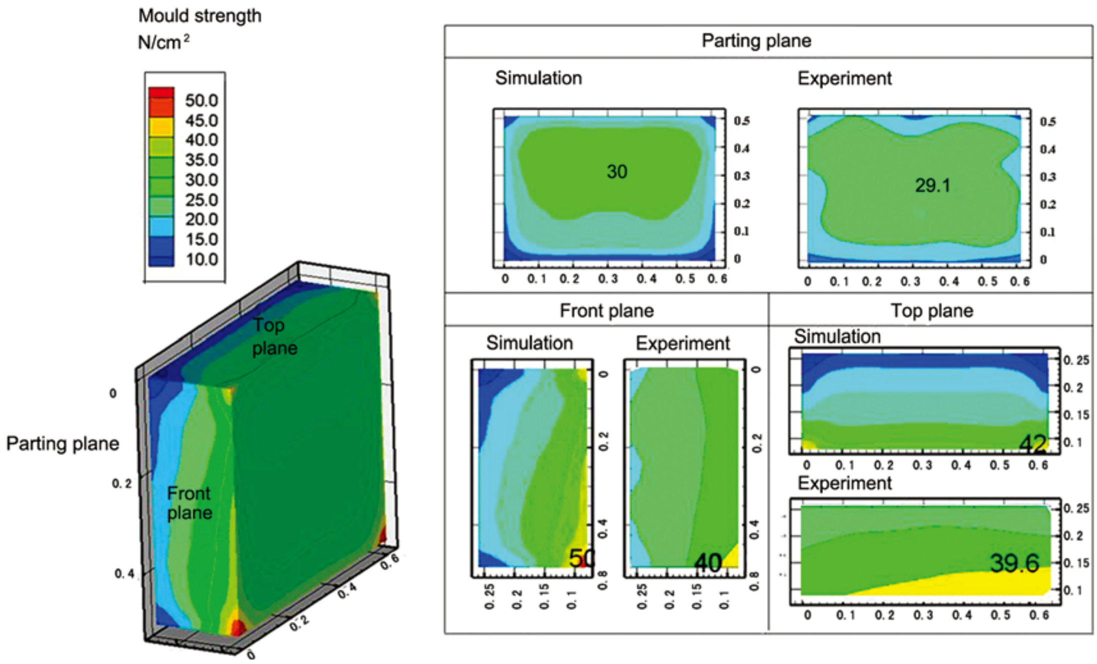

Fig.7: The comparison between the simulated results and experimental results (without pattern)

2.3.2 A case with pattern

In this case, a pattern plate with nine sleeve pattern inserts was considered. To highlight the results, the mould strength on the parting plane and three longitudinal sections through the center of sleeve pattern are chosen for comparison purpose (Fig.8).

It can be seen from Fig.8 that the contour results for both simulation case and experiment case are roughly similar. First, on the parting plane, the range of mould strength value is from 8 N/cm^2 to 24 N/cm^2. The mould strength near the edges and root pocket regions have very low value of about 10 N/cm^2. Second, for all 3 longitudinal sections, the regions close to parting plane are weak, while the regions close to squeeze plane are strong. Third, under the same compacting condition, the deeper the pattern inserts the weaker the mould strength. Compared with the limited data points obtained from the experiment, numerical simulation is advantageous in providing more detailed information, such as the "bridge phenomenon" at the root parts of pockets.

However, a careful analysis between the simulation and experiment reveals that: (a) mould strength calculated is smaller than that of the experimental measurement; and (b) the distribution of mould strength in simulation is more even than that in experiment.

2.3.3 Discrepancy between the simulated and experimental result

From above analysis, it can be concluded that the numerical simulation using FEA gives approximately correct information regarding the mould strength and its spatial distribution. Such results reflect the actual situation and can provide useful information for optimizing mold design. The discrepancy between the simulated and experimental might be due to the following facts:

(1) The sand density distribution in the flask prior to squeezing: Sand is filled into the flask with compressed air, and the bulk density of sand varies at different regions. For simulation, respective "initial" density is assigned as constants for different regions before squeezing.

(2) Some simple assumptions are made in simulation, for example, both the squeeze plate and the flask are assumed as rigid body, which means that the squeezing force is completely used for sand compaction. Such assumption leads to even mould strength distribution in simulation.

(3) Sampling problem with experimental measurement: The mold strength contour of experiment results are plotted with limiting data points. Besides, there might be some systemic

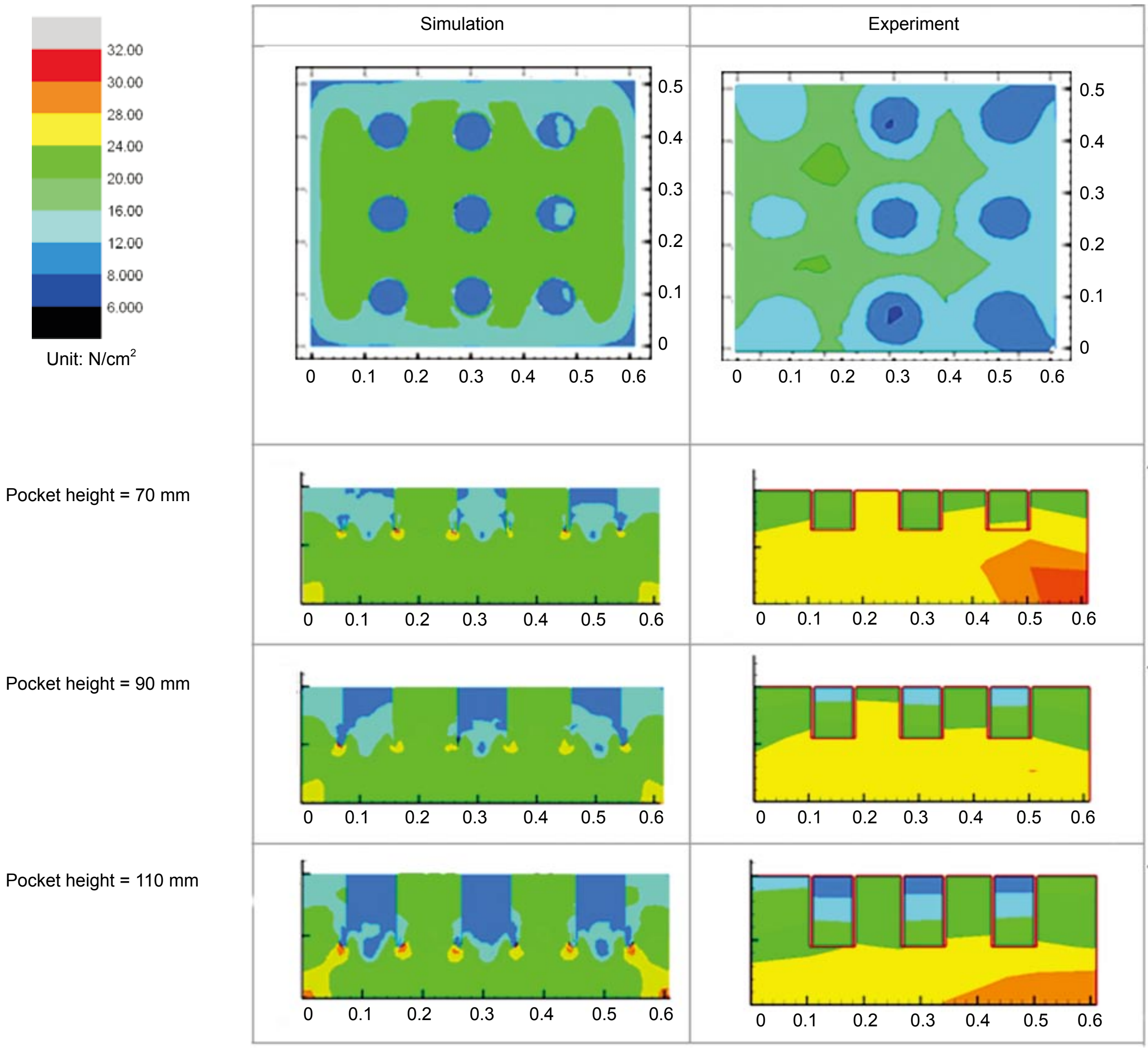

Fig.8: Comparison between the simulated result and the experimental result (with pattern)

measurement errors.

3 Conclusions

(1) High pressure squeeze is the most popular and important moulding sand compaction method for green sand moulding. Numerical simulation is an effective way for optimizing the moulding process.

(2) Drucker-Prager/Cap is a typical mechanical model for discrete materials. In this model, both sand grains property and the nonlinear features of squeezing process are considered. The simulation results are in good accordance with the practical results and give detailed information. ABAQUS incorporated with Drucker-Prager/Cap is an appropriate model for solving nonlinearity problem associated with the squeezing compaction process of moulding sand.

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