THEORETICAL ANALYSIS OF RECTANGULAR CLAY PASTE EXTRUSION

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Abstract

An important aspect of clay paste extrusion is the pressure as a function of extruded velocity/distance traveled. Therefore, the present theory concentrates on deriving basic equations that control the clay paste flow behaviour of rectangular extrusion process during the steady-state flow. The main parameters which control the extrusion pressure are the effective stress in compression of the clay paste, the geometry of extrusion tools and billet, operational conditions and the coefficients of friction between the barrel and the die land surfaces. The theoretical extrusion pressure results were analyzed and discussed thoroughly. Finally, it can be concluded that the present theoretical analysis serves to place the present approach in the context of work on other extrudable materials of different geometry. In addition, it can be used as an effective tool for evaluating and obtaining clay paste materials with optimized properties for extrusion process.

Key-words: clay plasticity, extrusion pressure, coefficient of friction.

INTRODUCTION

Extrusion is a technique of conformation of powders, used for the processing of ceramic products since the 18th century. It is a technique of production associated with a low cost and high productivity, for products of cross-section mainly constant. Extrusion of clay has been employed successfully for mass production, for traditional construction materials, refractories, electronic substrates, composites and others [1,2]. Generally the extrusion process consists of several stages such as, feeding into the cylinder/barrel, extruding through the die, flow through the die-land and the ejection of the product. These phases can be carried out by employing different types of machines. An extrudate so formed can then be dried and sintered, removing the liquid phase and burning out any binders that may have been added, to form a finished ceramic product [3]. It is known that the extrusion mechanisms may occur in a laminar flow type which takes place in the container, and plug flow occurs in the die-land. These mechanisms depend on the geometry of the tooling and the flow properties of the clay paste, and consequently an expression has been put forward to predict the extrusion pressure. The success of the extrusion process of clay paste is controlled by tool geometry, moisture and lubricants, type and amount of binder, ingredients particle size and distribution, temperature and others. Needless to say, the plasticity of clay paste is an extremely important factor for the success of the extrusion process. Plasticity, in this case, and particularly in clay mineral systems, is defined as a property that shows shape changes without rupture when a clay body with added water is submitted to an external force. Furthermore, when the force is removed or reduced below a value corresponding to the yield stress, the shape is maintained [4-9]. However, the plasticity determination is not always an easy task since it cannot be immediately interpreted and applied. In fact, there are several direct and indirect methods for measurement and characterization of the plasticity of a clay body, although its experimental determination, in some cases, is operator dependent, which in turn may produce different results between different methods. Among these methods, the Atterberg's plasticity index, the Pfefferkorn's plasticity index, the stress/strain curves, the indentation and rheological measurements, are the most used. In this context, a mathematical model for evaluation of the plasticity of clay bodies was developed from applied concepts of the plasticity theory by using the stress/strain diagram under compression [10-11]. Several other works have been published concerned with the different aspects of the extrusion, such as, flow behaviour, die and die-land geometries, velocity factor and shearing index and others (4-7).

In the derived expressions proposed in this work, empirical constants determined from the composition of the ingredients are not needed. The main objective here is to present semi-theoretical models to predict the average extrusion pressure based on the modified plasticity equations. However, certain factors such as the coefficients of friction and the effective flow stress of the clay are used from previously published work (10-11).

THEORETICAL ANALYSIS

Approximate treatment

The extrusion process consists of forcing the clay paste workpiece through a die thereby reducing its cross-sectional area from A_0 to A and increasing its length. In this analysis it is assumed that the steady-state has been reached, thus the average ideal extrusion pressure (μ_{comp}=μ=0) for uniform deformation is given by

$$\sigma_{ave}\Big|_{\mu=0} = 1{,}5 \int_0^{\ln\frac{A_0}{A_1}} \bar{\sigma} d\bar{\varepsilon} \qquad \text{(A)}$$

where μ is the coefficient of friction between the cylinder wall and the clay paste, and a shear factor (=1,45-1,55) can be introduced into Eq.(A), which tends to improve the prediction of the extrusion pressure over a wide range.

The above relation does not take into account the cylinder wall friction, therefore to take this parameter into account, then consider the equilibrium in the extrusion direction, as shown in Fig.1. Using the boundary condition where $\sigma_z=(\sigma_{ave})_{\mu=0}$ at $z=L_c$ the average extrusion pressure with wall friction can be expressed as

$$P_{total} = (\sigma_z)_{total} = \left\{1 + \exp\left[\frac{4\mu_w}{D_0}(z - L_c)\right]\right\} 1{,}5 \int_0^{\ln\frac{A_0}{A_1}} \bar{\sigma} d\bar{\varepsilon} \qquad \text{(B)}$$

It has been demonstrated experimentally, especially with metal, that at a certain distance L_c there is a rise in the pressure near the end of the extrusion process. At this point, funneling effect becomes apparent, and is called "coring point". It is fundamental to predict theoretically the average extrusion pressure from Eq.(B), then flow stress of the clay paste from compression test must be known. However, this has been treated and analyzed mathematically by the authors for clay paste and can be expressed as follows [10],

$$\bar{\sigma} = \sigma_z = -\bar{\sigma}_{comp} \exp\left[\frac{2\mu}{h}(r_f - r)\right] \tag{C}$$

The axial compressive load can be evaluated from $F = \int_0^{r_f} 2\pi r \sigma_z dr$ and using Eq.(C), thus

$$F = -2\pi\bar{\sigma}\left[-\frac{h}{2\mu}\left(r_f + \frac{h}{2\mu}\right) + \frac{h^2}{4\mu^2}\exp\left(\frac{2\mu r_f}{h}\right)\right] \tag{D}$$

This expression will be used for the determination of the load vs. the variation in diameter for each compressively tested clay paste. In this way, a more accurate approach, in contrast to the other existing methods, such as the Atterberg's and Pfefferkorn's plasticity indices, is expected for obtaining ceramic bodies with optimized plasticity for a given application [10].

In addition Eq.(C) can be inserted in Eq.(B) and integrated, and also by replacing h by z and D_0 by R_0 to maintain consistency, the expression for average extrusion pressure when $\alpha = 90^{\circ}$ can be expressed as

$$P_{total} = 0,75\frac{\bar{\sigma}_{comp}}{(R_f - R_0)}\frac{z}{\mu_{comp}}\left\{1 + \exp\left[\frac{2\mu_w}{R_0}(z - L_c)\right]\right\}\left\{1 - \exp\left[\frac{2\mu_{comp}}{z}(R_f - R_0)\right]\right\} \tag{E}$$

<u>Analysis of Extrusion through Rectangular Die</u>

The extrusion process of clay paste and the free body in equilibrium are shown schematically in Fig.1. The average pressure in the left end of the rectangular portion zone B is taken from Sach´s theory [12] and is given by

$$P_{ave} = \frac{2\bar{\sigma}}{\sqrt{3}} \frac{(1+B)}{B} \left[\left(\frac{h_b}{h_a} \right)^B - 1 \right] \tag{F}$$

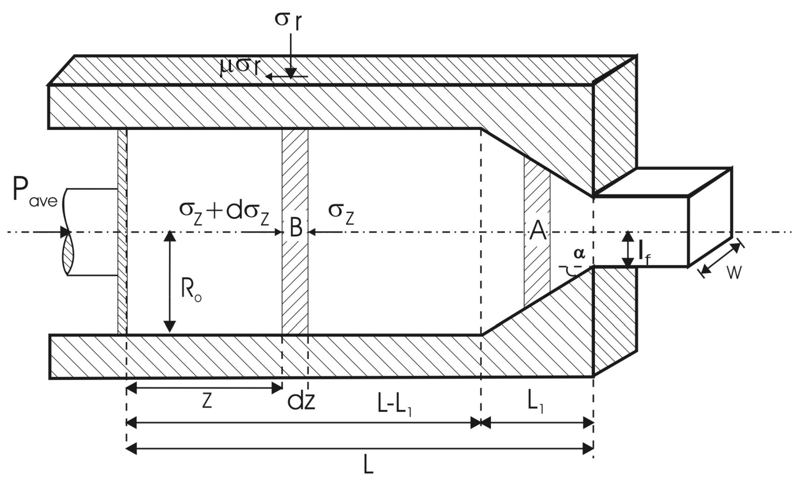

Fig.1. Diagrammatic sketch of rectangular die extrusion of clay paste process

where B = $\mu_W \cot \alpha$, α is the semicone angle of the die and $\bar{\sigma}$ is the flow stress of clay paste in compression test, Eq. (D). On the other hand, the equilibrium of forces in the tapered zone A can easily be established, and assuming a biaxial state of stress, then the equation can be integrated. Now, in the integrated expression putting the value x=0 , and the average ideal extrusion pressure given in Eq.(E), the final theoretical expression for the average extrusion pressure of clay paste through a rectangular die can be determined and is expressed as follows

$$P_{ave} = \sqrt{3} \frac{\bar{\sigma}_{comp}}{(l_f - R_0)} \frac{z}{\mu_{comp}} \left\{ 1 - \exp\left[\frac{\mu_{comp}}{z} (l_f - R_0) \right] \right\} *$$

$$* \left\{ \left\{ 1 + \frac{2}{\sqrt{3}} \frac{(1+B)}{B} \left[\left(\frac{R_0}{l_f} \right)^B - 1 \right] \right\} \exp\left\{ 2B \left[-\frac{L}{R_0} \tan\alpha + \left(1 - \frac{l_f}{R_0} \right) \right] \right\} - 1 \right\}$$

(G)

EXPERIMENTAL PROCEDURE

The prediction of the theoretical results will be determined by compressibility curves of the clay paste with different humidity levels. The materials used for the execution of the experiments were the AC12, AC39 and Kaolin clays, whose chemical composition is given in Table (1), [8-9].

Table 1 - Chemical composition (wt.%) of clays AC12, AC39 and Kaolin, obtained by XRF.

	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	LoI
AC12	69.41	18.51	2.20	0.82	0.05	0.08	2.91	0.73	0.01	0.14	5.15
AC39	51.61	32.57	1.04	1.59	1.48	0.89	1.57	0.08	0.03	0.12	9.02
Kaolin	45.52	38.50	0.40	traces	traces	0.10	0.25	------	------	------	13.57

LoI: Loss on Ignition at 1000 ºC.

The as-received clays were disaggregated in a ball mill and then sieved (20 mesh/840 µm), so that 1 kg of powder for each type of clay was obtained. The moisture content of the clays was determined from samples with about 50g of the material introduced into porcelain crucibles, which were placed in the oven at 120 ±5°C for 24 hrs. Samples having a moisture content of 52 wt.%, 56 wt.% and 60 wt.% for the AC12, AC39 and kaolin clays respectively were prepared and homogenized by mechanical mixing and subsequently, left in a sealed plastic container for 24 hrs for moisture equilibrium. In a later stage, cylindrical specimens were manually prepared in PVC moulds with 47.70 mm diameter and 49.80 mm height. In order to evaluate qualitatively the stress state along the longitudinal section, some of the specimens were sectioned and marked vertically with fine lines. These samples were submitted to different uniaxial compressive loadings as shown in Fig.2. By inspecting Fig. 2, it can be observed that barreling has taken place, and this is due to the friction between the ends of the specimen and the deforming tools/punch. Due to this, the coefficient of friction was taken into account as one of the mathematical parameters to analyze the forces that act on a cylindrical clay compact and was also assumed to be constant. Four specimens of each type of clay having different moisture contents were tested. This procedure was repeated for the other types of clay as given in Table 1. The average diameters were measured by means of digital photographs performed at each pause of the machine, using the software Corel Draw 11.

DISCUSSION OF RESULTS

Before any comparison between the theoretical and the experimental results, it is fundamental to determine the flow stress (effective stress) of the clay paste subjected to uniaxial compression as explained previously. Typical load-radial expansion curves for different moisture levels for each type of the tested clay are shown in Fig. 3. Initially a small elastic strain occurs followed by a relatively high plastic strain, which terminates with the material's rupture. In addition, all the curves shown demonstrated similar behaviour to that in literature [1-2]. It is evident that the elastic limit of these materials is relatively small, and was not included in the theoretical model. Similar behaviour was obtained for the other tested clay pastes.

Fig. 2. Sectioned sample showing strain lines representing the stress distribution

Therefore, by applying the iterative process [14], it was possible to determine the average coefficient of friction and the effective compressive flow stress for each type of clay with a specific moisture content, using Eqs. (C) and (D). Fig. 3 demonstrated that the theoretical curves (Eq. (D)) correlated well with the experimental data for μ_W =0 from which it could be interpreted that this simple model can be used for different types of clay with variable amounts of moisture content.

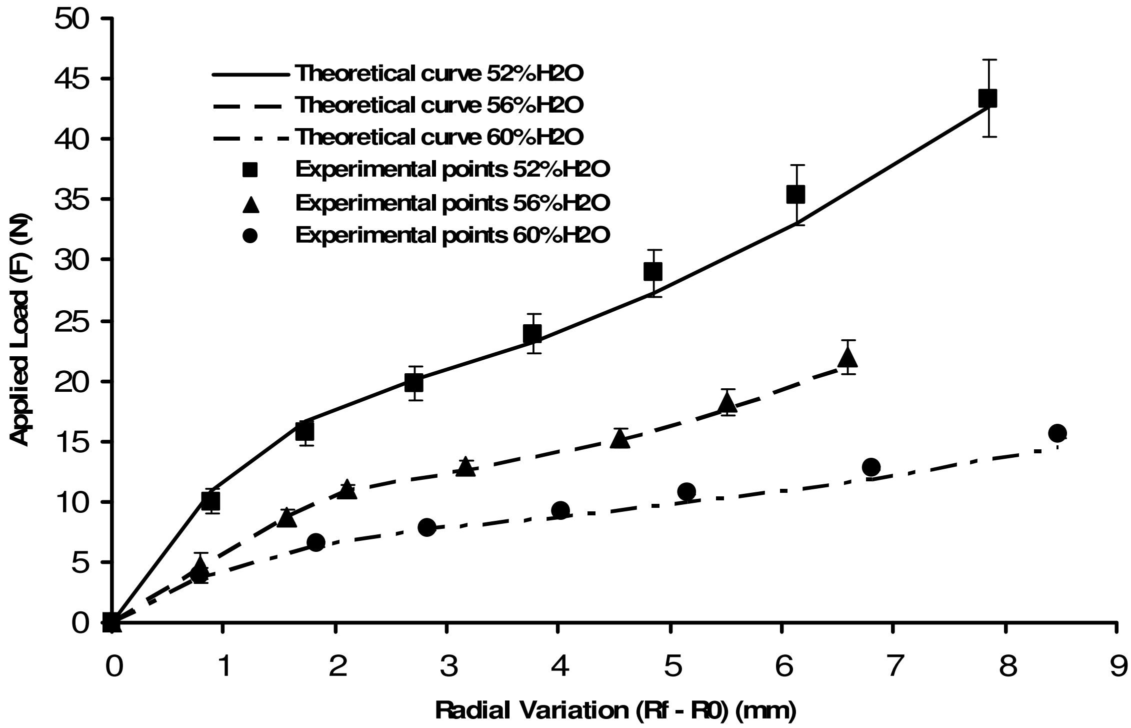

Fig. 3 Comparison between theoretical curves and experimental points for kaolin clay paste having different levels of moisture

Previously published experimental extrusion curves had been carried out with pastes and reproduced here for comparison purposes [3]. The experimental curve shown in Fig. 4, demonstrates the variation of the extrusion pressure as a function of punch travel. Evidently, this curve consists of two principal and easily recognizable phases: 1- the coining phase, where the initial compression of the clay paste caused a rapid build-up of pressure; 2- the steady-state phase, where the pressure stabilizes noticeably as the extrusion process proceeds steadily.

The theoretical analysis of extrusion pressure for tapered die which is given in Eq.(G), involves several process parameters and projected a better understanding of the paste extrusion process. It appears that the predominant factors which govern the extrusion pressure are the coefficients of friction μ_W and μ, which were determined by the curve fitting technique. This becomes clear from the plot of the

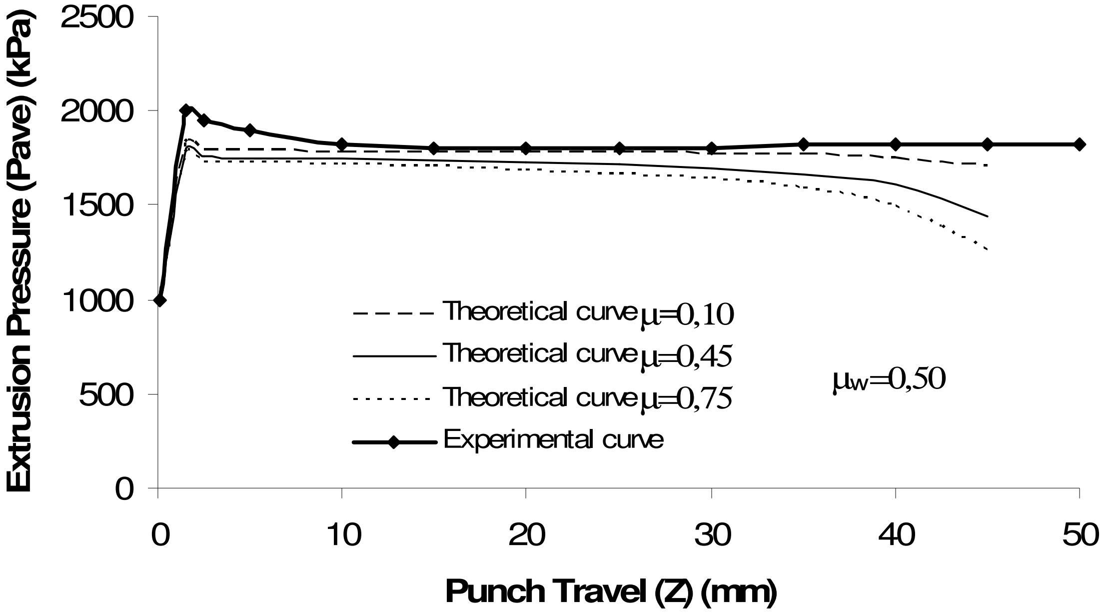

Fig. 4 Comparison between theoretical (analytical approach) and experimental curves for the extrusion process of kaolin clay paste for different coefficients of friction for the compression test

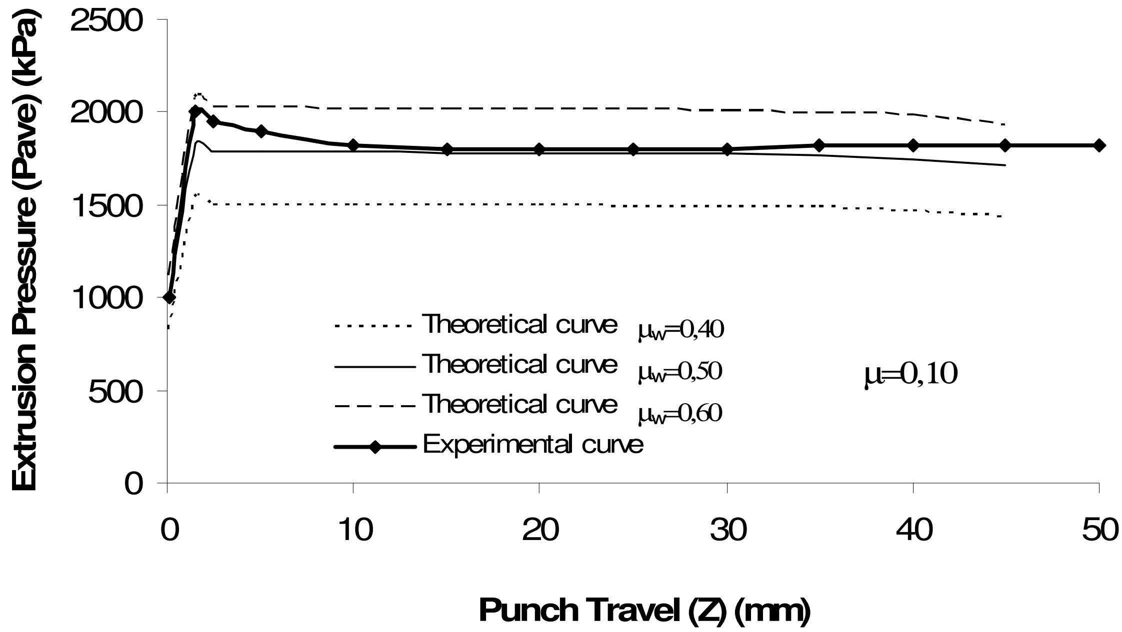

Fig. 5. Comparison between theoretical (analytical approach) and experimental curves for the extrusion process of kaolin clay paste for different coefficients of friction of the cylinder wall

extrusion pressure as a function of the punch travel for various values of μ_W and μ, as shown in Figs. 4 and 5. On close examination of these figures, it becomes evident that certain values of the coefficient of friction can be selected so that the best fit occurs between the theoretical and the experimental curves. Needless to say, the chosen values were μ_W = 0,50 and μ= 0,10. These values were obtained from the curve fitting technique since they are not available so easily in published literature. It must be mentioned that, although the coefficient of friction can really be a dynamic variable as a function of the stress, processing parameters and porosity, which is an acceptable procedure, here it is assumed to be a constant, due to the difficulty of its formulation [(14)]. A theoretical curve using these values and α= 30° demonstrated remarkable agreement as shown in Fig. 6. The coefficient of friction for the cylinder wall is rather high, this compensates for the fact that the die land effect was not considered in the present analysis.

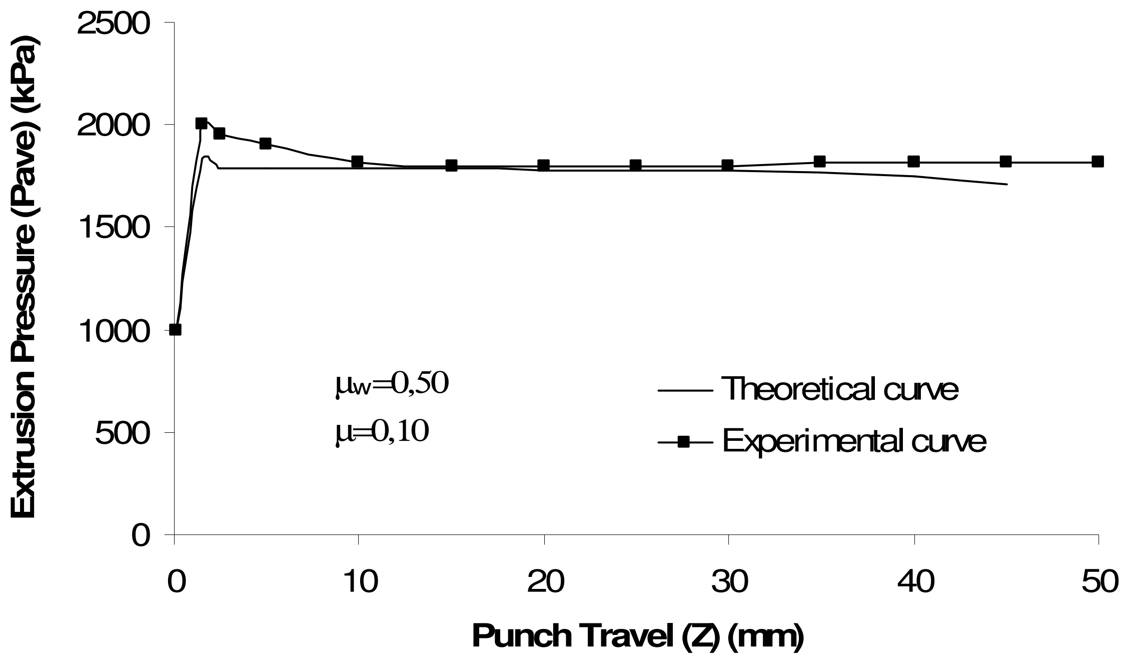

Fig. 6. Comparison between theoretical (analytical approach) and experimental curves for the extrusion process of kaolin clay paste for defined coefficients of friction

CONCLUSION

The factors that influence the behavior of the clay during its processing were used to evaluate the average extrusion pressure. Among these factors, it was clear that, the effective flow compressive stress of the clay subjected to uniaxial compression is a predominant factor. This being in addition to the coefficients of friction between the cylinder wall and the compression surface which were estimated by trial and error technique. The involved parameters in the equation have remarkable influence on the predicted results of the extrusion pressure, such as the moisture content, type of clay, die dimension, and others. The excellent agreement between the experimental and the theoretical results makes the present theory more reliable and a potentially useful tool for the evaluation of clay materials with optimized properties for a given application. The use of this theory will help reduce the number of experiments needed for qualifying preparation of the required moisture and chemical compositions of the clay paste. Also, it is worth mentioning, that care must be taken in estimating the effective flow stress and the coefficients of friction otherwise this may lead to unrealistic results of the pressure.

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