1. Introduction
Depending on the dewatering apparatus the expression process can be distinguished into the filtration sub-process and the consolidation sub-process. The whole process is referred to gauging or dewatering process, which is usually realised in the praxis in the so called press-filters [2]. The compressible cake consists of fine particles which are more or less compressible dependent mainly on the particle contact stiffness. The cake height $h_F$ increases during the filtration time. After filtration it is convenient to consolidate the cake by applying a mechanical pressure in this second stage so that the cake height $h_C$ decreases. The decreasing volume of the cake leads to a minimum amount of water in the pores. As a result, a very dense particle packing saturated with liquid is obtained. Both, filtration and consolidation are considered here as a one-dimensional dynamic problem in a reducing process chamber. The chamber co-ordinate $x$ is positive defined in direction to the piston. In the expression process the liquid flows through a compressed particle packing and therefore, the flow rate difference between solid and liquid has to be taken into account [1]. The dynamic cake formation, with increasing height up to $h(F)$ and decreasing height down to $h(C)$ causes the liquid drag force acting between the particles. This leads to an axial particle pressure $p_s$ transferred versus the contacts.

The knowledge of the compression behaviour of the particle packings of the packing density $\varepsilon_{s,0}$ (paste) is necessary to calculate the mechanical properties like yield limit, isostatic tensile strength, stationary angle of internal friction and viscosity [3]. The aim of this work is the investigation of the dewatering dynamic of fine limestone particle packings ($d_{50} = 1.2 \, \mu m$) with and without inserting electrolytes as well as at different pH-values. In aqueous media the particles form aggregates within the micron range. In this range of particle size solid–liquid separation is influenced by interfacial effects of the aggregates rather than by the size of the primary particles [8]. The change of electrostatic repulsive and van der Waals attractive interactions between particles may result in the flocculation of the particles and lead to a formation of flocs and produce a good separation. For the investigation a press-shear-cell is used and the experimentally measured characteristics of the filter cake heights and filtrate volume flow rates are compared to a dynamical filtration- and consolidation model developed by Reichmann [1], which includes the temporal and local changing packing density and the friction of the particles at the limiting walls.

2. Model description
For the description of the expression dynamics of the ultrafine limestone suspensions the dynamic process model according to Reichmann [1, 4, 5] is used. The commonly used model of Tiller-Shirato [6, 7] assumes average values for packing density and permeability with the assumption of their constant values during the constant pressure filtration and neglects the wall friction influence. As opposed to this classical model, the expression model of Reichmann [1, 4, 5] considers the dynamic values for packing density and the relative motion between particles and liquid. The lateral pressure and wall friction resistance (i.e. coulomb friction) of the particle packing are also observed. Both, a remarkable wall friction and a lateral pressure ratio $\lambda < 1$ indicate the conversion from isostatic suspension flow behaviour into anisotropic elastic-plastic mechanical behaviour of a liquid saturated particle packing. Eq. (1) considers the influence of material properties, i.e. particle pressure $p_s$, packing density $\varepsilon_s$, flow parameters $\lambda_W$, $\varphi_W$ and the
permeability $k$ during the expression process. The model assumes validity of Darcy's law, laminar pore flow and constant slice-element permeability. The filter medium resistance $RFM$ is a sum of medium resistance ($RFM,0$) and first particle layer resistance ($RFM,G$).

\[
\frac{\partial \varepsilon_s}{\partial t} = \frac{\partial}{\partial x} \left[ \varepsilon_s \frac{k}{\eta} \frac{\partial p_s}{\partial x} \right] - \frac{4}{\eta \cdot d_{gl}} \frac{\partial}{\partial x} \left[ \varepsilon_s \cdot k \cdot \tilde{\lambda} \cdot \tan \theta_W \cdot p_s \right] + \rho_{i,a,FM} \frac{\partial \varepsilon_s}{\partial x} \tag{1}
\]

The first term on the right side is a flow term, which characterizes the compression of the cake. The last term is a source term for the collected particles on the filter medium and the second term takes into consideration the wall friction. The resistance by wall friction in an expression process depends on the particle stress ratio at the wall $\lambda_W$, the wall friction angle $\theta_W$ and the ratio of cake height $h$ to the equivalent diameter $d_{eq}$ of the expression cell.

The solution function of Eq. (1) is dependent on time and locus. A detailed description of the initial and boundary conditions for the both sub-processes can be found at Reichmann [1].

3. The Press-Shear-Cell
To evaluate the model, the experimentally measurement of material properties as the packing density $\varepsilon_s,0$ and permeability $k_0$ at $ps = 0$, compressibility index $\beta$, permeability fitting constant $\delta$, isostatic tensile strength $p_a$, lateral pressure ratio $\lambda_w$, wall friction angle $\theta_W$ and the filter medium resistance of pure medium $RFM,0$ is necessary. These parameters were determined using the Press-Shear-Cell [4]. It is a combination of a laboratory filter, a compression-permeability cell and a medium pressure shear cell. Filtration experiments and in-situ shear experiments with the filter cakes can be carried out after the expression. This test apparatus is suitable to be applied on filtration processes at constant pressure. Compression-permeability tests are used to determine the packing density $\varepsilon_s$ and the permeability $k$. By the expression experiments the filtration and consolidation dynamics can be evaluated. After the filtration the flow behaviour of the filter cake can be measured by shear tests to determine the yield loci.

To investigate the material properties of a compressed cake, the feed suspension is filled in the ring chamber. The ring piston above the ring chamber is moved in direction to the suspension. The air between the piston and the suspension is removed by an open valve until the piston touches the upper suspension level, where the valve is closed. Thereafter a constant piston pressure is applied to drain the suspension. A sensor built in the piston surface obtains this pressure. Filtrate flows through the supported filter medium whereas the piston velocity equals the filtrate volume flow rate per unit filter area. To prevent suspension losses, Teflon double lip seals are fixed at the inner and outer circumference of the ring piston. If the filtrate runs dry, the cake is consolidated. The packing density $\varepsilon_s$ can be calculated easily from the consolidated cake height $h(t_c)$ obtained from piston position and the initial solid mass per filter surface $m_s, A$. The permeability $k$ can be calculated applying Darcy's law if the cake is permeated with filtrate and simultaneously recorded with a balance.

4. Result and discussion
The values of the process parameters which are required to solve the equation (1) can be found in [3]. The comparison between the non-flocculated filter cake and the 1 M NaCl-cake shows smaller permeabilities, larger packing densities, and larger isostatic tensile strength for the non-flocculated filter cake. The compressibility index is practically the same ($\beta \approx 0.076$ [3]); both filter cakes are compressible. The time dependent curves of the specific filtrate volume and the cake height were predicted and compared with the experimental tests after the determination of the process parameters. Considering the change of the specific
filtrate volume during the process time a very good agreement between model and experiment was observed (Fig 1 and 2).

![Graph](image1)

**Fig. 1:** Specific filtrate volume and cake height versus process time for expression of limestone suspension without electrolyte at $p = 200$ kPa

![Graph](image2)

**Fig. 2:** Specific filtrate volume and cake height versus process time for expression of 1 M NaCl-limestone suspension at $p = 200$ kPa

Furthermore the filtration and consolidation behaviour of ultrafine limestone suspensions at different pH-values were determined. The pH-movement influences the compression and flow behaviour of the limestone suspension. At the isoelectric point (attractive interparticular interaction) occurs a harder structure of the filter cake, that means to reach the same solid concentration a higher solid pressure has to be impressed in comparison to the repulsive interparticular interactions. The influence of the interparticular interactions on the flow and compression behaviour increases by decreasing particle size. The changing of the sediment stiffness (hardening or liquidation) by variation of the pH-value is, contrary to polymer flocculants, an almost reversible possibility to adapt the rheologic material behaviour to the requirements of the solid / liquid separation processes or apparatuses.
5. Conclusions
In this work the expression dynamics of ultrafine limestone suspensions with and without electrolyte were determined using a dynamic process model. The model results were compared with the experimental tests. A Press-Shear-Cell was used to investigate the expression behaviour of the consolidated limestone packings and to measure the most important material properties, i.e. packing density $\varepsilon$, permeability $k$, wall friction angle $\phi_W$ and lateral pressure ratio $\lambda$ for limestone filter cakes. It was shown that the time dependency of specific filtrate volume and cake height for the flocculated and non-flocculated suspension can be very well predicted by using the dynamic process model. The compression and flow behaviour of the limestone suspension can be influenced by moving the pH-value.

References