Vibration compaction of compressible filter cakes for mechanical deliquoring on a horizontal vacuum belt filter

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ABSTRACT

Compaction under oscillatory shear and low normal pressure is an alternative method for mechanical deliquoring of compressible filter cakes. After the proof of concept on a laboratory scale, this article deals with the application of the process to an existing continuous vacuum belt filter. For this purpose, a modular device was developed for vibration compaction on an indexing horizontal vacuum belt filter (HVBF). It is shown that vibration compaction of an industrially relevant material on the HVBF reduces the initial residual moisture of 39.9% after cake formation by up to 10.5 percent points. Significant mechanical deliquoring of the filter cake can be reached by vibration compaction already after a short process time of 15 s. The experimental results on a pilot scale reveal that the process can be applied to an existing HVBF.

KEYWORDS

filtration; mechanical deliquoring; compaction; oscillatory shear; compressible filter cakes; horizontal vacuum belt filter

1. Introduction

Cake filtration is a widely used process to separate solids from liquid in various sectors, including mining industry[1,2] or wastewater treatment.[3,4] After cake formation, a porous particle structure exists which is completely filled with liquid. To remove the remaining liquid from the filter cake, mechanical deliquoring measures can be used as an alternative to thermal drying. Since mechanical deliquoring requires 100 to 1000 times less energy than thermal drying, it is reasonable to mechanically remove the liquid from the filter cake to the maximum possible extent.[5]

A conventional post-deliquoring method is desaturation, where further liquid is driven out of the cake pores by a gas differential pressure. Especially for fine, compressible filter cakes, this leads to cake shrinkage, which benefits crack formation.[6–8] The lower flow resistance of the cracks in the filter cake causes a higher gas throughput at constant pressure difference and, hence, higher operating costs. In the worst case, a significant drop of the pressure difference occurs, which reduces the achievable residual moisture of the filter cake.

Cracking can be reduced by operation-specific or suspension-specific measures such as lowering the cake height[7] or targeted segregation during cake formation in two layers by controlling the suspension concentration and settling time.[8] Redeker et al.[9] found that the pre-compaction of filter cakes by squeezing prior to desaturation is an effective method to avoid cracking. Illies[10] proved that pre-compaction also accelerates the dewatering kinetics during the air-blowing step in the case of complete avoidance of cracking. Furthermore, compaction has the benefit of significantly contributing to further mechanical deliquoring of the filter cake in contrast to operation-specific or suspension-specific measures reducing cracking. Detailed investigations of filter cake shrinkage as a cause of crack formation by Wiedemann et al.[11–13] revealed that increasing pre-compaction of the filter cake is associated with a decrease of the shrinkage potential. The compaction pressures required to avoid cracking are high, e.g., 1391 kPa for limestone or 1833 kPa for red mud. It is possible to apply these high pressures for crack-free mechanical deliquoring in filter presses or membrane filter presses, but these apparatuses operate discontinuously. Due to the high achievable throughputs, cake filtration is preferably performed in continuous devices, such as vacuum drum or belt filters. Such high pressures are difficult to realize on continuous drum or belt filters due to the high stress on the apparatus components.

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Therefore, alternative methods are required for filter cake compaction and mechanical deliquoring.

It is already known from the use of belt filter presses that the superimposed input of a steady shear into the filter cake during squeezing has an additional compacting or deliquoring effect.[14,15] Using a self-developed press shear cell, Reichmann et al.[16] proved that an additional shear at low pressure can achieve the same degree of compaction as squeezing. Other authors also stated a positive effect of shear on filter cake consolidation in a lab-scale press shear cell for various particle systems.[17–19] Bickert and Vince[20] showed that a simple add-on flapper roller can improve mechanical deliquoring of coal filter cakes on horizontal vacuum belt filters (HVBFs). Höfgen et al.[21] developed High Pressure Dewatering Rolls (HPDR), a continuous device that uses steady shear in combination with pressure to enhance deliquoring. The application of oscillatory shear is a method widely applied for soil compaction. In the field of solid-liquid separation, Pearce[22] and Gundogdu et al.[23] successfully tested the use of oscillatory shear parallel to the filtrate flow to improve the mechanical deliquoring of filter cakes, but only on a discontinuous laboratory scale. In the mining industry, vibration compaction parallel to the filtrate flow has already been used for industrial HVBFs.[24] Vibration rollers improved deliquoring of gold tailings in comparison to conventional HVBF operation.[25] On the contrary, Illies et al.[26–28] investigated the use of vibrations perpendicular to the filtrate flow to compact filter cakes in a discontinuous laboratory apparatus. The investigations show that even at low normal pressures, significant filter cake compaction and mechanical deliquoring are possible due to the additional oscillatory shear. Furthermore, crack formation was reduced significantly by vibration compaction. Illies[28] also performed an energy assessment of the method which proved that the energy demand of vibration compaction is 100 to 1000 times lower compared to thermal drying.

The previous investigations on vibration compaction perpendicular to the filtrate flow by Illies et al.[26–28] have been carried out only on a discontinuous laboratory scale. However, cake filtration in industrial applications is preferably realized in continuous filtration apparatuses such as HVBFs to achieve high throughputs. Therefore, it is essential to verify the applicability of this technique for additional mechanical deliquoring of compressible filter cakes in an existing continuous filtration apparatus. This study addresses the transfer and scale-up of the method to an existing indexing HVBF. For this purpose, a novel modular unit for vibration compaction on indexing HVBFs has been developed and will be presented first. After implementing the vibration module on the indexing HVBF, the compaction and mechanical deliquoring effect of the module on an industrially relevant slurry was investigated for different frequencies and vibration times in the continuous pilot-scale apparatus. In addition, experiments were conducted in the discontinuous laboratory apparatus developed by Illies et al.[26] to compare the achievable compaction degrees on the laboratory and pilot scale and, thus, to evaluate the transferability of the laboratory results. Moreover, the discontinuous compaction by squeezing at different normal pressures was compared to vibration compaction on the HVBF.

2. Materials and methods

2.1. Model system characterization

The model material chosen for the investigations was a precipitated calcium carbonate (PCC) product which is a widely used filler in paper and plastic industries. In the synthesis of PCC, CO_2 is fed into a $Ca(OH)_2$ slurry, leading to the precipitation of calcium carbonate. To obtain the dry PCC powder, the aqueous slurry is filtered, before a final thermal drying step removes the remaining liquid.[29] For this reason, PCC is an industrially relevant model material suited for the investigations.

The solid density of the material is $2610\,\mathrm{kg/m^3}$ as measured by the Multivolume Gas Pycnometer MP 1305 (Micrometrics Instrument Corporation, USA) at a temperature of 20°C with helium 5.0. The particle aggregates, which consist of scalenohedral primary particles, have an irregular shape (see Figure 1). According to the volumetric particle size distribution in Figure 1, which was determined by the HELOS H0309 laser diffraction instrument (Sympatec GmbH, Germany) in deionized water, the median diameter of the product $x_{50,3}$ is 4.2 µm and the distribution width $span = \frac{x_{90,3} \quad x_{10,3}}{x_{50,3}}$ is 1.6. The specific surface area of the particles detected by the Brunauer-Emmett-Teller (BET) method in the Autosorb-1 gas sorption meter (Quantachrome Corporation, USA) is $4.7\,\mathrm{m^2/g}$. The model material was dispersed in deionized water, resulting in slurries with a solid volume fraction of 20%. The zeta potential of the slurry was 9.6 mV at a pH of 10.3 and an electrical conductivity of 0.035 S/m, measured by the AcoustoSizer II (Colloidal Dynamics, USA).

2.2. Continuous vibration compaction on the indexing horizontal vacuum belt filter

For the transfer of the vibration compaction process to a continuous filter apparatus, a HVBF was used.

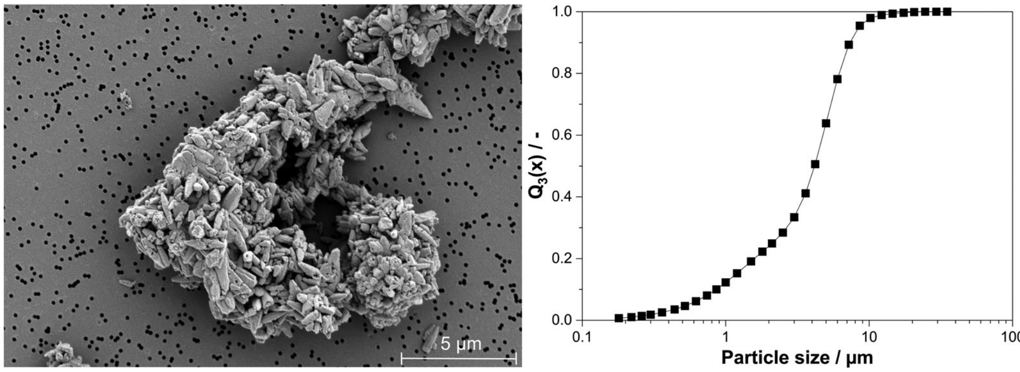

Figure 1. Particles of the model material imaged by a scanning electron microscope (left). Particle size distribution of the model material in deionized water, determined by the HELOS H0309 laser diffraction instrument (Sympatec GmbH, Germany) (right).

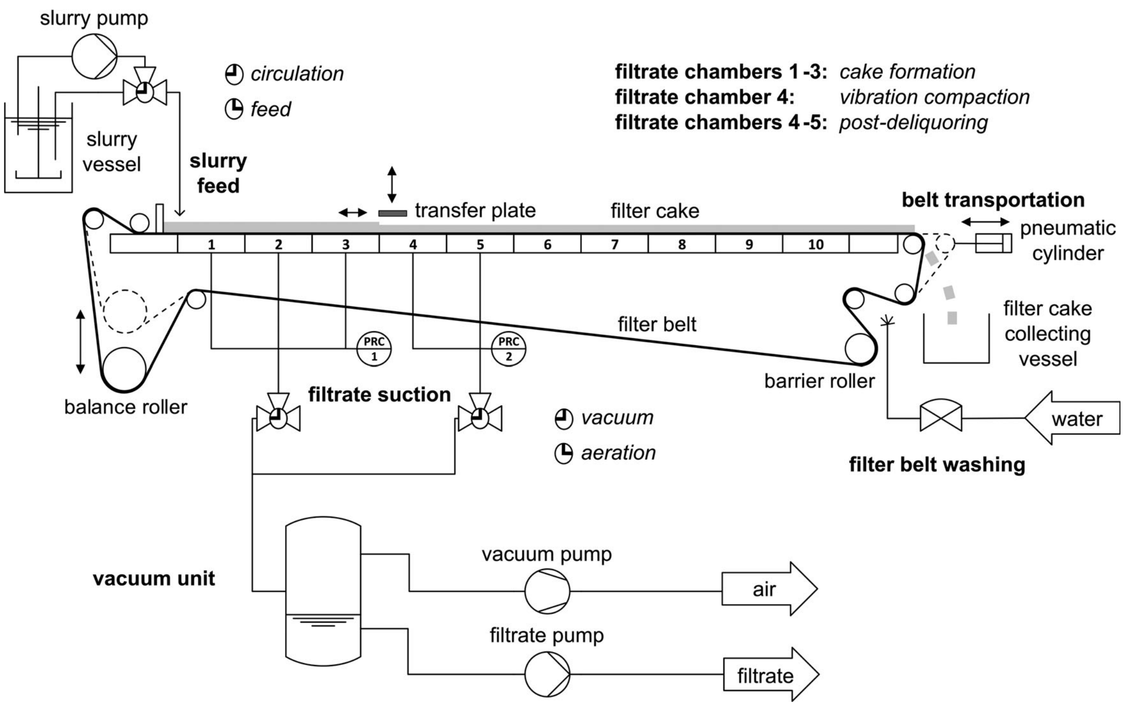

Figure 2. Schematic illustration of the indexing HVBF.

For this purpose, a modular vibration unit was developed to apply oscillatory shear to the filter cake formed on the HVBF. In the following sections, the setup of the HVBF, the developed vibration module, and the operating procedures and conditions of the experimental studies will be presented.

2.2.1. Setup of the horizontal vacuum belt filter

The continuously operating filter unit used is an indexing HVBF (BHS-Sonthofen GmbH, Germany) with a filter area of 0.1 m^2. The setup of the entire apparatus is shown in Figure 2. The key feature of the apparatus is the filter cloth, which is moved as an endless belt step by step over ten fixed square filtrate chambers with an area of 0.01 m^2 each. The slurry deliquoring process is performed during the stagnancy of the filter belt, while vacuum is applied to the filtrate chambers. Then, the vacuum in the filtrate chambers is released for the belt movement by a predetermined distance. During the belt movement, the cake is discharged and the filter belt is washed. The filter cloth is a multifilament twill fabric made of polypropylene type SEFAR TETEX© MULTI 05-4-660 K (SEFAR AG, Switzerland) with an air permeability of 4 l/(m^2s) at 20 mmH_2O. The belt moves by 40 mm during one indexing. A pneumatic cylinder coupled to a roller moves the belt forward. The barrier roller, which rotates in one direction only due to a barrier mechanism, ensures that only the part of the belt on the vacuum chambers is moved forward. The weight of the balance roller, which is vertically movable in contrast to the rest of the rollers, provides the belt tension. During belt transportation, the balance roller moves upwards. After the belt movement, the piston of the pneumatic cylinder moves back to its initial position. The part of the belt that has been moved forward is pulled back underneath the vacuum chambers by the balance rollers own weight. The balance roller moves back down to its initial position. During this process, the first five vacuum chambers are supplied with vacuum to prevent the advanced part of the belt from slipping back on the vacuum chambers.

To ensure the homogeneity of the slurry, it is stirred in a tank (V = 80 l) using an agitator type VJ 0.75 (RVT Rühr-und Verfahrenstechnik Maier & Richter GmbH, Germany) at a speed of 430 rpm. The particle system is dispersed in deionized water while stirring at least 30 min before the start of the filtration. The VF10 peristaltic pump (Verder Deutschland GmbH & Co. KG, Germany) pumps the slurry continuously in a circle with a constant flow rate. When the valve is switched over to feed for a defined time, the slurry flows onto the filter belt. This time determines the cake height after cake formation. After cake formation on the first three filtrate chambers, the filter cake is compacted in the front area of the fourth filtrate chamber, where a plate transfers an oscillatory shear into the filter cake. A pneumatic cylinder coupled to the transfer plate ensures that the module is moved upwards and downwards before and after belt transportation. In the rear of the fourth chamber and in the fifth chamber, final deliquoring takes place by applying a gas differential pressure to the filter cake. The TR 40 V (91) vacuum pump (Rietschle, Germany) with a pumping speed of 45 m^3/h and an ultimate pressure of 100 mbar is used for the vacuum supply in the first five filtrate chambers. The first three chambers as well as the fourth and fifth chambers can be supplied with a vacuum independently of each other. Two pressure sensors each record the applied pressure difference in the respective filtrate chambers.

After cake transportation through the last five filtrate chambers, where no further process steps occur, the cake is discharged into a collecting vessel. For cleaning the filter cloth, a nozzle then sprays tap water at a pressure of 150 kPa onto the filter belt during the belt movement.

2.2.2. Vibration module

To apply an oscillatory shear to the filter cake, a modular vibration unit was developed for the existing indexing HVBF, which can be seen in Figure 3. The concept of vibration generation is similar to that of the discontinuous lab-scale apparatus developed by Illies et al.[26]

An electric motor (Siemens AG, Germany) with a power of 0.55 kW generates a rotational motion. Via an eccentric with the eccentricity e and a rod, the rotational motion is converted into an oscillatory vertical motion. The rod is connected to a lever, which is attached to a pivoted shaft. Two further levers are mounted at right angles to the first lever on the shaft and on a slide. The levers convert the vertical motion of the rod into a horizontal motion of the slide. The system can generate a horizontal oscillation with a frequency of up to 50 Hz. The shear length of the horizontal oscillation l_s results from the eccentricity of the eccentric e and the dimensions of the levers s_1 and s_2:

$$l_s = 2e \cdot \frac{s_2}{s_1} \tag{1}$$

Using the holes in the first lever, the dimension s_1 and the shear length l_s can be adjusted.

The oscillatory slide is moved in a linear guiding unit. Below the slide, the transfer plate is fixed and applies the oscillatory shear to the filter cake. The rectangular transfer plate is 90 mm wide and 40 mm long. Thus, the length of the transfer plate corresponds exactly to the belt movement during one indexing of 40 mm. The vibration is put in by the transfer plate exclusively. The transfer plate is placed directly on the cake. Apart from that, there is a vibration decoupling between the indexing HVBF and the vibration module. A rectangular fixed frame surrounds the oscillatory transfer plate. The fixed frame and the slide guide are mounted to a holding plate. By connecting the holding plate to a pneumatic cylinder, the entire vibration module can be moved upwards and downwards. The pneumatic cylinder is also used to apply the normal pressure during vibration compaction. After the module is moved upwards for the vibration compaction, the frame is pressed against the filter cake in the peripheral area of the compaction zone during the vibration input. Thus, the frame provides a fixation of the filter cake in the area surrounding the compaction zone, so that the cake is not pressed out at the sides of the module during the vibration input. As the cake height of the filter cake is reduced by the vibration compaction, the frame is covered with sponge rubber on the bottom which deforms elastically when the frame hits the filter cake. This ensures that the frame is pressed against both the non-compacted and compacted filter cake in the area surrounding the compaction zone (see Figure 4).

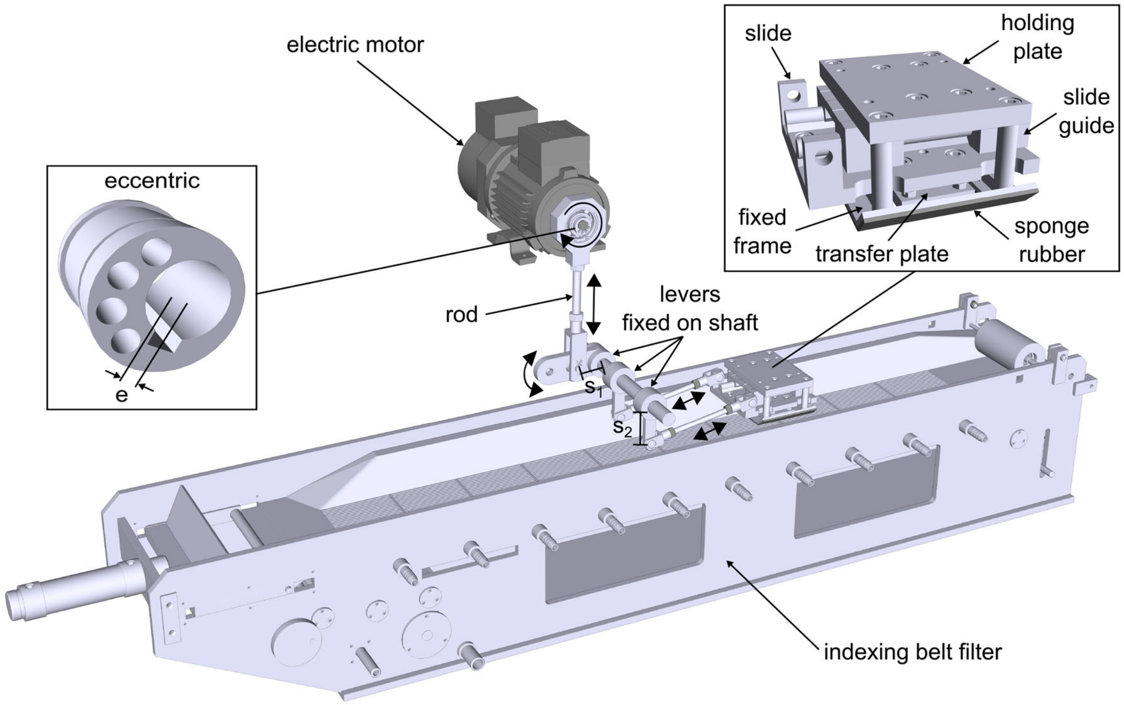

Figure 3. Setup to generate oscillatory shear on the indexing HVBF.

2.2.3. Operating procedure and conditions

The front area of the HVBF with the vibration module is shown in detail in Figure 4. First, a filter cake with a constant height of approximately 7.5 mm is formed on the first three filtrate chambers. After the slurry feed, it takes eight belt movements until the filter cake is fully formed and leaves the cake formation zone. Then, the filter cake, whose length corresponds to the belt movement during one indexing of 40 mm, is compacted for 15, 30, 60 or 90 s under oscillatory shear at different frequencies in the front area of the fourth filtrate chamber. The superimposed normal pressure during vibration compaction is 80 kPa. The constant shear length of the oscillatory shear is 4.5 mm. For residue-free removal of the cake after lifting the compaction module, a monofilament nylon filter cloth SEFAR NITEX© 03-5/1 (SEFAR AG, Switzerland) with a mesh size of approximately 5 µm is located underneath the frame and the transfer plate. After compaction, post-deliquoring of the cake takes place by applying vacuum in the fourth and fifth chamber. The vibration time at which the vibration compaction is investigated determines the cycle time which is defined as the period from the start of the belt movement to the next belt movement. The cycle time ranges from 28 s to 103 s. The specific solid mass throughput of the apparatus is between 329 kg/(m^{2}h) for a cycle time of 28 s and 90 kg/(m^{2}h) for a cycle time of 103 s.

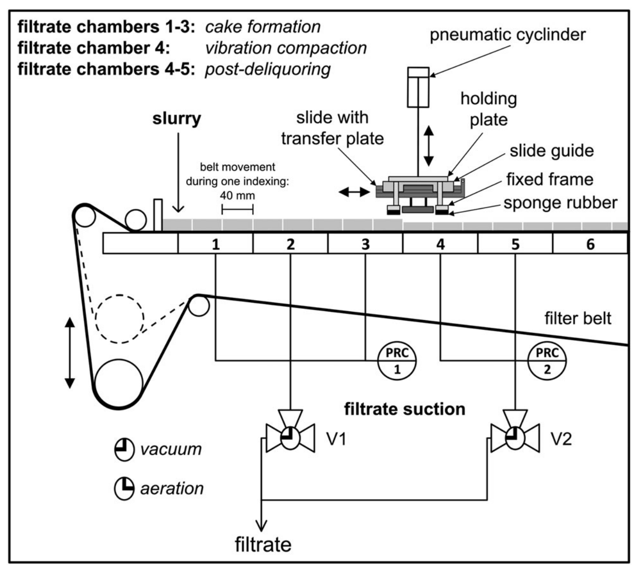

Figure 4. Schematic representation of the vibration module installed in the HVBF.

To clarify the indexing process, the differential pressure in the cake formation zone (PCR1) and in the vibration and post-deliquoring zone (PCR2) at a cycle time of 43 s (vibration time 30 s) is shown over time as an example in Figure 5. As the belt movement is performed by a pneumatic cylinder in the first 5 s, there is no vacuum in any of the chambers. After belt movement, the valve for slurry feed opens for 3 s and the slurry flows onto the filter belt. The slurry feed covers the moved-forward part of the filter belt in the front area of the first chamber. With the start of the slurry feed, vacuum is always applied to the first three chambers for 10 s, regardless of the performed cycle time. After vacuum has been applied for 10 s, the first three chambers are ventilated again. Therefore, no vacuum is applied in the cake formation zone for the remaining cycle time. This ensures that in all cases there is a fully saturated filter cake after crossing the cake formation zone on the first three chambers and no post-deliquoring takes place in the cake formation zone. The pressure difference in the first three chambers drops from initial 56 kPa to 45 kPa during this period. The reason for the drop in differential pressure is leakage at the filter belt, which is caused by the HVBF design. The filter belt covers not only the plane chambers, but also the angled side parts of the filtration channel (see Figure 3), which are not completely covered by the filter cake. Therefore, the vacuum pump pulls air past the filter cake at the side of the filter belt.

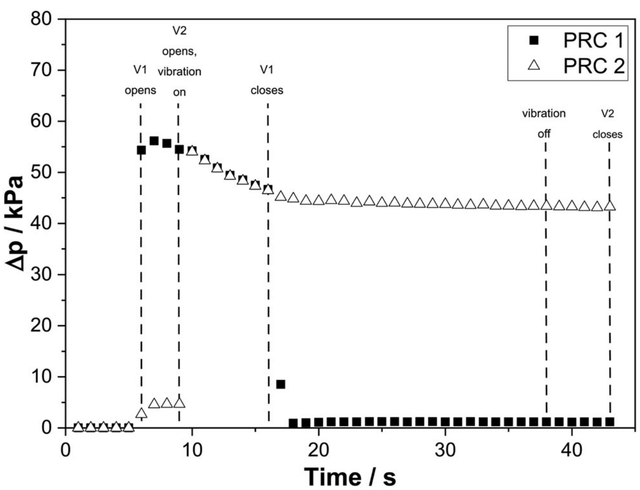

Figure 5. Differential pressure in filtrate chambers 1-3 (PRC1) and 4-5 (PRC2) at a cycle time of 43 s.

Vibration compaction and post-deliquoring on the fourth and fifth filtrate chambers start after the slurry feed. At the same time, valve 2 opens and vacuum is applied to the fourth and fifth chamber. At the beginning of opening valve 2, the pressure difference is at approximately 55 kPa and then falls to a constant value of 45 kPa. After the investigated vibration time, in this case 30 s, the vibration compaction is stopped by switching off the electric motor (vibration off). As it takes time for the transfer plate to come to a complete stope after the electric motor is switched off, vacuum is still applied in chambers 4 and 5 for another 5 s. Therefore, the post-deliqouring time is 35 s per cycle. Depending on the investigated vibration time, the post-deliquoring time ranges between 20 and 95 s per cycle.

As no further process steps are carried out on the remaining filtrate chambers 6 to 10 and the cake is just transported over these chambers for the cake discharge, there is no vacuum in these chambers at any time.

2.3. Discontinuous vibration compaction on a laboratory scale

Along with the experiments on the HVBF, studies were run with the same experimental parameters in the discontinuous laboratory apparatus developed by Illies et al.[26] A detailed description of the setup and operation of the apparatus shown in Figure 6 can be

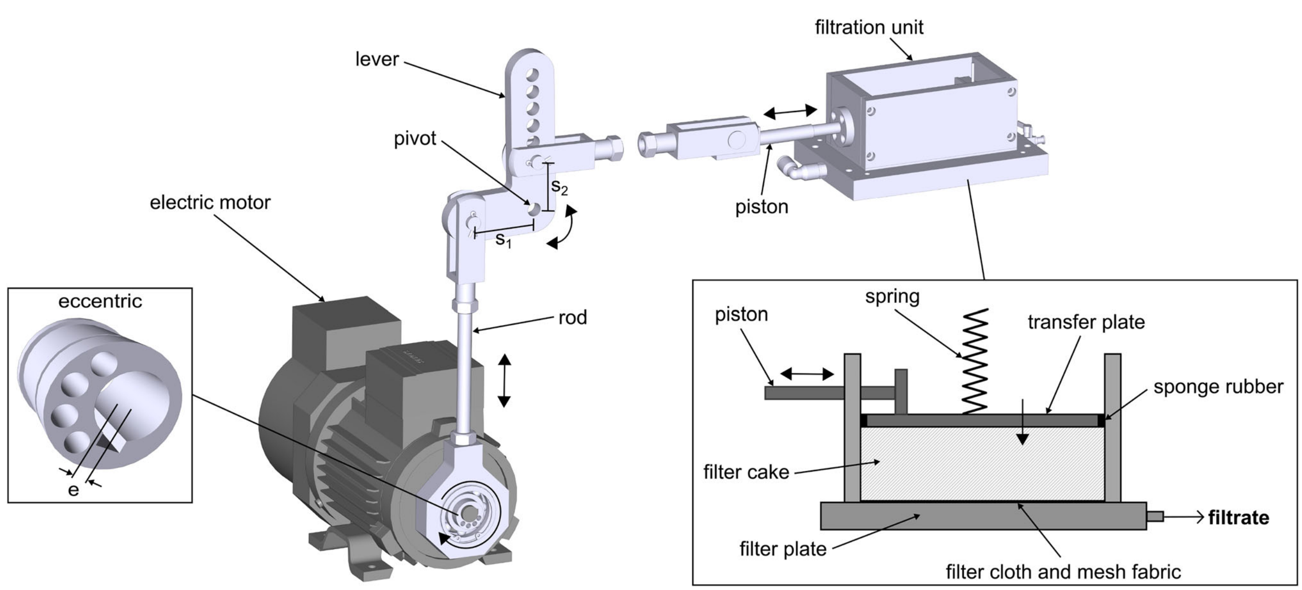

Figure 6. Setup of the discontinuous laboratory apparatus developed by Illies et al.[26] for the application of oscillatory shear to filter cakes.

found in Illies et al.[26] The generation and transfer of the oscillatory shear are nearly identical to those of the vibration module on the HVBF described in Chapter 2.2.

After filling the slurry into the filter plate, the filter cake forms at a vacuum-based differential pressure of 50 kPa. The filter cake height is about 7.5 mm, as on the HVBF. The used filter cloth is a SEFAR NITEX© 03-5/1 which is used underneath the transfer plate and frame of the vibration module in the pilot apparatus as well, supported by a stainless steel mesh with a width of 1 mm (GKD – Gebr. Kufferath AG, Germany). The transfer plate is then put on the filter cake and vibration compaction begins. Similar to the vibration module on the HVBF, the maximum achievable frequency is 50 Hz and the shear length l_s calculated from the dimensions of the lever s_1 and s_2 the eccentricity of the eccentric e by Eq. 1 is set constant to 4.5 mm. During the application of oscillatory shear, a normal pressure of 80 kPa is present on the filter cake, which results from an applied vacuum in the filter plate. The compression force by the spring is responsible for a defined contact between transfer plate and filter cake. However, the contribution of the spring force to filter cake compaction is negligible.

2.4. Compaction by squeezing in the compression-permeability cell

To investigate the consolidation of the filter cake under compression parallel to the filtrate flow, the compression-permeability (CP) cell developed and described in detail by Alles[30] was used. Experiments with the CP cell were conducted to compare the compaction effects by oscillatory shear and squeezing.

Figure 7 shows the CP cell. It includes a cake formation unit with a filtrate bottom drain covered by the SEFAR NITEX© 03-5/1. The filtration area is 51.5 cm^2. After filling the unit, the slurry is subjected to a compression by a piston. Normal pressure is increased in a stepwise manner from 80 to 1000 kPa, after the equilibrium state is reached in the respective step. The piston is covered by the Supor© 100 hydrophilic polyethersulfone membrane with a pore size of 0.1 µm (Pall Corporation, USA). A TLH 100 electrical position sensor (Novotechnik Messwertaufnehmer OHG, Germany) measures the position of the piston. It is used to determine the filter cake height h_c over time. The filtrate only flows off through the bottom filter cloth. The duration of each compression step was set to 60 min to ensure that the compaction equilibrium is reached in all cases. The results showed that the predetermined time of 60 min is sufficient for a state of equilibrium to be reached in each step.

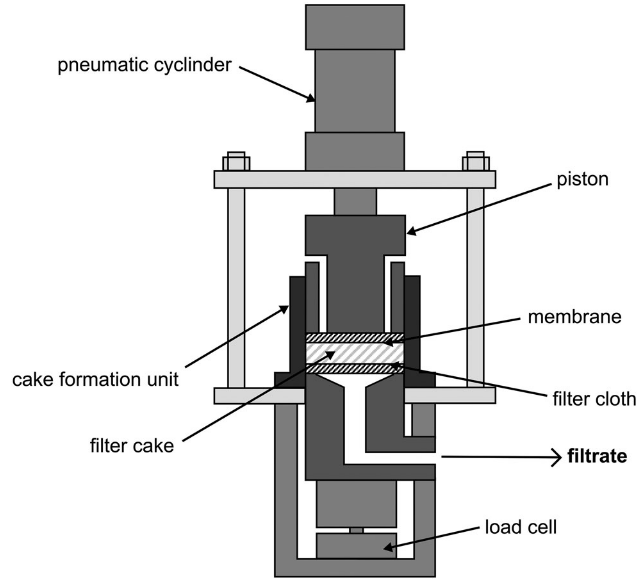

Figure 7. Setup of the CP cell described in detail by Alles.[30]

2.5. Filter cake analytics

To analyze the deliquoring and compaction states after the respective process steps in the pilot and laboratory apparatus, we determine the residual moisture RM of the filter cake. The residual moisture RM is defined as the ratio between the liquid mass m_l in the filter cake and the total wet filter cake mass m_{tot}. Compaction progress after the application of oscillatory shear can be evaluated on the basis of the residual moisture RM of the filter cake, since the capillary entry pressure is not exceeded at the maximum superimposed pressure difference of 56 kPa. Thus, no desaturation of the filter cake occurs during the entire process. To determine the residual moisture, samples are taken from the filter cake by using a cylindrical sampler with a diameter of 12 mm. Having dried the samples for 24 h at a temperature of 100° C, residual moisture RM can be calculated from the wet cake mass m_{tot} and the dry solid mass m_s:

$$RM = \frac{m_l}{m_{tot}} \cdot 100\% = \frac{m_{tot} - m_s}{m_{tot}} \cdot 100\% \qquad (2)$$

Even after consolidation in the CP cell, the filter cake is fully saturated. In this case, residual moisture RM is calculated from the porosity ϵ, which is the pore volume V_p relative to the total volume of the cake V_{tot}. The difference between the total volume V_{tot} and the solid volume V_s corresponds to the pore volume V_p. After the end of the experiment, the entire filter cake dries, resulting in solid cake mass m_s.

Knowing the solid density ρ_s, the filter area A, the solid mass m_s, and the cake height h_c, Eq. 3 is applied to calculate the porosity ϵ of the cake after each compression stage.

$$\epsilon = \frac{V_p}{V_{tot}} = \frac{V_{tot} - V_s}{V_{tot}} = 1 - \frac{\frac{m_s}{\rho_s}}{Ah_c} \tag{3}$$

Since the liquid volume V_l is equal to the pore volume V_p for a saturated filter cake, the residual moisture RM can be calculated by using the porosity ϵ, the solid density ρ_s, and the fluid density ρ_l.

$$RM = \frac{m_l}{m_{tot}} \cdot 100\% = \frac{V_l\rho_l}{V_l\rho_l + V_s\rho_s} = \frac{\epsilon\rho_l}{\epsilon\rho_l + (1-\epsilon)\rho_s} \cdot 100\% \tag{4}$$

3. Results and discussion

The experimental data with error bars are based on three experiments. The error bars represent the standard deviations unless explicitly stated otherwise.

3.1. Compaction and deliquoring effect under oscillatory shear and normal pressure on the horizontal vacuum belt filter

Figure 8 shows the residual moisture of the filter cake that can be reached after compaction under oscillatory shear at a normal pressure of 80 kPa on the HVBF for different frequencies and vibration times per cycle. In addition, the residual moisture achieved after compaction by squeezing at 80 kPa without vibration input (0 Hz) is presented. Sampling is performed directly after compaction under the transfer plate of the vibration module. The value at 0 s represents the reference residual moisture after cake formation and passing the first three filtrate chambers. The standard deviations of the residual moisture are low, apart from a few exceptions, which indicates high data reproducibility. Evaporation effects can have a strong impact on the very small sample mass taken, depending on seasonally changing ambient conditions, and can lead to high standard deviations. Although the time from the end of the experiment to the gravimetric analysis is kept as short as possible, there may be some deviations between samples. After sampling, sometimes more cake residue adhere outside the sampler and must be carefully removed before gravimetric analysis. As a result, the time until gravimetric analysis can be prolonged and evaporation effects have a greater impact. In addition, some small cake residues can still adhere to the filter cloth after sampling. Therefore, the result may deviate slightly, since a residual moisture profile over the cake height has to be assumed.

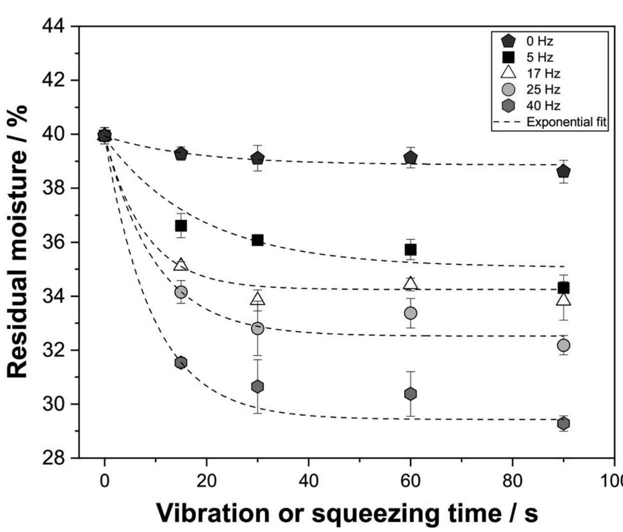

Figure 8. Residual moisture of the filter cake after cake formation and after compaction under oscillatory shear at a shear length of 4.5 mm and low normal pressure of 80 kPa on the HVBF. The dashed lines represents the exponential data modeling by using Eq. 5.

A clear reduction of the residual moisture compared to cake formation can be detected for all frequencies from only 15 s vibration compaction. With increasing vibration time, the residual moisture continues to decrease slightly until no significant change is observed anymore. A stationary compaction equilibrium is already reached after approximately 30 s. Furthermore, the compaction and deliquoring effect by vibration compaction increases with rising frequency. When the transfer plate squeezes the filter cake at the normal pressure of 80 kPa without oscillatory shear, residual moisture is only minimally reduced. Vibration compaction at the lowest frequency of 5 Hz investigated already results in higher deliquoring. This illustrates the additional effect of oscillatory shear on filter cake compaction and deliquoring.

Overall, the typical exponential compaction kinetics under oscillatory shear and low normal pressure is evident, which can be described using a simple exponential function as done by Illies et al.[26]:

$$RM(t) = RM_\infty + B \cdot e^{\frac{t}{\vartheta}} \tag{5}$$

Here, RM_∞ is the minimum achievable residual moisture in the stationary equilibrium state, t the vibration or squeezing time, B the consolidation potential, and ϑ another fitting parameter. In OriginPro 2019 b, the exponential equation is fitted to

Table 1. Fitting parameters from modeling the data in Figure 8 with Eq. 5 and the experimentally determined minimum residual moisture RM_{min}. The deviation of the determined minimum residual moisture RM_{∞} is given by the standard error of the fit.

Frequency / Hz	RM_{min} / %	RM_{∞} / %	B /	ϑ / s	R^2 /
0	38.6 ± 0.4	38.9 ± 0.2	1.1	17.5	0.7866
5	34.3 ± 0.5	35.1 ± 0.7	4.8	18.6	0.9213
17	33.8 ± 0.7	34.2 ± 0.2	5.7	7.9	0.9786
25	32.2 ± 0.4	32.5 ± 0.4	7.4	10.0	0.9807
40	29.3 ± 0.3	29.4 ± 0.3	10.5	9.4	0.9943

the data in Figure 8 for the four frequencies using the Levenberg-Marquardt algorithm. The fitting parameters, the corrected coefficients of determination, and the experimentally determined minimum residual moisture are listed in Table 1.

The high coefficients of determination and the similarity of the experimentally determined and calculated minimum achievable residual moistures in compaction equilibrium reflect the good approximation of the experimental data by the fitted Eq. 5. The compaction potential B describes the difference between the residual moisture after cake formation $RM(t = 0)$ and the minimum achievable residual moisture after vibration compaction RM_{∞}. While compaction by squeezing at 80 kPa only reduces the residual moisture by 1.1 percent points, vibration compaction at 5 Hz lowers residual moisture by 4.8 percent points. After vibration compaction at the highest frequency of 40 Hz, residual moisture is even reduced by 10.5 percent points. The input of oscillatory shear thus contributes enormously to deliquoring the investigated product on the HVBF, before post-deliquoring by a gas differential pressure follows in the next step.

However, the success of vibration compaction is material specific. Previous studies by Illies[28] showed differences in the compaction behavior of kaolin, ground calcium carbonate, and precipitated calcium carbonate under oscillatory shear. Particle properties of the filter cake, such as especially the particle size distribution as well as the particle shape, decisively determine the success of vibration input for cake compaction and deliquoring. For compaction by a normal pressure, Tiller et al.[31] already found correlations between particle properties and compactability. Decisive for the compactability of a filter cake is its initial state before mechanical expression. Smaller particles below 10–20 μm form more open filter cakes due to higher interparticle forces compared to gravitational forces. Then, smaller particles can be compacted more by mechanical expression. Also, an irregular particle shape provides a more porous cake structure compared to spherical particles. The investigated precipitated calcium carbonate product also exhibits an open structure after cake formation with a high residual moisture content of 39.9 ± 0.3% and porosity of 64.5 ± 0.7%, which can be attributed to the small average particle size of about 4.2 μm and the irregular particle shape. Vibration application induces a particle rearrangement, causing parts of the initial high void volume fraction to be filled more by particles. As a result, liquid is displaced from the void volume of the filter cake and a more compacted pore structure is achieved. With rising vibration time and frequency, particle rearrangement increases, resulting in higher compaction states.

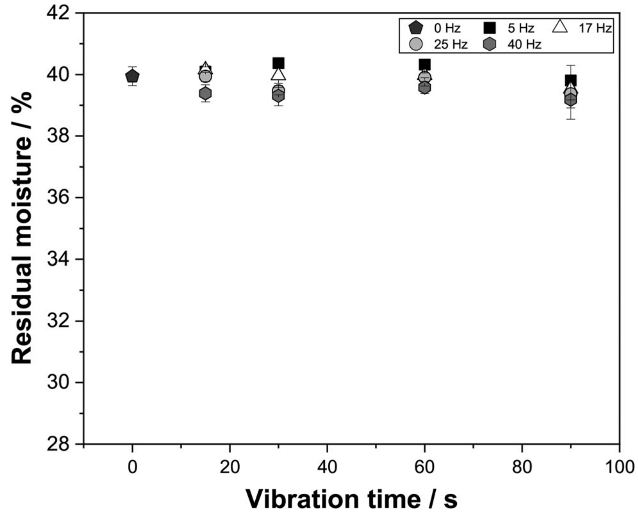

Figure 9. Residual moisture after cake formation with and without parallel compaction under oscillatory shear at a shear length of 4.5 mm and low normal pressure of 80 kPa.

To determine residual moisture after cake formation, which represents the reference residual moisture at 0 s in Figure 8, no vibration compaction is applied. Therefore, it must be checked whether vibration compaction on the fourth filtrate chamber already affects cake formation on the first three filtrate chambers. Figure 9 shows the residual moisture of filter cakes after cake formation during parallel vibration compaction at different vibration times and frequencies. The value at 0 s is the reference residual moisture after cake formation without the influence of vibration.

For all frequencies and vibration times, residual moisture hardly or only very slightly changes after cake formation due to the influence of oscillatory shear. Within the standard deviation of the values, no significant influence of vibration on cake formation can be observed. This implies that vibration decoupling of the vibration module from the HVBF is effective. Vibration compaction of the filter cake, hence, takes place in a defined manner in the front area of the fourth filtrate chamber directly below the vibration module.

3.2. Effect of the post-deliquoring step for different process operations of the horizontal vacuum belt filter

The influence of the final post-deliquoring step by a gas differential pressure across the filter cake must be considered for different process operations of the HVBF. We studied the influence of post-deliquoring directly after cake formation, after prior compaction for 90 s per cycle by squeezing at a normal pressure of 80 kPa, and by vibration input with a shear length of 4.5 mm and a normal pressure of 80 kPa. The cycle time and post-deliquoring time per cycle were constant for all process operations and amounted to 103 s and 95 s, respectively. Sampling took place after the filter cake had crossed the five vacuum chambers supplied with vacuum. The residual moistures of the filter cake for the different process operations are compared to the reference residual moisture after cake formation in Table 2.

The post-deliquoring step directly after cake formation reduces residual moisture slightly only in spite of a high cycle time of 103 s and a total post-deliquoring time of 475 s. Application of the gas differential pressure across the filter cake hardly contributes to the mechanical deliquoring of the filter cake. The reason is the small pressure difference between 55 and 45 kPa. It does not cause the capillary entry pressure to be exceeded and the filter cake to be significantly desaturated. The low pressure difference only induces a normal shrinkage of the filter cake, resulting in a displacement of just small amounts of liquid.

When the filter cake is compacted by squeezing at 80 kPa prior to post-deliquoring, an additional reduction of the residual moisture by about 1 percent point can be achieved. While squeezing the filter cake at 80 kPa results in a residual moisture of 38.6 ± 0.4%, subsequent post-deliquoring reduces the residual moisture to 38.0 ± 0.1%. The effect of post-deliquoring is about as low as without prior compaction by squeezing. Comparing the residual moistures of the filter cake after vibration compaction at the same cycle time without (see Table 1) and with subsequent post-deliquoring (see Table 2), just a slightly lower residual moisture with post-deliquoring is found. The reduction potential of post-deliquoring in this case is in the same range as directly after cake formation or after prior compaction by squeezing.

Hence, vibration compaction mainly contributes to mechanical deliquoring of the filter cake after cake formation. Due to the low pressure difference, the contribution of the final post-deliquoring step to mechanical dewatering of the filter cake is marginal.

Table 2. Residual moisture of the filter cake after cake formation and after post-deliquoring with und without previous compaction by squeezing at 80 kPa or by oscillatory shear at a shear length of 4.5 mm and normal pressure of 80 kPa for 90 s (cycle time 103 s).

	Residual moisture / %
Cake formation	39.9 ± 0.3
No compaction	39.0 ± 0.2
Squeezing at 80 kPa	38.0 ± 0.1
Vibration compaction at 5 Hz	34.1 ± 0.7
Vibration compaction at 17 Hz	33.0 ± 0.5
Vibration compaction at 25 Hz	31.5 ± 0.5
Vibration compaction at 40 Hz	28.6 ± 0.5

3.3. Comparison of vibration compaction on laboratory and pilot scale

In addition to the experimental studies on the HVBF, tests were carried out in the discontinuous laboratory apparatus under the same process conditions. The results from the laboratory apparatus can be found in Figure 10. Here, the residual moisture after vibration compaction at a normal pressure of 80 kPa and a shear length of 4.5 mm and after squeezing at 80 kPa is plotted against the vibration or squeezing time. The residual moisture at 0 s represents cake formation at a pressure difference of 50 kPa as reference condition.

In analogy to the results from the HVBF, residual moisture decreases exponentially after vibration compaction and after compaction by squeezing. The

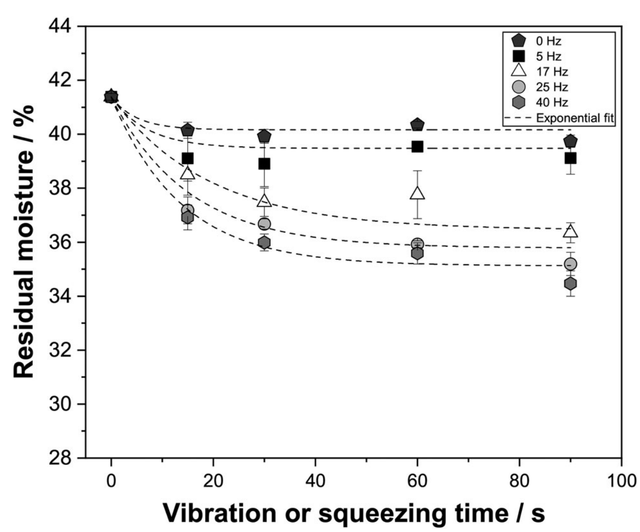

Figure 10. Residual moisture of the filter cake after cake formation and after compaction under oscillatory shear at a shear length of 4.5 mm and a normal pressure of 80 kPa in the laboratory apparatus. The dashed line represents exponential data modeling by using Eq. 5.

Table 3. Fitting parameters from modeling the data in Figure 10 with Eq. 5 and the experimentally determined minimum residual moisture RM_{min}. The deviation of the determined minimum residual moisture RM_∞ is given by the standard error of the fit.

Frequency / Hz	RM_{min} / %	RM_∞ / %	B /	ϑ / s	R^2 /
0	39.7 ± 0.2	40.2 ± 0.1	1.2	5.0	0.8674
5	38.9 ± 0.8	39.5 ± 0.1	1.9	7.1	0.9788
17	36.3 ± 0.4	36.5 ± 0.4	4.9	19.2	0.9845
25	35.2 ± 0.4	35.8 ± 0.2	5.6	15.1	0.9921
40	34.5 ± 0.5	35.1 ± 0.4	6.3	13.7	0.9877

residual moisture decreases with time until the equilibrium state. Increasing the frequency also reduces the residual moisture of the filter cake. Compacting under oscillatory shear at a superimposed normal pressure of 80 kPa results in a lower residual moisture than compaction by squeezing at 80 kPa. This also underlines the additional benefit of oscillatory shear for filter cake compaction and dewatering.

The reduction of residual moisture due to squeezing and vibration can also be modeled with the simple exponential Eq. 5. Table 3 lists the fitting parameters and the corrected coefficients of determination from the data fitting using Eq. 5 as well as the experimentally determined minimum residual moisture. The good agreement of the experimentally determined and calculated minimum residual moistures and the high coefficients of determination suggest that the data are approximated well by the exponential model.

A comparison of the results of the laboratory apparatus and the HVBF reveals significant differences. Already after cake formation, a slightly higher residual moisture is found in the laboratory apparatus than in the pilot apparatus. The reason for this is a higher pressure difference during cake formation in the pilot apparatus. While the pressure difference is kept constant at 50 kPa on the laboratory scale, the pressure difference on the pilot scale is higher than 50 kPa at the beginning of filtration before it drops to about 45 kPa. After squeezing the filter cake at 80 kPa on the HVBF, a significantly lower residual moisture of 38.9 ± 0.2% is reached compared to the laboratory apparatus. In the laboratory apparatus, residual moisture can be reduced slightly to a value of 40.2 ± 0.1% by squeezing. More effective squeezing on the pilot scale can be attributed to the higher normal pressure. On the HVBF, a pneumatic cylinder applies the normal pressure of 80 kPa mechanically. In contrast to this, normal pressure on the laboratory scale is generated by a vacuum pressure difference of 80 kPa across the filter cake, which presses the plate against the filter cake. The normal pressure on the filter cake surface is probably much lower, since the sponge rubber around the transfer plate does not completely seal the filter cake surface and air can enter the system.

Vibration compaction on the HVBF also is far more effective than in the laboratory apparatus. On the HVBF, the minimum achievable residual moisture (see Table 1) after vibration compaction is lower than in the laboratory apparatus (see Table 3) for all frequencies. On the HVBF, a residual moisture of 35.1 ± 0.7% is reached after vibration compaction at 5 Hz. On the laboratory scale, such a residual moisture is achieved at the highest frequency of 40 Hz only. At 40 Hz, the residual moisture of the filter cake on the pilot scale is even 5.7 percent points lower than on the laboratory scale. Generation and transmission of oscillatory shear are almost identical in both apparatuses and the tests were carried out with the same parameter settings. It can be assumed that the higher compaction and deliquoring effect on the HVBF comes from the higher superimposed normal pressure. Using the laboratory apparatus with a similar product, Illies[27] already found that a higher superimposed normal pressure of 80 kPa compared to 20 kPa in the lower to medium frequency range results in a higher compaction effect. At 40 Hz, however, the higher normal pressure at 80 kPa did not result in a higher compaction effect similar to that obtained in this study. Illies[28] assumed that the influence of normal pressure on the compaction behavior is dominated by two opposing phenomena. On the one hand, a higher normal pressure increases the interparticle adhesion forces, which affect the compaction effect, as was outlined by Tomas[32] and Youd.[33] On the other hand, a higher pressure gradient causes an improved displacement of the pore fluid according to Darcy's law, which encourages compaction. However, the results indicate a much more beneficial effect of the superimposed normal pressure. Along with the improved drainage of pore fluid during compaction, particle rearrangement is enhanced by a higher normal pressure. While the oscillatory shear mainly causes a rearrangement of particles perpendicular to the filtration direction, the higher normal pressure may stimulate particle rearrangement in the filtration direction.

3.4. Comparison of continuous vibration compaction on the horizontal vacuum belt filter and compaction by squeezing in the CP cell

For many solid-liquid separation processes, either a HVBF or a filter press can be used, which is why the two devices are often in competition with each other.

The CP cell is suited for investigating the filter cake compaction that takes place in a filter press on a laboratory scale. As squeezing of the filter cake represents the conventional compaction method, it is the benchmark for the alternative compaction method under oscillatory shear. Additional experiments were conducted in the CP cell to compare the deliquoring and compaction results achieved by continuous vibration compaction on the HVBF and by squeezing as in the filter press. Figure 11 shows the minimum achievable residual moistures after vibration compaction and compaction by squeezing at 80 kPa on the HVBF, as obtained from data modeling using Eq. 5. The minimum achievable residual moisture after compaction in the CP cell at different normal pressures can also be seen in Figure 11. Small standard deviations are also noted for the residual moisture determined after compaction by squeezing in the CP cell. The deviations result from cake residues remaining on the membrane, filter cloth, and cake forming unit after the removal of the compacted filter cake for gravimetric determination of the solid mass m_s (see Eq. 3).

What stands out first is that a lower residual moisture can be achieved in the CP cell at a normal pressure of 72 kPa compared to a slightly higher normal pressure of 80 kPa on the HVBF. The values in the CP cell represent the residual moisture of the cake under the pressure load produced by the piston, while the samples on the HVBF were taken after the pressure load. Therefore, the difference can be explained

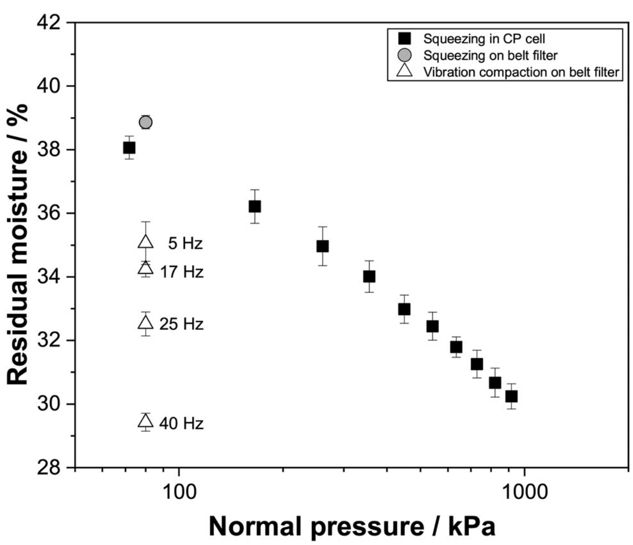

Figure 11. Minimum achievable residual moisture of the filter cake after compaction at different normal pressures in the CP cell, after compaction at a normal pressure of 80 kPa, and after vibration compaction at a normal pressure of 80 kPa and a shear length of 4.5 mm on the HVBF. The achievable residual moisture on the HVBF results from data modeling using Eq. 5.

by elastic expansion of the compressible filter cake after the removal of the pressure load on the HVBF. As a result, the filter cake pulls residual fluid out of the filter cloth or filtrate chamber after the transfer plate has been lifted.

Vibration compaction on the HVBF at a frequency of 5 Hz and a normal pressure of 80 kPa results in a residual moisture of 35.1 ± 0.7%, which is achieved by squeezing at a normal pressure of about 200 kPa. Vibration compaction at 25 Hz and a normal pressure of 80 kPa reduces the residual moisture of the filter cake to a value of 32.5 ± 0.4%, while compaction by squeezing requires a normal pressure of about 500 kPa to obtain the same result. At a frequency of 40 Hz, residual moisture is even lower than that of squeezing at the maximum normal pressure of 917 kPa in the CP cell. Vibration compaction on the HVBF at a lower normal pressure of 80 kPa results in the same or even higher deliquoring or compaction degrees than squeezing in the normal pressure range of 72 to 917 kPa. Especially for mechanically more sensitive materials, the significantly smaller normal pressure of 80 kPa in vibration compaction is advantageous compared to compaction by squeezing as in filter presses. Moreover, HVBFs have the advantage of continuous operation compared to filter presses. It may be doubted whether such high normal pressures as in the CP cell are feasible for filter cake compaction and dewatering on an existing HVBF. Existing HVBFs might not be designed to handle the high pressure load. Moreover, it must be considered whether the deliquoring and compaction states determined in the CP-cell can be transferred to the HVBF at all, since elastic recovery effects of the compressible filter cake may occur after the squeezing module is lifted.

4. Conclusions

The findings reported here prove that compaction of compressible filter cakes under oscillatory shear at a low normal pressure is applicable to an existing indexing HVBF using a modular device. The developed modular device reduces the initial residual moisture of 39.9% after cake formation by a maximum of 10.5 percent points for the industrially relevant material investigated. When vacuum on the HVBF is insufficient for a major desaturation of the material, vibration input mainly contributes to mechanical deliquoring after cake formation. Transfer of the process to a continuous filtration system is difficult, as the time available for vibration compaction is limited. However, the vibration module has a significant compaction and deliquoring effect already after a short process time. This confirms the suitability of this technique for indexing HVBFs. Compared to conventional compaction by squeezing, vibration compaction on the HVBF leads to the same or even lower residual moisture at a much lower normal pressure. Especially for compressible materials that have been dewatered mechanically in discontinuous filter presses so far, vibration compaction on a continuous HVBF can remove the same amount or even more liquid from the filter cake. Further tests with other materials are needed to better assess the applicability of the process. This would also provide correlations between material properties and compaction behavior under oscillatory shear to improve the knowledge of the compaction mechanism.

By comparing the results of the laboratory apparatus and the HVBF, it was found that significantly higher deliquoring degrees are achieved by vibration compaction on the HVBF. The laboratory apparatus is useful for checking basic compactibility of a product under oscillatory shear. However, it does not allow for an exact prediction of the compaction rate that can be achieved in the HVBF. The reason for the discrepancy is the normal pressure that is applied mechanically to the HVBF. The higher normal pressure has a positive effect on the compaction of the filter cake. Further studies are needed to obtain a more detailed knowledge of the compaction mechanism and in particular the influence of normal pressure during vibration compaction. In this context, normal pressure in the laboratory apparatus should be applied mechanically in analogy to the HVBF to improve the transferability of laboratory results for the process design.

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Disclosure statement

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