Filter cake compaction by oscillatory shear

Sarah Illies, Harald Anlauf, Hermann Nirschl

Institute of Mechanical Process Engineering and Mechanics, Karlsruhe Institute of Technology, Karlsruhe, Germany

Straße am Forum 8, 76131 Karlsruhe, Germany.

ABSTRACT

We investigate the influence of oscillatory shear on the compaction of filter cakes for different model materials. The model systems investigated vary in particle size and shape and therefore show different compaction characteristics. Parameters varied are frequency and number of cycles as well as normal pressure. The effect of oscillatory shear is compared to the compaction obtained by applying solely mechanical pressure. Results show that by applying oscillatory shear, a significant reduction of compaction pressure needed to obtain a certain degree of compaction can be obtained. However the advantage over conventional pressing is different for each particle system. We further evaluate the effect of compaction on the degree of cracking that occurs during filter cake desaturation. The compaction achieved by oscillatory shear leads to a significant reduction in filter cake cracking.

KEYWORDS

Cake Filtration, Compressibility, Compressible Filter Cakes, Consolidation, Dewatering, Shear, Shear Enhanced Filtration

INTRODUCTION

Filter cake compaction under a force in normal direction has been studied intensely experimentally and theoretically in the past decades [e.g. 1-3]. There are reasons to assume that the addition of a second compaction mechanism has the potential to further reduce cake porosity, due to the anisotropic structure that results from the way how a filter cake is formed [4,5]. We propose to superimpose compaction pressure with a shearing motion in order to reach higher degrees of compaction at a given pressure. Shear can be applied in a steady or in an oscillatory way. For steady shear, the effect of improved compaction is mainly known from belt filter presses [6-9] and from the investigation of expression and flow behavior of fine saturated particle systems [10-12]. To our knowledge there are currently no investigations on application of oscillatory shear for filter cake compaction, only for vibration in vertical direction [15,16]. However examples can be found in particle technology [17] and soil mechanics [18]. The systems under investigation are usually in a dry state though and the particle size range considered is much larger than the one to be expected in compressible filter cakes. So far little attempt has been made to directly link the effect of added shear to a distinct experimental parameter. One parameter that has been considered is the applied shear rate [4,13,14], however results are contradictory.

In this paper we investigate the influence of oscillatory shear on the compaction of filter cakes. We present the experimental setup used for applying oscillatory shear and first results for three model systems. Shear frequency, number of cycles and superimposed normal pressure were varied. Results are compared to compaction behavior in a compression-permeability cell. At last, the influence of compaction on filter cake cracking during desaturation is investigated.

MATERIALS AND METHODS

Sample preparation and characterization

Three different model systems were used, precipitated calcium carbonate (PCC), ground calcium carbonate (GCC) and kaolin. While kaolin typically shows a plate-like particle shape, GCC and PCC particles are of irregular shape. Particle system characteristics and the volume concentrations used are summarized in Table 1. Suspensions were prepared with deionized water. The compaction behavior of each particle system was measured in a step-pressure experiment in a compression-permeability cell (CP cell) with a filter area A of 51.5 cm². The compaction behavior was investigated within a pressure range from 50 to 1000 kPa. Filter cake resistance was determined by flowing the filter cake with deionized water at a pressure difference of 20 kPa after consolidation at each pressure step was completed. From cake height h_c, filter area A, solid density ρ_s and dry mass m_s, porosity ε was calculated (equation (1)). For a saturated filter cake, residual moisture RM can then be obtained from porosity ε, solid density ρ_s and the density of the pore liquid ρ_l (equation (2)). Filter cake resistance was calculated from cake height h_c, pressure difference Δp, flux q, dynamic viscosity η and filter medium resistance R_m according to equation (3).

$$\epsilon = 1 - \frac{m_s}{\rho_s A h_c} \quad (1)$$

$$RM = \frac{\epsilon \rho_l}{\epsilon \rho_l + (1-\epsilon)\rho_s} \cdot 100\% \quad (2)$$

$$r_c = \frac{1}{h_c}\left(\frac{\Delta p}{q\eta} - R_m\right) \quad (3)$$

Experimental setup

The filter cake was formed in a vacuum filtration unit with a filter area A of (6x12) cm=72 cm² (Figure 1) at 80 kPa vacuum. A monofilament nylon filter medium (SEFAR NITEX 03-5/1) supported by a stainless steel sintered material (Siperm R200, Tridelta Siperm GmbH, Dortmund, Germany) was used. Oscillatory shear was generated by an electric motor coupled to a frequency converter. The rotational motion is converted to a horizontal shearing motion by means of a modified crank-slider mechanism (Figure 2). The maximum piston displacement in one direction over one cycle is equivalent to the maximum shear length l_s and can be calculated from crank radius e and the distances s_1 and s_2 of the lever according to equation (4):

$$l_s = 2e \cdot \frac{s_2}{s_1} \quad (4)$$

Table 1: Particle system and suspension characteristics

Particle system	density (kg/m³)	mean particle size (µm)	span (-)	suspension concentration (v/v %)
PCC	2610	5.2	1.4	20
GCC	2700	5.4	3.1	20
Kaolin	2600	8.1	3.0	10

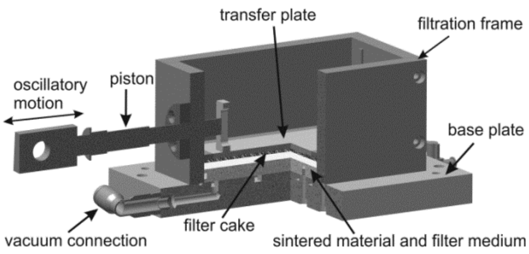


Figure 1: Vacuum filtration unit used for oscillatory shear experiment

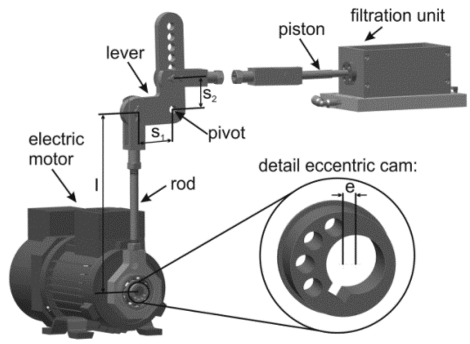


Figure 2: Experimental setup for generation of oscillatory shear

The piston displacement l_s can be varied in discrete steps by changing the distance s_2. To transfer oscillatory shear to the filter cake a stainless steel plate (further referred to as transfer plate) was placed onto the filter cake and connected to the piston. In order to achieve a well-defined contact of transfer plate and cake surface, a spring was pressed onto the plate by a pneumatic cylinder (not shown in Figure 1 and Figure 2). The pressure onto the filter cake due to the spring force and the mass of the transfer plate is in the range of 2-3 kPa and can thus be neglected. Normal pressure of 20 and 80 kPa is applied during oscillatory shear by a vacuum pump (UNO6, Pfeiffer Vacuum GmbH, Asslar, Germany).

For desaturation of the filter cake after compaction by oscillatory shear, a pressure vessel was used.

Experimental procedure

In a typical experiment the filter cake was formed under a vacuum of 80 kPa. The filtration was interrupted as soon as about half the cake surface was visibly dry. The transfer plate was placed onto the filter cake and connected to the piston. Then the spring was brought down onto the transfer plate, vacuum was applied and the electric motor was started to apply oscillatory shear. The duration of oscillatory shear was varied from 30 to 600 seconds, depending on oscillation frequency. Following the compaction step, the transfer plate was removed and the filter cake was either removed from the filtration unit and analyzed directly or built into the pressure vessel and subjected to gas pressure to investigate the cracking behavior. After desaturation crack area was documented with a camera (Canon PowerShot SX260HS) and measured by image analysis ImageJ 1.47b. The filter cake was then dried at a temperature of 105±5 °C for 24 hours to determine solid dry mass.

RESULTS AND DISCUSSION

Sample characterization

Figure 3 shows how filter cake resistance varies with increasing solidosity of the filter cake. For this comparison the sample materials were compacted in a CP cell as described in the previous section. Kaolin shows the highest variation in resistance within the normal pressure range investigated whereas GCC shows the lowest variation. The dimension of resistance is similar for GCC and PCC.

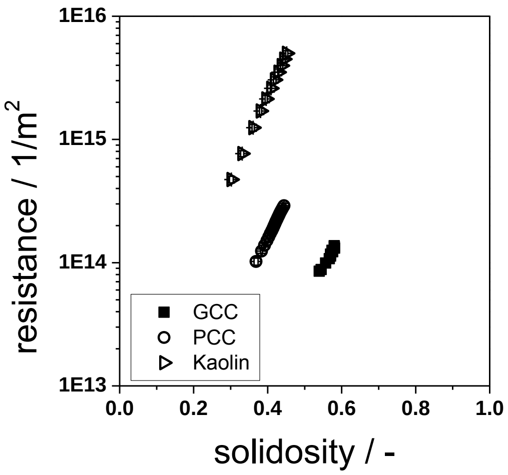


Figure 3: Variation in height-specific resistance with solidosity for the three model materials ground calcium carbonate (GCC), precipitated calcium carbonate (PCC) and kaolin.

Compaction behavior under oscillatory shear

In general it can be observed that for all three samples, compaction by applying oscillatory shear was successful. The compaction kinetics however differ drastically with the compaction of GCC being the fastest and kaolin the slowest. For GCC, residual moisture reaches a steady state value already within 30 seconds, which is the shortest time that could be technically realized, due to the starting behavior of the apparatus. Evaluation of the compaction kinetics was thus not possible in this case. For PCC and kaolin, the compaction follows an exponential decay law. The steady state value of residual moisture for each parameter set can thus be evaluated by data fitting. The steady state value of residual moisture is subsequently referred to as RM_f.

The compaction of filter cakes by oscillatory shear is a complex process with the individual parameters being interdependent. The influence of oscillation frequency and normal pressure on the compaction behavior highly varies between the particle systems investigated. For PCC, the reduction of residual moisture with rising number of cycles at 20 kPa normal pressure for various frequencies is shown in Figure 4. Residual moisture decreases and approaches a steady state value with exception of the data at 17 s^{-1}. In this case, RM_f could still be obtained from the data fit, as described previously. A rather large gap in residual moisture between the low frequencies (5 and 10 s^{-1}) and the higher frequencies (25 and 40 s^{-1}) can be observed, indicating that there is a threshold that determines the limit of compaction. For compaction under vertical excitation of the sample similar observations have been reported by Barkan in terms of a threshold acceleration necessary for compaction [19]. At oscillation frequencies of 5, 17 and 40 s^{-1} the experiments have been repeated at 80 kPa superimposed pressure difference. Here the situation is different: For both 5 and 17 s^{-1} oscillation frequency, the steady state value of residual moisture RM_∞ is considerably lower than for 20 kPa. The development of all curves is similar, indicating that the compaction in this case depends almost entirely on the number of cycles. Pressure difference influences different aspects of the compaction process: On the one hand, with increasing normal pressure the contact forces will also increase [20,21] On the other hand, pore fluid removal is controlled by Darcy's law. With higher pressure, the pore fluid can be removed more quickly. A more detailed discussion of the compaction characteristics of PCC under oscillatory shear can be found elsewhere [22].

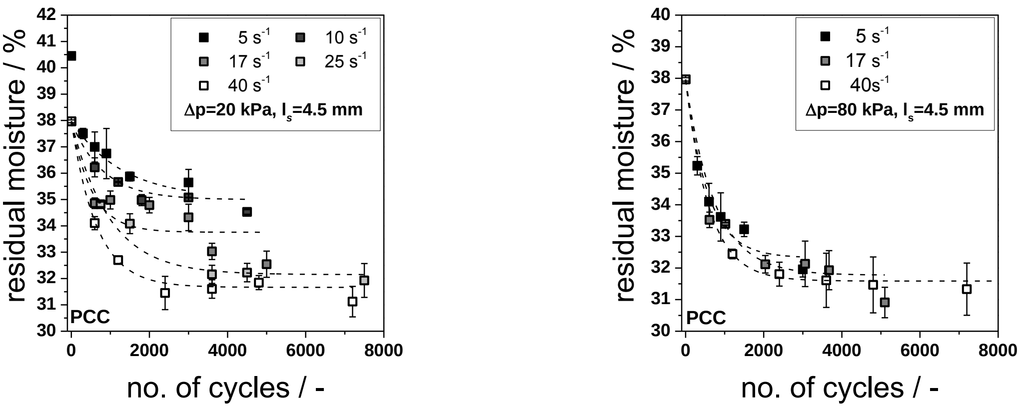
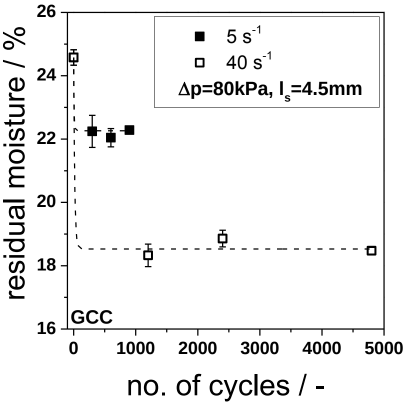


Figure 4: Reduction of residual moisture of PCC filter cake with number of cycles for varied frequencies at normal pressure of 20 kPa (left) and 80 kPa (right). The data point at zero number of cycles denotes residual moisture obtained after filter cake formation at 80 kPa without further dewatering of the sample.

GCC and kaolin in contrast still show a frequency dependence of RM_f at 80 kPa normal pressure. For GCC (Figure 5, left), a pronounced gap between the compaction result at 5 s^{-1} and 40 s^{-1} oscillation frequency can be observed. For Kaolin, compaction at 5 s^{-1} and 17 s^{-1} oscillation frequency yield the same result. However by increasing the frequency to 40 s^{-1}, further reduction in RM_f can be obtained.



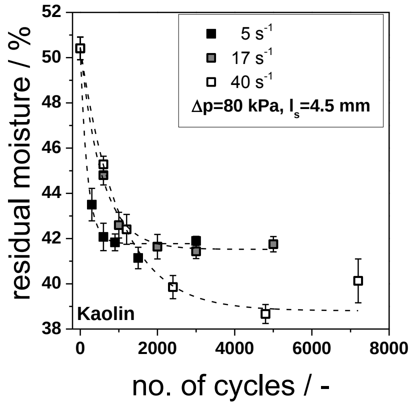


Figure 5: Reduction of residual moisture with number of cycles for different oscillation frequencies and 80 kPa normal pressure for GCC (left) and kaolin (right) filter cakes. The data point at zero number of cycles denotes residual moisture obtained after filter cake formation at 80 kPa without further dewatering of the sample

Comparison of compaction in oscillatory shear and in CP cell setup

To evaluate the effectiveness of oscillatory shear for compaction, the data is compared to compaction in a CP cell. The values of steady state residual moisture RM_f for CP cell and oscillatory shear experiments are shown in Figure 6 as a function of normal pressure. In general it can be said that by adding oscillatory shear, similar values of residual moisture as in CP cell experiments are attainable. For PCC, the value of RM_f at 20 kPa normal pressure, 5 s^{-1} oscillation frequency and 4.5 mm displacement is equivalent to compaction at a normal pressure of approximately 400 kPa in a piston pressure device. This corresponds to a twentyfold reduction in normal pressure needed to achieve the same degree of compaction. For this material, to achieve the same value of RM_f in CP cell experiments, the normal pressure required ranges from a twelvefold (80 kPa normal pressure, 5 s^{-1}, l_s=4.5 mm) up to a fiftyfold (20 kPa normal pressure, 25 s^{-1}, l_s=4.5 mm). Similar observations can be made for GCC whereas for kaolin, compaction at normal pressure higher than 300 kPa leads to values of residual moisture that could not be obtained by oscillatory shear. However in the pressure range below 300 kPa, the application of oscillatory shear still yields lower values of residual moisture. The difference in compaction behavior of kaolin might be due to the card-house structure that plate-like particles tend to form. One can imagine that this kind of structure is at first easily disturbed by introducing a shear force. However, once a majority of the particles has been rearranged and is stacked in layers, significantly higher normal forces might be necessary to further compact the filter cake.

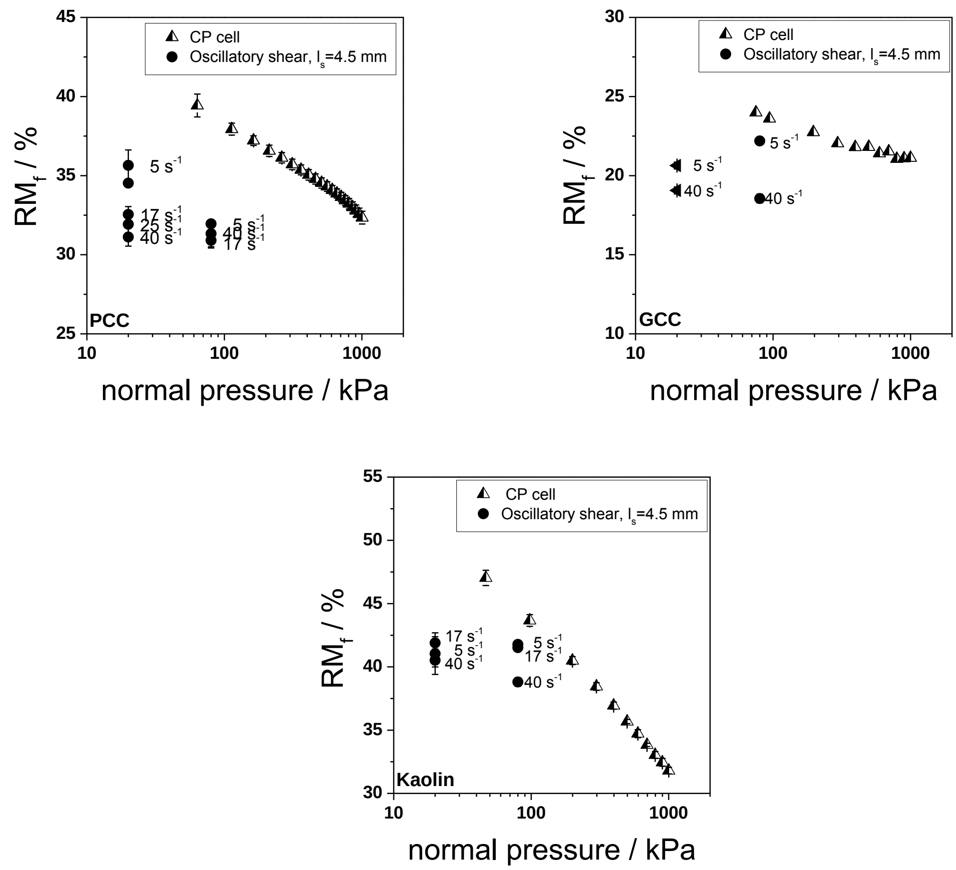


Figure 6: Comparison of residual moisture obtained by oscillatory shear and in a CP cell for PCC (top left), GCC (top right) and kaolin (bottom). Data labels denote oscillation frequency.

Influence of oscillatory shear on filter cake cracking

PCC filter cakes show pronounced cracking during desaturation without precedent compaction of the filter cake [23]. Filter cake compaction by oscillatory shear highly reduced the degree of cracking that occurred after filter cake desaturation at a pressure difference of 340 kPa. In Figure 7 the degree of cracking obtained after compaction at 5, 17 and 40 s^{-1} oscillation frequency is shown for 20 and 80 kPa normal pressure. Already at low frequency and low normal pressure, a significant reduction of crack ratio can be achieved. Within the experimental error, no influence of normal pressure on crack ratio reduction was found.

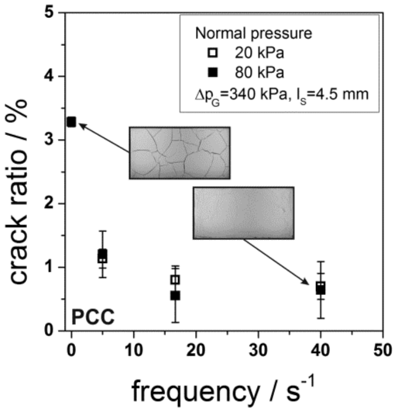


Figure 7: Change of crack ratio with frequency after desaturation at gas pressure Δp_G=340 kPa. The reference point at zero frequency is the crack ratio after filter cake formation at 80 kPa and desaturation at 340 kPa.

CONCLUSION

Applying oscillatory shear to a saturated filter cake was found to be a promising method for filter cake compaction. In general compaction is improved with increasing oscillation frequency and there is also an ultimate limit of compaction. Compaction kinetic follows an exponential decay law. At constant normal pressure, oscillatory shear leads to lower values of residual moisture compared to compaction in a piston pressure device. However for kaolin filter cakes, compaction by piston pressure ultimately lead to lower values of residual moisture, which might be due to the structure formed by kaolin particles. For PCC compaction by oscillatory shear also lead to a significant reduction in filter cake cracking.

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