The interparticle adhesion forces of very fine powders which can enormously exceed their weight and cause disturbances in powder flow. This powder flow can be stopped by channelling or bridging during discharging from a silo or bunker hopper. Thus, continuous dosing with a constant powder density and flow rate is not possible. As a solution of this problem, the powder flow can be improved considerably by applying mechanical vibrations as flow promotion. The tests are carried out with sinusoidal oscillations this type of mechanical vibration is created by an unbalanced motor of a vibration hopper. To characterise these sinusoidal oscillations, the maximum vibration velocity and vibration frequency are used.

The flow characteristics like effective angle of internal friction, major principal stress and uniaxial compressive strength are determined versus the intensity of mechanical vibration. A vibrating shear tester has been used to determine the flow properties. The goal was to check the hopper dimension obtained by vibrating shear tester at two full-scale silos equipped by a vibrating hopper (“bin activator”).

Preliminary shear tests with different cohesive powders have been carried out. An ultrafine limestone powder called Calcite MX10 (mean diameter \( d_{50} = 1.7 \mu m \)) has been chosen to achieve - in this case desired - flow disturbances like bridging and channelling during silo hopper discharge only driven by gravity. The limestone powder is provided by the company sh minerals GmbH in Heidenheim, Germany. In a first step the influence of mechanical vibrations on the flowability is determined in laboratory scale. To quantify the vibrational powder flowability, a vibrating shear tester is used. During the powder flow mechanical vibrations are applied directly into the shear zone, but perpendicular to the main shear direction. Here, the shear displacement (amplitude of vibrations) is comparatively small ± 70 µm. Thus, the yield limits of this lateral shear stresses are not reached. However, the powder within the shear zone is activated by these oscillations; that leads to reduced shear strength and the flow behaviour is gradually improved [1].

The vibrating shear tester was designed according to Roberts [2, 3]. But, the shear deformation is forced by pulling instead of pushing to avoid bending of the shear lid. The ground plate is excited by sinusoidal oscillations. On both shear base and shear ring an acceleration sensor is mounted. Accelerations are measured by sensors for the input signal and the response at the shear ring. The measurements are accomplished in a stress range from 0.5 kPa to 16 kPa with a constant shear rate of 2 mm/min. From the attenuation or amplification between exciting and resulting signals the powder properties like elasticity, viscous damping, and COULOMB-damping have been determined [4].

To prove the results from the lab shear tests, experiments on the full-scale silos are carried out. Therefore the testing facilities of the companies Coperion Waeschle GmbH & Co KG in Niederbiegen and Zeppelin Silo- und Apparatetechnik GmbH in Friedrichshafen, Germany are used.

Those test facilities have test silos with volumes of 3.3 m³ and 30.0 m³. Whereby, the silo diameters are 1050 mm and 2400 mm, respectively.
The discharge of the selected ultrafine cohesive limestone powder from two different silos is investigated. During the experiments the frequency and amplitude of oscillations, and the annular gap width are varied. Additionally, different operation times of the vibrating hopper are investigated. The vibrating hoppers are provided by the companies WAM GmbH in Altlußheim and Schäffer Verfahrenstechnik GmbH & Co. KG in Thierhaupten, Germany. The vibrating hopper is mounted to the silo taking a hopper interface. To connect the vibrating hoppers to the interface hoppers diameters of 600 mm and 1300 mm are necessary, respectively. By the vibrating hopper sinusoidal oscillations are applied on the powder within the silo. The vibrating hopper is driven by an unbalanced motor. By adjusting the unbalanced mass the amplitude and frequency of oscillations can be changed.

To determine the mass flow rate the silo is bedded on load cells and the total weight of the silo is continuously measured. The oscillation acceleration is continuously measured, too. Four accelerations sensors are mounted on the silo test rigs. In case of test rig “A”, there are two sensors on the vibrating hopper, one sensor on the hopper interface and one sensor inside the silo within the powder. But unfortunately, the support breaks during a discharge test and the internal sensor was destroyed and discharged with flowing powder. The powder is discharged from the silo hopper into a flexible intermediate bulk container (FIBC) – so-called big bag. Additionally, at test rig “B” two sensors are mounted on the vibrating hopper and two sensors on the hopper interface. However here, the powder is filled into a second silo by pneumatic conveying and not into big bags. Powder volumes of 2.5 m³ and 25 m³ are handled during the tests.

The powder flow characteristics like major principal stress, uniaxial compressive strength, and effective angle of internal friction are determined by the vibrating shear tester. According to the powder flow characteristics the critical hopper dimensions are calculated using Jenike’s design method [5]. The outlet dimensions of the selected vibrating hoppers were 323 mm on the outlet and 325 mm on the annular gap. But according to above shear test results discharge width of 903 mm (conical outlet) and 452 mm (annular gap) are necessary to avoid bridging at gravitational discharge without applying vibrations. Thus, bridging happens in the silos that have been confirmed by the full-scale tests. With increasing vibration velocity the minimum outlet width to avoid bridging decreases and the maximum hopper angle to obtain mass flow increases [1]. The silo discharge is enabled.

There are two bottlenecks for powder flow within vibrating hoppers, the annular gap inside the hopper and the outlet width. The vibrating hopper can be overwhelmed with powder if the mass flow rate of the annular gap is bigger than the flow rate through the outlet. If the complete volume of the vibrating hopper below the annular gap is filled, an undesired consolidation of the powder occurs by the applied vibrations. To prevent this undesired consolidation and compression, vibrating hoppers have to be operated with idle periods.

A model suggested by Tomas [7] is used to calculate the steady-state discharge velocities. Within the model the minimum outlet width considers the powder flowability tested by the shear cell. The hopper dimensions are included by the hopper angle and the outlet width. During the discharge the powder is expanding (dilatancy) and generates a depression within the pores and flow channels of shear zones. Air is permeating in theses pores or channels and the discharge of fine powders is hindered by the air counter-flow through the pores of the moving bed. This resistance of powder discharge is determined by the fluid drag (pressure drop) of the moving bed expressed by the Euler number. This Euler number
characterises inversely the permeability of the powder and increases strongly with decreasing particle or pore size, respectively.

The steady-state velocity of the powder within the annular gap is calculated taking the measured mass flow rates and the dimensions of the vibrating hopper. A constant bulk density is assumed at the annular gap.

There are two steady-state discharge velocities for the annular gap and the outlet; these are the maximum velocities and also maximum mass flow rates. The velocity within the gap depends on the gap width; the velocity at the outlet is independent from the gap width. If this maximum velocity at the outlet is reached, a bigger annular gap does not lead to larger mass flow rate. However, the velocity within the annular gap is limited by the geometrical condition at the outlet.

At first the discharge velocity within the annular gap increases to a maximum and then the velocity decreases, because the maximum velocity at the outlet is reached, the volume below the annular gap is filled and the powder flow is slowed down in the gap. For this reason the annular gap governs the powder flow in region I; afterwards the maximum velocity on the conical outlet dominates the powder discharge.

To calculate the time to fill the hopper volume below annular gap, a mass balance for this store volume is considered. Up to the maximum operation time, undesired consolidation does not occur and the bulk density is assumed to be constant as already mentioned. For longer operation times the powders is consolidated within the store volume and the bulk density is increasing.

Additionally, the necessary time to empty this volume can be calculated - idle time or period without excitation of vibrations. Therefore it is assumed, that powder flow through the annular gap is immediately stopped after switch-off the vibrations.

The maximum degree of filling is given by the total volume of the vibrating hopper by means of a completely filled volume. For safe operation without undesired consolidation the filled volume of the vibrating hopper should not exceed 80%.

At the full-scale tests, the operation time intervals have been found to be between 20 s to 30 s and the idle periods between 40 s to 80 s. These model calculations results in 30 s for operation and 60 s for idle of vibrating hopper. That results in a sufficient agreement.

Never the less, the fit between calculated and real mass flow rates should be improved to avoid too large differences between model calculation and the problematic discharge and dosing behaviour of cohesive ultrafine powders in hoppers.

To summary the investigations: Due to the mechanical vibrations, ultrafine cohesive powder discharge is enabled and influenced by the maxi-mum vibration velocity. The discharge rate can be controlled by pulsed operation of the vibrating hopper. In contrast, continuous operation of the vibration hopper leads to a decrease of discharge velocity and rate. It is possible to predict necessary operating and idle periods (pulsed operation) by calculation of the discharge velocities at the annular gap of a vibrating hopper and at the outlet.

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