



Standard Shear Test Method for Bulk Solids Using the Schulze Ring Shear Tester¹

This standard is issued under the fixed designation D 6773; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This method covers the apparatus and procedures for measuring the unconfined yield strength of bulk solids during both continuous flow and after storage at rest. In addition, measurements of internal friction, bulk density, and wall friction on various wall surfaces are included. The SI system of units has been used throughout.

1.2 The most common use of this information is in the design of storage bins and hoppers to prevent flow stoppages due to arching and ratholing, including the slope and smoothness of hopper walls to provide mass flow. Parameters for structural design of such equipment may also be derived from this data. Another application is the measurement of the flowability of bulk solids, for example, for comparison of different products or optimization.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 ASTM Standards:

- D 653 Terminology Relating to Soil, Rock, and Contained Fluids²
- D 6128 Standard Shear Testing Method for Bulk Solids Using the Jenike Shear Cell³

3. Terminology

3.1 Definitions of terms used in this test method are in accordance with Terminology D 653.

3.2 *adhesion test, n*—a static wall friction test with time consolidation.

3.3 *angle of internal friction, ϕ_i, n* —the angle between the axis of normal stress (abscissa) and the tangent to the yield locus.

3.4 *angle of wall friction, ϕ', n* —the arctan of the ratio of

the wall shear stress to the wall normal stress.

3.5 *bin, n*—a container or vessel for holding a bulk solid, frequently consisting of a vertical cylinder with a converging hopper. Sometimes referred to as silo, bunker or elevator.

3.6 *bulk density, ρ_b, n* —the mass of a quantity of a bulk solid divided by its total volume.

3.7 *bulk solid, n*—an assembly of solid particles handled in sufficient quantities that its characteristics can be described by the properties of the mass of particles rather than the characteristics of each individual particle. It may also be referred to as a granular material, particulate solid, or powder. Examples are sugar, flour, and ore.

3.8 *bunker, n*—synonym for *bin*, but sometimes understood as being a bin without any or only a small vertical part at the top of the hopper.

3.9 *consolidation, n*—the process of increasing the unconfined yield strength of a bulk solid.

3.10 *critical state, n*—a state of stress in which the bulk density of a bulk solid and the shear stress in the shear zone remain constant during shear under constant normal stress.

3.11 *effective angle of friction, δ, n* —the inclination of the effective yield locus (EYL).

3.12 *effective yield locus (EYL), n*—straight line passing through the origin of the σ, τ -plane and tangential to the steady state Mohr circle, corresponding to steady state flow conditions of a bulk solid of given bulk density.

3.13 *elevator, n*—synonym for *bin*. Commonly used in the grain industry.

3.14 *failure (of a bulk solid), n*—plastic deformation of an overconsolidated bulk solid subject to shear, causing dilation and a decrease in strength.

3.15 *flow, steady state, n*—continuous plastic deformation of a bulk solid at critical state.

3.16 *flow function, FF, n*—the plot of unconfined yield strength versus major consolidation stress for one specific bulk solid.

3.17 *granular material, n*—synonym for *bulk solid*.

3.18 *hopper, n*—the converging portion of a bin.

3.19 *major consolidation stress, σ_1, n* —the major principal stress given by the Mohr stress circle of steady state flow. This Mohr stress circle is tangential to the effective yield locus.

3.20 *Mohr stress circle, n*—the graphical representation of a

¹ This test method is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.24 on Characterization and Handling of Powders and Bulk Solids.

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² *Annual Book of ASTM Standards*, Vol 04.08.

³ *Annual Book of ASTM Standards*, Vol 04.09.

state of stress in coordinates of normal and shear stress, that is, in the σ , τ -plane.

3.21 *normal stress*, σ , n —the stress acting normally to the considered plane.

3.22 *particulate solid*, n —synonym for *bulk solid*.

3.23 *powder*, n —synonym for *bulk solid*, particularly when the particles of the bulk solid are fine.

3.24 *silo*, n —synonym for *bin*.

3.25 *shear test*, n —an experiment to determine the flow properties of a bulk solid by applying different states of stress and strain to it.

3.26 *shear tester*, n —an apparatus for performing shear tests.

3.27 *time angle of internal friction*, ϕ_t , n —inclination of the time yield locus of the tangency point with the Mohr stress circle passing through the origin.

3.28 *time yield locus*, n —the yield locus of a bulk solid which has remained at rest for a certain time under a given normal stress for a certain time.

3.29 *unconfined yield strength*, f_c , n —the major principal stress of the Mohr stress circle being tangential to the yield locus with the minor principal stress being zero.

3.30 *wall normal stress*, σ_w , n —the normal stress present at a confining wall.

3.31 *wall shear stress*, τ_w , n —the shear stress present at a confining wall.

3.32 *wall yield locus*, n —a plot of the wall shear stress versus wall normal stress. The angle of wall friction is obtained from the wall yield locus as the arctan of the ratio of the wall shear stress to wall normal stress.

3.33 *yield locus*, n —plot of shear stress versus normal stress at failure. The yield locus (YL) is sometimes called the instantaneous yield locus to differentiate it from the time yield locus.

4. Summary of Test Method

4.1 A representative sample of bulk solid is placed in a shear cell of specific dimensions.

4.2 When running an instantaneous or time shear test, a normal load is applied to the cover, and the specimen is presheared until a steady state shear value has been reached. The shear stress is then immediately reduced to zero.

4.3 An instantaneous test is run by shearing the specimen under a reduced normal load until the shear force goes through a maximum value and then begins to decrease.

4.4 A time shear test is run similarly to an instantaneous shear test, except that the specimen is placed in a consolidation bench for the specified time between the preshear and shear steps.

4.5 A wall friction test is run by sliding the specimen over a coupon of wall material and measuring the frictional resistance as a function of normal, compressive load.

4.6 A wall friction time test involves sliding the specimen over the coupon of wall material, stopping and leaving the load on the specimen for a predetermined period, and then sliding it again to see if the shearing force has changed.

5. Significance and Use

5.1 Reliable, controlled flow of bulk solids from bins and

hoppers is essential in almost every industrial facility. Unfortunately, flow stoppages due to arching and ratholing are common. Additional problems include uncontrolled flow (flooding) of powders, segregation of particle mixtures, useable capacity which is significantly less than design capacity, caking and spoilage of bulk solids in stagnant zones, and structural failures.

5.2 By measuring the flow properties of bulk solids, and designing bins and hoppers based on these flow properties, most flow problems can be prevented or eliminated (1).⁴

5.3 For bulk solids with a significant percentage of particles (typically, one third or more) finer than about 6 mm (1/4 in.), the unconfined yield strength is governed by the fines (–6 mm fraction). For such bulk solids, strength and wall friction tests may be performed on the fine fraction only.

6. Apparatus

6.1 The Schulze Ring Shear Tester (Figs. 1-6) is composed of a base 1 and a casing 2. The casing 2 contains the driving and measuring units and carries the working table 38.

6.2 The driving axle 5 (with detachable plastic cap 6) causes the shear cell 4 to rotate. The driver pins at the underside of the shear cell must set in the toothed wheel at the driving axle 5 to ensure a close connection between shear cell and driving axle. The driving axle is driven by an electric motor and can rotate to the right or to the left. In order to shear the bulk solid sample, the driving axle 5 along with the shear cell 4 rotate clockwise (as seen from the top). The electric motor is controlled from the front panel 35 at the front side of casing 2 (Fig. 3). The motor and drive system cause the shear cell to rotate at a speed adjustable between 0.007 and 0.13 rad/min.

6.3 The shear cell lid 7 as well as the bottom of the shear cell 4 has bent bars made of stainless steel (Fig. 4) to prevent slipping of the bulk solid at the lid or the bottom of the shear cell.

NOTE 1—The standard cell has 20 bars, each of which is 4 mm tall ($h_{Mi} = 4$ mm, Fig. 8).

6.4 The crossbeam 8 sits on the lid 7 and is fixed with two knurled screws 9. The crossbeam 8 has several functions: In the center of the crossbeam 8 is a fixed axis 10 with a hook to append the hanger 11 (in Figs. 3 and 4 only the handle of the hanger standing out from the driving axle can be seen). Rollers at the ends of the crossbeam and the removable guide rollers 12 prevent movement of lid 7 from the centered position.

6.5 A hook 14 at the upper end of the axis 10 of the crossbeam 8 is fastened to the balance arm 15. This arm along with counterweight 29 (Fig. 6) serves to compensate for the weights of lid 7, crossbeam 8, hanger 11, and tie rods 13. The counterweight 29 is found at the rear side of the balance arm 15. The movable counterweight 29 is shifted along the balance arm to adjust the counterweight force. The fixation screw 18 (knurled screw) fixes the counterweight 29 on the balance arm. For more precise adjustment of the counterweight force, the balance arm 15 is provided additionally with a smaller movable weight 30. After unscrewing the knurled screw, which is the

⁴ The boldface numbers in parentheses refer to the list of references at the end of this standard.

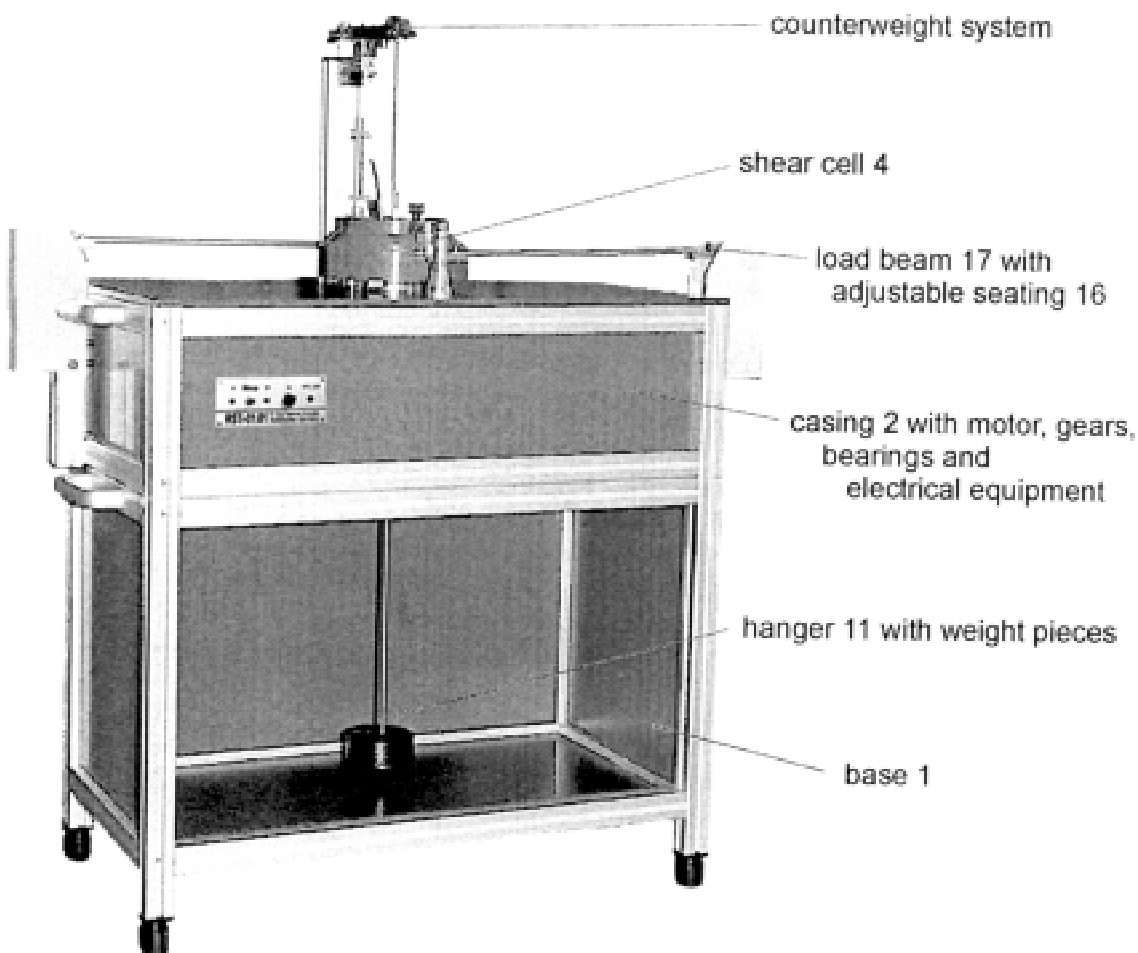


FIG. 1 Ring Shear Tester (Overall View)

major part of the movable weight 30, the movable weight 30 can be shifted along the balance arm. When the counterbalance weight is well adjusted, the lid, crossbeam, tie rods, and hanger do not press on the bulk solid sample; that is, the vertical stress at the surface of the bulk solid sample is equal to zero.

6.6 A digital displacement indicator 31 (Fig. 7) is used for the measurement of the height of the bulk solid sample.

6.7 Bolts at the ends of the crossbeam 8 are used to append the tie rods 13. Therefore, a circular hole is at one end of each tie rod 13. The opposite end is provided with an elongated hole for suspending in the adjustable seating 16 attached to the load beam 17. The seatings 16 are adjustable to enable the adjustment of the horizontal position of the lid 7.

6.8 The rotation of the lid 7 is prevented by the tie rods 13 which transfer the tensile force to the load beams 17.

6.9 The bottom part of the hanger 11, which hangs on the crossbeam 8 and serves for exerting a normal load N on the bulk solid sample, is located within the base 1 (Fig. 1). The hanger has a circular plate 19 at its lower end for holding the weight pieces.

6.10 The base 1 has four adjustable stands 3 (Fig. 5), with which the Ring Shear Tester is to be adjusted accurately in a horizontal position.

6.11 For control of the motor drive a front panel 35 (Fig. 3)

is at the front side of the casing 2.

6.12 The load beams 17 are connected parallel. Each load beam should be capable of measuring a force up to 200 N with a precision of 0.02 % of full scale. Thus, the total measuring range, which is twice the measuring range of one load beam, is 400 N. The signal from the force transducer is conditioned by an amplifier and shown on a recorder.

NOTE 2—Danger! To avoid overloading of the load beams, the indicated maximum normal load must not be exceeded!

6.13 For the Schulze Ring Shear Tester RST-01.01 different shear cells are available. The dimensions of the Standard cell and a smaller cell can be taken from Table 2 and Fig. 8. For special purposes (for example, reduced internal volume) other dimensions are also available.

6.14 The time consolidation bench serves for the storage of shear cells with bulk solid samples under load.

6.14.1 The time consolidation bench (Fig. 9) is composed of a frame Z1, on which are fastened three supporting plates Z2. One small shear cell (type S, volume approx. 200 cm³) can be placed on each plate. The shape of the plate Z2 centers the shear cell.

6.14.2 Through the central depression of the time consolidation crossbeam 26 the normal load is exerted during time

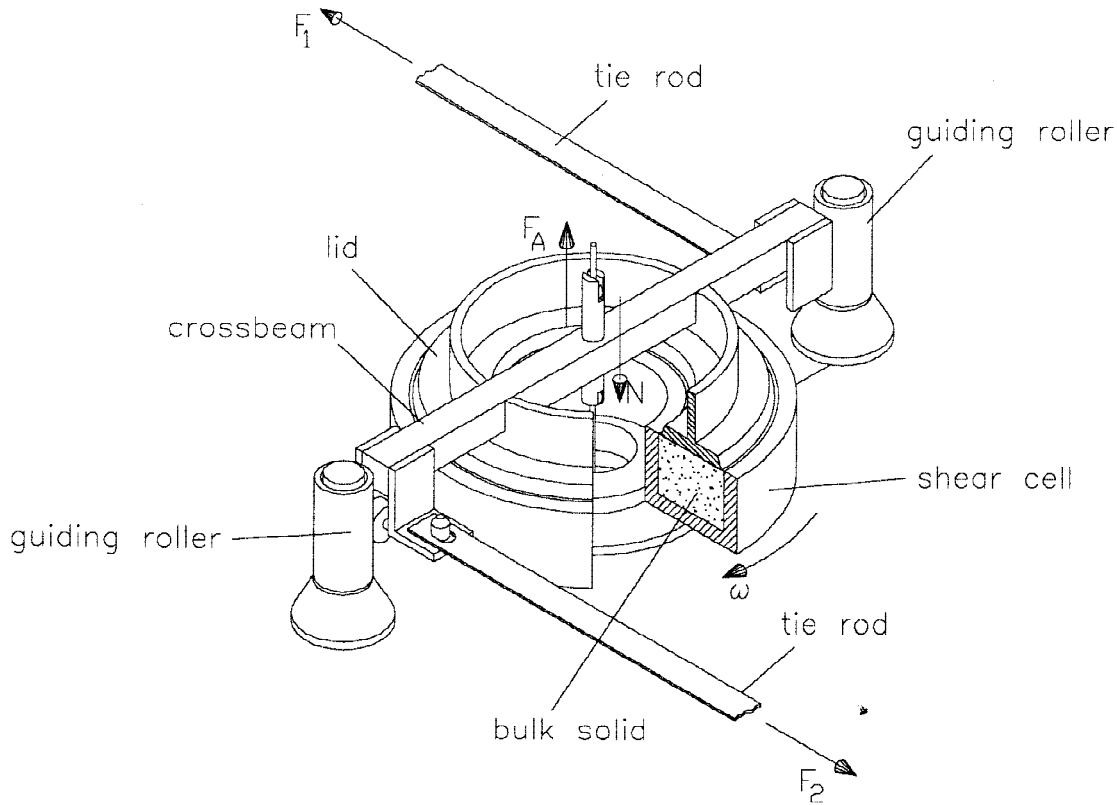


FIG. 2 Shear Cell (in Principle)

consolidation as shown in the left part of Fig. 9. The lower end of the loading rod Z4 is equipped with a central tip.

6.14.3 The transparent cylindrical plastic cap Z3, when pressed on plate Z2, protects the samples from the surrounding atmosphere (for example, to reduce changes of the moisture of the bulk solid samples). This cap Z3 is joined to the loading rod Z4 through a rubber bellows Z8.

6.14.4 At the upper end of the loading rod Z4 a disk Z5 is fastened for supporting weight pieces by which the vertical load for time consolidation is applied.

6.14.5 The fixing screw Z6 serves for the fixation of the loading rod Z4 in the upper position (Fig. 9, on the right). For moving the loading rod upwards or downwards, the fixing screw must be unscrewed somewhat. In the loading position (Fig. 9, on the left) the fixing screw must remain unscrewed.

6.14.6 For horizontal alignment, the time consolidation bench is provided with four adjustable feet Z7.

6.15 The wall friction cells allow the measurement of wall yield loci from which wall friction angles can be calculated.

6.15.1 The bottom ring 48 of the wall friction cell (see Fig. 10) contains the wall material sample to be tested. The wall material coupon is placed on an appropriate number of spacer rings 51. The thickness of each spacer ring is 2 mm.

6.15.2 To prevent any relative circumferential displacement between the bottom ring 48 and the wall material coupon, four driving pins 50 are installed at the outer wall of the bottom ring 48. The annular wall material coupon has to be provided with notches for these driving pins so that bottom ring and wall material coupon are interlocked. The required dimensions of

the wall material coupon are shown in Fig. 11.

6.15.3 The lid 49 (Fig. 12) has bent bars from stainless steel to prevent slipping of the bulk solid at the lid of the shear cell. Additionally, the lid of a wall friction cell is provided with downwards protruding edges at the inner and outer radius.

6.15.4 The dimension of the wall shear cell are shown in Table 1 and Fig. 13.

6.16 A spatula having a rigid, sharp, straight blade at least 50 % longer than the width of the annulus of the shear cell, and at least 20 mm wide, is needed.

6.17 A laboratory balance having a maximum capacity of at least 50 N with a precision of 0.01 % or better is required.

6.18 The laboratory used for powder testing should be free of vibrations caused by traffic or heavy machinery. Ideally, the room should be temperature and humidity controlled, or, if this is not possible, it should be maintained at nearly constant ambient conditions. Direct sunlight, especially on the time consolidation bench, is to be avoided.

NOTE 3—Temperature- and humidity-sensitive materials may need to be tested at different temperatures and moisture contents, because this often happens in industrial environments. The laboratory environment must approximate production for meaningful testing.

7. Specimen Preparation

7.1 Filling the Cell (Fig. 14):

7.1.1 Fill the shear cell 4 uniformly in small horizontal layers by a spoon or spatula without applying force to the surface of the material until the material is somewhat over the top of the cell wall. The filling should be conducted in such a

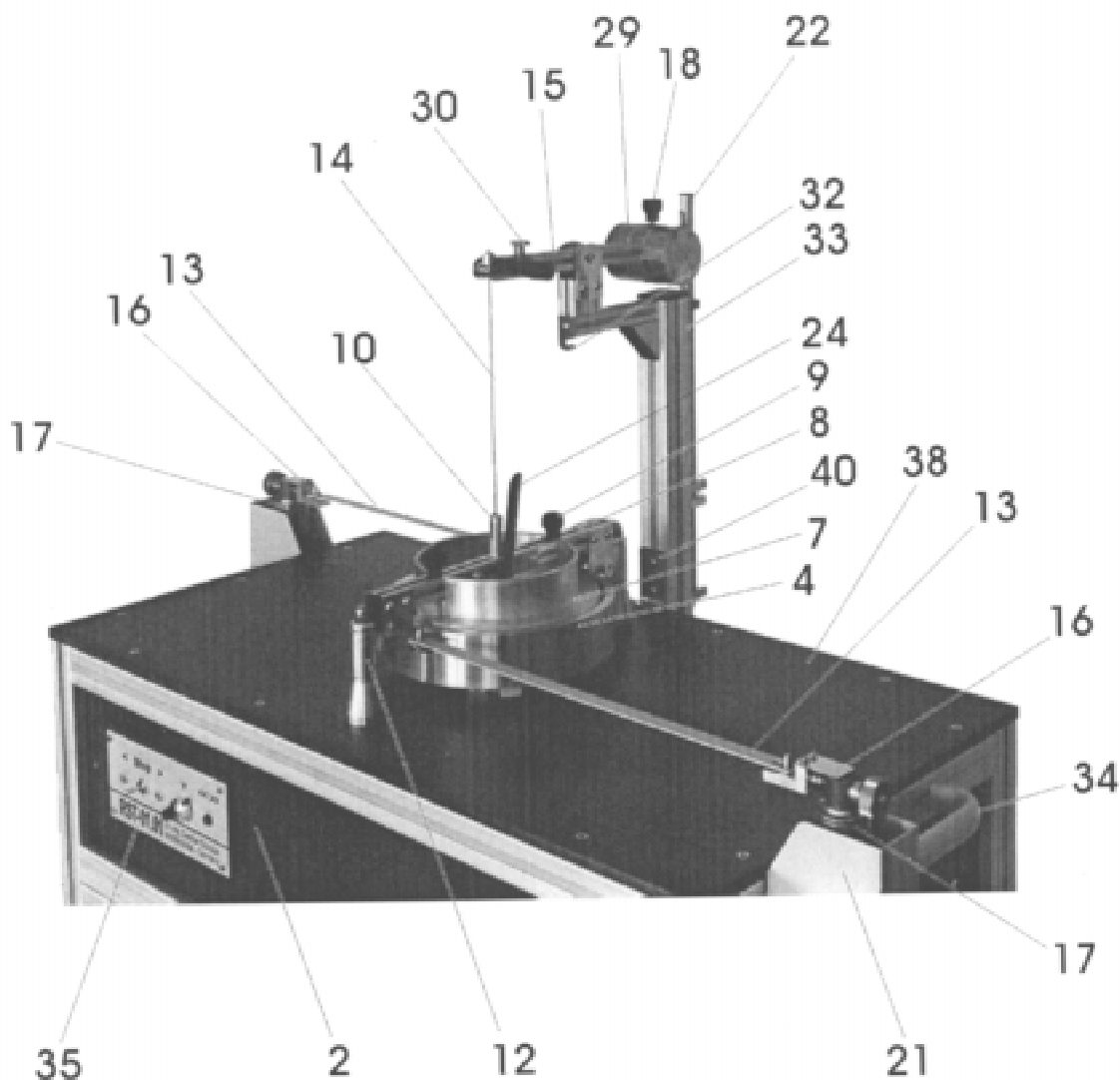


FIG. 3 Ring Shear Tester (Upper Part)

way as to ensure that there are no voids within the cell.

7.1.2 Remove excess material in small quantities by scraping off with a blade 1 until flush with the top of the annulus. At first the blade should be scraped counterclockwise across the ring one or two times in a zigzag motion. Then the blade should be scraped around the annulus counterclockwise, as shown in Fig. 14a, whereby the blade should be inclined by an angle $\alpha = 15$ to 30° to the radial direction. The blade should always be held vertically or tilted by a few degrees to the vertical (angle $\beta = 0^\circ$ to 10°) as shown in Fig. 14b. Do not exert a downward force on the material with the blade.

NOTE 4—If coarse particles are present, scraping may tear them from the surface and alter the structure. In such cases it is better to attempt to fill the cell so that the material surface is flush with the annulus after filling.

8. Procedure

8.1 Shear Testing Procedure

8.1.1 Synopsis:

8.1.1.1 A point of a yield locus is measured in two steps: At first, a bulk solid sample is consolidated (preshear) with a selected weight m_{wp} to develop a shear zone in which steady state flow occurs. Then the strength of the consolidated sample is measured (shear).

8.1.1.2 The time consolidation is measured using a similar procedure as for the Jenike Shear Tester (see Standard D 6128).

8.1.2 Preshear:

8.1.2.1 If necessary, clean the outside of the shear cell. Then weigh the shear cell with contents. Note the total mass m_{ges} .

8.1.2.2 Ascertain that the power supply is turned on.

8.1.2.3 Put the filled shear cell 4 on the driving axle 5 (Fig.

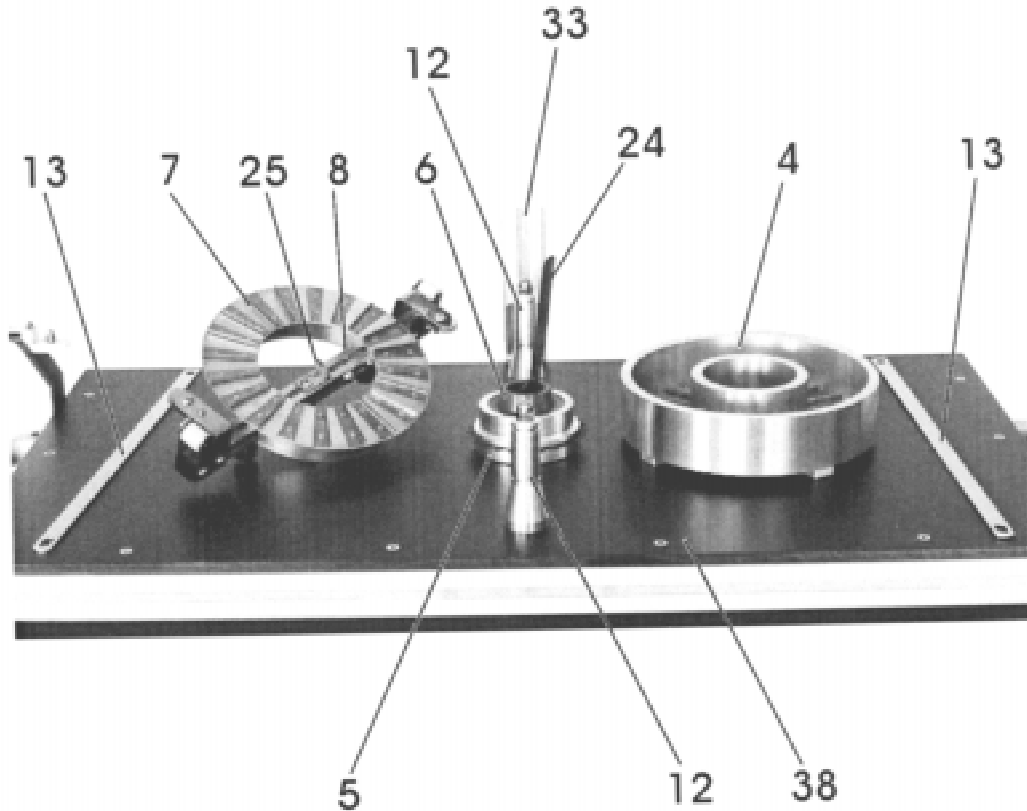


FIG. 4 Upper Part of the Ring Shear Tester, Shear Cell Removed

15). Ensure that the drivers on the underside of the shear cell engage the toothed wheel of the driving axle 5.

8.1.2.4 Select the first preshear normal stress $\sigma_{p,1}$ on the basis of the bulk density of the test material, in accordance with the following table:

ρ_b (kg/m ³)	$\sigma_{p,1}$ (kPa)
< 300	approximately 1.5
300 to 800	approximately 2.0
800 to 1600	approximately 2.5
1600 to 2400	approximately 3.0
> 2400	approximately 4.0

NOTE 5—Follow 8.1.2.5-8.1.2.9 only if the normal load at preshear is greater than 15 N. Otherwise go to 8.1.2.10.

8.1.2.5 Connect crossbeam 8 and lid 7 using the knurled screws 9. Fasten screws only very slightly. Position the lid concentrically on the shear cell and turned a few degrees counterclockwise to its shear position (shear position: longitudinal axis of the crossbeam is perpendicular to the front edge of the casing 2). The open side of hook 25 in the center of crossbeam 8 should be directed to the right. Locate handle 24 of hanger 11 on the right side of crossbeam 8 (Fig. 16).

8.1.2.6 Put tie rods 13 on both the bolts at the ends of crossbeam 8 (circular holes of tie rods 13) and seatings 16 at load beams 17 (long hole of the tie rod 13).

NOTE 6—The tie rods 13 should have some clearance in the seatings 16; that is, the tie rods must not be stressed at this stage. Important: If it is not possible to connect the tie rods as described above, do not move the lid manually since this would influence the test result. Only use the motor

drive to turn the shear cell with the lid in a position where it is possible to connect the tie rods to the load beams.

8.1.2.7 Append hanger 11 at hook 25 at the lower side of crossbeam 8.

8.1.2.8 Carefully put a weight piece on the circular plate 19 of hanger 11 (weight needed for preshear or smaller weight).

8.1.2.9 Remove hook 14, which is connected to the balance arm, from its off-position mounting 32 and append it to the central axis 10 (this already has been done in Fig. 16).

NOTE 7—To do this, the front end of the balance arm must be pulled down at the black handle 46 provided for this (the handle is not shown in all figures; see Fig. 6).

NOTE 8—Follow 8.1.2.10-8.1.2.14 if the normal load at preshear is less than 15 N. (These steps can also be used alternatively to 8.1.2.5-8.1.2.9.)

8.1.2.10 Connect crossbeam 8 and lid 7 using the knurled screws 9. Fasten screws only very slightly. Remove hook 14, which is connected to the balance arm, from its off-position at mounting 32 and append it to the central axis 10. The lid is then in a “lifted position.”

8.1.2.11 Put at least one weight piece on the circular plate 19 of the hanger 11.

NOTE 9—The mass on the hanger can be less than or equal to that needed for preshear, but should not exceed 1 kg.

8.1.2.12 Hold the lid in its lifted position with one hand and append hanger 11 at hook 25 at the lower side of crossbeam 8.

8.1.2.13 Carefully place the lid concentrically on the shear

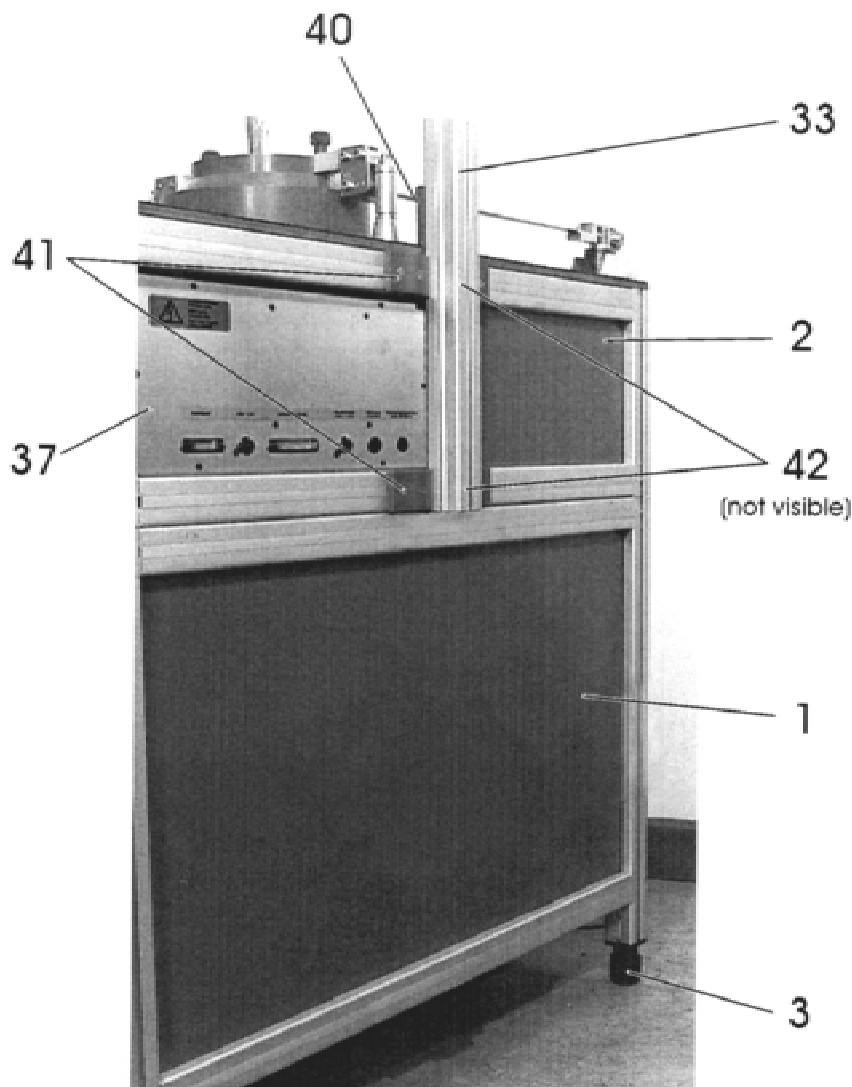


FIG. 5 View on the Reverse Side of the Ring Shear Tester

cell on the bulk solid sample. The lid must be in a position turned a few degrees counterclockwise to its shear position (shear position: longitudinal axis of the crossbeam is perpendicular to the front edge of the casing 2). The open side of hook 25 in the center of crossbeam 8 should be directed to the right. Locate handle 24 of hanger 11 on the right side of crossbeam 8 (Fig. 16).

8.1.2.14 Put tie rods 13 on both the bolts at the ends of crossbeam 8 (circular holes of tie rods 13) and the seatings 16 at load beams 17 (long hole of the tie rod 13).

NOTE 10—The tie rods 13 should have some clearance in the seatings 16; that is, the tie rods must not be stressed at this stage. If it is not possible to connect the tie rods as described above, use the motor drive to turn the shear cell with the lid to an appropriate position.

8.1.2.15 If not already done (at 8.1.2.8 or 8.1.2.11, respectively), put additional weight pieces on the hanger 11 for adjusting the normal force required for preshear. If the lid sinks down more than around 10 mm, refill the shear cell (remove the shear cell from the tester and go back to 7.1).

NOTE 11—At the beginning of preshear, some powder may escape, which is one reason why the lid may sink. Provided that 8.1.2.15 is followed, loss of powder can be neglected.

8.1.2.16 Check the adjustment of the rotational velocity (front panel 35). The circumferential velocity at the mean diameter should be 1 to 2 mm/min.

8.1.2.17 Start the motor (front panel 35).

NOTE 12—After some time both tie rods 13 are transferring tensile forces. The total force F (“shear force”) is then measured.

8.1.2.18 As soon as the shear force F is constant (stationary flow is reached), Fig. 17, reverse the direction of rotation of the shear cell. After both load beams are relieved (shear force $F = 0$), continue rotating the shear cell until the tie rods 13 have about 1 mm clearance in the seatings 16. Then stop the motor.

8.1.2.19 Record the force F measured at stationary flow.

NOTE 13—If the shear force does not reach a constant value, stationary flow can be assumed if, after 30 mm of shear displacement (measured at the mean radius of the shear cell annulus), this force does not increase more than 0.05 % per mm of shear displacement. If this condition has not

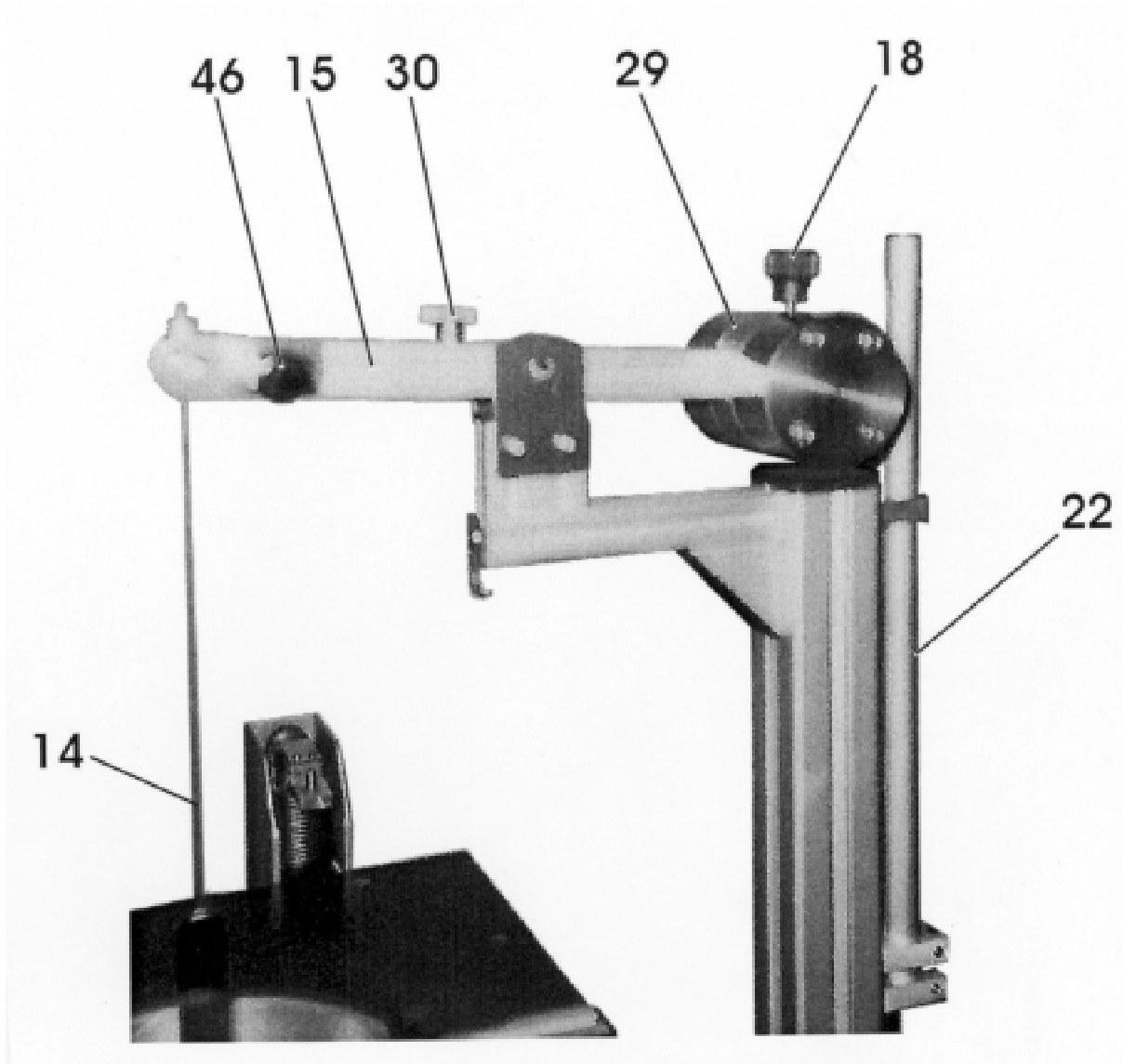


FIG. 6 Counterweight System

TABLE 1 Wall Shear Cell Dimensions

	Standard Wall Friction Cell, Type WM
Cross-section (lid) A_D	226 cm ²
r_{iD}	51 mm
r_{aD}	99 mm
r_{iSZ}	42.5 mm
r_{aSZ}	107.5 mm
h_{SZ}	24 mm
h_{Mit}	4 mm
Material	Aluminum

been achieved after 30 mm of displacement, preshear should be continued until it is met. If the technician decides to terminate preshear before this condition is met, it should be noted before continuing with the test.

The shear force should not decrease during preshear. If it starts to do so after a period of constant value, preshear should be stopped immediately and the steps starting with 8.1.3 begun.

Constancy of the values of the steady state shear stress τ_p obtained after preshear is an indication of the reproducibility of consolidation. With correctly consolidated samples individual values of the steady state shear

stress should not deviate by more than $\pm 5\%$ from the average steady state shear stress for the given preshear normal stress. With some particulate solids (particularly coarser particles), however, this tolerance cannot be achieved. If this happens it should be noted by the technician performing the test.

8.1.3 Shear:

8.1.3.1 Select a shear normal stress level σ_s within the range of 25 to 80 % of the preshear normal stress level σ_p , and replace the weight m_{wp} by a smaller weight m_{ws} . Switch on the motor again in the forward direction.

NOTE 14—After the tie rods 13 are tensed again, the shear force rapidly increases, goes through a maximum representing the yield shear force, and then begins to decrease (Fig. 17). This part of the test is called shear.

NOTE 15—The value τ_s is the shear stress at failure (peak shear point) for the selected shear normal stress σ_s at the selected preshear normal stress σ_p . Metal-to-powder friction, which may occur at the side walls of the shear cell and at the tips of the bars under the lid, is assumed to be negligible because the areas where metal-to-powder friction may occur are very small compared to the cross-section of the shear plane, and therefore ignored.

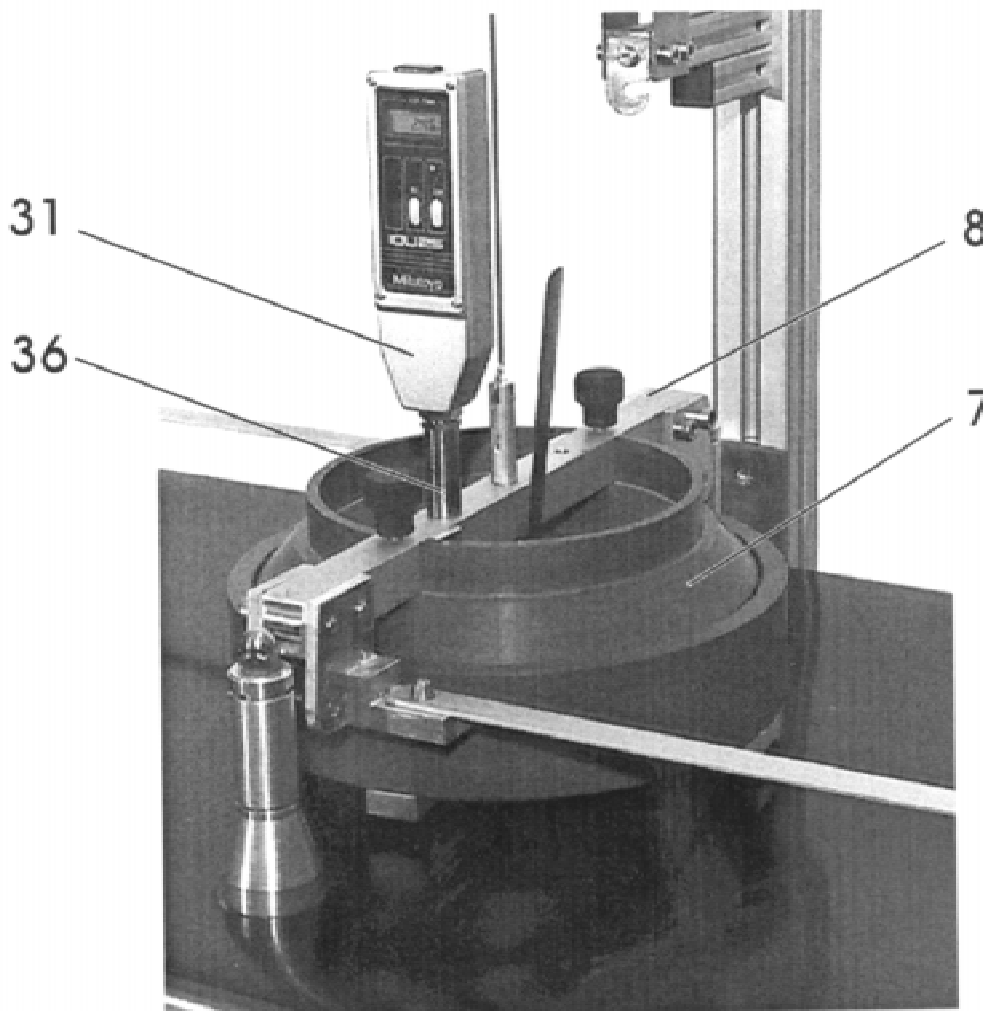


FIG. 7 Determination of the Height of The Specimen

8.1.3.2 Switch on the digital displacement indicator 31. After the display of the indicator shows “0.00 mm,” set the indicator on the crossbeam 8. Position the probe tip through a hole in the crossbeam 8 in such a way that it presses on top of the inner side wall of the shear cell 4 and the spacer tube 36 is in contact with the upper surface of the crossbeam 8 (Fig. 7). Note the displacement indicated on the display.

8.1.3.3 Repeat the measurement at the opposite side of the crossbeam.

8.1.3.4 Remove the indicator 31.

8.1.3.5 Calculate the mean value of both measured displacements, which is the mean decrease in height Δh of the bulk solid sample. Note this mean value.

8.1.3.6 Drive back the shear cell 4 until tie rods 13 are relieved. Then switch off the motor.

8.1.3.7 Remove tie rods 13.

8.1.3.8 Unhook hook 14 from the central axis 10 thus deactivating the counterbalance system.

8.1.3.9 Remove weight pieces from the hanger 11.

8.1.3.10 Unhook hanger 11 from the hook 25 at the lower side of the crossbeam 8.

8.1.3.11 Take off the shear cell 4 along with the lid 7.

8.1.3.12 Empty the shear cell; if necessary clean the shear cell, the lid and the driving axle.

8.1.4 *Additional Tests:*

8.1.4.1 Repeat 7, 8.1.2, and 8.1.3.

8.1.4.2 Select 3 to 5 shear normal stress levels σ_s within the range of 25 to 80 % of the preshear normal stress level σ_p , and repeat 7, 8.1.2, and 8.1.3.

8.1.4.3 Select higher preshear normal stress levels so that:

$$\begin{aligned}\sigma_{p,2} &= 2\sigma_{p,1} \\ \sigma_{p,3} &= 4\sigma_{p,1} \\ \sigma_{p,4} &= 8\sigma_{p,1}\end{aligned}$$

NOTE 16—Some adjustment in preshear normal stress levels may be necessary in order to cover the range of major consolidation stresses σ_1 necessary to accurately calculate critical arching and/or ratholing dimensions.

8.1.4.4 Repeat 7, 8.1.2, 8.1.3, and 8.1.4.2 for each selected preshear normal stress level.

NOTE 17—Following the procedure given in 7, 8.1.2, and 8.1.3 (Procedure A) requires a new filling of the shear cell for each measurement; that is, each point on a yield locus. In the literature a second measuring

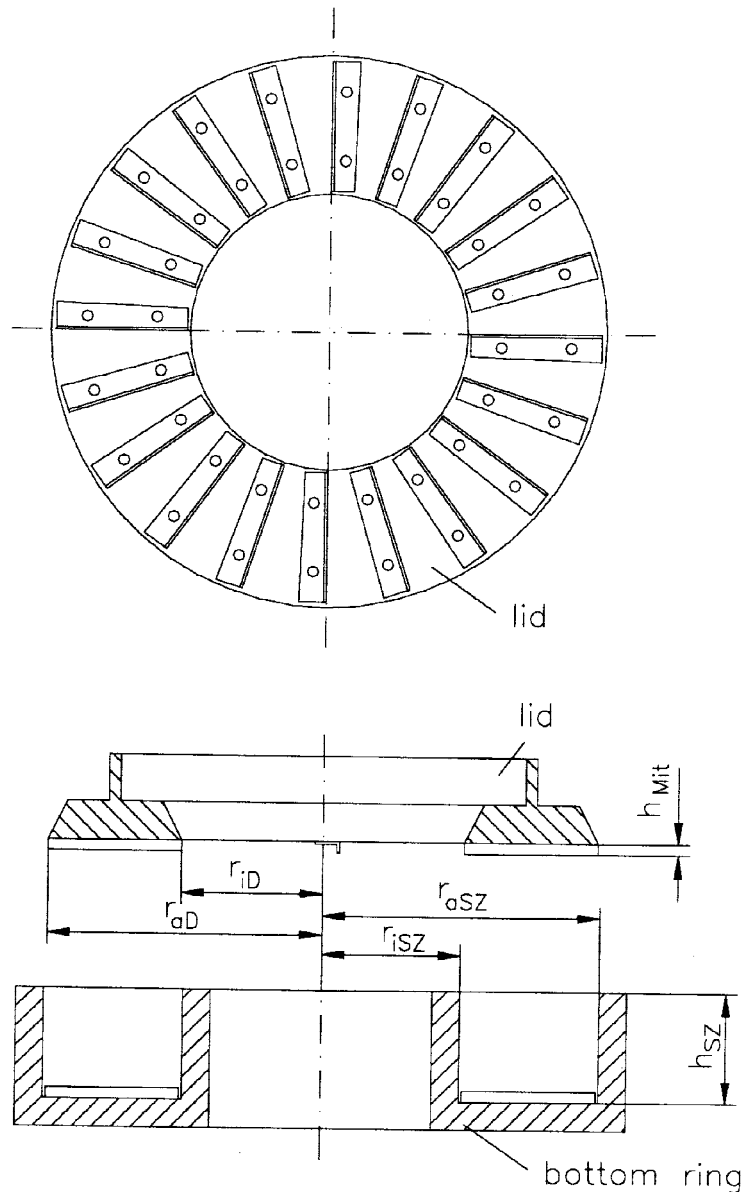


FIG. 8 Main Dimensions of Shear Cell

TABLE 2 Shear Cell Dimensions

	Standard Cell, Type M	Small Cell, Type S
Internal volume V_{SZ}	ca. 900 cm ³ ^A	ca. 200 cm ³ ^A
Cross-section (lid) A_D	226 cm ²	79 cm ²
r_{iD}	51 mm	31 mm
r_{aD}	99 mm	59 mm
r_{iSZ}	50 mm	30 mm
r_{aSZ}	100 mm	60 mm
h_{SZ}	40 mm	24 mm
h_{Mit}	4 mm	4 mm
Material	Aluminum or Stainless Steel	Aluminum or Stainless Steel

^A Exact volume to be determined for each cell.

procedure (Procedure B) is frequently recommended (for example, in (3)), where several points of a yield locus are determined using the identical bulk solid specimen several times. In this case, one would jump again and again from 8.1.3.1 back to 8.1.2.17 until all desired measuring points are

determined. Only then would 8.1.3.2 and the following steps be performed.

Procedure B is generally the preferred procedure, since it is less time consuming than Procedure A. Unfortunately, some bulk solids are sensitive to shear deformation and, as a result, their shear stress values decrease with large shear deformation. Sometimes a result of this can be that Procedure B yields too small values of the unconfined yield strength (2). To determine if Procedure B is appropriate, examine a new bulk solid first with this procedure. Repeat the first measuring point at the end. If the prorated shear stress is noticeably smaller than at the first measurement (say, a difference greater than 2.5 %), Procedure A should be used for the product under consideration, or at least the number of shear points measured using Procedure B should be limited.

If Procedure B is applicable, the sample should be sheared only until the shear force becomes constant. Frequently, if the shear displacement is large at the first preshearing of a bulk solid sample, the shear force passes over a product dependent, weak maximum (2). Afterwards a constant

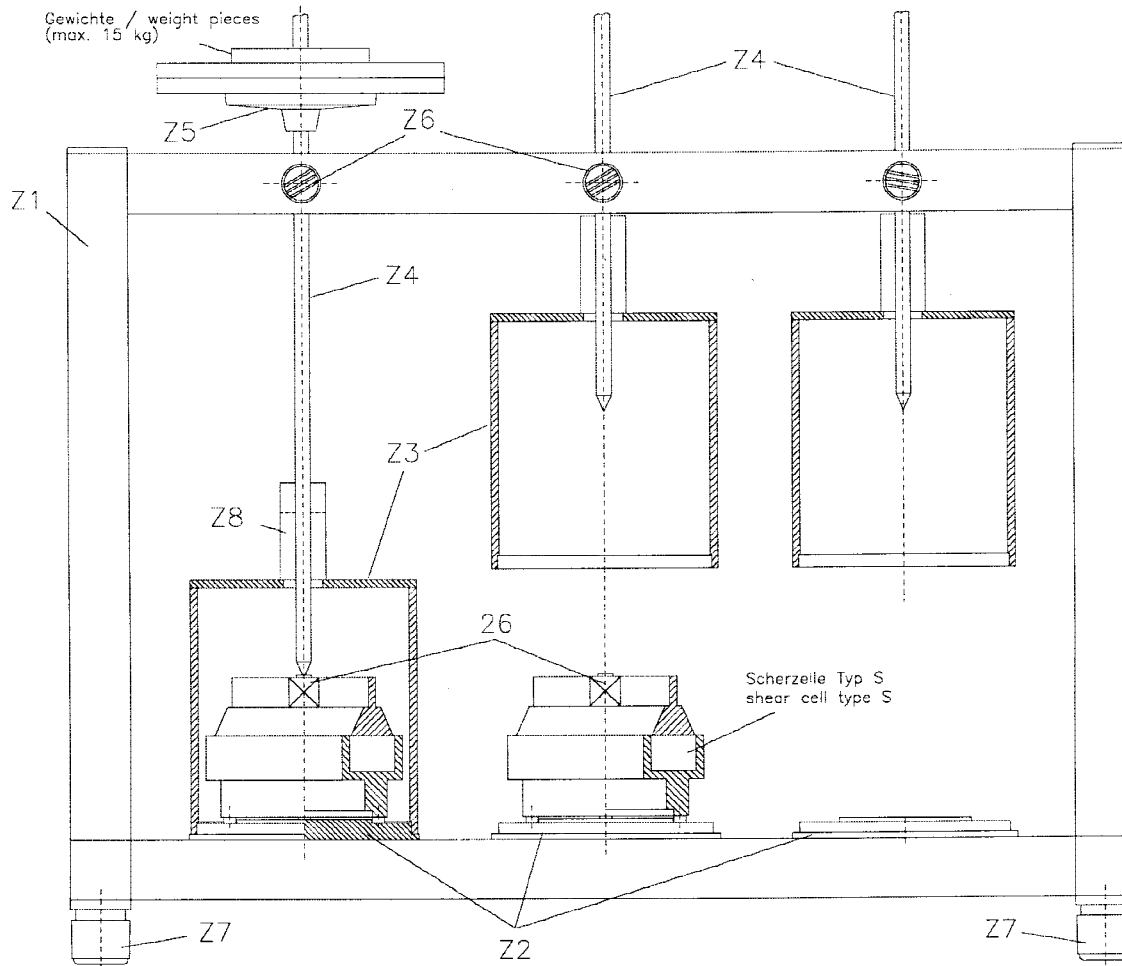


FIG. 9 Time Consolidation Bench

shear force somewhat smaller than the maximum shear force is reached. Do not wait until this lower level is reached. The preshearing is finished when the maximum is reached; that is, the shear force no longer increases, and the shear force does not yet start to decrease again. One can ascertain this condition easily, if the shearing velocity is not too high.

In principle, all measurement results, as those of other shear testers, have to be considered critically and applied with the necessary caution and care.

8.1.5 Prorating:

8.1.5.1 Ideally all values of the preshear shear stress, τ_p , for a given preshear normal stress would be identical. This would occur if the specimen were perfectly homogeneous, and specimen preparation completely repeatable. However, because of unavoidable experimental variation there is a scatter of τ_p values which affects the value of the shear stress, τ_s .

8.1.5.2 To minimize the scatter, all measured shear stresses, τ_s , may be corrected to take into account scatter in the preshear shear stresses, τ_p . This empirical procedure is called prorating, and prorated values of τ'_s of the measured values τ_s are evaluated using the following equation:

$$\tau'_s = \tau_s (\tau_{p,m} / \tau_p) \quad (1)$$

where:

$\tau_{p,m}$ = average of the pre-shear shear stresses, τ_p , of the corresponding pre-shear normal stress level (yield locus). Prorating assumes that variations in consolidation produce variations in shear stress, τ_s , that are proportional to the corresponding variation in preshear shear stress, τ_p .

8.1.6 Determination of Valid Shear Points:

8.1.6.1 For each consolidation condition (σ_p), plot prorated and averaged shear points S_i (σ_s, τ'_s) of repeated measurements and the averaged preshear point P (σ_p) on a σ, τ -diagram (Fig. 18).

8.1.6.2 To determine whether a yield point is valid the following procedure is adopted.

8.1.6.3 Fit by means of a least squares fit a straight line called the yield locus YL to the three highest points S_2, S_3 and S_4 (Fig. 18).

8.1.6.4 If the straight line passes through or above point P , it can be used for further calculation. If, however, the straight line passes below point P (Fig. 19), either additional shear points should be run or the test should be redone at a different level of consolidation.

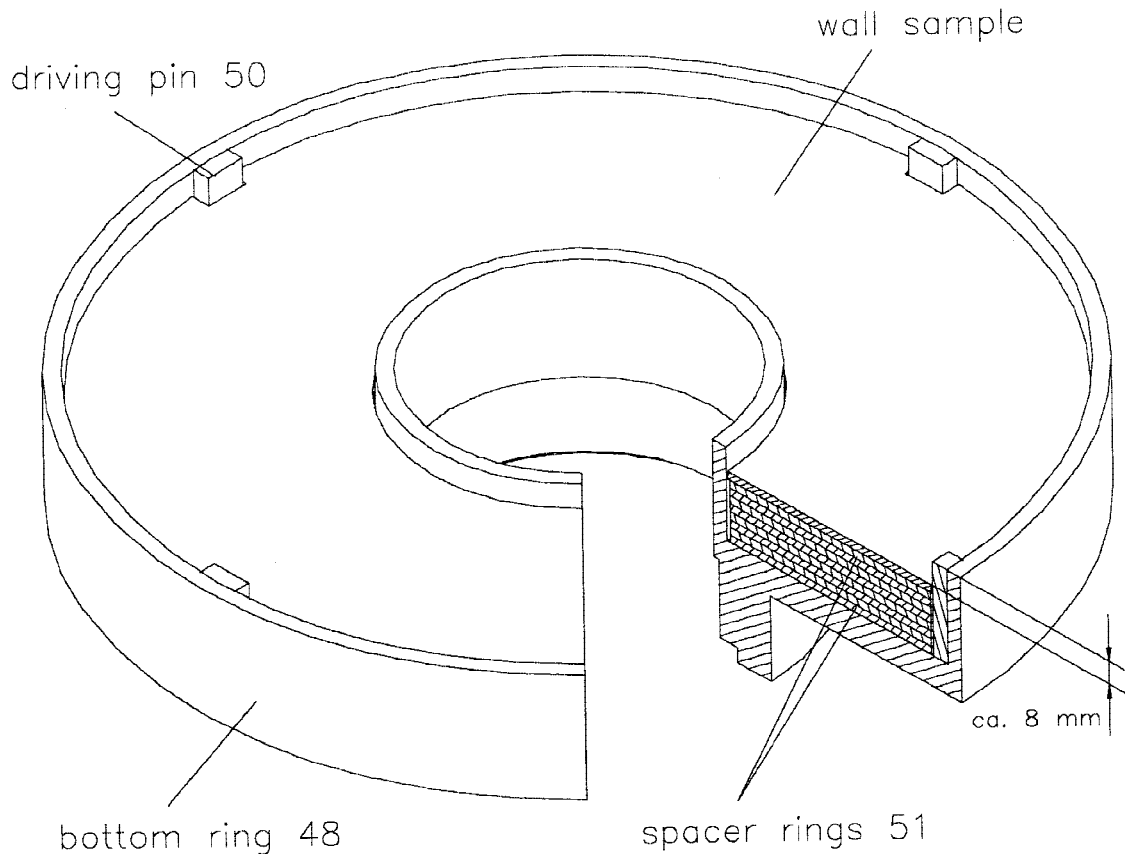


FIG. 10 Wall Friction Cell (Bottom Ring)

NOTE 18—From an inspection of the σ, τ -diagram it can be seen that the shear points on a yield locus are not equally spaced from zero normal stress to preshear normal stress, but begin at a certain minimum value of normal stress and end some distance before the preshear normal stress is reached. Considering the situation in more detail, Fig. 20 shows one yield locus with a preshear point P and four valid shear points S_1-S_4 . One Mohr circle, 1, (the steady state Mohr circle) is drawn through the preshear point P and tangentially to the extrapolated yield locus (the point of tangency is shown on Fig. 20 as B and defines the end point of the yield locus).⁵ A second Mohr circle, 2, (the unconfined strength Mohr circle) is drawn, passing through the origin and tangential to the extrapolated yield locus (this point of tangency is denoted by A in Fig. 20). Yield points to be considered must lie between the points of tangency A and B . Points to the left of A or right of B may be valid or invalid; thus, for the purposes of this test method, they are ignored.

NOTE 19—Points to the left of point A are ignored because they represent a state where tensile stresses can occur in the shear cell. This can be seen by considering the yield point on Fig. 20 marked by $S_{(-)}$, below point A . If a Mohr circle 3 is drawn through this point which is tangential to the extrapolated yield locus, part of that circle will lie to the left of the origin indicating negative normal stresses, that is, tensile stresses.

8.2 Shear Testing Procedure for Time Consolidation

8.2.1 When a particulate solid is exposed to a normal or compressive stress for some time it may gain strength. This

gain in strength can be measured using the Schulze Ring Shear Tester, and the effect is called time consolidation.

8.2.2 Time consolidation is carried out using a consolidating bench which consists of several shear cells which can be independently loaded. The time that the specimens sit at rest is specified according to the application.

NOTE 20—A critically consolidated specimen could be prepared by preshearing with weight m_{wp} . After attaining steady state flow, the rotation of the shear cell is stopped but the direction is not reversed. The shear zone formed thus remains under the normal and shear stresses corresponding to steady state flow and is kept in this state for a defined time t . If the shear cell rotation is then reversed, the shear force will drop to zero and the actual shear test may be performed in the usual way. For materials that gain strength during time consolidation, a higher shear strength will be measured. In a σ, τ -diagram the time yield locus for time consolidation will lie above the instantaneous flow yield locus.

If the effect of time consolidation in the Schulze Ring Shear Tester were measured as described above, one test would monopolize the shear tester for a very long time. Creep of the specimen could also cause a decrease in the applied shear force during the resting phase.

8.2.2.1 Before starting with time consolidation measurements, make sure that the time consolidation bench is level. Use the four adjustable feet Z7 (Fig. 9), if necessary.

8.2.3 Specimen Preparation and Preshear Time Effect:

8.2.3.1 After completion of instantaneous testing and evaluation, perform time tests at the same preshear normal stress levels.

⁵ This method of constructing the steady state Mohr circle is specified by the EFCE and Jenike. Alternative methods of construction have been proposed. See for example, Peschl (5).

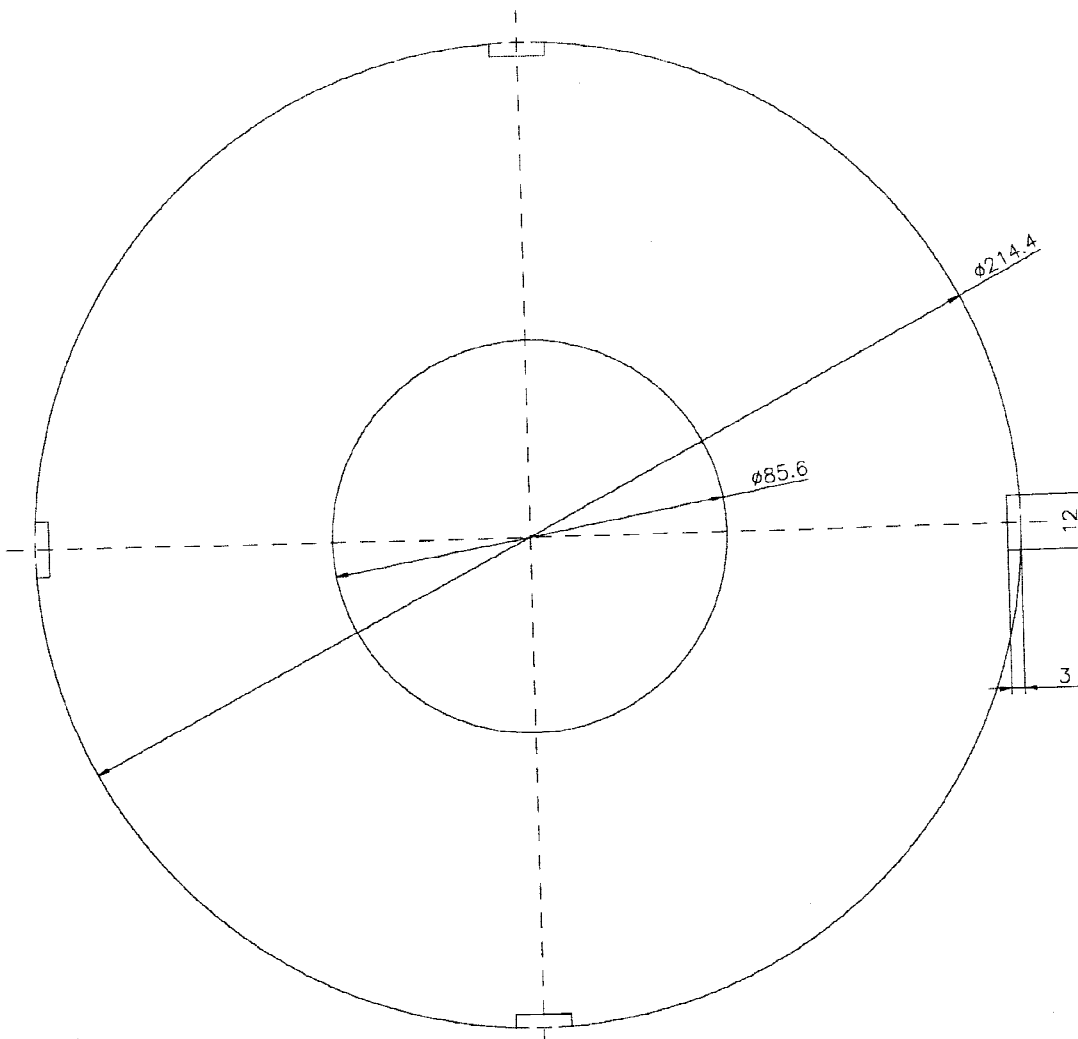


FIG. 11 Dimensions of Wall Material Sample

NOTE 21—For a selected preshear normal stress, specimen preparation and preshear are the same as for the instantaneous test.

8.2.4 Time Consolidation:

8.2.4.1 Perform each test for time consolidation in the following way. Using the shear tester, prepare and preshear samples with weight m_{wp} in the normal manner and then reverse the rotation of the shear cell after preshear.

8.2.4.2 Remove the already relieved tie rods 13.

8.2.4.3 Carefully unhook hook 14 of the counterbalance system from the central axis 10 of the crossbeam 8.

8.2.4.4 Remove the weight pieces from the hanger 11.

8.2.4.5 Unhook hanger 11 from the hook 25 on the lower side of the crossbeam 8.

8.2.4.6 Completely unscrew the knurled screws 9, which join the crossbeam 8 with the lid 7.

8.2.4.7 Carefully remove crossbeam 8 from lid 7.

8.2.4.8 Carefully put time consolidation crossbeam 26 centrally on the lid 7.

8.2.4.9 Fix plastic cap Z3 of time consolidation bench in its upper position with the help of the fixing screw Z6 (Fig. 9, right position).

8.2.4.10 Remove the shear cell 4 along with the lid 7 from driving axle 5 carefully and without vibrations. Put the shear cell on a free supporting plate Z2 of the prepared time consolidation bench (Fig. 9, medium position).

8.2.4.11 Hold plastic cap Z3 with one hand, and loosen the fixing screw Z6 with the other hand. Then let down the plastic cap slowly, thereby leading loading rod Z4 with one hand so that it runs against the centric tip (or pit) of the time consolidation crossbeam 26. Push plastic cap Z3 over plate Z2 (Fig. 9, left position).

NOTE 22—The plastic cap must not hit against shear cell or lid. Any shocks can influence the bulk solid sample and lead to incorrect measurement results.

8.2.4.12 Select the weight m_{wt} in such a way that the stress state in the specimen during time consolidation is the same as during preshear (that is, steady state flow).

NOTE 23—During preshear a normal stress as well as a shear stress is acting, although on the consolidating bench only normal stresses can be applied. Through nearly 40 years of industrial practice with the Jenike Shear Tester (see Standard D 6128), it has been found that the stress state

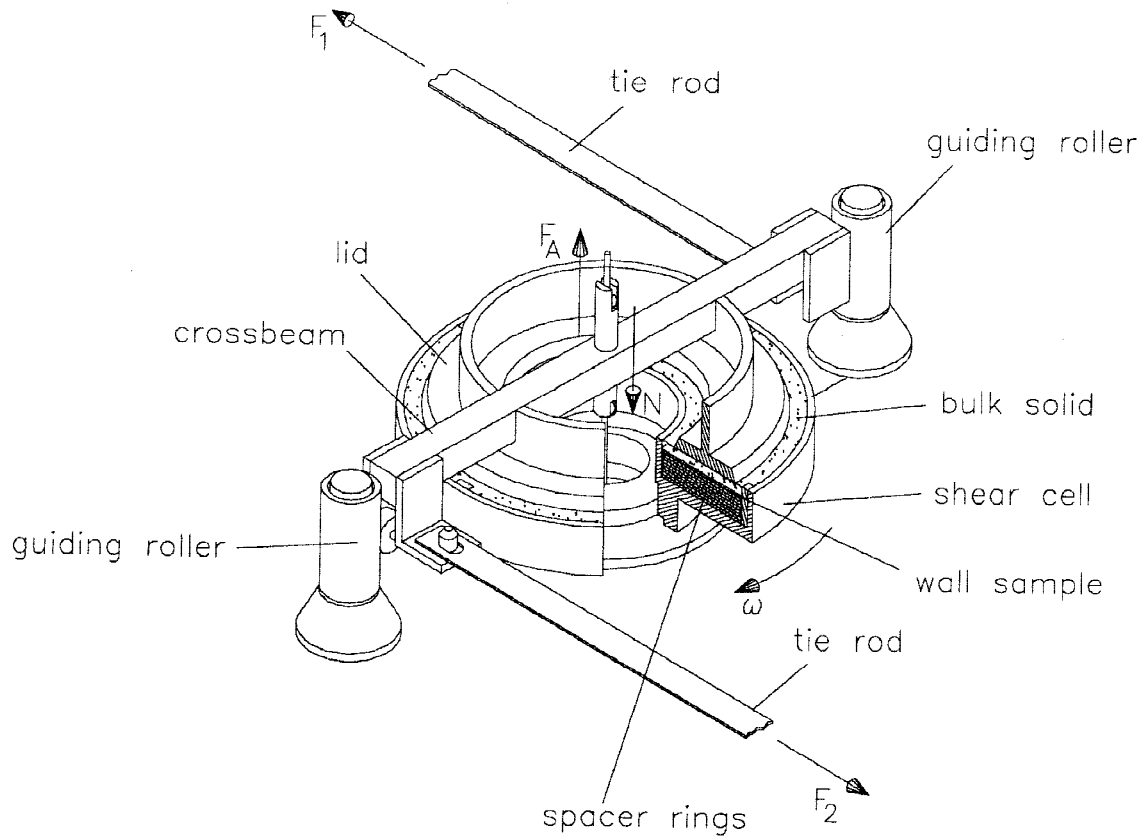


FIG. 12 Wall Friction Cell Placed on the Ring Shear Tester

developed by the application of normal stress alone can successfully approximate that developed in steady state flow. The Mohr circle shown in Fig. 20 is drawn through point *P* (steady state flow) and is tangential to the yield locus. During time consolidation, the specimen is loaded with the major principal stress σ_1 of that Mohr circle as shown in Fig. 20.

8.2.4.13 Calculate the force, which must act on the bulk solid at time consolidation, from:

$$F_i = \sigma_1 A_D \quad (2)$$

NOTE 24—The mass of the bulk solid in the area of the bars of the lid is neglected here, because it only produces a normal stress on the order of magnitude of 10 to 50 Pa (depending on the bulk density of the bulk solid).

When using a time consolidation bench, the weights of the lid 7 (mass m_L) and the time consolidation crossbeam 26 (mass m_{CB}) as well as the weights of the loading rod Z4 with the disk Z5 (mass m_C) are acting on the bulk solid sample. Thus, for an exact adjustment of the load one has to determine the masses of lid 4, time consolidation crossbeam 26, and loading rod Z4 with disk Z5. To obtain mass m_{Wt} of the weights which have to be placed on disk Z5 of the time consolidation bench, these masses have to be subtracted from mass $m_i = F_i/g$, which would exert the force F_i as determined following equation (2) :

$$m_{Wt} = (F_i/g) - m_L - m_{CB} - m_C \quad (3)$$

The remaining mass m_{Wt} is to be exerted through weight pieces on the bulk solid sample; that is, corresponding weights have to be placed on disk Z5 of the time consolidation bench when the sample under consideration is loaded.

Often one can neglect the masses of loading rod Z4 and disk Z5, so that one subtracts only the masses of lid 7 and time consolidation crossbeam 26 from mass $m_i = F_i/g$:

$$m_{Wt} = (F_i/g) - m_L - m_{CB} \quad (4)$$

When Eq 4 is used, the results of the time consolidation measurements gain some additional safety with regard to silo design for flow, since the masses of the loading rod Z4 and the disk Z5 will cause a somewhat larger time consolidation.

Since the shear strength after time consolidation is not very sensitive to the force σ_1 , it is sufficient to select m_{Wt} to satisfy Eq 3 to within $\pm 5\%$.

NOTE 25—To reduce the danger of falling weights, put the weight pieces one after the other on disk Z5, turning each weight piece by about 90° relative to the weight piece below.

8.2.4.14 Store the sample under load for the given time interval.

NOTE 26—The time consolidation bench may not be subjected to shocks or vibrations during this time. Also pay attention to constant temperature. Do not expose the samples in the time consolidation bench to direct sunlight.

8.2.4.15 After the chosen time *t* has elapsed, remove the guide rollers 12 (see Figs. 2 and 3) from the ring shear tester.

8.2.4.16 Carefully remove the weight pieces from disk Z5 of the time consolidation bench.

8.2.4.17 Carefully lift up loading rod Z4 with plastic cap Z3 and fix the loading rod Z4 in its upper position with fixing screw Z6 (Fig. 9, medium position).

NOTE 27—The plastic cap must not hit against shear cell or lid. Any shocks can influence the bulk solid sample and lead to incorrect measurement results.

8.2.4.18 Remove the shear cell 4 along with the lid 7 from

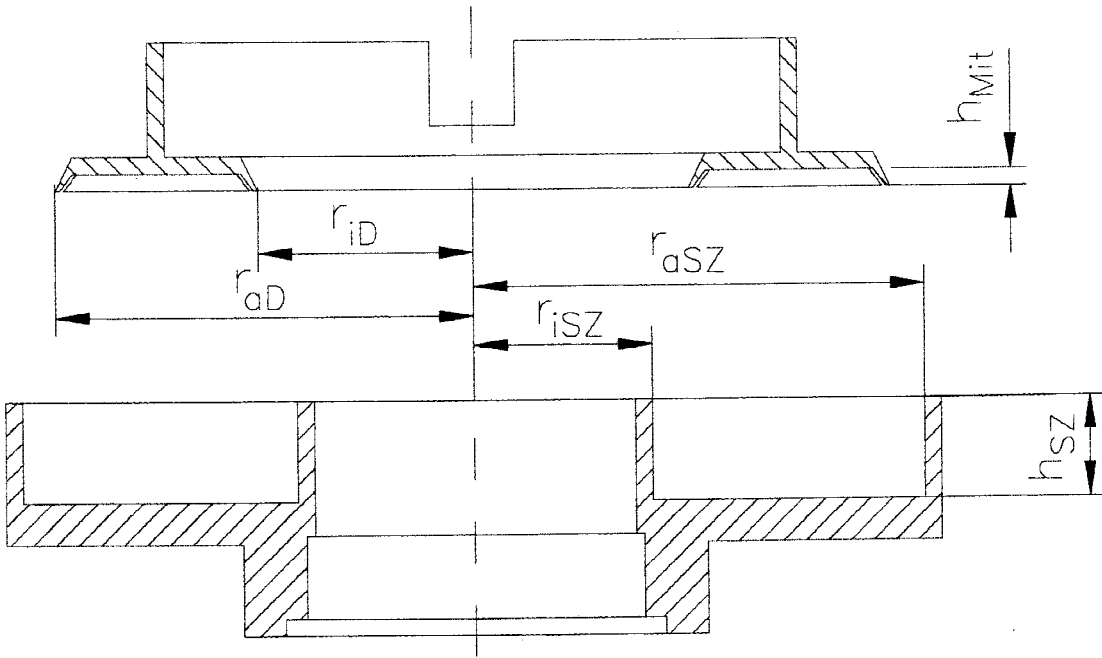


FIG. 13 Main Dimensions of Wall Friction Cell

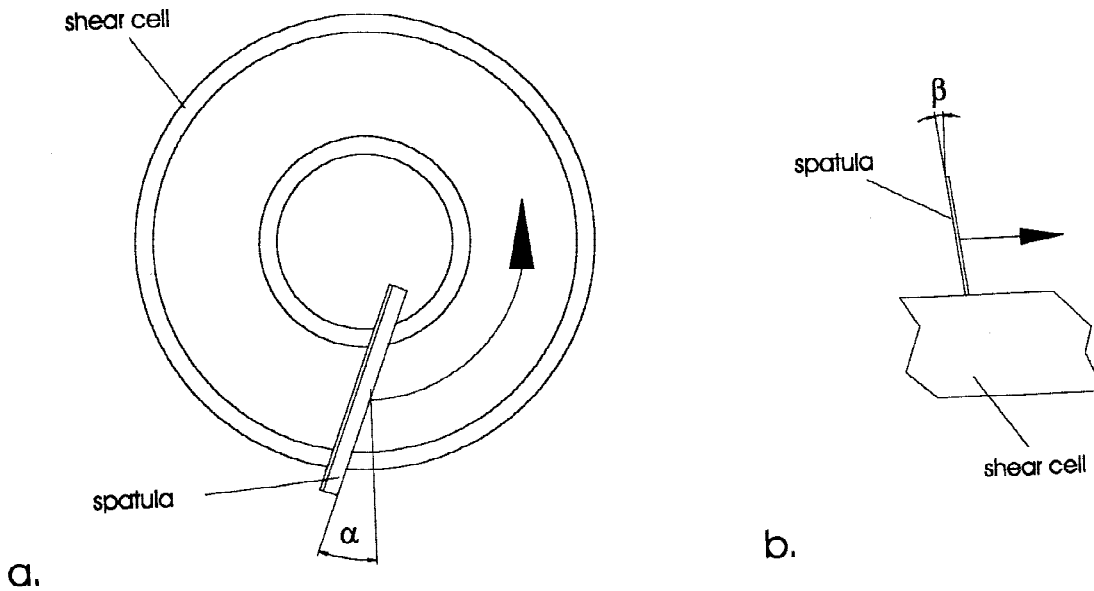


FIG. 14 Scraping Off Excess Powder

the supporting plate Z2 carefully and without vibrations. Put the shear cell on driving axle 5 of the ring shear tester.

8.2.4.19 Remove time consolidation crossbeam 26 from lid 7.

8.2.4.20 Carefully put crossbeam 8 on lid 7 and fix it into position with knurled screws 9. Tighten knurled screws 9 only loosely.

8.2.4.21 Append hanger 11 carefully at hook 25 which is located on the lower side of the crossbeam 8.

8.2.5 Shear of Specimen After Time Consolidation:

8.2.5.1 Select a weight m_{wS} . Perform shear in the same manner as for instantaneous flow. For time tests, select no more than three shear normal stress levels for each preshear stress.

NOTE 28—Due to the scatter obtained in time shear tests, it is recommended that they be performed at least twice at each shear normal stress. Only use the higher (highest) value.

8.2.6 Validity of Time Shear Points:

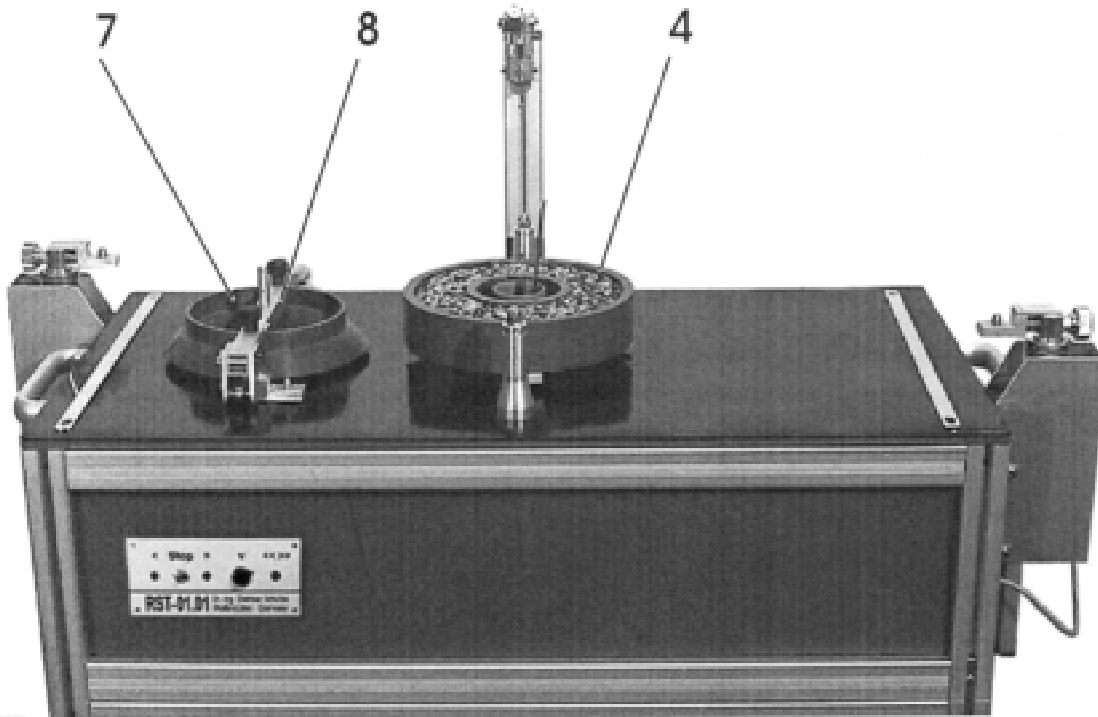


FIG. 15 Ring Shear Tester with Shear Cell on Driving Axle 5

8.2.6.1 Plot the time shear points in σ , τ -coordinates (Fig. 21) and draw a straight line called the time yield locus TYL through the highest shear point and parallel to the instantaneous yield locus (for that particular preshear normal stress level). Draw a Mohr circle through the origin and tangential to this straight line.

NOTE 29—Those time shear points which lie to the right of this point of tangency A_t of the Mohr circle to the straight line time yield locus are considered valid. The normal stress applied at shear for the highest time yield point S_{3t} is generally less than the normal stress applied at the end point, B , of the instantaneous yield locus.

8.3 Procedure for Wall Friction

8.3.1 When measuring the friction between the particulate solid and a coupon of silo wall material in a wall friction test, add spacers and a coupon of wall material to the shear cell bottom ring. Shear the specimen contained in bottom ring over the wall material coupon under different wall normal stresses σ_w and measure the resulting wall shear stresses τ_w .

8.3.2 Selection of Wall Friction Normal Stress Levels:

8.3.2.1 Select six wall friction normal stress levels σ_{w1} to σ_{w6} where σ_{w1} is the smallest normal stress. The largest normal stress σ_{w6} should be approximately equal to the major consolidation stress $\sigma_{1,2}$ of the second preshear normal stress, $\sigma_{p,2}$. The smallest normal stress σ_{w1} will normally include the hanger without weights.

8.3.3 Wall Coupon and Material Specimen Preparation:

8.3.3.1 Wash the wall material coupon and dry thoroughly before the test. Do not touch the surface after washing with bare hands.

8.3.3.2 Insert the spacer rings 51 and the wall material sample in the bottom ring 48 (Fig. 10). The distance between

upper edge of the bottom ring 48 and upper surface of the wall material sample should total about 8 to 10 mm.

8.3.3.3 Weigh the bottom ring 48 with content (note total mass m_{wand}).

8.3.3.4 Connect crossbeam 8 and lid 49 using the knurled screws 9.

8.3.3.5 Fill the bottom ring 48 with the bulk solid to be tested. See 7.1.

8.3.3.6 If necessary, clean the bottom ring 48 from outside. Then weigh the bottom ring 48 with content (note total mass $m_{w,ges}$).

8.3.3.7 Ascertain that the power supply is switched on.

8.3.3.8 Put the filled bottom ring 48 on driving axle 5 (in analogy to Fig. 15). The drivers at the underside of the shear cell must engage in the toothed wheel at the driving axle 5.

8.3.3.9 Carefully place the lid 49 concentrically on the bottom ring 48 on the bulk solid sample. The lid 49 must be in a position turned a few degrees counterclockwise to its shear position (shear position: longitudinal axis of the crossbeam 8 is perpendicular to the front edge of the casing 2). The open side of the hook 25 in the center of the crossbeam 8 should be directed to the right. Locate handle 24 of the hanger 11 on the right side of crossbeam 8 (in analogy to Fig. 16).

8.3.3.10 Put the tie rods 13 on both the bolts at the ends of crossbeam 8 (circular holes of tie rods 13) and the seatings 16 at the load beams 17 (long hole of the tie rod 13).

NOTE 30—The tie rods 13 should have some clearance in the seatings 16; that is, the tie rods must not be stressed at that stage. Important: If it is not possible to connect the tie rods as described above, do not move the lid manually! This would influence the test result. Only use the motor drive to turn the shear cell with the lid in a position where it is possible

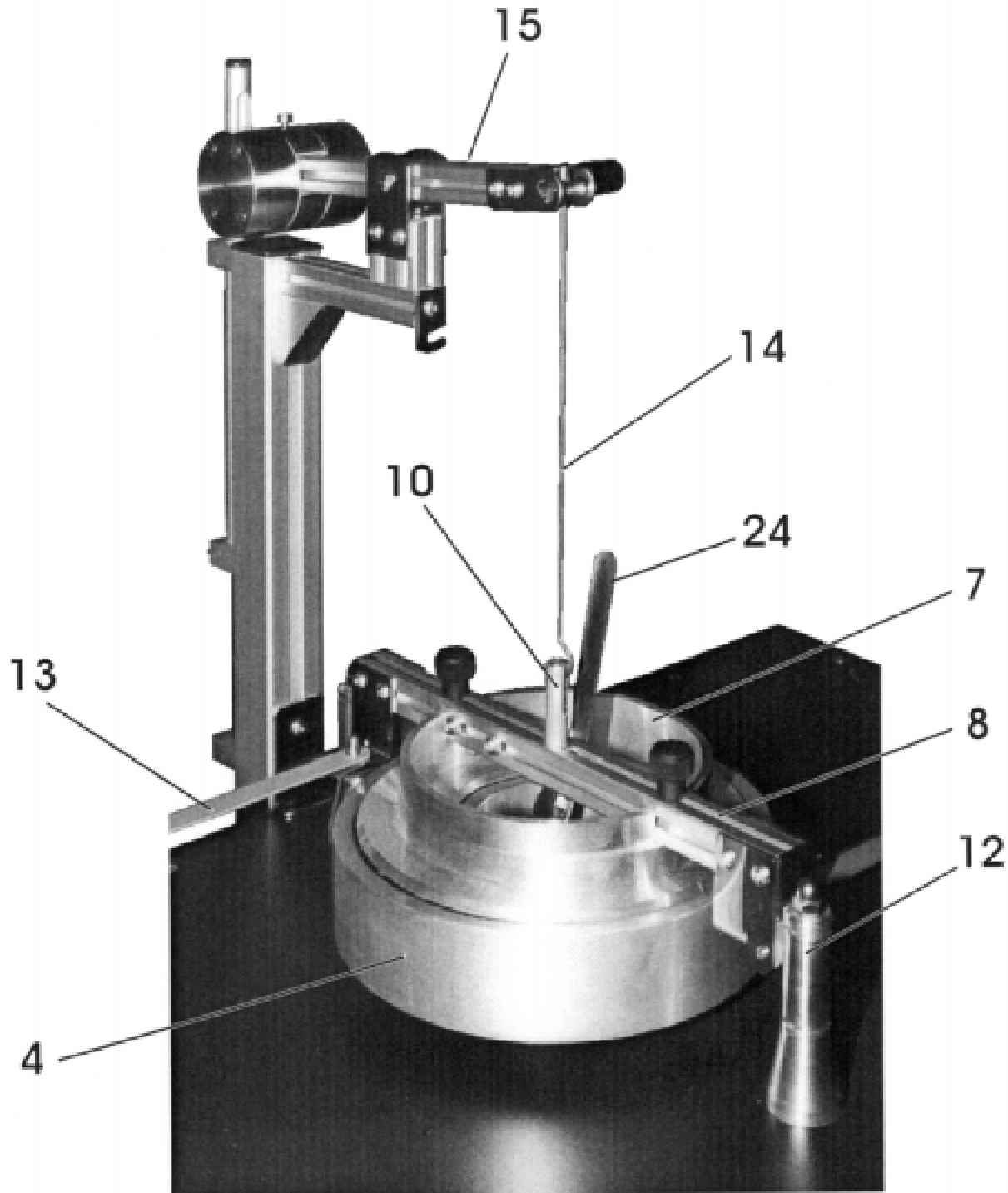


FIG. 16 Shear Cell 4 and Lid 7 Connected to Hanger 11, Counterbalance System and Tie Rods 12

to connect the tie rods to the load beams!

8.3.3.11 Append hanger 11 at hook 25 on the lower side of crossbeam 8.

8.3.3.12 Carefully put appropriate weight pieces on the circular plate 19 of the hanger.

NOTE 31—The total weight of the weight pieces on the hanger must be less than or equal to the maximum normal load to be used for the wall friction measurement.

8.3.3.13 Remove hook 14, which is connected to the balance arm, from its off-position mounting 32 and append it to the central axis 10 (in analogy to Fig. 16).

NOTE 32—To do this, the front end of the balance arm must be pulled down at the black handle 46 provided for this (the handle is not shown in all figures; see Fig. 6).

NOTE 33—If the lid sinks down very much, the lower edge of the lid may touch directly the upper surface of the wall material sample, thus

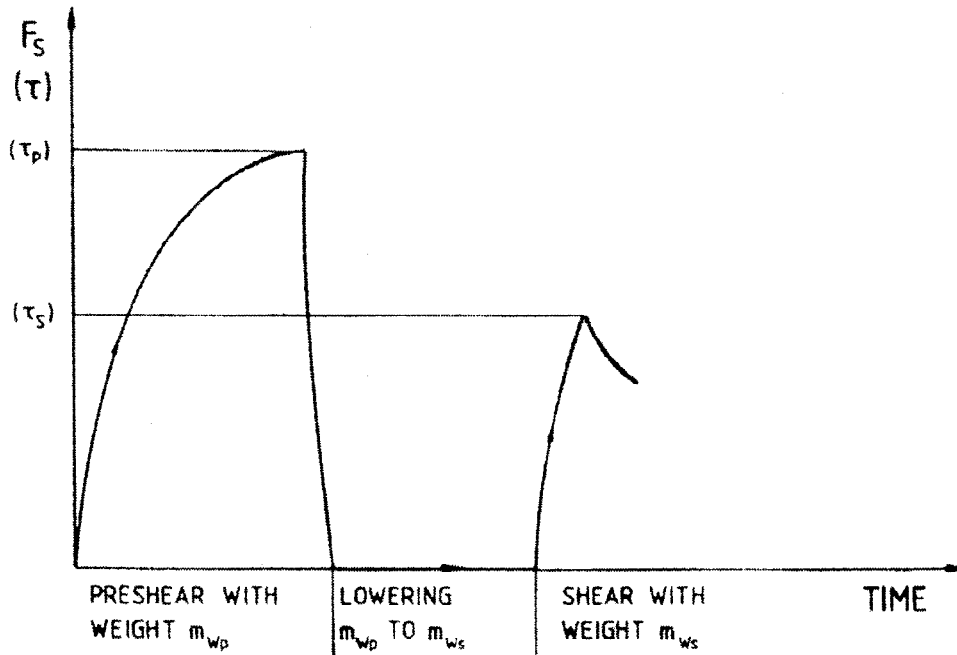


FIG. 17 Stress-Strain Curves—Preshear and Shear

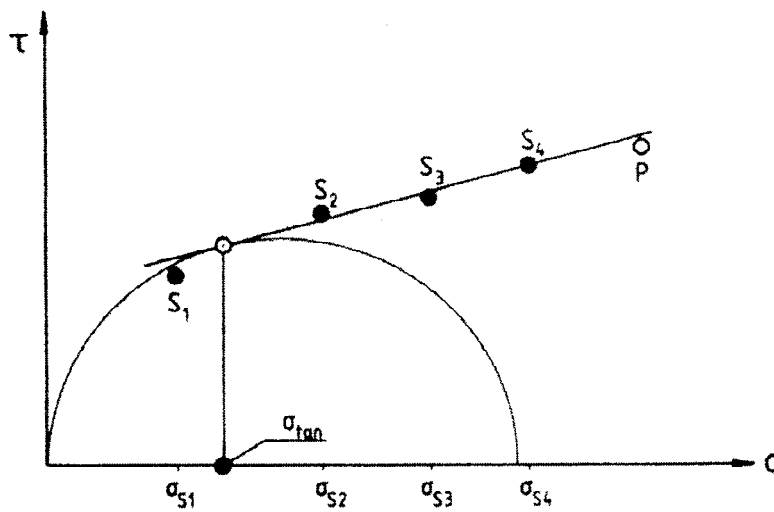


FIG. 18 Yield Locus and Data Points

causing incorrect measurement results. If this happens, remove the shear cell from the tester, remove the lid from the bottom ring, and add additional bulk solid into the bottom ring following procedure starting at 8.3.3.5.

8.3.3.14 Check the adjustment of the rotational velocity (front panel 35). The circumferential velocity at the mean specimen diameter should be 1 to 2 mm/min.

8.3.4 Wall Friction Tests:

8.3.4.1 Start the motor.

NOTE 34—After some time, both tie rods 13 are transferring tensile forces. The total force F (“shear force”) is then measured.

8.3.4.2 Determine by visual inspection of the recorder chart when the shear stress τ_{w6} has reached a constant value. Then remove weight(s) until the normal stress is reduced to σ_{w5} .

Continue to rotate cell during removal of the weights. When the shear stress has again reached a constant value, record the shear stress τ_{w5} and remove more weights to reduce the normal stress to σ_{w4} . When the shear stress has again become constant, record the stress τ_{w4} . Continue this procedure over the range of selected normal stresses.

NOTE 35—Be careful that the lid 49 does not touch the upper surface of the wall material sample thus causing incorrect measurement results! If this happens, additional bulk solid must be filled into the shear cell. Remove the shear cell from the tester and go to 8.3.3.5.

8.3.4.3 To terminate the measurement, drive back the shear cell until the tie rods 13 are relieved.

8.3.4.4 Switch off the motor.

8.3.4.5 Remove tie rods 13.

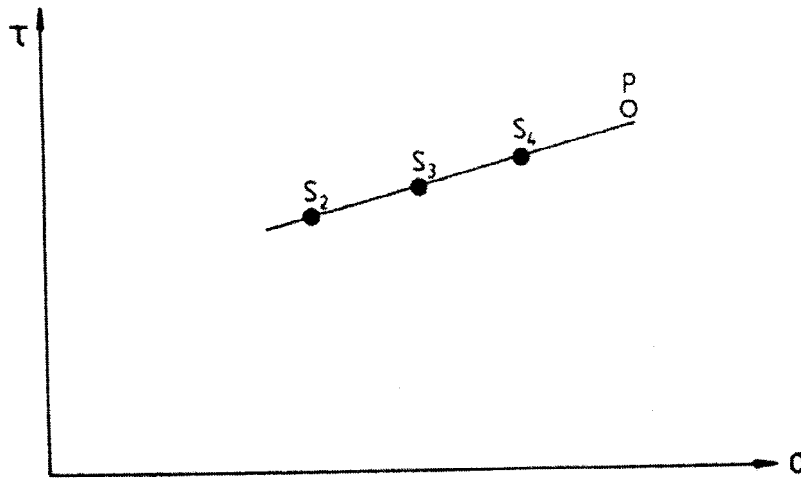


FIG. 19 End Point Above Fitted Line

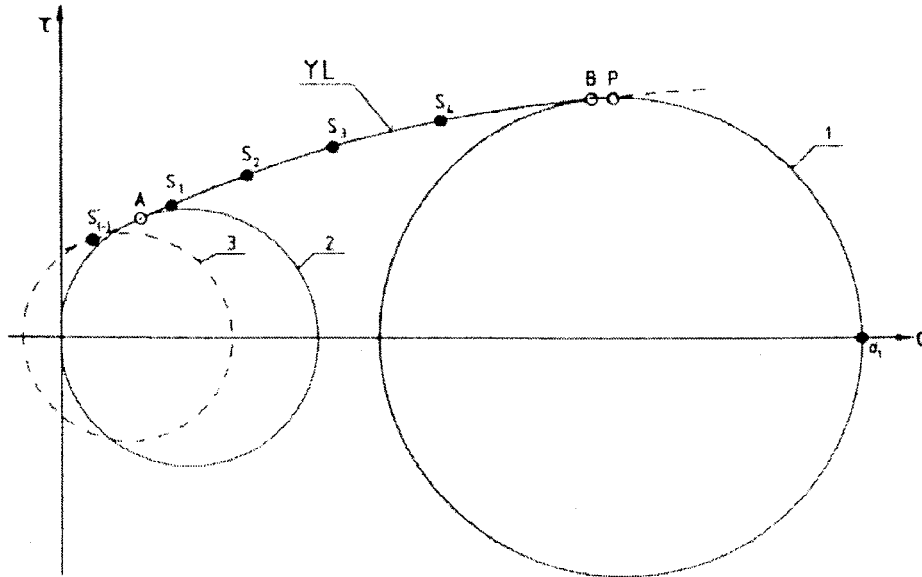


FIG. 20 Yield Locus Showing Valid Shear Points

8.3.4.6 Unhook hook 14 from the central axis 10, thus deactivating the counterbalance system.

8.3.4.7 Remove weight pieces from the hanger 11.

8.3.4.8 Unhook hanger 11 from the hook 25 on the lower side of the crossbeam 8.

8.3.4.9 Take off the bottom ring 48 along with the lid 49.

8.3.4.10 Empty the bottom ring 48; if necessary clean the bottom ring 48, the lid 49, and the driving axle 5.

8.3.4.11 Repeat wall friction tests two to three times with new samples of the particulate solid.

NOTE 36—Sometimes there will be a rapid oscillation of the indicated shear force because of slip-stick behavior. The shear stress maxima recorded during shear should be used to evaluate the wall friction angle ϕ' .

NOTE 37—In many cases, there is no distinct difference between static and kinematic friction. However, the shear force may pass through a

maximum when starting a wall friction test; that is, there is a peak shear stress at τ_{w6} . If static friction is suspected, the static angle of wall friction can be determined as follows: A test is performed as described above but when the shear force has passed through the maximum, the direction of rotation is reversed. After the shear force has fallen to zero, the weight on the hanger is reduced and the motor is started again. The shear force will again pass through a maximum and the procedure of reversing the direction of rotation and reducing the weight is repeated. The peak values of τ_w are used to evaluate the static angle of wall friction.

8.4 Wall Friction Time Tests

8.4.1 Static wall friction tests with time consolidation are also known as adhesion tests.

8.4.2 Cut three coupons of the same wall material and wash and dry them thoroughly.

8.4.3 Perform a wall friction test using wall friction normal stresses σ_{w6} to σ_{w1} , to obtain a defined compaction of the

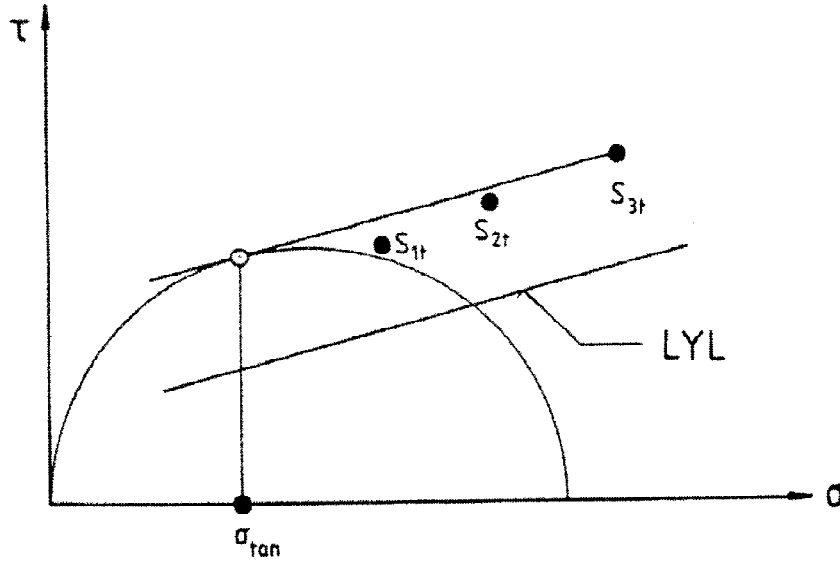


FIG. 21 Validity of Points on the Time Yield Locus

particulate solid particles. Increase the load to σ_{w6} and perform a shear test until the shear stress attains a constant value. Without stopping, reduce the load to σ_{w5} . When the shear stress again reaches a constant value, stop and reverse the direction of shear cell rotation.

NOTE 38—This step can be considered as wall friction “preshear,” which gives the “initial” shear stress τ_{wp5} .

8.4.4 Remove the weights and hanger and very carefully place the bottom ring with material specimen and wall coupon onto a consolidating bench.

NOTE 39—At this time the material specimen will have little or no adhesion to the wall plate and may move slightly. This does not negate the test.

8.4.5 Using the weight carrier or hanger with appropriate weights, apply the normal stress σ_{w5} . If a weight carrier is used, calculate the appropriate weights required using Eq 3.

8.4.6 After the chosen time t has elapsed, transfer the bottom ring with material specimen and wall coupon to the shear tester. Take care not to bump the specimen during this transfer as any break in the adhesive bond will nullify the test. Using the weight hanger and weights, load the shear lid to give a normal stress σ_{w5} and perform shear in the normal way. The shear stress will pass through a maximum, the “time” wall friction shear stress, and is given the symbol τ_{wt5} .

8.4.7 The pair of stresses (σ_{w5} , τ_{wt5}) define the point S_{w5} . Using the second wall coupon, obtain another point (σ_{w3} , τ_{wt3}) by preshearing the specimen under normal stresses of σ_{w4} and σ_{w3} and time consolidate it at σ_{w3} as described above. Obtain a third point (σ_{w1} , τ_{wt1}) using the normal stresses σ_{w2} and σ_{w1} for preshear and σ_{w1} for time consolidation. Further points (σ_{w4} , τ_{wt4}) and (σ_{w2} , τ_{wt2}) can be measured using the same procedure.

9. Calculation and Interpretation of Results

9.1 Data Processing for Instantaneous Shear Tests:

9.1.1 Calculate the mean bulk density in the shear cell ρ_b by dividing the mass m_{SG} of the bulk solid by its volume V_{pr} .

$$\rho_b = m_{SG}/V_{pr} \quad (5)$$

NOTE 40—The mass m_{SG} follows from the total weight of the filled shear cell, m_{ges} , and the mass of the bottom ring of the shear cell, m_B :

$$m_{SG} = m_{ges} - m_B \quad (6)$$

The volume of the bulk solid after consolidation, V_{pr} , is to be calculated from the volume of the shear cell, V_{SZ} , and the lid displacement measured at the test, Δh :

$$V_{pr} = V_{SZ} - A_{SZ} \Delta h \quad (7)$$

where:

A_{SZ} = cross-sectional area of the shear cell.

9.1.2 Calculate the Normal Stress σ —To calculate the normal stress σ acting in the shear zone, the normal force N has to be divided by the cross-sectional area of the lid A_D .

$$\sigma = N/A_D \quad (8)$$

The normal force N consists of the mass of the weight pieces on the hanger, m_G , and the mass of the bulk solid layer in the region of the bars at the lid.

$$\sigma = (m_G g)/A_D + g \rho_b h_{Mit} \quad (9)$$

where:

g = acceleration due to gravity (approximately 9.81 m/s^2).

NOTE 41—The height of the layer of bulk solid in the region of the bars, h_{Mit} is assumed to be equal to the height of the bars.

9.1.3 The shear stress in the bulk solid specimen is calculated from the moment M_d acting during shear. This moment results from the product of the total force F measured with the two load beams and the moment arm $r_s = 0.125 \text{ m}$:

$$M_d = r_s F \quad (10)$$

NOTE 42—The two load beams are connected in parallel, so that the total force F (sum of the forces acting at the two load beams) is measured.

NOTE 43—The shear stress τ acting in the shear zone is assumed to be constant over the cross-section of the shear cell. The circumferential force, which is acting on the lid due to the shear stress, follows from the product of shear stress τ and the cross-sectional area of the lid, A_D . This force (τA_D) also causes a moment about the rotational axis of the shear cell.

9.1.4 Calculate the moment arm r_m of force τA_D from:

$$r_m = 2/3 (r_{aD}^3 - r_{iD}^3)/(r_{aD}^2 - r_{iD}^2) \quad (11)$$

where:

r_{iD} , r_{aD} = inner and outer radius of the lid.

9.1.5 From equilibrium of moments (moment due to force F and moment due to shear stress τ), calculate the mean shear stress τ acting in the bulk solid specimen:

$$\tau = M_d/(r_m A_D) = r_s F/(r_m A_D) \quad (12)$$

9.1.6 Evaluate results separately for every chosen value of the preshear normal stress, although all points should be shown on one σ, τ -diagram.

9.1.7 Plot the preshear point P and all valid shear points for one given preshear normal stress level in σ, τ -coordinates. Draw a smooth line through the valid points and extrapolate it to the preshear normal stress. If this line passes above or through point P , use it for further calculations. If it passes below point P , plot a new line passing through point P and fit it to all the valid yield points.

9.1.8 Draw a Mohr circle through the origin, tangential to this smooth line, the instantaneous yield locus (YL in Fig. 22).

NOTE 44—The higher point of intersection of this Mohr circle with the σ -axis is the unconfined yield strength f_c .

9.1.9 Draw a second Mohr circle through point P , tangential to the instantaneous yield locus in such a way that the point of tangency is to the left of the preshear point P .

NOTE 45—The upper point of intersection of this Mohr circle with the normal stress axis is the major consolidation stress σ_1 . In this way the pair of values, f_c and σ_1 , associated with this particular yield locus are produced, these values all being associated with the major consolidation stress σ_1 .

NOTE 46—The yield locus is normally found to show a small curvature, convex upwards. With many particulate solids a straight line is a sufficient approximation. If the yield locus is approximated as a straight line for all particulate solids, then subsequent calculations are much simpler but in some cases somewhat conservative results may be obtained; that is, a higher f_c value will be determined than when using a fitted curve.

9.1.10 Determine the angle of internal friction of the particulate solid ϕ_i for each major consolidation stress, σ_1 by

measuring the angle between a yield locus and the σ -axis.

NOTE 47—Since this angle varies with σ when using a smooth line yield locus, its value should be read from the linearized yield locus (LYL), which is the tangent to the two Mohr circles characterizing the major principal stresses σ_1 and f_c (Fig. 22).

9.1.11 Draw a straight line through the origin, tangential to the major principal stress Mohr circle. This line, which is the effective yield locus (EYL), forms an angle δ with the axis, called the effective angle of friction. For a given preshear normal stress and value of σ_1 , determine a mean bulk density ρ_b .

NOTE 48—The above calculation produces values of f_c , ϕ_i , δ and ρ_b , for each σ_1 . By making measurements at several preshear normal stresses the dependencies of f_c , ϕ_i , δ and ρ_b on σ_1 can be determined as shown in Fig. 23.

9.1.12 Fit a smooth curve through the pairs of points (σ_1, f_c) . See Fig. 23e. The σ_1 and f_c coordinates should be to the same scale. The dependency of f_c on σ_1 is called the Flow Function (FF) for instantaneous flow.

NOTE 49—The Flow Function usually has a slight curvature convex upwards.

9.1.13 Fit a smooth curve through the points (σ_1, δ) as shown in Fig. 23d. Also plot in a similar way ϕ_i and ϕ_t as shown in Fig. 23c and ρ_b as shown in Fig. 23a.

NOTE 50—For cohesive materials, δ will decrease with increasing σ_1 .

9.2 Evaluation of Time Shear Test Data:

9.2.1 Carry out evaluations separately for each preshear normal stress level. Plot the valid time shear points for each preshear normal stress level in σ, τ -coordinates (Fig. 24). Fit a smooth line through the points. This smooth line is called the time yield locus.

9.2.2 Draw a Mohr circle through the origin and tangential to the time yield locus.

NOTE 51—The highest point of intersection of this Mohr circle with the σ -axis is the time unconfined yield strength, f_{ct} . This value, together with the major consolidation stress for instantaneous flow, σ_1 , for each selected preshear normal stress gives the values σ_1, f_{ct} that are used in plotting the time flow function, FF_t .

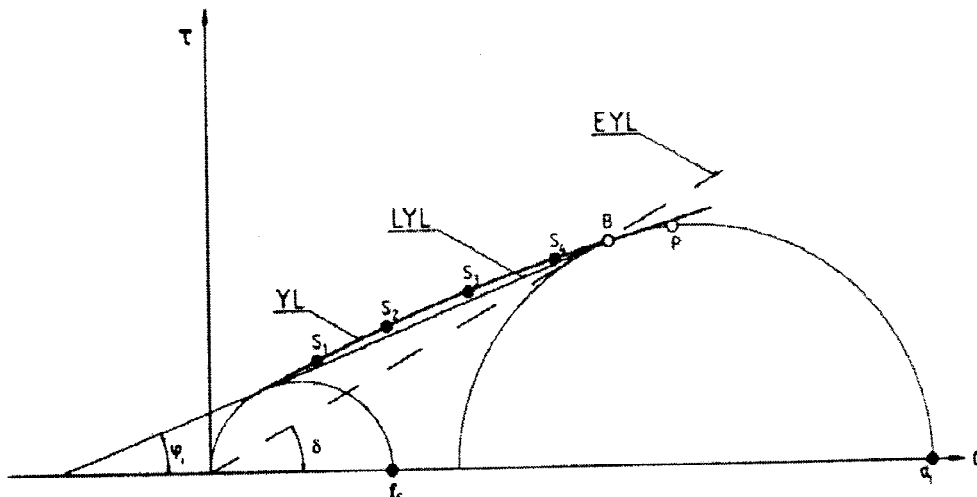


FIG. 22 Mohr Circles, Angles of Friction and Yield Locus

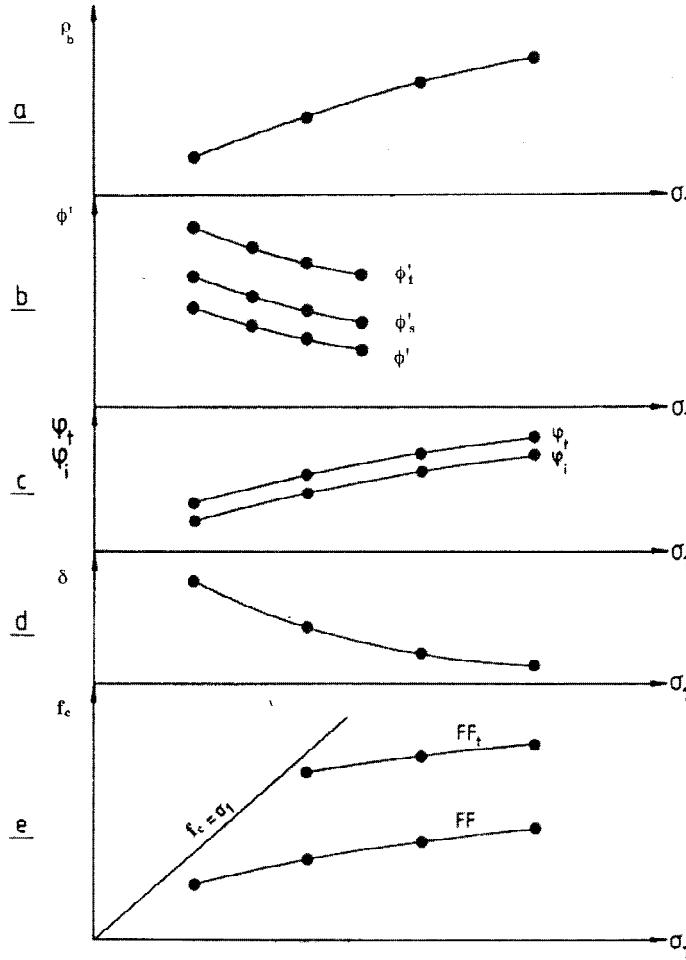


FIG. 23 Powder Properties as a Function of σ_1

NOTE 52—The angle between the time yield locus and the σ -axis is the time angle of internal friction, ϕ_t for that particular σ_1 (Fig. 24).

9.2.3 Plot the time flow function, FF_t by fitting a smooth curve or a straight line to the pairs (σ_1, f_{ct}) from each yield locus.

9.3 Evaluation of Wall Friction Test Data:

NOTE 53—The bulk density ρ_b , which prevails during the wall friction test, cannot be determined accurately due to the small height of the bulk solid specimen and the influence of the specially designed lid. Therefore, no equations for this are presented.

9.3.1 Calculate the mass m_{SG} of the bulk solid in the shear cell.

$$m_{SG} = (m_{w,ges} - m_{wand}) \tag{13}$$

NOTE 54—The shear zone is assumed to be located directly at the surface of the wall material sample. The normal force acting on the wall results from the weight pieces on the hanger (mass m_G) and the mass m_S of the bulk solid between the shear zone and the lid (mass $m_S < m_{SG}$).

9.3.2 Calculate the mass m_S of the bulk solid between shear zone and lid from the mass of the bulk solid in the shear cell multiplied with the ratio of the area of the lid, A_D , to the cross-sectional area of the shear cell, A_{SZ} :

$$m_S = m_{SG} A_D/A_{SZ} \tag{14}$$

9.3.3 Calculate the wall normal stress σ_W :

$$\sigma_W = (m_G + m_S) g/A_D \tag{15}$$

9.3.4 The shear stress in the bulk solid sample is calculated from the moment M_d acting during shear. The moment results from the product of the total force F measured with the two load beams and the moment arm $r_S = 0.125$ m (see 9.1.3):

$$M_d = r_S F \tag{16}$$

NOTE 55—The bulk solid is “fixed” at the lid whereas the wall material sample is rotating with the bottom ring of the shear cell. Thereby a shear stress, the “wall shear stress” τ_W , is exerted on the wall material surface. Hence, the shear zone is directly at the surface of the wall material sample. The wall shear stress τ_W is assumed to be constant over the cross-section of the shear zone.

9.3.5 Calculate the circumferential force, which is acting on the lid due to the shear stress, from the product of wall shear stress τ_W and the cross-sectional area of the lid, A_D . This force ($\tau_W A_D$) also causes a moment about the rotational axis of the shear cell. The moment arm r_m of force $\tau_W A_D$ is calculated from Eq 11 in 9.1.4.

9.3.6 From equilibrium of moments (moment due to force F and moment due to wall shear stress τ_W), calculate the mean shear stress τ_W acting on the wall material sample:

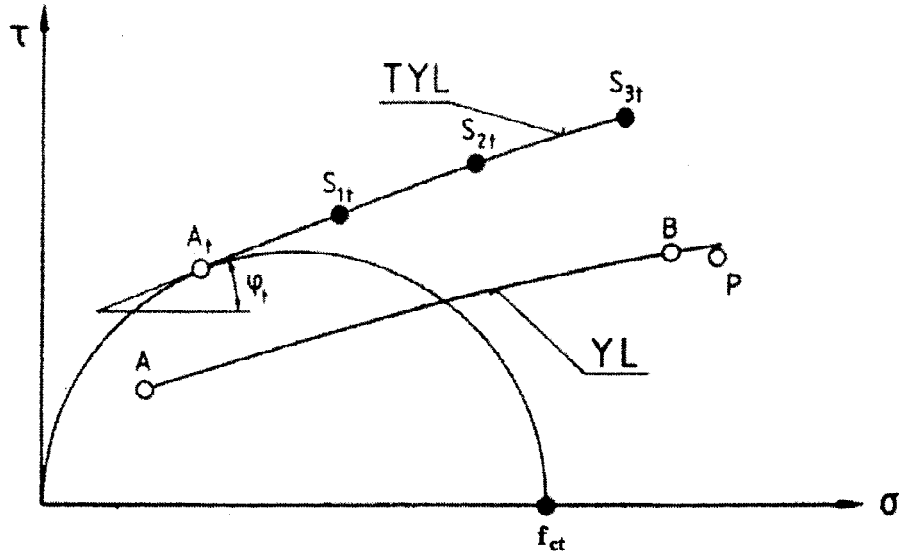


FIG. 24 Time Yield Locus

$$\tau_w = M_d(r_m A_D) = r_s F / (r_m A_D) \quad (17)$$

9.3.7 Plot the points σ_{wi} , τ_{wi} on σ , τ -coordinates and draw a smooth line through the points (Fig. 25).

NOTE 56—This is the wall yield locus (WYL) of the particulate solid on the specific wall material. The plot of the WYL will be a straight line or a curve convex upwards.

9.3.8 If the wall yield locus is a straight line passing through the origin, then $\phi' = \text{constant}$. Otherwise, superimpose a steady state flow Mohr circle associated with a yield locus and a major consolidation stress σ_1 on the WYL. Determine the upper point of intersection of the WYL with the steady state flow Mohr circle and draw a straight line through the origin and this point of intersection. The angle that this straight line subtends with the σ -axis is the kinematic angle of wall friction ϕ' at this particular major consolidation stress σ_1 .

9.3.9 By repeating the procedure with consolidating Mohr circles associated with higher preshear normal stresses, obtain the corresponding values (σ_1 , ϕ') for each preshear normal stress.

9.3.10 Obtain the static angle of wall friction ϕ'_s by using the σ_{wi} , τ_{wi} -values of the peaks. The steady state values give the kinematic angle of wall friction ϕ' .

9.3.11 Plot ϕ' and ϕ'_s as a function of σ_1 as shown in Fig. 23b.

9.4 Evaluation of Wall Friction Time Test Data:

9.4.1 Evaluate wall friction time tests in a similar way to kinematic wall friction tests. Plot the points S_{wi} on σ , τ -coordinates and fit them by a smooth line called the time wall yield locus (TWYL). The analysis gives a time angle of wall friction ϕ'_t for each of the σ_1 values of the superimposed

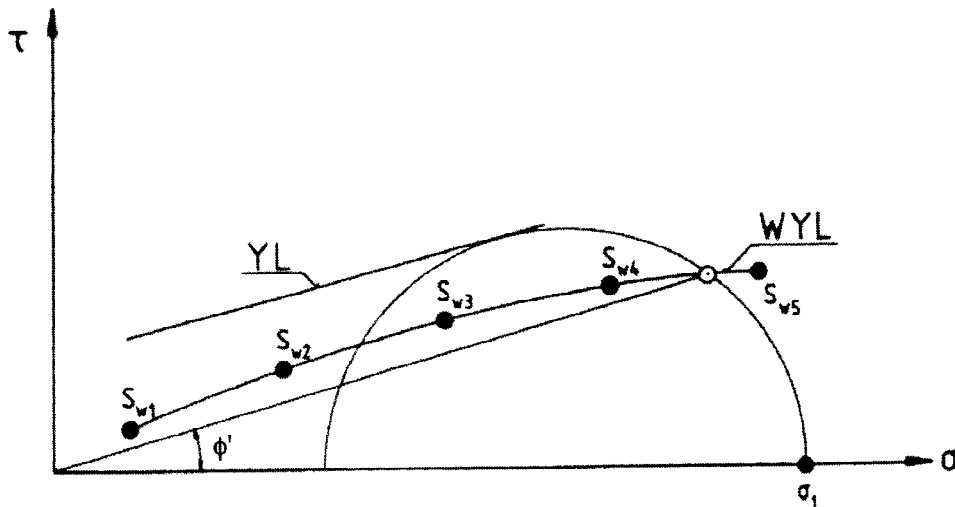


FIG. 25 Wall Yield Locus

steady state Mohr circles.

9.4.2 Plot ϕ'_i as a function σ_1 as shown in Fig. 23b.

10. Report

10.1 Provide in plot form the following properties as a function of σ_1 :

10.1.1 Unconfined yield strength, f_c , that is, flow function, FF .

10.1.2 Time unconfined yield strength, f_{ct} , that is, time flow function FF_t .

10.1.3 Effective angle of friction, δ .

10.1.4 Bulk density, ρ_b .

10.1.5 Angle of internal friction, ϕ_i for instantaneous flow.

10.2 When required by the application, provide in plot form the following additional properties as a function of σ_1 :

10.2.1 Angle of internal friction, ϕ_i after time consolidation.

10.2.2 Angle of kinematic wall friction, ϕ' .

10.2.3 Angle of static wall friction, ϕ'_s .

10.2.4 Angle of time wall friction, ϕ'_t .

11. Precision and Bias

11.1 *Precision*—Data are being evaluated to determine the precision of this test method. In addition, Subcommittee D18.24 is seeking pertinent data from users of the test method.

11.2 *Bias*—There is no accepted reference value for this test method; therefore, bias cannot be determined.

12. Keywords

12.1 bulk solid; effective angle of friction; effective yield locus; flow function; flowability; Jenike Shear Cell; internal friction angle; kinematic wall friction angle; powder; Schulze Ring Shear Tester; translational shear tester; unconfined yield strength; wall friction

ANNEXES

(Mandatory Information)

A1. LIST OF SYMBOLS

A_D	m^2	cross sectional area of shear cell lid
A_{SZ}	m^2	cross sectional area of shear cell (bottom ring)
F	N	shear force
f_c	N/m^2	unconfined yield strength
f_{ct}	N/m^2	time unconfined yield strength
F_t	N	force, which must act on the bulk solid at time consolidation
g	m/s^2	acceleration due to gravity ($g = 9.81 \text{ m/s}^2$)
h_{Mit}	m	height of the bars at the shear cell lid
h_{SZ}	m	internal height of the shear cell
Δh	m	vertical lid displacement
m_B	kg	mass of shear cell (bottom ring)
m_C	kg	mass of loading rod Z4 and disk Z5 (time consolidation bench)
m_{CB}	kg	mass of time consolidation crossbeam (part 26)
M_d	Nm	momentum (torque)
m_G	kg	mass of weights
m_{ges}	kg	total mass of shear cell (bottom ring, without lid) and bulk solid
m_L	kg	mass of shear cell lid (part 7)
m_S	kg	mass of bulk solid beneath lid in wall friction shear cell
m_{SG}	kg	total mass of bulk solid in shear cell
m_t	kg	mass which results in force F_t ($F_t = g m_t$)
$m_{w,ges}$	kg	mass of wall friction shear cell (bottom ring) with spacer rings, wall material
m_{Wand}	kg	mass of wall friction shear cell (bottom ring) with spacer rings and wall material sample
m_{Wp}	kg	mass of weights during preshear
m_{Ws}	kg	mass of weights during shear
m_{Wt}	kg	mass of weights during time consolidation
N	N	normal load
P		averaged preshear point
r_{aD}	m	outer radius of the annular lid
r_{aSZ}	m	outer radius of the specimen in the bottom ring of the shear cell
r_{iD}	m	inner radius of the annular lid
r_{iSZ}	m	inner radius of the specimen in the bottom ring of the shear cell
r_m	m	moment arm of shear stress
r_s	m	moment arm of shear force F
S_i		prorated and averaged shear point
t	h	consolidation time
V_{pr}	m^3	volume of the bulk solid specimen
V_{sz}	m^3	internal volume of the shear cell (bottom ring)
α	°	angle defined in 14 a
β	°	angle defined in 14b

δ	°	effective angle of friction
ϕ'	°	kinematic angle of wall friction
ϕ'_{s}	°	static angle of wall friction
ϕ'_{t}	°	time angle of wall friction
ϕ_i	°	angle of internal friction
ϕ_t	°	time angle of internal friction
σ	N/m ²	normal stress
σ_1	N/m ²	major principal stress of a yield locus
σ_p	N/m ²	preshear normal stress
σ_s	N/m ²	shear normal stress or normal stress at shear
σ_w	N/m ²	wall normal stress
ρ_b	kg/m ³	bulk density
τ	N/m ²	shear stress
τ_p	N/m ²	shear stress at preshear
$\tau_{p,m}$	N/m ²	average shear stress at preshear
τ_s	N/m ²	shear stress at failure (shear point)
τ_{st}	N/m ²	shear stress at failure (shear point) measured during time consolidation test
τ'_s	N/m ²	prorated shear stress at failure
τ_w	N/m ²	wall shear stress
τ_{wp}	N/m ²	initial shear stress in wall friction time test
τ_{wt}	N/m ²	time wall shear stress

A2. SELECTION OF SAMPLE, SHEAR CELL, AND TEST WEIGHTS

A2.1 Sample Selection

A2.1.1 For meaningful results select a representative sample of the particulate solid with respect to moisture content, particle size distribution and temperature. For the tests, approximately 10 L of the material should be available, and a fresh material should be used for each individual test specimen. If such a quantity is not available, use a smaller shear cell. If as a last resort shear tests have to be repeated on the same specimen, then before each test the material should be well loosened.

A2.1.2 The flowability of a particulate solid is usually significantly dependent on its moisture content which at equilibrium depends on the ambient humidity. In view of the significant influence of moisture, the amount anticipated during actual storage and flow should be closely reproduced in the test specimen, for example, by equilibrating it to this humidity. To prevent moisture evaporation or adsorption it is advisable to keep the test material in an airtight container, replacing the cover of the container between tests. To prevent inhomogeneities in water content, stir the material in the container regularly and, during the test, handle the specimen and the shear cells rapidly. Upon completion of time tests recheck the moisture in the solid from the shear cells. Ideally, measurements should be made in an air-conditioned room with controlled humidity.

A2.1.3 The effect of particle size distribution is not as perplexing as it might appear. During the flow of a mass of mixed particle sizes, the large particles move bodily while the solid shears primarily across the fines. The coarse particles contribute little to the cohesion of the mass. Therefore the flowability of the mass depends on the properties of the fines. The Schulze Ring Shear Tester is suitable for testing particulate solids with particle sizes of up to about 5 % of the width of the shear cell annulus. Coarser particles should be removed by hand. When removing the larger particles, it is necessary, in so far as possible, to retain the structure of the solid and the moisture content of the fines. If there is danger that by sieving the structure of the solid will be altered, spread the material gently on a tray and remove the larger particles by hand. Do not

screen fibrous solids, whose strength is due to the interlocking of the fibers. Take great care to ensure that the particles do not segregate between sample withdrawal and testing (for example, during transport coarse particles can segregate towards the surface of a material in a container and, if this surface material is taken for shear testing, it will have a lower shear strength). If tests are repeated on the same specimen, take care not to lose fines, for example, by ventilation.

A2.1.4 The effect of temperature on the flowability of solids may be significant. Tests of such solids require a temperature controlled environment.

A2.1.5 The effect of vibration on the shear strength of particulate solids is not treated in this standard. However, since vibrations influence the shear strength of particulate solids to a considerable extent, take care that during measurements, the shear cell is completely free of any vibration either from the force measuring stem driving mechanism, or from the test room.

A2.2 Shear Cell Selection

A2.2.1 The “standard shear cell,” type M, has a relatively large cross-sectional area A_{SZ} of approximately 230 cm² and a sample height of 40 mm (see Table 2).

NOTE A2.1—This cell offers the broadest range of applicability with regard to testing bulk solids. Furthermore, shear cells of this size have been investigated in the past by many comparative tests, from which it was found that these cells are suitable to correctly measure flow properties.

A2.2.2 The cross-sectional area A_{SZ} of the “small shear cell” type S is only about 85 cm², and its sample height is 24 mm (Table 2).

NOTE A2.2—The maximum particle size of bulk solids to be tested using this cell is smaller than with the standard shear cell. Furthermore, measurements at low stresses are less precise, because of, among other factors, the smaller diameter and the smaller area of the cell. The latter leads to the shear force F measured with the load cells being only about 20 % of the shear force F of the standard cell at identical shear stresses in the bulk solid sample.

NOTE A2.3—An advantage of the smaller cell is that a smaller amount of bulk solid is required for a test, because the sample volume of the small

shear cell is only about 200 cm³ in comparison to about 900 cm³ for the standard shear cell. Furthermore, a smaller dead weight is required for the small shear cell in order to attain a certain normal stress in the bulk solid sample. Thus, the small cell is especially appropriate for time consolidation tests.

NOTE A2.4—Comparative tests with the standard shear cell have shown the small cell sometimes measures slightly larger shear stresses. This leads to the yield loci being shifted to somewhat larger shear stresses, which results in somewhat larger unconfined yield strengths. This results in some additional conservatism with regard to silo design to prevent arching and ratholing. For comparative tests, this effect does not play a role as long as the same shear cell type is always used.

A2.3 Equivalence Between Weights and Stresses

A2.3.1 In this standard the loading of shear cells by weights is expressed in the form of the normal stress in the shear plane.

Selection of the masses of weights corresponding to preshear normal stresses may be rounded up to 1 kg if above 4 kg and to 0.5 kg if below 4 kg. Selection of the masses of weights corresponding to shear normal stresses may be rounded up to kilograms if above 6 kg, to 0.5 kg if between 2 and 6 kg and to 0.1 kg if below 2 kg. This rounding up procedure is used only for the selection of weights. From the total of the masses in question, calculate the normal stress to an accuracy of 10 Pa.

A2.3.2 In order to attain the required degree of accuracy measure all weighed components to a precision of 1 g. Although weights are normally well within the required tolerance, it is advisable to check them on purchase. A recently calibrated balance is suitable for this.

REFERENCES

- (1) Jenike, A. W., Storage and Flow of Solids, Bulletin 123, Utah Engineering Experiment Station, 1964 (Rev. 1980).
- (2) Schulze, D.: Development and Application of a Novel Ring Shear Tester (Entwicklung und Anwendung eines Neuartigen Ringscherggerätes), Aufbereitungstechnik 35 (1994) 10, pp. 524-535 (German/English).
- (3) Schulze, D., Heinrici, H. and Zetzener, H.: The Ring Shear Tester as a Valuable Tool for Silo Design and Powder Characterization, Powder Handling & Processing, 13, No. 1, January/March 2001, pp. 19-24.
- (4) Carr, J. F. and Walker, D. M.: An Annular Shear Cell for Granular Materials, Powder Technology, 1 (1967/68), pp. 369-373.
- (5) Peschl, I.A.S.Z.: Measurement and Evaluation of Mechanical Properties of Powders, Powder Handling and Processing, 1, No. 2, June 1989, pp. 135-142.

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