Designation: D6773 – 16

Standard Test Method for Bulk Solids Using Schulze Ring Shear Tester[1]

1. Scope*

1.1 This test 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.

1.2 This test method covers operation of the manually-controlled Schulze Ring Shear Tester. An automated version of this tester is also available. Its method of testing bulk solids is similar in principle to that described in this test method.

1.3 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.

1.4 All observed and calculated values shall conform to the guidelines for significant digits and rounding established in Practice D6026.

1.4.1 The procedures used to specify how data are collected/recorded or calculated in this standard are regarded as the industry standard. In addition, they are representative of the significant digits that generally should be retained. The procedures used do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the user's objectives: and it is common practice to increase or reduce significant digits of reported data to be commensurate with these considerations. It is beyond the scope of this standard to consider significant digits used in analysis methods for engineering design.

1.5 *Units*—The values stated in SI units are to be regarded as standard. No other units of measure are included in this standard.

1.6 *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:*[2]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D2216 Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass

D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction

D4753 Guide for Evaluating, Selecting, and Specifying Balances and Standard Masses for Use in Soil, Rock, and Construction Materials Testing

D6026 Practice for Using Significant Digits in Geotechnical Data

D6128 Test Method for Shear Testing of Bulk Solids Using the Jenike Shear Cell

3. Terminology

3.1 *Definitions*—For common definitions of technical terms in this standard, refer to Terminology D653.

4. Summary of Test Method

4.1 A representative specimen 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.

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[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] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

***A Summary of Changes section appears at the end of this standard**

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, usable 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)**.[3]

5.3 For bulk solids with a significant percentage of particles (typically, one third or more) finer than about 6 mm (¼ 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.

NOTE 1—The quality of the result produced by this standard is dependent on the competence of personnel performing it, and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D3740 are generally considered capable of competent and objective testing/sampling/inspection/etc. Users of this standard are cautioned that compliance with Practice D3740 does not in itself ensure reliable results. Reliable results depend on many factors; Practice D3740 provides a means of evaluating some of those factors. Practice D3740 was developed for agencies engaged in the testing or inspection (or both) of soil and rock. As such it is not totally applicable to agencies performing this standard. However, users of this standard should recognize that the framework of Practice D3740 is appropriate for evaluating the quality of an agency performing this standard. Currently there is no known qualifying national authority that inspects agencies that perform this standard.

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 enable 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 specimen, 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 2—The standard cell has 20 bars, each of which is 4 mm tall (h_{Mit} = 4 mm, Fig. 7).

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 counterbalance 29 (Fig. 6) serves to compensate for the masses of lid 7, crossbeam 8, hanger 11, and tie rods 13. The counterbalance 29 is found at the rear side of the balance arm 15.

6.6 A digital displacement indicator 31 (Fig. 8) is used for the measurement of the height of the bulk solid specimen.

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.

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, is located within the base 1 (Fig. 1). The hanger has a circular plate 19 at its lower end for holding the applied mass pieces.

6.10 For control of the motor drive a front panel 35 (Fig. 3) is at the front side of the casing 2.

6.11 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. (**Warning—**To avoid overloading of the load beams, the indicated maximum normal load must not be exceeded.)

6.12 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. 7. For special purposes (for example, reduced internal volume) other dimensions are also available. The following table provides a rough indication of the applicability of various cell sizes based on maximum particle size of the bulk solid (monodisperse = narrow particle size distribution, for example, plastics pellets, grain). Values in parentheses are valid if particles are not brittle.

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

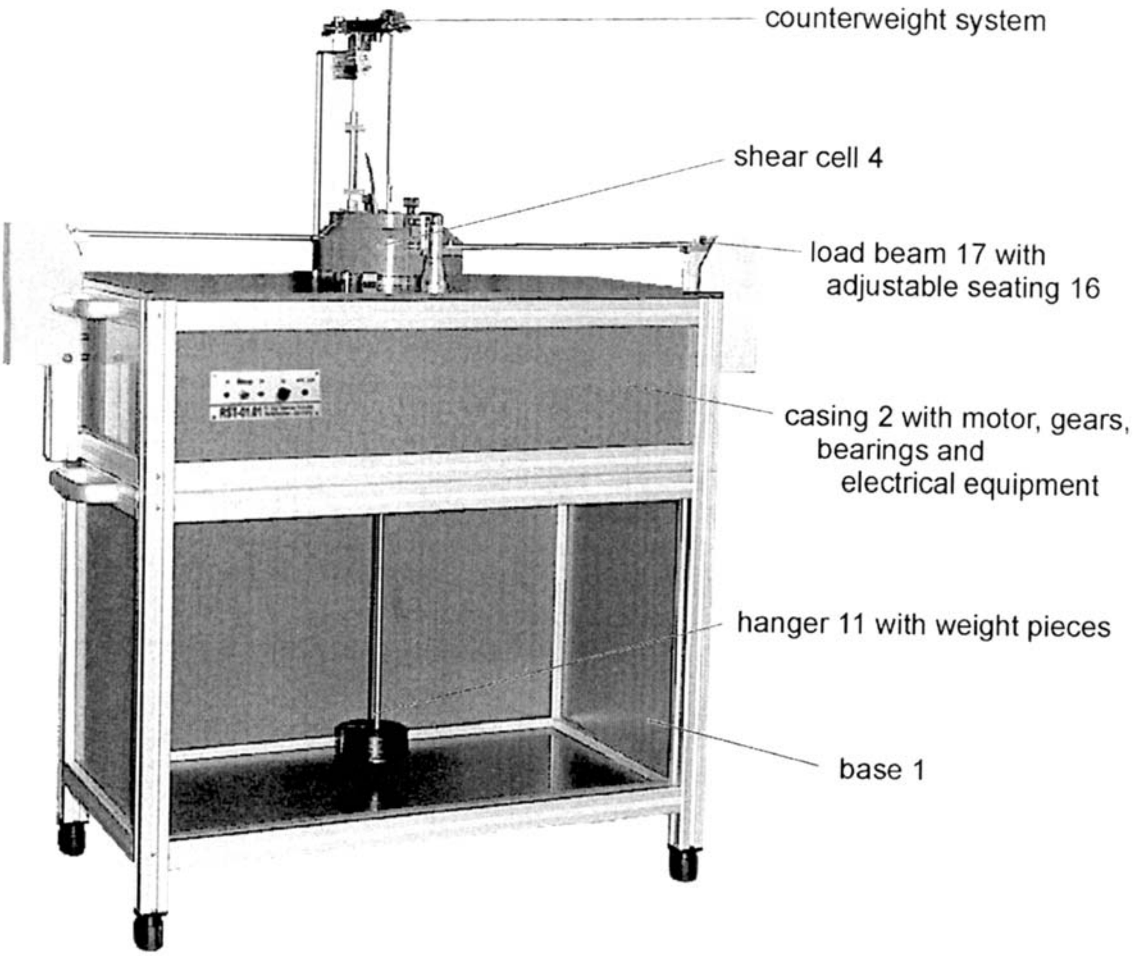

FIG. 1 Ring Shear Tester (overall view)

	maximum particle size, x_{max}	
Shear cell type	monodisperse	broad distribution, 0 ... x_{max}
M	5 mm	10 mm
S	2.5 mm	5 mm
MV10	1 (1.5) mm	2 (3) mm
SV10	0.75 (1) mm	1.5 (2) mm

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

6.13.1 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 cm^3) can be placed on each plate. The shape of the plate Z2 centers the shear cell.

6.13.2 Through the central depression of the time consolidation crossbeam 26 the normal load is exerted during time consolidation as shown in the left part of Fig. 9. The lower end of the loading rod Z4 is equipped with a central tip.

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

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

6.13.5 The fixing screw Z6 serves for the fixation of the loading rod Z4 in the upper position (Fig. 9, on the right).

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

6.14.1 The bottom ring 48 of the wall friction shear cell (see Fig. 10) contains the wall material coupon to be tested.

6.14.2 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.

6.14.3 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 shear cell is provided with downwards protruding edges at the inner and outer radius.

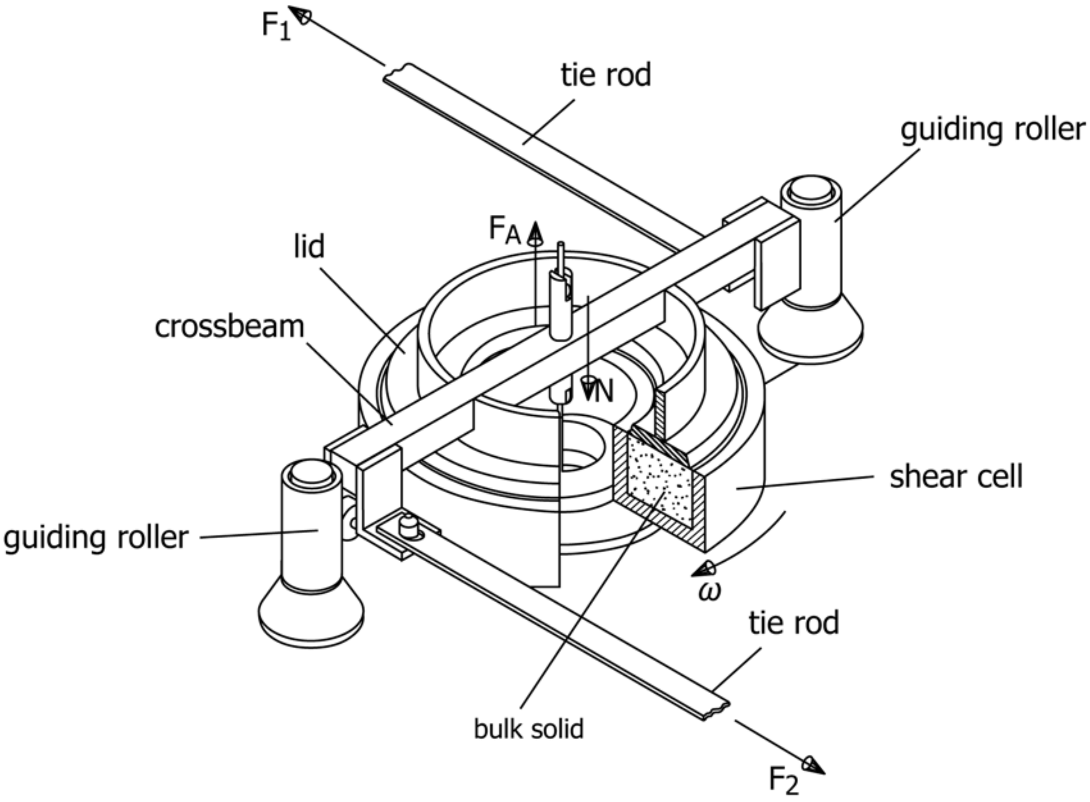

FIG. 2 Shear Cell (in principle)

6.14.4 The dimensions of the wall friction shear cell are shown in Table 1 and Fig. 13.

6.15 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.

6.16 A laboratory balance having a maximum capacity of at least 5 kg with a precision of 0.01 % or better is required.

7. Specimen Preparation

7.1 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 (water) contents, because this often happens in industrial environments. The laboratory environment must approximate production for meaningful testing.

7.2 *Setup:*

7.2.1 Shift the movable counterbalance 29 along the balance arm to adjust the force caused by the counterbalance mass.

NOTE 4—The fixation screw 18 (knurled screw) fixes the counterbalance 29 on the balance arm.

7.2.1.1 After unscrewing the knurled screw, which is the major part of the movable mass 30, shift the movable mass 30 along the balance arm, if necessary, for more precise adjustment of the force caused by the counterbalance mass.

NOTE 5—When the counterbalance mass is well adjusted, the lid, crossbeam, tie rods, and hanger do not press on the bulk solid; that is, the vertical stress at the surface of the bulk solid is equal to zero.

7.2.2 Adjust the seatings 16 to level the lid 7.

7.2.3 Adjust the four adjustable stands 3 on base 1 (Fig. 5) to level the Ring Shear Tester.

7.2.4 Unscrew the fixing screw sufficiently so as to be able to move the loading rod upwards or downwards. In the loading position (Fig. 9, on the left) the fixing screw must remain unscrewed.

7.2.5 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

7.3 *Filling the Cell* (Fig. 14)*:*

7.3.1 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 cell is slightly overfilled with material. The filling should be conducted in such a way as to make sure that there are no voids within the cell.

7.3.2 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 $\beta = 0°$ to 10°) as shown in Fig. 14b. Do not exert a downward force on the material with the blade.

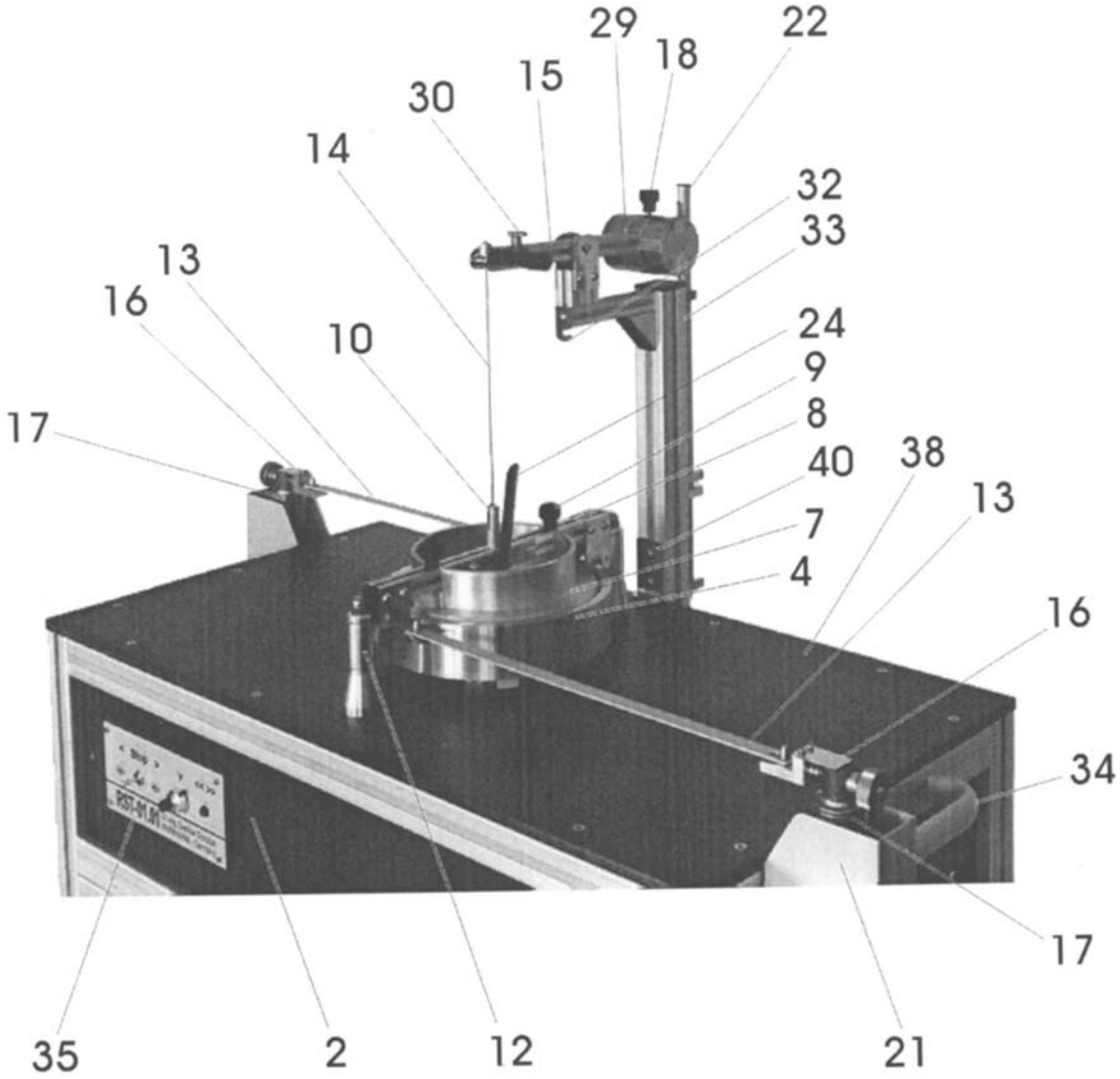

FIG. 3 Ring Shear Tester (upper part)

7.3.3 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.

7.3.4 If necessary, clean the outside of the shear cell. Then determine the mass of the shear cell with contents. Note the total mass m_{tot}.

7.4 *Wall Friction:*

7.4.1 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.

7.4.2 *Selection of Wall Friction Normal Stress Levels:*

7.4.2.1 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 principal 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 applied masses.

7.4.3 *Wall Coupon and Material Specimen Preparation:*

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

7.4.3.2 Insert the spacer rings 51 and the wall material coupon in the bottom ring 48 (Fig. 10). The distance between upper edge of the bottom ring 48 and upper surface of the wall material coupon should total about 8 to 10 mm.

NOTE 6—The thickness of each spacer ring is 2 mm.

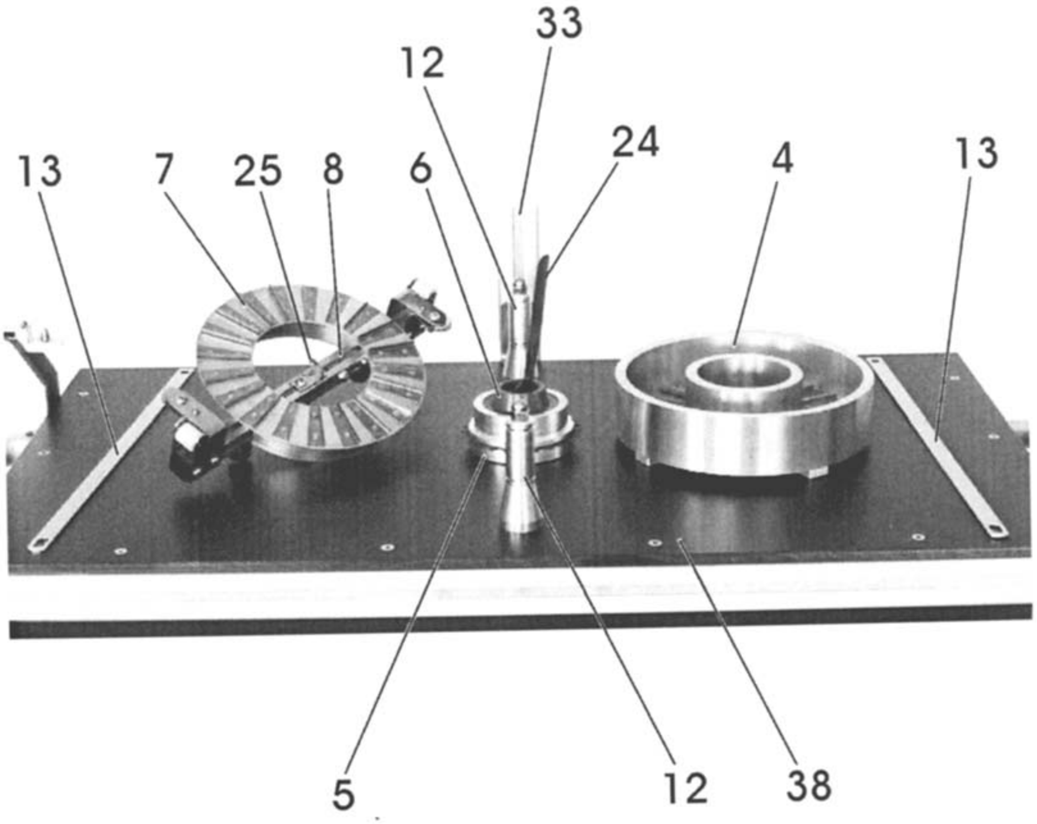

FIG. 4 Upper Part of the Ring Shear Tester, Shear Cell Removed

7.4.3.3 Determine the mass of the bottom ring 48 with content (note total mass m_{wall}).

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

7.4.3.5 Fill the bottom ring 48 with the bulk solid to be tested. See 7.3.

7.4.3.6 If necessary, clean the bottom ring 48 from outside. Then determine the mass of the bottom ring 48 with content (note total mass $m_{W,tot}$).

7.4.3.7 Ascertain that the power supply is switched on.

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

7.4.3.9 Carefully place the lid 49 concentrically on the bottom ring 48 on the bulk solid specimen. 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).

7.4.3.10 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).

(1) 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 to connect the tie rods to the load beams.

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

7.4.3.12 Carefully put appropriate applied mass pieces on the circular plate 19 of the hanger.

NOTE 7—The total mass of the applied mass pieces on the hanger must be less than or equal to the maximum normal load to be used for the wall friction measurement.

7.4.3.13 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). 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).

(1) If the lid sinks down very much, the lower edge of the lid may touch directly the upper surface of the wall material coupon, thus causing incorrect measurement results. If this happens, remove the shear cell from the tester, remove the lid

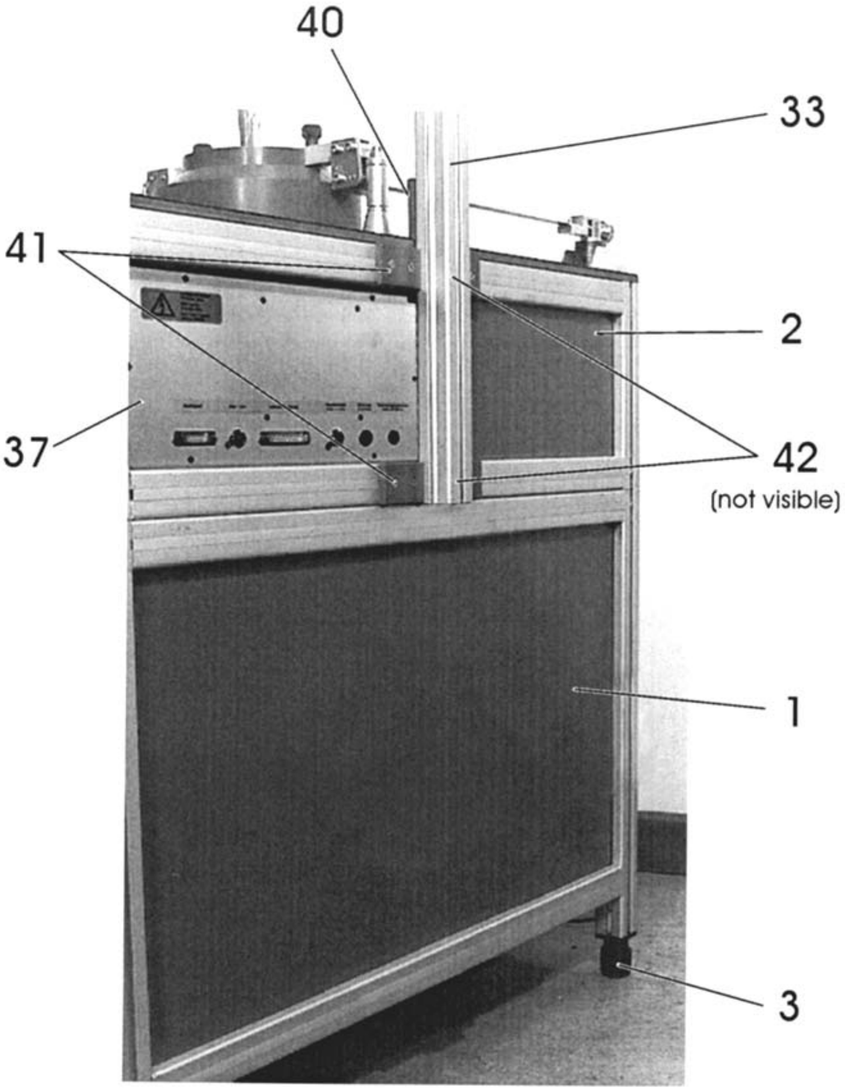

FIG. 5 View on the Reverse Side of the Ring Shear Tester

from the bottom ring, and add additional bulk solid into the bottom ring following procedure starting at 7.4.3.5.

7.4.3.14 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. Procedure

8.1 *Procedure for Instantaneous Shear Test*

8.1.1 *Preshear:*

8.1.1.1 Ascertain that the power supply has been turned on at least 15 min to ensure that the unit is properly warmed up.

8.1.1.2 Put the filled shear cell 4 on the driving axle 5 (Fig. 15). Make sure that the driver pins on the underside of the shear cell engage the toothed wheel of the driving axle 5.

8.1.1.3 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

8.1.1.4 Follow 8.1.1.5 – 8.1.1.10 only if the normal load at preshear is greater than 15 *N*. Otherwise go to 8.1.1.12.

NOTE 8—The latter procedure is necessary so as to not over-consolidate a bulk solid specimen at small normal loads.

8.1.1.5 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).

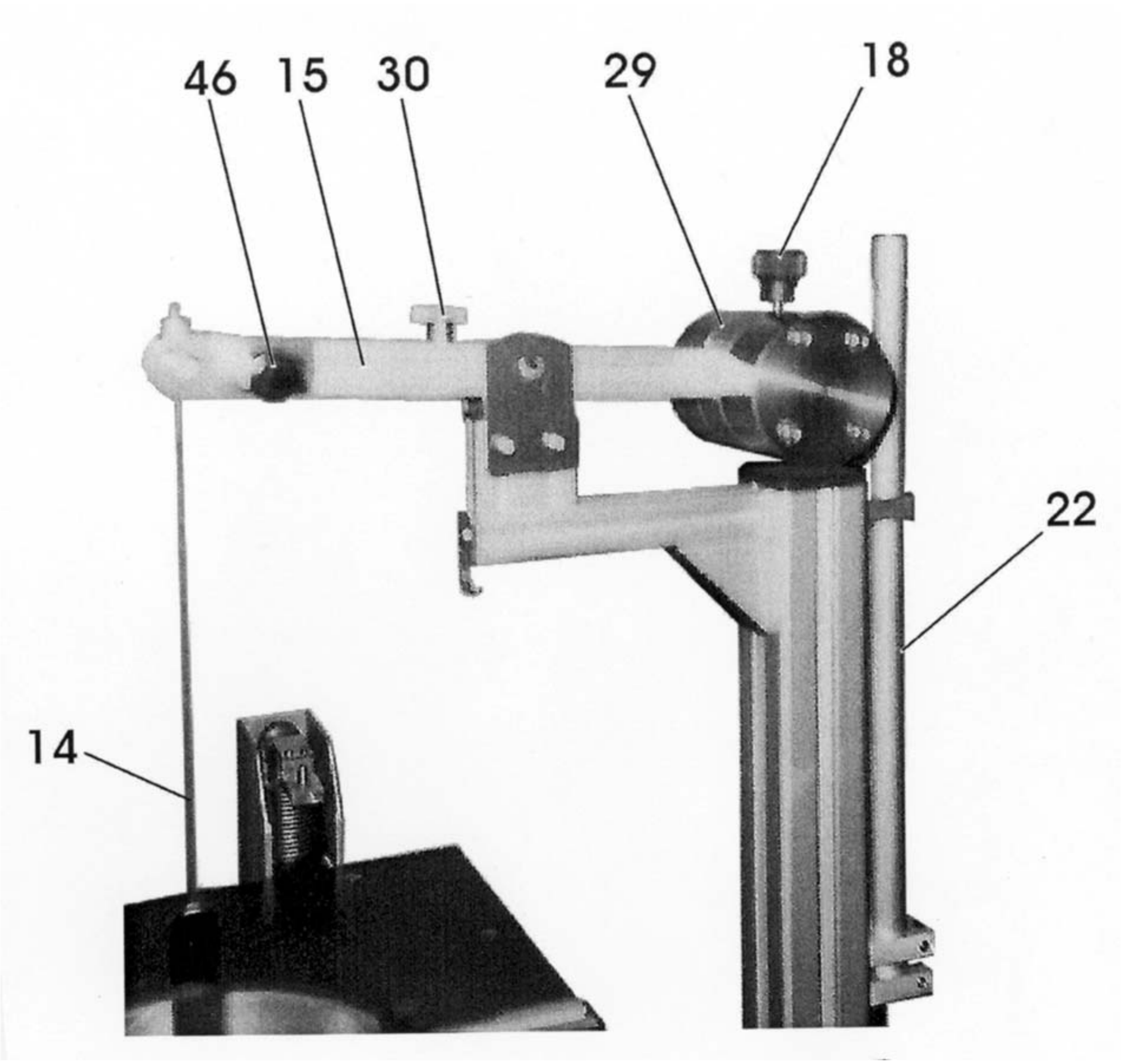

FIG. 6 Counterbalance System

TABLE 1 Wall Friction Shear Cell Dimensions

	Standard Wall Friction Shear 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

8.1.1.6 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).

8.1.1.7 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, 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.

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

8.1.1.9 Carefully put an applied mass piece on the circular plate 19 of hanger 11 (mass needed for preshear or smaller mass).

8.1.1.10 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). To do this, the front end of the balance arm must be pulled down

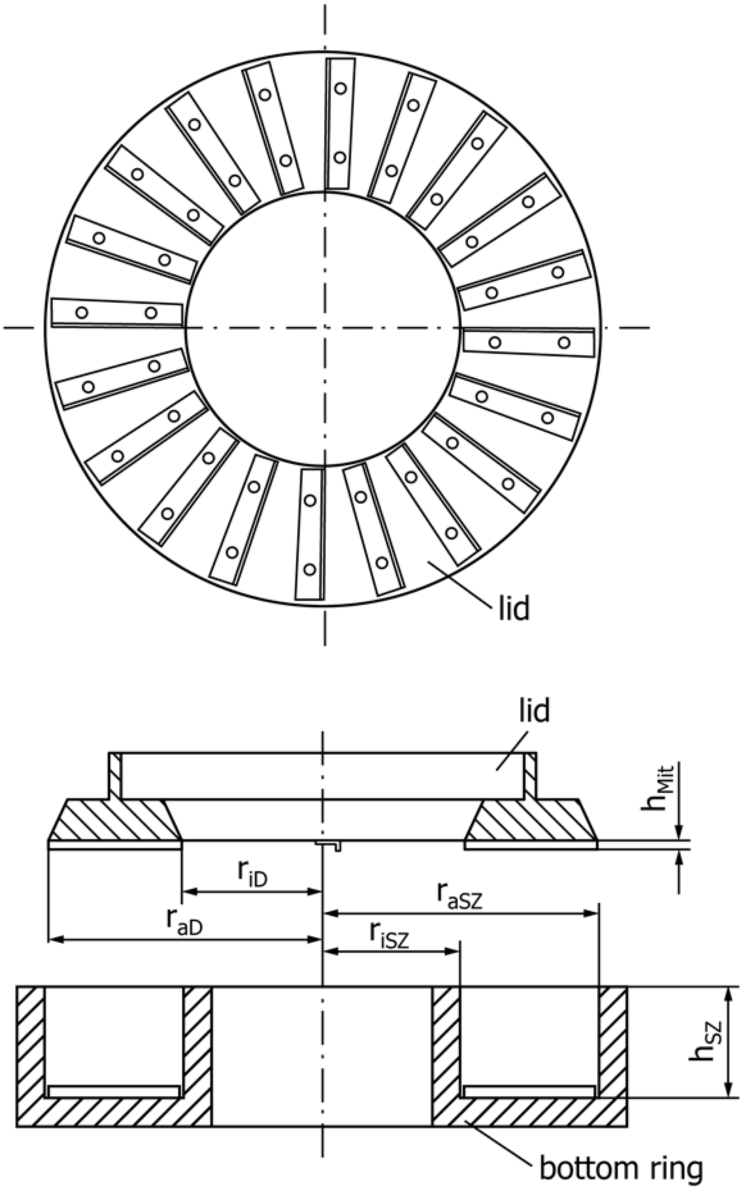

FIG. 7 Main Dimensions of Shear Cell

at the black handle 46 provided for this (the handle is not shown in all figures; see Fig. 6).

8.1.1.11 Follow 8.1.1.12 – 8.1.1.16 if the normal load at preshear is less than 15 *N*. (These steps can also be used alternatively to 8.1.1.5 – 8.1.1.10.)

8.1.1.12 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."

8.1.1.13 Put at least one applied mass 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.

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

8.1.1.15 Carefully place the lid concentrically on the shear cell on the bulk solid specimen. 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).

8.1.1.16 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). The tie rods 13 should have some clearance in the seatings 16; that is, the tie

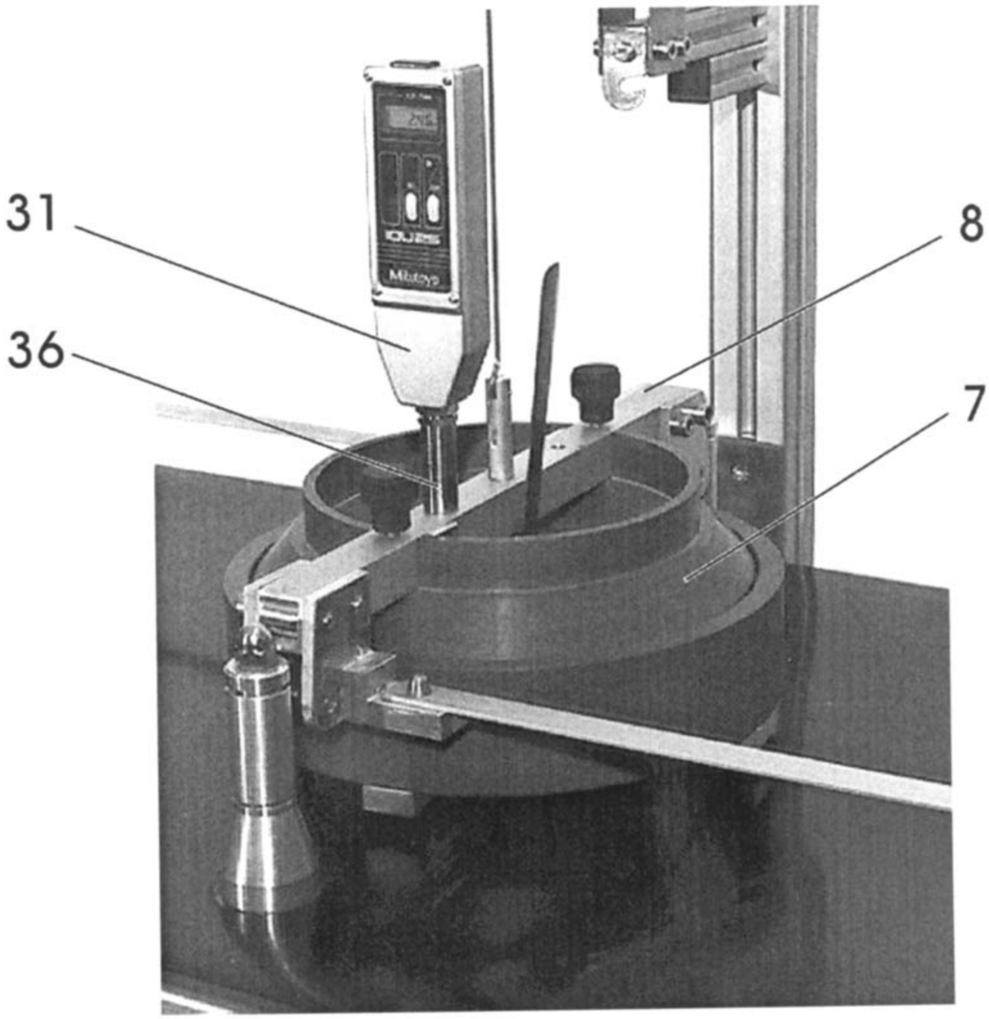

FIG. 8 Determination of the Height of the Specimen

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.

rods must not be stressed at this stage. If it is not possible to connect the tie rods in this manner, use the motor drive to turn the shear cell with the lid to an appropriate position.

8.1.1.17 If not already done (at 8.1.1.9 or 8.1.1.13, respectively), put additional applied mass 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 7.3).

NOTE 10—At the beginning of preshear, some powder may escape, which is one reason why the lid may sink. Provided that 8.1.1.17 is followed, loss of powder can be neglected.

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

8.1.1.19 Start the motor (front panel 35).

NOTE 11—After some time both tie rods 13 are transferring tensile forces. The total force *F* ("shear force") is then measured.

8.1.1.20 As soon as the shear force *F* stops increasing (steady-state 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.

8.1.1.21 Record the force *F* measured at steady-state flow.

(1) If the shear force does not reach a constant value, steady-state flow can be assumed if, after 30 mm of shear

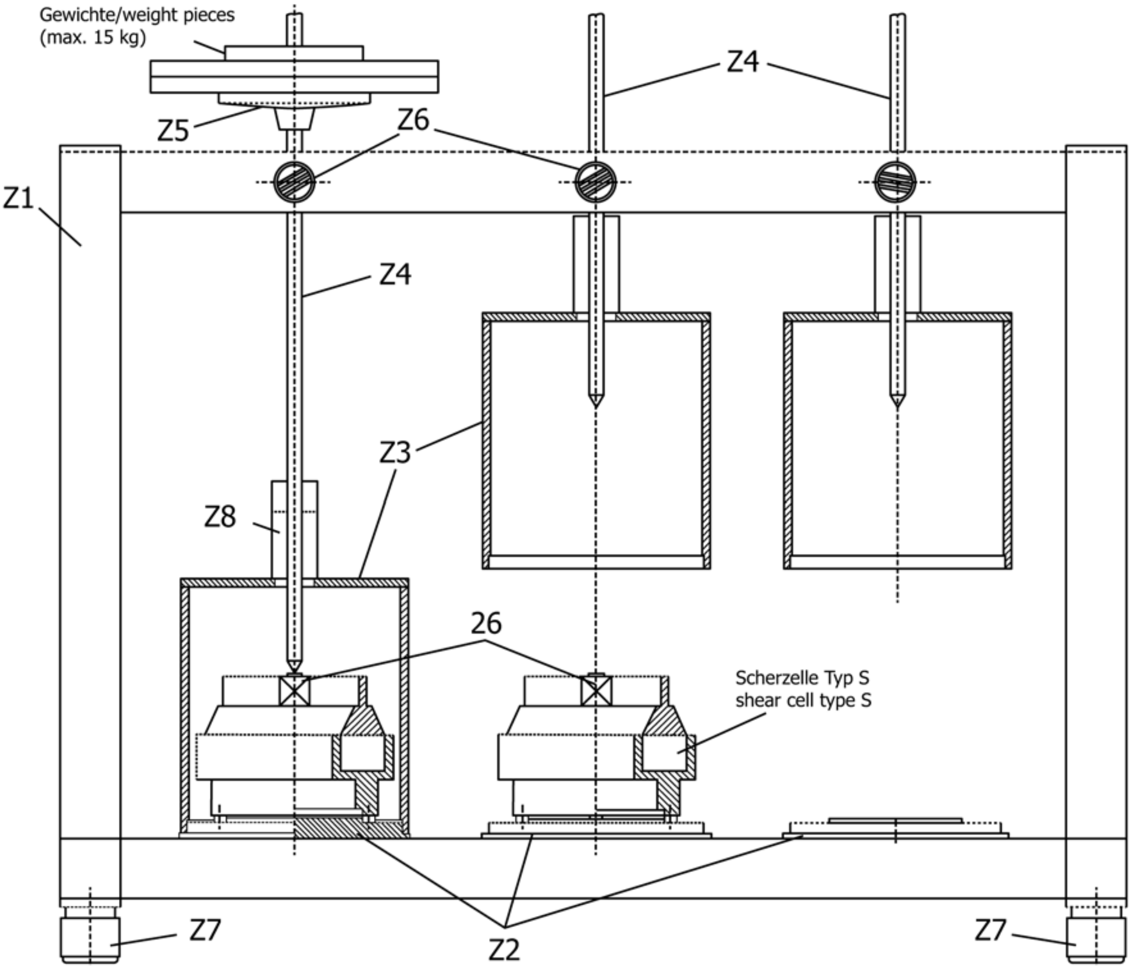

FIG. 9 Time Consolidation Bench

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 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.

(2) 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 8.1.2 begun.

(3) 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 specimens individual values of the steady state shear stress should not deviate by more than ±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.

8.1.2 *Shear:*

8.1.2.1 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 mass m_{Wp} by a smaller mass m_{Ws}. Switch on the motor again in the forward direction.

NOTE 12—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 13—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.

8.1.2.2 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. 8). Note the displacement indicated on the display.

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

8.1.2.4 Remove the indicator 31.

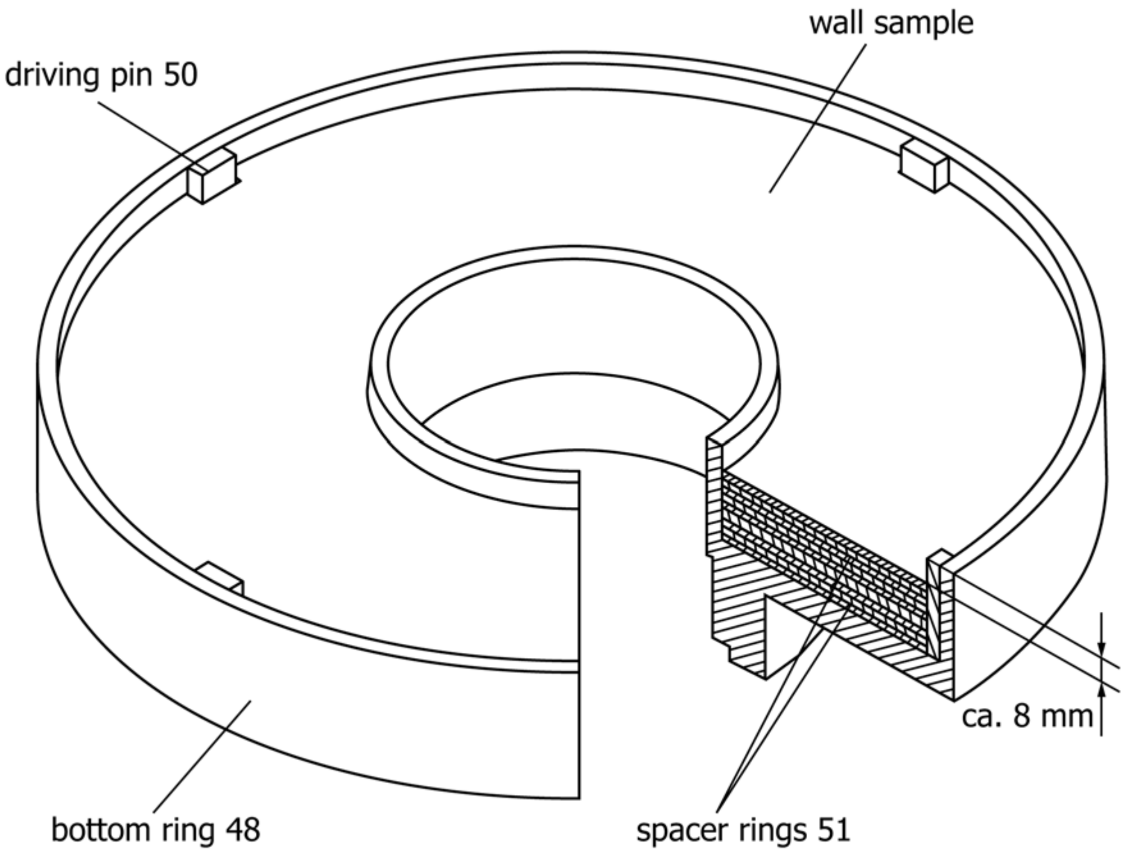

FIG. 10 Wall Friction Shear Cell (bottom ring)

8.1.2.5 Calculate the mean value of both measured displacements, which is the mean decrease in height Δ*h* of the bulk solid specimen. Note this mean value.

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

8.1.2.7 Remove tie rods 13.

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

8.1.2.9 Remove applied mass pieces from the hanger 11.

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

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

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

8.1.3 *Additional Tests:*

8.1.3.1 Repeat 7, 8.1.1, and 8.1.2.

8.1.3.2 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, 8.1.1, and 8.1.2.

8.1.3.3 Select higher preshear normal stress levels so that:

$$\sigma_{p,2} = 2\sigma_{p,1}$$
$$\sigma_{p,3} = 4\sigma_{p,1}$$
$$\sigma_{p,4} = 8\sigma_{p,1}$$

NOTE 14—Some adjustment in preshear normal stress levels may be necessary in order to cover the range of major principal stresses σ_1 necessary to accurately calculate critical arching and/or ratholing dimensions.

8.1.3.4 Repeat 7, 8.1.1, 8.1.2, and 8.1.3.2 for each selected preshear normal stress level.

NOTE 15—Following the procedure given in 7, 8.1.1, and 8.1.2 (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 procedure (Procedure B) is frequently recommended (for example, in (**2**)), 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 8.1.2.1 back to 8.1.1.19 until all desired measuring points are determined. Only then would 8.1.2.2 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 (**3**). 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 specimen 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 specimen, the shear force passes over a product dependent, weak maximum (**3**). Afterwards a constant 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.

8.2 *Shear Testing Procedure for Time Consolidation*

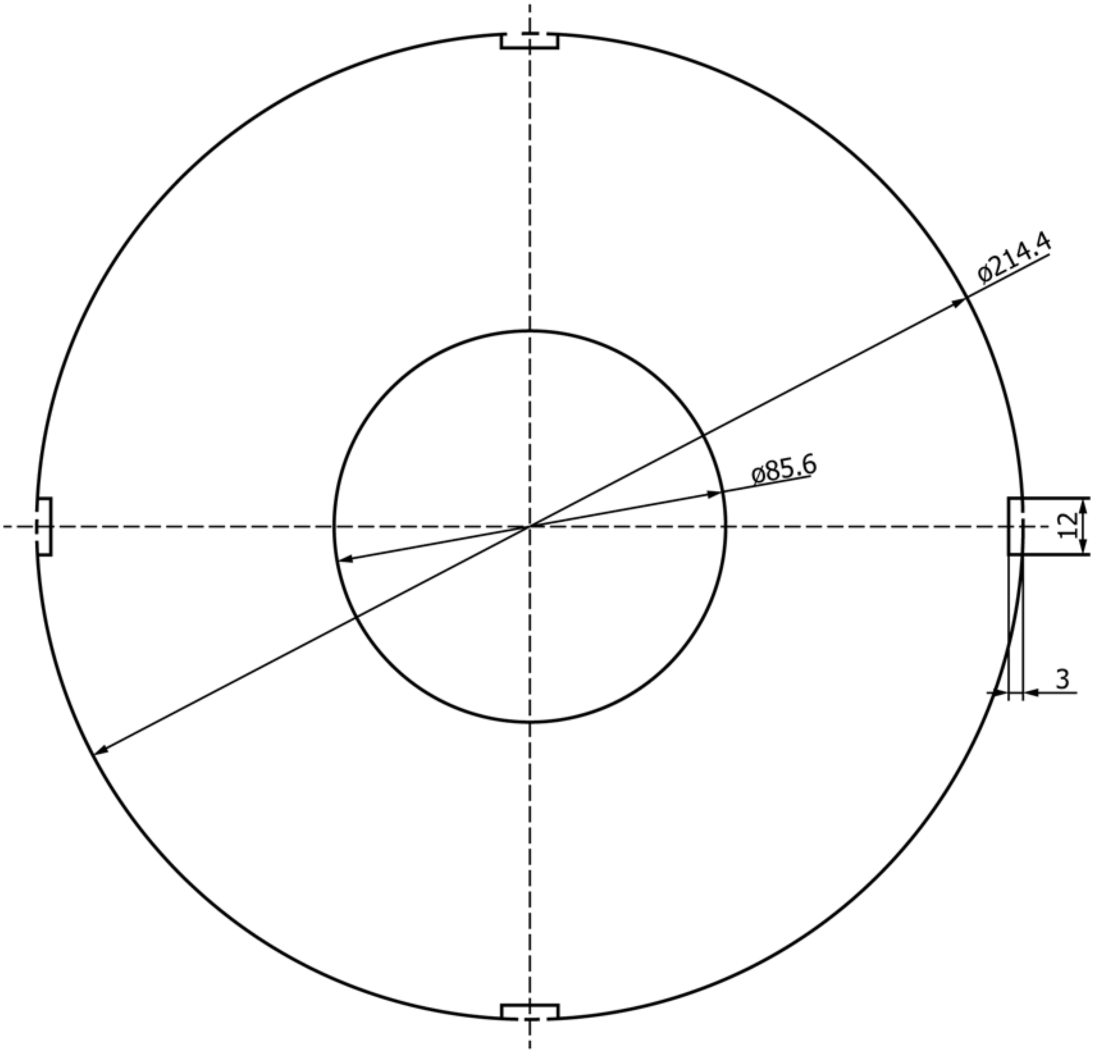

FIG. 11 Dimensions of Wall Material Coupon

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.

8.2.2.1 As an alternative to using a consolidation bench, consider the following: a critically consolidated specimen is prepared by preshearing with applied mass 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.

NOTE 16—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.

8.2.3 *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.

NOTE 17—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 specimens with applied mass 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. For this step as well as the following through 8.2.4.11, be careful not to bump or jar the lid or cell; otherwise the results will be incorrect.

8.2.4.4 Remove the applied mass pieces from the hanger 11.

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

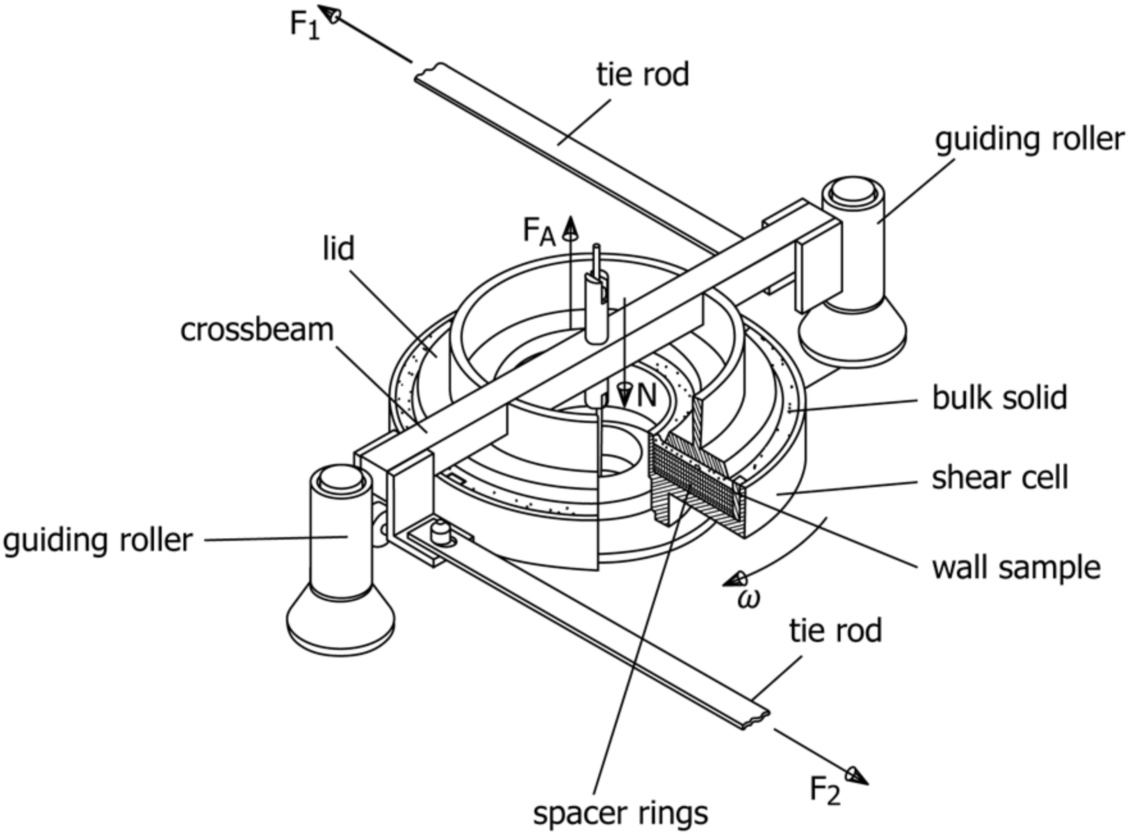

FIG. 12 Wall Friction Shear Cell Placed on the Ring Shear Tester

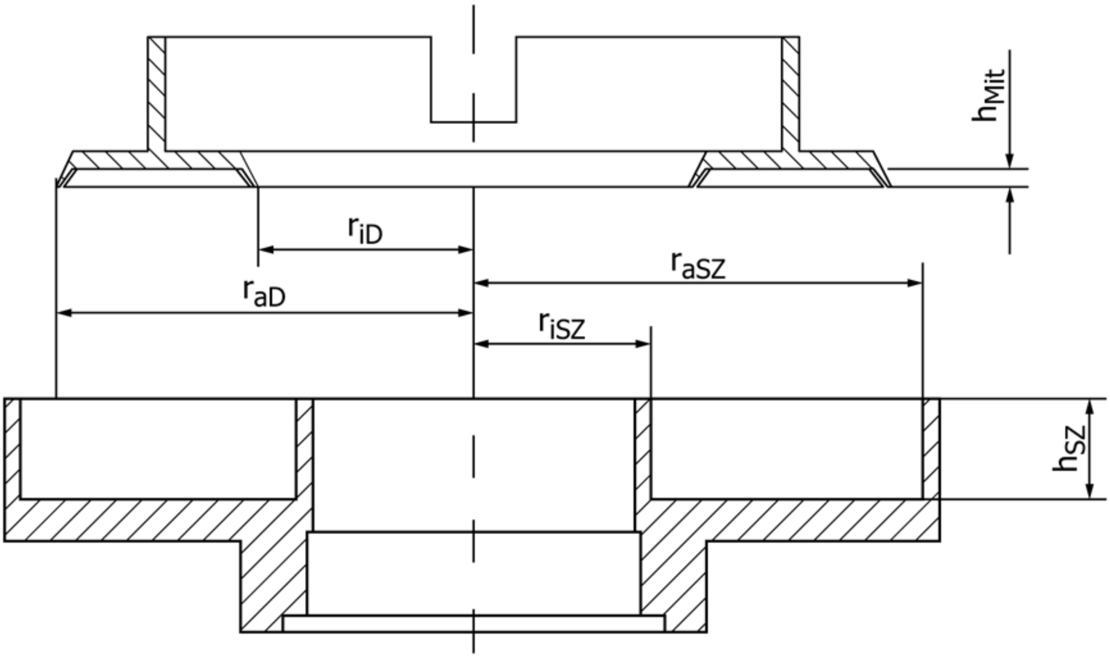

FIG. 13 Main Dimensions of Wall Friction Shear Cell

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

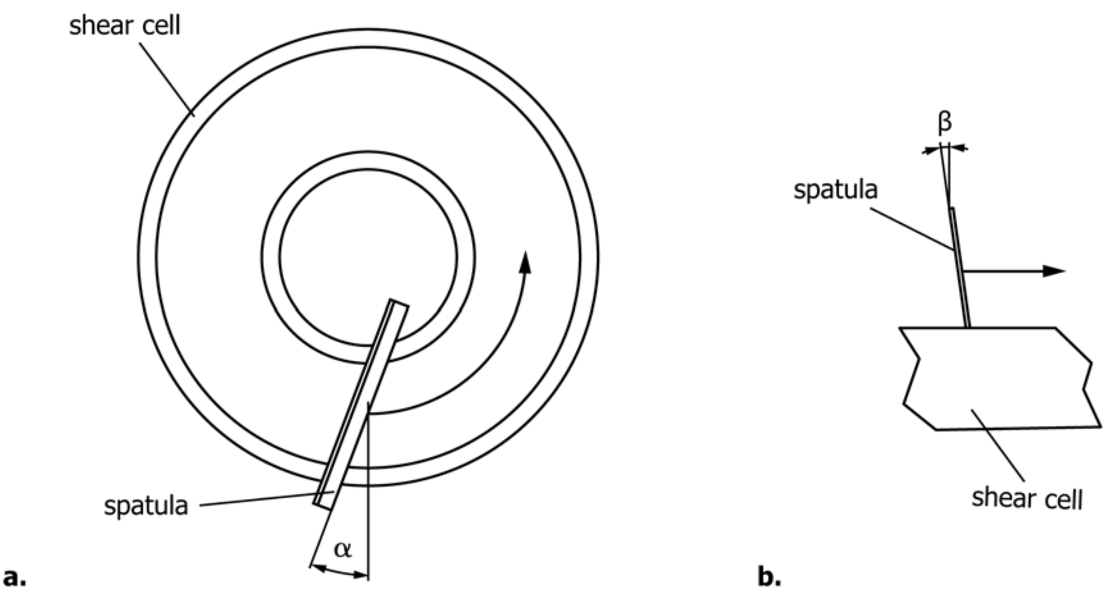

FIG. 14 Scraping Off Excess Powder

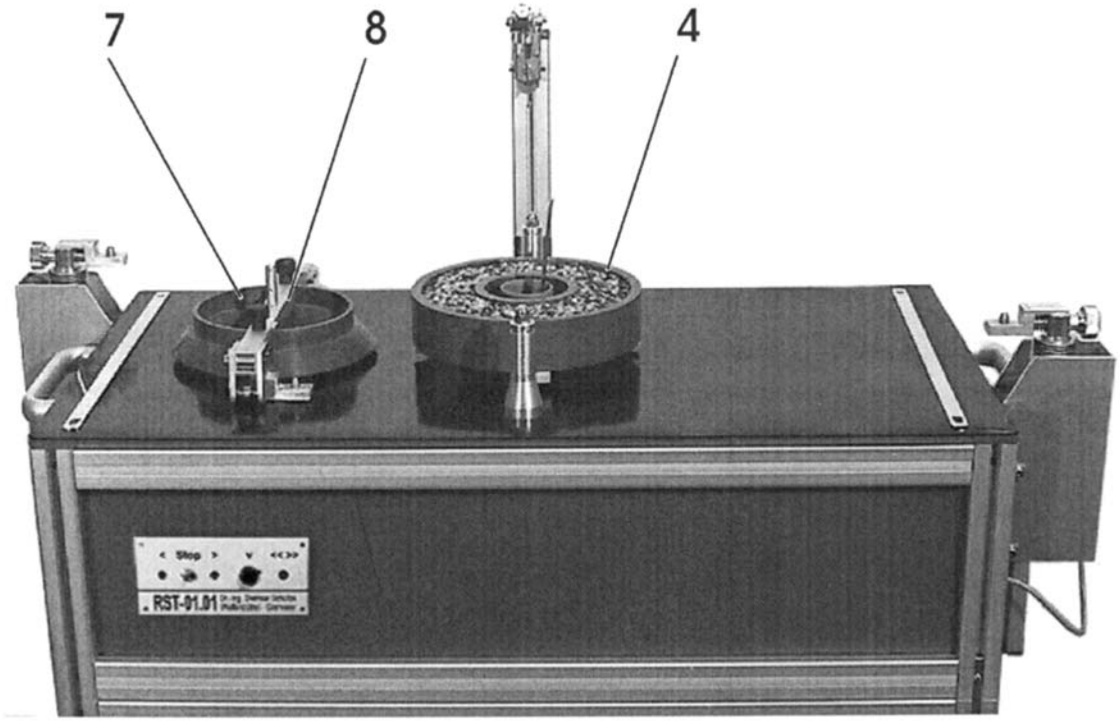

FIG. 15 Ring Shear Tester with Shear Cell on Driving Axle 5

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).

(1) The plastic cap must not hit against shear cell or lid. Any shocks can influence the bulk solid specimen and lead to incorrect measurement results.

8.2.4.12 Select the applied mass 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).

8.2.4.13 The Mohr circle shown in Fig. 18 is drawn through point *P* (steady state flow) and is tangential to the yield locus.

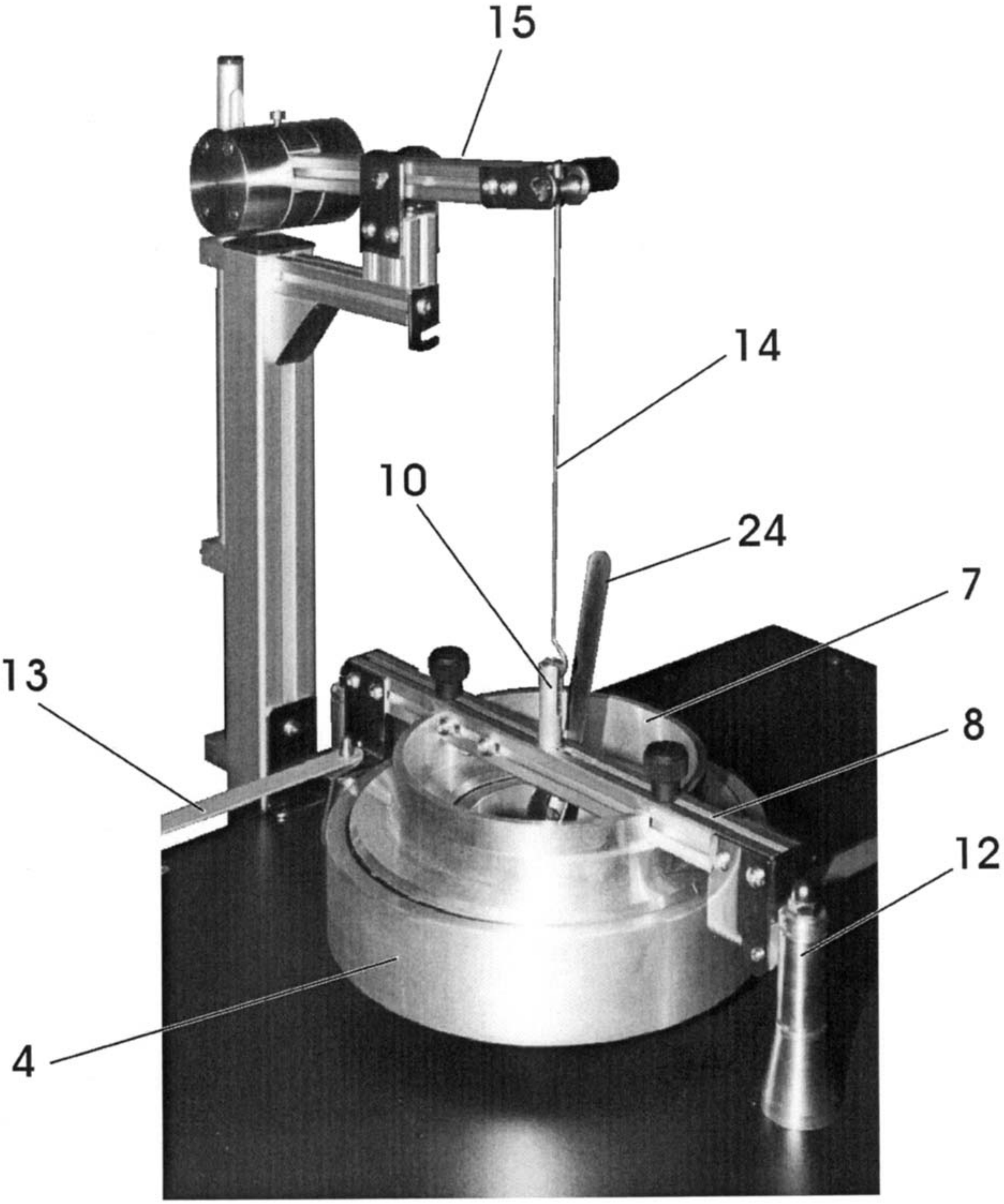

FIG. 16 Shear Cell 4 and Lid 7 Connected to Hanger 11, Counterbalance System and Tie Rods 12

During time consolidation, the specimen is loaded with the major principal stress σ_1 of that Mohr circle as shown in Fig. 18.

NOTE 18—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 D6128), it has been found that the stress state developed by the application of normal stress alone can successfully approximate that developed in steady state flow.

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

$$F_t = \sigma_1 A_D \tag{1}$$

NOTE 19—The mass of the bulk solid in the area of the bars of the lid

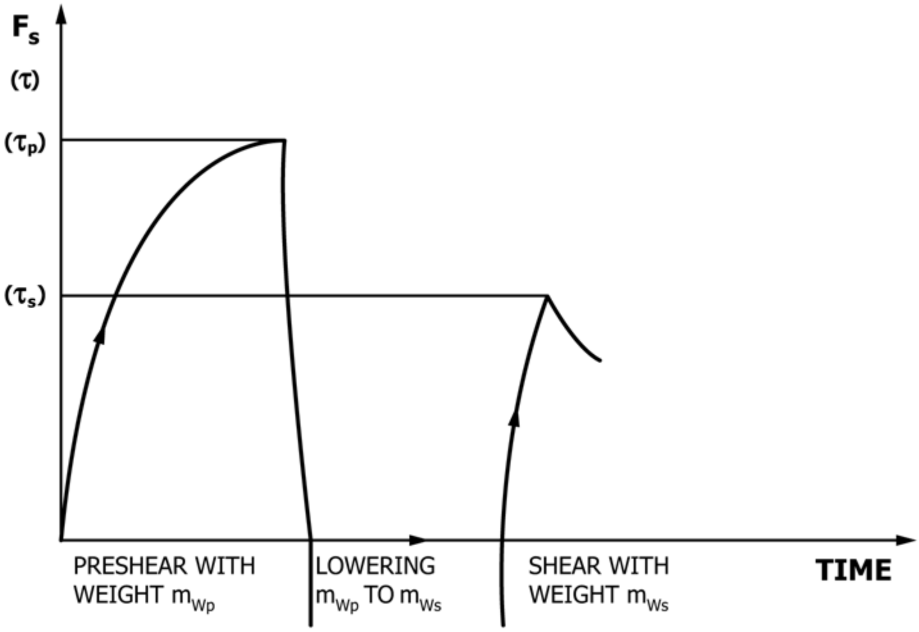

FIG. 17 Stress-Strain Curves—Preshear and Shear

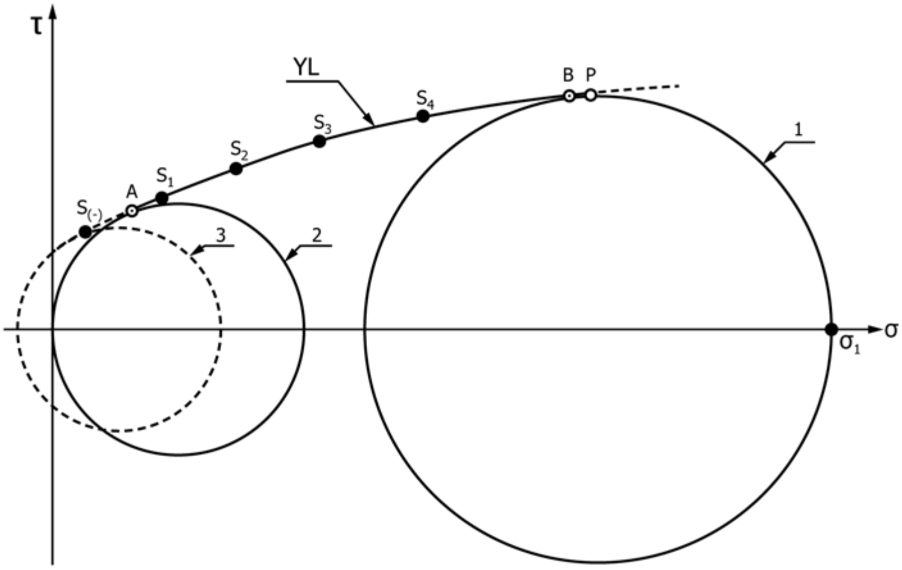

FIG. 18 Yield Locus Showing Valid Shear Points

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 masses of the lid 7 (mass m_L) and the time consolidation crossbeam 26 (mass m_{CB}) as well as the masses of the loading rod Z4 with the disk Z5 (mass m_C) are acting on the bulk solid specimen. 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 masses which have to be placed on disk Z5 of the time consolidation bench, these masses have to be subtracted from mass $m_t = F_t/g$, which would exert the force F_t as determined following equation (2) :

$$m_{Wt} = (F_t/g) - m_L - m_{CB} - m_C \tag{2}$$

The remaining mass m_{Wt} is to be exerted through applied mass pieces on the bulk solid specimen; that is, corresponding applied masses have to be placed on disk Z5 of the time consolidation bench when the specimen 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 $m_t = F_t/g$:

$$m_{Wt} = (F_t/g) - m_L - m_{CB} \tag{3}$$

When Eq 3 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.

8.2.4.15 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 2 to within ±5 %.

NOTE 20—To reduce the danger of falling masses, put the applied mass pieces one after the other on disk Z5, turning each applied mass piece by about 90° relative to the applied mass piece below.

8.2.4.16 Store the specimen under load for the time interval specified by the requesting agency or client.

(1) 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 specimens in the time consolidation bench to direct sunlight.

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

8.2.4.18 Carefully remove the applied mass pieces from disk Z5 of the time consolidation bench. For this step as well as the following through 8.2.4.23, be careful not to bump or jar the lid or cell; otherwise the results will be incorrect.

8.2.4.19 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).

(1) The plastic cap must not hit against shear cell or lid. Any shocks can influence the bulk solid specimen and lead to incorrect measurement results.

8.2.4.20 Remove the shear cell 4 along with the lid 7 from the supporting plate Z2 carefully and without vibrations. Put the shear cell on driving axle 5 of the ring shear tester.

8.2.4.21 Remove time consolidation crossbeam 26 from lid 7.

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

8.2.4.23 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 mass 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 21—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.

8.3 *Procedure for Wall Friction:*

8.3.1 Start the motor.

NOTE 22—After some time, both tie rods 13 are transferring tensile forces. The total force F ("shear force") is then measured.

8.3.2 Determine by visual observation of the recorder chart when the shear stress τ_{w6} has reached a constant value. Then remove applied mass(es) until the normal stress is reduced to σ_{w5}. Continue to rotate cell during removal of the applied masses. When the shear stress has again reached a constant value, record the shear stress τ_{w5} and remove more applied masses 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.

8.3.2.1 Be careful that the lid 49 does not touch the upper surface of the wall material coupon 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 7.4.3.5.

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

8.3.4 Switch off the motor.

8.3.5 Remove tie rods 13.

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

8.3.7 Remove applied mass pieces from the hanger 11.

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

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

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

8.3.11 Repeat wall friction tests two to three times with new specimens of the particulate solid.

NOTE 23—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 24—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}.

8.3.12 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 applied mass 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 applied mass 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 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 25—This step can be considered as wall friction "preshear," which gives the "initial" shear stress τ_{wp5}.

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

NOTE 26—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 carrier or hanger with appropriate applied masses, apply the normal stress σ_{w5}. If a carrier is used, calculate the appropriate masses required using Eq 2.

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 hanger and applied masses, 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 or Interpretation of Results

9.1 *Data Processing for Instantaneous Shear Tests:*

9.1.1 *Prorating:*

NOTE 27—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.

9.1.1.1 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:

$$\tau'_s = \tau_s\,(\tau_{p,m}/\tau_p) \quad (4)$$

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.

9.1.2 *Determination of Valid Shear Points:*

9.1.2.1 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 $P(\sigma_p)$ on a σ, τ-diagram (Fig. 19).

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

9.1.2.3 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. 19).

9.1.2.4 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. 20), either additional shear points should be run or the test should be redone at a different level of consolidation.

(1) 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. 18 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. 18 as *B* and defines the end point of the yield locus).[4] 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. 18). 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.

(2) Points to the left of point *A* are ignored because they represent a state where tensile stresses can occur in the shear

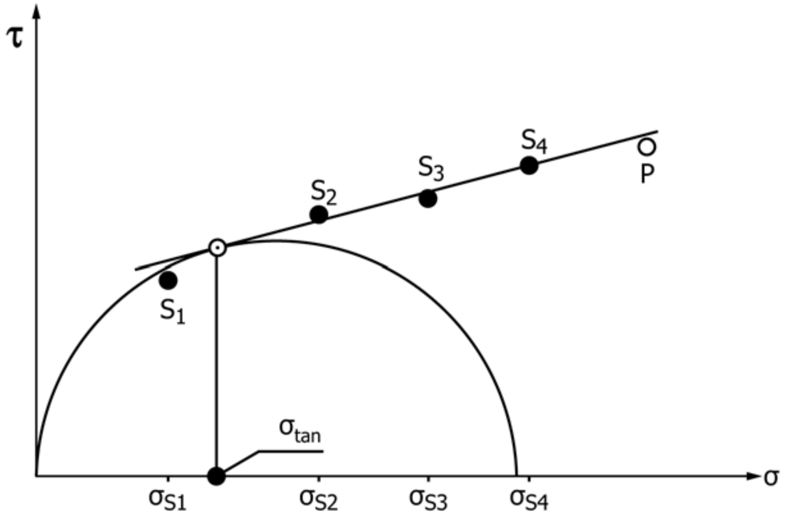

FIG. 19 Yield Locus and Data Points

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[4] 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 (**4**).

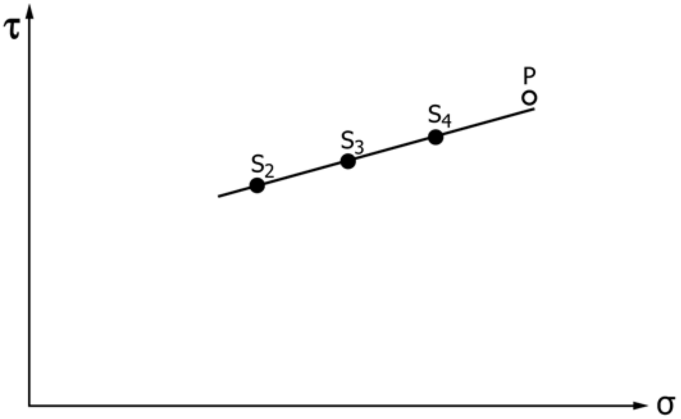

FIG. 20 End Point Above Fitted Line

cell. This can be seen by considering the yield point on Fig. 18 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.

9.1.3 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}.

$$\rho_b = m_{SG}/V_{pr} \tag{5}$$

NOTE 28—The mass m_{SG} is determined from the total mass of the filled shear cell, m_{tot}, and the mass of the bottom ring of the shear cell, m_B:

$$m_{SG} = m_{ges} - m_B \tag{6}$$

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

$$V_{pr} = V_{SZ} - A_{SZ}\,\Delta h \tag{7}$$

where:

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

9.1.4 *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.

$$\sigma = N/A_D \tag{8}$$

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

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

where:

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

NOTE 29—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.

9.1.5 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 $r_s = 0.125$ m:

$$M_d = r_s F \tag{10}$$

NOTE 30—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 31—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.

9.1.6 Calculate the moment arm r_m of force τA_D from:

$$r_m = 2/3\,\left(r_{aD}^{\;3} - r_{iD}^{\;3}\right)/\left(r_{aD}^{\;2} - r_{iD}^{\;2}\right) \tag{11}$$

where:

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

9.1.7 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:

$$\tau = M_d/\left(r_m A_D\right) = r_S\, F/\left(r_m A_D\right) \tag{12}$$

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

9.1.9 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.

9.1.10 Draw a Mohr circle through the origin, tangential to this smooth line, the instantaneous yield locus (YL in Fig. 21).

NOTE 32—The higher point of intersection of this Mohr circle with the σ-axis is the unconfined yield strength f_c. Calculate to three significant digits.

9.1.11 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 33—The upper point of intersection of this Mohr circle with the normal stress axis is the major principal stress σ_1. Calculate to three significant digits. 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 principal stress σ_1.

NOTE 34—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.

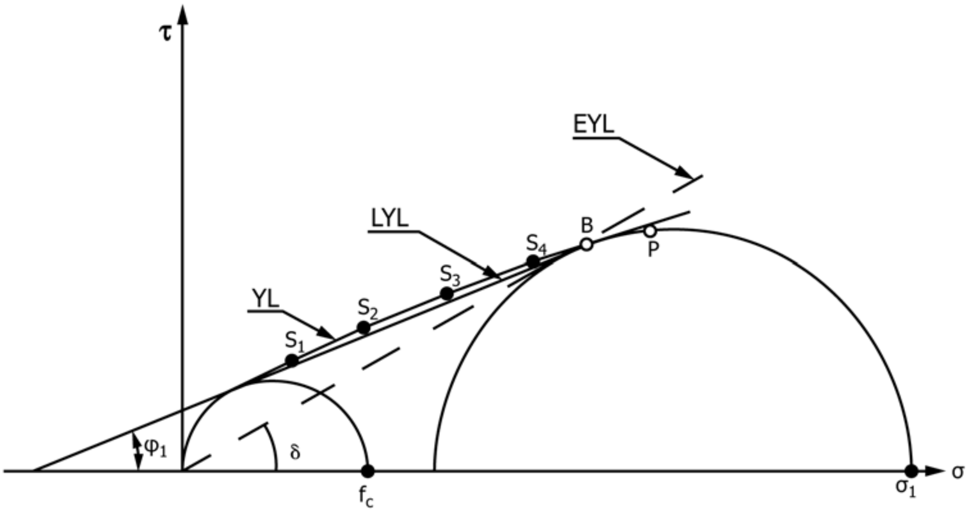

FIG. 21 Mohr Circles, Angles of Friction and Yield Locus

9.1.12 Determine, to the nearest 1°, the angle of internal friction of the bulk solid φ_i for each major principal stress, σ_1 by measuring the angle between a yield locus and the σ-axis.

9.1.12.1 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. 21).

9.1.13 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. It should be determined to the nearest 1°. For a given preshear normal stress and value of σ_1, determine a mean bulk density ρ_b to four significant digits.

NOTE 35—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. 22.

9.1.14 Fit a smooth curve through the pairs of points (σ_1, f_c). See Fig. 22e. 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 36—The Flow Function usually has a slight curvature convex upwards.

9.1.15 Fit a smooth curve through the points (σ_1, δ) as shown in Fig. 22d. Also plot in a similar way φ_i and φ_t as shown in Fig. 22c and ρ_b as shown in Fig. 22a.

NOTE 37—For cohesive materials, δ will decrease with increasing σ_1.

9.2 *Evaluation of Time Shear Test Data:*

9.2.1 *Validity of Time Shear Points*—Plot the time shear points in σ, τ-coordinates (Fig. 23) 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.

9.2.2 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.

9.2.3 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.

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

9.2.4.1 The highest point of intersection of this Mohr circle with the σ-axis is the time unconfined yield strength, f_{ct}. Calculate to three significant digits. This value, together with the major principal 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.

9.2.4.2 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) to within 1°C (Fig. 24).

9.2.5 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 38—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.

$$m_{SG} = \left(m_{w,ges} - m_{Wand}\right) \tag{13}$$

NOTE 39—The shear zone is assumed to be located directly at the surface of the wall material coupon. The normal force acting on the wall results from the applied mass 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 annular area of the lid, A_D, to the cross-sectional annular area of the shear cell, A_{SZ}:

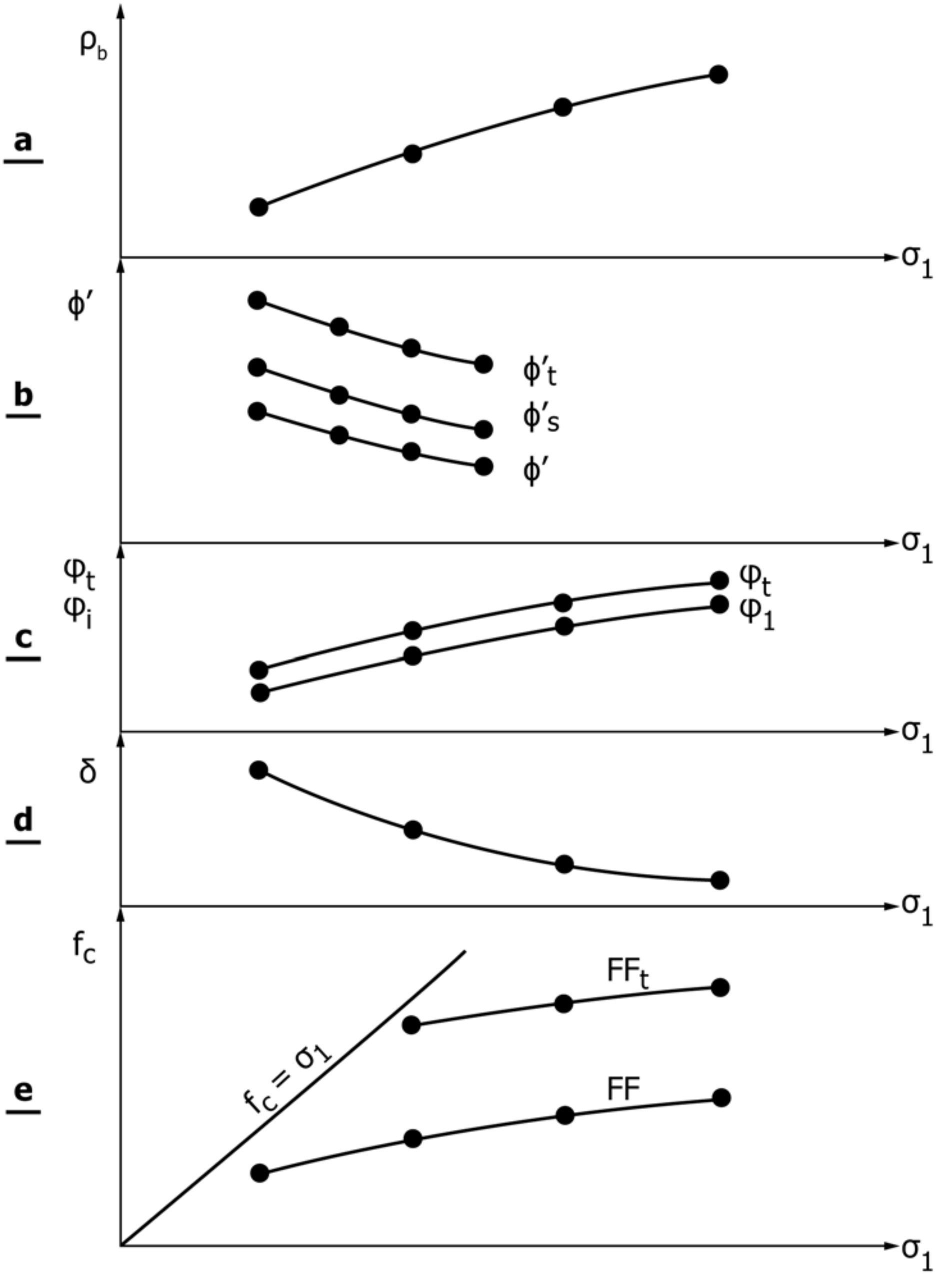

FIG. 22 Powder Properties as a Function of σ_1

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

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 specimen 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 9.1.5):

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

NOTE 40—The bulk solid is "fixed" at the lid (that is, lid and bulk solid are moving at same velocity), whereas the wall material coupon 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 coupon. 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 9.1.6.

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 coupon:

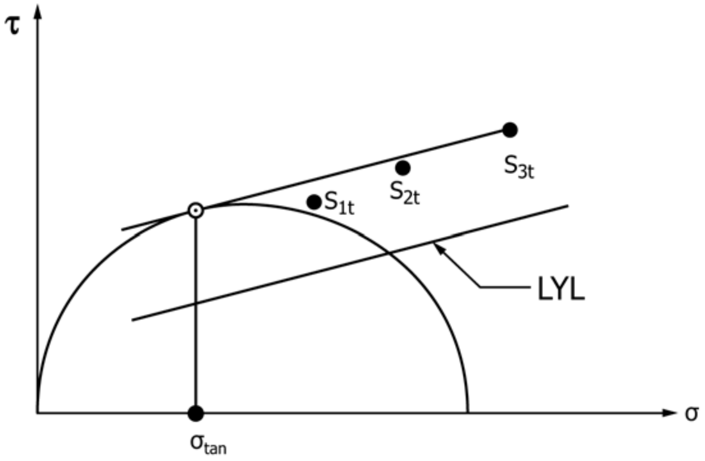

FIG. 23 Validity of Points on the Time Yield Locus

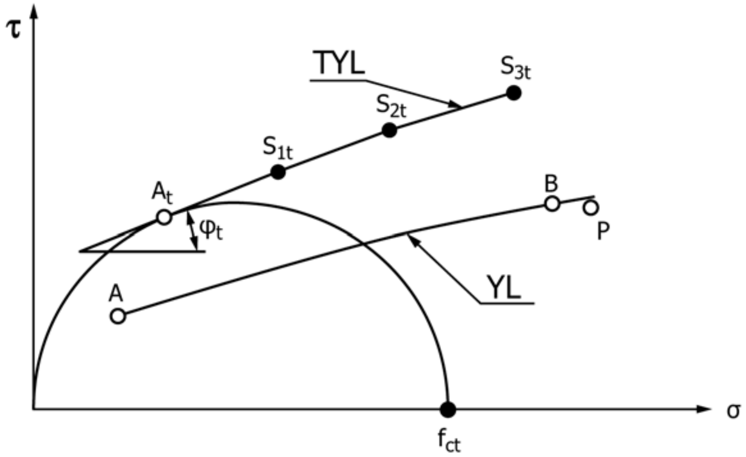

FIG. 24 Time Yield Locus

$$\tau_W = M_d/(r_m A_D) = r_S F/(r_m A_D) \quad (17)$$

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 41—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.

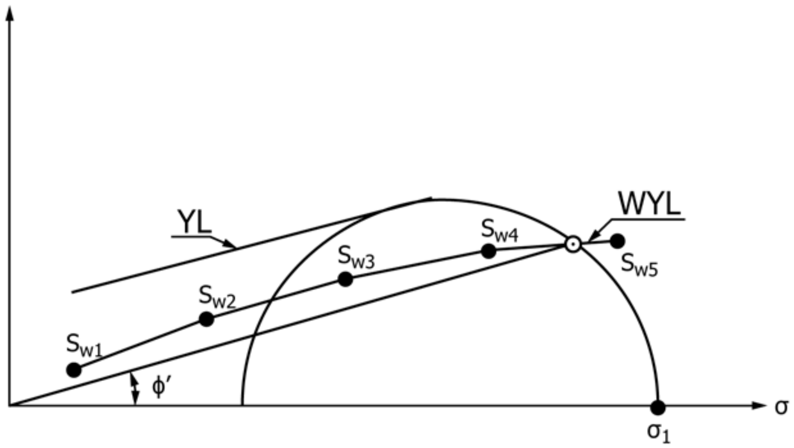

FIG. 25 Wall Yield Locus

9.3.8 If the wall yield locus is a straight line passing through the origin, then ϕ' = constant. Otherwise, superimpose a steady state flow Mohr circle associated with a yield locus and a major principal 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 principal stress σ_1 to within 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' to within 1°.

9.3.11 Plot ϕ' and ϕ'_s as a function of σ_1 as shown in Fig. 22b.

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_{wt} 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 steady state Mohr circles.

9.4.2 Plot ϕ'_t as a function σ_1 as shown in Fig. 22b.

10. Report: Test Data Sheet(s)/Form(s)

10.1 The methodology used to specify how data are recorded on the test data sheet(s)/form(s), as given below, is covered in 1.4.

10.2 Report as a minimum the following general information (data):

10.2.1 Requesting agency or client, and/or

10.2.2 Identifying number for job or project,

10.2.3 Technician name or initials, and

10.2.4 Date test was run.

10.3 Report as a minimum the following sample information (data):

10.3.1 Generic name of powder tested,

10.3.2 Chemical name of sample, if known,

10.3.3 Specimen moisture (water) content, if determined. Record value to nearest 0.1 %. Indicate method used to determine moisture if not Test Method D2216,

10.3.4 Temperature of specimen to the nearest 1°C, and

10.3.5 Sample particle size to two significant digits using procedure specified by requesting agency or client.

10.4 Provide in plot form the following properties as a function of σ_1. Report all stresses to three significant digits and all angles to nearest 1°C:

10.4.1 Unconfined yield strength, f_c, that is, flow function, *FF*.

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

10.4.3 Effective angle of friction, δ.

10.4.4 Bulk density, ρ_b to four significant digits.

10.4.5 Angle of internal friction, φ_i for instantaneous flow.

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

10.5.1 Angle of internal friction, φ_t after time consolidation.

10.5.2 Angle of kinematic wall friction, ϕ'.

10.5.3 Angle of static wall friction, ϕ'_s.

10.5.4 Angle of time wall friction, ϕ'_t.

11. Precision and Bias

11.1 *Precision*—Test data on precision is not presented due to the nature of the powder and other bulk solids tested by this standard. It is either not feasible or too costly at this time to have ten or more laboratories participate in a round-robin testing program. In addition, it is either not feasible or too costly to produce multiple specimens that have uniform physical properties. Any variation observed in the data is just as likely to be due to specimen variation as to operator or laboratory testing variation.

11.1.1 Subcommittee D18.24 is seeking any data from the users of this standard that might be used to make a limited statement on precision.

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 ($g = 9.81\ m/s^2$)
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	total 'mass of applied masses
m_{tot}	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 ($F_t = g\ m_t$)
$m_{w,tot}$	kg	mass of wall friction shear cell (bottom ring) with spacer rings, wall material
m_{wall}	kg	mass of wall friction shear cell (bottom ring) with spacer rings and wall material coupon
m_{Wp}	kg	mass during preshear
m_{Ws}	kg	mass during shear
m_{Wt}	kg	mass 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 APPLIED MASSESS

A2.1 Sample Selection

A2.1.1 For meaningful results select a representative sample of the particulate solid with respect to moisture (water) 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 (water) content which at equilibrium depends on the ambient humidity. In view of the significant influence of moisture (water), 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 water 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 (water) in the solid from the shear cells. Ideally, measurements should be made in an air-conditioned room with controlled humidity. One might also consider storage in a temperature- and humidity-controlled chamber.

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 (water) 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 specimen 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 cm^2 and a specimen 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 cm^2, and its specimen 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 specimen.

NOTE A2.3—An advantage of the smaller cell is that a smaller amount of bulk solid is required for a test, because the volume of the small shear cell is only about 200 cm^3 in comparison to about 900 cm^3 for the standard shear cell. Furthermore, a smaller dead mass is required for the small shear cell in order to attain a certain normal stress in the bulk solid specimen. 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 Masses and Stresses

A2.3.1 In this standard the loading of shear cells by applied masses is expressed in the form of the normal stress in the shear plane. Selection of the applied masses 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 applied masses 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 applied masses. 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 determine the mass of all components to a precision of 1 g. Although applied masses are normally well within the required tolerance, it is advisable to check them on purchase. A recently calibrated balance is suitable for this.

SUMMARY OF CHANGES

In accordance with Committee D18 policy, this section identifies the location of changes to this standard since the 2008 edition that may impact the use of this standard.

(1) Added reference to D2216.
(2) Removed definitions in Section 3 since they already appear in Terminology standard D653.
(3) In a few instances, "sample" replaced by "specimen" or vice-versa.
(4) Revised Section 10 text.

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