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Experimental Investigation of Some Important Soy Shreds Characteristics

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1. Introduction

The world-wide increase in the production and trade in bulk solids has led to the construction of increasingly large silos for the storage of an increasing number of bulk solids, of which the characteristics are sometimes not well known. Therefore, it is not surprising that some bulk solids behave rather fickly when stored in silos. Soy shreds, the remainder of soy beans when the oil is extracted, can be considered as such a bulk solid. Soy shreds are rich in proteins (44–49%), and are therefore used as (a component of) forage. When stored in silos, soy shreds behave as a cohesive bulk solid.

In combination with a research program during which wall pressures in a soy shreds silo were measured [1] [2] [5], some important soy shreds characteristics were investigated in the laboratory. The tested soy shreds samples had an average moisture content of 13.8%, while their average temperature was 20°C. The tests were carried out for a pressure range that includes the pressures recorded in the above-mentioned silo.

2. Particle Size Distribution of Soy Shreds

The sieve curve in Fig. 1 is the average of three individual sieve tests. The average particle size d_{50} is about 1.7 mm. 95% of the soy shreds have a size between 0.5 and 5.0 mm. It should be made clear, however, that soy shreds (as is indicated by the name) do not so much consist of grains as of shreds with the mentioned dimensions.

3. Investigation of Flow Properties Using the Jenike Method

3.1 Measurement of Instantaneous Yield Loci

The experimental investigation of the flow properties of soy shreds was carried out using an enlarged specimen of the Jenike shear tester [1] [3] [4].

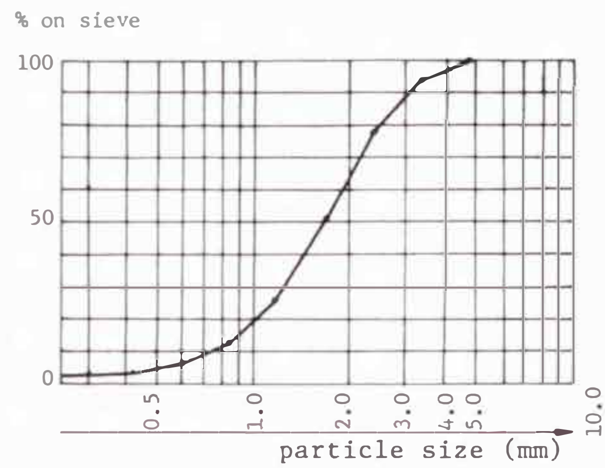

Fig. 1: Sieve curve of soy shreds samples

The apparatus consists of a lower closed bottom ring, an open upper ring, resting on the bottom ring (both rings having a cross-section of 75 cm^2), and a cover with a bracket. The cross-section of 75 cm^2 was necessitated by the dimensions of the individual shreds.

When both rings are filled with soy shreds, a vertical force N can be applied to the cover, which then transmits a vertical pressure σ to the soy shreds. Under those circumstances, a horizontal shear force F can be applied to the bracket of the cover (Fig. 2). Since F acts in the plane of contact between both rings of the shear cell, it solely introduces a shear stress τ along the (imposed) shear plane. Actually, the shear force F is introduced by imposing a displacement s of the upper ring with respect to the bottom ring, with a constant velocity of 2 mm per minute.

The shear test is carried out in three stages [3]. Preconsolidation aims at preparing the sample for consolidation, during which the recorded relationship between τ and s (the sample being subjected to a vertical pressure σ_c) should be as described by curve (a) in Fig. 3. The aim of both stages is to guarantee an as constant as possible degree of consolidation of different samples before shear is started. During that third stage, the vertical pressure σ_i is only a fraction of σ_c and the relationship between τ and s is as represented by curve (b) in Fig. 3. The peak value of τ is τ_i.

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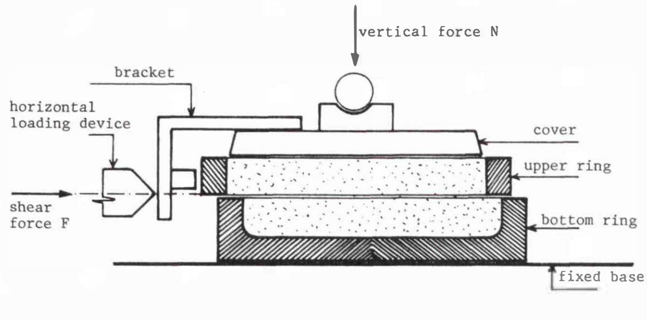

Fig. 2: Jenike shear cell

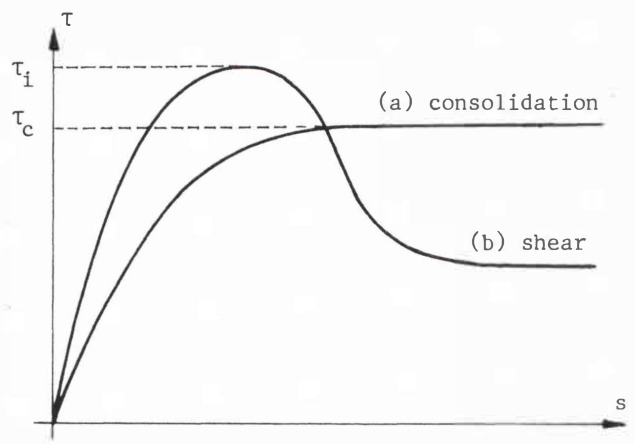

Fig. 3: Relationship between shear stress τ and horizontal displacement s during consolidation and shear

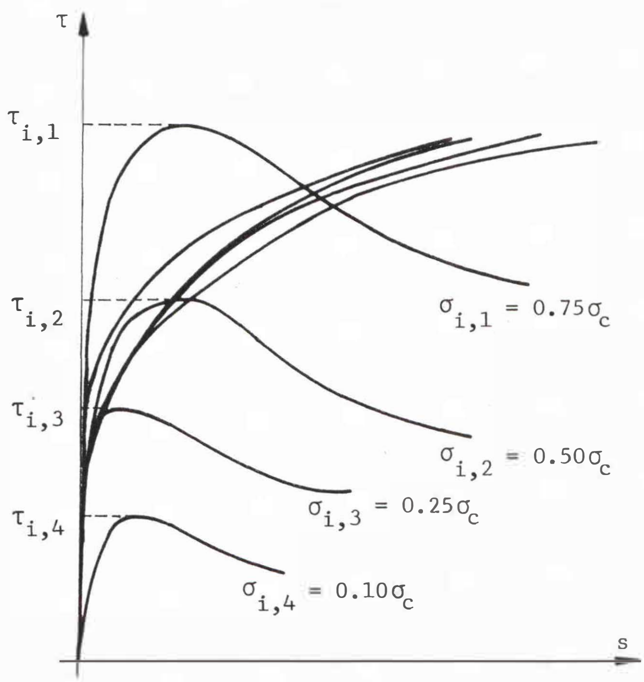

Fig. 4: Curves recorded during consolidation and shear — all tests were performed with nearly identical σ_c and τ_c (10 and 8.5 N/cm^2)

The number of shear tests necessary to determine a complete yield locus can be confined to four. Those four tests are characterized by nearly identical values of the stresses σ_c and τ_c during consolidation, but by values of the stress σ_i during shear that are different among themselves: 0.75 σ_c, 0.50 σ_c, 0.25 σ_c and 0.10 σ_c. Fig. 4 gives an example of the curves recorded during four tests with nearly identical σ_c and τ_c. Experience has learned that the best-fitting straight line through the four measured points (σ_i, τ_i) is a very good approximation of the yield locus YL (Fig. 5). Such a yield locus has a definite terminus, since the stresses at which all samples were subjected during the tests, were limited by the stress state described by σ_c and τ_c. The terminus E is thus found as the point of contact between the calculated yield locus and the Mohr circle through (σ_c, τ_c) which has its centre on the σ-axis.

During each test, the specific gravity γ of the soy shreds is measured. The value of γ is used as an acceptance criterion: if it differs more than 2% from the average value of γ corresponding with four shear tests with the same σ_c and τ_c, the test results are rejected.

The yield locus provides us with the values of some important parameters (Fig. 5):

— consolidating pressure σ_1
— unconfined yield pressure σ_p
— flow function $ff_c = \sigma_1/\sigma_p$
— angle of internal friction ϕ_i
— angle of effective friction ϕ_e (the effective yield locus EYL is the straight line through the origin tangent to the largest Mohr circle).

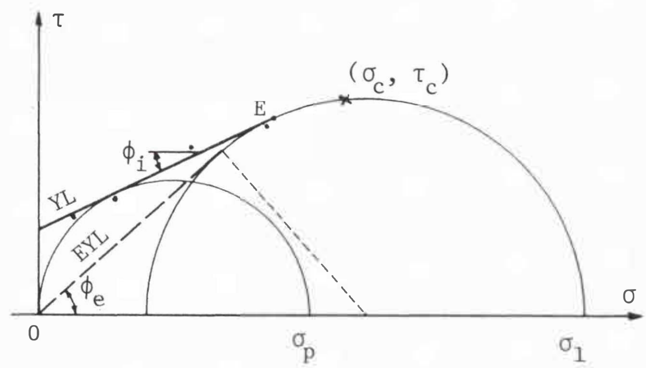

Fig. 5: Yield locus and most important characteristics

Once a number of yield loci have been determined, the relationship between σ_p, ff_c, ϕ_i and ϕ_e on the one hand, and σ_1 on the other hand, can be investigated.

3.2 Time Effect

Time consolidation (i.e. consolidation of a bulk solid under a load lasting for a given time) can influence the flow properties of soy shreds appreciably. This can be verified experimentally by placing the entire shear cell in a consolidating bench after completion of preconsolidation and consolidation (Fig. 6). During a period of time t (the consolidating time) the soy shreds are subjected to a vertical pressure σ_1, being the consolidating pressure derived from previous

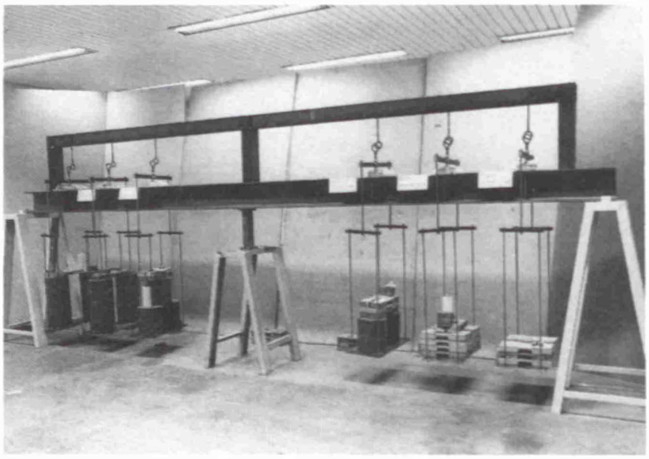

Fig. 6: View of the consolidating bench

shear tests without time consolidation. Subsequently the shear cell is removed from the consolidating bench to the actual test set-up, and subjected to shear. In a σ-τ diagram, the stresses σ_i and τ_i recorded during shear represent a point of the time yield locus, which lies above the instantaneous yield locus corresponding with σ_1. The terminus *E* is found as the point of contact between the time yield locus and the Mohr circle through (σ_1, 0) which has its centre on the σ-axis.

3.3 Test Results and Interpretation

17 yield loci were determined experimentally. The consolidating pressure σ_1 and the consolidating time *t* were taken as the principal variables. σ_1 turned out to be almost the double of σ_c.

Table 1 reviews the flow properties of soy shreds as derived from the measured yield loci. In order to show the time effect clearly, all yield loci and their largest Mohr circles corresponding with a given value of σ_1, were drawn in a σ-τ diagram. An example is given in Fig. 7 (σ_1 = 21.35 N/cm^2). The yield locus lies higher and has a steeper slope as the soy shreds were longer subjected to consolidating pressures. Especially the increase of cohesion produces a rise of the unconfined yield pressure, which becomes more obvious as σ_1 increases.

An overall summary of the research into the flow properties of soy shreds can best be obtained by plotting the values of the flow function ff_c, as given in Table 1, against σ_1 (Fig. 8). The curves in Fig. 8 are not based on any mathematical expression. When they are compared with the Jenike classification of the flowability of bulk solids:

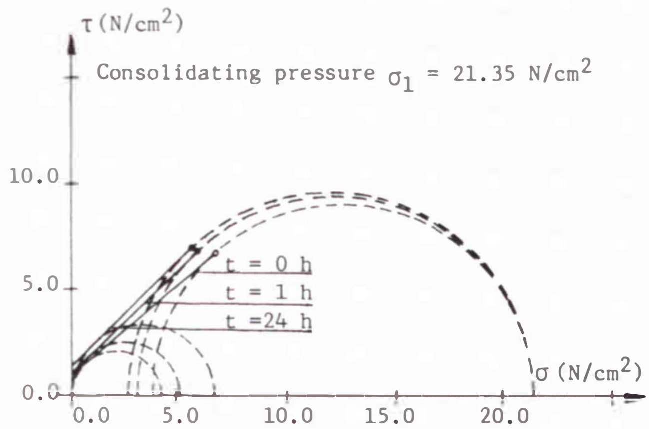

Fig. 7: Instantaneous yield locus and time yield loci with their corresponding largest and smallest Mohr circles

Table 1: Flow properties of soy shreds as derived from 17 measured yield loci

Consolidating time	Consolidating pressure	Terminus of yield locus		Cohesion	Unconfined yield pressure	Flow function	Angle of internal friction	Angle of effective friction
	σ_1	σ_E	τ_E	c	σ_p		ϕ_i	ϕ_e
(h)	(N/cm^2)	(N/cm^2)	(N/cm^2)	(N/cm^2)	(N/cm^2)	$ff_c = \sigma_1/\sigma_p$	(°)	(°)
0	3.01	0.75	0.87	0.04	0.22	13.68	47.93	49.37
0	5.88	1.70	1.80	0.19	0.88	6.68	43.50	46.77
0	10.52	3.31	3.33	0.51	2.20	4.78	40.43	45.36
0	21.35	6.78	6.74	0.98	4.22	5.06	40.36	44.99
0	30.54	8.59	9.26	0.89	4.24	7.20	44.24	47.23
0	40.83	11.88	12.44	1.17	5.45	7.49	43.50	46.40
1	3.01	0.63	0.85	0.07	0.41	7.34	50.87	53.47
1	5.88	1.58	1.80	0.25	1.18	4.98	44.61	49.00
1	10.52	2.93	3.28	0.52	2.42	4.35	43.87	48.47
1	21.35	5.85	6.66	1.11	5.15	4.15	43.52	48.99
1	30.54	8.25	9.81	2.25	10.23	2.99	42.51	50.53
1	40.83	10.48	12.72	2.41	11.50	3.55	44.53	50.90
24	5.88	1.45	1.79	0.28	1.37	4.29	46.07	51.08
24	10.52	2.82	3.28	0.58	2.74	3.84	43.82	49.72
24	21.35	5.51	6.74	1.44	6.76	3.16	43.90	51.24
24	30.54	7.03	9.67	2.57	12.49	2.45	45.28	54.90
24	40.83	8.95	12.95	3.76	18.51	2.21	45.78	56.56

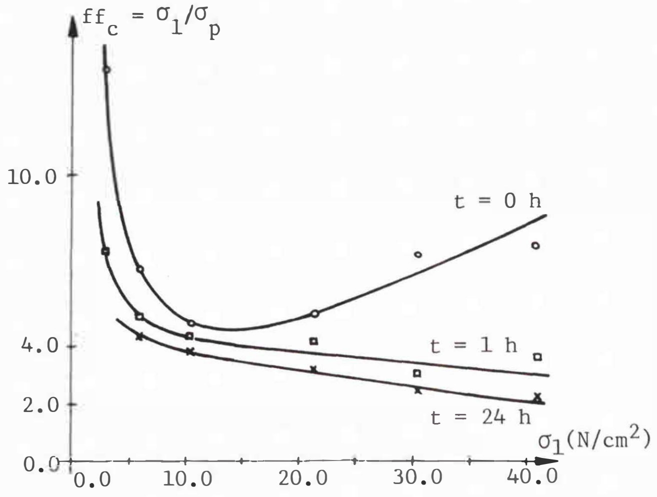

Fig. 8: Flow function ff_c

$ff_c < 2$: very cohesive and non-flowing
$2 < ff_c < 4$: cohesive
$4 < ff_c < 10$: easy-flowing
$10 < ff_c$: free-flowing,

a number of conclusions can be drawn:

— Soy shreds, when not subjected to a time consolidation, behave easy-flowing. After a time consolidation of 1 hour under a consolidating pressure σ_1, soy shreds become cohesive for values of $\sigma_1 \geqq 15$ N/cm^2. For a time consolidation of 24 hours, this happens for $\sigma_1 \geqq 8$ N/cm^2.

— A remarkable difference between the curve for $t = 0$ h and those for $t = 1$ h and $t = 24$ h is observed, namely for the part where $\sigma_1 > 18$ N/cm^2. For $t = 0$ h, flowing gets less difficult as σ_1 increases from 18 N/cm^2 on. For $t = 1$ h and $t = 24$ h on the contrary, flowing gets more difficult. This is due to the caking of the soy shreds, which is the result of a strongly marked increase of cohesion under time consolidation. The afore-said possibly implies that the time after which the soy shreds start to cake is about 1 hour, for $\sigma_1 = 18$ N/cm^2.

Cohesive bulk solids, when stored in silos, can build stable domes from one wall to another. Such a dome cannot exist when the greatest pressure σ_b working along its thrust line, satisfies the following condition:

$$\sigma_b > \sigma_p \quad (1)$$

For the prismatic part of a rectangular silo, σ_b can be calculated as [4]:

$$\sigma_b = b\,\gamma/\sin 2\phi_w \quad (2)$$

where b: breadth of the silo, γ: specific gravity of the bulk solid, ϕ_w: angle of friction between bulk solid and silo wall.

When the case of soy shreds in a silo with smooth concrete walls is considered, $\gamma = 6.5$ kN/m^3 [5] and $\phi_w = 28°$ (Table 3). Eqs. 1 and 2 yield the condition:

$$b > 127.5\,\sigma_p \quad (3)$$

(b in meter, σ_p in N/cm^2)

The minimum breadths, calculated in accordance with Eq. 3, are given in Table 2 as a function of σ_1 and t. The values of σ_p that were used correspond with the curves drawn in Fig. 8. The figures in Table 2 clearly show, and this cannot be overstressed, that soy shreds are a cohesive material, strongly influenced by time consolidation and mostly requiring a continuous circulation when stored in silos.

Table 2: Minimum width (in meters) if arching of soy shreds is to be avoided

t (h)	σ_1 10 N/cm^2	σ_1 20 N/cm^2	σ_1 30 N/cm^2	σ_1 40 N/cm^2
0	2.60	5.20	5.98	6.22
1	2.93	6.71	11.25	17.00
24	3.36	8.23	15.00	24.88

Table 3: Angle of friction between soy shreds and several wall materials

Wall material	Angle of friction (°)	
	Static $\phi_{w,st}$	Dynamic $\phi_{w,dyn}$
Rolled steel (with mill scale)	28.0	28.0
Rolled steel, descaled	14.0	12.8
Rolled steel, descaled and painted with red lead	22.3	19.4
Rolled steel, descaled and painted with zinc-phosphate paint	34.7	34.7
Concrete with a fairly rough surface	35.4	33.2
Concrete with a smooth surface	28.0	28.0
Triplex glass	13.8	13.8
Plywood	19.1	14.9

4. Angle of Friction Between Soy Shreds and Several Wall Materials

4.1 Measurement of Wall Friction

The bottom ring of the Jenike shear cell is replaced by a cylindrical sample of the wall material to be tested. The upper ring is placed on the sample and then filled with soy shreds, which are subjected to a vertical pressure σ. A horizontal shear force F is applied to the upper ring by imposing a displacement s of that ring with respect to the wall-material sample, with a constant velocity of 2 mm per minute. The recorded relationship between F and s is as sketched in Fig. 9. The peak of the diagram corresponds with static wall friction, the horizontal threshold with (pseudo-) dynamic wall friction.

A complete wall yield locus can be determined by measuring the shear force F (or the corresponding shear stress τ) for several values of the normal stress σ.

4.2 Test Results

The angle of friction between soy shreds and eight different wall materials was determined. For each material, the shear stress τ was recorded for six different values of the normal

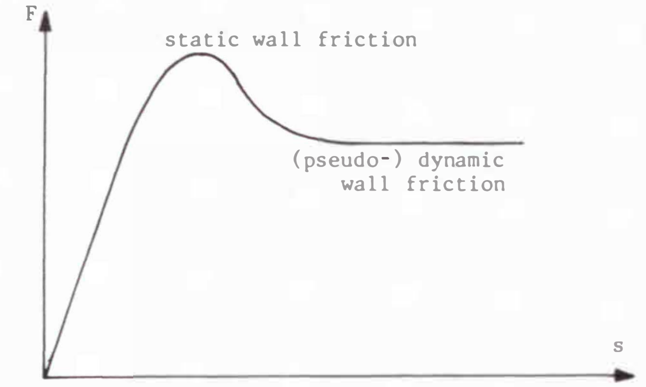

Fig. 9: Relationship between shear force F and horizontal displacement s during a wall-friction test

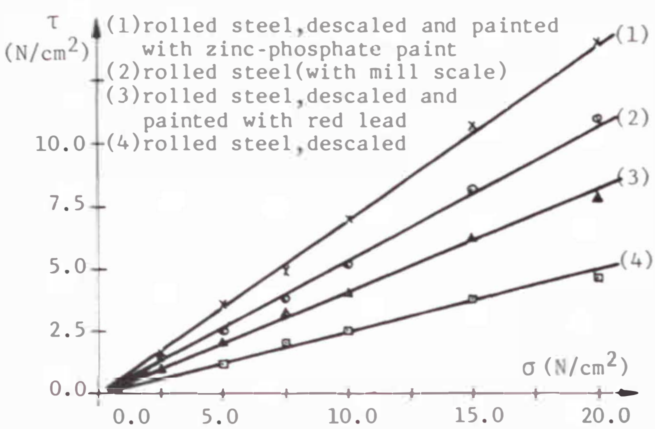

Fig. 10: Some examples of measured wall yield loci

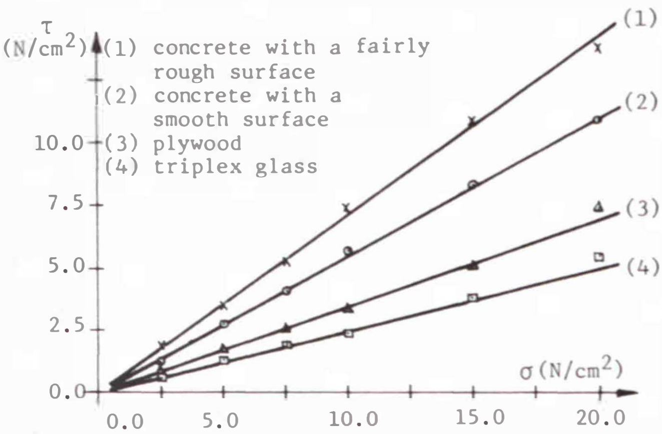

Fig. 11: Some examples of measured wall yield loci

stress σ: 2.5, 5.0, 7.5, 10.0, 15.0 and 20.0 N/cm². In all cases, and for both static and dynamic friction, the wall yield loci were very near to straight lines through the origin (Figs. 10 and 11), so that the angles of friction ϕ_w could be considered constant. Table 3 gives the recorded angles ϕ_w for all tested wall materials. The high value of ϕ_w for a surface of descaled rolled steel painted with zinc-phosphate paint, is due to the plasticity of the coat of paint. The soy shreds hooked on to the coat, which is why the recorded friction lies between the actual wall friction and the internal friction of soy shreds.

5. Caking of Soy Shreds

5.1 Experimental Determination of t_c

The upper ring of the Jenike shear cell is placed on the bottom ring, and both rings are filled with soy shreds. The soy shreds are covered with a circular steel plate, on which a vertical force N_v is applied. N_v introduces an average vertical pressure σ_v in the soy-shreds sample. σ_v is evidently a principal stress. When, after a period of time, the cover and the load N_v are removed, and the upper ring is carefully detached from the bottom ring, it is sometimes observed that the soy shreds in the upper ring do not fall down but remain in the ring (Fig. 12). The soy shreds have clearly built a dome that is stable when loaded only with its own nett weight. The time t_c after which soy shreds start to cake under a given principal stress σ_v, can be determined relatively simple by a try-and-error procedure.

Fig. 12: Soy shreds cake in upper ring of Jenike shear cell

5.2 Test Results

t_c was determined for seven values of σ_v: 5, 7.5, 10, 15, 20, 30 and 40 N/cm². To represent the test results in a t_c-σ_v diagram, the reciprocal of a polynomial of degree four with the constant term being equal to zero is assumed to provide the best description. The four unknown parameters can be determined using the method of least squares. This results in

$$t_c = 1000\,(A\sigma_v + B\sigma_v^2 + C\sigma_v^3 + D\sigma_v^4)^{-1} \qquad (4)$$

where:

t_c in minutes
σ_v in N/cm^2
$A = -19.3199\ 10^{-4}$
$B = 11.0236\ 10^{-2}$
$C = -44.7516\ 10^{-4}$
$D = 51.6790\ 10^{-6}$

The curve represented by Eq. 4 is drawn in Fig. 13. As shown in Table 4, the agreement between the measurements and the values of t_c calculated with Eq. 4, is excellent. If t_c is calculated for $\sigma_1 = \sigma_v = 18$ N/cm^2, one obtains $t_c = 66$ minutes, which is in good agreement with one of our findings resulting from the analysis of the measured flow functions ff_c.

If the principal stresses acting in the soy shreds stored in a silo are known, Eq. 4 offers a good estimate of the minimum frequency with which the soy shreds should be circulated if caking is to be avoided. Although caking may not make discharge of the silo impossible, it should not be neglected, since the presence of soy shreds lumps can hinder a fluent discharge and since caking may possibly result in the building of walls in the silo. In a soy shreds silo at Ghent, a soy shreds wall with the following dimensions was observed: height 26 m, width 8.5 m and thickness 4 m [1] [5].

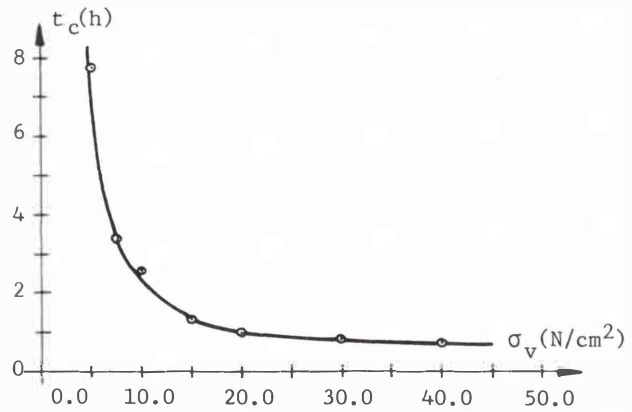

Fig. 13: Caking of soy shreds

Table 4: Caking of soy shreds

Pressure σ_v (N/cm^2)	t_c (minutes)	
	Measured	Calculated
5	465	451
7.5	205	224
10	155	142
15	80	81
20	60	61
30	50	50
40	45	45

6. Dependence of Specific Gravity of Soy Shreds on Consolidating Time

6.1 Experimental Determination of γ/γ_o

Again, the upper ring of the Jenike shear cell is placed on the bottom ring, and both rings are filled with soy shreds. These are covered with a circular steel plate, on which a vertical force N_v is applied, thus introducing an average vertical pressure σ_v (which is also a principal stress). The volume of the soy shreds is determined by measuring regularly the height of the circular cover at a number of points. The ratio of the volume at a point of time t to the volume of the unloaded sample ($t = 0, \sigma_v = 0$) is inversely proportional to the ratio γ/γ_o of the corresponding specific gravities.

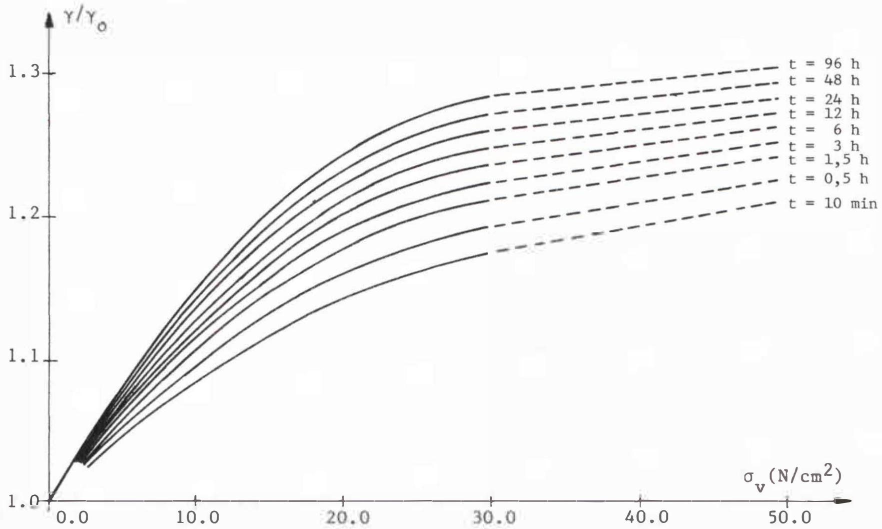

Fig. 14: Dependence of specific gravity of soy shreds on consolidating pressure, the consolidating time taken as a parameter

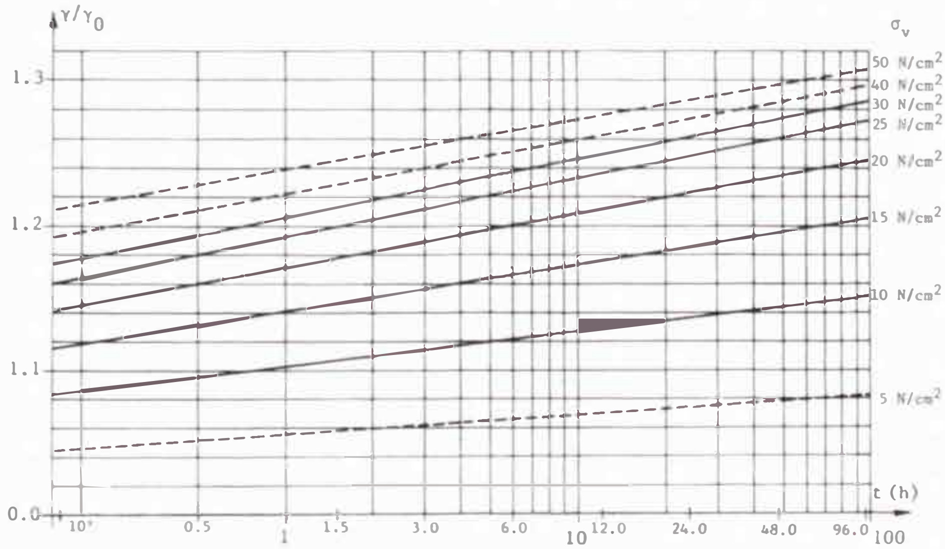

Fig. 15: Dependence of specific gravity of soy shreds on consolidating time, the consolidating pressure taken as a parameter

6.2 Test Results

Measurements were carried out for σ_v = 10, 15, 20, 25 and 30 N/cm^2 at several points of time (varying from 10 minutes till 96 hours after loading of the samples).

As a result, the following relationship was derived:

$$\frac{\gamma}{\gamma_o} = 1 + [A(t) \cdot \sigma_v + B(t) \cdot \sigma_v^2] \cdot 10^{-2} \quad (\sigma_v \leqq 30\ \mathrm{N/cm^2}) \quad (5)$$

Linear extrapolation into the area described by $\sigma_v > 30$ N/cm^2 (Fig. 14) yields

$$\frac{\gamma}{\gamma_o} = 1 - 9B(t) + C(t) \cdot \sigma_v \cdot 10^{-2} \quad (\sigma_v > 30\ \mathrm{N/cm^2}) \quad (6)$$

γ_o = specific gravity of soy shreds at $t = 0$ ($\sigma_v = 0$)
t = consolidating time (in minutes)
σ_v = consolidating pressure (in N/cm^2)
$A(t) = \ln(3.3411 \times t^{0.1266})$
$B(t) = \ln(0.9828 \times t^{-0.0023})$
$C(t) = A(t) + 60\,B(t)$

Fig. 15 shows γ/γ_o as a function of log t for several values of σ_v. Only the full lines correspond to test results.

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