Flow property measurement using the Jenike shear cell for 7 different bulk solids

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Abstract

It is essential to understand the effect of material characteristics such as size and moisture content on the flow of bulk solids. In this study, instantaneous flow properties (cohesion, angle of internal friction) of 3 different sand samples (Yalıköy, Safaalanı and yellow), soda, limestone, dolomite and clay were measured at intrinsic moisture contents by using Jenike shear tester. Additional tests were also performed for low and high moisture contents of Yalıköy sand. Flowability of solids which is characterized by flow function (or flow index) was investigated for studied materials and a classification was made.
It has been found that cohesion values increase with increasing normal stress values and high moisture content and small particle size also increase the cohesion values. Beside, there is not significant difference between the angle of internal friction values at different stress levels. The material which has the hardest flow is clay and soda has the easiest flow among the studied materials. While clay and soda have been classified as cohesive and free flowing material, all other materials have been found in easy flowing material class. It can be said that high moisture content and small particle size has an adverse effect on the flow. While the flow of Yalıköy sand at low moisture content has been easier than its intrinsic moisture content, a more difficult flow hasn't been obtained at high moisture content as expected.

Keywords: Shear testing, yield locus, Jenike shear tester, flow properties, flow function

1. Introduction

Of all the materials handled and produced by the chemical and process industries are in the solid state and always in particulate form. In the chemical industry alone the quantity of the product in the particulate form is greater than 30% of the whole. These materials are ranging from agrochemicals to pigments, from detergents to foods, from plastics to pharmaceuticals. The handling (storage, transportation and charging) of these materials is an important operation in these industries. With the increase in the need to store bulk solids, reliable flow from storage devices has become more important than ever before. However, surveys on the performance of the processes designed to produce particulate products have shown inadequate design and poor system reliability. From an energy point of view, the handling operations have performed wastefully and improvements in techniques could lead to considerable savings over a wide range of industries [1].

Some materials flow better than others and it is well known that wet and fine solid materials flow poorly and cause obstructions in the flow. Therefore, it is essential to understand the effect of material characteristics such as size, composition and moisture content on the static and dynamic behavior of solid materials in silos (bunker, bin). Determining the flow properites of bulk solids is the first mandatory step of silo design procedure and it is important for a proper and efficient bin design.

The standard method to characterize flow properties of solid materials is the shear testing which provides the information for the yield locus of the solid in question. All of the other flow properties (angle of internal friction, cohesion, flow function, kinematic angle of wall friction, etc.) of solids are also determined from the yield loci. Shear testing is based on the information of shear stress values against normal stress values and these are obtained by sliding the material inside itself under defined load values.

The aim of this study is to determine the flow properties of some raw materials used in glass industry by shear tests and to understand the effect of parameters such as moisture content and mean particle size on the flow of materials.

2. Theory

2.1. Yield Locus

The shear stress (τ) generated along a defined plane depends on the normal stress (σ) exerted on this plane. If a material is subjected to a shearing action, a characteristic relation is obtained between normal and shear stresses for each material. This relationship is graphically shown in σ-τ coordinates (namely Mohr diagrams) and the curve - always a straight line- obtained finally is the yield locus for a bulk material. All of the flow parameters of bulk materials are obtained from these yield loci [2]. A yield locus is an important tool in determining the flow properties of bulk materials.

There are generally two types of bulk materials such as free flowing and cohesive in relation to their flow properties. It can be seen from the form and position of yield locus in the Mohr diagram which type of material is. A cohesive bulk material is named as Coulomb solid and expressed by a linear yield locus in soil mechanics:

$$\tau = \tan\phi\sigma + C \qquad (1)$$

τ is the shear stress, σ is the normal stress, C is the cohesion and ϕ is the angle of the internal friction of the material. ϕ is an indication of the friction coefficient within the material. It has a constant value as it changes at low consolidation stress levels in the case of curved yield locus [3]. A yield locus for a cohesive solid is shown in Figure 1.

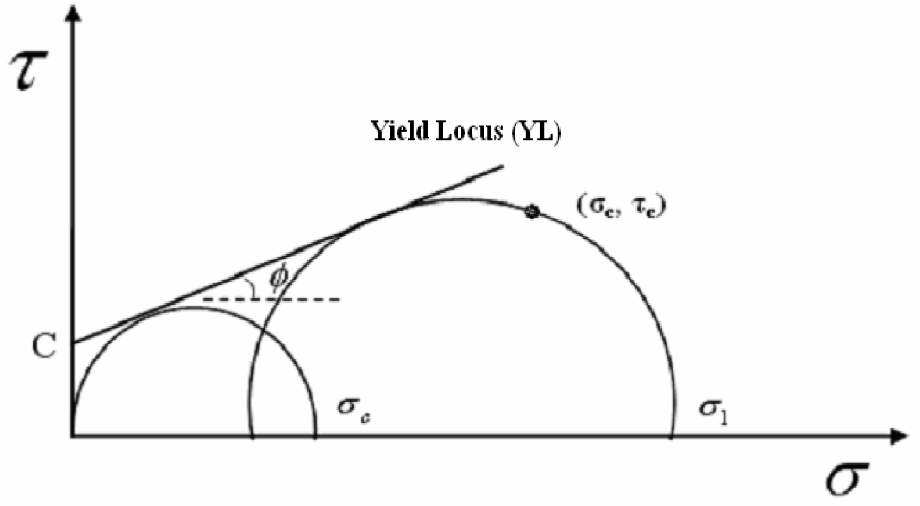

Fig. 1. Yield locus for a cohesive solid and related parameters [3]

In order to initiate the motion within the solid body (flow-plastic deformation) at least one point on the Mohr circle should correspond to a failure plane. The location of the failure plane on the Mohr circle is obtained by the tangency of the material yield locus to the Mohr circle. From this point of view, Mohr circles have an important role in defining characteristic properties of bulk materials using yield locus [3, 4].

2.2. Flow Function

Major principal stress in the steady state flow is called major consolidation stress (σ_1). σ_1, acting on critical consolidation condition, is determined by drawing the Mohr circle (steady state Mohr circle) passing through the point (σ_c, τ_c) which represents the consolidation conditions in shear tests (Figure 1). The circle is tangent to the yield locus and the intersection of circle with normal stress axis gives σ_1 value. Unconfined yield stress (σ_c) is the maximum normal stress value which a solid having a free and stressless surface flows or deforms. While yield locus of a solid is known, σ_c is found by drawing a Mohr circle (unconfined yield stress Mohr circle) tangent to the yield locus and passing through the orijin ($\sigma=\tau=0$). There is a corresponding value of σ_c for each consolidation stress (σ_1), σ_c increases as consolidation stress increases. If σ_c values are plotted against σ_1 values, flow function (FF) of the material is obtained and it characterises the flow capability of a bulk material [3, 5, 6].

A straight line approach can be made for most material's flow function [6, 7]. Material cohesiveness shows increase with inreasing slope values regarding flow function graph, decrease in slope values illustrates a easier flow of solid (Figure 2). As the flow functions having different slopes can belong to different materials, it also represents the same solid at different moisture contents. The flow index (ff_c), defined as the inverse slope of the flow function (FF), is used to classify powder flowability with higher values representing an easier flow [7]. This classification is given in Table 1.

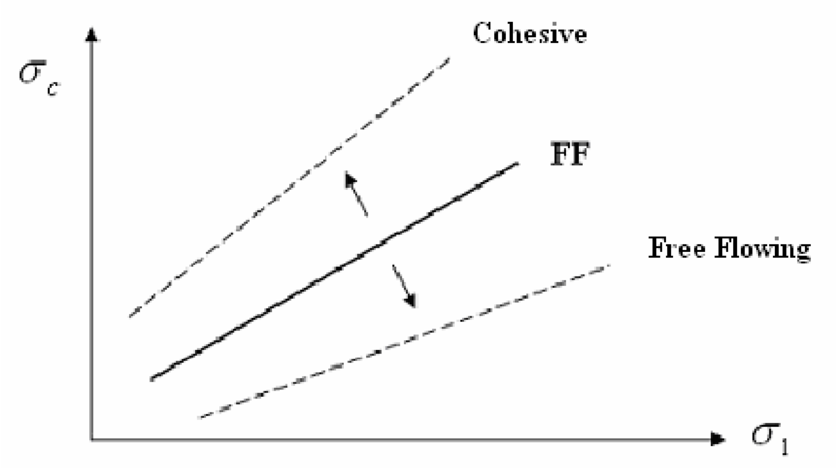

Fig. 2. Solid propety according to FF slope

Solids may contain both fine and coarse particles in different sieve sizes, therefore the flow properties of fine fraction of the solid is always dominant in solids flowability. This situation can be explained by the truth that shearing action occurs through the fine particles within the solid [5]. Hence, the higher the fine particles ratio in the solid, namely the smaller the mean particle size of the solid, the higher the shear stresses obtained with these solids under same loads. This means that the flow of the material will be difficult. The fine particles have also more impact in solids cohesion than the coarse particles do. So, the higher the fine particles fraction in the solid, the higher the cohesion values obtained. Moisture content may make a material cohesive and the flow may happen in a difficult way. As the moisture content increases, the cohesion values increase depending on the increasing capiler forces between the particles.

Table 1. The classification of powder flowability by flow index (ff_c) [7]

Flowability	Hardened	Very cohesive	Cohesive	Easy flowing	Free flowing
Flow index (ff_c)	< 1	< 2	< 4	< 10	> 10

2.3. Determining the Flow Properties

The relationship between the normal and shear stresses in solids is determined experimentally under different loads and this experimental procedure is known as shear tests. All of the flow properties of bulk solids are based on the yield loci obtained by these shear tests. There are so many different shear test apparatuses available to measure the flow properties of solids. The flow properties are determined by directly (linear, ring [8, 9] and rotational shear testers [10, 11, 12]) or indirectly (2 or 3 axial cells [8, 11]). The working principle of all test apparatuses are similar; as a constant vertical load is applied to the sample, a horizontal force is applied to shear the sample under this load. Test apparatuses fundamentally differ in applying vertical loads to the sample [8, 11, 13].

Stress is applied in one direction in direct shear test apparatuses, the direction of the principal stress is constant and doesn't change during tests. Jenike test apparatus [2, 5, 14] is an example to these test apparatuses and it is the most well-known shear tester. The reason for the preference of Jenike type shear tester; widespread usage in industry and obtaining the flow function which is an important parameter in predicting the flowabilitiy of a bulk material according to the test results. Besides, the disadvantages are the limited movement distance of the shear cell and the requirement of a certain level of expertise in appropriate specimen preperation and obtaining an optimum consolidation level for the specimen. Finally, this apparatus should be used when time is not a critical factor and the flow function of the material is required [8, 11]. Being an altenative to the Jenike shear tester having a dead load applied in vertical, Puri and Lapido [15, 16] have suggested a computer controlled test apparatus which has vertical load decreasing continuously. Similarly, Tsunakawa and Aoki [17] have improved a direct shear cell arranged to make a compressed loading.

3. Materials and Methods

3.1. Materials

3 different sand samples (yellow sand, Yalıköy and Safaalanı sand), soda, limestone, dolomite and clay were used to determine the flow properties. Some physical properties of materials used in the tests are shown in Table 2. Moisture measurements of test samples were done by substracting the dry weight of the sample from the initial weight. Dry weight is the weight of a determined quantity of sample after waiting in a drying oven at 105 ^{o}C for 24 hours. Different moisture contents of Yalıköy sand were achieved by adding water to the original sample or substracting water from the sample by drying. These sand samples were waited for a time in an enclosed vessel to get a homogenised sample (The given moisture results are the arithmetic mean of the several measurements). Mean particle size of samples were calculated by taking the arithmetic mean of the distribution obtained from the sieve analysis. Bulk density (ρ_b) values were determined by weighing materials in a graded measuring cylinder (dropping the cyclinder with material in it 3-4 times from a 2-3 cm height). ρ_c values are again the density values obtained at the highest consolidation/compression levels of materials in the shear tests performed.

Table 2. Some physical properties of used materials

Material	Moisture content (%)	Mean particle size (μm)	ρ_b (g/cm^3)	ρ_c (g/cm^3)
Yalıköy sand	3.6	131	1.1083	1.4879
Safaalanı sand	4	132	1.1104	1.3050
Yellow sand	7	133	1.1533	1.4046
Limestone	0.04	413	1.6596	1.9012
Dolomite	0.025	335	1.7951	2.0097
Soda	0.25	365	1.1542	1.2697
Clay	0.24	43	0.8131	1.2560

Chemical analysis of the used materials was made in ŞİŞECAM laboratories and analysis results have been illustrated in % composition in Table 3. The analysis method used in determining the chemical content of materials is XRF (X-Ray Fluorescence Spectroscopy).

Table 3. Chemical analysis results of used materials

Material	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	K_2O	Na_2CO_3
Yalıköy sand	99.23	0.20	0.05	0.18	0.01	0.04	0.06	-
Safaalanı sand	92.45	4.03	0.06	0.04	0.04	0.02	2.35	-
Yellow sand	99.00	0.25	0.11	0.24	0.05	0.04	0.08	-
Limestone*	0.20	0.08	0.03	-	54.54	1.22	-	-
Dolomite*	0.28	0.13	0.05	-	31.96	20.50	-	-
Soda	-	-	-	-	-	-	-	99.69
Clay	78.21	14.76	0.33	0.38	0.16	-	0.08	-

* The analysis results are only given in oxides, remaining is the losses due to the super heating.

3.2. Method

Jenike type shear tester with standard size shear cell (D=95 mm) was used in the tests to determine the flow properties of materials, other dimensions are also the same as standard shear cell [14, 18]. Jenike shear tester mainly consists of a circular cross sectional shear cell which is located on the frame of the machine and the load applying parts both in vertical (normal load) and horizontal (shear load) directions. Normal load is applied to the system-shear cell- by means of a gravity vertical loading system (weight hanger). The shearing action is also provided by means of an electromechanically driven loading stem. This system moves the loading stem horizontally at a rate of approximately 2.5 mm/min. The shear force is measured with a load cell and indicated on a strip chart type flatbed recorder. The shear cell is illustrated schematically in Figure 3 and consists of a base (1), a shearing ring on the base (2) and a shearing lid (3) with a loading bracket (4) and a pin (5) attached to it. Vertical load is applied to the lid by means of a weight hanger (6) with standard weights (7) on it. A horizontal force is applied to the bracket by a mechanically driven measuring stem (8). The results of shear tests are generally expressed in terms of stresses. As the cells are loaded by weights and recorder gives force values, the corresponding stress values is calculated by considering the cross-sectional area of shear cell.

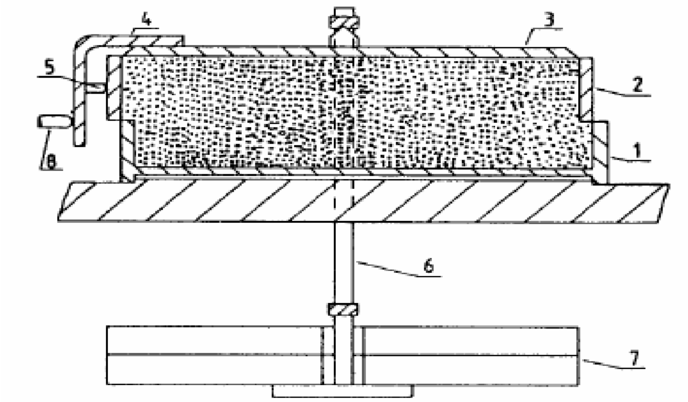

Fig. 3. The schematic diagram of Jenike shear cell

The standard test method carried out in this study (standard test method for instantaneous flow using the Jenike shear cell) is defined in the publication of European Federation of Chemical Engineering [18]. The same procedure was applied in obtaining datas and data validation and experimental precautions were obeyed in the same way as described. For each flow function four yield loci were obtained at different stress levels (pre-shear normal stress levels) and four point were obtained for each yield locus. The shear test generally consists of two steps. The first step is the consolidation (pre-shear) step in which a criticially consolidated sample is prepared (an optimization is required). The second step is the attainment of steady state flow in the shear cell which is called as shear step. Shear points on yield locus with failure point (require for material to flow) shear stress values were obtained for a defined shear normal stress at a selected pre-shear normal stress. Each point of yield locus was repeated two times in the tests.

4. Results and Discussion

4.1. Yield Locus

The points obtained for yield loci have drawn in σ-τ coordinates and straight lines have been fitted for these points. Cohesion (C) and angle of internal friction (ϕ) values for materials have found from the equations belong to the straight lines [19] according to the Mohr-Coulomb model (Eq. 1) at each stress level (Table 4).

Table 4. Flow parameters found from yield loci at selected pre-shear normal stress levels

Material	Moisture Content (%)	Pre-shear Normal Stress (kPa)	C (kPa)	tanϕ	Angle of internal friction, ϕ (°)
Yalıköy sand	3.6	4.12	0.8797	0.6714	33.9
		8.55	1.3828	0.6264	32.1
		17.96	2.2645	0.5862	30.4
		31.80	2.7369	0.5922	30.6
Yalıköy sand	1	4.11	0.8192	0.6074	31.3
		8.54	1.0619	0.605	31.2
		17.96	1.6739	0.651	33.1
		31.79	2.5279	0.6	31.0
Yalıköy sand	14	4.12	1.1372	0.6206	31.8
		8.55	1.4473	0.6246	32.0
		17.96	2.1708	0.59	30.5
		31.80	2.7968	0.6021	31.1
Limestone	0.04	3.00	0.2121	0.7703	37.6
		6.66	0.4388	0.7527	37.0
		12.07	0.6937	0.7458	36.7
		23.69	0.9304	0.7424	36.6
Dolomite	0.025	3.01	0.3436	0.7138	35.5
		6.69	0.6461	0.7057	35.2
		12.08	0.9015	0.7116	35.4
		23.71	1.1408	0.7119	35.5
Yellow sand	7	2.92	0.6631	0.6308	32.2
		5.62	1.1753	0.4986	26.5
		10.76	1.5427	0.5572	29.1
		20.87	2.3209	0.5752	29.9
Safaalanı sand	4	2.91	0.6272	0.5462	28.6
		5.62	0.8791	0.5633	29.4
		10.75	1.2078	0.6042	31.1
		20.85	1.6042	0.6194	31.8
Soda	0.25	2.92	0.1881	0.7483	36.8
		6.59	0.3435	0.7638	37.4
		11.98	0.5318	0.7499	36.9
		23.61	1.0659	0.7535	37.0
Clay	0.24	2.69	0.8357	0.5747	29.9
		5.19	1.4238	0.5504	28.8
		10.73	2.4255	0.5474	28.7
		20.84	3.8582	0.6085	31.3

Angle of internal friction values for a spesific material don’t change significiantly at different stress levels as seen from Table 4, approximately between 30-40°. Only the value for yellow sand at second stress level is different from the other three values. Angle of internal friction values for limestone, dolomite and soda have higher values differently from the other materials. As these values don’t give any idea about material flowability, it can be stated that these angle values are higher for the materials which have low moisture content and seem to have easy flow.

An increase has been observed in cohesion values of materials as normal stress values increases (Table 4). The reason is the pressing of the material particles under increasing load and sticking together more tightly. For the two materials under the same loads, it may be said that the material which has the higher cohesion value either has higher moisture content or lower particle size than the other. Cohesion values show increase as the sticking of particles together becomes easier with the increasing moisture content or the decreasing particle size. For the yellow and Safaalanı sands having almost the same mean particle sizes, higher cohesion values have been obtained under the same loads for yellow sand which has a higher moisture content. The increase in cohesion values with the increased moisture content for Yalıköy sand can also be seen from Table 4. Comparing limestone and dolomite, it is seen that cohesion values obtained for dolomite are higher which has a lower particle size. Very high cohesion values have been founded for clay which is the lowest particle sized material. It can only be predicted the flow of a material being either easier or harder to the others by comparing the cohesion values under the same loads.

4.2. Flow Function

σ_1 ve σ_c values have been determined at each consolidation level with the aid of yield loci by obtaining the draw of apprapriate Mohr circles on the yield loci graphs. The variation of σ_c with σ_1 is important for bulk solid materials and this relation gives the flow function of the materials in question. The flow functions obtained are illustrated in Figure 4.

According to the results in Figure 4, the flow will be difficult for the material having a higher slope value or its flow function relatively staying upper to the others. For this reason, the material which has the hardest flow is clay among the studied materails. Beside, soda has the easiest flow to occur. Obtaining the hardest flow for the clay can be related with its mean particle size comparatively small to the other’s. At this point, it can be easily said that small particle size has an adverse effect on the material flow. Supporting to this result, for the materials limestone and dolomite having almost the same moisture content, it is seen that the flow is more difficult for dolomite having a smaller mean particle size than limestone. Therefore, regarding to this result, it can be expected that the flow of soda is harder than limestone as it has a higher moisture content. However, the sliding of soda particles over each other has become easier considering that soda has a smoother particle shape (spherical) comparing to the others and this resulted in being the material which has the easiest flow.

Observing the flow functions of Yalıköy sand obtained at different mositure contents, it is seen that the flow function defined at low moisture content (%1) is under the flow function at intrinsic moisture content. This is the indication of occuring an easier flow at low moisture contents. It can be expected that a more difficult flow will occur at high moisture contents regarding to this reached conclusion. Therefore, although the higher shear stresses have been obtained under same loads at high moisture content, if flow functions are considered it has been observed that the flow function for %14 moisture content underlies the %3.6 moisture content flow function. This situation is reverse at low consolidation levels; the values at high moisture content, namely the flow function line, are higher. The reason for obtaining lower σ_c values at high stress levels for %14 moisture content of Yalıköy sand (comparing with the sand of % 3.6 moisture) may be the penetration of water molecules exceedingly to the solid particles intervals. This may help the particles slide over each other (flow) easily. As a similar situation, considering the yellow and Yalıköy sands having the similar particle size, while it is expected the flow function of yellow sand having a higher moisture content to stay higher, its flow function remains under the Yalıköy sand's. Finaly, it can be said that the flow will be more difficult as the mositure content of the material increases and the high moisture contents over a specified value could make the flow to occur easily.

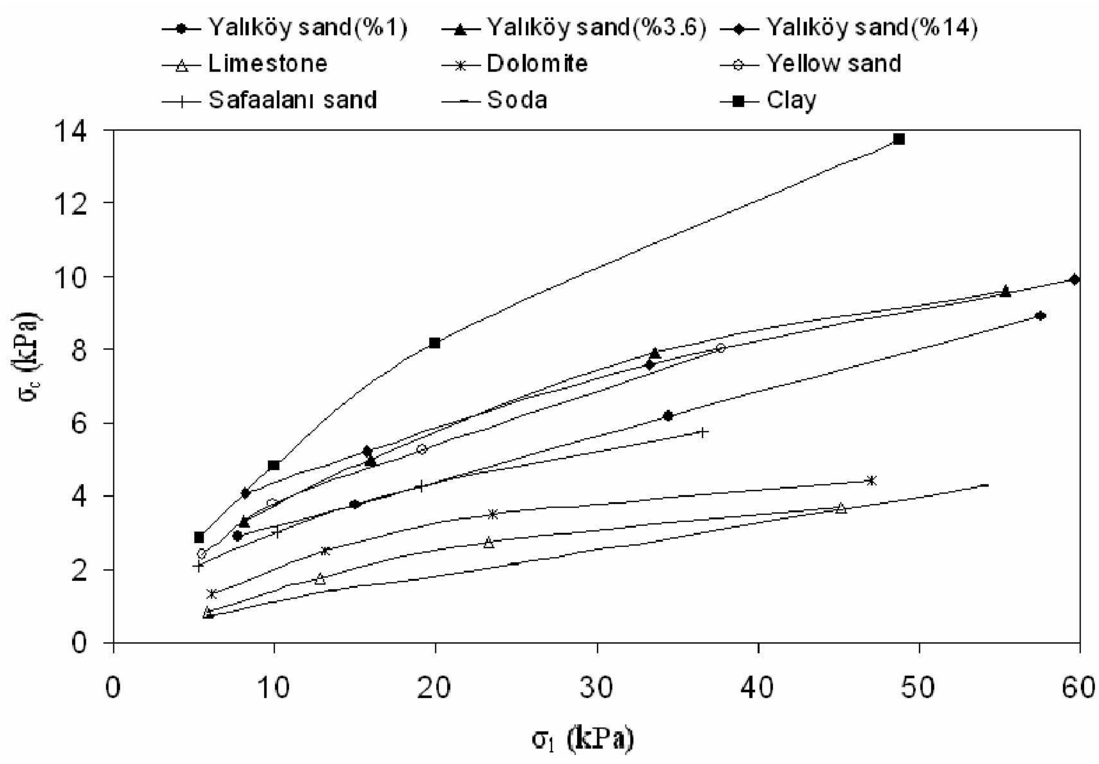

Fig. 4. Flow functions for different materials

It is required to express the flow functions with equations in an appropriate form in order to use them in silo design calculations. When the flow functions are generally expressed by a second degree curve, it is seen from the graph that this can be a good approach considering the defined points (Figure 4). Because, it is clear that many materials have a limited stress function, namely σ_c increases with increasing consolidation stress and reaches a limited value at the end. Therefore, expressing the flow functions like this will result in low values for outlet dimensions of silos to be degined [19]. When a straight line is fitted through the points obtained for flow function, the regression coefficient values (R^2) of straight lines found for many materials are rather low. It is seen from Figure 4 that last points of some flow functions cause this result. At this point, it can be thought that last points to be removed from the flow functions. Finally, as the all the points defined at the tests have been used for the flow functions of some materials (yellow sand and soda), the equations for flow functions of all other materials have defined by using only first three points. A classification has also been made according to the slope values of defined equations and has been given in Table 5.

Table 5. The classification of materials due to the flow functions

Material	Moisture Cont. (%)	Mean particle size (μm)	FF	ff_c	Classification
Yalıköy sand	3.6	131	0.1780	5.6	Easy flowing
	1	131	0.1211	8.3	Easy flowing
	14	131	0.1123	8.9	Easy flowing
Yellow sand	7	132	0.1665	6.0	Easy flowing
Safaalanı sand	4	133	0.1546	6.5	Easy flowing
Limestone	0.04	413	0.1078	9.3	Easy flowing
Dolomite	0.025	335	0.1218	8.2	Easy flowing
Soda	0.25	365	0.0726	13.8	Free flowing
Clay	0.24	43	0.3598	2.8	Cohesive

It is seen from the results in the Table 5 that the flow of materials become harder with the decreasing flow index (ff_c) values. Many materials are in easy flowing material class. Otherwise, soda and clay are classified as free flowing and cohesive material. The effect of moisture content and mean particle size on the material flow are evident, high moisture content and small particle size make the material difficult to handle. As the sands used are closer to the cohesive material class, limestone and dolomite are also closer to the free flowing material class. Yalıköy sand couldn't have gone out from easy flowing material class although its moisture content was changed. It is seen that the Yalıköy sand at low mositure content is closer to the free flowing material class which provides an easier flow and even this situation may be more evident at lower moisture contents. While a lower value (<5.6) for flow index is expected at high moisture content, a higher value has been obtained. This value at high moisture content (ff_c=8.9) is even higher than the value found at low moisture content. Therefore, it is seen that the flow function at high moisture content is over the flow function at low moisture content.

5. Conclusions

Four yied locus (YL) have been determined at different stress levels for all used materials at the end of the tests. Cohesion (C) and angle of internal friction (ϕ) values have been found at each stress level due to the yield locus results. ϕ values don't change significiantly at different stress levels, differ in the range of 30-40^o. Cohesion values increase with increasing normal stress values. High moisture content and small particle size also cause an increase in cohesion values and consequently a difficulty in material flow.

Clay has been determined as the hardest material to flow and soda has the easiest flow according to the flow functions of the materials. It has been concluded that small particle size and high moisture content make the flow generally harder to occur. Due to the results of tests made for different moisture contents of Yalıköy sand, it is seen that the moisture increase effect the flow in a negative way up to a defined optimum value and may facilitate the flow after this value.

A classification has also been made for materials according to the slope values of equations determined for flow functions of materials. Many materials (Yalıköy sand, Safaalanı sand, yellow sand, limestone, dolomite) are in easy flowing material class considering the classification. Differently, soda is in free flowing and clay is in cohesive material class. Yalıköy sand again stays in the easy flowing material class at both high and low moisture contents.

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