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Testing mechanical properties of food powders in two laboratories - degree of consistency of results**

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A b s t r a c t. Two research groups conducted experiments on the mechanical properties of granular materials of plant origin in two distant laboratories without mutual knowledge about running similar projects. Recently established cooperation of a Spanish research group led by Ayuga and Polish research group led by Horabik allowed for in-depth comparison of results. Materials tested in two locations were: wheat, lentils, rapeseeds, sugar and wheat meal. Material characteristics determined were: strength properties (the angle of internal friction, φ and the cohesion, c), the modulus of elasticity, E and the Poisson's ratio, ν. Test equipments applied were: direct shear, triaxial compression and uniaxial compression apparatuses. In general, analysis of results of testing in the two laboratories have shown that to obtain consistent results strict concordance in material state, equipment and test conditions is necessary. To resolve the problem standardization of parameters and methods of their determination should be undertaken on an international level.

K e y w o r d s: granular material, elastic and strength parameters, uniaxial and triaxial tests, direct shear test

INTRODUCTION

Granular materials are important constituents in numerous industrial processes. Industries producing chemicals, cosmetics, pharmaceuticals, biotechnology, ceramics, food, energy, paper/wood, metals, cement, glass, minerals, consumer products and plastics strongly depend on granular materials. A single shift in physical conditions can drastically change the performance of a process in those industries. Even though granular materials appear simple, they display an astounding range of complex behaviour that has largely been unexplored. Research in this area that has been intensively performed in last 40 years has had important implications for manufacturing and new processes.

The most important technologies of process engineering involving granular materials as listed at 'Powder, bulk solids' portal are: pneumatic conveying, transport, size reduction, spheroidization, screening, coating, mixing (blending), segregation, product consistency, weighing, metering, packaging and bagging, storage, stratification, dust collection, instrumentation and control, feeding and quality control. Each of the above requires specific equipment. To assure reliable processing and efficiency of equipment exact values of material parameters are necessary. Contemporary granular mechanics is to a large extent based on theory and measurement techniques that have been formulated by Jenike (1961) in his work 'Gravity flow of bulk solids'. Simultaneously, in recent decades increases in the number of processes and operations involving granular materials have resulted in a growing need for new theory and technology. This was accompanied with growing interest in investigations of physical properties of granular materials. Development and refinement of methods for determination of physical properties of granular materials has been particularly important. Despite unquestionable progress in measurement methods mechanical properties of granular materials measured in various laboratories can vary greatly. A significant source of the wide range of results is due to the large number of measurement methods and a lack of standard experimental procedures. Some factors strongly influencing properties of food powders such as moisture content, bulk density, packing structure and load history (remain out of control that-delete) contributes to this observed variability.

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In the case of food powders three groups of material parameters are in particular interest of industrial practice: strength properties, elastic constants and flowability. Strength properties: angle of internal friction, φ, effective angle of internal friction, δ and cohesion c are the parameters of Mohr-Coulomb yield condition and methods used in their determination are standardized in design codes *eg* Eurocode 1 (2003). These parameters are crucial for the estimation of pressures of granular materials exerted on storage structures, as well as for design of hoppers and chutes for reliable flow. Elastic constants: modulus of elasticity, E and Poisson's ratio, ν, are based on the assumption of elasticity of granular material at a certain level of consolidation pressure (Sawicki and Świdziński, 1998). These parameters are of particular interest to professionals using computer aided design that recently has become very common tool in modeling flow and pressure states in storage silos (Ayuga *et al*., 2005). Flowability is frequently used as a measure of the quality of granular product that influences its end-use value for some materials. Variation in the flowability of ingredients may be a significant source of errors during weighing and proportioning that can result in non- uniformity of the finished product.

The objective of this work was to compare the results of experiments involving the determination of material parameters of grain and food powders performed independently at two distant laboratories (Moya *et al*., 2002; Ramirez *et al*., 2004; Stasiak and Molenda, 2004). Analysis of the results was expected to identify sources of discrepancies and to indicate means to achieve consistency of results obtained in different laboratories. Only strength parameters and elastic constants were compared because no comparable testing of flowability was performed at the two locations.

MATERIALS

The two research groups have tested wide range of materials, in some cases under several levels of moisture content. Materials tested in both locations under similar levels of normal pressure were: wheat, lentils and rapeseeds, sugar and wheat flour.

PARAMETERS AND METHODS OF DETERMINATION

Strength parameters

Strength properties under consideration are the angle of internal friction, φ and cohesion, c. Both of these parameters are determined using a shear cell (Fig. 1). Equipment needs, procedures and analysis techniques for the determination of these properties is described in Eurocode 1 (2003). The shear cell diameter D (Fig. 1) should be at last 20 times the maximum particle size and not less than 40 times the mean particle size. The height H (identify H on drawing 1) should be between 0.3 and 0.4 D. The maximum particle size is limited to ensure that any interaction of the material with the wall of the shear cell will not influence the measured property. To begin this test the sample should be poured into the test cell, without vibration or other compacting forces and a reference stress, σ_r applied. The top plate of the shear cell is then rotated clockwise and anticlockwise about the vertical axis several times through an angle of at least 10 degrees to consolidate the sample.

The Eurocode 1 shearing procedure is as follows:

1. The reference stress, σ_r, should be approximately equal to the vertical stress in the stored material.

2. Shearing of the sample should be carried out at a constant rate of approximately 0.04 mm min^{-1}.

3. To calculate the strength parameters of granular materials the maximum shear strength, τ, should be used. This value is developed at or before the horizontal displacement of the shear cell has reached a value of Δl = 0.06D.

4. At least two tests should be carried out as defined in (5) and (6) below.

5. The first sample should be tested at a normal stress condition of σ_r to obtain the failure shear stress, τ_a.

6. The second sample should first be preloaded to a normal stress condition of σ_r and just brought to shear failure in a similar manner to that of the first sample. Shearing is then stopped and the applied shear load reduced to zero. The normal stress on the second sample should then be reduced to a value causing approximately half the reference stress (σ_b = $\sigma_r/2$) and sheared again to obtain the failure shear stress, τ_b.

Two parameters of the material, the cohesion c and angle of internal friction, φ_i (see Fig. 1) can be determined

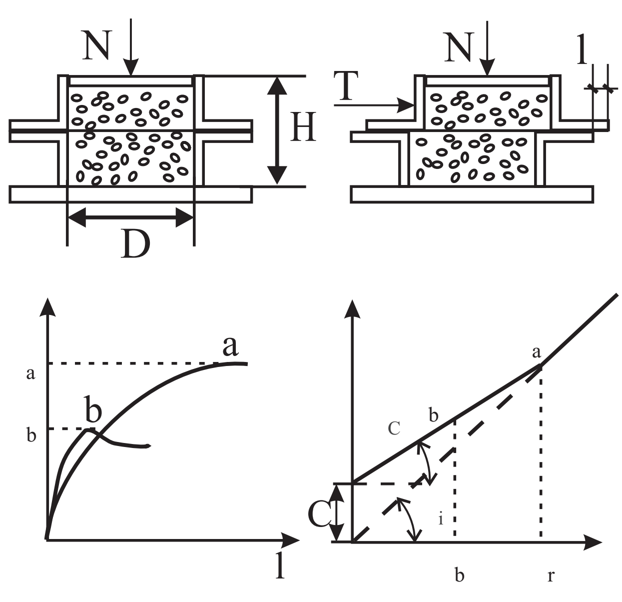

Fig. 1. Direct shear apparatus and determination of strength parameters based on the preconsolidation stress, σ_r.

using this test. These parameters are used in silo design to define the effects of a stored solid's strength on silo pressures after the silo has been filled. The loading angle of internal friction φ_i for the stored solid should be calculated as:

$$\varphi_i = \arctan(\tau_a/\sigma_r). \quad (1)$$

The cohesion, c, that develops in the stored solid under the reference stress, σ_r, should be calculated as:

$$c = \tau_a - \sigma_r \tan \varphi_c, \quad (2)$$

in which:

$$\varphi_c = \arctan \frac{\tau_a - \tau_b}{\sigma_r - \sigma_b}, \quad (3)$$

where φ_c is the unloading internal friction angle for an overconsolidated material.

The magnitude of the cohesion, c, varies with respect to the consolidation stress and is not considered to be a fixed property of the solid. For a cohesionless material (where $c = 0$) frictional strength is described only by the angle of internal friction, φ_l, that is equal to φ_c.

Strength parameters can also be determined using triaxial compressions tests. In triaxial compression tests (ASTM D2850-95, 1999) cylindrical samples of granular material are encased in a rubber membrane while its bases are rigid circular plates. The sample is confined in a tight chamber and pressurized through liquid filling the space around the sample. The sample is deformed axially and the axial compressive force is measured. The test is completed when deformation of the sample reaches 20% *ie* the maximum value allowed by standards (ASTM D2850-95, 1999; UNE 103402, 1998). Mohr-Coulomb strength envelopes are determined using stress-strain curves and strength parameters are calculated in a way identical to that of direct shear test.

In experiments performed in Spain (Moya *et al*., 2002, Ramirez *et al*., 2004) strength parameters of granular materials were determined using both direct shear and triaxial compression tests.

Parameters of elasticity

Within the limits of elasticity, the linear ratio of the stress to strain is termed the modulus of elasticity or Young's modulus, E. The tangent modulus of elasticity is the slope of the stress-strain diagram at any point. The secant modulus of elasticity is stress divided by strain at any given value of stress or strain. It is also called stress-strain ratio. To consider it in the case of granular materials linearity of load - deformation diagram of the sample have to be assumed and achieved at least in a vicinity of tested load conditions. That usually requires pre-consolidation of the sample. Poisson's ratio, ν, is the ratio of transverse contraction strain to longitudinal extension strain in a stretched bar. In the case of granular material elasticity of the sample has to be assumed similarly to conditions of determination of modulus of elasticity.

A model describing the total vertical strain in granular materials under loading was developed by Sawicki (1994). This equation is based on the elasto-plastic approach and assumes during loading both reversible (elastic) and irreversible (plastic) strains develop in the sample. Plastic, ε_z^p and elastic, ε_z^e, strains develop in the material during loading:

$$\varepsilon_z = \varepsilon_z^e + \varepsilon_z^p, \quad (4)$$

$$\varepsilon_z = D_1 \ln(1 + D_2 \sigma_{z0}^a) + \frac{\sigma_{z0}}{E}\left(1 - \frac{2\nu^{*2}}{1-\nu^*}\right), \quad (5)$$

where: ε_z - total vertical strain, ε_z^p - plastic vertical strain, ε_z^e - elastic vertical strain, σ_{z0} - mean vertical pressure on the top cover, E - modulus of elasticity, ν^* - equivalent of Poisson's ratio for loading $\nu^*=K_o/(1+K_o)$, K_o - slope of straight line $\sigma_x=K_o\sigma_z$, D_1, D_2, α - model parameters.

K_o, which is used to calculate the equivalent Poisson's ratio, ν^*, during loading, is the ratio of the horizontal stress, σ_x and vertical stress, σ_{z0}, during consolidation of the sample. During this phase of compression the horizontal deformation, which is the sum of plastic and elastic horizontal strains, is zero ($\varepsilon_x=\varepsilon_x^e+\varepsilon_x^p=0$). D_1 and D_2 are compaction coefficients. Originally Sawicki (1994) assumed the value of the exponent α to be equal to 3/2, but in our examination the value of α was treated as a variable to obtain a better fit of the experimental results to the model curve.

Two phases of the unloading can be observed (Fig. 2). The first phase is characterized by a purely elastic deformation and was used in the determination of elastic constants, the modulus of elasticity, E and Poisson's ratio, ν. The second stage of unloading is characterized by both elastic and plastic deformations. It was assumed that the material reversible response is governed by Hooke's law:

$$\varepsilon_x^e = \frac{1}{E}[(1-\nu)\sigma_x - \nu\sigma_{z0}], \quad (6)$$

$$\varepsilon_z^e = \frac{1}{E}[\sigma_{z0} - 2\nu\sigma_x]. \quad (7)$$

During the first phase of unloading (path AB) granular materials exhibit a linear r elationship which is characteristic of elastic deformation. Assuming that $\varepsilon_x^e = 0$ from Eq. (6)

$$\frac{\sigma_x}{\sigma_{z0}} = \frac{\nu}{1-\nu}$$

is obtained and applying the assumption that

$$\varepsilon_z = \varepsilon_z^e$$

to Eq. (7) ε_z may be expressed as below:

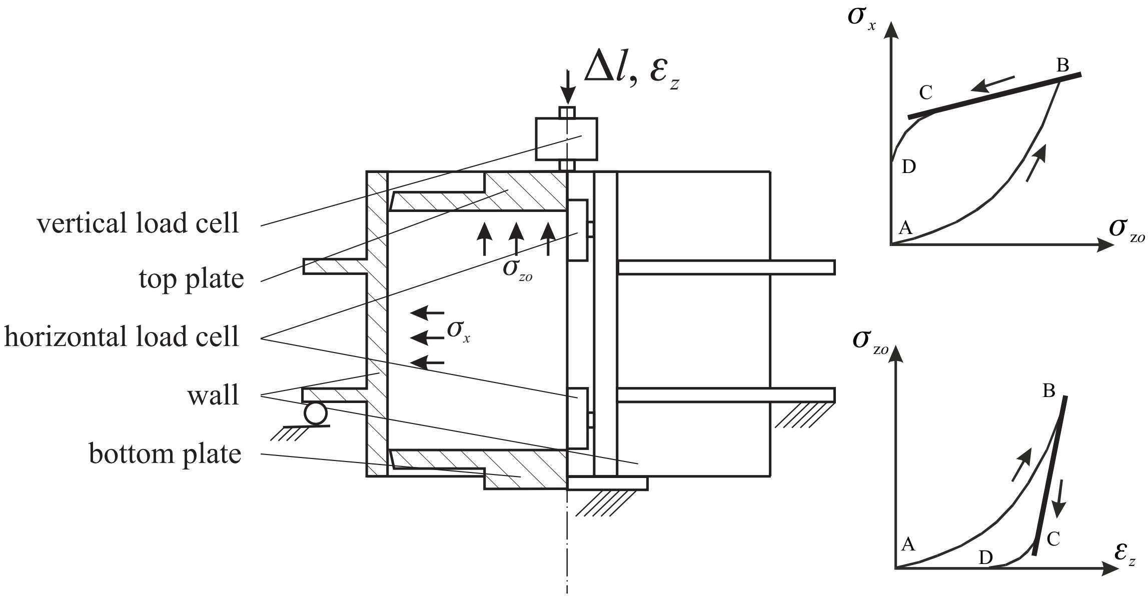

Fig. 2. Uniaxial compression apparatus and determination of modulus of elasticity.

$$\varepsilon_z = \frac{\sigma_{z0}}{E}\left(1 - \frac{2\nu^2}{1-\nu}\right). \quad (8)$$

Elastic constants were determined using experimental results measured during the linear phase of unloading. The ratio of horizontal stress, σ_x, to vertical stress, σ_{z0}, was assumed constant (elastic state of stress) and the slope of the straight portion of the curve defined by A, where $A = \sigma_x/\sigma_{z0} = \nu/(1-\nu)$. Values of A for different granular materials were estimated using linear regression procedure applied to experimental values of stresses (Fig. 3). Knowing A, values of Poisson's ratio, ν, were calculated as:

$$\nu = \frac{A}{1+A}. \quad (9)$$

Values of modulus of elasticity, E, were estimated using relationship $\sigma_z(\sigma_{z0})$ (Eq. (5)) with experimental values of ε_z and σ_{z0}, and ν determined as described above.

Both research laboratories utilized oedometric apparatus to determine, E and ν. The oedometric apparatus utilized by the Polish research group consisted of an oedometer whose walls were formed by two semicircular halves cut along the axis.

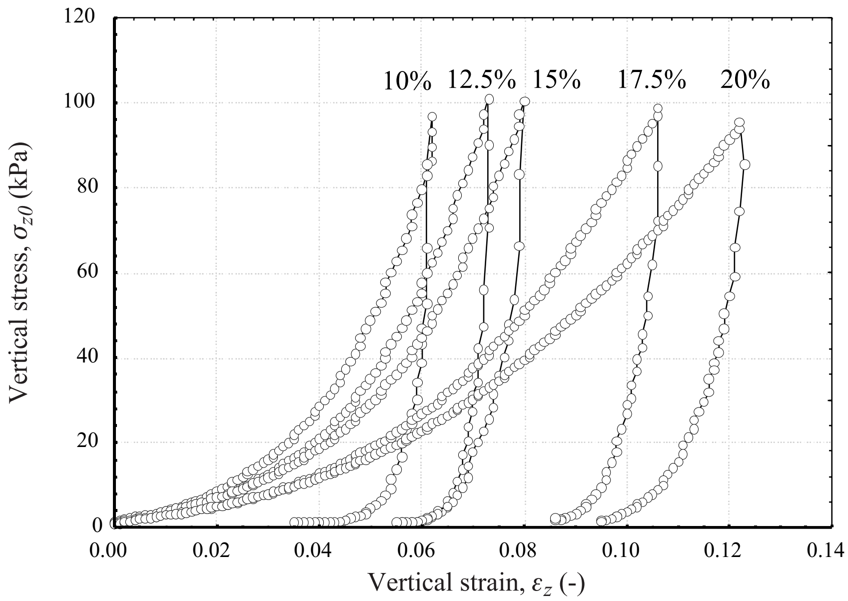

Fig. 3. Stress - strain relationships for uniaxial compression of wheat of five levels of moisture content.

The two semicircular halves were connected with four load cells installed in pairs on the two connection lines, restoring cylindrical shape of the wall. Bottom and top plates of the chamber transmitted the vertical load through the load cells. The experimental setup allowed for the determination of mean lateral pressure, σ_x, mean vertical pressure on the bottom, σ_z, and the mean vertical pressure acting on the top plate, σ_{z0}. The surface of the cylinder walls was smooth while the surfaces of the top and bottom plates were rough.

During testing the granular material was poured into the test chamber, without vibration or any other compacting action. The test sample was 80 mm high and 21 cm in diameter. The bedding was loaded in compression to the reference vertical stress, σ_{z0} of 100 kPa using a universal testing machine at a constant loading rate of 0.35 mm min^{-1}. The displacement of the sample was measured using an inductive transducer having an accuracy of 0.01 mm. Loading was followed by unloading which took place at the same speed of deformation until σ_{z0} of 0 kPa reached. Tests were conducted on wheat, barley, oat and rye and rapeseeds.

The oedometric apparatus utilized by the Spanish research group consisted of an oedometer, but without the possibility of measurement of horizontal pressure. The oedometric modulus of elasticity of the sample E' was determined using relationship between stress increment ΔP and relative displacement during compression:

$$E' = \frac{\Delta P}{-\frac{\Delta h}{h_0}}, \qquad (10)$$

where: Δh - change in sample height during compression, h_0 - initial height of the sample.

The modulus of elasticity, E, of the material was determined at discrete vertical pressures using the following equation:

$$E = E'\frac{1-\nu-2\nu^2}{1-\nu}. \qquad (11)$$

Each sample was subjected to a vertical compressive load that was doubled every 24 h. It was assumed that the granular materials reached their maximum consolidation over this period. Vertical pressures of 9, 18, 37, 74, 148 and 296 kPa were applied. Loading cycles were followed by unloading cycles in which the vertical pressures were decreased in a stepwise manner over discrete 24 h periods in a similar fashion as that of loading.

In the laboratory in Spain, Poisson's ratio, ν, was determined using a triaxial test apparatus. The ratios – K_0, ratio and ν – were determined as follows:

$$K_0 = \frac{\sigma_x}{\sigma_y} = \frac{\nu}{1-\nu} \qquad \nu = \frac{K_0}{1-K_0}. \qquad (12)$$

Confining pressures (identical with lateral pressure, σ_x) of 100, 200 and 300 kPa were applied. The maximum normal stress, σ_y, at each lateral stress applied was taken to calculate the K_0 value. That way, during the K_0 test, three different values of Poisson's ratio were obtained at different lateral stresses.

RESULTS

Strength parameters

Strength parameters measured by the two different laboratories are presented in Table 1.

For wheat and lentils the angle of internal friction, φ and cohesion, c, were determined at both locations using a direct shear tester. In test performed in Spain the angles of internal friction for wheat and lentils were determined to be approximately 22 and 25°, respectively. These values were not dependent on the shearing speed over a test range from 0.06 to 0.63 mm min^{-1}. In Poland, values of φ for wheat at 10% m.c. were determined to be equal to 26 degrees while for lentils at14% m.c., φ was determined to be 14°. Wheat was tested over a range of moisture contents from 10 to 20% and φ was found to increase with an increase in moisture content from 26 to 35°.

Cohesion of wheat in tests conducted in Spain was found approximately equal to 7.5 kPa and not dependent on shearing velocity, V, while c for lentils was found to vary over a range form 10 to 14.7 kPa. In tests conducted in Poland, c for wheat was found to vary over a range from 0.9 kPa for 10% m.c. to 5.1 kPa for 17.5% m.c., while in the case of lentils, a value of c of 2.1 kPa was found. The ratio of values for wheat was 0.85, while for lentils it was 1.78. Discrepancies in values of cohesion obtained from the two different laboratories were also high. In the case of lentils values obtained in Spain were approximately seven times higher than values in Poland. The probable reason for this extremely high discrepancy is the analysis technique used in the determination of cohesion. Cohesion was determined by estimating the intersection point of the Mohr-Coulomb failure criterion along the τ axis of the τ - σ reference system. This required an extrapolation of a straight line to zero normal pressure. The higher the normal pressure under which c was determined the higher c and an error of determination.

Determination of strength parameters in Spain were performed using four types of equipment (Table 1). At a deformation speed of 0.065 mm min^{-1} angles of internal friction for wheat were determined to be 22.1, 21.2, 23.5 and 20.8°, while in the case of lentils values of φ of 25.2, 26 and 27° were determined. Thus the highest differences were of factor 1.13 and 1.07 for wheat and lentils, respectively. These results show that values obtained in the same laboratory, even using different equipment, were much more consistent as compared to values obtained in Poland. Two factors might contribute to that effect: a difference in materials

T a b l e 1. Strength parameters determined in two laboratory locations for wheat, lentils, sugar, and wheat flour

	Angle of internal friction (deg)			Cohesion (kPa)		
Laboratory location: Spain						
			Circular shear tester, D = 100 mm			
			Velocity (mm min^{-1})			
	0.065	0.32	0.63	0.065	0.32	0.63
Wheat	22.1	22.2	22.1	7.00	7.55	7.71
Lentils	25.2	25.0	25.6	10.44	14.70	10.58
Sugar	-	30.9	-	-	0	-
Wheat flour	-	32.5	-	-	0	-
			Square shear tester, 100 x 100 mm			
Wheat	21.2	20.8	21.9	7.65	6.77	2.87
Lentils	26.0	26.3	27.5	5.69	5.86	0.95
			Triaxial compression test, D = 38 mm Velocity (mm min^{-1})			
	1.02	0.19	0.51	1.02	0.19	0.51
Wheat	23.5	23.4	-	5.67	11.81	-
Lentils	27.0	-	-	0	-	-
Sugar	-	-	35.3	-	-	17.46
Wheat flour	-	-	32.5	-	-	0
			Triaxial compression test, D = 101 mm			
Wheat	20.8		19.7	6.37		7.72
Lentils	-		20.9	-		12.31
Laboratory location: Poland						
			Circular shear tester, D = 210 mm, V = 10 mm min^{-1}			
Wheat		25.7-35.5*			0.9-2.3*	
Lentils		14.3			2.1	
			Circular shear tester, D = 60 mm, V = 2 mm min^{-1}			
Sugar		27.8-33.2**			3.6-3.9**	
Wheat flour		26.5-30.4**			2.7-1.3**	

*m.c. – 10-20%, **σ_r – 30-100 kPa.

themselves and/or seemingly slight differences in experimental procedure. Results obtained for sugar and wheat flour confirm possibility of difference in materials. Values of the angle of internal friction obtained in Spain using two triaxial chambers were 30.9 and 35.3° for sugar while for wheat flour values of 32.5 and 32.5° were obtained. In Poland φ was found to decrease with an increase in pressure over a range of 27.8 to 33.2° in the case of sugar, and over a range of 26.5 to 30.4° in the case of wheat flour. Therefore, the varition in test results between the two laboratories was in the case of tested powders narrower than that of seeds. Because both sugar and flour are processed products it is believed that the variation in product density and particle characteristics between materials produced in Spain and that of Poland are much more similar than agricultural seeds that can vary signficantly with respect to variety, growing season, and agricultural practices.

Characteristics of elasticity

Modulus of elasticity measured by the two different laboratories are presented in Table 2.

The modulus of elasticity were determined at both locations using a uniaxial test procedure for wheat, sugar and wheat flour. In these investigations the results determined by the Spanish laboratory showed that the modulus of elasticity, E, of wheat was found to increase with an increase in normal stress. Values of E were determined to be during increased loading to be 4.45 MPa for σ_r at 14.7 kPa and 5.8 MPa at 113 kPa, while during a decrease in loading the value of E was determined to be 32.9 MPa at 79.1 kPa. A maximum value of E of 64.3 MPa was obtained during the unloading phase of testing at a normal pressure of 158 kPa. During similar testing in Poland modulus of elasticity values for wheat decreased from 22 to 11 MPa with an increase in

T a b l e 2. Moduli of elasticity, E, and oedometer modulus, E' (MPa) of wheat, sugar, and wheat flour tested in the two loboratory locations

Laboratory location: Spain					
	Uniaxial compression test (UCT)				
Vertical pressures	14.70	113.04	316.51	158.25	79.13
Wheat (E)	4.45	5.78	28.80	64.30	32.90
Vertical pressures	11.30	90.43	361.72	180.86	90.43
Sugar (E')	1.64	7.90	16.14	138.25	73.80
Sugar (E)	1.46	7.02	14.34	122.82	65.60
Wheat flour (E')	1.61	1.50	4.65	67.08	20.90
Wheat flour (E)	1.32	1.22	3.80	54.82	17.10
Laboratory location: Poland					
	UCT D = 210 mm, V = 0.35 mm min^{-1}, σ_{max} = 100 kPa				
Wheat	22.4-11.1*				
Sugar	30.8				
Wheat flour	18.5				

*m.c. – 10-20%.

moisture content from 10 to 20 %. In Poland, the modulus of elasticity of sugar and flour were determined to be 30.8 and 18.5 MPa, respectively, both at a σ_r of 100 kPa. In Spain, at a normal pressure of 79.1 kPa, the modulus of elasticity of sugar was determined to be 65.6 kPa while that of flour was 17.1 kPa. Value of E for sugar in Poland was approximately two times lower than those found in Spain, while in the case of wheat flour similar values were found at both locations. From Table 2 it can be observed that the modulus of elasticity is strongly influenced by load history *ie* the level of pressure and phase of loading – unloading cycle. The probable reason of divergence of values of E obtained by the two laboratories was thought to be associated with the procedure used in the consolidation of the test sample. Figure 3 shows stress – strain relationships for uniaxial compression of wheat at five different levels of moisture content. From these curves it can be be observed how different values of E, the tangent to the stress/strain curve, could be obtained depending on the location of point of estimation.

Poisson's ratio

Values of Poison's ratio found at the two different laboratories are shown in Table 3. In Spain testing under pressures of 100, 200 and 300 kPa have shown a tendency of ν to decrease with an increase of pressure. Testing in Poland was conducted at constant pressure of 100 kPa and values of ν obtained for this σ_r will be compared below. At both laboratories the Poisson's ratio for sugar was found to equal to 0.21 for all test conditions. For wheat flour, Poisson's ratio was determined to be 0.26 by the laboratory in Spain while 0.16 for the laboratory in Poland. For lentils, values of Poisson's ratio varied from 0.30 to 0.35 for tests conducted in Spain at two different loading rates, while Poisson's ratio was determined to be 0.24 for tests conducted in Poland. In Spain tests were conducted for wheat using two different diameter testers. Large differences in Poisson's ratio was found between samples of two different sizes. At two different loading rates, values of ν of 0.29 and 0.27 were determined for samples using a 38 mm in diameter test chamber, for a 101 mm sample values of ν of 0.34 and 0.37 were determined. In Poland value of Poisson's ratio of 0.19 to 0.22 were determined for wheat over a variation in moisture content of 10 to 20% m.c.

REASUMPTION

Values of angle of internal friction for dry wheat were determined in Spain to vary over a range from 19.7 to 23.5°, the lowest value was determined using a triaxial compression test while the highest value was determined using a direct shear test. Value of the angle of internal friction for wheat were determined in Poland to be 25.7°. Test results for φ for both sugar and wheat flour were relatively close at the two locations. For dry wheat cohesion, c, values were distinctly higher in tests conducted in Spain where values ranged from 6.37 to 7.72 kPa, while in Poland cohesion values of 0.9 kPa were obtained. Values of modulus of elasticity found in Poland were for all materials markedly higher than obtained in Spain. For dry wheat at a vertical pressure of approximately 100 kPa a value of E of 22.4 MPa was determined, which is 3.1 times higher than the value of E of 7.2 MPa determined in Spain for the same material. Poisson's ratios, ν, under pressure of 100 kPa were found higher in Spain except for sugar in which a value of 0.21 was measured at both locations.

Review of results enabled the authors to distinguish conditions that should be fulfilled in order to obtain good agreement of material parameters determined in different, distant laboratories. Conditions to be satisfied may be

T a b l e 3. Poison's ratio, ν, for wheat, lentils, sugar and wheat flour obtained in the two laboratory locations

Test, *D* (mm)	Material	Velocity (mm min^{-1})	Confining pressure (kPa)		
			100	200	300
Laboratory location: Spain					
38[1]	Wheat	1.02	0.29	0.28	0.28
	Wheat	0.19	0.27	0.27	0.27
	Lentils	1.02	0.32	0.29	0.29
	Lentils	0.19	0.34	0.31	0.30
	Sugar	0.19	0.21	0.21	0.21
	Wheat flour	0.19	0.26	0.24	0.22
101[1]	Wheat	1.02	0.34	0.32	0.30
	Wheat	0.51	0.37	0.34	0.33
	Lentils	1.02	0.32	0.30	0.30
	Lentils	0.51	0.35	0.31	0.30
Laboratory location: Lublin					
210[2]	Wheat	0.35		0.22-0.19*	
	Lentils	0.35		0.24	
	Sugar	0.35		0.21	
	Wheat flour	0.35		0.16	

1 – triaxial compression test, 2 – UCT, *m.c. – 10-20%.

included into three groups regarding: material, construction features of test equipment and values of test parameters. Lower differences in values of measured parameters of materials were found for wheat flour and sugar than for seeds. The probable reason for this effect is that powders have better defined states after processing which normally involves following standardized technology moreso than raw materials such as seeds that differ according to variety, climate and conditions of cultivation. Measurement technique was also found to influence values of obtained parameters. For example in testing the angle of internal friction of lentils Moya *et al*. (2002) determined that a 20% different was found between the test results of a direct shear test and that of a triaxial compression tester when determining the same parameter. Sharp differences in values of other parameters resulted from variations in the moisture content of materials, normal pressure and velocity of deformation applied. Horabik and Molenda (2002) found that the internal angle of friction varied from 25.7 to 35.5°, or 1.4 times with an increase in moisture content from 10 to 20%. Vertical pressure strongly influenced values of the modulus of elasticity as reported by Moya *et al*. (2002). For the pressure increasing from 14.7 to 316 kPa an increase in *E* of wheat from 4.45 to 28.8 MPa was noted, while during unloading values of *E* at a vertical pressure of 158 kPa were determined to be 64.3 MPa. Considerable influence of deformation velocity on measured parameters was also observed. Stasiak and Molenda (2004) in their testing of internal friction have furthermore shown that certain combinations of speed of testing and normal pressure produce frictional vibrations that sometimes strongly disturbed estimation of parameters.

CONCLUSION

Analysis of results of testing in the two laboratories have shown that to obtain consistent results strict concordance in material state, equipment and test conditions is necessary. To resolve the problem standardization of parameters and methods of their determination should be undertaken on an international level.

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