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Mechanical properties of some granular agricultural materials used in silo design

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A b s t r a c t. The aim of this research was to provide values for different material properties considered in either traditional or more recent numerical silo design methods. Different samples of granular agricultural materials commonly stored in silos were tested. Common geotechnical devices have been used in order to make the replications easier. Based on these experiments it was determined that the different material properties were not affected by the test velocity, except in the case of Poisson ratio. From a practical point of view, the test velocity correlates well with the sliding velocity of grain during discharge. The values obtained for material properties considered in traditional silo design methods were similar to those reported by other authors. No significant differences were observed in the results obtained when using either the square shear box or the circular shear cell. The same conclusion was reached when comparing the results from direct shear tests with preconsolidated and unconsolidated samples. This means that simplified devices and procedures can be used in agricultural grains against other products. Finally, a table with the recommended values for the different parameters determined for each sample tested was provided in this work.

K e y w o r d s: granular material, mechanical testing, friction, Poisson ratio, dilatancy

INTRODUCTION

Traditional theories, especially that of Janssen in 1895, are commonly used by most international Standards for silo design. These theories utilize such material properties as the angle of internal friction (ϕ), the grain-to-wall friction coefficient (μ), and the specific weight (γ). Values for all these properties are commonly found in the literature. All of these theories are suitable for predicting grain loads inside bins under static conditions. However, during discharge, the loads generated inside the bin are higher than those registered under static conditions. The application of numerical methods to silo design began in the mid - 1970. Since then, many numerical methods, such as the finite element method, have been used in the design of silos. Most recently, the discrete element method has been used to study problems related to material flow and the material-silo structure interaction (González-Montellano *et al*., 2011; Wiącek and Molenda, 2011).

To accurately model silo loads, it is necessary to consider additional material properties not taken into account in the traditional methods, such as the dilatancy angle (ψ), the modulus of elasticity (E), and Poisson ratio (ν). However, for many agricultural materials these values are not commonly found in the literature. Therefore, it has been necessary, when applying the finite element method, to use values considered by other researchers or even randomly select other values for use in these models, which has resulted in some inaccuracies.

Therefore, the aim of this work was to provide mechanical properties for different agricultural materials commonly stored in commercial agricultural silos. Some of these parameters are utilized in traditional silo design methods and hence they are compared with values reported by other authors. However, there is a lack of data in the literature for many parameters used in silo modelling using the finite element method. Therefore, values for these new parameters have been provided in this work to get a better understanding of the interaction that exists between the grain and the silo structure.

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MATERIALS AND METHODS

The material properties determined in this work were the angle of internal friction (ϕ), the apparent cohesion (C), the grain-to-wall friction coefficient (μ), the dilatancy angle (ψ), Poisson ratio (ν), Young modulus (E), and the specific weight (γ).

Descriptions related to testing methodology were previously provided by the authors in Moya *et al.* (2002, 2006). Therefore, it was decided to include in this paper only the most important information related to the way the different tests were carried out. Direct shear tests were conducted using two different shaped shear cells: a square shear cell 10 cm on a side and 3 cm deep, and a circular shear cell 10 cm in diameter and 3 cm deep. With some of the samples used in this work, especially corn and sunflower, the ratio of sample size to grain size is far below 40, as recommended by Eurocode 1 Part 4. Nevertheless, it was not possible for the authors to get a larger shear box because of the limitations of the shear device used. Regardless, the data provided herein is still important since there are no data in the international literature for some of these parameters. In addition, other researchers *eg* Härtl *et al*. (2011) conducted direct shear tests considering a limit for the sample size to grain size ratio of 5%, which is similar to that used by the authors. The tests were conducted at three different shear velocities (0.065, 0.32, and 0.63 mm min^{-1}) and at three different normal pressures (100, 200 and 300 kPa, respectively). In addition, consolidated and unconsolidated tests were conducted using the circular shear box. Thus, the influence of the preconsolidation level on the stress-strain curves could be determined. Each test was replicated three times with the square shear box. Consolidated and unconsolidated tests were conducted using the circular shear box. Depending on the type of test conducted either two or three replications were conducted. For the dilatancy angle, only the highest value was considered in this work in order to be used in silo design.

A modified shear box was used to determine the grain-to-wall friction coefficient. Two different surfaces were tested; concrete and steel, using both the square and the circular shear boxes. In addition, two different concrete moulds were used, a smooth one and a rough one, with the square shear box. In this type of test, only one velocity (0.63 mm min^{-1}) was used. Prior to beginning each test, a consolidation time ranging between 5 and 45 min was applied depending on the sample tested. Each test was replicated twice.

Two types of triaxial tests were conducted, K_0 tests and tests allowing free lateral deformation of the sample. Confining pressures of 100, 200 and 300 kPa were applied. Three replications were conducted for K_0 tests, whereas for tests allowing free lateral deformation of the sample only two replications were carried out.

Values obtained for the angle of internal friction and the apparent cohesion from the tests allowing free lateral deformation of the sample were compared with those obtained from the direct shear tests. The test was finished once the sample reached an axial strain of 20%, which is the maximum rate allowed by the standards (ASTM D2850-03a, 2007; UNE 103402, 1998). Specimens of two different sizes 38.1 mm (1.5 in) and 101.6 mm (4 in) in diameter, respectively, were used in the triaxial tests. In addition, two different test velocities were used: 1.02 and 0.19 mm min^{-1} (0.04 and 0.0075 in min^{-1}, respectively) for specimens 38.1 mm in diameter, whereas for specimens 101.6 mm in diameter velocities of 1.02 1 and 0.51 mm min^{-1} (0.04 and 0.02 in min^{-1}, respectively) were selected. As suggested by the Standards ASTM D2850-03a (2007) and UNE 103402 (1998), the membrane effect was considered. However, the results showed that the value for this correction factor was small when compared with the deviation obtained in the determination of the deviatoric stress.

Oedometer tests were conducted to determine the void ratio of the sample as a function of the vertical stress applied. Vertical pressures of 9, 18, 37, 74, 148, and 296 kPa were applied during each loading step, respectively. During the unloading cycle, the vertical pressure was decreased in a similar step-wise manner as that of the loading cycle. Three oedometer devices were used with the different samples tested.

The variation in specific weight (or bulk density, by converting the units kN m^{-3} into kg m^{-3} *eg* by multiplying the results by 98.1, approximately) was determined with respect to vertical pressure. Tests were conducted using a geotechnical device, the Standard Proctor mould and a compression press. A maximum vertical pressure of 300 kPa was applied and three different velocities were tested: 1.524, 0.382, and 0.102 mm min^{-1} (0.06, 0.015, and 0.004 in min^{-1}, respectively). Each test was replicated three times.

Real specific weight was obtained in order to determine the void ratio as a function of this parameter. A test tube was employed and a certain volume of water was placed and measured inside it. The grain sample used in each test was weighed and then it was placed inside the test tube containing the previously determined water volume. Immediately, the volume increment was measured and thus this parameter could be obtained.

Finally, the samples were dried in an oven at temperatures of 55 and 105 to 110°C, as recommended by Lebegue and Boudakian (1989) to determine the dry basis moisture content of the samples. The importance of considering this parameter is due to its influence on some material properties, as stated by Molenda and Stasiak (2002), among others.

All these tests were performed with six samples: 'Prevision' oats, 'Kym' barley, sunflower, corn, 'Camacho' wheat, and lentil vetch.

RESULTS

The values of the angle of internal friction obtained using both the circular (consolidated or unconsolidated) and square shear box at the three different velocities are shown in Table 1. The largest angles of internal friction were measured when testing sunflower and corn. Values ranging between 28 to 31° for sunflower and from 25 to 30° for corn were measured. Meanwhile, the smallest values were measured during the tests with 'Camacho' wheat (21 to 22°) and 'Prevision' oats (21 to 25°). In addition, corn presented the maximum variation (21%) in the results obtained for this material property from the different types of direct shear tests carried out. In this case, this maximum difference took place between the circular and the square shear cells. For 'Prevision' oats and 'Kym' barley, this difference was 18% and 17%, respectively. For oats, this difference was observed with the circular shear cell at the same velocity by varying the consolidation state of the sample. Meanwhile, for 'Kym' barley it was obtained with the square shear cell at different test velocities. The smallest variation in test results was observed for wheat. 'Camacho' wheat was the sample that presented the lowest difference (8%) between the circular and the square shear cells, at different test velocities. It was followed by lentil vetch (9%) and sunflower (12%).

Figure 1 shows the stress-strain curves for corn. In this case, the lateral to normal stress ratio was plotted on the y-axis, and the horizontal displacement was plotted on the x-axis. For this sample, the maximum lateral-to-vertical stress ratio reached was about 0.50. From these curves, the Mohr-Coulomb strength envelopes could be plotted.

The results obtained for the apparent cohesion for each material are listed in Table 1.

Values are shown for tests conducted using the circular shear box (consolidated and unconsolidated) and square shear box at different sliding velocities. For these tests, corn had the greatest value for this parameter (36.36 kPa) at 0.065 mm min^{-1} for the unconsolidated direct shear test. On the contrary, 'Prevision' oats had the lowest values for the apparent cohesion, followed by 'Camacho' wheat. It should be noted that for some samples and tests values of 0 kPa were obtained, as was the case of 'Kym' barley, corn, and sunflower. On the contrary, corn was the sample with the highest values for this material property.

Figure 2 shows the Mohr-Coulomb strength envelopes obtained for corn using the square shear cell when the least squares fitting technique was used. The slope of the curve provides the angle of internal friction, whereas the intersection point between that curve and the y-axis provides the value of the apparent cohesion. The regression curves obtained were $y = 0.47x + 5.84$ ($R^2 = 0.98$); $y = 0.48x + 3.86$ ($R^2 = 0.97$), and $y = 0.49x – 1.38$ ($R^2 = 0.99$) for tests carried out at 0.065, 0.32, and 0.63 mm min^{-1}, respectively. For this sample, the results obtained at a test velocity of 0.63 mm min^{-1} were slightly different from those measured at the two other test velocities used (0.065 and 0.32 mm min^{-1}, respectively).

Table 1. Values obtained for the angle of internal friction and apparent cohesion. Direct shear test

Sample	Velocity (mm min^{-1})						Cc
	0.065		0.32		0.63		
	Sq	Cu	Sq	Cu	Sq	Cu	
	Angle of internal friction ϕ (°)						
'Kym' barley	25.4±0.6	–	21.6±1.0	–	24±0.7	25.2±0.7	25.3±1.5
Corn	25.2±1.1	25.8±2.5	25.6±1.5	30.4±0.9	26.3±0.8	27.5±1.5	30.1±1.1
'Prevision' oats	23.5±0.4	–	24.4±0.7	–	23.9±0.8	24.8±0.9	21.0±0.5
Sunflower	28.1±1.4	27.6±0.7	29.8±0.9	28.9±1.0	28.5±1.3	28.8±0.8	30.9±0.7
Lentil vetch	26.0±0.5	25.2±0.5	26.3±0.3	25.0±0.7	27.5±0.4	25.6±0.9	25.3±0.9
'Camacho' wheat	21.8±0.4	22.1±0.3	21.5±0.4	22.2±0.4	20.6±0.5	22.1±0.2	21.3±0.2
	Apparent cohesion C (kPa)						
'Kym' barley	-1.61±3.49	–	10.72±28.37	–	2.61±6.05	8.43±18.53	6.75±19.42
Corn	5.84±11.47	36.36±83.78	3.86±14.90	10.70±18.87	-1.38±7.95	16.64±34.04	4.96±12.12
'Prevision' oats	2.33±4.17	–	1.10±7.20	–	3.10±8.61	-10.08±22.66	4.69±12.49
Sunflower	4.48±8.89	20.84±41.13	-3.60±6.50	8.65±16.32	0.71±1.38	9.37±17.66	2.60±4.46
Lentil vetch	5.69±11.92	10.44±22.71	5.86±12.04	14.70±32.52	0.95±1.85	10.58±23.03	1.57±3.46
'Camacho' wheat	2.87±7.32	7.00±17.49	3.23±8.41	7.55±18.87	5.50±14.98	7.71±19.21	6.31±16.31

Sq – tests using the square shear cell, Cu – unconsolidated tests using the circular shear cell, Cc – consolidated tests using the circular shear cell.

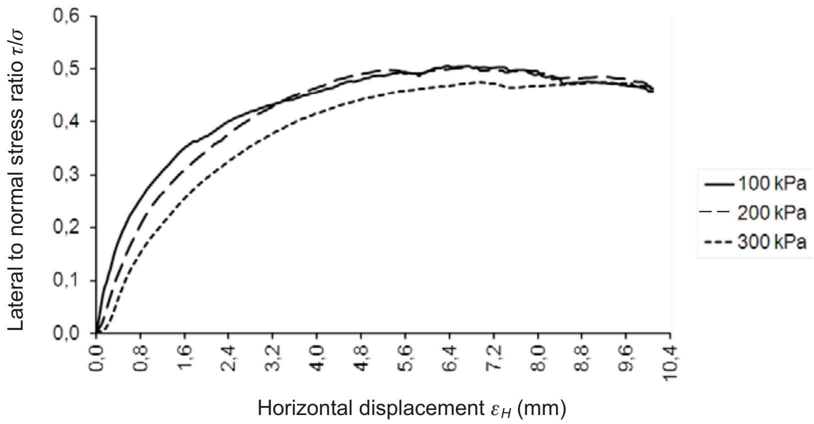

Fig. 1. Stress-strain curves obtained for corn tested at 0.065 mm min^{-1} using the square shear cell.

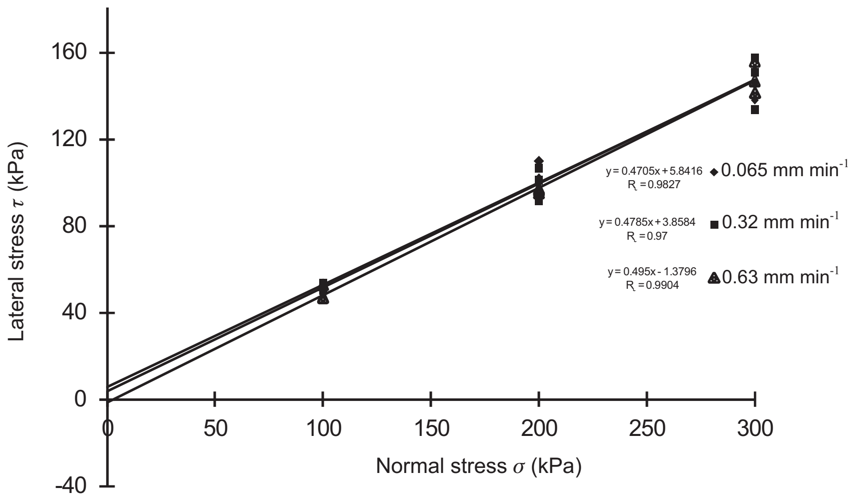

Fig. 2. Mohr-Coulomb strength envelopes obtained for corn using the square shear cell.

The results obtained for the dilatancy angle are shown in Table 2. It should be noted that these results were measured at a normal pressure of 100 kPa, which is a value for the normal pressure commonly reached in commercial storage bins storing granular agricultural materials. 'Prevision' oats was the only sample in which dilation did not occur during the different shear tests carried out. As for the remaining samples, it should be noted that corn presented the highest values for this material property (32.7° at 0.065 mm min^{-1} during the unconsolidated test), followed by lentil vetch (24.3° using the square shear cell at 0.32 mm min^{-1}), and 'Camacho' wheat (23.1° using the square shear box tested at a velocity of 0.065 mm min^{-1}).

Figure 3 shows the deformation curves obtained for corn using the square shear cell tested at 0.065 mm min^{-1}. For these curves, dilation was observed during the shear tests. As a general trend for samples, in which dilatancy was observed, the greatest vertical strain was observed for the curve corresponding to a normal stress of 100 kPa, whereas the smallest vertical strain was observed with 300 kPa.

The results obtained from the grain-on-wall friction tests are provided in Table 3. When a steel mould was used, the value of this coefficient was greater with the circular shear cell than with the square shear cell. This was due to the fact that the materials used for these friction surfaces were not exactly the same, with the surface of the circular shear box being slightly rougher. For the square shear cell using the steel mould, the largest grain-on-wall friction coefficient was measured with sunflower (0.21), whereas the smallest grain-on-wall friction coefficient was measured during tests with 'Kym' barley (0.13). Nevertheless, for tests carried out with the steel mould using the circular shear cell, the largest grain-on-wall friction coefficient was measured using corn (0.26), whereas the smallest value was once again measured

T a b l e 2. Values obtained for the dilatancy angle. Direct shear test

Sample	Velocity (mm min^{-1})						
	0.065		0.32		0.63		Cc
	Sq	Cu	Sq	Cu	Sq	Cu	
‘Kym’ barley	4.9	–	4.0	–	4.0	3.0	3.0
Corn	27.1	32.7	24.3	29.8	20.3	30.2	24.2
‘Prevision’ oats	0	–	0	–	0	0	0
Sunflower	9.7	0	4.0	0	3.0	0	0
Lentil vetch	23.1	18.9	24.3	19.1	20.3	16.7	14.8
‘Camacho’ wheat	23.1	14.4	13.7	9.8	12.9	8.0	9.0

Explanations as in Table 1.

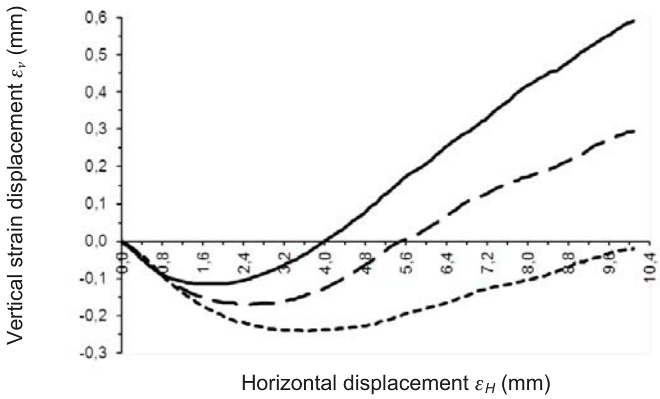

Fig. 3. Deformation curves obtained for corn using the square shear cell. Explanations as in Fig. 1.

T a b l e 3. Values obtained for the grain-to-wall friction coefficient

Sample	Steel		Concrete	
	Square	Circular	Square	Circular
‘Kym’ barley	0.13±0.01	0.21±0.01	0.41±0.02-0.43±0.01	0.41±0.01
Corn	0.15±0.02	0.26±0.02	0.50±0.01-0.56±0.02	0.51±0.03
Sunflower	0.21±0.01	0.22±0.01	0.51±0.01-0.53±0.01	0.52±0.01
‘Camacho’ wheat	0.14±0.00	0.24±0.01	0.39±0.01-0.41±0.01	0.44±0.03

using ‘Kym’ barley (0.21). The variation obtained in these values ranged from 4.5% for sunflower up to 42% for corn and ‘Camacho’ wheat, whereas ‘Kym’ barley varied by 38%. With respect to the results obtained using the concrete moulds, ‘Camacho’ wheat produced the lowest grain-on-wall friction values using the square shear box (0.39-0.41), whereas corn produced the greatest values (0.50-0.56). When the circular shear cell was used, ‘Kym’ barley produced the smallest grain-on-wall friction values (0.41), whereas sunflower produced the largest ones (0.52).

The values obtained for the angle of internal friction using the triaxial tests are listed in Table 4. Where no values are shown, no tests were developed at those axial strains. The results showed that for specimens 38.1 mm in diameter, no general trend could be observed with respect to an increase in the angle of internal friction as the axial strain increased. Lentil vetch did not follow the same trend as that observed for the remaining samples when comparing the values obtained at an axial strain of 10 and 20%. At an axial strain of 10%, lentil vetch had the highest internal friction

T a b l e 4. Values obtained for the angle of internal friction and apparent cohesion. Triaxial test

Variety	Specimen (mm)													
	38.1								101.6					
	Test velocity (mm min^{-1})													
	1.02				0.19				1.02			0.51		
	Axial strain rate (%)													
	10	20	30	>30	10	20	30	>30	10	20	>20	10	20	>20
	Angle of internal friction ϕ (°)													
'Kym' barley	24.1 ±0.58	28.0 ±0.62	–	–	–	–	–	–						
Corn									20.1 ±1.20	19.5 ±1.23	–	–	–	–
Sunflower	17.1 ±1.14	23.0 ±1.24	–	–	–	–	–	–						
Lentil vetch	27.0 ±0.43	26.0 ±0.27	–	–	–	–	–	–	–	–	–	20.9 ±1.13	20.9 ±1.13	–
'Camacho' wheat	23.5 ±0.37	24.6 ±0.50	24.4 ±0.54	24.4 ±0.42	23.4 ±0.51	24.0 ±0.33	23.8 ±0.21	24.1 ±0.29	20.8 ±0.76	21.9 ±0.50	22 ±0.45	19.7 ±0.99	20.8 ±0.39	–
	Apparent cohesion C (kPa)													
'Kym' barley	-6.06 ±13.93	-7.66 ±14.80	–	–	–	--	–	–						
Corn	27.77 ±96.69	36.76 ±91.82	–	–	–	--	–	–	11.74 ±34.11	17.39 ±52.54	–	–	–	–
Lentil vetch	-23.74 ±47.49	-14.48 ±30.02	–	–	–	--	–	–	–	–	–	12.31 ±34.06	12.31 ±34.06	–
'Camacho' wheat	5.67 ±13.28	8.12 ±18.15	10.63 ±24.05	11.56 ±26.03	11.81 ±27.90	13.16 ±30.05	16.38 ±37.54	15.10 ±34.16	6.37 ±17.43	6.82 ±17.44	6.45 ±16.33	4.72 ±13.91	6.26 ±16.81	–

value (27°), whereas sunflower had the lowest value (17.1°). Nevertheless, ‘Kym’ barley had the highest internal friction value (28°) when tested at a velocity of 1.02 mm min^{-1} and at an axial strain of 20%, whereas sunflower showed the lowest value (23°) for the same conditions. It should be noted that for ‘Camacho’ wheat the angle of internal friction was 24° for all the tests carried out with this specimen. For the specimen 101.6 mm in diameter, it should be noted that the three samples tested showed similar values at different axial strains and test velocities, although ‘Camacho’ wheat values varied between 20 and 22°. Lentil vetch reached a value of 21°, which was about 5 to 6° lower than those obtained using the specimen 38.1 mm in diameter. The variation observed for this material property with the different samples tested at different axial strains ranged between 4% for lentil vetch and 26% for sunflower. For specimens 101.6 mm in diameter the variation ranged between 0% for lentil vetch and 10% for ‘Camacho’ wheat.

The apparent cohesion can also be determined from triaxial testing. The measured values for these materials are shown in Table 4. The results showed that when the specimen 38.1 mm in diameter was used, two samples, ‘Kym’ barley and lentil vetch, did not have apparent cohesion. However, for the two remaining samples the greater the axial strain, the higher the value of the apparent cohesion, except for ‘Camacho’ wheat tested at 0.19 mm min^{-1} at an axial strain greater than 30%. For this sample, the values were higher when tested at 0.19 mm min^{-1} than those obtained at a test velocity of 1.02 mm min^{-1}. It should be noted that large values of apparent cohesion were observed when testing sunflower (28 and 37 kPa at axial strains of 10 and 20%, respectively). For specimens 101.6 mm in diameter, no general trend could be observed. For most samples, the greater the axial strain, the higher the apparent cohesion. Nevertheless, a slight reduction in the value of this property was observed for ‘Camacho’ wheat tested at 1.02 mm min^{-1} at an axial strain greater than 20%. In this case, all the samples tested presented values for the apparent cohesion. In fact, for lentil vetch the same value for this material property was obtained at axial strains of 10 and 20%. In addition, no apparent trend could be determined based on the size and shape of the specimens. For the 101.6 mm diameter shear cell, the largest value of cohesion was determined with lentil vetch, whereas for the 38.1 mm diameter specimen the largest cohesion value was measured with ‘Camacho’ wheat.

The values obtained for Poisson ratio (ν) using both specimens 38.1 and 101.6 mm in diameter are listed in Table 5. Using the 38.1 mm-diameter specimen, it should be noted that ‘Prevision’ oats produced the largest values for this material property. Thus, at a normal pressure of 100 kPa, a value of 0.36 was measured at a test velocity of 1.02 mm min^{-1}, whereas a value of 0.41 was measured at a velocity of 0.19 mm min^{-1}. On the contrary, ‘Camacho’ wheat produced the smallest values for this parameter, with values of 0.29 and 0.27 measured at test velocities of 1.02 and 0.19 mm min^{-1}, respectively. Both of these values were measured at a normal pressure of 100 kPa. In addition, for the same value of normal pressure both ‘Camacho’ wheat and sunflower had lower values when tested at a test velocity of 0.19 mm min^{-1} than those obtained at a test velocity of 1.02 mm min^{-1}. For the samples tested using the 101.6 mm-diameter specimen, ‘Camacho’ wheat had the highest values, while corn

T a b l e 5. Values obtained for Poisson ratio. Triaxial test

Variety	Specimen (mm)	Test velocity (mm min^{-1})					
		1.02			0.19		
		Confining pressure					
		100 kPa	200 kPa	300 kPa	100 kPa	200 kPa	300 kPa
‘Kym’ barley	38.1	0.35±0.01	0.30±0.00	0.28±0.00	0.36±0.01	0.32±0.01	0.30±0.01
‘Prevision’ oats		0.36±0.01	0.34±0.01	0.33±0.01	0.41±0.01	0.38±0.00	0.36±0.01
Sunflower		0.33±0.02	0.31±0.02	0.29±0.02	0.31±0.03	0.30±0.00	0.29±0.01
Lentil vetch		0.32±0.01	0.29±0.00	0.29±0.01	0.34±0.01	0.31±0.01	0.30±0.01
'Camacho' wheat		0.29±0.02	0.28±0.01	0.29±0.01	0.28±0.01	0.27±0.01	0.27±0.01
		1.02			0.51		
Corn	101.6	0.31±0.01	0.29±0.01	0.29±0.01	0.30±0.01	0.28±0.00	0.27±0.01
Lentil vetch		0.32±0.01	0.30±0.01	0.30±0.01	0.35±0.02	0.31±0.01	0.30±0.01
‘Camacho’ wheat		0.34±0.02	0.31±0.01	0.30±0.00	0.37±0.02	0.34±0.01	0.33±0.01

produced the lowest values. Test velocity did not appear to influence the test results. Thus, for 'Camacho' wheat and lentil vetch the greatest values were obtained at the highest test velocity (0.37 and 0.35, respectively), whereas the opposite was true for corn (0.30 at a test velocity of 0.51 mm min^{-1} and 0.31 at a test velocity of 1.02 mm min^{-1}). However, a significant decrease in Poisson's ratio values was observed when the lateral pressure was increased from 100 to 200 kPa. This variation ranged between 14% for 'Kym' barley tested at 1.02 mm min^{-1} and 0% for 'Camacho' wheat tested at 0.19 mm min^{-1}. Lentil vetch varied by 11% when tested at 0.51 mm min^{-1} using the specimen 101.6 mm in diameter, whereas it varied by only 9% when the specimen 38.1 mm in diameter was used. This variation was much lower when lateral pressure was increased from 200 to 300 kPa. Thus, in some cases no variation in the value of Poisson ratio was obtained, as was the case of 'Camacho' wheat tested using the specimen 38.1 mm in diameter, lentil vetch tested at 1.02 mm min^{-1}, or corn tested at the same velocity. It should be noted that sunflower varied by 10% when tested at 1.02 mm min^{-1}, whereas the remaining samples varied by 3 to 7%, generally lower than the variation obtained when lateral pressure increased from 100 to 200 kPa. Finally, it should be mentioned that lentil vetch presented similar values for Poisson ratio using both 101.6 and 38.1 mm in diameter specimens. On the contrary, at a normal pressure of 100 kPa, 'Camacho' wheat reached a greater value (0.05 greater) when the specimen 101.6 mm in diameter was used at a test velocity of 1.02 mm min^{-1} (its value was 0.34) with respect to that obtained using the specimen 38.1 mm in diameter (the value was 0.29). This value was 0.1 greater when tested at 0.51 mm min^{-1} using the greatest specimen (its value was 0.37) with respect to that obtained using the smallest one (0.27).

The values of Young modulus as a function of normal pressure are shown in Table 6. These values were measured using oedometer tests. The range of the values determined for this material property was dependent on the Poisson ratio values presented in Table 5. From these results, it should be noted that 'Prevision' oats and sunflower were the samples which had the smallest range of values, with average values of about 4 000 kPa for oats and about 4 300 kPa for sunflower, respectively, at a normal stress of 90.43 kPa during the unloading cycle. On the contrary, corn had the greatest values for this parameter at the same normal pressure, with an average value of 35 750 kPa. During the unloading cycle, when normal pressure decreased from 90.43 to 45.22 kPa, the modulus of elasticity for 'Camacho' wheat decreased by 39%, followed by sunflower (41%) and 'Prevision' oats (42%). For the same conditions, corn had the largest decrease in Young modulus (51%), followed by 'Kym' barley (49%), and lentil vetch (47%).

Figure 4 shows the typical shape of these curves when the void ratio is graphed as a function of normal pressure. In this case, the sample used was lentil vetch.

The variation in the apparent specific weight (or bulk density, depending on the units used) as a function of normal stress is shown in Table 7. The friction between the different grains used in this test and the mould was considered. The results obtained showed that sunflower had the lowest initial bulk density (4 kN m^{-3}) followed by 'Prevision' oats (about 4.7 kN m^{-3}). On the contrary, lentil vetch produced the greatest value for this parameter (8.4 kN m^{-3}), followed by 'Camacho' wheat (8.1 kN m^{-3}). During these tests, 'Prevision' oats exhibited an increase in its specific weight (reached at a normal pressure of 300 kPa) of approximately 26%, with respect to the initial value (corresponding to a normal pressure of 0 kPa). For sunflower, an increase of 17% in

T a b l e 6. Values obtained for Young modulus. Oedometer test

P (kPa)	Sample					
	'Kym' barley	Corn	'Prevision' oats	Sunflower	Lentil vetch	'Camacho' wheat
11.30	683±21.9	1 070±21.9	384±87.7	274±12.7	1 560±1 26.6	1 285±312.5
22.61	477±15.6	747±14.8	153±34.7	331±15.6	907±73.5	1 402±341.5
45.22	639±21.2	1 897±39.6	254±58	453±21.2	1 821±147.8	2 255±548.7
90.43	1 078±35.4	3 710±77.1	462±1 04.6	567±26.9	3 499±283.5	3 730±907.2
180.86	2 236±96.9	5 314±92.6	827±1 14.6	737±15.6	9 264±367.7	7 624±1 120
361.72	3 852±140.7	6 500±218.5	1 371±1 21.6	864±14.9	13 038±247.5	9 373±1 126
180.86	30 858±1 333	67 366±1 179	25 376±3 502	10 336±213.6	59 019±2341	5 7626±8 463
90.43	9 111±297	35 733±739	4 037±918	4 329±203.7	19 886±1 611	1 9658±4 781
45.22	4 474±1 46.4	18 271±377.6	1 704±3 87.5	1 764±82.7	9 390±760.8	7 732±1 881
22.61	2 387±77.8	9 819±202.9	723±1 64.1	871±41.0	4 010±324.6	6 570±1 598
11.30	776±25.5	4 013±82.7	313±71.4	310±14.1	1 125±91.2	3 031±7 37.5

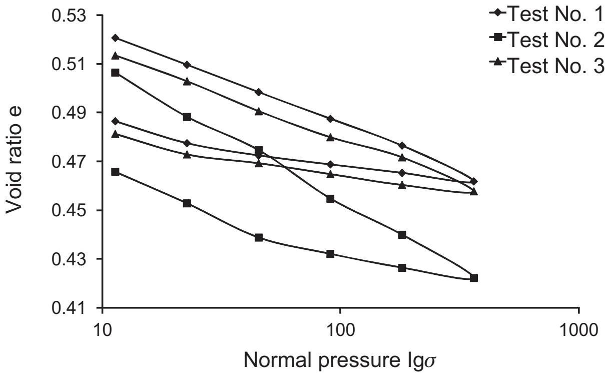

Fig. 4. Oedometer curves obtained for lentil vetch.

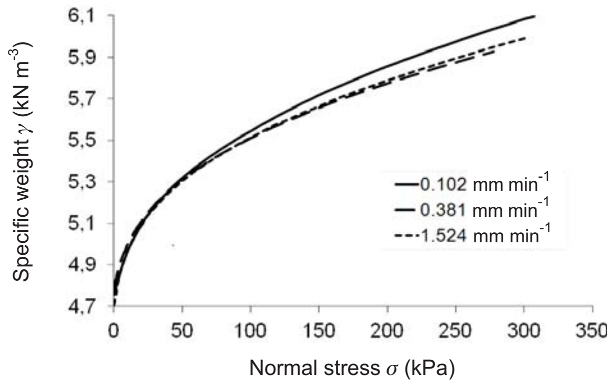

Fig. 5. Variation of the specific weight with normal pressure. 'Prevision' oats.

T a b l e 7. Variation of the specific weight (or bulk density*) with normal stress

Sample	Apparent specific weight γ (kN m^{-3})							
	Normal stress (kPa)							
	0	25	50	75	100	125	150	200
'Kym' barley	6.24±0.04	6.52±0.08	6.64±0.09	6.72±0.09	6.79±0.10	6.85±0.10	6.90±0.10	6.99±0.11
Corn	7.31±0.01	7.39±0.00	7.43±0.01	7.47±0.01	7.50±0.01	7.53±0.01	7.54±0.02	7.61±0.01
'Prevision' oats	4.75±0.03	5.22±0.01	5.40±0.01	5.53±0.02	5.64±0.03	5.74±0.04	5.82±0.04	5.96±0.06
Sunflower	4.01±0.02	4.18±0.02	4.28±0.02	4.36±0.02	4.44±0.02	4.52±0.03	4.59±0.03	4.72±0.05
Lentil vetch	8.43±0.02	8.56±0.02	8.62±0.02	8.66±0.02	8.69±0.02	8.71±0.02	8.73±0.02	8.77±0.03
'Camacho' wheat	8.11±0.01	8.23±0.01	8.29±0.01	8.33±0.02	8.36±0.02	8.39±0.02	8.41±0.02	8.45±0.03

*Bulk density results can be obtained by multiplying results by 98.1 and it should be expressed in kg m^{-3}.

T a b l e 8. Values obtained for the real specific weight

Sample	Real specific weight (kN m^{-3})
'Kym' barley	11.39±0.14
Corn	12.63±0.16
'Prevision' oats	10.22±0.18
Sunflower	7.73±0.33
Lentil vetch	12.86±0.23
'Camacho' wheat	12.72±0.12

specific weight was measured, 11% for 'Kym' barley, whereas for corn, lentil vetch, and 'Camacho' wheat this increment was 4%.

The typical shape of the curves obtained for this parameter as a function of the normal stress applied is plotted in Fig. 5. In this case, the sample used was 'Prevision' oats.

The values obtained for the real specific weight show that lentil vetch and 'Camacho' wheat had the largest values (12.8 kN m^{-3}) followed by corn (12.6 kN m^{-3}). On the contrary, sunflower had the lowest value for this parameter (7.7 kN m^{-3}) followed by 'Prevision' oats (10.2 kN m^{-3}). These results are summarized in Table 8.

The moisture content values obtained for the different samples tested at the two different drying temperatures used, 55 and 105 to 110°C, are provided in Table 9. Corn had the greatest moisture content (13.7% at a temperature of 105-110°C), whereas sunflower had the lowest one (6.3% at that temperature). When analysing the percentage of water lost by the different samples when dried at a temperature of 55° C with respect to that obtained at 105 to 110°C, it was observed that 'Prevision' oats and sunflower displayed the greatest loss (36%) in the moisture content. On the contrary, 'Camacho' wheat lost (29%) and was the sample with the minimum loss among the different samples tested.

T a b l e 9. Moisture content for the different samples tested at two different drying temperatures

Sample	Moisture content H (%)	
	55° C	105-110°C
'Kym' barley	8.83	11.92
Corn	10.28	13.71
'Prevision' oats	7.37	10.00
Sunflower	4.66	6.34
Lentil vetch	7.86	10.46
'Camacho' wheat	8.63	11.15

DISCUSSION

With respect to the angle of internal friction, from these results no conclusions could be drawn for this material property concerning either the influence of test velocity or the type of test used. The results obtained for this material property were similar to those provided by other authors such as Zhang and Britton (2003), Molenda and Horabik (2004), Lebegue and Boudakian (1989), Muir and Sinha (1988) or Molenda and Horabik (2004) for wheat and barley, corn, sunflower, and oats, respectively. It should be noted that the results for wheat were approximately three degrees smaller than those obtained by Molenda *et al.* (2002b) and by Molenda and Horabik (2004) using direct shear tests, whereas the results for barley were about two degrees smaller than those reported by the same authors. These differences could be attributed to either the type of the shear box or the manner in which these tests were conducted. For wheat, differences of approximately four degrees were observed between these values and those reported by Molenda *et al.* (2006) when the comparing results obtained for granular agricultural materials in two laboratories located in different countries, Spain and Poland, respectively.

For the apparent cohesion, the results were dependent on the test velocity used with the different samples tested and no general trend was observed. Thus, it could be concluded that test velocity did not have an influence on the results obtained for this material property. These results could have been produced by the type of sample used and the orientation of the grains inside the shear box, which does play an important role in the variation of these values. The relatively high value obtained for corn compared with the remaining samples could be due to its moisture content, since that sample presented the highest value. However, no clear explanation could be provided for the differences observed when using the circular and the square shear boxes for this sample. Probably, the way the bedding was formed during the test and the orientation of the grains inside the shear box could play an important role. It should also be noted that the use of the least squares fitting provided slightly higher values for this parameter than those that could be obtained when normal pressures lower than 100 kPa had been applied in the tests developed here. In this case, for the low values of normal pressure, a curve instead of a straight line could have been obtained for the Morh-Coulomb failure envelope, thus reducing the values obtained for the apparent cohesion. The results for wheat, barley, corn, and oats were similar to those reported by Molenda and Horabik (2004) using direct shear tests. In the case of wheat, the values obtained here were slightly higher, at least by 2 kPa, than those provided by Molenda *et al.* (2002b). A noteworthy aspect is the great values observed for the standard deviation. These deviations were caused by the method used to obtain the apparent cohesion. As described previously, these values were obtained from regression curves, where minor variations in their slope caused relatively great variations in the apparent cohesion values. This limitation should be considered when using these results.

However, with respect to the dilatancy angle, no conclusions could be made about the influence of test velocity on these results. No general trend was observed. In addition, the type of test did not appear to have an influence on these results. As with many material properties, the orientation of the grain during the shear tests is thought to influence the values obtained for the dilatancy angle when using the same sample subjected to different test conditions. Similar results for this material property were observed by Moya *et al.* (2006) for wheat.

With respect to the grain-on-wall friction coefficient, no significant variations were obtained between the circular and the square shear cells when the concrete mould was used. According to Thompson *et al.* (1988), a wear-in effect can occur which affects the values of this material property. Therefore, as several tests were replicated, the differences obtained between the rough and the smooth concrete moulds decreased. The values obtained with these moulds were much greater than those obtained with the steel mould because of the initial relative roughness. These differences ranged between 183% for 'Camacho' wheat and 241% for sunflower. Similar differences were observed by Rusinek and Molenda (2007) for rapeseed and by Ramirez *et al.* (2009) when using the same types of surfaces with powdered agricultural products such as confectioner sugar and granulated sugar. Very small values (0.135±0.002) for the coefficient of friction between wheat and smooth galvanized steel were obtained by Molenda *et al.* (2002a). However, these values were similar to those obtained herein for the steel surface using the square shear cell.

It should also be mentioned that the values obtained for this material property were similar to those reported by other researchers *eg* Britton and Moysey (1986), Muir and Sinha (1988), Thompson *et al.* (1998), Ayuga *et al.* (2001), and Zhang and Britton (2003), among others. However, the assertion by Molenda *et al.* (2000) that the grain-on-wall friction coefficient for wheat on smooth galvanized steel surfaces decreases as a function of the number of tests could not be checked.

The results obtained from direct shear tests showed that no significant differences occurred depending on the pre-consolidation level applied to the samples.

The triaxial tests were carried out allowing free lateral deformation of the sample. The results showed that the average variation in the angle of internal friction at different axial strain rates was lower using the larger diameter specimen (101.6 mm in diameter) than that of the smaller diameter specimen (38.1 mm in diameter). It is believed that the average particle size to the specimen size ratio had an influence on the test results. The results were similar to those reported by Molenda and Horabik (2004) for barley using direct shear tests. Nevertheless, the results reported by these authors from direct shear tests were approximately 1.5° and 6° higher than those obtained here using triaxial tests for wheat and corn, respectively.

The apparent cohesion was determined using these type tests as well. It should be noted that barley did not have any apparent cohesion, which differed from the trend observed for the same material by Molenda and Horabik (2004) using direct shear tests. However, even when the types of tests carried out were different, the results obtained for wheat and corn were similar to those reported by these authors. As explained for the direct shear tests, the relatively great values obtained for the standard deviation were caused by regression curves. In a similar way, this limitation should be considered when using these values.

When comparing the results obtained from the direct shear tests with those obtained from the triaxial tests, it could be concluded that agricultural grains behaved in a different way than those observed with soils. Thus, with some samples, like corn and sunflower, the values obtained for the angle of internal friction were greater with plane strain tests than those obtained using triaxial deformation tests, according to the results obtained by other researchers *eg* Schanz and Vermeer (1996) with sands. However, 'Kym' barley did not behave in a similar way. Therefore, the general trend observed by these researchers could not be checked with all granular materials used in this work. Molenda and Horabik (2004) did not find significant differences when comparing results from direct shear tests and triaxial tests for wheat at five different moisture contents except at the 10% grain moisture content. However, they could not find a clear explanation for this case. Ramirez *et al.* (2009) observed that the values for the angle of internal friction were higher when using triaxial tests than those obtained from direct shear tests for tests conducted using powdered agricultural products and sugar.

For K_0 tests, a general trend was observed for the different samples tested. The greater the lateral pressure applied, the lower the values of Poisson ratio (as stated in Moya *et al.*, 2002, 2006 and Ramirez *et al.*, 2009 for powdered agricultural materials). However, for 'Camacho' wheat, for tests conducted at 0.19 mm min^{-1} using the specimen 38.1 mm in diameter, the value of this material property was the same at the three lateral pressures applied. Although there is a lack of data for this material property in the literature, the results obtained herein were similar to those used by Zhang and Britton (2003) for wheat and barley. Nevertheless, they differed from those provided by Molenda and Stasiak (2002) for barley, wheat, or oats at different moisture contents, or those reported by Molenda *et al.* (2002) for wheat. The values were obtained from Young modulus, which may account for the differences. The orientation of the grain can play an important role in the elastic properties of these granular agricultural materials.

From the oedometer tests, the most important values are those corresponding to a normal pressure of 90.43 kPa during the unloading process. Hence, only the elastic behaviour of the sample was taken into account (Moya *et al.*, 2006; Stasiak *et al.*, 2010). This normal pressure is usually reached inside commercial bins. These values are shown in Tables 10 and 11 and are recommended values for Young modulus.

The results obtained for wheat and barley were similar to those reported by Molenda and Stasiak (2002) at different moisture contents and by Molenda *et al.* (2002b) for wheat. Nevertheless, the values corresponding to oats were lower in our case than those reported by those authors. The manner in which these tests were conducted may have influenced these results. Finally, according to Stasiak *et al.* (2007), it could be observed that the higher the hydrostatic pressure, the higher the modulus of elasticity.

The results obtained from apparent specific weight tests showed that the influence of the friction between the grains and the mould could be neglected since the variation was less than 1% in all the cases. Nevertheless, it was taken into account, as commented in the results section. 'Prevision' oats and sunflower produced the greatest variation in these values as normal stress increased. The same materials also exhibited the smallest decrease in Young modulus during the unloading cycle. This implies that they were the most compressible and the least elastic of all the samples used in this work. Corn was determined to be the least compressible and the most elastic sample. As expected, the general trend was that the greatest variation in the specific weight corresponded to the samples that presented the lowest initial values for this material property. Another important conclusion that could be drawn from these tests was that test velocity did not have an influence on the results obtained for this material property.

For this parameter, the values obtained for wheat and barley were similar to those determined by other authors *eg* Britton and Moysey (1986), and Zhang and Britton (2003), among others. The results for wheat were similar to those reported by Molenda and Horabik (2004), whereas for barley their values were approximately 1.6 kN m^{-3} higher than those obtained herein. The results for wheat were also slightly higher, by about 0.8 kN m^{-3}, than those provided by

Table 10. Range of values obtained for the different material properties

Sample	Material property									
	ϕ (°)	C (kPa)	μ Steel	μ Concrete	γ_{ap} (kN m^{-3})	γ_r (kN m^{-3})	ψ (°)	E (kPa)	ν	H (%)
'Kym' barley	21.6-28	0-10.72	0.13-0.21	0.41-0.43	6.79	11.39	0-4.9	9111	0.35-0.36	11.92
Corn	19.5-30.4	0-36.36	0.15-0.26	0.50-0.56	7.50	12.63	0-32.7	35733	0.30-0.31	13.71
'Prevision' oats	21.0-24.8	0-4.69	–	–	5.64	10.22	0	4037	0.36-0.41	10
Sunflower	17.1-30.9	0-36.76	0.21-0.22	0.51-0.53	4.44	7.73	0-9.7	4329	0.31-0.33	6.34
Lentil vetch	20.9-27.5	0-14.70	–	–	8.69	12.86	0-24.3	19886	0.32-0.35	10.46
'Camacho' wheat	19.7-24.6	2.87-16.38	0.14-0.24	0.39-0.44	8.36	12.72	0-23.1	19658	0.27-0.37	11.15

Table 11. Recommended values for the different material properties

Sample	Material property									
	ϕ (°)	C (kPa)	μ Steel	μ Concrete	γ_{ap} (kN m^{-3})	γ_r (kN m^{-3})	ψ (°)	E (kPa)	ν	H (%)
'Kym' barley	24.8	5.50	0.17	0.42	6.79	11.39	4.9	9 111	0.36	11.92
Corn	25	18	0.20	0.53	7.50	12.63	32.7	3 5733	0.31	13.71
'Prevision' oats	22.9	2.50	–	–	5.64	10.22	0	4 037	0.41	10
Sunflower	24	18.50	0.21	0.52	4.44	7.73	9.7	4 329	0.33	6.34
Lentil vetch	24.2	7.50	–	–	8.69	12.86	24.3	19 886	0.35	10.46
'Camacho' wheat	22.2	9.50	0.19	0.42	8.36	12.72	23.1	19 658	0.37	11.15

Molenda *et al.* (2002b). Meanwhile, the corn values were similar to those published by Britton and Moysey (1986), Thompson *et al.* (1998), and Mc Neill *et al.* (2004) and about 1 kN m^{-3} lower than those provided by Molenda and Horabik (2004). The values for sunflower did not differ from those reported by Britton and Moysey (1986) or Lebegue and Boudakian (1989), among others. Finally, the oats values were similar to those published by Britton and Moysey (1986) and Muir and Sinha (1988), but they were 1.7 kN m^{-3} lower that those obtained by Molenda and Horabik (2004). It should be noted that no comparable data could be found in the literature for lentil vetch.

The samples with the greatest values of apparent specific weight also had the greatest values for the real specific weight and *vice-versa*. As a general trend, the values of real specific weight were lower than those reported by other authors (Muir and Sinha, 1988) for oats, barley, wheat or sunflower. Nevertheless, the corn values were similar to those reported by Shan (1996). These results were possibly caused by the techniques used when conducting these tests. It should be noted that this parameter is not often found in the literature. The values for lentil vetch could not be compared since no other data could be found in the international bibliography.

Table 10 list the range of values for the different material properties determined in this work for the different samples tested, whereas Table 11 provides the recommended values for each of these properties and for each sample. Most of the recommended values included in this table correspond to the average values of those listed in the different tables provided in the document. As an exception, the recommended values for the dilatancy angle and Poisson ratio are the maximum values of all these listed in the tables.

CONCLUSIONS

1. As a general trend, the values for the different material properties were not affected by the test velocity, except in the case of Poisson ratio.

2. The values for the material properties considered in traditional methods, such as the angle of internal friction, the grain-to-wall friction coefficient or the specific weight, were similar to those reported previously in the literature.

3. The values for the angle of internal friction were similar when either direct shear tests or triaxial tests were carried out.

4. No significant differences were observed between the results obtained using the square shear box and the circular shear box when the dilatancy angle or the grain-to-wall friction coefficients were determined. However, for the angle of internal friction no apparent trend could be obtained from the results obtained using the two different shear boxes.

5. There were no significant differences between the direct shear tests conducted with pre-consolidated samples and those carried out with unconsolidated samples.

6. Test velocity did not have an influence on the values obtained for the apparent specific weight when normal pressure was increased.

7. Simplified tests based on common geotechnical devices can be used to determine mechanical parameters of agricultural grains in order to be used on calculations of silo pressures, both by classical algebraic theories and numerical methods.

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