EFFECT OF MOISTURE CONTENT ON COEFFICIENTS OF FRICTION AND ANGLE OF REPOSE FOR DIFFERENT TYPES OF GRAINS

Benedito C. BENEDETTI and José T. JORGE

Departamento de Pré-Processamento
de Produtos Agropecuários

Faculdade de Engenharia Agrícola
Universidade Estadual de Campinas

Caixa Postal: 6011
13081 Campinas, São Paulo, Brasil

ABSTRACT

The objective of this work was to determine the effect of moisture content on angle of repose, internal coefficient of friction and coefficients of friction with aluminium, concrete, galvanized steel, hardboard, and plywood surfaces. The grains used were beans, maize, peanuts, rough rice, soybeans and wheat. Four levels of moisture content were considered: 10, 15, 20 and 25%, wet basis.

In general, the coefficients of friction indicated a tendency to increase with increasing moisture content. The internal coefficient of friction also showed a similar tendency. The galvanized steel surface showed lower coefficients of friction while the concrete surfaces presented higher ones. The experimental data were fitted into a third degree polynomial model. The resulting equations had good correlation coefficients and significant levels of 1.0% for all products and surfaces, except for rough rice with aluminium and concrete.

The angle of repose increased with increasing moisture content for maize, rough rice, soybeans and wheat. The experimental data fitted into a first degree model showed levels of significance of 1.0%. The angle of repose of beans and peanuts also increased when the moisture content increased, but the experimental data were best represented by a third degree polynomial model at the same significance level.

INTRODUCTION

For the proper and successful design of grain storage structures, materials handling and processing equipment some information regarding the physical properties of grains must be known. Some of these properties, including the internal coefficient of friction, the coefficient of friction and angle of repose, are greatly influenced by parameters such as size, shape, particle orientation and moisture content.(Mohsenin, 1970)

Several methods have been used to determine these properties. Brubaker and Pos (1965) used a test facility with a positive drive table that moved linearly and horizontally at a constant speed. They reported that the static coefficient of friction was significantly influenced by the moisture content of the grains and test surfaces. In a similar study, Bickert and Buelow (1966) found that the friction coefficients of corn and barley are affected by moisture content. They suggested a first degree equation to represent the experimental data.

Snyder et al. (1967) also used similar apparatus and found that the coefficient of kinetic friction of wheat on metal surfaces increased when the grain or surface moisture content increased. In addition, they concluded that normal pressure and velocity had little effect on kinetic friction coefficients. Lawton (1980) determined the static coefficient of friction between cereal grains and various silo materials. He reported that the static coefficient of friction, in general, increased with the moisture content of the grain. Among the materials tested, concrete exhibited the highest coefficients of friction.

Clark and McFarland (1973) proposed using the Instron Universal Testing Equipment for determining coefficients of friction which could be calculated from the graphs produced by the equipment. Tosello (1975) also used a similar technique although he adapted a more practical device for putting the grains in contact with surfaces.

Kramer (1944) found that the angle of repose of rough rice increased rapidly if its moisture content went beyond 16-17%. Fowler and Wyatt (1960) studied on wheat, sand, rapeseed and millet the effect of moisture content on the angle of repose and found a positive relationship between the two. Values of angle of repose were reported by Lorenzen (1959) for wheat, maize and barley at different moisture content.

Published data of coefficients of friction and angle of repose show a wide range of values. There is practically no data available for these characteristics for varieties of grains grown in Brazil.

The objective of the present study was to verify the effect of moisture content on angle of repose, internal coefficient of friction and coefficients of friction with aluminium, concrete, galvanized steel, hardboard, and plywood surfaces of the following grains: beans, maize, peanuts, rough rice, soybeans and wheat.

MATERIALS AND METHODS

The following grains, with their varieties in parentheses, were used in the experiments: peanuts (Tatú), rough rice (IAC-47), beans (Aysó), maize (Maya XX), soybeans (Paraná) and wheat (IAC-25).

Before the experiments were carried out the moisture content, grade and size of the grains were determined. Moisture content was measured in a ventilated oven at 105 °C for a period of 24 hrs. Then the grade and size of the grains were determined by the recommended methods of the Brazilian Agency for Agricultural Exports.

In a later stage the grains were conditioned to moisture content levels of 10, 15, 20 and 25%, wet basis.* For drying, an oven at a low temperature was used. Whenever the moisture content of the grains needed to be increased, a specific amount of distiled water was added evenly to the samples, after which the grains were mixed and stored in plastic containers until equilibrium moisture content was established.

The plastic containers were kept in a room at 4.0 ± 1.0 °C. They were removed 24 hrs before each test and placed into the room where the experiments were carried out, at 25.0 ± 1.0 °C and relative humidity of 65 ± 1 %,.

1. Coefficients of Friction

Coefficients of friction were determined using the apparatus developed by Tosello (1975) shown in Figure 1. Basically this consisted of a horizontal support (F) which was sustained over a rigid platform (N) on which different material surfaces (G) could be placed. A rectangular bottomless acrylic box (K) with a length of 0.148m, a width of 0.130m and a height of 0.082m was used to hold the grains. To reduce the friction of the system, the box was supported by four rollers. The rollers also provided a fixed clearance between the box and the surface, allowing that only the grains come into contact with the surface. A steel cable (I) connected the box (K) and the point (J) where the force was applied. A pulley (H) could be adjusted to guarantee that the applied force was in the same vertical direction as the dynamometer and also in the horizontal direction of the friction surface.

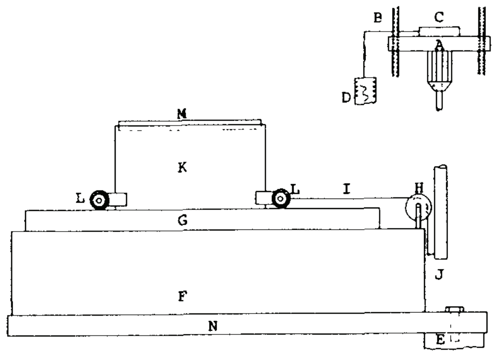

Fig.1. Diagram of the apparatus for determination of coefficients of friction with surfaces.

This apparatus was attached to the base (E) of the Instron Universal Testing Instrument. A steel bar of 0.1m length was fixed to the lower end of the load cell(A). The cable (I) could be connected to the steel bar through a hook welded to the end of this bar allowing the application of the force. The applied force and displacement were recorded by a chart recorder (D) connected to the Instron.

A rectangular piece of metal (M), with variable weight and smaller dimensions than the rectangular box, was used to provide the normal force between the friction surface and the sample.

Five different surfaces were used in this study namely aluminium, galvanized steel, concrete, hardboard and plywood.

---

* all moisture content in this paper are in wet basis.

Three repetitions were carried out for each combination of grain, surface, moisture content level and normal force. Three normal forces ranging from 5.366 to 8.742 kgf were applied.

2. Internal Coefficient of Friction

The internal coefficient of friction was studied using the apparatus shown in Figure 2. The only difference was that the horizontal support and surfaces in Fig.1 were replaced by another rectangular acrylic box. The dimensions of this box were 0.195m long, 0.150m wide and 0.08m high. It could hold the material in a such way that the grains could come into direct contact with others in the bottomless box (G).

Each combination of grain, moisture content level and normal force was repeated three times. Three normal forces ranging from 5.396 to 8.772 kgf were used.

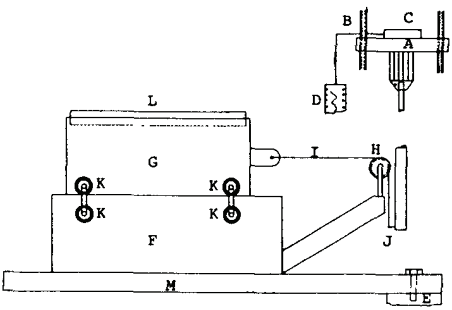

Fig.2. Diagram of the apparatus for determination of internal coefficient of friction.

Preliminary tests indicated a combination of 0.5 cm/min for the velocity of the load cell and 20 cm/min for the chart recorder. The Instron Equipment was calibrated to give a value of 0.05 kgf for each division on the force axis of the graph scale. From the graph for each test, the static coefficient of friction could be calculated by relating the force necessary to start the movement to its normal force.

3. Angle of Repose

Angle of repose was determined using the apparatus shown in Figure 3, which consisted of a rectangular acrylic box (B), (0.5m x 0.2m x 0.4m) which allowed the visualization of the measurement process. The grains were held in a triangular container (A) which was placed on the top of the box (B). To enable the grains to flow into the box a gateway (C) was fixed to the lower part of the container. An instrument with a protractor attached to it was used for measuring the angles.

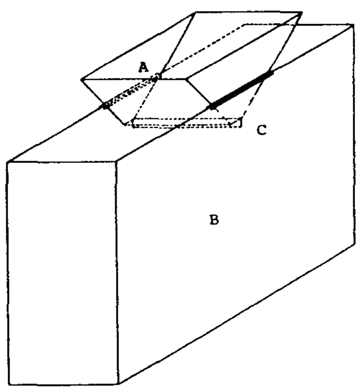

Fig.3. Diagram of the apparatus for angle of repose measurement.

Before the tests, the gateway was opened at different positions and the one which best provided a constant and uniform rate for the grains was established.

For each test the triangular container was filled with grains. Then the gateway was opened so that the flow could start. The angle of repose was measured at four different positions, two for each side of the box, and the average of these values gave the characteristic angle of repose for that particular test. Five repetitions were carried out for each grain and moisture content levels.

RESULTS AND DISCUSSION

1. Frictional Coefficients

Table I shows a summary of the data for friction experiments where each value expresses the average of nine data points (three normal forces and three repetitions).

Table I. Coefficients of friction on various surfaces and internal coefficients of friction for grains at various moisture contents.

Product	MC (%)	Aluminium	Concrete	Galv. steel	Hardboard	Plywood	Internal coef.
Beans	10	0.329	0.334	0.200	0.259	0.323	0.627
	15	0.248	0.383	0.200	0.205	0.276	0.659
	20	0.244	0.261	0.159	0.163	0.227	0.560
	25	0.361	0.608	0.262	0.445	0.520	1.017
Maize	10	0.262	0.230	0.184	0.228	0.247	0.725
	15	0.173	0.224	0.136	0.395	0.315	0.482
	20	0.273	0.448	0.234	0.420	0.424	0.598
	25	0.481	0.438	0.306	0.474	0.457	0.596
Peanuts	10	0.248	0.457	0.185	0.311	0.272	1.021
	15	0.331	0.624	0.286	0.446	0.393	1.065
	20	0.249	0.364	0.232	0.399	0.552	0.876
	25	0.572	0.640	0.575	0.503	0.765	1.222
Rough rice	10	0.388	0.533	0.221	0.316	0.364	0.694
	15	0.367	0.491	0.235	0.324	0.487	0.776
	20	0.369	0.473	0.161	0.344	0.440	0.493
	25	0.361	0.492	0.202	0.506	0.542	0.830
Soybeans	10	0.246	0.433	0.256	0.214	0.267	0.640
	15	0.193	0.393	0.146	0.226	0.237	0.756
	20	0.242	0.299	0.113	0.443	0.372	0.816
	25	0.312	0.479	0.249	0.475	0.469	1.039
Wheat	10	0.174	0.338	0.168	0.151	0.163	0.590
	15	0.240	0.409	0.198	0.208	0.197	0.777
	20	0.164	0.355	0.143	0.280	0.222	0.597
	25	0.329	0.488	0.301	0.388	0.372	0.833

In general, on the surfaces tested, the lowest coefficients of friction were obtained with galvanized steel and the highest with concrete. However, in some tests, plywood and hardboard surfaces showed higher coefficients as compared to those of concrete. The internal coefficient of friction presented higher values for all grains and moisture content levels than the coefficients of friction with surfaces.

Maize, soybeans and wheat presented lower values for friction coefficients with galvanized steel, plywood and concrete surfaces when compared with those reported by Brubaker and Pos (1965), except for wheat and soybeans with galvanized steel at 10% moisture content. Higher values were also obtained for maize with plywood and steel surfaces compared to those of Bickert and Buelow (1966). Wheat also presented substantially different values from those found by Lawton (1980). Coefficients of friction for rough rice with concrete were similar to those found by Kramer (1944), but were lower than the coefficients reported by the same researcher for galvanized steel.

In general, rough rice and peanuts exhibited the highest values for friction coefficients and wheat the lowest.

Several factors could be responsible for the differences between the results obtained in this experiment and those reported in the literature. Some of these are: differences in experimental techniques and apparatus; moisture content of the grains; variation in the grain samples and contact surfaces and temperature and humidity conditions under which the experiments were conducted.

The values of coefficients of friction at low moisture content (traditional way of storage) were substantially different compared to those at high moisture content (wet storage). This indicates that special care must be taken when designing storage structures or handling equipment in accordance with by which the grain will be stored, dry or wet storage.

Table I and Figure 4 indicate that there is a tendency for the coefficient of friction to increase when the moisture content increases. These findings are limited to the moisture content ranges from 10 to 25%.

A third degree polynomial model was used to correlate the coefficient of friction to the moisture content. All data points, at a particular moisture content level, were used. It should be noted that the coefficient of friction was not affected by the normal force, a fact also reported by Bickter and Buelow (1966) and Snyder et al. (1967). The model used was:

$$\mu = a_1 + a_2 * M + a_3 * M^2 + a_4 * M^3 \qquad (1)$$

where: μ = coefficient of friction
M = moisture content, decimal
a_1, a_2, a_3, a_4 = constants

The constants of this model, coefficients of correlation and significance levels, for all grains, are shown in Table II. The curves for wheat which were drawn with the equations of this table are given in Figure 4.

Except for the equations for rough rice with aluminium and concrete surfaces, all other relations can be used to predict the coefficient of friction and internal coefficient of friction at different moisture content levels. Since the data were correlated at a high level of significance (1.0%) and high correlation coefficients, it is expected that these equations could be used for design purposes with high level of certainty.

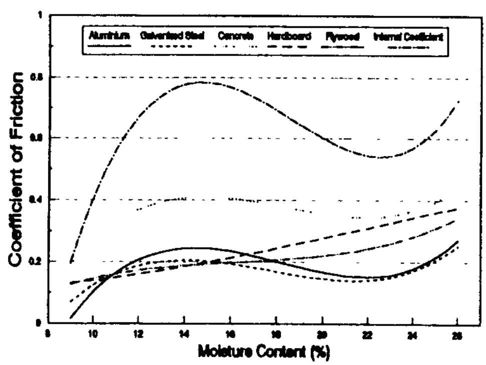

Fig.4. Effect of moisture content on the coefficient of friction of wheat.

Table II. Constants of the equation $\mu = a_1 + a_2*M + a_3*M + a_4*M$, correlation coefficients and level of significance, for grains with surfaces and internal coefficient of friction.

Product	sur-face	a1	a2	a3	a4	r
Beans	Al	1.139	-11.276	41.319	-36.782	0.943 *
	Ga	-0.827	19.672	-120.301	233.053	0.938 *
	Co	-3.667	74.409	-441.520	838.649	0.995 *
	Hb	-0.588	19.410	-140.315	310.096	0.981 *
	Pl	-0.768	23.728	-164.537	353.729	0.993 *
	In	-3.156	71.597	-434.391	846.696	0.964 *
Maize	Al	1.296	-16.144	67.075	-62.813	0.994 *
	Ga	1.391	-21.747	118.643	-196.165	0.945 *
	Co	2.599	-46.530	284.716	-532.208	0.985 *
	Hb	-1.735	33.488	-173.119	297.732	0.937 *
	Pl	0.389	-4.850	42.203	-86.854	0.979 *
	In	4.743	-71.171	384.888	-665.802	0.912 *
Peanuts	Al	-1.814	41.212	-254.987	502.331	0.994 *
	Ga	-1.879	40.891	-250.667	494.213	0.973 *
	Co	-3.318	73.917	-442.023	826.674	0.878 *
	Hb	-0.191	7.209	-32.124	69.465	0.991 *
	Pl	-1.338	30.675	-171.552	308.842	0.860 *
	In	-1.514	51.884	-328.967	648.124	0.827 *
Rough Rice	Al	0.778	-6.644	35.270	-61.438	0.574 ns
	Ga	-1.398	30.404	-180.631	338.131	0.974 *
	Co	0.777	-2.889	6.286	2.770	0.457 ns
	Hb	-0.330	13.031	-86.203	189.272	0.973 *
	Pl	-2.796	55.856	-311.052	563.538	0.994 *
	In	-6.841	141.842	-848.235	1612.424	0.968 *
Soybeans	Al	1.081	-14.822	78.029	-124.753	0.981 *
	Ga	0.604	-3.462	-3.519	42.755	0.976 *
	Co	-0.649	22.989	-153.184	309.799	0.974 *
	Hb	2.358	-42.402	258.099	-470.317	0.919 *
	Pl	1.749	-28.059	161.354	-277.842	0.991 *
	In	-0.323	16.789	-90.084	172.902	0.931 *
Wheat	Al	-2.248	44.252	-254.176	466.347	0.989 *
	Ga	-1.475	30.711	-181.444	341.885	0.986 *
	Co	-1.758	37.756	-213.441	387.530	0.992 *
	Hb	0.128	-0.907	12.043	-18.775	0.996 *
	Pl	-0.349	9.259	-54.260	111.074	0.997 *
	In	-5.103	102.232	-573.892	1026.727	0.965 *

* significance level of 1.0%
ns no significance level

Al= Aluminium; Ga= Galvanized steel; Co= Concrete; Hb= Hardboard; Pl= Plywood; In= Internal Coefficient of Friction.

2. Angle of Repose

Table III shows the angle of repose obtained for different grains. Each value represents the average of five data points. The experimental data were fitted to a linear model and the resulting equations may be seen in Table IV.

The angle of repose for maize, rough rice, soybeans and wheat increased when moisture content increased. Kramer (1944), Lorenzen (1959) and Fowler and Wyatt (1960) obtained similar results. In general, the values of angle of repose were smaller than those given by Lorenzen (1959) for maize and Fowler and Wyatt (1960) for wheat.

Fowler and Wyatt (1960) explained the reasons for the increasing angle of repose with moisture content. They suggested that the variation of angle of repose with moisture content is due to the surface layer of moisture surrounding each granule and that surface tension effects become predominant in holding aggregates of granules together.

Table III. Angle of Repose (degrees) for grains at various moisture contents.

Product	Moisture Content (%)			
	10	15	20	25
Beans	33.8	33.4	33.9	35.8
Maize	29.2	30.2	33.5	38.0
Peanuts	34.4	35.8	34.9	35.2
Rough Rice	32.2	33.0	34.2	35.3
Soybeans	29.5	29.4	30.8	32.3
Wheat	31.7	33.1	37.4	38.2

Table IV. Linear regression and coefficients of correlation for angle of repose (Á, degrees) as function of moisture content (*M*, %) for grains.

Product	Equation	r
Beans	Á = 31.9 + 0.122 * M	0.688 ns
Maize	Á = 22.3 + 0.569 * M	0.961 *
Peanuts	Á = 34.5 + 0.030 * M	0.201 ns
Rough Rice	Á = 29.8 + 0.215 * M	0.875 *
Soybeans	Á = 26.8 + 0.212 * M	0.851 *
Wheat	Á = 26.7 + 0.476 * M	0.943 *

* level of significance of 1.0%
ns no level of significance.

The angle of repose of beans and peanuts did not exhibit linear correlation with moisture content but a tendency to increase with moisture content was also noticed. The best correlation for the data was obtained with a third degree polynomial equation. These equations are:

$$Á = 36.7 - 31.7 * M + 22.7 * M^2 + 282.1 * M^3 \quad (2)$$

for beans, (r = 0.839 and 1.0% of significance level)

$$Á = 11.5 + 428.4 * M - 2430.3 * M^2 + 4374.8 * M^3 \quad (3)$$

for peanuts, (r = 0.824 and 1.0% of significance level)

where: Á = angle of repose, degrees
M = moisture content, decimal

The equations derived for these grains can be used to predict the changes in angle of repose with moisture content, within range studied. Figure 5 illustrates the effect of moisture content on the angle of repose of grains.

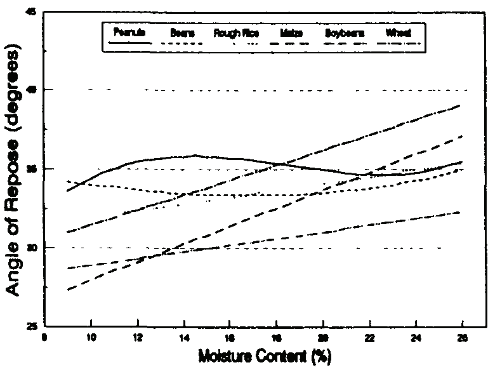

Fig.5. Effect of moisture content on the angle of repose of grains.

CONCLUSIONS

1. In general, there is a tendency for the coefficients of friction to increase with increasing moisture content.
2. A galvanized steel surface showed smaller, and concrete higher, values of coefficient of friction .

3. A number of regression equations were developed to predicted coefficients of friction at different moisture contents, except for rough rice with aluminium and concrete.

4. The values of coefficients of friction at low moisture content differed substantially as compared with those obtained at high moisture content levels.

5. Angle of repose increases with increasing moisture content for maize, rough rice, soybeans, wheat,beans and peanuts.

6. First degree equations to predict the values of angle of repose were developed for maize, rough rice, soybeans and wheat.

REFERENCES

Bickter, W.G. and Buelow, F.H. (1966) Kinetic friction of grains on surfaces. Trans. Am. Soc. Agric. Engrs **9**:129-131.

Brubaker, J.E. and Pos, J. (1965) Determining static coefficient of friction of grains on structural surfaces. Trans. Am. Soc. Agric. Engrs **8**:53-55.

Clark, R.L. and McFarland, H.A. (1973) Granular materials friction apparatus. Trans. Am. Soc. Agric. Engrs **16**:1198-1199.

Coordenadoria de Assistência Técnica Integral, Secretaria da Agricultura, Governo do Estado de São Paulo (1975) ClassificaÇão de produtos agropecuários, subprodutos e residuos de valor econômico.

Fowler, R.T. and Wyatt, F.A. (1960) The effect of moisture content on the angle of repose of granular solids. Austr. J. Chem. Eng. **june**:5-8.

Kramer, H.A. (1944) Factors influencing the design of bulk storage bins for rough rice. Agric. Engng **25**:463-466.

Lawton, P.J. (1980) Coefficients of friction between cereal grain and various silo wall materials. J. agric. Engng Res. **25**:75-86

Lorenzen, R.T. Moisture effect on granular friction of small grain. Am. Soc. Agric. Engrs, paper 59-416.

Mohsenin, N.N. (1970) Physical properties of plant and animal material, Vol. 1, Gordon & Breach, New York.

Snyder, L.N., Roller,W.L. and Hall, G.E. (1967) Coefficients of kinetic friction of wheat on various metal surfaces. Trans. Am. Soc. Agric. Engrs **10**:411-413,419.

Tosello, A. (1975) Equipamento experimental para determinaÇão de coeficiente de atrito de grãos; atrito interno e atrito com paredes de diversos materiais; em conjugaÇão com o equipamento Instron Universal. Ci. Cult. Supl. **27**(7):491.

LES EFFETS DE LA TENEUR EN EAU SUR LES COEFFICIENTS DE FRICTION ET L'ANGLE DE REPOS DE DIFFERENTS TYPES DE GRAINS

B.C. BENEDETTI et J.T. JORGE

Facultade de engenharia Agricola,
Universade Estadual de Campinas
Caixa Postal 6011, 13081 Campinas, Sao Paulo, Brasil

RESUME

L'objectif de ce travail a été de mesurer l'effet de la teneur en eau sur les coefficients de friction contre des surfaces d'aluminium, de béton, d'acier galvanisé, de carton et de contre-plaqué, le coefficient de friction interne et l'angle de repos des haricots, du maïs, des arachides, du riz brut, du soja et du blé. Quatre teneurs en eau ont été prises en compte : 1O, 15, 20 et 25 % d'humidité de base.

En général, les coefficients de friction ont fait preuve d'une tendance à augmenter avec l'élévation de la teneur en eau. La surface en acier galvanisé a présenté divers coefficients de friction tandis que les surfaces de béton présentaient des coefficients plus élevés. Les données expérimentales ont été intégrées en un polynôme du troisième degré. Les équations résultantes avaient de bons coefficients de corrélation et des taux concluants de 1,0 % pour tous les produits et toutes les surfaces, sauf le riz brut avec des surfaces d'aluminium et de béton.

L'angle de repos a augmenté avec l'élévation de la teneur en eau du maïs, du riz brut, du soja et du blé, et les données expérimentales intégrées en un polynôme de premier degré ont présenté des taux de signification de 1,0 %. l'angle de repos des haricots et des arachides a également augmenté avec l'élévation de la teneur en eau, mais les données expérimentales ont été mieux représentées par un polynôme du troisième degré au même taux de signification.