RESEARCH ON THE VISCO-ELASTIC BEHAVIOUR OF SOME VARIETIES OF CHEESE WITH MOLD, RIPENED UNDER SPECIFIC CONDITIONS
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CERCETĂRI PRIVIND COMPORTAREA VÂSCOELASTICĂ A UNOR SORTIMENTE DE BRÂNZĂ CU MUCEGAI, MATURATE ÎN CONDIȚII SPECIFICE

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ABSTRACT
Mold-ripened cheeses exhibit complex mechanical behavior, influenced by factors such as degree of ripening, water content, fat content, and type of mold (white or blue). This study explored the viscoelastic behavior of four types of mold-ripened cheeses to highlight their physicochemical properties, taking into consideration that the viscoelasticity influences their texture, stability and behavior during storage and processing. Analyzing the local pressures applied to the cheese samples, for a contact surface with the cheese samples of approximately 51.5 mm², the pressure levels vary between 40 kPa (for Roquefort cheese) and 50 kPa (for Dorblu cheese); the pressure for the other two types of cheese falls within this range. The data obtained from this study confirmed that penetration resistance and yield stress values provide valuable information in cheese production, in particular for the texture and firmness of cheeses at various stages of the manufacturing process.

REZUMAT
Brânzeturile maturate cu mucegai prezintă un comportament mecanic complex, influențat de factori precum gradul de maturare, conținutul de apă, conținutul de grăsime și tipul de mucegai (alb sau albastru). Această lucrare a avut scopul de a studia comportamentul vâscoelastic a patru tipuri de brânzeturi maturate cu mucegai, pentru a le evidenția proprietățile fizico-chimice, ținând cont de faptul că vâscoelasticitatea influențează textura, stabilitatea și comportamentul acestora în timpul depozitării și prelucrării. În urma analizei presiunilor locale aplicate pentru brânzeturile analizate, la o suprafața de contact cu mostrele de brânză de circa 51,5 mm², presiunea a înregistrat valori între 40 kPa pentru brânza Roquefort și 50 kPa pentru brânza Dorblu. Datele obținute din acest studiu au confirmat că rezistența la penetrare și tensiunea de biocurgere oferă informații valoroase în producția de brânzeturi, în diferite etape ale procesului de fabricație.

INTRODUCTION
Brie, Camembert, Roquefort and Dorblu are all well-known cheeses, but they differ significantly in their ingredients, manufacturing process, texture, taste and origin.

Brie cheese originates from Île-de-France region of France and is made from cow`s milk (usually pasteurized, but it can also be unpasteurized). It has a soft, creamy texture with an edible white mold rind (*Penicillium candidum*) and is typically aged for 4 to 6 weeks. The flavor is smooth, delicate, slightly buttery, with hints of nuts and fruit. It is placed in a large round shape, with a diameter of 23-36 cm and a thickness of 2.5-3 cm.

Camembert cheese originates from France, specifically from the Normandy region, and is made from cow`s milk (usually unpasteurized for traditional Camembert). It also has a soft, creamy texture with an edible white mold crust (*Penicillium candidum*) and a maturation period of about 3 to 5 weeks. The taste is intense, fruity, slightly salty, with flavors of mushrooms and cream ((*Linton, 2008)*.

Roquefort cheese also originates from France, specifically from Roquefort-sur-Soulzon region, and is made from sheep's milk (Lacune sheep milk). It has a semi-hard, crumbly texture, with blue mold veins (*Penicillium roqueforti*) and an intense, spicy, salty taste with flavors of nuts and mushrooms. The maturation period is longer, usually between 3 and 6 months. It is shaped in a cylindrical form, with a diameter of about 19-20 cm a thickness of 8-10 cm.

Dorblu cheese originates from Germany and is made from cow's milk (pasteurized) with a semihard, creamy texture, blue mold veins (Penicillium roqueforti), and a salty, slightly spicy taste with flavors of cream and mushrooms, typically shaped in round molds. The maturation period is usually between 2 and 3 months.

At a storage temperature of 4-10°C, the storage time (about 77 days) has a significant impact on the rheological behavior of blue mold cheeses, which does not occur at different storage temperatures. The compression force with large deformation and the viscoelastic moduli show values that decrease with storage time, while the nonlinear viscoelastic behavior increases. Results obtained by the authors of the study (*Joyner, 2017*) indicated that the microstructure of the samples weakened and was easily deformed as storage time increased. Thus, blue cheese can be stored at 4-10°C without significant changes in its composition or mechanical behavior.

The amount of mold in blue cheese has a significant influence on the quality of the cheese. The quantity and distribution of mold inside the cheese influence its appearance, color, structure, taste, and smell, and are evaluated by experts with appropriate sensory knowledge and skills. The authors of the studies (*Brosnan and Sun, 2004; Caccamo et al., 2004; Jelinski et al., 2007; Kulmyrzaev et al., 2008; Ganchovska et al, 2019; Ganchovska et al, 2021*) propose a computerized method for evaluating the appearance (color and structure).

It has also been found that the physical parameters of blue mold cheeses (such as Valdeon) are affected by the maturation time. Cheese aged for 120 days shows higher values of the elasticity moduli G′, G″, and G*, and a more elastic disposition, but also lower values of fracturability and chewiness (*Diezhandino et al., 2016*).

The storage modulus (G′) and loss modulus (G″) of cheeses show increasing values from the surface towards the interior, while strain and tan δ decreased, as reported in the study (*Karoui et al, 2003*).

For uniaxial creep behavior in cheddar cheeses with different fat contents, tests were conducted at 1, 3, 6, and 12 weeks of age, at a temperature of 40°C and a stress of 1119.5 Pa. The creep data were modelled using a six-element Kelvin model, and the instantaneous slope of the creep curve was defined as the viscoelasticity index. The results from the study show that the estimated viscoelasticity index could be used to predict cheese melting (*Kuo et al, 2000*).

Studying the rheological behavior of cheeses provides information related to texture and structure that can be useful for a better understanding of the complex aging behavior of cheese. Different authors show that fat content, testing temperature, and aging time have a significant impact on the viscoelastic parameters of cheeses, critical stress and strain, complex modulus G*, and breaking stress, and they present positive correlations with phase angle and breaking strain (*Bagher et al., 2020*).

In the uniaxial compression process of rectangular pieces of processed cheese with cream, the applied force was measured using the Hounsfield H1KS equipment. The Maxwell model for creep/constant stress experiments shows that stress increases linearly with time, and experimental force-displacement curves were plotted for the slow strain-stress test. The Maxwell viscoelastic model was validated by comparing numerical results with experimental data *(Ipate G., et al., 2019*).

Experiments on stress relaxation, after a 10% compression on an Instron-type equipment, performed on Cheddar cheeses with four different fat contents, two different moisture contents, and four storage durations, showed that Peleg's empirical models better describe the stress relaxation behavior of processed cheese (at over 50°C), and eight-element Maxwell models better describe the cheese behavior than three- or six-element Maxwell models. The stress relaxation experiments showed viscoelastic differences in cheeses due to reduced fat content, increased moisture, and melting temperature or cheese aging (*Venugopal V., Muthukumarappan K., 2001*).

Physico-mechanical analyses for mold cheese involve evaluating the physical and mechanical properties that can affect the quality, texture, consistency, and behavior of the cheese both during the manufacturing process and throughout storage and consumption.

These analyses may include compression tests to determine texture, where the cheese's resistance to compression is measured, which is an important indicator of cheese firmness, as well as penetration tests to evaluate how easily an object can penetrate the cheese, providing data on its softness or hardness (*Calzad et al., 2014*).

Cheese elasticity is the property that indicates the cheese's ability to return to its original shape after being subjected to deformation. Elasticity tests are important to evaluate how the cheese behaves during handling and slicing (*Garcia C.A. et al., 2018; Vandenberghe E. et al., 2013; Hassan L.K. et al., 2020*). Cheese cohesion refers to the cheese's ability to remain compact without crumbling, which is essential to ensure that the cheese does not break apart when cut or chewed. Additionally, adhesion refers to how well the cheese sticks to different surfaces. This can influence how the cheese behaves when used in various culinary preparations. Furthermore, the analysis of water content and humidity is important because these factors influence the cheese's texture, as well as its ability to spread or melt.

This study characterizes four types of mold cheeses, matured at temperatures and periods corresponding to the technological process recommendations for each type, after compression tests with a cylinder of 8.1 mm in diameter, at constant speeds, determining the variation of force-deformation parameters. The results presented in this paper, as well as the results of other researchers' studies in the field, can provide valuable information to specialists in the production and research of these cheeses.

MATERIALS AND METHODS

A fundamental understanding of the behavior of food products under mechanical stresses is essential for determining the energy requirements for various processing operations, as well as for designing machines, equipment, and facilities that process these products (*Ionescu, M. et al., 2016*).

For four types of mold-ripened cheese (Brie, Dorblu, Camembert, and Roquefort) purchased from commercial networks, viscoelastic behavior tests were conducted using the Hounsfield/Tinius Olsen H1-KS mechanical testing apparatus, equipped with a 1000 N load cell and an 8.1 mm diameter pressing cylinder.

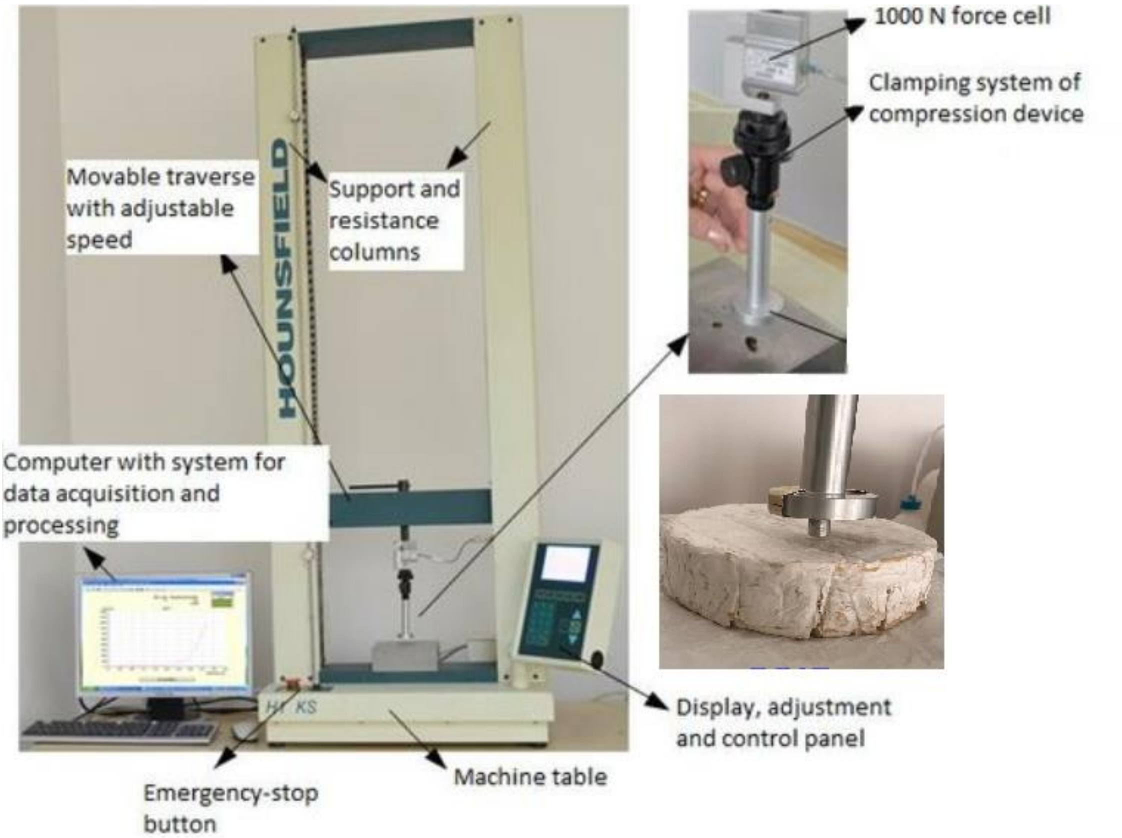

Fig. 1 - Hounsfield / Tinius Olsen model H1 KS device for mechanical tests

The main components of the equipment are: support columns; a fixed flat plate for supporting the sample; a pressing head with a movable flat plate parallel to the base plate; a display, adjustment, and control panel; a load cell; and a data acquisition system (computer) with QMAT software (Fig. 1).

In the case of the used apparatus, the resistant force exerted by the tested material sample is measured by a load cell, which can be easily and quickly changed through a special mechanism depending on the material being tested. For measuring displacement, the apparatus has a precision of ±0.001 mm, and the movement speed can range from 0.001 mm/min to 1000 mm/min.

In the QMAT program, the parameters used in the experiments were set. First, the pressing head speed was set to 100 mm/min, the loading range was set to 25 N, the extension range was set to 5 mm, the hold load target was set to 2.5 N, and the hold load time was set to 180 s.

After acquisition, the samples of cheese were stored in the refrigerator at an average temperature of 8ºC. The determination was performed at ambient temperature (by the end of the measurements, the temperature did not exceed 19.7 ºC). Each type of cheese requires specific preservation treatment and optimal conditions to ensure quality and safety during storage (*Najera A.I. et al., 2021*).

Fig. 2 – Aspects of the tests conducted on mold-ripened cheeses

Additional details about the analyzed cheeses can also be mentioned, for which prior tests were conducted in the faculty's laboratories (Table 1).

Table 1

Physical characteristics of the analyzed cheese samples

Cheese type	Camembert	Brie	Dorblu	Roquefort
Maturation period (days)	30	30	60	75
Mass of analyzed samples (g)	249	200	100	100
Height of samples (mm)	40	50	60	60
Width (mm) (at which the cuts were made)	100 110 90	75 60 50	55 35 20	80 60 50
Nutritional value (kcal)	216	334	413	346
pH	6.7	7.5	6.2	6.0
Fat (g/100g)	13.5	17	29	29.8
Total proteins (g/100g)	23.5	20	19	21.1
Dry matter (%)	45.5	45	48	48
Salt (g/100g)	1.5	1.3	1.7	3.5

After setting up the equipment as mentioned, the cylinder was positioned and adjusted in the apparatus to make contact with the sample to be analyzed, and it was ensured that the force and extension/displacement were set to 0. Then, the 'START' button was pressed to begin the analysis.

For the set movement speed and small displacements of the pressing head (at intervals of 0.01 mm), the apparatus recorded the resistant force. For Brie and Dorblu cheeses, the final displacement was on the order of 2-3 mm, for Camembert cheese on the order of 5-6 mm, and for Roquefort cheese, the test continued as far as the apparatus allowed, up to displacements on the order of 10 mm, as presented in Table 2.

The regression line of the displacement of the testing head correlated with the resistant force has the form:

$$F = \mathrm{a} \cdot d + \mathrm{b} \text{ (N)} \tag{1}$$

where:

F is the resistant force at a displacement *d (mm)* of the testing cylinder, in N; a – is the slope of the regression line, which gives the angles relative to the two axes; b – is the intercept on the origin of the considered line.

This phenomenon occurs mainly in the first part of the experiment because as the testing cylinder penetrates deeper into the sample, the shape of the force-displacement curve changes.

Regarding the influence of pressure on cheeses, it is particularly important to conduct tests on the behavior of cheeses under various pressure categories, as in the tests performed and presented in this paper.

RESULTS

The mechanical or rheological tests performed on cheeses can be used as study tools to characterize cheese functionality, and the results of these analyses can guide necessary adjustments in the manufacturing process to achieve a consistent and high-quality product.

The evaluation of the force required to cut the cheese is an indicator of its texture. Softer cheeses require less cutting force, while harder ones require more force (*Skordaris G. et al., 2022; Goh S.M. et al., 2005*). Moreover, the texture density of the cheese can provide information about its composition, including the ratio of solids to liquids, and the tensile strength test measures resistance to forces that tend to tear the cheese, which is relevant for cheeses that need to maintain structural integrity in various applications. All these tests are part of the rheological profile analysis of cheeses and provide information about viscoelasticity and beyond.

Each type of cheese requires specific preservation treatments and application conditions to ensure the quality and safety of the cheese during storage. High hydrostatic pressure processing (HHP) is an advanced non-thermal technology used for food processing, including cheeses. During the treatment, the product is subjected to high pressure (400–600 MPa - on an industrial scale) for 10–20 minutes at a temperature below 45°C, and the applied pressure is transmitted instantly throughout the food, regardless of its size, shape, and composition (*Nájera A.I. et al., 2021; Koutsoumanis K., et al., 2022*). However, the literature confirms that the timing of the high-pressure (HP) treatment (400-600 MPa, 7 min) is also important because it can lead to significant changes or not in microbiology, proteolysis, instrumental texture, and sensory parameters (*Delgado F.J. et al., 2012*). Thus, the timing of the treatment can result in changes in the appearance, smell, and texture, as well as the aroma and elasticity of the cheese.

The experimental test results show displacements on the order of 0.01 mm, for which the resistant forces were recorded in N. Based on these values, the force-deformation curves were plotted. The paper selects and presents the most significant values of these curves, highlighting changes in their trajectory (shape).

From the analysis of the data in Table 2, it can be observed that for the same values of displacement of the pressing cylinder, the resistant force differs among the four types of cheese (at least for the tested samples). For displacements of about 1.5 mm and approximately 3.2 mm, the resistant force for Dorblu and Brie cheeses is relatively similar, around 2.5 N. For Camembert cheese, this force value is only reached at a displacement of approximately 5 mm, while for Roquefort cheese, this value is not achieved even at a displacement of nearly 10 mm (referring here to the average values from the three measurements performed).

Table 2

The values of the characteristic points of the average curves for the tests on the cheeses

Roquefort			Brie			Camembert			Dorblu	
Extension, mm	*Force, N*		*Extension, mm*	*Force, N*		*Extension, mm*	*Force, N*		*Extension, mm*	*Force, N*
0	0		0.07	0.015		0	0.030		0.01	0.030
0.40	0.133		0.5	0.077		0.22	0.110		0.40	0.763
0.50	0.227		0.75	0.280		0.45	0.257		0.50	0.840
1.00	0.673		1.00	0.532		0.67	0.373		0.75	1.313
1.50	1.053		1.50	1.085		0.90	0.497		1.00	1.757
2.00	1.267		2.00	1.622		1.12	0.603		1.25	2.257
2.50	1.367		2.28	1.733		1.35	0.687		1.49	2.545
3.00	1.447		2.50	1.963		1.57	0.790			
3.50	1.533		2.74	2.105		1.80	0.880			
4.00	1.600		3.00	2.390		2.02	0.967			
4.50	1.643		3.19	2.500		2.25	1.057			
5.00	1.663					2.47	1.183			
5.50	1.69					2.70	1.300			
6.00	1.700					2.92	1.393			
6.50	1.723					3.15	1.500			
7.00	1.733					3.37	1.590			
7.50	1.747					3.60	1.703			
8.00	1.767					3.82	1.847			
8.50	1.750					4.05	1.947			
9.00	1.823					4.20	2.053			

Roquefort		Brie		Camembert		Dorblu	
Extension, mm	*Force, N*	*Extension, mm*	*Force, N*	*Extension, mm*	*Force, N*	*Extension, mm*	*Force, N*
9.50	1.987			4.27	2.187		
9.71	2.067			4.33	2.267		
9.92	2.115			4.50	2.360		
				4.72	2.390		
				4.95	2.460		
				5.03	2.430		

This phenomenon aligns with information from the literature, which states that cheeses with white mold (such as Brie or Camembert) are generally softer than blue mold cheeses (such as Roquefort, Gorgonzola, or Stilton). Brie and Camembert have a creamy, soft texture, almost like butter, and are covered with a fine white mold crust. In contrast, blue mold cheeses, while they can also be creamy, are usually firmer and sometimes even crumbly. Dorblu cheese has a creamy but firm texture; it is not as soft as Brie or Camembert but also not as crumbly as some of the more mature blue mold cheeses.

Based on the measured values in the laboratory and summarized in Table 2, the graphs presented in Figures 3 and 4 were plotted.

From the analysis of the graphs in Figure 3, it is observed that for small displacements of the sample cylinder, the variation in resistant force as a function of the sample head displacement is relatively linear. This phenomenon was observed both for each of the three (or four) tests conducted and for their average.

The analysis of the graphs reveals that, for Brie cheese, the inclination of the regression line relative to the horizontal axis ranges between 44-47°, with a regression coefficient R^2 of over 0.994.

For Camembert cheese, the deformation is slightly higher for the same values of resistant force compared to the previous case, and the angle of the regression line relative to the deformation axis ranges from 25-27°, with a regression coefficient R2>0.992. In the case of Dorblu cheese, the regression lines for the three measurements show angles relative to the displacement axis between 58–63°, with a regression coefficient R^2>0.987. However, for the average values of the three measurements, the regression line shows an angle of 26.2°, with a correlation coefficient R2=0.994, which is as expected given the previously stated values.

All this occurs, however, for the considered units of measurement, namely mm for displacements and N for resistant forces, at small displacements of the test head, as mentioned earlier.

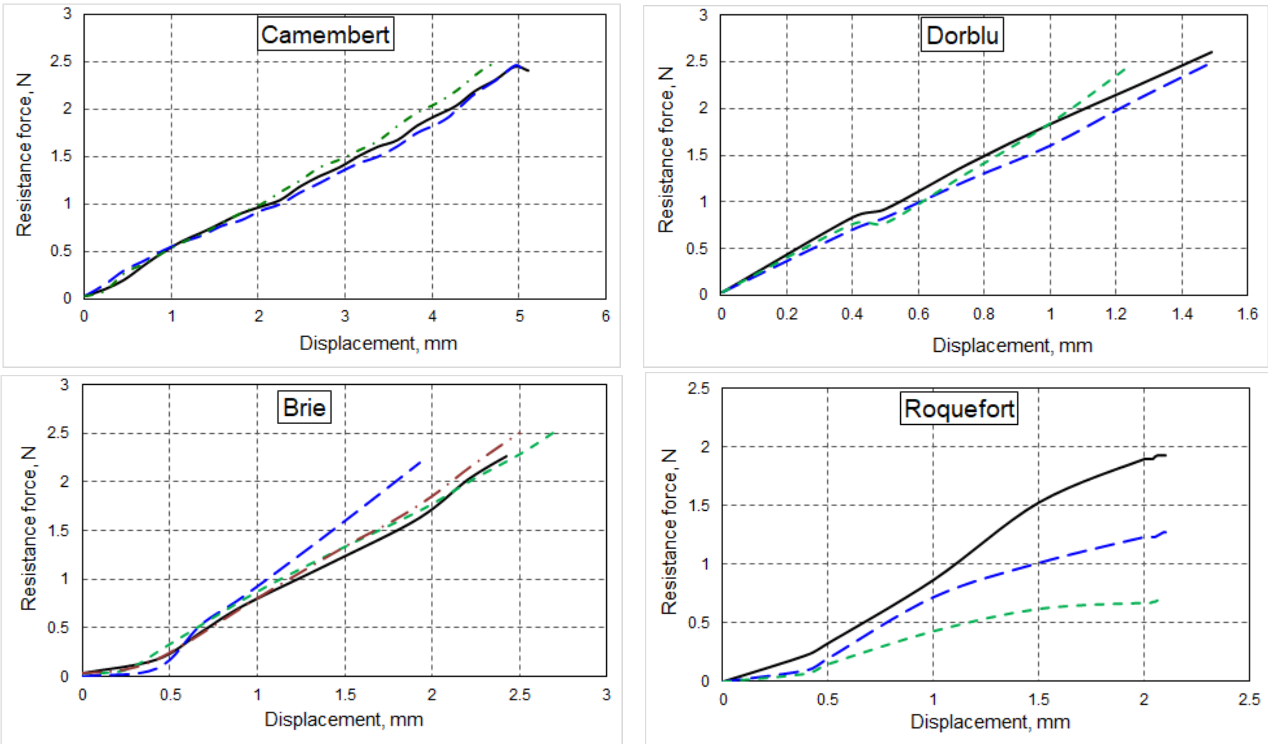

Fig. 3 – Resistive force correspondence – displacement for small displacement values, for the analyzed cheeses

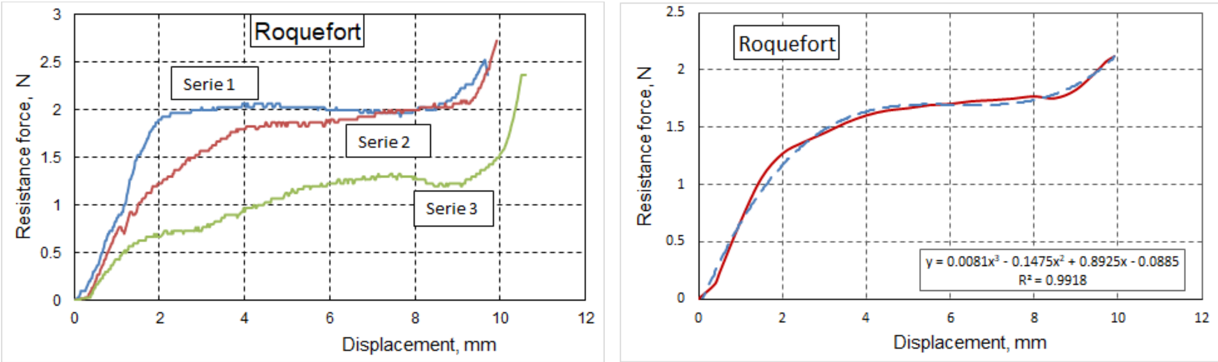

Fig. 4 – The final shape of the force-deformation (creep) curves for Roquefort mold cheese

For Dorblu cheese, the regression line equation for the average values of the three measurements has a correlation coefficient R^2=0.997, with a slope of 1.7254 and an intercept of 0.0278.

For Roquefort cheese, the situation is slightly more complex. A linear variation between displacement and the resistant force during pressing can only be observed at very small displacements of the test head. The angles in this part of the curves are less than 45°, specifically ranging between 19-44.5°, with a correlation coefficient R^2>0.970. This result reflects the texture of the cheese, which varies at different points on the samples.

However, in this type of cheese, the shape of the force-deformation curves is more sophisticated, initially presenting a relatively linear increase up to displacements of about 2-3 mm, followed by a relatively constant variation, with a pronounced increase in force in the final part of the curves, for small displacement variations.

Cheeses with mold have varied textures, and their reaction to a simple finger press can provide clues about the type and degree of ripeness of the cheese. When pressed, Brie or Camembert cheeses are quite soft and yield easily under pressure, but depending on the degree of ripeness, the center can be either firm or very creamy, almost liquid. The white mold crust may be slightly firmer, but it also yields under pressure, revealing the creaminess beneath.

In blue mold cheeses (Dorblu, Gorgonzola, Roquefort), the texture is firmer than in white mold cheeses, but they still yield easily under pressure, especially the creamier ones. However, more matured cheeses can be crumblier and denser. Generally, softer mold cheeses will yield easily under pressure, while more mature and dense ones will offer more resistance.

Mold cheeses react differently to various levels of pressure, depending on the type and degree of ripeness. Thus, the degree of ripeness plays an essential role in the cheese's reaction to pressure. Fresh cheeses are more elastic and yield more easily, while matured ones become denser and crumblier. The moisture content of the cheese also influences its reaction to pressure; moister cheeses (such as the less matured ones) will deform more easily and flow more quickly under pressure.

Under high pressure, Brie and Camembert cheeses will flatten significantly, and the creamy layer inside will flow freely, compromising the structure. In contrast, mature blue mold cheeses present resistance and will crumble or crack, with the texture becoming crumbly.

Analyzing the local pressures applied to the cheese samples, the contact surface with the cheese samples is approximately 51.5 mm², and the pressure levels range between 40 kPa (for Roquefort cheese) and 50 kPa (for Dorblu cheese). The pressure for the other two types of cheese falls within this range.

The pressure-deformation curves for mold cheeses reflect how these cheeses react to the application of pressure. Depending on the type of cheese and its degree of ripeness, the curves can vary considerably in terms of shape as well as values, as previously observed.

In white mold cheeses (Brie, Camembert), the curve initially has a steep slope (large deformation for small pressure), reflecting the fact that the cheese is very soft and yields easily. As the pressure increases, the curve flattens, the initial deformation becoming proportional to the applied pressure, with reduced elasticity. When the cheese reaches a critical point, the deformation increases rapidly as the structure gives way.

In blue mold cheeses (such as Dorblu), the curve is less steep than in soft cheeses (as seen in fig. 3), indicating greater resistance to pressure. However, there is still a zone where the cheese will begin to yield more quickly to increasing pressure, with the deformation also increasing.

If the regression curve of the average force-deformation values for Roquefort blue mold cheese is analyzed (fig. 4, right), it can be observed that the shape of the curve can be approximated by a third-degree equation. However, it is difficult to determine which parameters each coefficient of the mathematical expression depends on (structure, texture, moisture, ripening period, temperature, etc.).

As general observations, it can be said that softer cheeses have steeper pressure-deformation curves at the beginning, indicating easy deformation under small pressures, while in matured and denser cheeses, a more extensive elastic zone is found with more controlled deformation up to a critical point, after which a sudden failure occurs (as observed in fig. 4).

CONCLUSIONS

It can be stated that the physical-mechanical tests and analyses applied to cheeses, especially those with mold, are crucial for assessing their functionality and determining whether the technological process has been adequate.

The physical-mechanical characteristics of moldy cheeses depend not only on the manufacturing process but also on the conditions of maturation and subsequent storage.

When testing the rheological characteristics of these cheeses, especially through flow tests, the force-deformation curves show variations depending on the type of cheese and the maturation period. It should be noted, however, that the initial part of the curves is relatively linear, with a more or less steep slope that varies depending on the specific type of cheese.

The results obtained confirm that white mold cheeses (Camembert and Brie) are generally softer than blue mold cheeses (Roquefort and Dorblu). In the cutting tests, it was observed that soft cheeses with a higher water content and a lower degree of ripening, such as Camembert and Brie, exhibit increased elasticity and progressive deformation.

The flow tests can be used to adjust maturation parameters such as temperature, humidity, and duration to achieve the desired characteristics of the cheese. Flow tests are essential in the cheese industry for understanding and controlling the physical properties of the final product, thus contributing to maintaining its quality and uniformity.

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