QUALITY CHARACTERIZATION OF WINE CORK STOPPERS USING COMPUTER VISION

CARACTÉRISATION DE LA QUALITÉ DES BOUCHONS DE LIÈGE POUR BOUTEILLE DE VIN PAR ANALYSE D'IMAGE

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Abstract : Image analysis techniques were applied on the surface of wine cork stoppers (tops and lateral cylindrical surface) of seven commercial quality classes to characterize their porosity.
An increasing trend from the best to the worst quality classes was found for features related to area of pores (i.e. maximum length and width or pore maximum area) and concentration variables (i.e. porosity coefficient or number of pores per 100 cm^2). Shape variables were rather constant and mean values showed no differences between quality classes.
Variation of the pores characteristics within each quality class was large especially in the mid-quality range. Therefore there were no statistically significant differences to allow the isolation of the all quality classes and overlapping was particularly important in the medium-quality classes.
The reduction of grading into only three quality classes allowed to isolate statistically different subsets based on porosity coefficient and number of pores per 100 cm^2. These variables can be selected for further development into quality grades specification of wine cork stoppers.

Résumé : La surface de bouchons de liège de vin appartenant à sept classes de qualité commerciale a été étudiée par analyse d'image de la surface latérale et des bases pour caractériser leur porosité.
Les résultats montrent que les variables qui sont en relation avec la dimension des pores (i.e. longueur et largeur maximale ou superficie maximale) ou avec leur concentration (i.e. coefficient de porosité et nombre de pores par 100 cm^2) varient avec la classe de qualité et augmentent avec la diminution de la qualité. Les variables de forme des pores ont été constantes sans différences entre les classes de qualité. Par exemple, les bouchons de la classe de qualité Extra ont une porosité moyenne de 1.4 % pour la surface latérale avec des pores de 3.1 mm^2, et avec une largeur ou longueur de 3.1 mm, alors que les bouchons de la deuxième classe de qualité ont 4.2 % de porosité avec pores de 8.7 mm^2, 5.3 mm de largeur et 4.6 mm de longueur, et les bouchons de cinquième classe de qualité ont 6.2 % de porosité et pores avec 26.5 mm^2, 7.3 mm de largeur et 11.9 mm de longueur.
Dans chaque classe de qualité les différentes variables ont une grande variabilité, particulièrement dans les classes moyennes. Cette variabilité entre bouchons de la même classe surpasse dans beaucoup de cas la variabilité entre classes de qualité qui ne se montrent donc pas différentes statistiquement.
La porosité mesurée par le coefficient de porosité est en relation avec la superficie maximale des pores (r= 0.837) et avec le diamètre maximal (r = 0.849) des bases des bouchons et avec le nombre des pores par 100 cm^2 (r = 0.809) de la surface latérale des bouchons.
La réduction du nombre de classes de qualité des bouchons à seulement trois classes permet d'obtenir des différences statistiquement significatives entre classes utilisant comme variables de caractérisation le coefficient de porosité et nombre de pores par 100 cm^2. Ces variables peuvent être sélectionnées pour le développement futur de spécifications de qualités de bouchons de liège.

Keywords: wine cork stoppers, quality classes, computer image vision analysis, pores, porosity

Mots clés : bouchons de liège, classe de qualité, analyse d' image, pores, porosité

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J. Int. Sci. Vigne Vin, 2005, **39**, n°4, 209-218

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INTRODUCTION

Natural cork stoppers are an unmatched closure in quality wines undergoing bottle aging. Cork is the outer bark of cork oaks (*Quercus suber* L.) where it forms a continuous layer with an appreciable thickness that surrounds stems and branches (GRAÇA and PEREIRA, 2004). It is a cellular material, chemically stable, and with specific properties e.g. combining low density and permeability to liquid and gases with high compressibility and recovery (FORTES *et al*., 2004; PEREIRA, 1988; PEREIRA *et al*., 1987), that have given cork a worldwide recognition as a wine bottle sealing.

In the industrial processing, the raw cork planks are visually appreciated by skilled operators and graded into classes with homogeneous thickness and quality (COSTA and PEREIRA, 2004). Quality depends on the extent of the natural porosity and on the presence of defects (GONZALEZ-ADRADOS and PEREIRA, 1996; PEREIRA *et al.*, 1996; GONZALEZ-ADRADOS *et al*., 2000). The final products such as discs and stoppers of natural cork are also classified into several quality classes using electronic equipments that apply image analysis techniques for detection and measurement of pores. Stoppers or discs of good quality classes have only few pores with small dimensions and no cracks nor holes due to insect damages while poor quality classes are aesthetically less appealing showing an increased porosity, discontinuities and enlarged areas of wood inclusions (RADEVA *et al.*, 2002; CHANG *et al.*, 1997).

The quality classification of wine cork stoppers is the economic most important task in the industrial processing due to the price difference between classes, i.e. extra quality stoppers may be up to ten times more expensive than 4th cork quality stoppers (PEREIRA *et al*, 1994). In spite of this, the commercial classification has not yet quantified the quality parameters and grading in the cork industry has no standard criteria (CHANG *et al*., 1997). The classification usually results from contract agreements based on reference samples (LOPES and PEREIRA, 2000).

Classification is a practical pattern recognition problem with identification of defects e.g. pores, by extraction from the cork mass background with image thresholding and quantification of geometrical and distribution features. Several studies have investigated the use of image analysis techniques for quantification of porosity in cork planks (GONZALEZ-ADRADOS *et al*., 2000; GONZALEZ-ADRADOS and PEREIRA, 1996; PEREIRA *et al*., 1996; MOLINAS and CAMPOS, 1993) and in cork discs (LOPES and PEREIRA, 2000). So far, characterization of the surface porosity on natural cork stoppers has not been published.

This paper presents the results on the use of image analysis techniques applied to the surface of cork stoppers of seven commercial quality classes in order to analyze differences among quality classes and to identify the features that determine the cork grading. This is a prospective study that looks forward towards the adoption of a standard quality classification of stoppers in the cork and wine industries.

MATERIALS AND METHODS

I - DATA COLLECTION

A set of 168 wine cork stoppers (24 mm x 45 mm, diameter x length) from a cork industry were used, distributed equally into seven quality classes: Extra, Superior, First, Second, Third, Fourth and Fifth (24 cork stoppers in each class). These cork stoppers were carefully graded into the seven quality classes by sampling after inspection in the automated vision system in the cork industry and subsequent selection by two skilled operators. Figure 1 exemplifies the differences between the stoppers of the seven quality classes.

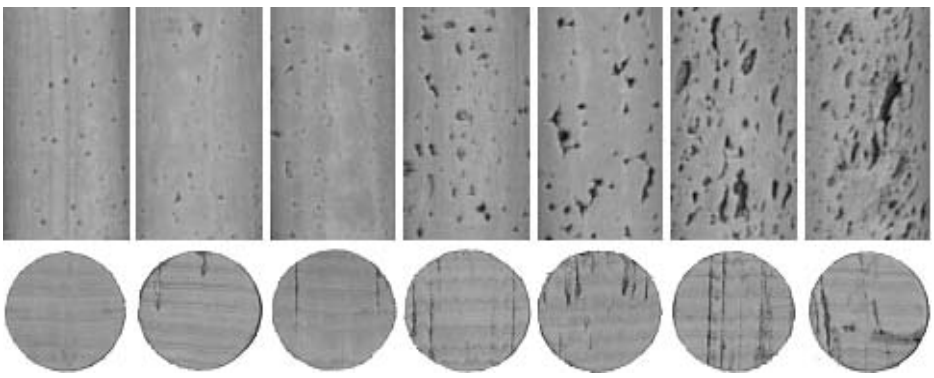


Figure 1 - Cylindrical surface (bodies) and tops of cork stoppers from seven quality groups ordered from best (Extra) to worst (5th) quality (from left to right)

Surface latérale et bases des bouchons de liège de sept classes de qualité de la meilleure qualité (Extra) à la pire qualité (5e) (de gauche à droite)

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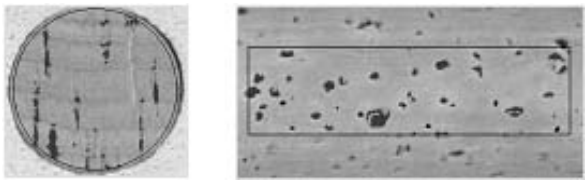


Figure 2 - Frames used for image analysis measurements in the top (circular) and body (rectangular) of the cork stopper with an overlay of pores detection based on thresholding.

Cadres utilisés en analyse d'image pour les bases (cercle) et le corps (rectangle) des bouchons de liège superposés avec la détection de pores faite par limite de couleur.

II - IMAGE ACQUISITION AND PROCESSING

The image surface of the body of cork stoppers (cylindrical lateral surface) and of the tops (circular bases) was acquired with a CCD-IRIS/RGB camera in an acquisition Kaiser RS1 Board with a controlled illumination apparatus, connected to a computer that processes the image using Analysis® software (version 3.2). Four frames of the body of each cork stopper were acquired, the first perpendicular to the cork growth rings (as observed in the tops of the cork stoppers) and the other three subsequently taken in perpendicular sections by rotating the stopper 90º in the right direction. The frames totalled 1668 mm^2 corresponding to 50 % of the total area of the stopper's body. Two circular frames were taken for the two tops totalling 782 mm^2 and covering 86 % of the tops total area (figure 2).

Optimal conditions for visualization and thresholding were selected to acquire images for each cork stopper such as illumination compensation and orthogonal position correction with the longest axis (height) along the X-axis. The maximum and minimum gray-levels of pixel intensity for defects extraction from the cork mass in image thresholding on cylindrical body and on tops were, respectively: Red 143-163 and 126-164; Green 135-158 and 114-156 and Blue 120-143 and 118-161.

III - DATA ANALYSIS

A set of variables was collected from the image analysis characterizing the dimension, shape and concentration of the pores in the cork stoppers body and top.

The dimension type variables included: area (A, mm^2), width (e, mm), length (L, mm), diameter (D, mm) defined as the orthogonal distance between two parallel lines that completely include the pore and the equivalent diameter (Deq, mm) defined as the diameter of the circle that has an area equal to the area of the pore $Deq = 2.\sqrt{\frac{area}{\partial}}$.

The shape type variables considered were: shape factor (sf), defined as $4\pi . area / perimeter^2$ measuring the roundness of the pores, esfericity (ϕ) that describes the elongation of the pore by using central moments (value 1 for a perfect circular particle) and aspect ratio (ar) as the maximum ratio between width and length of a bounding rectangle of the pore.

The concentration type variables included the next neighbour distance (nnd, mm), defined as the distance to the closest pore.

These data were filtered, and only pores with an area equal or superior to 0.5 mm^2 were kept for analysis because small porosity is functionally and aesthetically irrelevant and only brings higher variance and variability to the sample (LOPES and PEREIRA, 2000 ; GONZALEZ-ADRADOS and PEREIRA, 1996; PEREIRA *et al.*, 1996).

Each cork stopper was characterized in relation to tops and body by several calculated variables: porosity coefficient (ε, %), defined as the percentage of pore area of the total frame area and total number of pores per 100 cm^2 (N, no/100 cm^2).

All of the variables collected from the image analysis for each pore were averaged and transformed into cork stopper top and body variables. For dimension variables maximum values were also calculated: maximum area of pores (A_{max}, mm^2), maximum width of pores (e_{max}, mm), maximum length of pores (L_{max}, mm), and maximum equivalent diameter (Deq_{max}, mm).

The statistical analysis used the exploratory analysis of data and the multisample hypotheses one-way analysis of variance included in the SSPS® package searching for the characterization of pore features in relation to the commercial classification.

RESULTS

I - CHARACTERIZATION OF CORK STOPPERS FEATURES

The values obtained for the main pore variables in the seven quality classes of the cork stoppers are summarized in tables I, II and III respectively for dimension, shape and concentration variables. The values of most variables, namely of dimension and concentration variables (tables I and III), differed between the quality classes, with stoppers in the best classes showing less and smaller pores. The variation between stoppers in the same quality class was large as seen by the values of the standard deviation for most variables.

In the cylindrical bodies of the cork stoppers most of the dimension and concentration variables showed an increasing trend from the Extra to the 5th quality class without exceptions, and in the tops the increasing trend of variables with the decreasing quality was similar except for the 4th and the 5th quality class where the maximum area of pore decreased from 19.4 mm^2 to 12.2 mm^2.

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Table I - Mean and standard deviation (in brackets) of pore dimension variables of the body and top surfaces of cork stoppers discriminated by quality classes

Moyenne et écart type (entre parenthèse) des variables de dimension des pores mesurées sur la surface latérale et sur les bases des bouchons de liège de différentes classes de qualité

Cork stopper variable	Cork stopper quality class						
	Extra	Superior	1st	2nd	3rd	4th	5th
Body							
A_{max} (mm^2)	3.1 (1.7)	5.7 (2.9)	5.8 (3.3)	8.7 (3.5)	11.4 (6.6)	13.4 (6.6)	26.5 (26.2)
L_{max} (mm)	3.1 (1.3)	3.5 (1.1)	4.3 (1.6)	4.6 (1.4)	6.5 (2.9)	7.7 (3.4)	11.9 (7.8)
e_{max} (mm)	3.1 (1.1)	4.9 (2.2)	4.4 (1.5)	5.3 (1.7)	6.1 (2.1)	6.1 (2.2)	7.3 (2.4)
D_{mean} (mm)	1.6 (0.2)	1.8 (0.2)	1.9 (0.2)	2.1 (0.3)	2.1 (0.3)	2.2 (0.3)	2.5 (0.6)
Deq_{max} (mm)	1.9 (0.5)	2.6 (0.6)	2.6 (0.7)	3.3 (0.7)	3.7 (1.0)	4.0 (1.0)	5.3 (2.4)
Top							
A_{max} (mm^2)	3.5 (3.5)	7.4 (6.2)	7.0 (5.6)	9.1 (5.6)	10.8 (7.4)	19.4 (15.4)	12.2 (8.0)
L_{max} (mm)	6.4 (5.1)	9.6 (6.3)	9.1 (4.9)	10.7 (5.6)	11.7 (4.3)	13.8 (5.0)	12.0 (5.4)
e_{max} (mm)	1.5 (0.7)	2.1 (1.1)	2.5 (1.2)	2.8 (1.1)	4.1 (2.6)	4.2 (1.9)	3.6 (2.0)
D_{mean} (mm)	3.0 (1.6)	4.3 (2.5)	3.5 (1.1)	3.4 (1.1)	3.7 (1.1)	3.8 (1.2)	3.8 (1.2)
Deq_{max} (mm)	1.9 (0.9)	2.8 (1.2)	2.8 (1.1)	3.3 (1.0)	3.6 (1.1)	4.7 (1.8)	3.7 (1.3)

Table II - Mean and standard deviation (in brackets) of pore shape variables of the body and top surfaces of cork stoppers discriminated by quality classes

Moyenne et écart type (entre parenthèse) des variables de forme des pores mesurées sur la surface latérale et sur les bases des bouchons de liège de différentes classes de qualité

Cork stopper variable		Cork stopper quality class						
		Extra	Superior	1st	2nd	3rd	4th	5th
Body	sf_{mean}	0.6 (0.1)	0.6 (0.1)	0.6 (0.1)	0.6 (0.1)	0.6 (0.1)	0.5 (0.1)	0.5 (0.1)
	ϕ_{mean}	0.3 (0.1)	0.3 (0.1)	0.3 (0.1)	0.3 (0.1)	0.3 (0.1)	0.3 (0.1)	0.3 (0.1)
	ar_{mean}	1.9 (0.2)	2.1 (0.2)	2.2 (0.4)	2.2 (0.3)	2.1 (0.3)	2.3 (0.3)	2.3 (0.3)
Top	sf_{mean}	0.4 (0.1)	0.3 (0.1)	0.3 (0.1)	0.4 (0.1)	0.4 (0.1)	0.4 (0.1)	0.5 (0.1)
	ϕ_{mean}	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	0.2 (0.1)	0.2 (0.1)	0.2 (0.1)	0.1 (0.1)
	ar_{mean}	3.9 (1.2)	4.4 (1.6)	4.0 (1.0)	3.5 (0.7)	3.8 (1.1)	3.4 (0.6)	3.8 (0.9)

Table III - Mean and standard deviation (in brackets) of pore concentration variables of the body and top surfaces of cork stoppers discriminated by quality classes

Moyenne et écart type (entre parenthèse) des variables de concentration des pores mesurées sur la surface latérale et sur les bases des bouchons de liège de différentes classes de qualité

Cork stopper variable		Cork stopper quality class						
		Extra	Superior	1st	2nd	3rd	4th	5th
Body	ε_{mean} (%)	1.4 (0.8)	2.1 (0.8)	2.5 (1.1)	4.2 (1.8)	4.5 (1.4)	5.7 (2.5)	6.2 (2.8)
	N (no/100 cm^2)	128 (61)	176 (61)	151(61)	254 (58)	260 (59)	281 (58)	242 (59)
	nnd_{mean} (mm)	2.2 (0.5)	2.4 (0.5)	2.3 (0.3)	2.0 (0.6)	2.1 (0.2)	2.1 (0.3)	2.1 (0.4)
Top	ε_{mean} (%)	1.1 (0.8)	1.7 (1.0)	2.2 (1.6)	4.0 (2.6)	4.3 (1.8)	8.2 (4.2)	4.7 (3.0)
	N (no/100 cm^2)	66 (35)	66 (34)	96 (33)	159 (31)	170 (31)	258 (33)	162 (33)
	nnd_{mean} (mm)	2.1 (1.1)	2.5 (0.7)	2.2 (0.5)	1.8 (0.4)	1.9 (0.6)	1.8 (0.4)	2.1 (0.5)

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For bodies the largest pore was on average 3.1 mm^2 and 26.5 mm^2 for Extra and 5th quality classes respectively (table I), and the maximum length of pores corresponded to 6.8 % of the total length of the cork stopper for the Extra quality class (3.1 mm in 45 mm), to 10.2 % (4.6 mm) for the 2nd quality class and 26.4 % (11.9 mm) for the worst quality class.

No trend from best to worst quality class was found for the values of esfericity, aspect ratio and shape factor both in tops and in bodies of cork stoppers (table II).

The porosity coefficient in bodies was 1.4 %, 4.2 % and 6.2 % respectively for the Extra, 2nd and 5th classes. The total number of pores per 100 cm^2 ranged between 128 and 281, respectively for Extra and 4th quality classes (table III). In the tops the porosity coefficient ranged between 1.1% (Extra) and 8.2 % (4th class) and the total number of pores increased from 66 and 258 pores per 100 cm^2, respectively from Extra to the 4th class (table III).

The variation range with quality class of maximum pore area and porosity coefficient in tops and in bodies was similar while the number of pores presented a larger

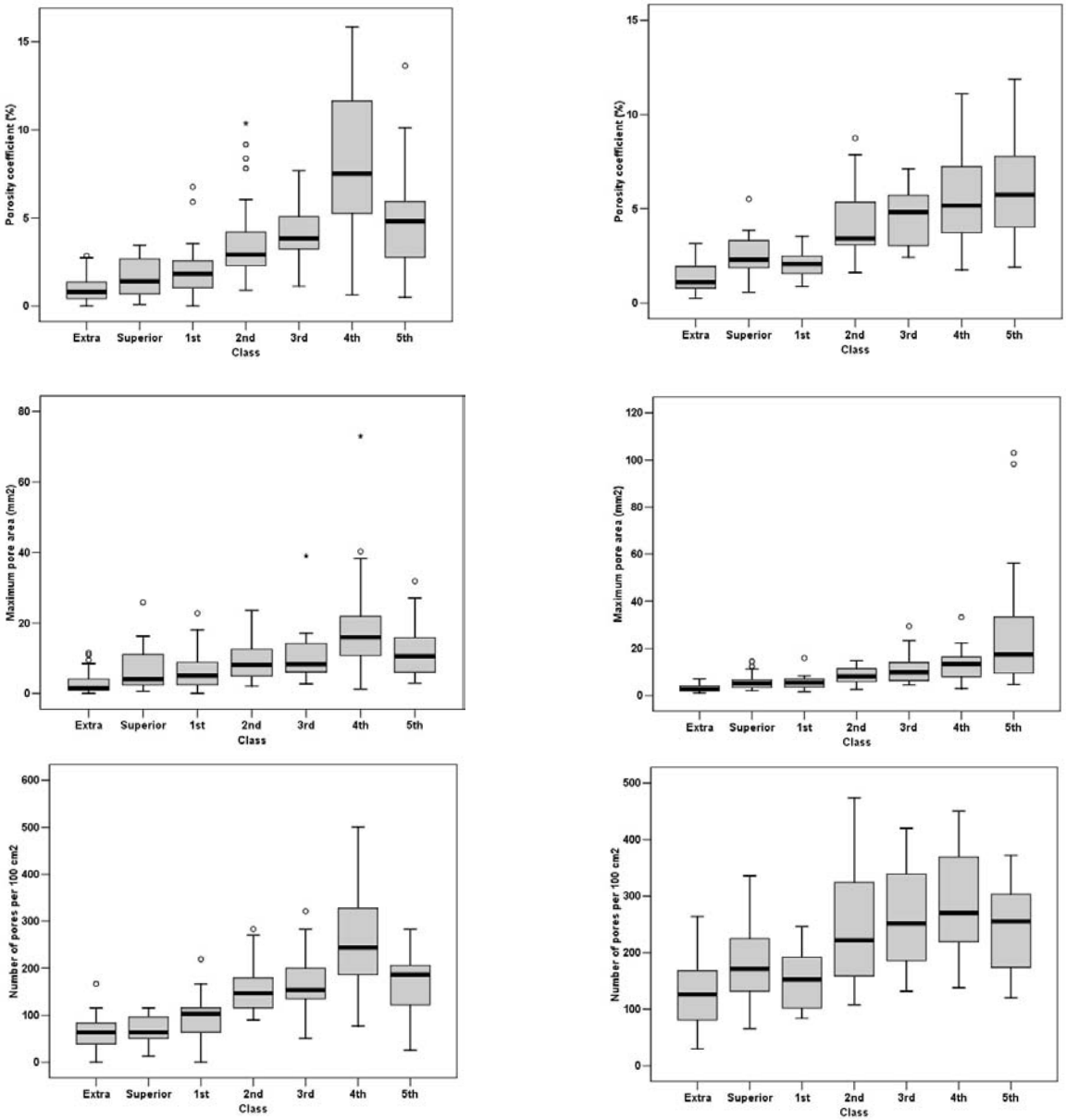


Figure 3 - Box plots of porosity coefficient (ε), maximum pore area (Amax) and number of pores per 100 cm^2 (N), for the seven quality classes. Left: Cork stoppers tops. Right: Cork stoppers bodies or cylinder surfaces

Représentation du coefficient de porosité (ε), de la superficie maximale des pores (Amax) et du nombre de pores par 100 cm^2 (N), pour les sept classes de qualité. Gauche : bases des bouchons de liège. Droite : superficie latérale des bouchons de liège

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Table IV - Pearson's correlation coefficient (r) between variables for cork stoppers tops and bodies. * and ns indicate significance at P < 0.05 and not significant, respectively.

Coefficient de correlation de Pearson (r) entre variables des bases et de la surface latérale des bouchons de liège. * et ns indiquent la significance pour P < 0.05 et non significative, respectivement.

	Cork stopper variable	ε	N	nnd_{mean}	A_{max}	L_{max}	e_{max}	Deq_{max}
_	ε	1.000						
	N	0.757*	1.000					
	nnd_{mean}	-.276*	-.397*	1.000				
Top	A_{max}	**0.837***	0.465*	-.167*	1.000			
	L_{max}	0.686*	0.374*	-.125 ns	0.712*	1.000		
	e_{max}	0.707*	0.492*	-.201*	0.694*	0.465*	1.000	
	Deqmax	**0.849***	0.512*	-.162*	0.955*	0.831*	0.703*	1.000
	ε	1.000						
	N	0.809*	1.000					
	nnd_{mean}	-.387*	-.173*	1.000				
Body	A_{max}	0.686*	0.258*	-.163*	1.000			
	L_{max}	0.658*	0.272*	-.169*	0.821*	1.000		
	e_{max}	0.548*	0.343*	-.060 ns	0.515*	0.290*	1.000	
	Deq_{max}	0.776*	0.387*	-.173*	0.645*	0.814*	0.645*	1.000

Table V - Pearson's correlation coefficient (r) for three cork stoppers variables, porosity coefficient (ε), maximum pore area (A_{max}) and number of pores per 100 cm^2 (N) discriminated by tops and bodies features and by cork quality classes.* and ns indicate significance at P < 0.05 and not significant, respectively.

Coefficient de corrélation de Pearson (r) pour trois variables caractérisant les bouchons de liège, coefficient de porosité (ε), superficie maximale des pores (A_{max}) et nombre de pores par 100 cm^2 (N) discriminées entre bases et surface latérale des bouchons de liège et entre classes de qualité. * et ns indiquent la significance pour P < 0.05 et non significative, respectivement.

Cork stopper variable	Cork quality classes							
	Extra	Superior	1st	2nd	3rd	4th	5th	Total
ε	0.692*	0.205	0.156	0.689	0.333	0.609*	0.594*	0.704*
A_{max}	0.471*	0.405*	0.093	0.193	0.110	0.121	0.102	0.222
N	0.205	0.286	0.135	0.616*	0.151	0.262	0.584*	0.559*

variation range for bodies in relation to tops (figure 3). The amplitude of variation increased in the worst qualities, as seen for pore maximum area.

The linear correlation between variables in tops and bodies is shown in table IV. All dimension variables e.g. maximum equivalent diameter and pore maximum area have high linear correlation coefficients with the other variables. Only the mean next neighbor distance has not significant correlation values at a significance level of 0.05 (table IV).

In tops the porosity coefficient presents the highest linear correlation coefficient with maximum pore area and with the maximum equivalent diameter, respectively 0.837 and 0.849. In bodies the porosity coefficient shows the highest linear correlation with the number of pores, 0.809 (table IV).

The linear correlation between tops and bodies of three selected variables, porosity coefficient, maximum pore area and number of pores per 100 cm^2 showed higher statistical significant values for the porosity coefficient (r = 0.704) (table V). When discriminated by quality classes, the porosity coefficient shows a stronger linear correlation between tops and bodies in the extreme classes (Extra, 4th and 5th). The maximum pore area showed a strong linear correlation only in the Extra and Superior classes and the number of pores in mid and poor quality classes (2nd and 5th class). A large variability of cork stoppers features occurred in all the in-between quality classes, thereby weakening the linear correlation coefficient.

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II - COMPARISON BETWEEN QUALITY CLASSES

The ANOVA tests performed for tops and bodies for features like porosity coefficient, maximum pore area, number of pores per 100 cm^2, maximum width and length and equivalent diameter showed that the null hypothesis was rejected at all cases, that is, it was concluded that there were significant statistical differences between wine cork stoppers quality classes. Tukey's multiple comparison tests showed which means significantly differ at an alpha level of 0.05 and homogeneous subsets were achieved for each feature (figure 4).

Figure 4 shows a graphical representation of the Tukey's multiple comparison tests. For each variable, a line links the classes that are not statistically different from each other. As it can be observed the distinction between quality classes was not possible with either variable and significant overlapping between classes occurred.

Therefore in cork stoppers body surface the number of pores per 100 cm^2 showed only two statistically different groups $\mu_{Extra} = \mu_{Superior} = \mu_{1st} \neq \mu_{2nd} = \mu_{3rd} = \mu_{4th} = \mu_{5th}$, and classification of stoppers based on number of pores allows only to differentiate one better quality group constituted by Extra, Superior and 1st quality class and a second group by 2nd to 5th classes (figure 4). The porosity coefficient allowed a better quality grouping including Extra and Superior quality classes but no further discrimination was made in 1st to 5th class, $\mu_{Extra} = \mu_{Superior} \neq \mu_{1st} = \mu_{2nd} = \mu_{3rd} \neq \mu_{5th}$. A major overlapping of dimension variables like width was found in the mid classes, i.e. 1st to 3rd.

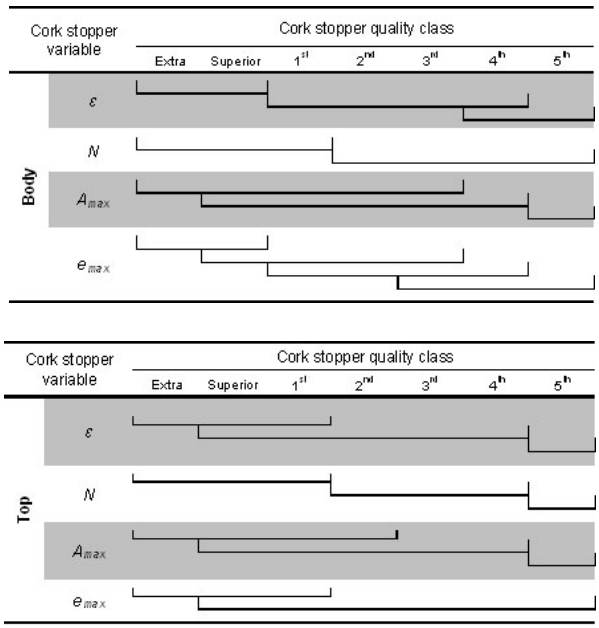


Figure 4 - Summary of Tukey's multiple comparison tests for pore variables of cork stoppers classified in seven quality classes. Classes linked by the same line cannot be differentiated using Tukey test at $\alpha = 0.05$

Résultat de la comparaison multiple de Tukey pour les variables des pores des bouchons de liège groupé en sept classes de qualité. Les classes liées par la même ligne ne peuvent pas être différenciées par le test Tukey avec $\alpha = 0.05$

In wine stoppers tops, the 4th class was isolated by mean differences in maximum pore area, porosity coefficient and number of pores per 100 cm^2. Similarly to bodies, a major overlapping occurred in dimension variables like maximum width in all the in-between classes (figure 4). The number of pores per 100 cm^2 showed three main groups: Extra, Superior and 1st as the best quality group, 2nd, 3rd and 5th as a middle quality group and the 4th class, as the worst quality group $\mu_{Extra} = \mu_{Superior} = \mu_{1st} \neq \mu_{2nd} = \mu_{3rd} = \mu_{5th} \neq \mu_{4th}$ (figure 4).

Due to the low statistically significant discrimination between classes given by multiple comparison tests in tops and in bodies, the initial sample of cork stoppers was regrouped in only three classes: a superior quality class (Extra + Superior + 1st), a medium quality class (2nd + 3rd) and an inferior quality class (4th + 5th). The Tukey's test was again applied to those three classes using the same sample size as previously (24 cork stoppers per class, randomly selected).

The ANOVA tests showed that there were significant statistical differences between these three quality classes of wine cork stoppers. The Tukey's multiple comparison tests were also conclusive and showed that, for tops and bodies, the mean values for the features porosity coefficient and pore maximum area for the three classes were significantly different (at an alpha level of 0.05). It means that when considering only three cork quality classes for tops and bodies there were significant differences between the population means for porosity coefficient, $\mu_{Superior} \neq \mu_{Medium} \neq \mu_{Inferior}$ (figure 5).

In bodies there is a significant difference among population means of the superior class and the Inferior class. Medium class presented for features like number of pores per 100 cm^2 and maximum width significantly differences with the Superior class, $\mu_{Superior} \neq \mu_{Medium} = \mu_{Inferior}$ (figure 5).

Tops were also significantly different among the three classes for the number of pores per 100 cm^2 ($\mu_{Superior} \neq \mu_{Medium} \neq \mu_{Inferior}$) but in relation to maximum width no conclusions could be made on how the medium class is related to Superior and Inferior classes since no subsets were achieved (figure 5). In addition, maximum pore area in bodies and in tops showed that there were also significant differences among the three classes and two

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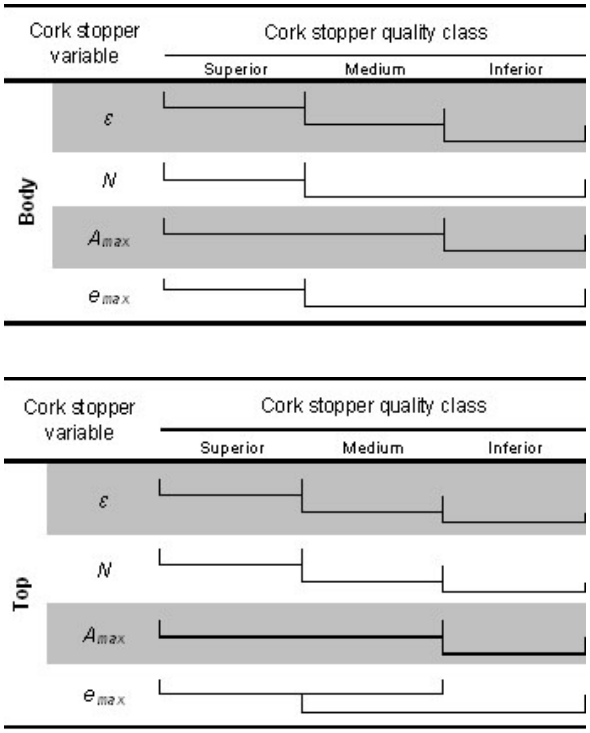


Figure 5 - Summary of Tukey's multiple comparison tests for pore variables grouped in three quality classes: Superior (Extra, Superior and 1st), Medium (2nd and 3rd) and Inferior (4th and 5th). Classes linked by a line cannot be differentiated using Tukey test at $\alpha = 0.05$

Résultat de la comparaison multiple de Tukey pour les variables des pores des bouchons de liège groupés en trois classes de qualité: Supérieure (extra, supérieure and 1ère), Moyenne (2e et 3e) et Inférieure (4e et 5e). Les classes liées par la même ligne ne peuvent pas être différenciées par le test Tukey avec $\alpha = 0.05$

subsets were achieved ($\mu_{Superior} = \mu_{Medium} \neq \mu_{Inferior}$) (figure 5).

DISCUSSION

The surface porosity shown by wine cork stoppers appears macroscopically differently in tops and in the lateral cylindrical surface, in this case also showing a radial variation. This results from the structural anisotropy of the cork planks and from the direction of boring of stoppers in the cork planks, which is made following a tree axial direction (FORTES *et al*., 2004). Therefore the tops of wine stoppers represent transversal sections of cork, while the lateral body contains two tangential sections (tangential to the growth rings), two radial sections (perpendicular to the rings) and all in-between sections (PEREIRA *et al.*, 1987).

The porosity characteristics of these sections were previously described for cork planks (FERREIRA *et al.*, 2000; GONZALEZ-ADRADOS *et al.*, 2000; PEREIRA *et al.*, 1996) and in general are related to the radial development of the lenticular channels in the cork of the living tree (GRAÇA and PEREIRA, 2004). The features of pores found in this study in the wine stoppers (tables I, II and III) agree with the general characteristics given previously for cork regarding dimensions, shape and concentration.

When considering different quality classes of wine stoppers it was found that the features of pores related to dimensions and concentration (i.e. porosity coefficient, linear dimensions, number) show a general gradation from best to worst qualities both in tops and in the lateral surface of bodies.

The surface features found in the wine stoppers of different qualities are comparable in order of magnitude to values published for cork planks of different qualities. For instance, Extra quality stoppers will have in their bodies a mean porosity of 1.4 % resulting from pores smaller than 3.1 mm^2, and 3.1 mm in width or length, while 2nd quality stoppers have 4.2 % porosity with pores less than 8.7 mm^2, 5.3 mm in width and 4.6 mm in length, and the 5th quality stoppers have 6.2 % porosity and pores up to 26.5 mm^2, 7.3 mm wide and 11.9 mm long (tables I and III). These results are in accordance to those referred by PEREIRA *et al.* (1996) for the tangential section of cork planks: a porosity coefficient between 3.3 % and 6.7 % and the largest pore area between 3.9 mm^2 and 26.3 mm^2.

As regards to tops, the Extra, 2nd and 4th class wine stoppers have mean porosities of 1.1 %, 4.0 % and 8.2 %, respectively, and the stoppers of all others quality classes are characterized by features with in-between values. These results are also in accordance to LOPES and PEREIRA (2000) who reported for the transversal section of cork porosity coefficient between 2.5 % and 8.0 % and to GONZALEZ-ADRADOS *et al.* (2000) who referred a somewhat larger interval of variation of 2.1 - 16.4 %.

In relation to the total number of pores per 100 cm^2 the results found here are similar to those reported by PEREIRA *et al.* (1996): maximum and minimum values of 13 and 292 per 100 cm^2 for the tangential section and 49 and 170 per 100 cm^2 for the transversal section of cork planks.

Several authors studied the use of the porosity coefficient to compare quality grades in cork planks or cork products and concluded that this variable could be a good indicator of cork quality. For instance, LOPES and PEREIRA (2000) concluded that it could be applied for the quality grading of champagne cork stoppers and

PEREIRA *et al.* (1996) used it as a sorting parameter for establishing cork planks quality classes.

The porosity, expressed by the porosity coefficient, is mostly correlated with maximum pore area, and with maximum equivalent diameter in bodies and with the number of pores in tops (table IV). The correlation between the porosity shown by tops and bodies (table V) showed an overall significant correlation (r=0.704) although stopper variation is important, especially in medium quality classes.

The porosity is higher and more variable in the lateral bodies than in tops (figure 3). This is a result of the intrinsic variability of cork and the difference in the area observed by image analysis, which is higher for the lateral surface than for tops. In the tops, only the tangential variation of cork is accounted for (corresponding to an observation of a 24 mm, as given by the diameter). In the body, in addition to this tangential variation, there is also an axial variation (corresponding to the 45 mm height of the stopper). The importance of dimension of the observed area for porosity determinations by image analysis was previously addressed for cork planks (PEREIRA *et al.*, 1996) that found a large variation within planks and advised a minimum area of observation of 225 cm^2 to classify cork planks.

The discrimination between seven (Extra to 5th) quality classes of wine stoppers using selected pore features was not statistically significant and a large overlapping due to between stoppers variability within the same class was present especially in the mid-quality range (figure 4).

In general, the different variables only allowed separating two or three quality groups (figure 4). The discussion on the poor discrimination between quality classes was previously made for cork planks and a reduction of grading into only three quality classes was proposed (GONZALEZ-ADRADOS and PEREIRA, 1996; BARROS and PEREIRA, 1987). This is largely the practice at present in the industrial units that commercialize cork planks, who make only good, medium and poor quality assortments. This was also tested in this study for the wine cork stoppers by grouping them in only three quality grades. A statistically more consistent classification was obtained based on features like porosity coefficient (figure 5).

Regardless of the commercial strategies and of the actual industrial practice of cork grading which is known to be far from objective and consistent (RADEVA *et al.*, 2002; CHANG *et al.*, 1997; BARROS and PEREIRA, 1987), this study aimed at analyzing the surface features of cork stoppers as given by image analysis that are relevant to their quality classification. The total area of pores, translated into a porosity coefficient and the maximum pore area were variables that proved relevant for quality estimation, while shape factors of pores or their density had no significance. These variables can therefore be selected for further development into prospective quantified quality grade specifications of wine cork stoppers.

CONCLUSIONS

Seven wine cork stoppers quality classes were characterized in regard to their porosity using image analysis techniques applied to tops and bodies. From best to worst, a general gradation was found for features related to dimensions of pores like pore area, width or length and concentration variables like porosity coefficient (porosity) or number of pores per 100 cm^2. Only shape variables were rather constant.

Variation of the pores characteristics within each quality class was large especially in the mid-quality range where the overlapping was particularly important. Therefore the statistically significant isolation of the seven quality classes could not be made based on any of the pore dimension or concentration features.

The reduction of the number of quality classes from seven to only three allowed a better isolation of different subsets. Grading natural cork stoppers into three quality classes was possible based on the porosity represented by porosity coefficient or number of pores per 100 cm^2. These variables could be selected for further development into quality grade specification of wine stoppers.

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Manuscrit reçu le 15 juin 2005 ; accepté pour publication, après modifications le 5 décembre 2005

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