NATURAL VARIABILITY OF SURFACE POROSITY OF WINE CORK STOPPERS OF DIFFERENT COMMERCIAL CLASSES

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Abstract

Aim : The aim of this study was to characterize the variability and to quantify the surface porosity of wine cork stoppers of different quality classes.

Methods and results : The porosity of 300 cork stoppers was characterized by image analysis on the lateral surface and tops. Porosity coefficient was 2.4 %, 4.0 % and 5.5 % for premium, good and standard stoppers, respectively. The lateral surface of stoppers was heterogeneous with respect to porosity features : the tangential regions presented higher porosity while the radial regions had larger pores.

Conclusion : The quality classes of cork stoppers can be differentiated by the mean values of the main porosity features of their surface. There is a natural heterogeneity of the porosity features over the external surface of cork stoppers that can be traced back to the biological basis of cork formation and the production process.

Significance and impact of the study : Natural cork stoppers are the premium product of the cork industry, with worldwide recognition of quality and performance as wine sealant. Due to the large sampling and detailed observation, the results presented in this study may be used for reinforcing quality requirements, e.g., with definition of standards to improve the classification system. A better understanding of cork intrinsic variability and of the anisotropy of porosity features shown by cork stoppers is important for performance development.

Key words : natural cork stoppers, quality classes, porosity, image analysis, lateral surface

Résumé

Objectif : L'objectif de ce travail a été de caractériser la variabilité et de quantifier la porosité de la surface des bouchons de liège de différentes catégories de qualité.

Méthodes et résultats : La porosité de 300 bouchons de liège a été caractérisée par analyse d'images de la surface latérale et des deux bases circulaires. Le coefficient de porosité était 2.4 %, 4.0 % et 5.5 %, respectivement pour les bouchons de qualité première, bonne et standard. La surface latérale des bouchons était hétérogène par rapport aux caractéristiques de porosité : les régions tangentielles présentaient une porosité plus élevée tandis que les régions radiales avaient des pores plus grands.

Conclusion : Les catégories de qualité des bouchons de liège peuvent être différenciées par les valeurs moyennes des caractéristiques principales de la porosité de leur surface. Les caractéristiques de la porosité ont une hétérogénéité naturelle sur la surface des bouchons qui est le résultat de la biologie de la formation du liège et de la méthode de production.

Signification et impact de l'étude : Les bouchons de liège sont le premier produit de l'industrie du liège avec une qualité et une performance reconnues mondialement pour la fermeture des bouteilles de vin. Basés sur un grand échantillonnage et une observation détaillée, les résultats de cette étude peuvent être utilisés pour le renforcement des critères de qualité, par exemple par la définition de standards de classification. La compréhension de la variabilité intrinsèque du liège et de l'anisotropie des caractéristiques de la porosité des bouchons de liège est importante pour le développement de leur performance.

Mots clés : bouchons en liège naturel, classes de qualité, porosité, analyse d'image, surface latérale

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INTRODUCTION

Natural cork stoppers are the premium product of the cork industry, and the commercial value of cork is determined by its suitability for the production of stoppers (Pereira, 2007).

Cork is a biological material with cellular structure, chemical inertia and specific mechanical behavior that provide an unmatched closure for bottles with worldwide recognition for its quality and performance as wine sealant (Pereira, 2007; Fortes *et al.*, 2004; Pereira, 1988; Pereira *et al.*, 1987). However, some cases of negative evolution of bottled wines have been attributed to cork stoppers as a result of their intrinsic variability. Although the underlying factors are still poorly understood, this variability has been used as an argument in some wine markets to replace cork stoppers for non-biological sealants such as synthetic stoppers and aluminum screw caps.

The response of the cork industry has been to reinforce quality requirements and control. The natural cork stoppers are classified into quality classes in function of the homogeneity of their external surface, which is mostly based on the extent of the apparent lenticular porosity, as seen by human or machine vision (Pereira, 2007; Fortes *et al.*, 2004). The traditional classification system used to evaluate cork quality is divided into a total of nine classes (flor, extra, superior, 1st to 6th), although a three-class system, i. e., premium, good and standard, might be better adapted to reality and performance requirements (Costa and Pereira, 2005, 2007; Pereira, 2007). It is empirically known that the quality classification of cork stoppers is subjective and therefore tends to vary between experts and even within individual on different occasions (Pereira, 2007). Quantification of this subjectivity showed that the disparity is higher in the mid-quality range (Melo and Pinto, 1989) and that the larger the set of classes considered, the more difficult and subjective is the classification.

Nowadays the evaluation of cork quality is made by visual analysis of the outer surface (lateral body surface and tops) using automated systems based on empirical algorithms using the results of image analysis. Several studies led to improvements in cork quality classification algorithms (Chang *et al.*, 1997; Vega-Rodríguez *et al.*, 2001; Radeva *et al.*, 2002; Costa and Pereira, 2006; Vitrià *et al.*, 2007; Jordanov and Georgieva, 2009; Paniagua *et al.*, 2010, 2011). The quantitative description of porosity has been made only recently by analyzing tops and lateral surface of stoppers of different quality classes (Costa and Pereira, 2005, 2006, 2007, 2009). The best classes include stoppers with few and very small lenticular channels, while the lower quality stoppers contain a noticeable porosity with greater pores sizes, but intra-quality grade variability was found to be high. Since the sampling in these studies was limited in the number of cork stoppers (i. e., 24 cork stoppers per class) and in the surface area covered by image analysis (i. e., 51 % of the stopper lateral surface), the question remains on the reasons underlying the variation in performance.

To overcome the limitations of the previous studies, this paper presents the results of a detailed observation of cork stoppers based on a large sample in order to encompass natural variability and to allow a broad confidence in the results. Moreover, this study was performed on the total external surface (lateral surface and tops) of stoppers of the three major quality grades: premium (including the top two commercial classes, flor and extra), good (superior and 1st) and standard (2nd and 3rd). Such classification follows the most actual tendency regarding cork stopper use by the quality wine markets. The goal was to characterize the variability and to quantify the surface porosity of wine cork stoppers from different commercial classes aiming at a better understanding and definition of the quality grading of natural cork stoppers. The wine bottling industry may therefore better establish their requirements for the quality classification of the stoppers.

MATERIALS AND METHODS

1. Data collection

A set of 300 stoppers (24 mm diameter x 45 mm length) was distributed equally into three quality classes: premium (flor and extra), good (superior and 1st) and standard (2nd and 3rd). The natural cork stoppers were collected at a major cork industrial unit before washing and surface treatment. They were randomly sampled after grading by the automated vision system and subsequently inspected by skilled operators, and finally graded into the three quality classes considered.

2. Image acquisition and processing

The surface image of the body (cylindrical lateral surface) and of the tops (circular bases) of the natural cork stoppers was acquired with an image analysis system that includes a digital 7 mega pixels in macro stand solution set on an acquisition Kaiser RS1 Board with a controlled illumination apparatus, connected to a computer using AnalySIS® image processing software (Analysis Soft Imaging System GmbH, Münster, Germany, version 3.1).

The visualization of all the stoppers was made using the same calibration and light intensity. The defects extraction was carried out inside two predefined regions of interest, one rectangular, for the lateral surface, with 423.92 mm^2, and another circular, for the tops, with 433.92 mm^2. Mean magnification values for stopper bodies and tops were 0.42440 and 0.36151, respectively. The image threshold

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was adjusted individually for each image and ranged in a RGB system from 65 to 135 for red, 60 to 115 for green, and 65 to 120 for blue.

The natural cork stoppers were individually analyzed. Two circular frames were acquired for the two tops, corresponding to 96 % of the total top area. The cylindrical lateral surface of the body was analyzed by acquiring eight successive frames, covering 100 % of the total lateral area, named A to H. The first frame (A) was set perpendicular to the cork growth rings and the others were subsequently taken by rotating the stopper 45º (Figure 1).

Knowing that the stoppers are punched out with the cylinder axis in the axial direction of the cork strip, the lateral surface of a stopper includes the tangential (frames A and E) and radial (frames C and G) sections of cork and all the in-between sections (frames B, D, F and H), while the tops correspond to transversal sections of cork (Pereira, 2007; Pereira *et al.*, 1987).

3. Data analysis

The layer of the extracted pores can be measured and quantitatively characterized as individual objects, while a defined observation area may be characterized by the mean values of its pores or by their concentration (Pereira, 2007).

The set of variables that characterize each pore as measured by image analysis was classified into dimension-, shape- and color-type variables. The dimension-type variables included: area; mean and maximum diameter, defined as the arithmetic mean and the maximum of all diameters (angle range between 0º and 179º, with step width of 1º); and mean and maximum rectangle, defined as the rectangle whose area is the average or the maximum of all rectangles. The shape-type variables included: shape factor, defined as (area/perimeter^2)*4π, measuring the roundness of the pores; sphericity, which describes the elongation of the pore (value of 1 for the perfect circular particle); convexity; aspect ratio, defined as the maximum ratio between width and length of a bounding rectangle of the pore; and orientation, measuring the angle of the longest chord linking the gravity centre to the periphery. The color-type variables included the value of red, green and blue (RGB system) for each pore.

These data were filtered and only pores with area equal or superior to 0.1 mm^2 were considered for the analysis. The pixel size was 0.05 mm and therefore the lowest pore area that could be resolved was 0.02 mm^2. The pores with an area inferior to 0.1 mm^2 represented on average 2.8 %, 1.9 % and 1.7 % of the total porosity and 42.2 %, 40.7 % and 46.5 % of the total number of pores for the premium, good and standard quality classes, respectively. Previous works from our laboratory considered only porosity superior to 0.5 mm^2 because small porosity is functionally and aesthetically irrelevant and only brings higher variance and variability to the sample (Costa and Pereira, 2006, 2007, 2009; Gonzalez-Adrados *et al.*, 2000; Pereira *et al.*, 1996; Lopes and Pereira, 2000).

Each frame of the lateral surface, the tops and the full lateral body of each stopper were characterized by several calculated variables: total area of pores, total number of pores, largest pore area, mean and maximum rectangle, mean and maximum diameter, porosity coefficient (defined as the proportion of the area occupied by pores), and number of pores per 100 mm^2. All the other dimension-, shape- and color-type variables collected for pores were averaged and transformed into cork stopper lateral section, top and body variables.

RESULTS AND DISCUSSION

1. Characterization of cork stopper quality classes

The different cork stopper quality classes were differentiated by the mean values of the main porosity features of their surface, namely by dimension and concentration variables, which are summarized in Table 1. There was an increasing trend in both lateral surface and tops, from the premium to standard quality class, for the dimension variables (number of pores, total area of pores, mean and maximum rectangle and diameter, and largest pore area) as well as for the concentration variables (porosity coefficient and number of pores per 100 mm^2). The premium stoppers showed less and smaller pores.

No between-class trend was found for the values of shape and color variables. The shape variables (shape factor, sphericity, convexity, aspect ratio) presented identical values between quality classes. This performance of shape variables was previously reported by Gonzalez-Adrados and Pereira (1996) and Costa and Pereira (2009). The color-type variables showed differences between classes although without a trend.

The mean porosity coefficient calculated for the lateral surface of the stoppers was 2.4 %, 4.0 % and 5.5 % for premium, good and standard quality classes, respectively (Table 1). At the 95 % confidence level, the porosity coefficient ranged from 2.2 to 2.5 % for premium stoppers, 3.7 to 4.3 % for good stoppers, and 5.1 to 5.8 % for standard stoppers. These values are within the range and exhibit similar trends to those reported in the literature. Costa and Pereira (2007) published porosity coefficients of 1.6 %, 4.6 % and 7.4 % for superior (extra, superior and 1st classes), standard (2nd and 3rd) and inferior (4th and 5th) grades, respectively. These authors also reported values of 1.4 % for extra, 2.1 % and 2.3 % for superior and 1st, and 4.2 % and 4.5 % for 2nd and 3rd quality classes, respectively (Costa and Pereira, 2009).

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Table 1 - Mean (n=100) and standard deviation (in parentheses) of the independent variables of the lateral surface and tops for the three quality classes of natural cork stoppers.

	Prenium	Good	Standard
Lateral surface			
Porosity coefficient (%)	2.4 (0.8)	4.0 (1.4)	5.5 (1.9)
Number of pores per 100 mm^2	4.6 (1.5)	5.6 (1.8)	5.9 (1.6)
Number of pores	156 (51)	190 (60)	201 (55)
Total area of pores (mm^2)	80.5 (28.3)	135.6 (48.6)	184.9 (65.8)
Mean rectangle (mm^2)	1.3 (0.5)	1.8 (0.6)	2.4 (0.8)
Maximum rectangle (mm^2)	20.8 (12.0)	39.4 (25.4)	53.9 (23.5)
Mean diameter (mm)	1.0 (0.2)	1.2 (0.2)	1.3 (0.2)
Maximum diameter (mm)	5.6 (1.7)	7.7 (2.4)	8.9 (2.1)
Largest pore area (mm^2)	5.7 (2.8)	10.6 (6.2)	16.1 (8.8)
Mean shape factor	0.5 (0.0)	0.5 (0.0)	0.5 (0.0)
Mean esfericity	0.3 (0.0)	0.3 (0.0)	0.3 (0.0)
Mean aspect ratio	2.0 (0.3)	2.1 (0.2)	2.1 (0.1)
Mean convexity	0.8 (0.0)	0.8 (0.0)	0.8 (0.0)
Mean red	64.6 (6.9)	74.4 (2.9)	61.5 (2.7)
Mean green	50.2 (7.9)	61.5 (3.1)	46.0 (2.6)
Mean blue	56.4 (6.9)	65.8 (2.4)	51.3 (2.2)
Tops			
Porosity coefficient (%)	2.1 (1.3)	3.1 (1.8)	3.7 (2.0)
Number of pores per 100 mm^2	2.5 (1.2)	3.3 (1.5)	3.5 (1.3)
Number of pores	22 (10)	29 (13)	30 (11)
Total area of pores (mm^2)	17.4 (10.9)	26.8 (15.5)	32.4 (17.4)
Mean rectangle (mm^2)	4.9 (5.7)	5.9 (5.5)	5.9 (4.8)
Maximum rectangle (mm^2)	58.3 (55.4)	86.8 (71.9)	89.7 (70.5)
Mean diameter (mm)	2.0 (1.0)	2.1 (1.0)	2.1 (0.8)
Maximum diameter (mm)	9.5 (4.7)	11.7 (5.4)	12.0 (5.1)
Largest pore area (mm^2)	5.7 (4.5)	9.0 (6.8)	10.2 (6.8)
Mean shape factor	0.4 (0.1)	0.3 (0.1)	0.3 (0.1)
Mean esfericity	0.2 (0.1)	0.2 (0.1)	0.2 (0.1)
Mean aspect ratio	3.7 (1.1)	3.6 (1.2)	3.4 (0.8)
Mean convexity	0.7 (0.0)	0.7 (0.0)	0.7 (0.0)
Mean red	63.5 (5.3)	64.2 (3.0)	61.2 (10.1)
Mean green	48.7 (5.1)	49.9 (3.3)	48.7 (11.2)
Mean blue	54.0 (3.5)	54.5 (2.8)	53.3 (9.0)

The differences between the values presented here and those published in other studies (Costa and Pereira, 2006, 2007, 2009) can be explained by the differences in the sampling size, which was much larger in the present study, and the fact that pore sizes superior to 0.1 mm^2 were considered instead of 0.5 mm^2, therefore allowing a more comprehensive and accurate characterization. In the present study, the proportion of pores between 0.1 mm^2 and 0.5 mm^2 that were discarded in the previous studies represented, on average, for the lateral surface, 23.7 %, 15.9 % and 11.6 % of the total porosity and 68.7 %, 62.9 % and 60.3 % of the total number of pores for premium, good and standard classes, respectively (Figures 2 and 3), while for the tops it represented 13.5 % of the total porosity in premium, 10.9 % in good and 9.0 % in standard stoppers. In both cases, there was a significant proportion of the total porosity that should be considered in a detailed characterization of stoppers,

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notwithstanding the irrelevant visual impact that such small pores might have.

The results obtained for cork stoppers tops had the same trend as described for the lateral surface. The porosity coefficient was 2.1 %, 3.1 % and 3.7 % for premium, good and standard quality classes, respectively (Table 1). These results can be compared with the values published by Costa and Pereira (2009), which ranged from 1.1 % for extra stoppers to 4.7 % for 5th quality stoppers.

For the body lateral surface, the large pores with size greater than 5 mm^2 represented on average 8.2 %, 20.6 % and 33.0 % of the total porosity for premium, good and standard quality classes, respectively (Figure 2), while corresponding only to 0.6 %, 1.8 % and 3.2 % of the total number of pores (Figure 3). For the tops, this class size represented 30.6 %, 44.6 % and 46.0 % of the total porosity for premium, good and standard quality classes, respectively.

In premium cork stoppers, small pores (area < 2 mm^2) represented 95.3 % in the body lateral surface and 89.3 % in the tops, which corresponds to 69.2 % and 39.7 % of the total porosity, respectively. On the other hand, in standard stoppers the small porosity represented only 40.6 % and 30.4 % of the total area of pores but 88.6 % and 86.9 % of the total number of pores in the body and tops, respectively.

The shape factor plotted as a function of pore size presented a decreasing trend in both lateral surface and tops for the three quality classes (Figure 4). On the contrary, the aspect ratio increased with increasing pore size, although this trend was more pronounced in tops (Figure 5).

The mean size of the largest pores in the lateral surface of cork stoppers was 5.7 mm^2, 10.6 mm^2 and 16.1 mm^2 for premium, good and standard classes, respectively (Table 1). These values are within the reported range of 3.5 mm^2 and 25.5 mm^2 for superior and inferior classes (Costa and Pereira, 2007) or the 3.1 mm^2 and 26.5 mm^2 range for extra and 5th class stoppers, respectively (Costa and Pereira, 2009).

The average RGB of pores was 74.4, 61.5 and 65.8 for good, and 61.5, 46.0 and 51.3 for standard stoppers (Table 1). The pores of premium stoppers presented a much larger scattering of RGB values than the other classes.

These results can be used to establish better requirements for the quality classification of the stoppers. The increasing trend shown by dimension and concentration variables, both in lateral surface and tops, suggests that these are the best variables to distinguish the quality classes. The porosity coefficient is probably the most important single

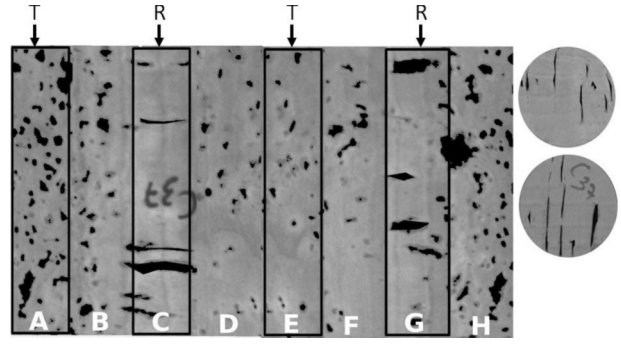


Figure 1 - Photographs of the cylindrical lateral surface (as a composition of eight successive pictures – frames A to H) and the two circular tops of one cork stopper. Arrows mark out the position of the different cork sections (T: tangential, R: radial).

variable since it expresses the extent of porosity and is correlated to size variables. On the contrary, shape variables do not seem to have discriminating power. These assumptions are in accordance with the variables selected by the classification system based on canonical and stepwise discriminant analysis presented by Costa and Pereira (2006). The color variables showed differences between classes. This observation suggests that they could be used in the quality classification and is accordance with Gonzalez-Adrados and Pereira (1996), who reported that color visual systems enable a better separation of the inferior quality class due to a more accurate detection of the pores.

The standard deviation for the dimension and concentration variables presented, with few exceptions, an increasing trend from best to worst quality class (e.g., the standard deviation of the porosity coefficient of the lateral surface was 0.8 % and 1.9 % for the premium and standard quality class, respectively) (Table 1). The standard deviation values also demonstrated a large variation between stoppers in the same quality class. For instance, the number of pores for the premium class presented a standard deviation of 51 pores, which means that approximately 68 % of the stoppers had between 105 and 207 pores in their lateral surface. This large range of values can be explained by the cork intrinsic variability. This variability between and within the three quality classes further corroborates that the traditional quality grading into nine classes is excessive in relation to the reality of cork variability (Costa and Pereira, 2005, 2007). Costa and Pereira (2006) reported that a classification in three quality classes improves the classification accuracy. This has been recognized by the industry and costumers and the present trade practice for the quality wines is to sort stoppers in premium-good-standard classes.

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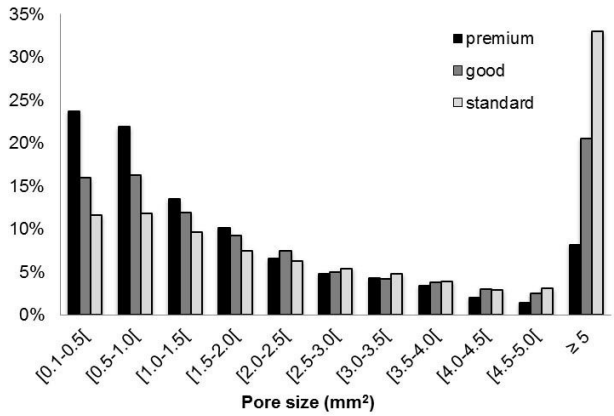


Figure 2 - Distribution of total porosity in the lateral surface as a function of pore size for the three quality classes of natural cork stoppers.

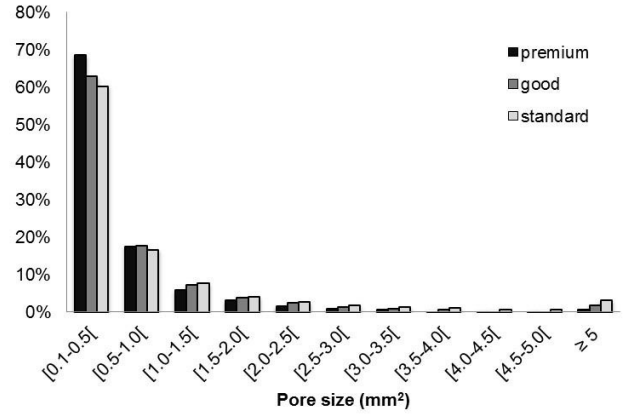


Figure 3 - Distribution of the number of pores in the lateral surface as a function of pore size for the three quality classes of natural cork stoppers.

On average, the stoppers belonging to each quality class can be described and distinguished from each other according to the characteristics of their pores. The stoppers from the premium class are characterized by an average porosity coefficient of 2.4 % and 2.1 % in their body and tops, respectively, with pores smaller than 5.7 mm^2 and with approximate 69 % of the porosity resulting from pores smaller than 2 mm^2. For the good quality class it will be expected to find, on average, a porosity coefficient of 4.0 % and 3.1 % in the lateral surface and tops, respectively, with pores up to 10.6 mm^2 and 9.0 mm^2. Stoppers belonging to the standard class will have a porosity coefficient of 5.5 % and 3.7 % in the lateral surface and tops, respectively, with pores smaller than 16.1 mm^2 and nearly 40 % of the porosity resulting from pores smaller than 2 mm^2.

2. Variation between tops and lateral surface

Tops showed different porosity features when compared to those observed in the lateral surface of the stopper (Table 1). Tops had a lower porosity coefficient and the difference increased with decreasing quality grade (12 %, 22 % and 33 % lower coefficient in relation to the lateral surface for premium, good and standard grade, respectively), and they had less pores per unit area (about 60 % of that in the lateral surface).

Pores in the tops were more elongated than in the lateral surface (Figures 4 and 5). For instance, the mean aspect ratio was 3.6 in the tops and 2.1 in the lateral surface (Figure 5, Table 1), and, on average, the pores were large (mean rectangle of 4.9 mm^2 in the tops and 1.3 mm^2 in the lateral surface for the premium grade).

These differences along with the relatively higher importance given by the human visual inspection to the lateral surface compared with tops suggest that the image analysis of the porosity features of the tops is of lesser impact for the quality classification and only of an aesthetical concern, as stated by Costa and Pereira (2006).

These differences are closely related to the biological development of the lenticular channels within the corkboard and the orientation of the cutting process for the production of stoppers (Pereira, 2007). The tops section the lenticular channels along their longitudinal axis, which runs approximately parallel to this section, thereby showing them as thin but long lines, as clearly seen in Figure 1.

The comparison of porosity between the two tops confirmed the existence of axial variation in the tree since both tops showed different porosity coefficients. A porosity ratio calculated between the top with the highest porosity and the other one showed a median value of 2.1, but extreme between-top differences could be found (e.g., 15.3 % and 0.2 % in the two tops of the same stopper). This variation can be practically used in the production of cork stoppers that have one of the tops covered with a covering cap, such as those designed for bottling fortified wines and spirits, i. e., by selecting the top with the lowest porosity as the apparent top.

3. Variation within the lateral surface

The stoppers are punched out from the cork strips so that their cylindrical axis is parallel to the axial direction of cork. Therefore, the lateral surface of the cork stoppers is not homogeneous relative to the section of cork and ranges from regions corresponding to tangential and radial sections of cork (Fortes *et al.*, 2004). The lenticular channels appear differently shaped in these two sections: in the radial section they look like elongated rectangular channels and in the tangential section they have an

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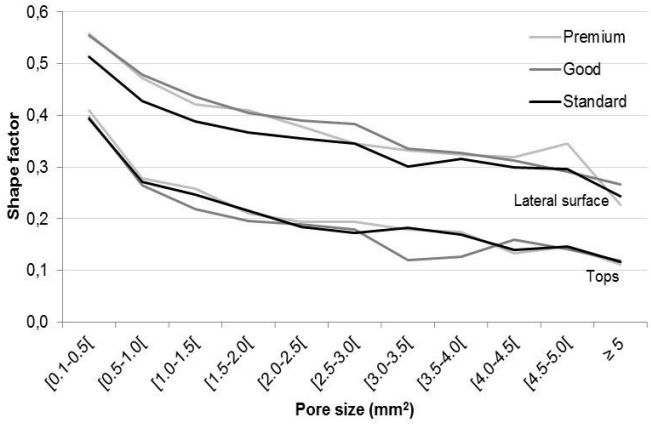


Figure 4 - Shape factor variation in lateral surface and tops as a function of pore size for the three quality classes of natural cork stoppers.

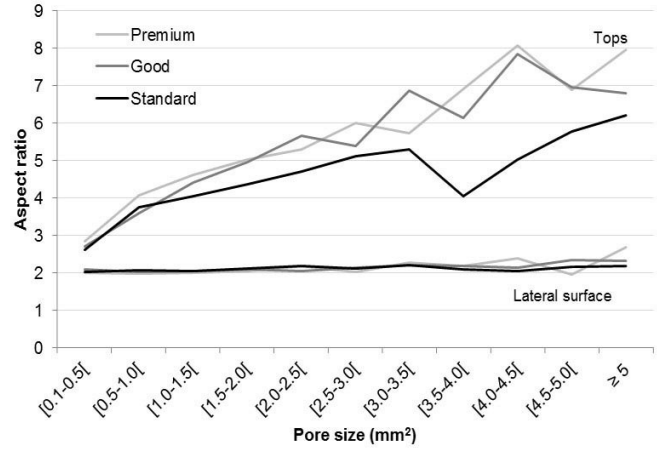


Figure 5 - Aspect ratio variation in lateral surface and tops as a function of pore size for the three quality classes of natural cork stoppers.

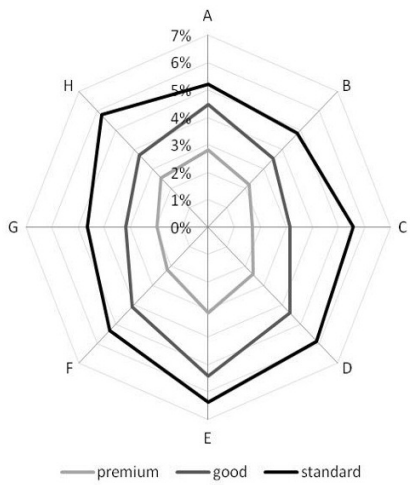


Figure 6. Variation of the porosity coefficient in the cork stoppers lateral surface (frames A to H) for the three quality classes. Mean (n=100).

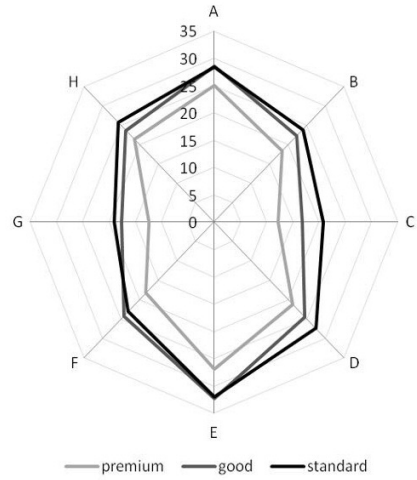


Figure 7. Variation of the number of pores in the cork stoppers lateral surface (frames A to H) for the three quality classes. Mean (n=100).

approximately circular to elliptical form (Pereira, 2007). The eight frames acquired by image analysis on the lateral surface of the cork stoppers represent the tangential (frames A and E) and radial sections (frames C and G) and the in-between sections (B, D, F and H), as shown in Figure 1. The described features of the sectioned lenticular channels are clearly visible in Figure 1 : the along-the-channel development of the lenticular channels is well visualized in the tops, and a part of this path is seen in the radial frames C and G, while the cross-sectional image of the lenticular channel is shown in the tangential frames A and E.

The present investigation has shown that the lateral surface of the cork stoppers is not homogeneous with regard to the distribution and characteristics of the lenticular channels. The most relevant results of the variation of pore features along the lateral surface of the stopper are shown graphically in Figures 6 to 11. These are star-type graphs where eight axes represent the different frames with a scale adequate for the variable under study. This type of representations allows a rapid grasp of the variation of the corresponding variable.

The dimension and concentration variables showed differences between frames in the three quality classes : frames A and E, corresponding to the tangential sections of cork, had a higher porosity coefficient and a higher number of pores when compared with frames C and G, corresponding to the radial sections of cork. These frames also presented higher values for the largest pore area and mean pore area.

Regarding the porosity coefficient, there was variation when moving around the lateral surface of the stopper,

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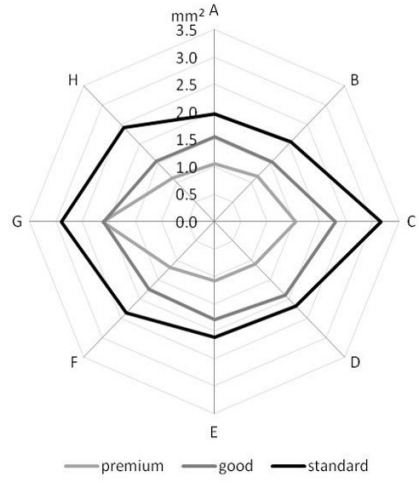


Figure 8 -Variation of the medium rectangle in the cork stoppers lateral surface (frames A to H) for the three quality classes. Mean (n=100).

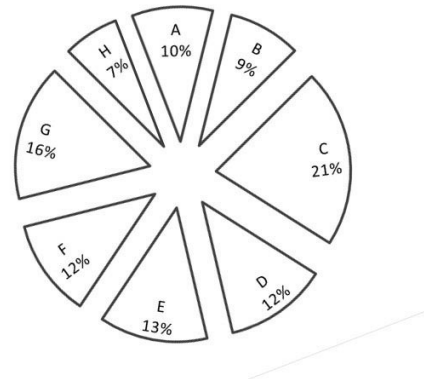


Figure 9 - Distribution for cork stoppers lateral surface (frames A to H) of the biggest pore (% of the total stoppers).

with maximal values for frames A and E (Figure 6). This was enhanced for the premium and good stoppers, for which the coefficient of porosity in frames A and E was 1.6 times superior to the value observed in frames C and G. For the standard stoppers, there was a more homogeneous distribution of porosity around the stopper (5.8 % in frames A and E, and 5.1 % in frames C and G).

The number of pores had a clear anisotropy in their distribution on the lateral surface of the cork stoppers, reaching maximal values in the A and E tangential frames and minimal values in the C and G frames (Figure 7). There was no significant difference between the three quality grades of stoppers. However, the mean values showed statistically significant differences between frames of the lateral surface, allowing the identification of three different groups: i) radial frames; ii) in-between frames; and iii) tangential frames.

Regarding the distribution of the mean dimension of the pores in the lateral surface, the radial frames (C and G) presented a significantly higher medium rectangle in all the quality classes, with values of 1.8 mm^2, 2.2 mm^2 and 3.1 mm^2 for premium, good and standard classes, respectively, in comparison with 1.1 mm^2, 1.7 mm^2 and 2.1 mm^2 in the A and E frames. Statistically significant differences occurred between the radial frames and all the others. The biggest pore was also preferentially located in the radial frames: 37 % of the largest pores lied in these two frames (Figure 9).

The distribution of porosity as a function of pore size showed different patterns for large, medium and small pores (Figure 10). The largest pores (above 5 mm^2) were located preferentially in the C and G frames, the smallest pores (below 1 mm^2 and from 1 to 2 mm^2) were located mostly in the A and E frames, while the medium sized pores (from 2 to 5 mm^2) were more evenly distributed along the lateral surface of the stopper.

Figure 11 shows that the distribution of pores as a function of orientation was independent of quality class. However, there was a clear difference between the orientation of the main axis of the pores around the stopper: in the radial frames (C and G) more than 55 % of the pores were approximately oriented parallel to the tops of the stopper (i. e., 0º to 45º and 135º to 180º orientation), while in the tangential frames (A and E) almost 80 % of total number of pores were approximately oriented along the stopper's axis (i.e., between 45º and 135º).

Independently of quality class, the shape factor was, on average, slightly higher in the tangential section than in the radial section (0.5 and 0.4, respectively). This can be explained by the fact that pores in the tangential section have an approximately circular to elliptical form while in the radial sections they are elongated rectangular channels.

There are no published data for the different sections in the lateral surface of cork stoppers. However, results can be compared with the data reported for the tangential and radial surfaces of cork planks and the rationale of the orientation of the stopper when bored from the cork plank (Pereira, 2007; Pereira *et al.*, 1996).

The pore features presented variation along the lateral surface of cork stoppers, which is not homogeneous in this aspect as it is clearly seen in the example shown in Figure 1. The main differences were observed between radial and tangential sections. In radial sections the lenticular channels are cut by a plane parallel or with a small angle with respect to its radial development axis, which leads to the occurrence of pores approximately

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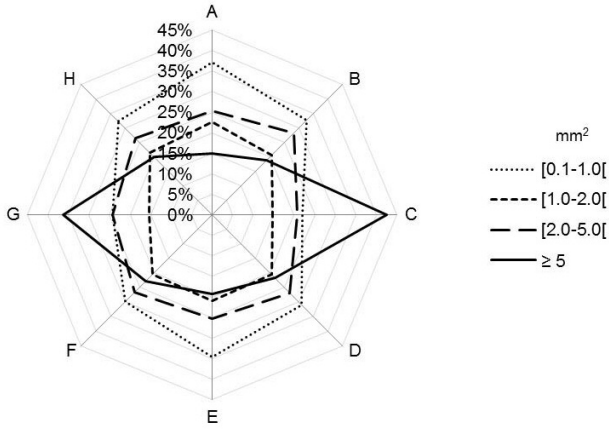


Figure 10 - Distribution of total porosity by pore dimension classes for the eight frames of the natural cork stoppers lateral surface.

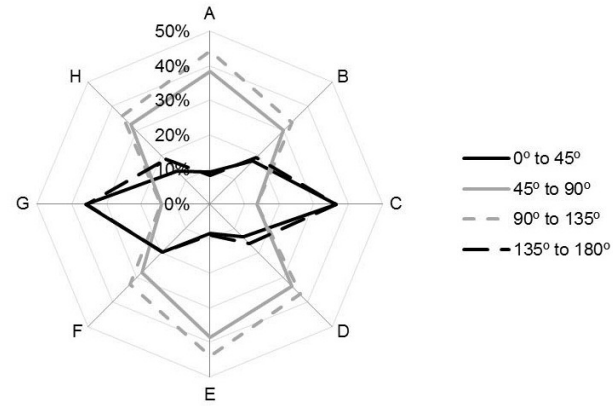


Figure 11 - Distribution of the total number of pores by pore orientation classes for the eight frames of the natural cork stoppers lateral surface.

parallel to the tops of the stopper and with an elongated shape, on average larger but fewer. On the other hand, the tangential sections present the cross-sectional image of the lenticular channel leading to pores that are oriented along the stopper's axle, in higher number and are visualized with an approximately circular to elliptical form (shape factor of 0.5). This surface variation of pore features was observed for the three quality classes with an increasing trend from best to worst quality class, namely for porosity coefficient and medium rectangle.

These results point out the importance of radial and tangential sections for the detailed characterization of cork stoppers porosity. Variables like tangential porosity coefficient, radial medium rectangle or the radial largest pore may therefore improve the accuracy of quality classification algorithms.

The variation of pore features along the lateral surface of cork stoppers can be related to their sealing performance as regards the leakage between stopper and bottleneck, which is evaluated by the liquid penetration in the interface (Fortes *et al.*, 2004). The highest depth of penetration should therefore occur in radial sections and the lowest in tangential sections.

The results obtained in this investigation may be used for reinforcing quality requirements of cork stoppers, including definition of standards, since the large sampling that encompassed the natural variability of cork and the detailed observation of surface porosity allow a broad confidence. Therefore the results may be used to develop better decision models for the quality classification of natural cork stoppers, i. e., by adding new decision variables or redefining class boundaries.

CONCLUSIONS

Quality classes of cork stoppers can be differentiated by mean values of the main porosity features of their surface, namely dimension and concentration variables, considering either the lateral surface or tops. These features showed an increasing trend from the premium to standard quality class.

Variation of pore features occurred along the lateral surface of cork stoppers, mainly between radial and tangential sections. Radial sections presented pores approximately parallel to the tops of the stopper, in a smaller number but with superior dimension and elongated shape. Tangential sections had pores oriented along the stopper's axis, in higher number and with circular to elliptical form.

The anisotropy of porosity features shown by cork stoppers is a consequence of the biological development of cork and of their production method. Understanding this variation is a relevant component in the analysis of performance of stoppers as wine sealants.

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