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ORIGINAL ARTICLE

Improvement of the manufacturing process of abrasive stones for honing

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Abstract In the present work, the mixing process of different components of abrasive stones of cubic boron nitride used for rough honing was studied. Stones are made by the sintering process of abrasive grains, a metallic bond, and a humectant that favors covering of each abrasive grain by the bond. Incorrect mixing of abrasive grains with the bond and humectant can result in stones with nonuniform abrasive grain distribution. As the abrasive stone wears out, grain distribution will vary and modify efficiency of the honing operation. Tin is the metal having the lowest melting point among metals in the bond. By means of a scanning electron microscope and energy-dispersive X-ray microanalysis, tin segregation was discarded, which could have led to abrasive grain segregation. Later, mixing tests of the different components of the stones were performed at different mixing times. Both homogeneity degree of the abrasive content of different samples in a mix and covering degree of abrasive grains by bond were determined through two new parameters introduced in the present study. It was noted that use of a chain to accelerate the mixing process excessively reduces covering degree of abrasive grains even at initial mixing times. The highest quantity of humectant is recommended in order to get better covering degree. Mixing time should be high enough to assure homogeneity degree of the mix but low enough to avoid excessive reduction of covering degree.

Keywords Honing · Abrasive stone · Cubic boron nitride · Mixing

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1 Introduction

Abrasive stones are made of three kinds of materials, namely abrasive, bond, and additives such as humectants. Abrasives are classified into conventional, which are based on Al_2O_3, SiC, or ZrO_2, and superabrasives, based on cubic boron nitride and diamond. Usual bonds contain a resin or a polymer, a ceramic material, or a metallic alloy. For obtaining stones with superabrasives, metallic bonds are mainly used with bronze, iron, or nickel. Standard procedures for manufacturing such stones are sintering, active brazing, and electrolytic processes [1]. Typical additives are lubricants and humectants [2].

When superabrasives with a metallic bond are used, due to electronic and chemical differences between metals and superabrasives, a good adhesion between abrasive grains and metallic particles is difficult [3]. In addition, differences in the thermal expansion coefficient between metals and ceramic materials lead to stresses that weaken or even destroy unions between them [4]. In those stones, defects such as sedimentation of abrasive grains towards the lower part of the stone near the metallic base or the formation of groups of abrasive grains are often observed. The fact that abrasive concentration varies leads to more or less material removal rate in the honing operation as it proceeds. This means that honing parameters, such as pressure of honing stones on the cylinders' surface, need to be changed.

Several patents propose methods for improving homogeneity of abrasive stones. For example, for stones made of different abrasives with a ceramic bond with silica and colloidal alumina, it is mixed with water and a flux to get a paste that later hardens and compacts, reducing voids in the structure and improving homogeneity of the honing stones [5]. In stones with resin bond, in which many times resin hardens before a correct mixture with abrasive, use of microbubbles was recommended in order to create a sponge

structure that favors mix of different components [6]. In addition, preformed agglomerated abrasive grains with an inorganic bond can be employed, which are later joined to obtain a more homogeneous abrasive stone [7]. For abrasive stones with metallic bond and cubic boron nitride (CBN) obtained by means of brazing, homogeneity can be improved by adding extremely high-hardness nanoparticles or increasing the humectant content [8]. Humectant is a temporary adhesive that is mixed either with the bond or with the abrasive before the mixing step and allows every grain to be evenly coated with the bond. Thus, abrasive grains are well distributed in the stone volume after sintering. When a ceramic bond is used, the usual humectants are polyethylene glycol (or other glycols), dextrin, and polyvinyl alcohol (or other alcohols) [9]. Polyethylene glycol is, in addition, a usual additive in the process for obtaining CBN cutting inserts by means of sintering with ceramic bond [10].

Homogeneity of a mix is difficult to be quantified. Yet, in 1970, more than 30 different indices had been collected, most of which were based on dispersion in some component's content [11]. Later, the universal homogeneity index or Buslik's index was defined as the negative logarithm of the sample weight required to obtain a standard deviation of 1 % in the measured richness of the samples withdrawn from a mixer. The test consists of increasing the sample size that is extracted until deviation of the samples' richness is reduced. Modified Buslik's index is defined in terms of volume instead of weight [12]. Such index has the disadvantage that a great number of tests are necessary for its determination. In the pharmaceutical industry, the usual criterion for the correct mix of powder and thus increased homogeneity of materials is relative standard deviation or variation coefficient [13].

Insufficient mixing of different components will often lead to a nonhomogeneous microstructure [7]. Thus, an increase of mixing time will, in principle, improve homogeneity of the mix before sintering. However, as the mixing operation proceeds, the quantity of bond covering a grain will be reduced, leading to the formation of groups or lumps of abrasive grains. Moreover, if an abrasive grain is covered by less quantity of bond, the density of the grain + bond will increase. Therefore, it will tend to fall down towards the base of the abrasive stone during the filling operation of the sintering mold. This will cause sedimentation of abrasive grains. Thus, abrasive concentration will increase from the top to the bottom of abrasive stones.

The main objective of the present work is to study and analyze the mixing step of the different components of abrasive stones for rough honing with metallic bond and CBN abrasive. First, by means of a scanning electron microscope (SEM) and energy-dispersive X-ray microanalysis (EDX), it was proved that segregation of abrasive grains is not caused by segregation of any of the bond's components. Once such possibility was discarded, mixing tests were performed with use or not of a chain for accelerating the mixing process in the mixing machine. In addition, mixing tests were performed with different humectant quantities. In all cases, homogeneity of abrasive quantities in the sample as well as in the bond quantity covering the abrasive grains was determined. For doing this, two new parameters namely homogeneity degree (*HD*) and covering degree (*CD*) were introduced.

2 Materials and methods

2.1 Materials

Abrasive stones are formed by a metallic base on which the mix of abrasive + bond + humectant is placed (Fig. 1). Dimensions of abrasive stones were 4.5×4.5×21 mm. In the test for determining segregation of tin, grain size 181 was used according to Federation of European Producers of Abrasives (FEPA) nomenclature [14]. In the mixing tests, a higher grain size of 252 was used in order to make easier the sieving process for separating the abrasive from the bond. The different tests performed as well as abrasive stones' characteristics are detailed in Table 1.

2.2 Methods

2.2.1 Segregation of Sn

Abrasive stones were previously polished in a Mecapol P230 polishing machine in three polishing steps:

- Polishing with a diamond disk of grain size 440 (Norton scale)
- Polishing with a diamond paste of particle size below 9 μm
- Polishing with a diamond paste of particle size below 3 μm

SEM and EDX analyses were performed in a scanning electron microscope JEOL JSM 6,400 with an X-ray-dispersive energy analyzer EDX-LINK-LZ5.

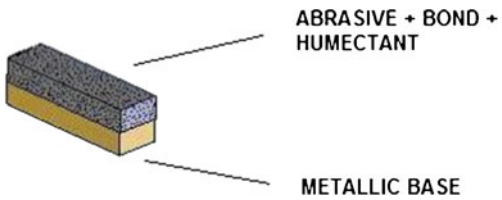

Fig. 1 Schematic drawing of abrasive stones

Table 1 Tests performed

Tests	Grain size of abrasive (FEPA)	Density	Quantity of humectant (drops·g abrasive^{-1})
Segregation of Sn	181	40	1.00
Mix with/without chain	252	50	1.00
Mix with different humectant quantities	252	50	1.00/1.25/1.50

In order to check segregation of tin, with melting point 231.9 °C, much lower than those of the rest of metals in the bond, Co, Cu, and Sn percentage of area was quantified by EDX. Quantifications were performed in one of the lateral surfaces of the stone, five of them near the upper surface and five more near the metallic base of the abrasive stone (Fig. 1). In order to compare results obtained in both locations considered for EDX quantification, percentage change between values was calculated as follows (Eq. 1):

$$Percentage\ change = \left(\frac{|Xl - Xu|}{Xu}\right) \cdot 100 \tag{1}$$

where *Xl* is percentage of area for a metal X obtained near the lower surface of the abrasive stone (in percent) and *Xu* is percentage of area for a metal X obtained near the upper surface of the abrasive stone (in percent).

2.2.2 Mixing tests

The manufacturing process of abrasive stones consists of the following operations: adding humectant to the abrasive, mixing the abrasive/humectant with the bond, pouring the mix in a graphite mold, and sintering by means of external resistance in the mold.

In all tests, the same quantity of abrasive and bond was used. Mixing of the bond with abrasive + humectant was performed in a WAB machine model Turbula T2C with a cylindrical container of base diameter 100 mm and height 150 mm (Fig. 2). Mixing times were 15, 30, 60, 90, 150, 300, 420, and 510 s.

Fig. 2 Mixing machine Turbula T2C

Abrasive grains were sieved with a 0.125-mm sieve according to ASTM 120. For weighing different quantities of abrasive and bond, an analytical balance Sartorius was used, with precision of 0.001 g and measuring range between 0.001 and 1,200 g.

In Turbula mixing machines, a chain is usually employed to speed up the mixing process. In the present work, tests with and without mixing chain were performed.

In previous tests, it had been noticed that the quantity of humectant employed influenced the homogeneity of the mix. For this reason, three different humectant quantities were taken into account. Humectant quantity influences the quantity of the bond covering the abrasive grains. If the quantity of the bond covering a grain size increases, grains will be more widely spaced. For this reason, groups or lumps of grains will less likely occur (Fig. 3).

In order to analyze the mixing step of the different components, on the one hand, homogeneity of abrasive quantities found in different samples extracted from the same mix was studied. On the other hand, covering degree of abrasive grains by the bond was also studied. For doing this, two new parameters were defined, *HD* and *CD*.

HD quantifies homogeneity of a mechanical mix, by means of the calculation of the variability in the quantity of abrasive in different samples extracted from the mix. Samples, which contain the abrasive, bond, and humectant, were placed on a sieve and washed with water in order to remove the bond and humectant through the sieve. Abrasive quantity on the sieve was weighed. *HD* is obtained as follows (Eq. 2):

$$HD = \frac{A_{ta} - \left(\frac{\sum_{i=1}^{n} |A_{ta} - A_i|}{n}\right)}{A_{ta}} \tag{2}$$

where *HD* is homogeneity degree; A_{ta} is the theoretical abrasive quantity per sample (in gram) according to initial quantities of the abrasive, bond, and humectant in the mix;

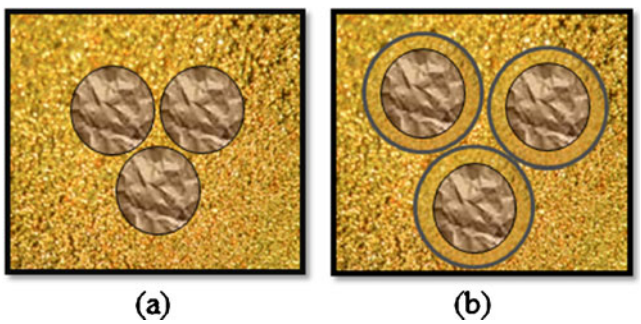

Fig. 3 Schematic drawing of abrasive grains in the mix: **a** not covered by bond, **b** covered by bond

A_i is the weighed quantity of abrasive in the ith sample (in gram) ($1 \le i \le n$); and n is the number of samples considered. In the present work, three samples were extracted from different places in the Turbula machine, for each quantity of humectant at each mechanical mixing time ($n=3$).

The highest possible value for *HD* is 1. This corresponds to the situation in which all samples extracted from the mix would have the same abrasive quantity, the theoretical abrasive quantity A_{ta}. The mix would then be completely homogeneous.

CD is related to the quantity of bond surrounding the abrasive grains. First, a sample of the mechanical mix (abrasive + humectant + bond) is weighed. Then it is sieved. Bond not surrounding abrasive grains goes through the sieve, while abrasive grains surrounded by bond remain on the sieve, *A* (in gram). After washing it with water, abrasive material is weighed, *B* (in gram). Calculation of *CD* is presented in Eq. 3.

$$CD = \frac{Lr}{Lt} = \frac{Q_A - Q_B}{Lt} \tag{3}$$

where *CD* is the covering degree; *Lr* is the residual quantity of bond + humectant in a sample after sieving (in gram), *Lt* is the theoretical maximum quantity of bond + humectant quantity per sample (in gram), in case all bond surrounded abrasive grains; Q_A is the quantity of abrasive + humectant + bond remaining on the sieve (in gram); and Q_B is the quantity of abrasive remaining on the sieve (in gram) after washing it with water.

3 Results

3.1 Segregation of Sn

Figure 4a shows a micrograph at magnification 650 of an abrasive stone of grain size 181 and abrasive concentration 40, while Fig. 4b corresponds to an EDX map of Co, Sn, and Cu. Components of bond B in Fig. 4a are not evenly distributed. The EDX map (Fig. 4b) shows cobalt particles C surrounded by copper and tin alloy D. Results of EDX quantification of Co, Cu, and Sn are presented in Table 2.

Percentage change between quantification location near the upper surface and quantification location near the base of the abrasive stone for Co was lower than 5 %. Percentage change for Cu was below 2.5 %. Percentage change for Sn reached 7.31 %. This means that some segregation for Sn is produced. However, it is not important enough to provoke segregation of abrasive grains towards the base of the abrasive stone.

Figure 5 depicts the transition zone between abrasive A and bond B in a micrograph at magnification 2,000. In the picture, the weak union between abrasive and bond is observed, with some discontinuities that were previously reported by Ding et al. [3, 15].

3.2 Mixing test with use of chain

In Fig. 6, results for parameters *HD* and *CD* were represented as a function of mixing time, either with or without use of mixing chain. From 0 to 150 s, parameter *HD* shows oscillations with time, both for use of chain or not (Fig. 6a). Between 150 and 300 s, *HD* increases. From 300 s, *HD* does not improve although mixing time is increased. Similar results are obtained with or without use of chain. Therefore, use of a mixing chain does not improve *HD*. *CD* decreases as a general trend with mixing time (Fig. 6b). During the first 100 s of mixing test, the behavior of *CD* is similar regardless of use of chain or not. If the chain is used, from 150 s on *CD* is almost zero. If the chain is not used, from 300 s on *CD* is almost zero. For this reason, use of mixing chain is not recommended since it does not improve *HD* and impairs *CD*.

3.3 Mixing test with different humectant quantities

In Fig. 7, *HD* and *CD* for different humectant quantities are shown as a function of mixing time. At mixing times below 150 s, the highest *HD* is achieved with 1.25 drops of humectant per gram of abrasive and the lowest *HD* with 1.5 drops of humectant per gram of abrasive (Fig. 7a). *HD* is unstable for the first steps of the mixing operation. From 150 s on, results are very similar regardless of humectant quantity employed. Figure 7b depicts that the higher the humectant quantity, the higher the covering degree is. Thus, when 1.50 drops of humectant per abrasive gram are used, *CD* improves significantly at all mixing times studied with respect to lower humectant quantities. For these reasons, 1.50 drops of humectant are recommended in order to obtain a high *CD*, provided that enough mixing time is assured, for example 150 s, to get a right *HD* of the mix.

4 Conclusions

In the present paper, the manufacturing process of CBN honing stones was improved. This will allow optimizing the honing process, thus enhancing productivity of abrasive stones and reducing machining time. This will also improve the quality of the machining operations performed. The main conclusions of the paper are as follows:

1. Two new parameters were introduced for studying the mixing process of different components of abrasive stones: homogeneity degree and covering degree. They

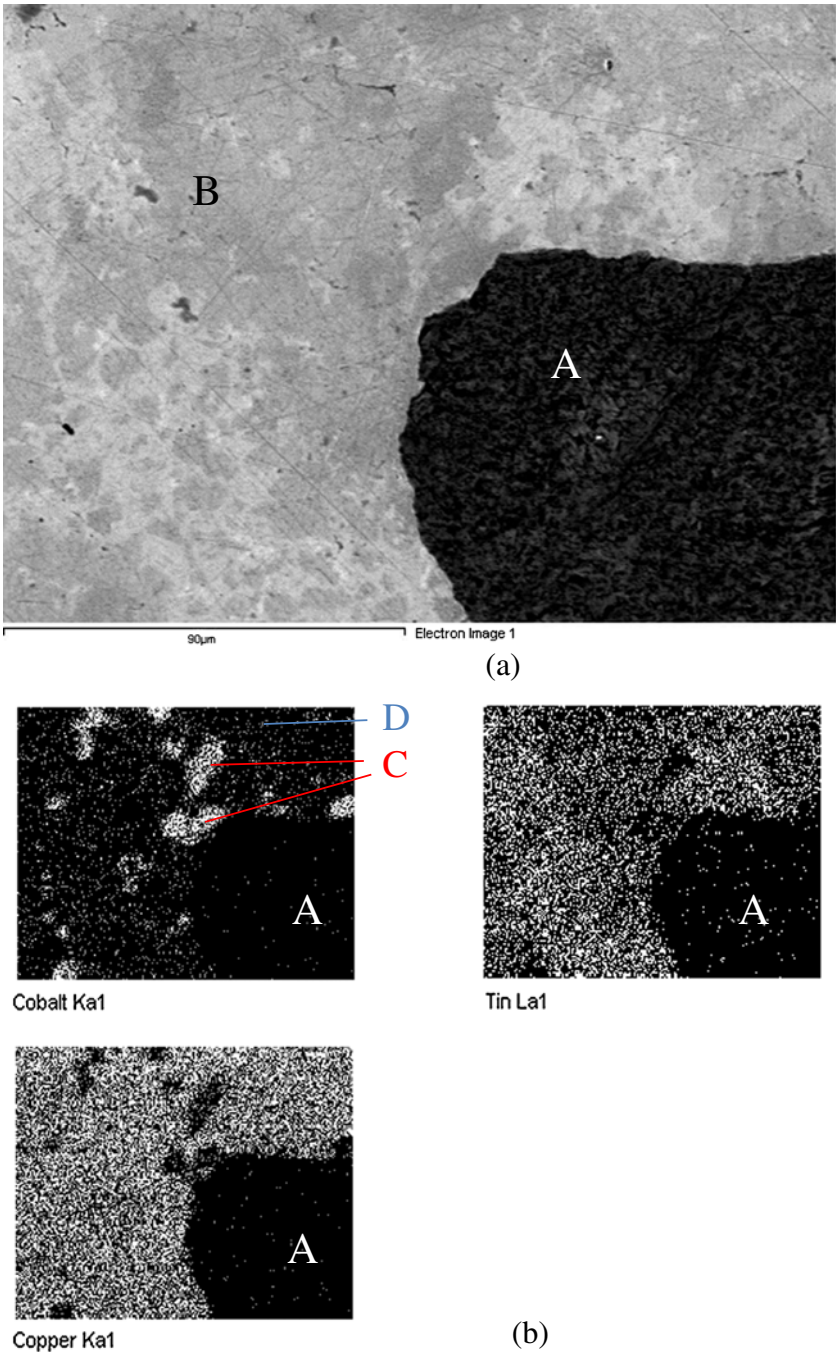

Fig. 4 **a** SEM micrograph of an abrasive stone of grain size 181 and density 40 (magnification, 650) (*A* abrasive, *B* bond). **b** EDX map (B=*C*+*D*, *C* cobalt, *D* copper and tin alloy)

Table 2 EDX quantification of Co, Cu, and Sn

Metal	Percentage of area near upper surface *Xu* (%)	Percentage of area near base *Xl* (%)	Percentage change (%)
Co	9.49	9.92	4.53
Cu	74.36	72.74	2.18
Sn	16.15	17.33	7.31

allow quantification of the homogeneity level of the mix and coating level of abrasive grains by bond at a certain mixing time, respectively.

2. As a general trend, increasing mixing time favors homogeneity degree, but it leads to a decrease of covering degree. Thus, in the present work, recommended mixing time is 150 s. Mixing time is high enough to assure homogeneity in the abrasive content of the mix but low enough to avoid excessive reduction of covering degree.
3. In the mixing step of the different components of the abrasive stone, use of a mixing chain to accelerate the

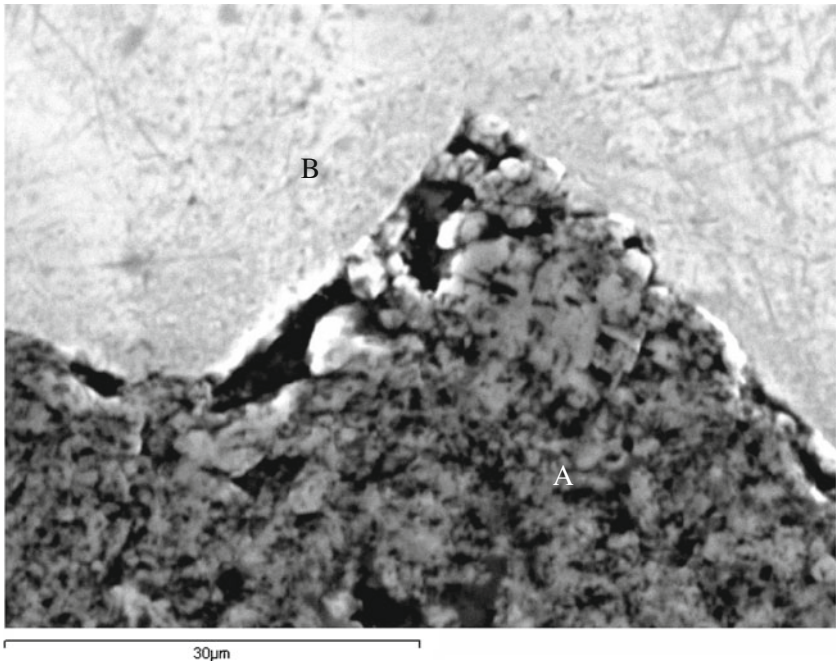

Fig. 5 SEM micrograph of an abrasive stone of grain size 181 and density 40 (magnification, 2,000) (*A* abrasive, *B* bond)

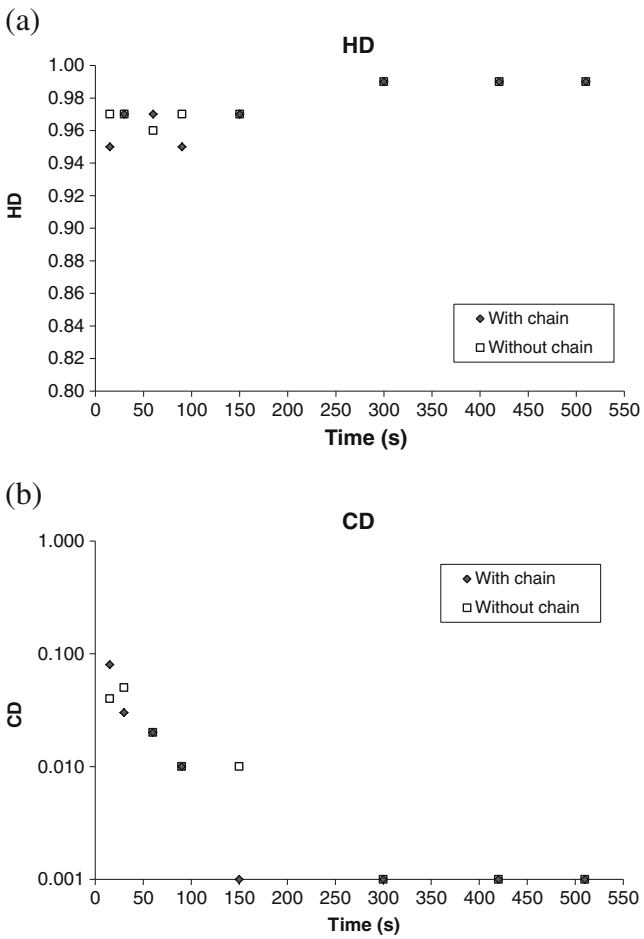

Fig. 6 **a** HD and **b** CD, with or without mixing chain

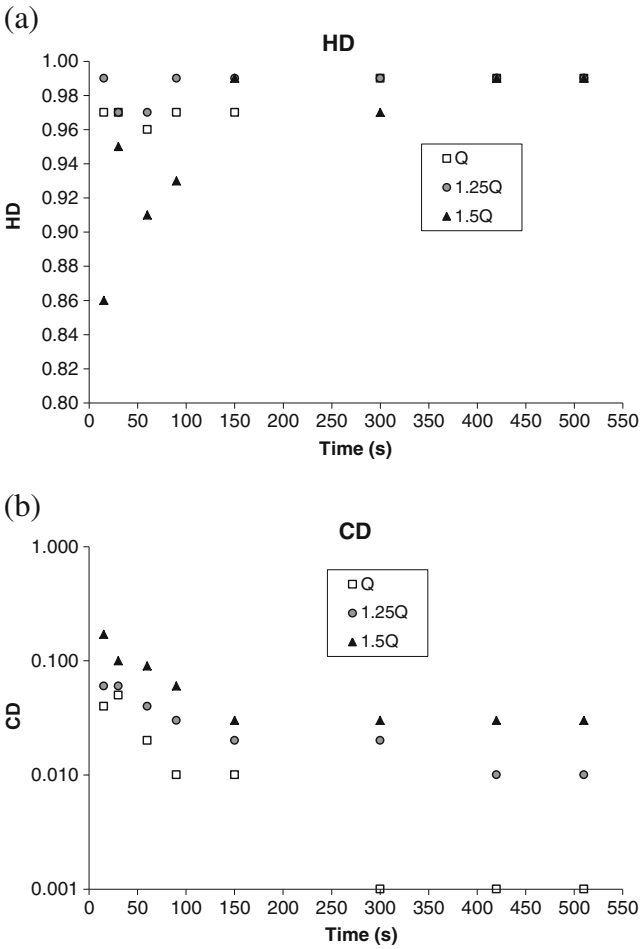

Fig. 7 **a** HD and **b** CD, with different humectant quantities

mix is not recommended, because the chain accelerates reduction of covering degree with mixing time without improving homogeneity degree.

4. In the present work, the most suitable amount of humectant to be used is 1.5 drops per gram of abrasive, which is the highest one among quantities studied. Use of a higher humectant quantity improves covering degree of each abrasive grain by bond. Homogeneity degree is high enough at the recommended mixing time of 150 s.

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