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Paste Plant Operations

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CHARACTERIZATION OF PACKING ABILITY OF COKE PARTICLES

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Abstract

This work aimed to investigate the reliability of the vibrated bulk density (VBD) test for estimating the void fraction and packing ability of coke particles. VBD is conventionally used in the anode industry to characterize the calcined coke and to determine the required amount of pitch and fine coke. High VBD may be achieved by dense particles while they do not necessarily result in a highly packed bed of particles since packing properties depend on particle shape factors. The apparent density of coke fractions was measured using image analysis. Then the inter-particle void fraction was calculated from the VBD. This void fraction indicates the packing ability of particles. VBD results did not follow the void fraction trend. It is shown that different cokes with equal VBD values might present different inter-particle void fractions. Nor is the VBD necessarily in agreement with intra-particle porosity. It is thus suggested to consider complementary parameters such as shape factors and particle porosity along with the VBD.

Introduction

Aluminum smelters are interested in high-density coke with good packing ability to improve the anode density. Dense anodes result in higher electrical conductivity, higher energy efficiency and lower anode consumption. High-density coke aggregates are essential for producing dense anodes. As coke intra-particle porosity is increased more pitch should be used in the anode paste mixture to fill the coke pores and to enhance the anode density. Packing ability of coke is also an important factor determining the anode density. Highly packed cokes yield in lower inter-particle voids thus requiring less pitch and enhancing the overall anode density.

Vibrated bulk density is a simple, rapid and inexpensive test method to obtain an indication of density and packing ability of coke. VBD of specific coke fractions has been correlated with anode density [1, 2] and found to be useful to determine the pitch demand. VBD is generally accepted as a reference method and is widely used by coke calciners and anode producers.

The VBD test faces however several challenges. First, numerous authors argued the repeatability and interpretation of VBD results. Lossius et al. [3] conducted a comparison between laboratories for ASTM and ISO standard test methods and showed that VBD has a limited repeatability and low between-laboratory precision. The results are dependent on the equipment and operator variability [4]. Modifications have been thus proposed to improve its repeatability [5, 6]. Second, there is not a good agreement between VBD and porosity level derived from mercury porosimetry [7]. Anode density correlates well with coke porosity below 5 μm in diameter [2] but VBD does not show the proportion of macro, meso and micro pores. A coke that meets the specifications may thus fail in producing dense anodes due to incorrect prediction of pitch demand. Third, VBD does not differentiate between the inter-particle and intra-particle porosity. Vitchus et al. [8] explained a paradox between VBD and particle porosity. VBD is significantly influenced by particle packing and inter-particle voids that are basically controlled by particle shape factors [8-11]. Therefore, smoother but more porous particles may result in a higher VBD. It was revealed for four different sources of coke that naturally occurring particles with smoother surfaces led to a higher VBD than the particles of the same coke crushed to the same size range [11]. Consequently, although VBD shows a combination effect of packing ability and coke porosity on final apparent density of a coke bed, it is not a reliable indication of porosity of coke particles.

Determining coke density is a big challenge due to its irregular shape. In this work efforts were made to evaluate the envelope density and shape factors of coke particles. The effect of shape of particles on the inter-particle voids (packing ability) in a vibrated bed of particles was evaluated. Particle shape factors were measured for four size fractions from five different sources of coke. Apparent density and VBD were measured. Then inter-particle and intra-particle porosities were calculated. The variations in VBD and void fraction between the particles were compared for the coke fractions and the influence of particle shape was studied. In addition, the reliability of VBD for estimating the packing ability and particle porosity was discussed.

Experimental procedures

Five calcined petroleum cokes (A-E) with size fractions of -4+8, -8+16, -16+30 and -30+50 US mesh were used. Table 1 shows the real density of the cokes measured by Helium pycnometer. Five shape factors were measured for every single fraction of the cokes. The shape factors were aspect ratio, sphericity, roundness, compactness and convexity as defined in Table 2. This measurement was performed by a Nikon Ephiphot optical microscope equipped with an image analysis system (Clemex, vision). These factors describe different aspects of a particle related to the packing behavior in a particle bed. Higher values of sphericity, roundness, compactness and convexity correspond to more spherical particles and regular shape.

Table 1. Real density of the calcined cokes

	A	B	C	D	E
Real density (g/cm^3)	2.075	2.063	2.074	2.057	2.073

Table 2. Particle shape factors measured by image analyzer

Shape factor	Definition
Aspect ratio	Ratio of longest dimension to shortest dimension. 
Sphericity	4.π.Area / (Perimeter)^2
Roundness	4.Particle area/π.(Circle diameter)^2 Quantifies the roundness of object's edges. 
Convexity	Convex perimeter / perimeter Quantifies the jaggedness of object's edges.  Convex perimeter Convexity
Compactness	4.π.Area / (Convex perimeter)^2

The apparent density of coke particles was measured. Apparent density is the ratio of the mass of a particle over its apparent or envelope volume. Apparent volume is defined as the external volume of a particle which includes the internal pores. Mass of particles was measured to the nearest 0.0001 g. Then, the particles were put in a mold of 2.5 cm diameter. Metallography polishing resin was poured in the mold under vacuum and let solidify to obtain a cylindrical resin sample containing all coke particles. The height and diameter of the samples were measured to the nearest 0.01 mm and sample volume was calculated. A section was cut from the samples and the two surfaces, marked with arrows in Figure 1, were polished. The area fraction of the particles was measured on each section using image analysis. Image analysis was performed on 56 images at 25X covering the whole surface of the section. The average area fraction was numerically considered the same as the volume fraction and multiplied by the sample volume to obtain the total apparent volume of coke particles only. The mass of particles was divided by their total apparent volume to obtain apparent density. Porosity inside the particles was determined by Equation 1.

$$\%Porosity = \frac{Real\ density - Apparent\ density}{Real\ density} \times 100 \qquad (1)$$

The VBD of each size fraction of the cokes was measured according to ASTM D4292 standard test method. One hundred grams (±0.01 g) of particles in a given size range were poured in a vibrating funnel and fed into a graduated cylinder during 70 to 100 s while the cylinder was vibrated at 60 Hz with an amplitude of 0.2 mm. The volume of vibrated particles was read after 120 s of vibration and VBD was calculated. The average of three measurements was used as the VBD value. Figure 2 shows the standard setup for this test. Void fraction between the vibrated particles was calculated by Equation 2.

$$\%Interparticle\ void = \frac{Apparent\ density - VBD}{Apparent\ density} \times 100 \qquad (2)$$

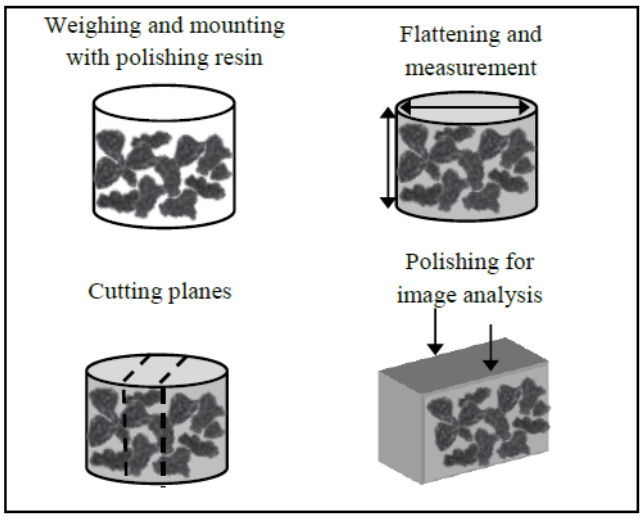


Figure 1. Schematic representation of the procedure used for measurement of apparent density of particles

Figure 2. Setup for vibrated bulk density

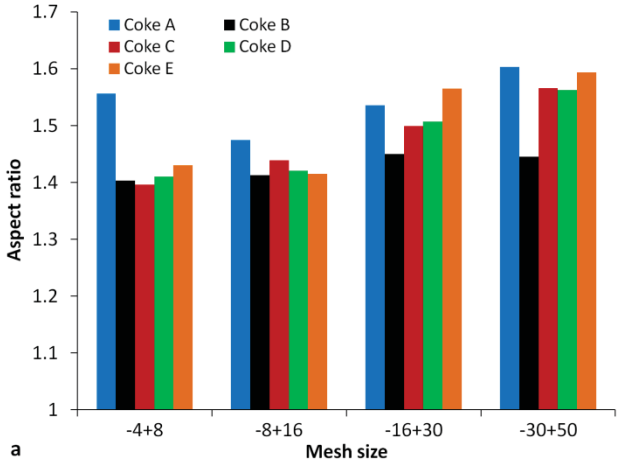
Results and discussion

Figure 3 represents the shape factors for different size fractions of the cokes. Coke B with high sphericity and compactness values had the most spherical particles among the cokes. Coke A revealed the highest aspect ratio and the lowest sphericity, roundness and compactness and thus had the most elongated and irregular particles. Cokes C and E had roundness and compactness values superior to those of coke A but inferior to those of coke B.

Figure 4 shows the apparent density for different size fractions of coke particles. Apparent density revealed an increasing trend with reduced particle size. This is due to the fact that the pores within the particles were destroyed during size reduction (Figure 5) and thus apparent density increased. However, the changes in the apparent density from one fraction to another were not similar for different sources of cokes. This is due to the fact that the cokes had different pore fractions and pore size distributions. In addition, they had different particle size distributions for each size fraction.

Figure 6 demonstrates the histogram of VBD for various size fractions. VBD revealed an increasing trend with reducing particle

size down to 50 mesh. This is explained by higher apparent density of particles for smaller size fractions, as indicated in Figure 4, that enhances the VBD. An interesting point was the disagreement between the VBD and particle porosity in some cases (Figures 5 and 6). For example, -8+16 mesh size for coke D showed a lower porosity than did coke E but a meaningful higher VBD was achieved for coke E. This higher VBD for coke E is due to the higher sphericity, roundness, convexity and compactness for coke E particles in this size fraction that enhanced its rearrangement and packing behavior. In another case cokes A, B and C had similar porosity for -16+30 mesh size but coke A had a lower VBD than cokes B and C for the same size fraction. Lower VBD for coke A can be explained by higher aspect ratio and lower roundness and compactness of this coke that resulted in more irregular particles and reduced the packing ability. In -30+50 fraction, cokes C and E had higher porosity than coke A but they revealed higher VBD than coke A. Lower sphericity, roundness and compactness as well as higher aspect ratio resulted in lower VBD for coke A. This indicates that the VBD test is not always a good indicator for coke porosity. In fact VBD is influenced by both particle porosity and the voids between the particles. Particle characteristics such as shape factors and inter-particle friction affect the packing ability and thus the VBD results [8, 12].



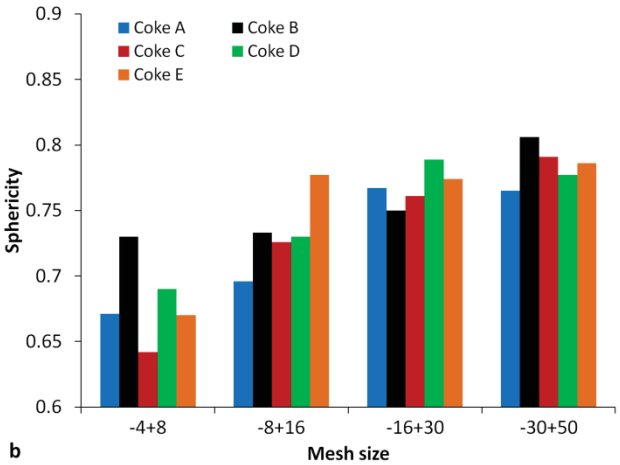
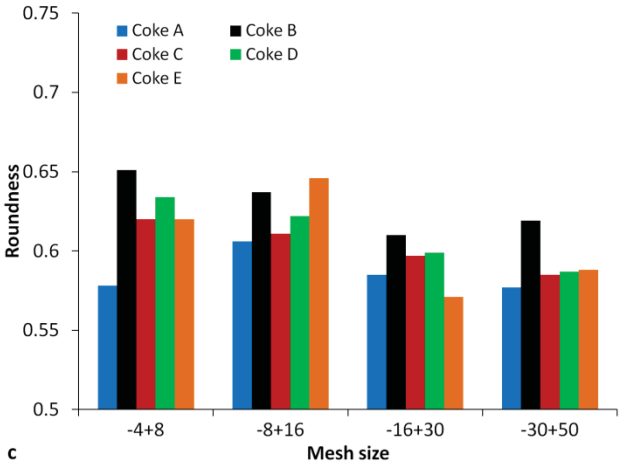
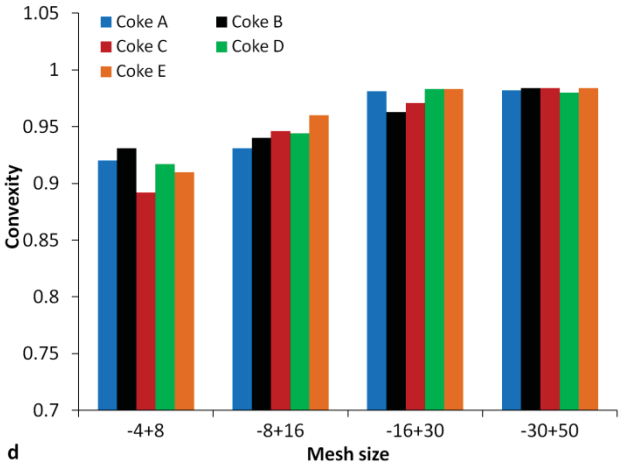


Figure 3. Shape factors for different size fractions of the cokes; (a) aspect ratio; (b) sphericity; (c) roundness; (d) convexity; (e) compactness





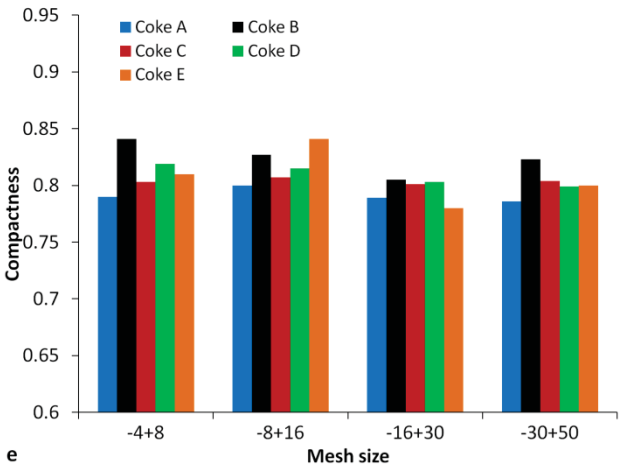


Figure 3. Shape factors for different size fractions of the cokes; (a) aspect ratio; (b) sphericity; (c) roundness; (d) convexity; (e) compactness (continued)

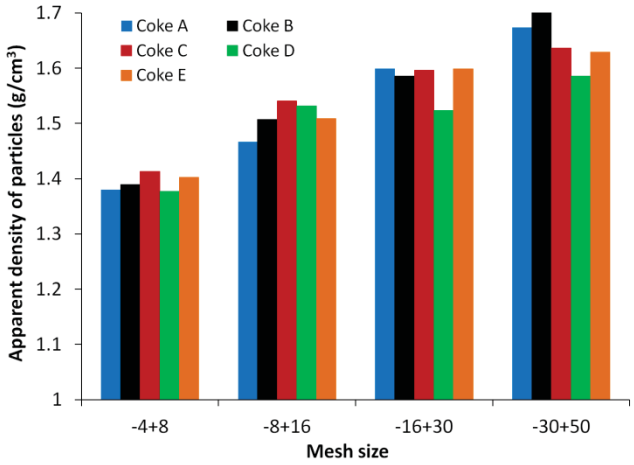


Figure 4. Apparent density for different size fractions of the calcined cokes

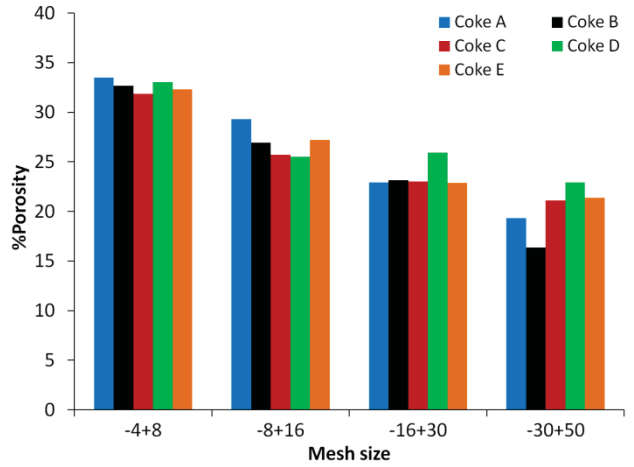


Figure 5. Porosity in various size fractions of the cokes

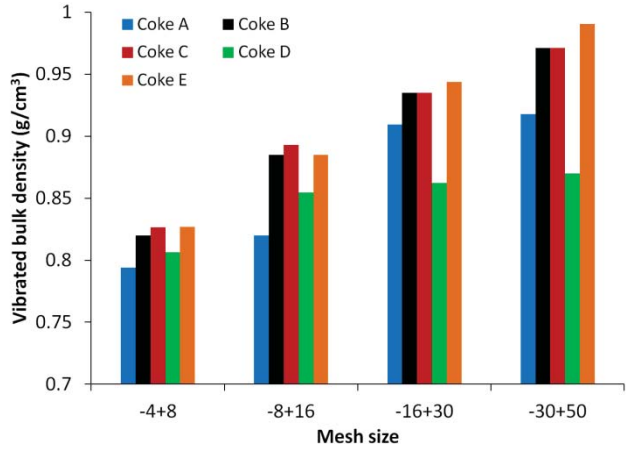


Figure 6. Vibrated bulk density for different size fractions of the cokes

Figure 7 shows the fraction of inter-particle voids after VBD test. This void fraction reveals the influence of particle shape and roughness on the packing behavior. This parameter is a measure of packing ability of particles. Cokes B, C and E had better packing properties and thus lower void fractions than cokes A and D. This is in agreement with particle shape factors in Figure 3. For example, the movement and rearrangement of coke A particles were restricted by irregular and elongated particles and thus resulted in a high volume of voids after vibration.

It is generally accepted and is seen in Figure 6 that VBD has an increasing trend towards smaller particles. Particle apparent density and inter-particle void are simultaneously changed with particle size reduction and affect the VBD. Void fraction for cokes A and D was increased with reducing the particle size. It can be explained by two facts. First, the number of contacts and thus the interaction between the particles increase for smaller particles. Second, irregular particles for Cokes A and D intensified the particle interaction and led to a higher volume of inter-particle voids. Therefore, enhanced apparent density for smaller particles (Figure 4) could not significantly contribute to the VBD of cokes A and D for -16+30 and -30+50 size fractions (Figure 6). Void fraction for cokes C and E did not increase with particle size reduction. It was even reduced towards -30+50 fraction. This is because these two cokes had more regular shape and spherical particles and a better packing ability. Lower inter-particle voids along with higher apparent density led to a continuous increase in VBD towards -30+50 fraction for cokes C and E (Figure 6).

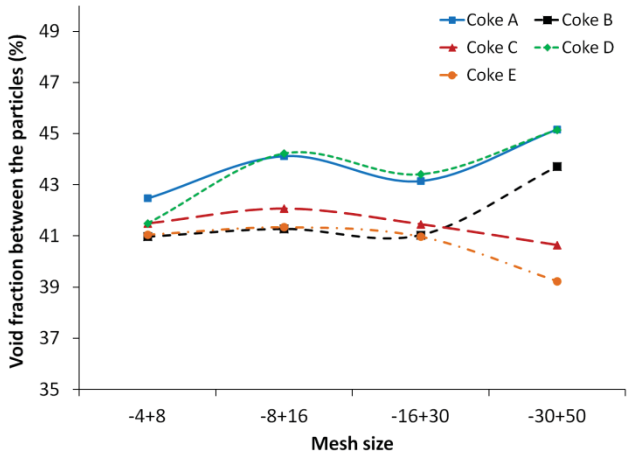


Figure 7. Void fraction between the particles after VBD test

Conclusions

Characteristics of calcined coke particles including the shape factors and envelope density were determined in this work. The influence of particle characteristics on the packing ability was studied and revealed useful information. Although apparent density of particles was a determining factor for VBD, particle shape was so important that in some cases it compensated the negative effect of particle porosity and could improve the VBD. Particle shape determines the rearrangement and packing behavior of particles during vibration. This study suggests that particle shape and porosity are the material properties that should be considered along with the real density and VBD to determine the packing behavior of coke and thus the anode density.

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