PHYSICAL AND MECHANICAL CHARACTERIZATIONS OF CARBON ANODES PRODUCED FROM DIFFERENT VIBRO-COMPACTORS

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Abstract

The aluminum industries in Quebec consume about 1.27 million tonnes per year of carbon for anode production. The anode quality is widely influenced by the quality of raw materials and the parameters of the manufacturing process which involves mixing, vibro-compacting, and baking. The anodes are regularly replaced at an interval of 20 to 30 days. This interval reduces when the anode quality is low. A better understanding of the vibro-compaction process would reduce the variation in the properties of formed anodes and thereby improve the anode performance during aluminum production. This, in turn, would reduce the cost and the greenhouse gas emissions. The focus of this work is to study the influence of vibro-compaction parameters on anode properties. The physical and mechanical characterization of anodes produced by different vibro-compactors was carried out. The article will present the results of this study.

Introduction

Physical and mechanical tests were performed on three green industrial carbon anodes. These anodes were formed on the same day with the same recipe, but in different vibro-compactors. Therefore, they were made with the same raw materials. The mixing and the vibro-compaction parameters were also the same. The only variable was the vibro-compactor since they were formed in three different compactors. To be able to characterize the mechanical properties of these anodes, a series of three-point bending tests according to the ISO 12986-1:2000 standard [1] and uniaxial compressive test according to the ASTM C695-91: 2005 [2] and ISO 18515:2007 (E) [3] standards were performed. Before doing these tests, the apparent density and electrical resistivity of all samples were measured according to ASTM D5502-00: 2010 [4] and ASTM D6120-97 [5], respectively. These measurements are necessary for the better interpretation of the mechanical tests results. The samples were taken from different anode positions in accordance to the sampling standard ASTM D6353-06 [6]. Figure 1 gives an overview of the positions of samples on the anode.

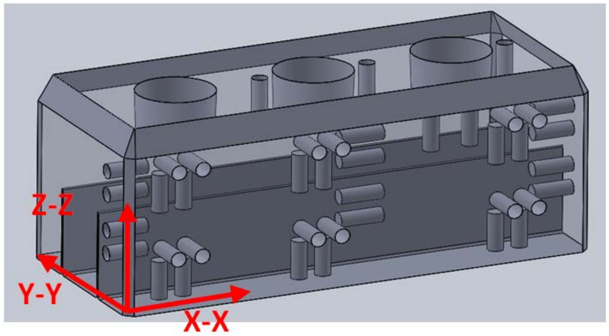

Figure 1 : Positions of samples on an industrial anode.

Test Methodology

<u>Three Point Bending Test [ISO 12986-1 : 2000]</u>

The three point bending test consists of applying a concentrated load on a sample simply supported at two points until failure. The maximum force F_{max} obtained at failure is used to calculate the flexural strength σ_{max}. Equation (1) shows the relationship used for the calculation of the maximum stress. The results of the test must be discarded if the fracture of the sample occurs outside the section which is limited by the supports as well as if the test duration time is less than 5 seconds. The test is performed at room temperature. The samples used for testing are circular with 50 mm diameter, *D*, and 130 mm in length. The length, *L*, between the supports is 80 mm with a loading rate equal to 1.27 mm / min. Figure 2 shows the equipment used for the three point bending test. It is a universal testing machine MTS Alliance RT100 with a maximum capacity of 100 kN.

$$\sigma_{max} = \frac{8.F_{max}.L}{\pi.D^3} \tag{1}$$

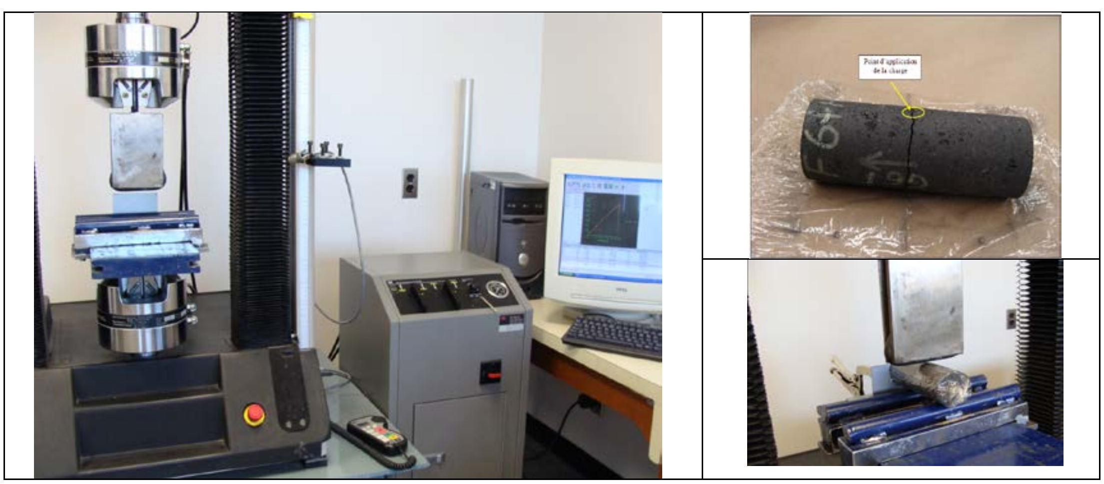

Figure 2 : Three point bending test.

19 samples were tested for each anode, consequently, a total number of samples were 57. During the test, it has to be verified continuously if the fracture of the sample occurs which mark the end of the test. The anode sampling was carried out in accordance with ASTM D6353-06 [6] as shown in figure 3.

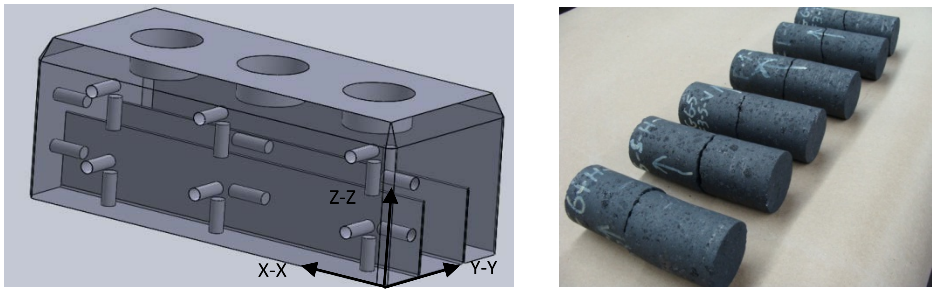

Figure 3 : Position of the samples tested in three point bending test.

Uniaxial Compressive Test [ASTM C695-91 : 2005 and ISO 18515:2007 (E)]

The carbon anodes can support large loads in compressive mode compared to other modes of support which are bending and tensile modes. The uniaxial compressive test allows the measurement of the compressive strength σ_{bB}, the stress-strain curve and the Young's modulus at room temperature. The maximum applied force, F, is recorded and used to calculate the compressive strength as shown in equation (2) where A represent the cross sectional area. The test sample must be straight and cylindrical with parallel end faces. The sample should have dimensions of 50 mm in diameter and 130 mm in length.

$$\sigma_{bB} = \frac{F}{A} \quad (2)$$

The equipment used for the uniaxial compressive test is shown in Figure 4. This is fatigue testing system Instron 8801 with a maximum capacity of 100 kN.

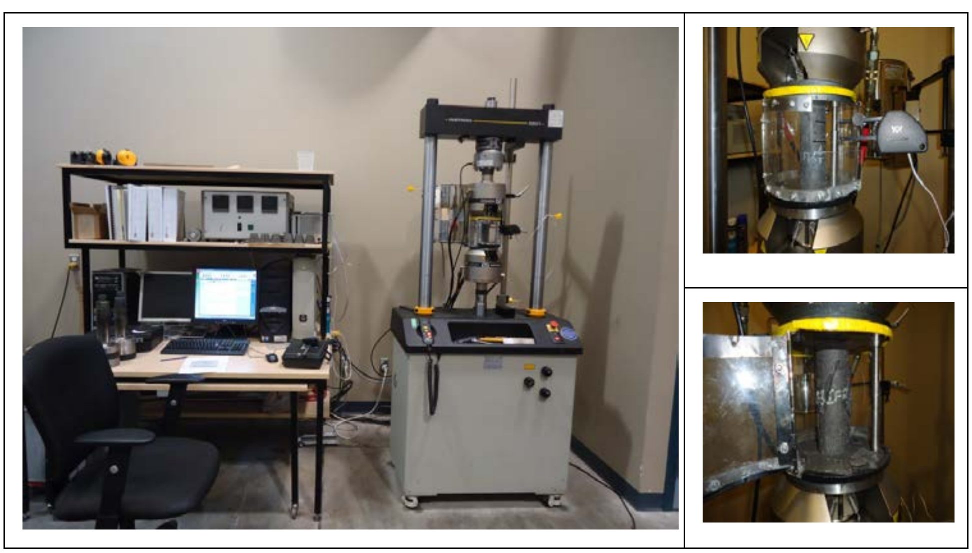

Figure 4 : Uniaxial compression test equipment.

Uniaxial tests were carried out using 22 samples per anode, therefore, total of 66 samples were tested. The positions of the samples tested in uniaxial compression are shown in figure 5. The positions of these samples were chosen to be close to those of the samples used in bending test.

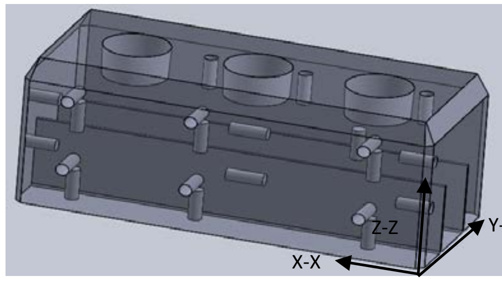

Figure 5 : Position of samples for uniaxial compressive test.

Apparent Density Measurement [ASTM D5502-00]

The apparent density is a very important measure for the characterization of the anodes. If the density is very low, the anodes are very porous. Their lifespan in the electrolysis cells will be shorter. However, if the density is too high, this might influence the mechanical properties of the anode by causing cracks and resulting in major financial losses. As it is well-known, the mechanical properties of anodes used in the Hall-Heroult process are of major importance. Therefore, a good compromise has to be found between these parameters.

The ASTM D5502-00 standard was used to measure the apparent density, *d*, of the samples. Initially, the samples were dried since they were taken in the presence of water in order to prevent the excessive dusting. The samples are cylindrical with a diameter of 50 mm and a length of 130 mm. To calculate the volume, *V*, the diameter was measured in four positions along the axes x and y axes and an average was taken. Regarding the length, again the average of four measurements was used. Finally, sample was weighed (*M*). Figure 6 shows the procedure for measuring the apparent density. 41 samples were tested for each anode (total of 123 samples). The calculation of the apparent density is carried out as follows:

$$d = \frac{M}{V} \tag{3}$$

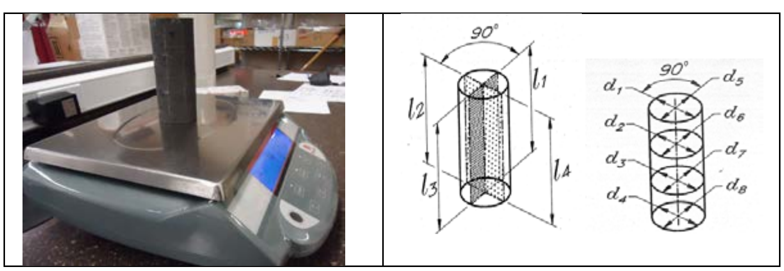

Figure 6 : Apparent density measurement.

Electrical Resistivity Measurement [ASTM D6120-97]

Electrical resistivity of a green anode is very high relative to the electrical resistivity of a baked anode. The measurements were performed on the same samples used for the apparent density measurements; therefore, 123 samples were tested. The device for holding the specimen is shown in figure 7.. An electric current, *I*, of 1 ampere intensity was passed through the sample. Thereafter, the average voltage, *V*, of the sample, on a section with 100 mm length (*l*), was measured using a voltmeter at eight different positions around the diameter. Equation (4) shows the formula used to calculate the electrical resistivity, *ER*, according to ASTM D6120-97 [5].

$$ER = \frac{V.A}{I.l} \tag{4}$$

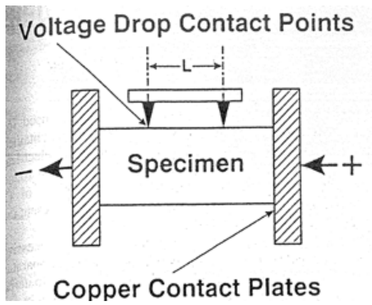

Figure 7 : Schematic of specimen holder [5].

Results and Discussions

The results obtained in the tree directions for all the tests were normalized. The normalisation was carried out by dividing each specific value by the average of all the results for each test. Table I presents the results of the flexural strength test for 57 samples. The tables II and III present the results of the compressive strength test and Young Modulus for 66 samples. The Young's modulus in compression was calculated from the slope of the stress-strain curve. The tables IV and V present the results of the apparent density and electrical resistivity measurement for 123 samples. The table VI presents a comparison between all the results in the three directions.

All tested anodes had a higher mechanical strength along the Y-Y axis compared to those measured on all the other axes. The apparent density measurements were also high for all samples along the Y-Y axis. The electrical resistivity of the samples was lower also on this axis. Each anode has three stub holes at the top where the rods are placed before the anodes are sent to the electrolysis cell. Regarding the samples situated at the bottom of the anode stub holes, their density and their mechanical strength were higher compared to those of the other samples. This section which is compacted by the vibro-compactor is shorter than the other parts of the anode and it is subjected to the same charge rate which explains the obtained result.

The mechanical properties of the samples which were situated between the stub holes were lower except for the anode N° 3. One reason for this result might be the uneven distribution of paste in the mold of the vibro- compactor. With the increasing compressive strength, Young's modulus increased except in the case of the anode N° 1 where it was variable.

Table I: Distribution report of bending stress along the three axes.

	Flexural strength					
	Anode N° 1		Anode N° 2		Anode N° 3	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Y-Y	1,12	0,91	1,03	0,47	1,09	1,11
Z-Z	1,01	1,04	1,01	0,93	0,86	1,45
X-X	0,97	0,93	0,99	0,97	1,1	1,19
Bottom of the holes	0,99		0,98		0,87	

Table II : Distribution report of the compressive stress along the three axes.

	Compressive strength					
	Anode N° 1		Anode N° 2		Anode N° 3	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Y-Y	0,96	0,78	1,04	1,18	1,06	1,32
Z-Z	0,92	1,29	0,99	1,35	0,87	1,39
X-X	0,9	1,73	0,99	0,52	1,03	0,91
Bottom of the holes	1,18	0	1,05	0	1,11	0
Between the holes	0,93	0,67	0,85	0,6	1,11	0,24

Table III : Distribution report of the Young’s modulus along the three axes.

	Young’s modulus					
	Anode N° 1		Anode N° 2		Anode N° 3	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Y-Y	1,09	0,95	1,39	4,12	1,04	0,38
Z-Z	1,09	1,73	0,93	0,3	0,88	0,38
X-X	1,12	1,81	0,97	0,3	0,89	0,88
Bottom of the holes	0,98	0	0	0	0,93	0
Between the holes	0,85	0,21	0,83	0,44	1,01	0,5

Table IV : Distribution report of the apparent density along the three axes.

	Apparent density					
	Anode N° 1		Anode N° 2		Anode N° 3	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Y-Y	0,94	0,54	0,94	0,48	0,94	0,61
Z-Z	0,93	1,08	0,94	0,54	0,93	1,16
X-X	0,93	1,61	0,94	0,48	0,93	1,37
Bottom of the holes	0,95	0,38	0,95	0,38	0,95	0
Between the holes	0,92	0,54	0,93	0,82	0,94	0

Table V : Distribution report of the electrical resistivity along the three axes.

	Electrical resistivity					
	Anode N° 1		Anode N° 2		Anode N° 3	
	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Y-Y	0,69	0,40	0,91	0,56	0,99	0,49
Z-Z	0,74	0,60	1,08	1,64	1,68	1,95
X-X	0,75	0,65	1,07	1,84	1,27	2,21
Bottom of the holes	0,81	0,21	0,96	0,38	1,05	0,18
Between the holes	0,87	0,35	1,25	2,66	0,87	0,88

Table VI: Comparison of physical and mechanical properties along the three axes.

	Flexural strength	**Compressive strength**	**Young modulus**	**Apparent density**	**Electrical resistivity**
Anode N°1	YY> ZZ >XX	YY> ZZ >XX	YY< ZZ <XX	YY> ZZ >XX	YY< ZZ <XX
Anode N°2	YY> ZZ >XX	YY> XX >ZZ	YY> XX >ZZ	YY> XX >ZZ	YY< XX <ZZ
Anode N°3	XX> YY >ZZ	YY> XX>ZZ	YY> XX>ZZ	YY> ZZ>XX	YY< XX <ZZ

Conclusions

The relation between mechanical strength and physical properties are not related automatically from each other. But each anode has its own particularity and its pattern for properties. From each anode tested it was observed that at the level of stub hole forming the mechanical and physical properties are with evidence different than the remains part of the anode. So the forming stub holes have an impact on the homogeneity on the anode bloc. The Young modulus and the compressive strength decreases with increasing electrical resistivity. The physical and mechanical properties of the three anodes tested were a slightly different from each other, especially in the case of anode N° 3. Also, the results highlighted that the characteristics of the vibro-compactor used during the forming process has an impact on the anode properties and anodes formed with different vibro-compactors can have different properties even if they are formed with the same paste. These results led to the development of a dynamic model of the vibro-compactor [7]. This model will make the correlation of the vibro-compaction parameters with the physical and mechanical properties of green carbon anodes possible. Each vibro-compactor have is own signature characteristic when we compare the strength at each axes by anode. Studying the parameter affecting the forming will be a great improvement on anode quality control.

Acknowledgements

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