Determination of optimum vibro-compaction time using sound analysis

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Abstract

The quality of carbon anodes plays an essential role in the production of primary aluminum. The vibro-compaction is one of the most important steps of the anode fabrication process, which affects the anode quality. Over and under-compacting results in anodes with high electrical resistivity, poor mechanical and physical properties. Therefore, the compaction conditions should be chosen carefully. A method and a sound analysis software were developed to determine the optimum vibration time using the sound generated by the vibro-compactor during anode compaction. This method was tested with a bench-scale system both in the laboratory and in the plant. It is simple, fast and inexpensive. The effect of anode raw materials (types of coke and pitch) and top-former bellow pressure of the vibro-compactor on the optimum compaction time as well as the effect of compaction time on anode properties were investigated. The results showed that there are three stages of anode formation during vibro-compaction, good quality anodes can be produced by using compaction time around the optimal value, and the utilization of sound analysis reduces the compaction time.

Keywords: Carbon anodes, vibro-compaction, optimum compaction time, aluminum production, under-compaction, over-compaction

1. Introduction

Primary aluminum is produced by electrolysis via Hall-Héroult process [1, 2] using carbon anodes, graphite cathodes, and alumina dissolved in cryolite. The energy required for the reduction of alumina to aluminum is supplied by electrical energy. The carbon anodes are produced using calcined petroleum coke, rejected green and baked anodes, recycled butts (aggregate) and coal tar pitch (binder). The anode paste obtained by mixing all the raw materials is compacted in a vibro-compactor to produce green anodes. The green anodes baked in open-pit anode baking furnaces to produce the baked anodes [3-4]. Then, the baked anodes are cooled and rodded before sending them to electrolysis. The baking step sets the final properties of the anodes. Defects (cracks, pores) formed during baking might be result of baking conditions as well as the raw material quality, and the green anode production conditions such as the parameters of mixing, compaction, and cooling.

The quality of anodes is very important in the production process, because it affects the metal quality, the production costs, and the greenhouse gas emissions. Furthermore, bad quality anodes disturb the stability of the electrolysis process and may cause the cell to dysfunction [5, 6]. Thus, the improvement of anode quality has become a concern for aluminum industry. The industry is constantly looking for better solutions through the implementation of quality control tools with the objective of approaching the optimum operation parameters of each unit involved in anode production.

Vibro-compactor has different operational parameters such as vibration force, frequency, and the compaction time, which affect the anode properties [7, 8]. The compaction time is one of the key parameters which is easy to adjust during the operation. An improper compaction time results in under-compacted or over-compacted green anodes, and reduces the anode quality. Hulse [9] found that the under-compacted anodes have larger porosity which results in reduced density and mechanical properties, and increased electrical resistivity. Porous anodes also lead to higher carbon consumption (operational cost) due to increased rates of side reactions with air and CO_2 (anode reactivity), consequently, higher GHG emissions. Furthermore, the energy consumption (operational cost) increases due to higher electrical resistivity. Over-compaction create stresses in the green anode, which causes crack formation during baking, again increasing the anode electrical resistivity [10]. Both under-compaction and over-compaction decrease the yield of the alumina reduction (aluminum production). There are a few studies on the impact of compaction time on

anodes throughout the literature. Hulse [9] has shown that the physical, mechanical, and electrical properties of the green anodes improve with increasing compaction time and pitch rate until the optimal compaction time is reached. Then, they start to deteriorate. Tkac [11] also obtained similar results.

There are also some attempts reported in the literature for determining the optimum compaction time of green anodes. Gao et al. [12] developed a method for determining the optimal compaction time by following the movement of a bar attached to the compactor cover. The time when the movement of the bar stopped was defined as the optimal compaction time. They correlated the optimal time with the anode size. According to this study, anode with a given size had one optimum compaction time. They did not consider that the anodes with similar sizes can have different optimum compaction times due to the non-homogeneity of raw materials, thus the anode paste. Jonathan et al. [10] used the acceleration of the vibro-compactor table to optimize the anode formation and correlated the green anode density with the compaction time, but the determination of optimum compaction time was difficult with this method.

During the present study, a method, a bench scale equipment, and a sound analysis software were developed to determine the suitable compaction time for each individual anode by using the sound generated by the vibro-compactor during the green anode formation. The sound was recorded via a microphone and analyzed with the developed software. In general, the compaction time is kept constant in the plants. However, due to the non-homogeneity of the raw materials, the optimum compaction time may be different for each anode. This method was validated and tested both on laboratory and industrial anodes.

Audible sound between 16 Hz to 16 kHz [13] was also used in different areas such as machine tools and machining [14], diesel engines [15], gears [16], welding [17], biology [18], and road safety [19]. An application of sound in primary aluminum production was also reported in the literature. It was applied to electrolysis cells as non-destructive methods to prevent anomalies during cell operation (both Söderberg and prebaked). The quality of the anodes was correlated with the sound of the bubbles recorded in the cell [20-21]. They found that the high gas flow through the anode cracks reduces the bubble noise underneath the anode. Therefore, low noise points out to the high number of cracks. Also, other problems such as the presence of anode pieces that has to be removed from the pot, splashing, erosion of gas manifolds, bath level, spike setting,

etc. can be related to sound produced by gas bubbles in the cell. The present study is the first study which uses the sound analysis to determine the optimum compaction time, thus improve green anode quality.

2. Methodology

A bench-scale experimental system was set up and a sound analysis software was developed to determine the optimum compaction time for each anode. The method was based on the change in the sound emitted by the vibro-compactor during the formation of green anodes.

The experiments were carried out both in the laboratory and in the plant. The laboratory scale anodes were produced in the carbon laboratory of the UQAC Research Chair on Industrial Materials/Chaire institutionnelle sur les matériaux industriels (CHIMI). The industrial anodes were produced in Aluminerie Alouette Inc. Sept-Îles plant.

2.1. Sound analysis

The software uses the "Fast Fourier Transform" (FFT), which is a method generally used for acoustics measurements. FFT converts the discrete data into a continuous data at different frequencies. The sound was recorded in time domain and converted to frequency domain. Thus, at any point of time, there was a value of sound intensity corresponding to each frequency. As, due to noises or other reasons, the intensity of sound for adjacent frequencies may vary and the variation would be difficult to analyze, averages for intensities corresponding to n number of frequencies were determined. That average intensity corresponding to the average of the frequencies was utilized for analysis. The averaging reduced spikes and helped in determining the change in sound level. A code in visual basic was developed for this purpose.

After the sound is recorded, the data is smoothed by taking the average of each (n) points. Then, the appropriate analysis frequency range (F) was determined. These two parameters play an essential role in signal processing. Subsequently, visualization of the results facilitates the determination of the optimal time sought. The recording and analysis of sound can be done simultaneously or sequentially.

The number of points (n) is used to smooth the sound curve in order to highlight irregularities in the signals as well as to eliminate undesired noise. This facilitates the determination of the phases of compaction and of the optimum compaction time. Thus, the value of (n) is determined by

keeping all the parameters constant and changing only (n). If (n) is too high, data is smoothed too much resulting in the loss of the characteristics of the curve. If it is too low, it is hard to detect the characteristics of the curve due to existing noise.

While a part of the recorded sound comes from the vibro-compactor, there are sounds coming from other equipment around the vibro-compactor. In order to eliminate this secondary noise and facilitate the comparison of the results, it is necessary to choose the suitable frequency range (F). The sound is therefore viewed as a function of time but in a frequency range. In order to determine the (F), the other parameters are fixed while the frequency range is varied. The desired range must have a fast (instantaneous) response and must clearly describe the phases of compaction.

Once determined, same (F) and (n) are used to analyze all the sound data. At the end, the data is converted back to the time domain with the Inverse Fourier Transformation (IFT). Using the rate of change in sound level and the defined thresholds, the different phases and the optimal time of compaction are determined.

2.2.Bench-scale equipment

2.2.1. Bench-scale experimental system

The experimental systems used in the laboratory and the plant are presented in Figure 1. It is composed of a unidirectional microphone placed next to the vibro-compactor and a data acquisition system which includes the developed sound analysis software. Unidirectional microphone captures the sounds in a specific direction from a space in a shape of cardioid. It eliminates the sounds in all other directions.

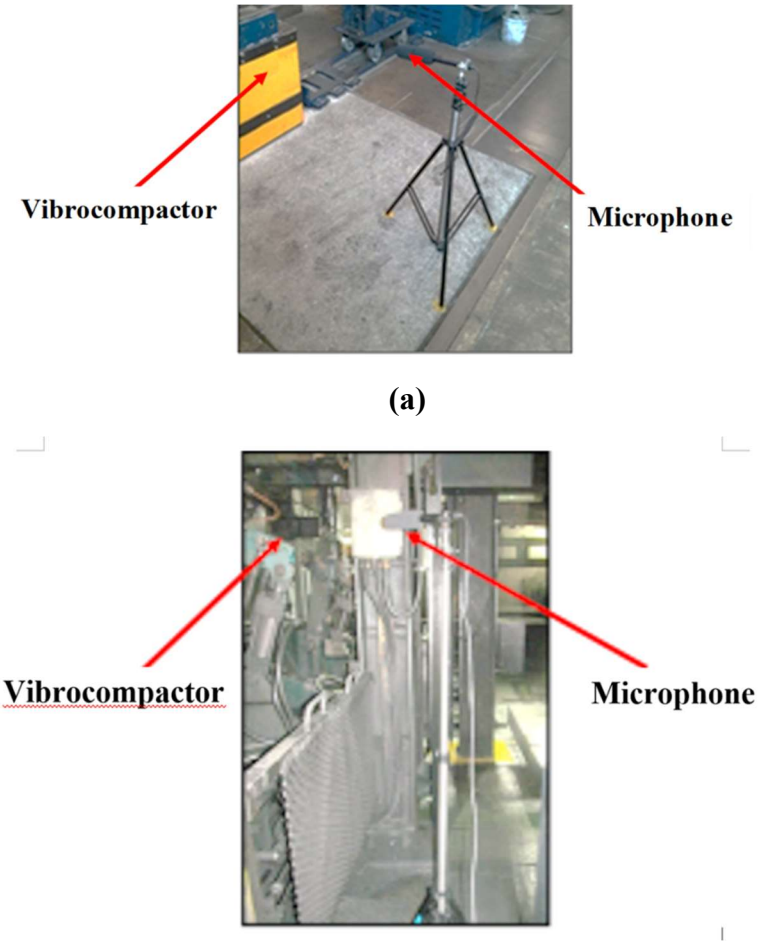


Figure 1: Bench-scale experimental system used in (a) the laboratory and (b) the plant

2.2.2. Experimental study in the laboratory

To produce the laboratory anodes, first calcined coke, rejected anodes, and butts (part of the anodes recuperated after the electrolysis) with a certain particle size distribution are mixed with pitch (binder) in an intensive mixer. This anode paste is compacted in a vibro-compactor to form a green anode. The sound of the vibro-compactor is registered for each anode.

The quality of the anodes depends on the raw materials (type of coke, the type of pitch, the particle size), the operating parameters used during anode production. These parameters affect the anode properties; therefore, they influence the optimal compaction time.

Two series of tests were carried out in the laboratory. The anodes produced in the carbon laboratory of Chair CHIMI at UQAC have similar properties to those of industrial anodes. Therefore, the

validation of the method was carried out with the laboratory anodes. In the first series, four anodes (Anode L1 to Anode L4) were produced using the compaction times t1 > t4 > t2> t3 for the validation. (L) indicates the laboratory anodes. t4 was the standard compaction time. Therefore, the anode produced using this time was taken as the standard (reference) anode. t2 was the optimum compaction determined with the sound analysis. The anode produced by compacting the anode t2 s and stopping the compaction manually when this time was detected by the software.

In the second series, two groups of anodes were made. First, four anodes (Anode L5 to Anode L8) were produced using the compaction time of the standard anode (t4) and baked using different heating rates. It is important to note that the same standard heating rate (h) was used up to 600°C, then the different heating rates were applied. The most of the volatiles are released before this temperature. Therefore, relatively slower heating rate (h) was used below 600°C in order to avoid a rapid volatile release which can cause crack formation. Above 600°C, heating rates faster than the standard (h<h1<h2<h3<h4) were used in order to compensate for the time lost due to the utilization of low heating rate below 600°C, hence increase the anode production rate.

After, another six anodes (Anode L9 to Anode L14) were produced with the aim of studying the effects of raw materials (types of pitch and coke) on compaction time.

The anodes were characterized by measuring their density, resistivity and compressive strength according to ASTM D5502-00, ASTM D6120-97, and ASTM C695-91:2005 [22, 23, 24], respectively. These properties were correlated with the compaction time to determine if the anodes are under or over-compacted.

2.2.3. Industrial measurement campaign

The plant tests were carried out during the industrial measurement campaign. First, the software was improved and the experimental system was standardized by determining the best position of the equipment relative to the vibro-compactor and the parameters in order to capture the vibro-compactor sound, and the first tests were carried out.

Then, the tests were carried out at the plant to study the effect of pitch percentages (Anode I1, to Anode I3), and variation of the top-former bellow pressure of the compactor (Anode I4 and Anode I5). The vibrating table represents one of the most important elements constituting a vibro-compactor. This table is isolated by using air cushions made of inflatable rubber. The top-former

bellow pressure refers to the pressure of the top air cushion. In order to obtain anodes which are produced using the optimum compaction time, the compaction was manually stopped when the optimum compaction time was detected by the software similar to the laboratory experiments.

These anodes were characterized in the carbon laboratory of Chair CHIMI at UQAC by measuring their density, electrical resistivity and compressive strength according to ASTM standards mentioned in the previous section. The characterization was carried out with 60 cores extracted from the industrial anodes. To do this, two small blocks were removed from the anodes (Figure 2(a)). These blocks were then cored as shown in Figure 2(b).

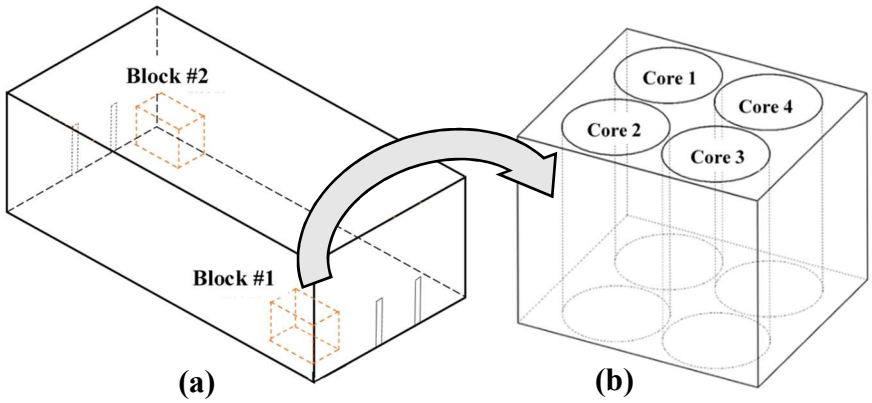


Figure 2: (a) Extraction and (b) coring plan of small anode blocks

After each core was numbered in the form AX-B-C where A is the anode number (Anode I1 to Anode I5 where (I) indicates the industrial anodes), B is the block number, and C is the core number. For example, A1-1-3 indicates that the core 3 comes from the block 1 of anode number 1.

3. Results and discussion

The results are presented in dimensionless form due to the confidentiality of the industrial results. They are obtained by dividing the values of the parameters by a reference value.

3.2. Characterization of the vibro-compaction of anodes

The analysis of the sound recorded both in the laboratory and the plant showed that there are three phases of anode compaction as shown in Figure 3:

- Phase 1: The reorganization of the pitch and coke particles observed as a rapid increase in sound level.
- Phase 2: The vibro-compaction of anode. In this phase, anode paste is compacted and a green anode is formed. This phase is characterized by a monotonic and flat curve.
- Phase 3: This phase indicates the end of the compaction. At this stage, the block is sufficiently compact and solid. This phase is observed first as an increase followed by a stabilization of the sound level which indicates the optimum compaction time.

Similar trend was observed by Rebaine [8] during the anode paste rigidity measurements in the laboratory.

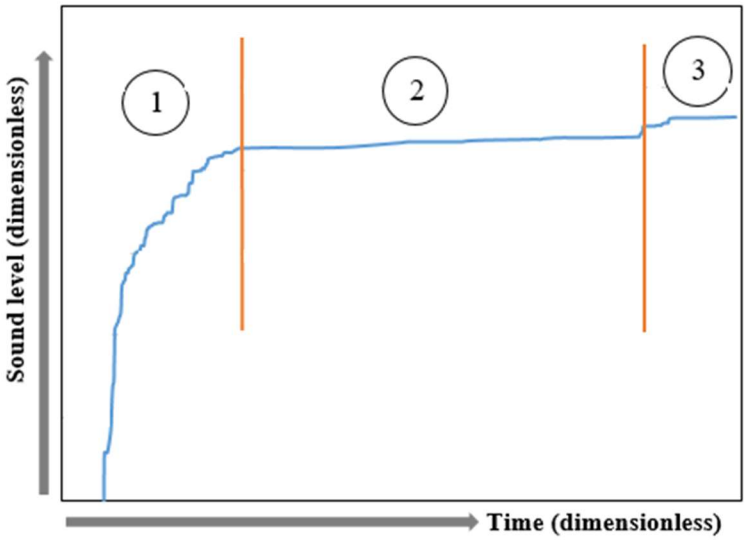


Figure 3: The phases of anode vibro-compaction (the optimum compaction time is at the beginning of the last plateau)

3.3. Laboratory anodes: Validation of the method

As it was explained in the methodology section, three series of anodes were produced in the laboratory.

3.3.2. First series of anodes

In the first series, four anodes (Anode L1 to Anode L4) were produced at different compaction times ($t_1 > t_4 > t_2 > t_3$), and characterized. t_4 and t_2 are the standard and optimum compaction times, respectively. These results were used to validate the method developed.

During characterization, green anode density (GAD), baked anode density (BAD), baked anode resistivity (BAR) and mass loss during anode baking were measured. The optimum time was detected for each anode during vibro-compaction using sound analysis. The over-compaction time was calculated by determining the difference between the actual compaction time used during the anode production and the optimum compaction time found from the sound analysis. Table 1 presents the results. In order to show the impact of compaction time on anode density, the over-compaction time is correlated with the BAD/GAD ratio (Figure 4). As it can be seen from this figure, the BAD/GAD ratio is greatest for the anode manufactured at the optimum compaction time (Anode L2 at t2) for which the residual stress due to the compaction is low in the anode. Utilization of this time prevents significantly the formation of cracks during the volatile release. This means that the anodes compacted with the compaction times of t1 (Anode L1) and t4 (Anode L4) are over-compacted whereas the anode compacted with the compaction time of t3 (Anode 3) are under-compacted.

The mass loss during anode baking is presented in Figure 5, and GAD and BAR are presented in Figure 6. The results for the mass loss are similar, and the anode with the optimum compaction time (Anode 2, L2, t2) has the second lowest mass loss. The electrical resistivity results show a similar trend, BAR of the anode with the optimum compaction time (Anode 2, L2, t2) has the second lowest value. Anode 1 (L1, t1) has the highest green density since it was the most over-compacted anode with longest compaction time. This anode (Anode 1, L1, t1) has also the highest mass loss and the lowest BAD/GAD ratio. Anode 3 (under-compacted) and Anode 4 (over-compacted) had higher electrical resistivities compared to that of Anode 2, which is compacted using the optimum time. The under-compacted anode (Anode 3) is indicated with a negative over-compaction time. Although it is over-compacted, the resistivity of Anode L1 is slightly lower than that of Anode L2. This is probably due to the higher green density of this anode compared to that of Anode L2.

Table 1: Results of the first validation (values are dimensionless)

Anode	Compaction time	Optimum compaction time	Over-compaction time	GAD	BAD	BAD/GAD	BAR	Mass loss (%)
L1	t_1	0.678	1.122	1.087	1.046	0.962	0.970	4.25
L2	t_2	0.660	0	1.060	1.031	0.973	1.041	4.11
L3	t_3	-	- 0.990	1.030	0.997	0.968	1.230	4.15
L4	t_4	0.764	0.436	1.037	1.005	0.969	1.145	4.07

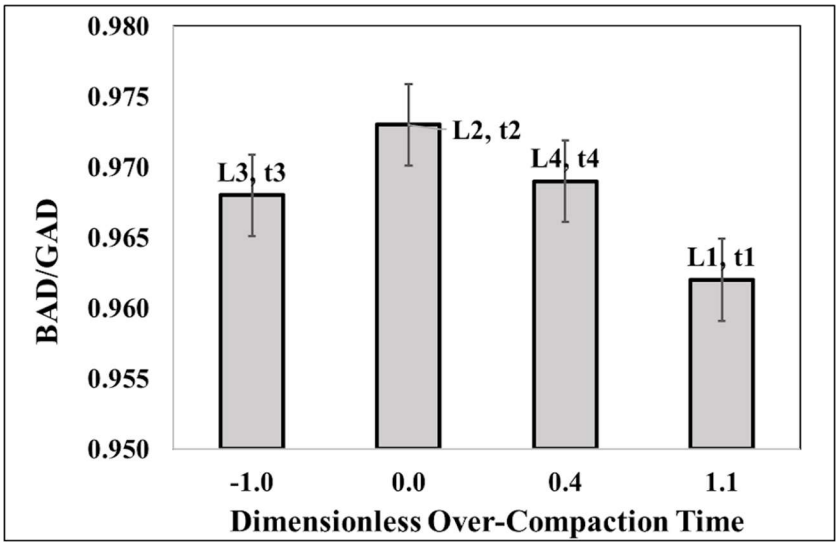


Figure 4: BAD /GAD of anodes as a function of over-compaction time

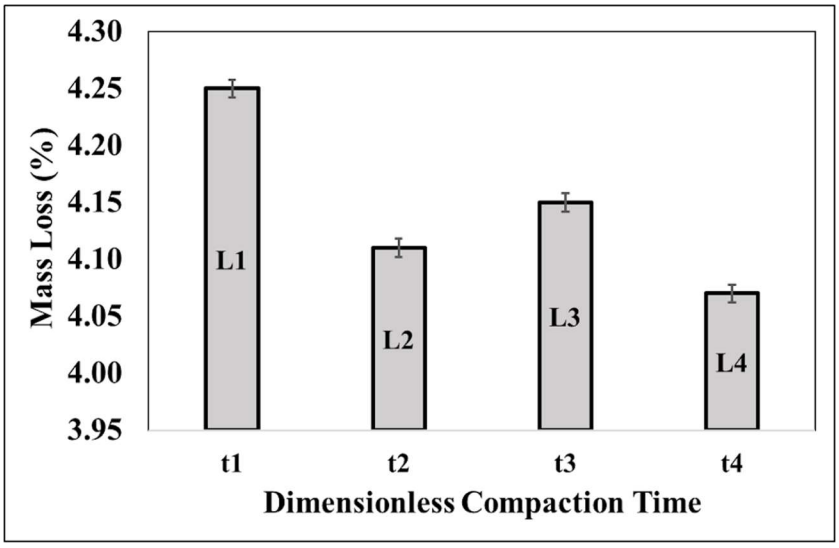


Figure 5: Mass loss during baking

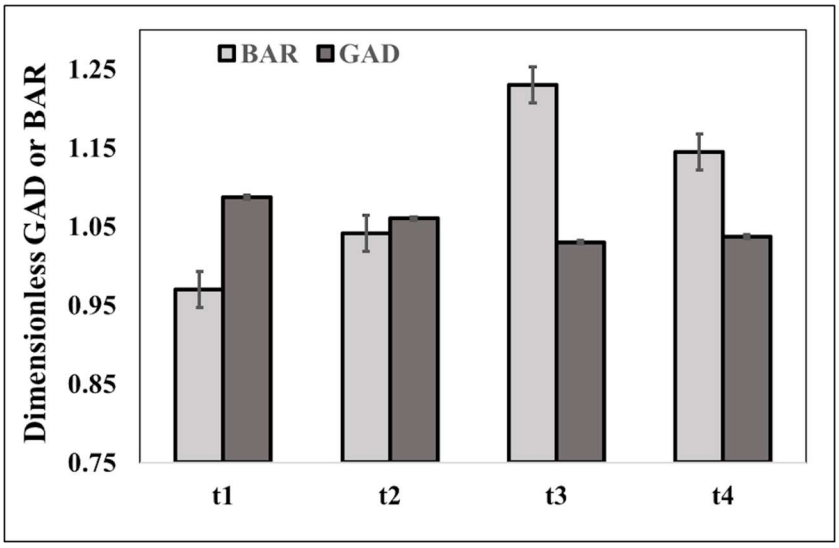


Figure 6: The electrical resistivity of the baked anodes and the density of the green anodes

3.3.3. Second series of anodes

For the second series, another four anodes (Anode L5 to Anode L8) were produced using the standard compaction time and their over-compaction time was calculated by taking the difference between the compaction time used and the optimum time determined with the sound analysis. They

were baked with the heating rate of "h" up to 600°C and with higher heating rates (h<h1<h2<h3<h4) afterwards. The results are presented in Table 2.

Although the same compaction time was used for these anodes, each has a different over-compaction time. This is due to the non-homogeneity of the raw materials used, which is the case also in the plant. This shows that the determination the compaction time of each individual anode will help to improve their quality.

Anode L7 had a compaction time close to the optimum time whereas Anode L5 was the most over-compacted anode. Anodes L6 and L8 were also over-compacted with similar over-compaction times. Figure 7 shows that the Anode L7 had the highest and Anode L5 has the lowest BAD/GAD ratio. Anodes L6 and L8 had similar over-compaction times, thus their BAD/GAD ratios were also similar.

As it can be seen from Table 2 and Figure 7, the BAD/GAD ratio is dependent on the over-compaction time, and increasing the heating rate after most of the volatiles are released, did not affect the results. This shows that the heating rate can be increased after 600°C to increase the production rate without affecting the anode quality.

Table 2: Results of the second validation (values are dimensionless)

Anode	Heating* rate	Optimum compaction time	Over-compaction time	Green anode density (GAD)	Baked anode density (BAD)	BAD/GAD
L5	h, h1	0.764	0.436	1.096	1.061	0.969
L6	h, h2	0.851	0.349	1.099	1.069	0.972
L7	h, h3	1.171	0.029	1.089	1.061	0.974
L8	h, h4	0.878	0.322	1.089	1.059	0.972

h<h1<h2<h3<h4

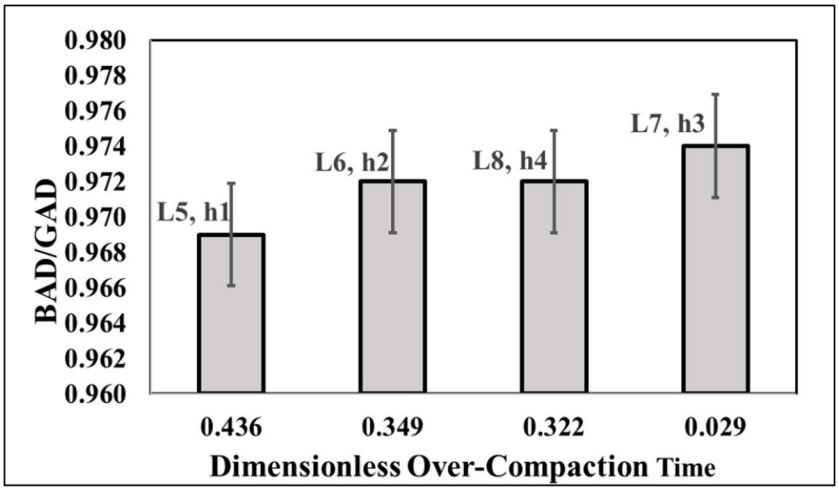


Figure 7: BAD/GAD vs, over-compaction time for the second series of anodes

3.2.3 Third series of anodes

3.2.3.1 Pitch type

Three anodes (Anode L9 to Anode L11) were produced using three different pitches. All the anodes were manufactured under standard conditions with the exception of the type of pitch. The three types of pitch used had different percentages of quinoline insolubles (QI1 < QI3 < QI2). Also, the size of the QI particles was different ($p_{QI1}<p_{QI2}<p_{QI3}$). Anode L9 was produced with the pitch (P1) containing smallest size QI (QI1) particles whereas the size of QI particles (QI3) was largest in the pitch (P3) used for the production of Anode L11. The anodes were baked and characterized. It can be seen from

Figure 8 presents GAD and BAD/GAD as a function of over-compaction time. GAD of the anode (L11) produced with the largest QI particles is the smallest, and GAD of the one produced with the smallest QI particles is the highest (L9). This result is in agreement with the previous work [25]. It was found that the pitch with greater QI particle size penetrates less into the pores of the coke particles, thus leading to a lower density since the pitch did not fill all the particle pores.

It can also be seen from the same figure that BAD/GAD increases with decreasing over-compaction time. BAD/GAD is largest for the anode (L11) which has the lowest over-compaction time probably due to less crack formation. The over-compacted anodes have usually more pores and cracks forming due to the release of the stresses created during vibro-compaction and the release of volatiles at the different stages of baking [9].

Table 3: Results for the anodes produced with different pitches

Anode	Pitch/ QI content/ QI particle size (p_{QI})	Optimum compaction time	Over-compaction time	GAD	BAD	BAD/GAD
L9	P1 / QI1 % / Smallest	1.070	0.130	1.039	1.015	0.978
L10	P2 / QI2 % / Medium	1.050	0.150	1.027	1.014	0.987
L11	P3 / QI3 % / Largest	1.110	0.090	1.011	1.017	1.005

QI1 < QI3 < QI2; $p_{QI1}<p_{QI2}<p_{QI3}$

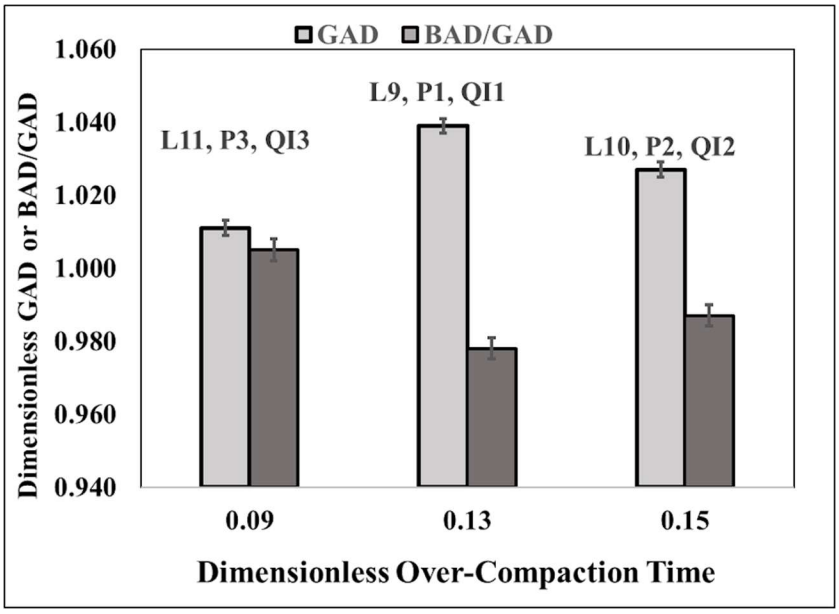


Figure 8: GAD and BAD/GAD as a function of compaction time of anodes made with pitches containing different QI content (QI1 < QI3 < QI2) and QI particle size ($p_{QI1}<p_{QI2}<p_{QI3}$)

3.2.3.2. Coke type

Three anodes were produced with three different types of coke (Anode L12 to Anode L14). These cokes represent a mixture of two types of coke: low sulfur coke (LSC) and high sulfur coke (HSC). Thus, their sulfur contents were different. Coke (Coke 1, S1) used for Anode L12 had the lowest sulfur content whereas coke (Coke 3, S3) used for Anode L14 had the highest. All the anodes were produced under the same standard conditions. Only the type of coke was different.

The results show that the GAD increases with increasing sulfur content as can be seen in Figure 9 and Table 4. Previous work has shown that low-sulfur coke has a higher percentage of open pores than high sulfur coke [26]. Also, it is reported in the literature that the increasing sulfur content increases the wettability of coke by pitch [27]. Therefore, Anode L12 has the lowest GAD and Anode L14 has the highest GAD.

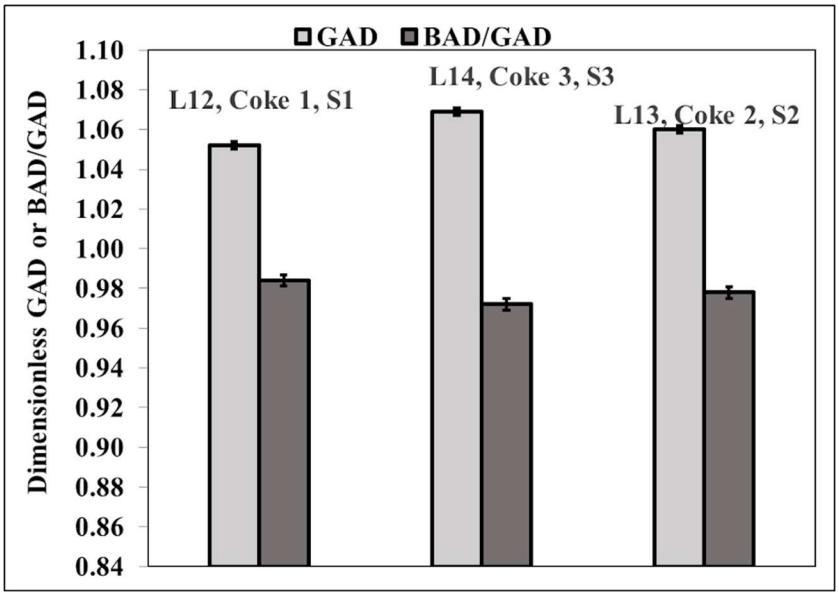
Again, the anode with the lowest over-compaction time (Anode L12) gives the highest BAD/GAD value. Anodes L13 and L14, which have relatively close over-compaction times (Table 4), have similar BAD/GAD values. This means that a compaction time that is closer to the optimum time result in less crack formation better BAD/GAD.

The results obtained from the laboratory anodes validate the developed method showing that the anodes compacted using the optimum time, in general, have better BAD/GAD ratios. This means if the compaction is stopped at the right moment, the anode does not build up extra stress that is released during baking leading to crack formation. The raw materials (pitch and coke) used in the plants are mixture of the raw materials coming from different suppliers. The composition of each anode can be slightly different. The results show the importance of determining the optimum compaction time for each anode. Even the anodes produced under similar conditions might have different optimum compaction times due to the non-homogeneity of the raw materials.

Table 4: Results for the anodes produced with different cokes (values are dimensionless)

Anode	% S in coke	Optimum compaction time	Over-compaction time	GAD	BAD	BAD/GAD
L12	S1 (Coke 1)	0.860	0.340	1.052	1.035	0.984
L13	S2 (Coke 2)	0.553	0.647	1.060	1.037	0.978
L14	S3 (Coke 3)	0.664	0.536	1.069	1.039	0.972

S1(Coke 1) < S2 (Coke 2) < S3 (Coke 3)



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359 Figure 9: GAD and BAD/GAD as a function of over-compaction time of anodes made with
360 cokes containing different sulfur contents (S1<S2<S3)

361

362 **3.3. Plant measurement campaign results**

363 In the plant, there are different noises. The noises may arise from different parts of the vibro-
364 compactor or other equipment. The objective was to record the sound of the cover of the compactor
365 mold hitting the anode top surface. Thus, distance and position of the microphone with respect to
366 the vibro-compactor mold was adjusted so that there was minimum noise captured from other
367 equipment and reasonable sound of the cover was captured. Maximizing the sound from the mold
368 was not the only criteria, minimization of other noises was also necessary. The level of sound
369 generated from the mold was less of a concern. The ability to record changes in sound level due to
370 the impact of mold cover with the anode surface was important. Based on this understanding, the
371 position of the microphone was determined. The position of the microphone was maintained the
372 same for all the measurements. The position may vary for other plants or other vibro-compactors.

373 First, the equipment is calibrated by determining the position of the microphone (ATR6550 used
374 at the normal mode) and its distance from the industrial vibro-compactor. After, the effects of the
375 pitch percentage and top-former bellow pressure were studied.

376

3.3.1. Pitch percentage

Three industrial anodes were produced to study the effect of the pitch percentage on compaction time in the plant (Anode I1, to Anode I3) containing different percentages of the same pitch (Table 5). Anode I3 had the lowest and Anode I2 had the highest pitch percentages (PP3<PP1<PP2). Anode I2 had the highest density since it had the highest pitch percentage and the lowest over-compaction time (Table 5). In fact, Anode I1 and Anode I2 have similar BAD/GAD ratios since they have similar over-compaction times compared to that of Anode I3 (Table 5). These anodes were produced at compaction times, which are relatively closer to their optimum values, thus avoiding excess crack formation during baking.

Figures 10 shows the electrical resistivity of these anodes before and after baking. It can be noted that the electrical resistivity decreases with the increase in the pitch percentage as it is also reported in the literature [9]. Also, the optimum compaction time increases with increasing pitch percentage (Table 5). Thus, it takes longer to compact an anode as the pitch percentage increases.

An addition, pitch helps to fill the void between the particles and in the pores, thus reducing the electrical resistivity of both green and baked anodes. However, there is a limit for increasing the pitch percentage. The excess pitch increases the electrical resistivity since electrical resistivity of pitch is higher than that of the coke but lower than that of the air in the voids. Anode I1 and I2 have similar resistivities in green state showing that this pitch percentage is close to the maximum.

Table 5: Densities of the industrial anodes containing different pitch percentages (PP3<PP1<PP2)

Anode	Pitch %	Over-compaction time	GAD	BAD	BAD/GAD
I1	PP1	0.058	1.112	1.073	0.965
I2	PP2	0.038	1.120	1.079	0.964
I3	PP3	0.183	1.113	1.068	0.959

Table 6: Electrical resistivity and compressive strength of the industrial anodes containing different pitch percentages (PP3<PP1<PP2)

Anode	Pitch %	Electrical resistivity	
		GAR	BAR
I1	1.010 (P1%)	1.182	0.998
I2	1.020 (P2%)	1.136	0.983
I3	1.000 (P3%)	1.648	1.041

GAR: Green anode resistivity; BAR: Baked anode resistivity

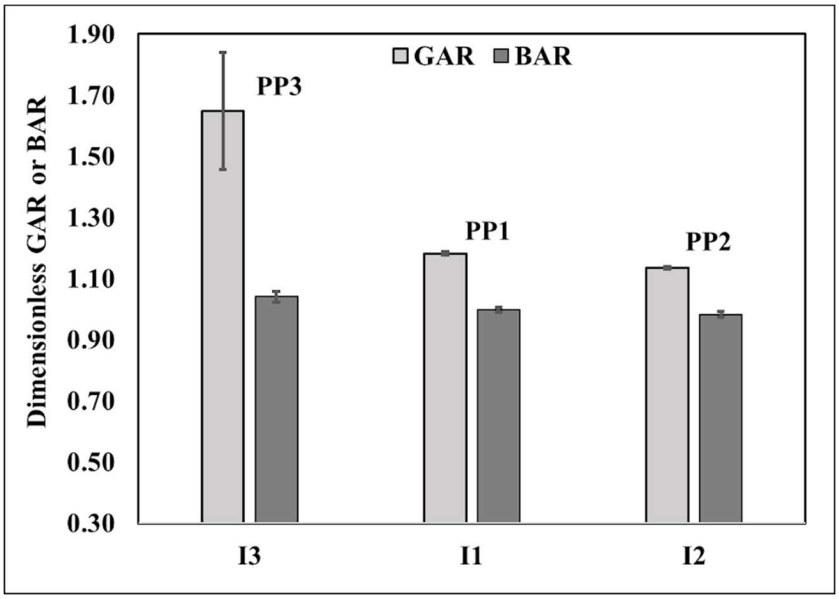

Figure 10: Green (GAR) and baked anode (BAR) electrical resistivities (PP3<PP1<PP2)

3.3.2. Top-former bellow pressure

The vibrating table of a vibro-compactor is isolated using inflatable rubber cushions (bellows) filled with compressed air. The pressure of these bellows affects the compression. To evaluate the impact of the top-former bellow pressure on the compaction time and anode properties, two anodes (Anode I4 and Anode I5) were produced. Varying this parameter significantly affects the vibro-compactor performance and can cause problems by exposing the compactor to extreme conditions.

Therefore, the range of this parameter is limited. The results shown in Tables 7 and 8 indicate that the density increased whereas resistivity and optimum compaction time decreased both for green and baked anodes with increasing top-former bellow pressure. High pressure facilitates the penetration of pitch between the coke particles and into the coke pores, hence improves the anode properties within the range studied. This result was also reported in the literature for laboratory green anodes [8]. It is therefore important to have optimal top-former bellow pressure in order to have better compaction at an optimum time.

Table 7: Optimum compaction time of the anodes produced with different top-former bellow pressure

Anode	Top-former bellow pressure	Optimum compaction time
I4	1.0	>1
I5	1.2	1

Tableau 8: Density, electrical resistivity and compressive strength of the anodes produced with different top-former bellow pressure

Anode	Density		Electrical resistivity	
	GAD	BAD	GAR	BAR
I4	1.021	0.984	1.906	1.121
I5	1.048	1.011	1.052	1.015

4. Conclusions and recommendations

The anode quality control is of great importance to the primary aluminum industry. It highly depends on the operating parameters. An improper choice of compaction time can lead to poor quality anodes, which cause problems during electrolysis. This article presents a method of determining the optimum compaction time using the sound of the vibro-compactor recorded during the compaction. This method makes it possible to determine the optimal compaction time for each individual anode, consequently leads to the improvement of baked anode properties.

Utilization of this method showed that the anodes go through three phases during vibro-compaction. The impact of compaction time on anode properties was assessed. The results showed that anodes compacted at the optimum time or close to the optimum time (low over-compaction time) generally acquire a better baked anode density for a given green anode density (high BAD/GAD ratio).

The raw materials affect the green anode density. Higher sulfur-containing coke and pitch with smaller QI particles result in greater green anode density. In any case, the best BAD/GAD ratio is achieved when the compaction time is closer to the optimum value. That is, potentially the best baked anode density for a given green anode density is obtained when the compaction is carried out at the optimum time.

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