MELTING AND DENSIFICATION OF ELECTRODE PASTE BRIQUETTES IN SØDERBERG ELECTRODES

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ABSTRACT

Safe and good operation of Søderberg electrodes is dependent upon high quality electrode paste coupled with correct electrode operating procedures. Good electrode performance depends further on proper melting and densification of the electrode paste. The melted paste should form a dense and viscous layer that prevents gasses from the baking process to move upwards. Both paste cylinders/blocks and briquettes can be used, but the procedures may differ between the various types of paste products.

For briquette columns the formation of the important viscous layer is obtained through melting and densification of the briquettes. By basic rheological studies of electrode paste and by laboratory tests of briquette beds at isothermal conditions we have achieved a better understanding of the melting process. The effects of temperature gradients, pressure and friction between the briquettes and the electrode casing have also been evaluated qualitatively in pilot scale experiment and in industrial scale tests.

The paper shows that melting and densification starts at a considerable lower temperature than the pitch softening temperature. It is concluded that the formation of a briquette electrode column depends on parameters as temperature, briquette column pressure and the friction. Operating conditions influencing the above parameters should be defined and established for each specific furnace operation. Such factors are e.g., charging and slipping procedures, column heating and electrical conditions.

1. INTRODUCTION

Søderberg electrode paste is produced in various shapes and sizes. Briquettes, cylinders and blocks are utilized with good results. The different shapes all have some advantages relative to shipping, handling and storage. The various shapes will also affect the control of softening/melting phase in the electrode column. Control of the paste softening level with cylinders or blocks is easily done by the "Molten Paste Level" (MPL) measurement. A MPL kept in the range 2 to 3 meters above the contact shoes is a normal control range. A stable, highly viscous paste layer acts as a dens stopper preventing baking gases to rise upwards in the column. The gases should exit downwards below the contact shoes. In cases where the MPL is too shallow, electrode segregation can occur.

Briquettes facilitate easy paste charging, eliminating the need for cumbersome lifting tongs. In cases with paste segregation we have had good experience with charging the paste partly as briquettes. Segregation is seldom seen when only briquettes are used. The charging of briquettes can be fully automated.

A main concern about briquette usage is the formation of “bridges” which can stop flow of paste in the electrode column. Knowledge on flow behavior of electrode paste in the column can also help to define safe and easy operation in relation to bridge formation. A key in this process is to understand and to control the paste flow properties.

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“Plasticity”, the percentage diameter change of a paste sample after a defined heat treatment, is used as a measurement of the paste’s ability to flow. The plasticity and the pitch softening point, provide information about the paste softening and flow behavior. However, to study and characterize the melting of the paste, simulating actual conditions, other methods are necessary. Elkem has developed a parallel plate viscometer for electrode paste characterization [1], which has shown itself to be an important tool in the production of high quality electrode pastes. A mathematical model for the flow behavior of a briquette bed has also been made [2], and Elkem is also working on empirical models based upon simple paste flow tests. At Infacon Nine in Quebec City, Amaro et al [3] presented initial studies on briquette melting in full-scale ferroalloy electrodes. The need for further work in this area was pointed out.

2. MEASUREMENTS OF ELECTRODE PASTE BEHAVIOR DURING MELTING

2.1 Flow Characterization of Electrode Paste

The typical electrode paste composition is a mixture of binder, coal tar pitch, and various carbon granular materials such as calcined anthracite, calcined petroleum coke and graphite. In case of briquette melting and densification we also have the two-phase system of air and electrode paste.

Normal electrode pitch is considered as a Newtonian liquid [4] and is easy to typify. Electrode paste, which typically consists of 70-80 % granular material, shows a more complex flow behavior because of particle-particle and particle-pitch interactions.

Flow properties depend on parameters such as pitch type and softening point, amount of pitch, carbon aggregate quality, shape and particle granulometry. Mixing parameters as mixing time, temperature and type of mixer are also known to influence the flow behavior. It is essential to have a clear understanding of the applied procedures when predicting the behavior of paste. For this purpose we have designed and constructed special laboratory- and pilot scale equipment.

- Flow behavior of a paste cylinder or “a single briquette” including apparent viscosity measurement
- Flow and densification of briquette bed at isothermal laboratory condition
- Measurement of interaction (friction) between electrode paste and steel casing
- Flow and densification of briquette bed in laboratory furnace with temperature gradients

In addition to these laboratory methods, an improved system for investigating flow behavior of a briquette bed in commercial sized electrodes has been developed.

2.2 Flow and Viscosity Measurement on Paste Cylinders

When a cylinder commences to melt in an electrode it is compressed between two other cylinders. In the laboratory this is simulated by placing a preheated cylinder between two parallel steel plates and measure the change of height with time, Figure 1. The test was designed to recreate the conditions that exist in a full-scale electrode, such as shear rates, temperature range 40-100ºC, and a large sample where effects of the size of the carbon particles can be neglected.

In full-scale electrodes paste cylinders will typically melt and disperse covering the whole column diameter within 6-24 hours. An average shear rate Vr, at periphery radius R, can according to Tørklep [2] be calculated by

$$Vr = (3R/h^2)\, dh/dt \qquad (1)$$

For a paste cylinder, with diameter 1 m and height 0.5 m, we get a rough estimate of the range of shear rates; $2 \times 10^{-4} - 5 \times 10^{-5}\ s^{-1}$. For a sample with diameter 0.17 m this corresponds to a flow test that typically lasts for 1-5 hours. The flow test has been standardized for a duration of minimum 20 hours.

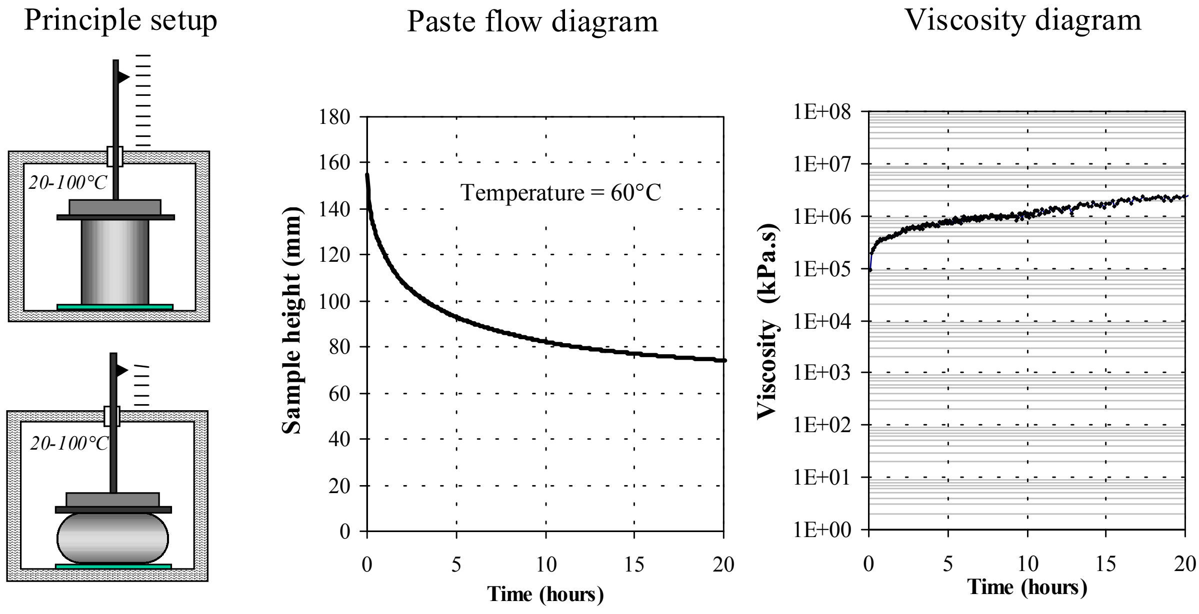

Figure 1. Flow test and viscosity measurement of a paste cylinder or "a single briquette". The weight placed on top of the cylindrical sample (Ø 0.17 m and h_0 = 0.16 m) equals the pressure from a column of approximately 2.5 m paste cylinders.

An example of test results are presented in Figure 1, *paste flow diagram.* The measurements can be used to calculate the apparent viscosity of the sample resulting in a better understanding of the flow. The method for the calculations has been described by Tørklep [2].

Figure 2 shows an *isoplot* of results from testing (ref. test in Figure 1) two parallel samples of various materials. The measurement system is considered to be good enough for the planned investigations.

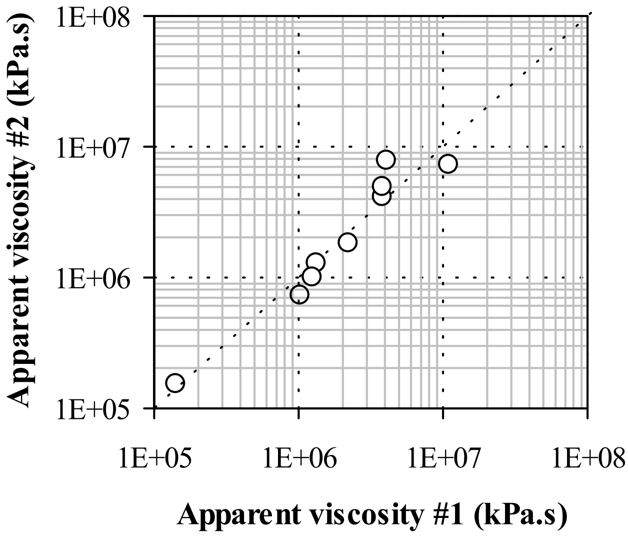

Figure 2. Isoplot of measured apparent viscosity (0.5 h). Different pastes are measured with two parallel samples. Ideal measuring system gives points on the diagonal line. Method in Fig.1.

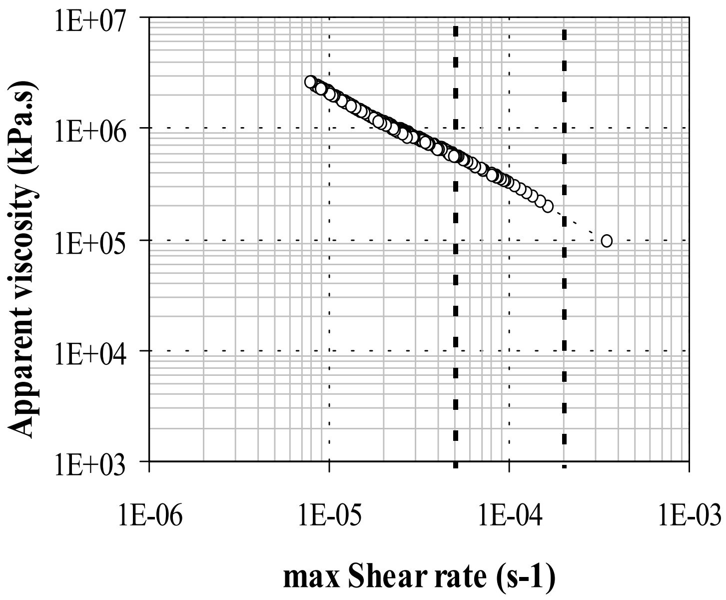

Figure 3. The apparent viscosity and shear rate relationship in electrode paste.

Figure 1 shows that the flow rate decreases with time. One explanation is the reduced pressure when cylinder diameter increases (constant weight). However, the *viscosity diagram* shows that the viscosity increases during the measurement. This means that the paste's resistance against flow increases during the test. A plot of viscosity versus shear rate shows a strong dependence, Figure 3. For a fluid this behavior is known as *shear thinning* and the behavior is important for the further understanding of the electrode paste flow.

The temperature of the paste is important for the flow rate, Figure 4. The consequence of the shear thinning behavior is that each temperature seems to give a corresponding minimum sample height.

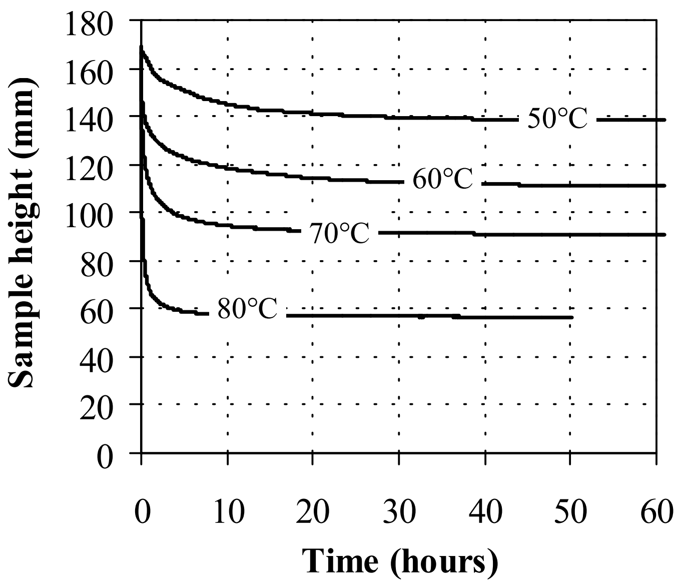

Figure 4. Temperature effect on paste flow. The paste used in this test has a lower plasticity than the paste tested in Figure 1.

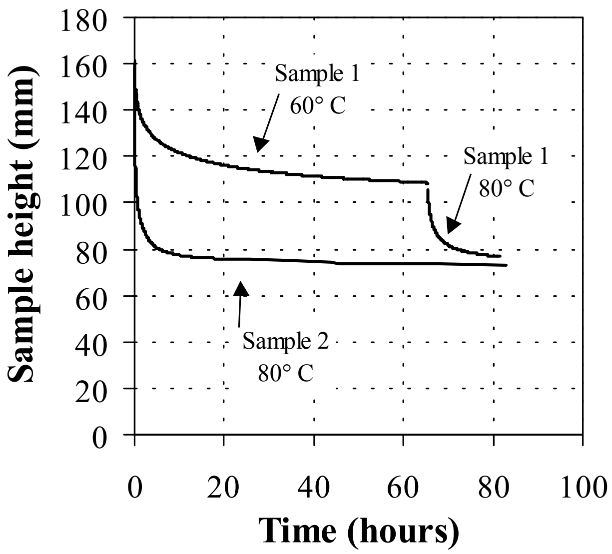

Figure 5. Comparison of flow curve at 80ºC with a curve obtained in "two step test"; 65 h at 60ºC followed by 15 h at 80ºC.

From the shear thinning behavior, Figure 3, it also follows that the "temperature-pressure" history is of importance for the flow in a new situation. This is demonstrated in Figure 5 where one electrode paste is tested in two different sequences. Sample 1 is first measured for 65 hours at 60ºC before the temperature was increased to 80ºC for 15 hours. During these 15 hours sample 1 had a height decrease of 30 mm. Sample 2, which was only measured at 80ºC, had a decrease in height of above 80 mm during the first 15 hours. At completion of the test the two samples had almost same height, although the routes were very different.

These types of measurements are especially suitable for characterizing the relationship of flow and viscosity with parameters such as binder softening point or amount of binder.

2.3 Flow Test of a Briquette Bed

The test described above is used for understanding and characterizing the melting of paste cylinders in electrodes. A bed of briquettes can be considered as small cylinders where each cylinder will have the same behavior as found in the cylinder test shown in Figure 4. However, in a briquette bed the pressure conditions with forces acting between the briquettes are much more complex.

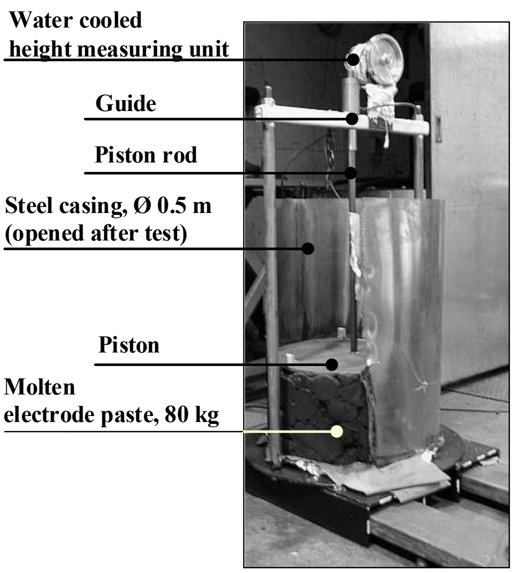

Figure 6. Pilot scale setup for flow test of briquettes in Ø 0.5 m diameter electrode. Weight is placed on top of the steel piston. The chamber temperature is changed in steps letting the paste briquette compaction stabilize at each temperature.

The principle for the simplest briquette flow test is shown in Figure 6. The whole setup is placed in a temperature-controlled chamber, and the measurements of height and temperature are recorded.

Figure 7 shows the results presented as a compaction diagram (apparent geometrical density versus time) of a briquette bed under a weight of 123 kg (6 kPa). This simple test has shown to be a helpful tool for studying the compaction of briquette beds under various conditions.

The same "shoulder effects" as seen in the single cylinder flow test are also observed in Figure 7. At a given temperature the density is stabilized at a specific level. The pitch "softening point" is 85°C (Mettler) in this paste. It should be noted that considerable densification takes place at temperatures lower than the pitch softening point.

The effect of pressure is illustrated in Figure 8. The same paste is again measured but now with a smaller weight on top of the briquette bed, 16 kg (0.8 kPa). As expected, the densities are lower with the reduced pressure, but the typical "shoulder behavior" is still present.

An interesting observation, which also was seen on the cylinder test, is that the time needed to reach a stable density level at each temperature decreases with increasing temperature. This seems to be important for the understanding of the conditions in some of the fairly cold, low load electrodes that have a lower molten paste level than ideally wanted

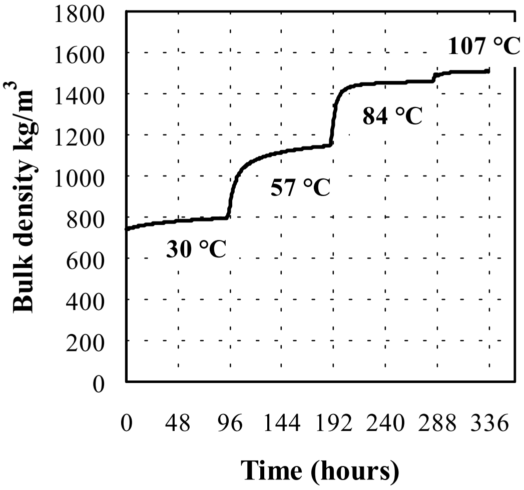

Figure 7. Compaction diagram of briquette bed at different temperature levels. High weight, 123 kg (6 kPa) on top of briquette bed. The paste's plasticity was 22 %.

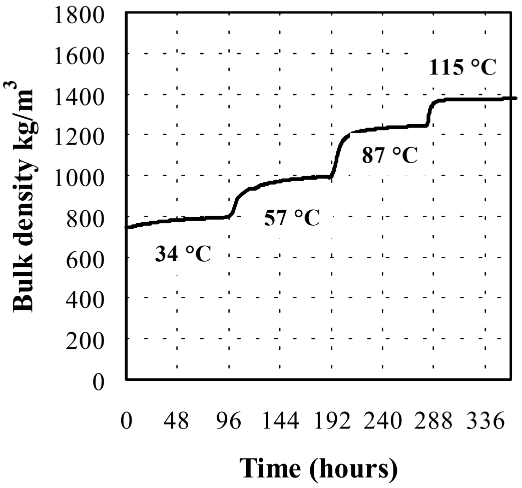

Figure 8. Compaction diagram of briquette bed at different temperature levels. Low weight, 16 kg, (0.8 kPa) on top of briquette bed. The paste's plasticity was 22%.

In order to understand the behavior of the briquette bed we have made the following model: the briquette bed is considered as many cylinders that individually will behave as single cylinders. In the contact points between two briquettes there will be an area with increased pressure. This is expected to be where the flow will start. As the contact areas grow the pressure will be reduced, shear rate decreases and the local apparent viscosity increases. Further compaction will not take place until temperature or pressure is increased. In a further work we will try to verify this.

2.4 Effect of Friction between Briquettes and Casing

The pressure in a layer of melting briquettes will influence the melting behavior. But the pressure is not proportional to the height of the briquette bed since the friction between electrode casing and the briquettes is also increasing with the bed height. In a simple setup shown in Figure 9, this effect is demonstrated in a small electrode, Figure 10.

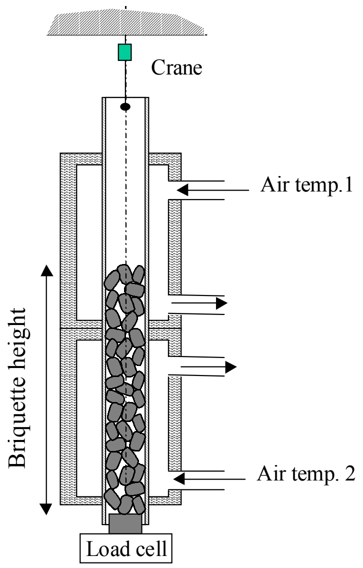

Figure 9. Setup for measurement of friction effects between paste Briquettes and steel casing. The electrode diameter is Ø 0.17 m.

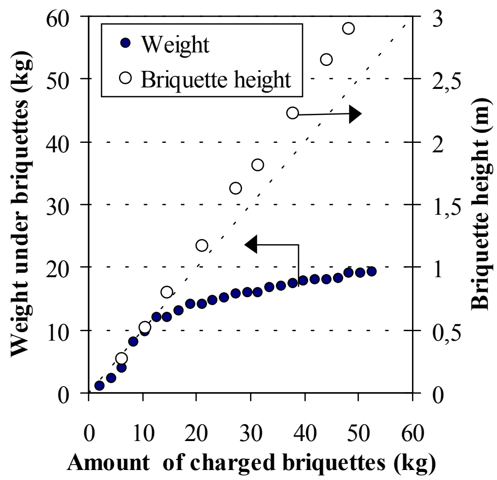

Figure 10. Result from friction test (at 20ºC) in small electrode diameter, Ø 0.17 m.

Figure 11 shows the weight under a briquette bed at 70ºC before and after a movement between the paste and the casing. Lifting the casing simulates the need for the electrode paste to move downwards in the casing due to the densification process.

Thirteen kilograms briquettes charged to the electrode only measured 5 kg after lifting. The casing carried the rest of the weight. After adding more briquettes, to a total of 20 kg, we measured 11 kg before the weight slowly decreased to a stable level of approximately 50 % of the charged amount.

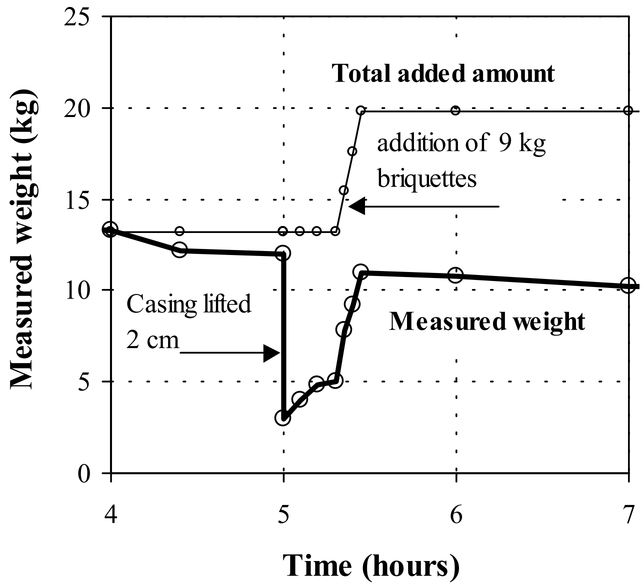

Figure 11. Results from friction test at 70ºC in small electrode diameter, Ø 0.17 m.

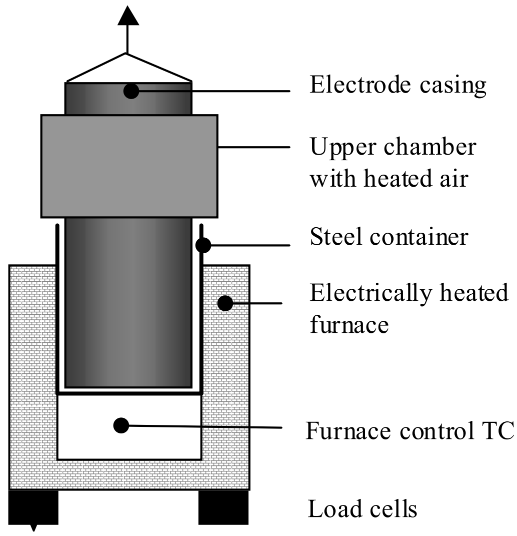

Figure 12. Test setup for briquette flow and friction testing inside 0.5 m diameter electrode.

Figure 12 shows a larger piece of equipment for testing a 0.5 m diameter electrode including casing fins. The electrode is hanging partly in a furnace placed on load cells.

This setup can determine the vertical temperature gradient (Figure 14), simulate flow and friction behavior under different conditions, Figure 13. The movement or the flow of the briquette bed is simply measured as the downward vertical displacement of the top of the briquette bed (relative to casing). Load cells measure the initial weight of briquettes. Then the casing is lifted approximately 20 mm, resulting in a reduction in measured weight. After 3 hours (time = 0), the furnace temperature was set to 90ºC and the system was left to stabilize for 20 hours.

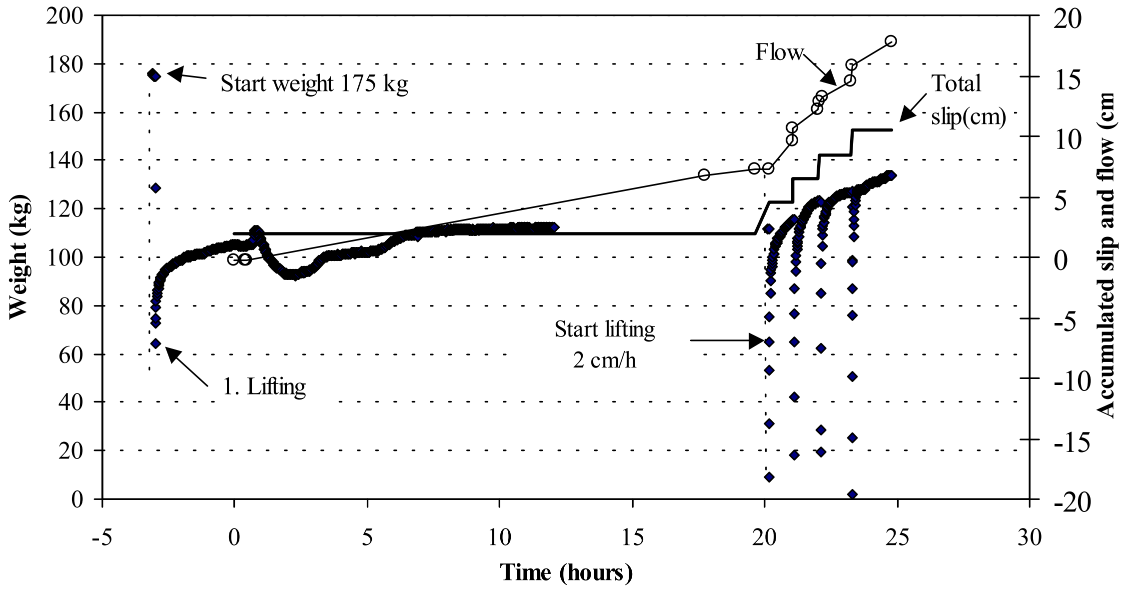

Figure 13. Friction and briquette flow test in Ø 0.5 m diameter electrode. The flow is measured as the relative downward movement of the top of the briquette bed. Furnace temperature set point 90°C at time = 0.

Only small changes in the weight were observed during this period. After reaching equilibrium, the electrode was lifted 20 mm every hour for 4 hours. The weight after each slip increased, but was still much lower than the initial briquette weight. Although the weight was reduced under each lift, the briquettes did sink into the casing at the same or slightly higher rate than the slipping.

In the test above, the furnace had a stable temperature and the paste was slowly heated. Some reported cases of bridging or formation of cavities in commercial size electrodes have occurred during furnace shut downs. The typical description is that the electrodes have cooled and after restarting the furnace, the slipping rate was faster than recovery of the temperatures in the upper part of the electrode column. We have demonstrated that the paste's history relative to temperature exposure and the pressure is important for the further flow (ref. 2.2). In case of bridging the temperatures are often reduced and the viscosity in the partly melted paste will be high and little flow will take place until the electrode is heated to the former temperatures or higher. Avoiding large temperature fluctuations during fast slipping is believed to be a key to avoid bridging.

2.5 Flow of Briquette Bed in Furnace with Temperature Gradients

In this test the setup in Figure 12 is slightly modified and a small steel plate, resting on top of the briquette bed, was connected to a wire displacement transducer mounted on top of the casing, Figure 14.

The flow curve from the test, Figure 15, shows that the briquette bed moves with a steady flow downward as the briquettes at the bottom are melting. After finishing the test, the electrode was cut and the compaction visually inspected, Figure 16. The temperature gradient indicates that the compaction of this paste was completed at approximately 80°C.

It is noted that the density of the center seems to take place higher up in the bed than the material close to the fins and to the outer casing. Friction between the briquettes and the casing is believed to be the explanation for this.

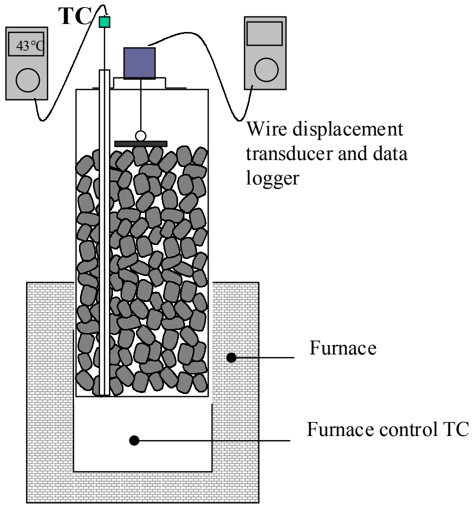

Figure 14. Setup of flow measurement of briquette bed in laboratory furnace with temperature gradient. Diameter Ø 0.5 m.

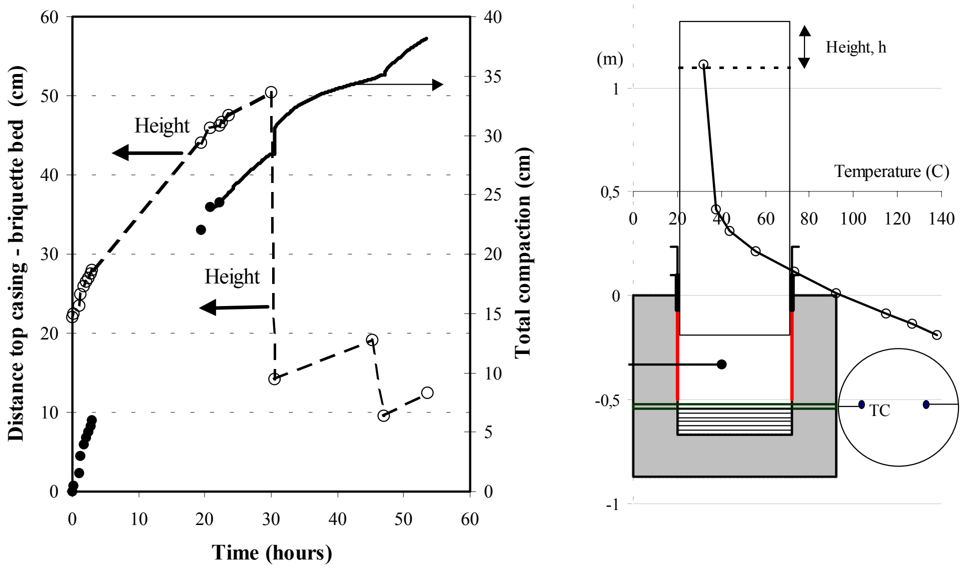

Figure 15. Flow and density test in furnace with temperature gradients. The paste flow (height = distance top casing to briquette bed) was followed by logging data from a wire displacement transducer. Briquettes were recharged twice. Furnace set point was 200ºC.

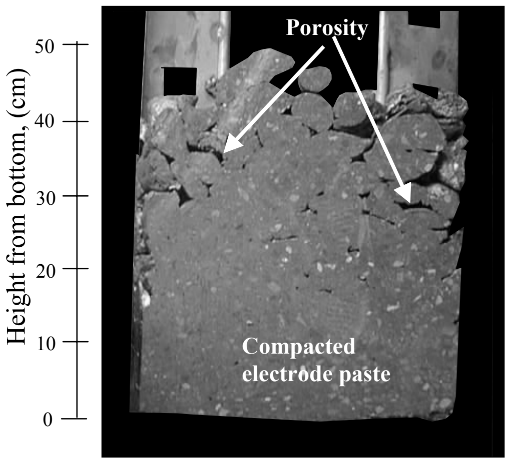

Figure 16. Ø 0.5 m diameter electrode with briquette cut after testing according to Figure 14 and 15.

The paste used in this test has a lower viscosity than the paste tested in Figure 7 and 8.

2.6 Briquette Flow Measurement in Commercial Scale Electrodes

In the full-scale electrode measurements, the same principle as described in [3] was used, but with automatic measuring and recording equipment of the briquette level (Figure 14). To obtain the complete representation, it is necessary to collect data of electrode slipping, current, load, and temperatures. Figure 17 shows the results from a test in a 15 MW furnace with Ø 1.15 m diameter electrodes producing 75 % FeSi. The briquette movement follows a special pattern that seems to depend on the charging frequency. After addition of one big-bag of briquettes the flow rate increased gradually before it again leveled out. During complete melting and densification the briquette bed density changes from 800 kg/m^3 to 1600 kg/m^3. This means that the occupied volume is 50 % of the volume at start and the accumulated movement of the briquette should be close to the accumulated slipping. The results confirm this, Figure 17. No signs of problems with the briquette melting were observed.

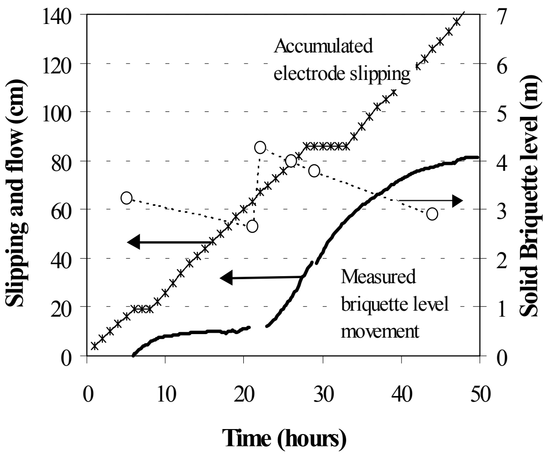

Figure 17. Measured briquette bed move-ment in Ø 1.15 m diameter industrial electrode (75% FeSi). Temperature on top of briquettes was 70-80ºC. Briquette was charged at time = 20 hours.

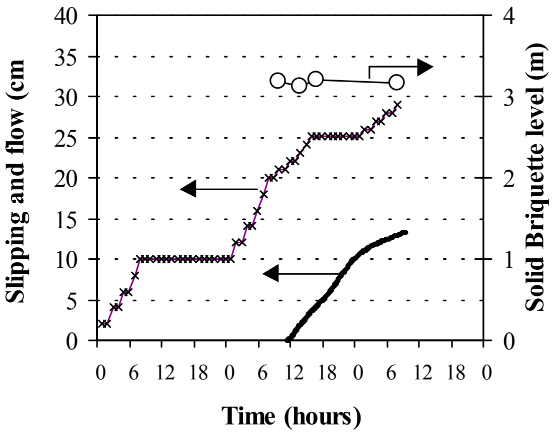

Figure 18. Measured briquette bed movement in a Ø 1.4 m diameter industrial electrode (FeMn). The temperature on top of briquettes was 40ºC.

The electrode investigated in Figure 17 was shut down for 4 hours (periods without slipping in Figure 17) each day during the electrical energy "peak hours". The slipping was stopped during these periods without any visible influence on the melting of the briquettes. Such observation is consistent with previous industrial scale measurement [3].

The electrode in Figure 17 is operated with a normal level of the current load, 6.0 A/cm^2, 70 cm slipping per day and with heated air (90ºC) blown into the suspension mantle. These electrode conditions can vary between electrodes and Figure 18 shows some result from an electrode (FeMn) with 4.2 A/cm^2, 0.2 - 0.3 m slipping per day and no heating of the mantle air. The slipping rate of this electrode is very low, and hence, a low melting rate is also needed. The measured briquette movement (or flow) shows an even appearance and with a rate close to the slipping rate. The melting performance seems to be good.

3. DISCUSSION

The understanding and control of the flow behavior of electrode paste is important regarding its formulation and application in ferroalloy production. The present work has documented several essential effects regarding melting of paste cylinders and briquette beds. Knowledge about the mechanisms makes it possible to produce types of pastes adapted to specific electrodes and furnace operations. Combining the right product with matching procedures ensures easy paste charging and safe electrode operation. Good characterization methods of the paste flow and densification are very important in this work.

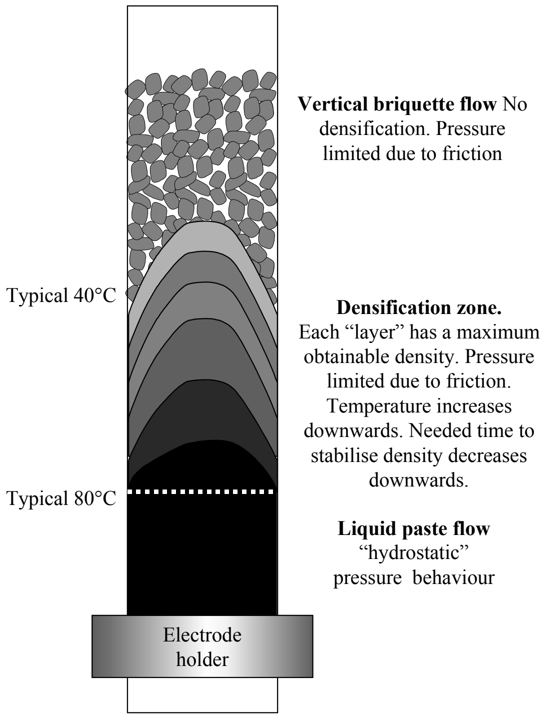

Figure 19. Schematic model of the flow and melting mechanism in upper part of a normal briquette column. Temperature for complete densification is suggested to be ≈ 80ºC but depends on parameters as pitch softening point and amount.

Electrode paste behaves like a granular-viscous material. Both paste cylinders/blocks and paste briquette beds have shown a *shear thinning* behavior, i.e. the viscosity in the material increases when the flow rate decreases. To establish a relationship with full scale electrodes we consider the melting of paste in industrial furnaces as a stepwise process where each step or layer can reach a certain degree of flow or density, see Figure 19. As the temperature increases, the time needed to adapt to a new density level will decrease. The briquette level just above complete compaction will then be the level that fastest adapts to a change in pressure or temperature. A flow of paste in the column will then be established. The continuity of such flow along time should be ideally obtained but in practice other factors may affect it. We hope to further investigate such deviations and its practical effects in future work.

One such factor could be friction between paste and casing affecting the pressure on the briquettes during densification especially on small diameter electrode column without heating. The design of the casing can also be of importance to minimize friction. However, although the friction influence is considerable, stable flow and densification have been measured in both laboratory tests and in industrial electrodes. A laboratory test resulted in near total compaction under a bed height of only 1 m and at an isotherm around 80ºC, Figure 16. The laboratory work indicates that compaction of briquettes is easier when a temperature gradient is present.

Some low current load electrodes have been reported to operate well with comparatively shallow briquette levels and at apparently low temperatures. With the mechanism and model above this can be explained.

A good performing electrode requires that the baking gases exit downwards below the contact shoes. For this reason, the electrode operation should aim to maintain a stable and thick highly viscous paste level. The continuous formation of new, highly viscous layers in an electrode charged with briquettes should obviously have an important role in terms of segregation control of the paste. Upper column temperatures, solid paste level, frequency of feeding and paste properties must be developed for each type of operation. There are indications that low slipping electrodes would work better with a lower solid paste than electrodes with high slipping. These because of a possible higher risk of bridging in the electrodes with low current and low temperatures. The higher residence time in these columns give the paste more time for densification, and hence, still they will have an acceptable liquid paste level. Electrodes with higher slipping seem to need a higher solid paste level and higher column temperatures in order to maintain the briquette densification process. However, these considerations are preliminary and have to be studied further.

4. CONCLUSION

Both paste cylinders and briquettes can give good operation as long as good electrode paste quality and correct operational procedures are employed.

Electrode paste is documented to have a "shear thinning" flow behavior, i.e. the resistance against flow increases when flow rate decreases. In practice: at a given temperature a cylinder will only be deformed to a certain height. For a briquette bed: a given temperature will only give paste flow to a certain bulk density.

Densification of the paste in a briquette column starts at temperatures lower than the pitch softening point. Such densification at comparatively low temperatures is important in order to avoid baking gases to move upwards. The use of briquettes will decrease the potential for segregation.

Concern about briquette bridging requires further knowledge on the mechanisms of flow in a furnace column.

For good electrode operating procedures, it is necessary to take the behavior and characteristic of the paste into consideration. Changing from one paste to another may call for adjusted procedures.

5. ACKNOWLEDGEMENTS

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