INSIGHTS INTO THE INFLUENCES OF PASTE ADDITIONS AND LEVELS ON SÖDERBERG ELECTRODE MANAGEMENT

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ABSTRACT

Tight control of electrode paste additions, hard and soft paste levels, baked zone position and electrode temperatures are integral to superior Söderberg electrode management practices. Paste addition is typically effected through briquettes, cylinders or large blocks. Each electrode paste form has its advantages and disadvantages, but probably a more crucial element from an electrode control perspective is the frequency and amount of electrode paste addition into a Söderberg electrode column.

The detrimental effects of excessive soft paste levels leading to Stokes' Law segregation of paste in the electrode column are well documented, while several operators have effectively implemented the use of electrode thermocouples to monitor paste temperatures and automated slipping algorithms to control baking conditions within electrodes. Somewhat less well appreciated are the negative influences of inadequate soft paste levels, especially when coupled with excessive paste cylinder or block additions and resulting high hard paste levels. The alternative of insufficient hard paste levels and associated overheated electrode paste must also be considered, and can contribute to paste segregation directly. This condition also has the potential to generate gas mixtures in the electrode column that are concurrently a potential health hazard, while being prone to spontaneous combustion.

Results of industrial trials on electric furnaces using Söderberg electrodes in a variety of applications from ferrochromium, to ferromanganese and even platinum-bearing base metal sulphides smelting are presented to illustrate the influence of paste loading practices on the dynamics of hard and soft paste levels. Possible electrode failure mechanisms attributable to inadequate paste level control will be discussed through some industrial examples. Suitable paste loading practices to mitigate the risks of inappropriate paste levels and associated electrode incidents are presented.

1. INTRODUCTION

Examination of the character of an electrode break surface provides a useful, but certainly not a definitive guide to diagnosis of potential causes of electrode breaks. Four characteristic electrode break types are identified (certainly not an exhaustive list - Figure 1).

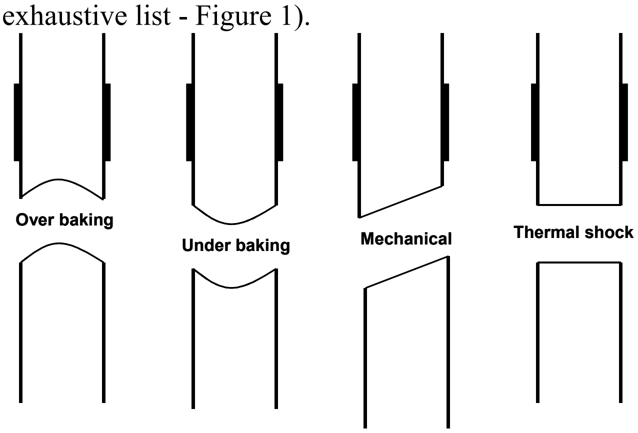

Figure 1. Schematic representation of four different break surfaces and typical causes of electrode breaks.

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The current investigation is largely focused on the "over-baked/under-slipped" electrode break shape where, in theory, the remaining electrode exhibits a concave cusp (convex cusp on the electrode stub to be removed) as a consequence of the crack roughly following the electrode-baking isotherm. In diagnosis of a spate of electrode breaks that were associated with difficulties in maintaining adequate soft paste levels, it was found the electrode breaks frequently exhibited concave cusps (Figures 2 and 3). Yet, investigation of slipping logs showed that the breaks had occurred some distance below the contact shoes, under conditions of more than adequate slipping, so could not readily be described as produced under "over-baked/under-slipped" conditions. Of concern, was the fact that similar electrode breaks appeared to be occurring on other sites, and in another ferroalloy sector.

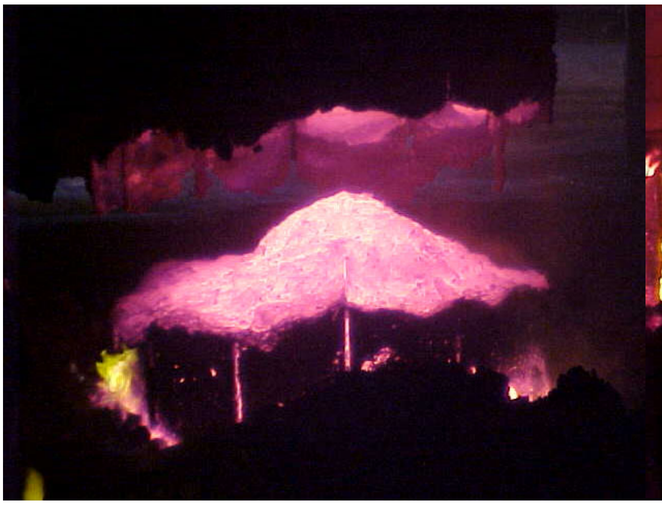

Figure 2. The shape of the break cusp may suggest an "over-baked" electrode, but slipping in excess of 36 cm per day contradicts this as a cause of the break (Electrode A). Conditions of low soft paste level and paste volatilisation were noted.

Figure 3. The shape of the break cusp may suggest an "over-baked" electrode, but slipping in excess of 40 cm per day again contradicts "over-baking" as a cause of the break (Electrode B).

Figure 4. Close-up of Electrode A shows significant paste segregation into brittle carbonised pitch binder and a coarse calcined anthracite aggregate.

Figure 5. Electrode B stub (± 2.2 m long) with evidence of segregation of larger aggregate from finer aggregate/pitch binder at the electrode periphery.

Closer examination of these electrode break surfaces showed them to be segregated into a pitch binder- and fine aggregate-depleted portion (aggregate-enriched) and a brittle, highly carbonised pitch binder-rich fraction (Figures 4-7). In addition, a broken electrode stub was found, where the outline of a paste cylinder that had not softened could be observed readily inside the core of the electrode (Figure 8). A further concern was evidence of circumferential cracks around electrodes that were repeated at regular intervals, and appeared associated with an increased incidence of electrode tip losses, and even electrode breaks. The latter phenomenon appeared to extend outside of the ferroalloys sector into electric smelting of platinum-bearing base metal sulphides (Figures 9 and 10).

Consequently, it was decided to devise a series of paste trials in order to study the dynamics of paste addition on paste levels and baking conditions, in an attempt to better diagnose the fundamental phenomena at play.

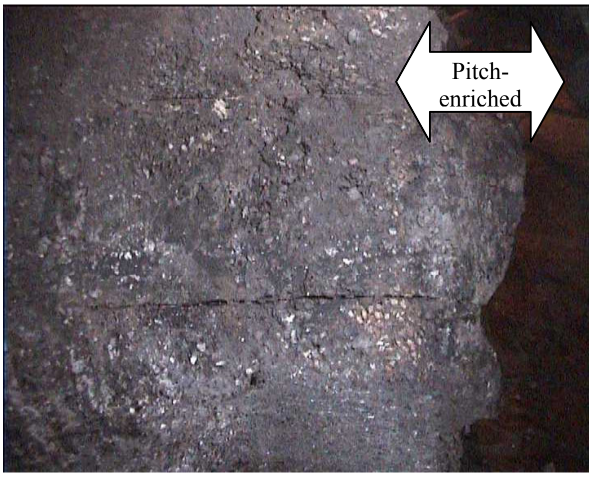

Figure 6. Close-up of Electrode B. It appeared well baked except for the region of break interface, which was brittle and characterised by carbonised pitch binder.

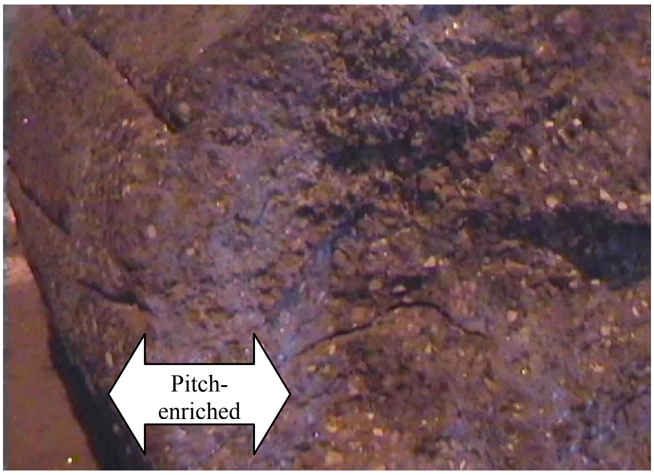

Figure 7. Possible evidence of segregation of aggregate from pitch at the electrode periphery (Electrode C). Aggregate-depleted periphery likely to be susceptible to crack propagation.

Figure 8. Remarkable broken Electrode D stub, showing the outline of a paste cylinder at the electrode core. Sure signs of inadequate control of paste addition, paste levels and baking.

Figure 9. Regularity of circumferential cracks around Electrode E may relate to a daily paste loading event. Associated with practices of dropping of paste cylinders and overloading hard paste.

Figure 10. 140 cm diameter Electrode F showing poor baking, fluted attack between fins and circumferential cracks and break.

Figure 11. Paste slinging and loading practice sub-standard with every cylinder dropped into the electrode column.

2. INDUSTRIAL PASTE TRIALS

2.1 Paste Trial Methodology

2.1.1 Paste loading trial procedure

The industrial paste trials involved:

- Observation of paste conditions within the electrode column, and measurement of:
  - Soft paste level ("SPL") = height of "liquid" paste above the bottom of the contact shoes
  - Hard paste level ("HPL") = height of solid paste measured above the SPL
- Measurement of cylinder dimensions
- Addition of a single paste cylinder, and re-measurement of SPL and HPL
- Repetition of the last two steps until the "desired" paste quantity had been added.

2.1.2 Paste loading trial result format

The results of paste loading trials are presented in graphs that show:

- Height of contact shoes, design SPL (2D, 2 electrode diameters measured from the bottom of the contact shoes) and design HPL (1D above the SPL, or HPL + SPL = 3D)
- Starting SPL measurement, which is also assigned as the starting minimum submerged hard paste level (strictly correct when the hard paste level, as defined, is zero, but obviously only truly representing a minimum submerged level when some existing hard paste is not already protruding into the soft paste level)
- The top of hard paste (i.e., HPL + SPL).

Following the addition of the first paste cylinder, the following are displayed:

- Resultant new SPL and HPL + SPL
- Calculated minimum amount of hard paste now submerged below the soft paste level into the electrode column (i.e., minimum submerged cylinder height)
- Theoretical SPL, calculated from the predicted displacement of soft paste by the amount of hard paste submerged below the soft paste level in the electrode column.

2.2 Results of Paste Trials

2.2.1 Typical paste levels

A typical electrode condition is illustrated in which soft paste levels and hard paste levels are marginally high at the start of addition of 3 paste cylinders (Figure 12).

As each cylinder is added (roughly 100 cm high), not too unexpectedly, the:

- Hard paste level and top of hard paste levels rise progressively;
- The soft paste level, and predicted soft paste level rise more marginally (only 1.1 cm after addition of the first paste cylinder) and reasonably coincidentally with each other;
- The minimum submerged cylinder height drops lower progressively.

In one similar trial involving the addition of 6 paste cylinders, measurements were taken some 20 minutes after final paste addition to investigate paste level dynamics. The measured HPL + SPL, and as a direct consequence the predicted minimum submerged cylinder height, were found to have dropped by 20 cm. This is believed to be as a result of delayed dynamics of soft and hard paste stabilizing to their equilibrium buoyant positions in the electrode column (see next Section), rather than any indication of hard paste softening rates.

2.2.2 Submergence of paste into contact shoes

A trial involving addition of 3 paste cylinders to an electrode with a low initial soft paste level of 171 cm and a high starting hard paste level of 632 cm is illustrated (Figure 13). Progressive paste addition led to an excessive final hard paste level of 827 cm. More significantly, it resulted in prediction of the hard paste entering into the contact shoes (minimum submerged cylinder height of 82 cm). This must be detrimental to control of the 450°C electrode baking isotherm.

On another site, historical records revealed that up to 18 cylinders had been added in a single loading event in the past. Given a low initial soft paste level, and assuming paste loading and minimum paste submergence similar to that recorded in a trial, a scenario can be projected of the effects of overloading paste cylinders (Figure 14).

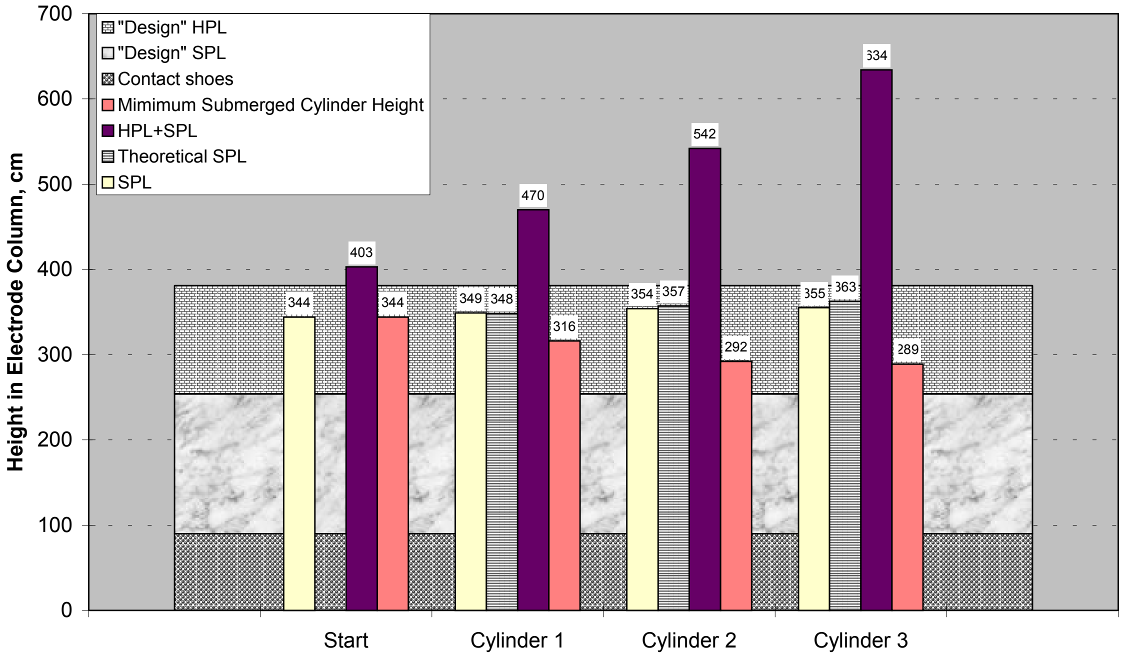

Figure 12. Results of a paste trial indicating the expected effects of progressive addition of 3 paste cylinders on increasing measured SPL, HPL + SPL and theoretical SPL, and on lowering the minimum submerged cylinder height, all measured relative to the bottom of the (90 cm high) contact shoes.

What is projected is that as paste cylinders are progressively added, the HPL + SPL rises to the point where the electrode column starts to become seriously overloaded. The shear mass of additional paste mass will induce unacceptable stresses on the electrode column, possibly above its design limit. Concurrent with this, the head of paste cylinders will start to force the base of the hard paste deeper and deeper into the electrode column. In the example shown, it is even predicted that the hard paste will enter into the critical contact shoe region. In a worst case scenario it would even be conceivable that the hard paste actually comes to rest on the paste baking zone located near the 450°C isotherm level.

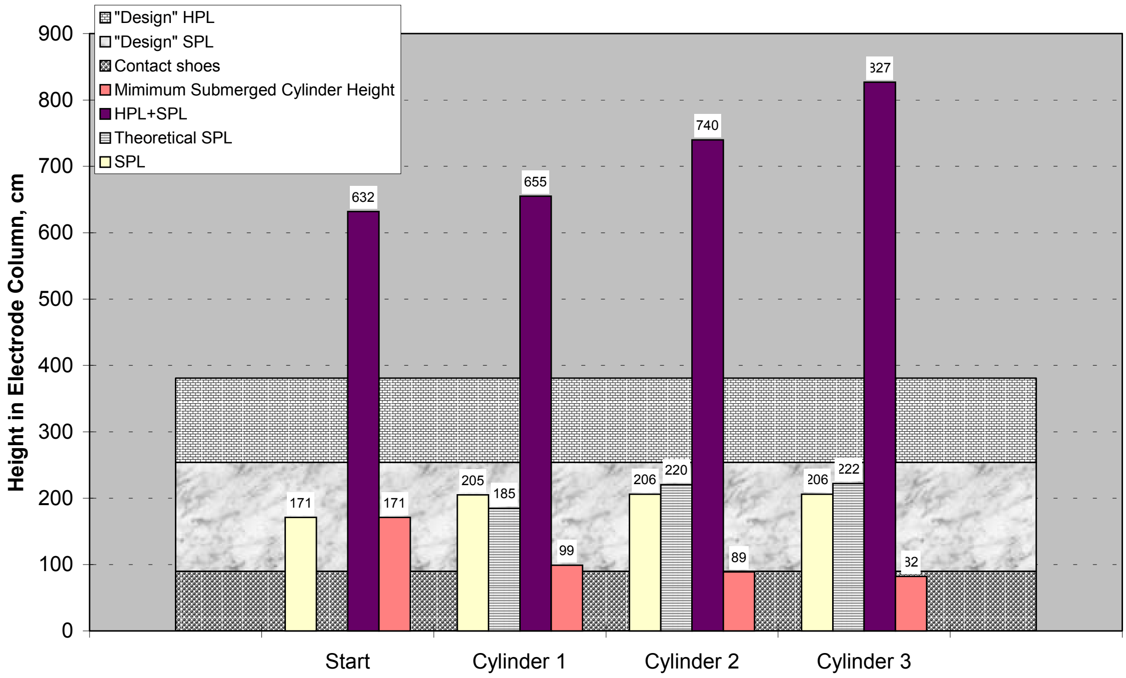

Figure 13. Results of a paste trial that indicates an electrode with low soft paste level and resultant submergence of the bottom of the paste cylinder into the contact shoes.

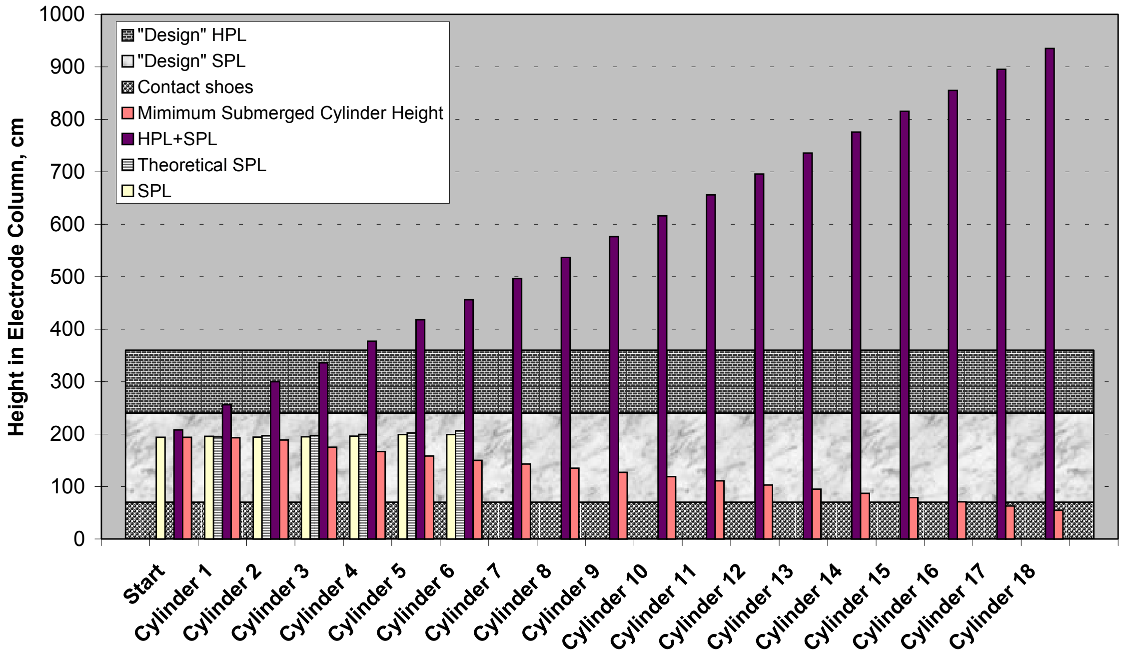

Figure 14. Results of a paste trial indicating physical addition of 6 paste cylinders. The potential impact of a discontinued practice of addition of paste to the top of the casing (up to 18 cylinders) is estimated, showing the entry of the solid paste into the contact shoes and critical baking zone.

2.2.3 Dropped paste cylinders

In this case (Figure 15), addition of paste was accomplished by dropping all of the paste cylinders down the column. The HPL rose progressively as expected, but no noticeable changes in SPL could be determined. This suggested that paste cylinders had bridged the column between the fins, so that it was not properly in buoyant contact with the soft paste. Observation of a paste cylinder wedged against a fin midway up the electrode column supported this conclusion. Dropping of paste cylinders is an errant practice, especially when it can result in a bridged electrode column.

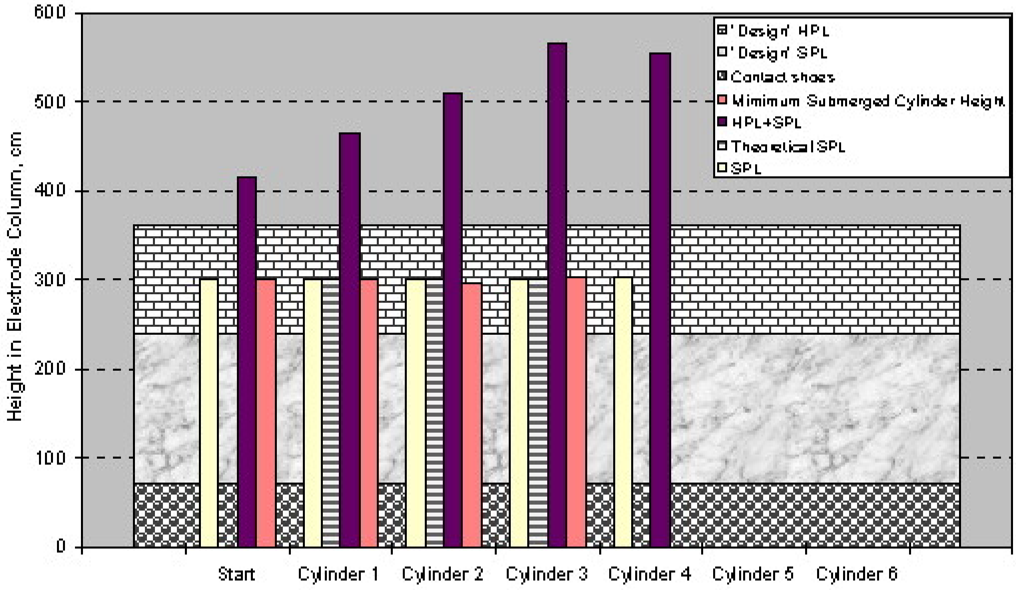

Figure 15. Results of a paste trial where paste addition seemingly had no influence on soft paste levels. Upon closer investigation, it was found that the practice of "dropping" paste cylinders into the electrode had caused a cylinder to get stuck in the fins above the soft paste, resulting in bridging of additional paste cylinders above, and out of contact with, the soft paste.

2.2.4 Contribution of high paste levels to an electrode break

The final industrial example involves a furnace with 1.4 m diameter electrodes that experienced electrode breaks on all three electrodes over the period of 3 days. As typically experienced, numerous factors contributed to the electrode failures, including some concentrate contamination of the electrode columns and excessive downtime and resultant thermal shock. However, there was also evidence of a contribution from excessive paste cylinder loading (6 cylinders added in one event – Figure 16) and low soft and high hard paste levels (227.9 cm and 1150.3 cm, versus a recommended minimum of 280 cm and maximum of 560 cm, respectively – Figures 17 and 18) to the electrode breaks.

In particular on electrode 2, back-calculation of the soft and hard paste levels and paste loading conditions coincident with the relative position of the electrode break some 45 days later, confirmed paste levels that were out of control (Figure 18). This probably contributed to electrode failure.

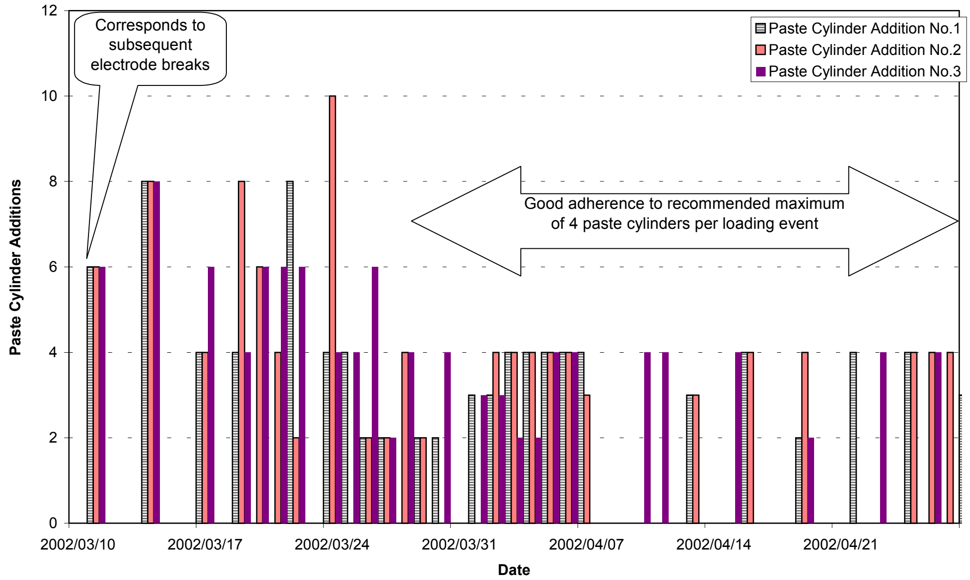

Figure 16. Plot of paste cylinder additions that initially were poorly controlled. Period of excessive paste cylinder additions can be correlated with subsequent electrode breaks.

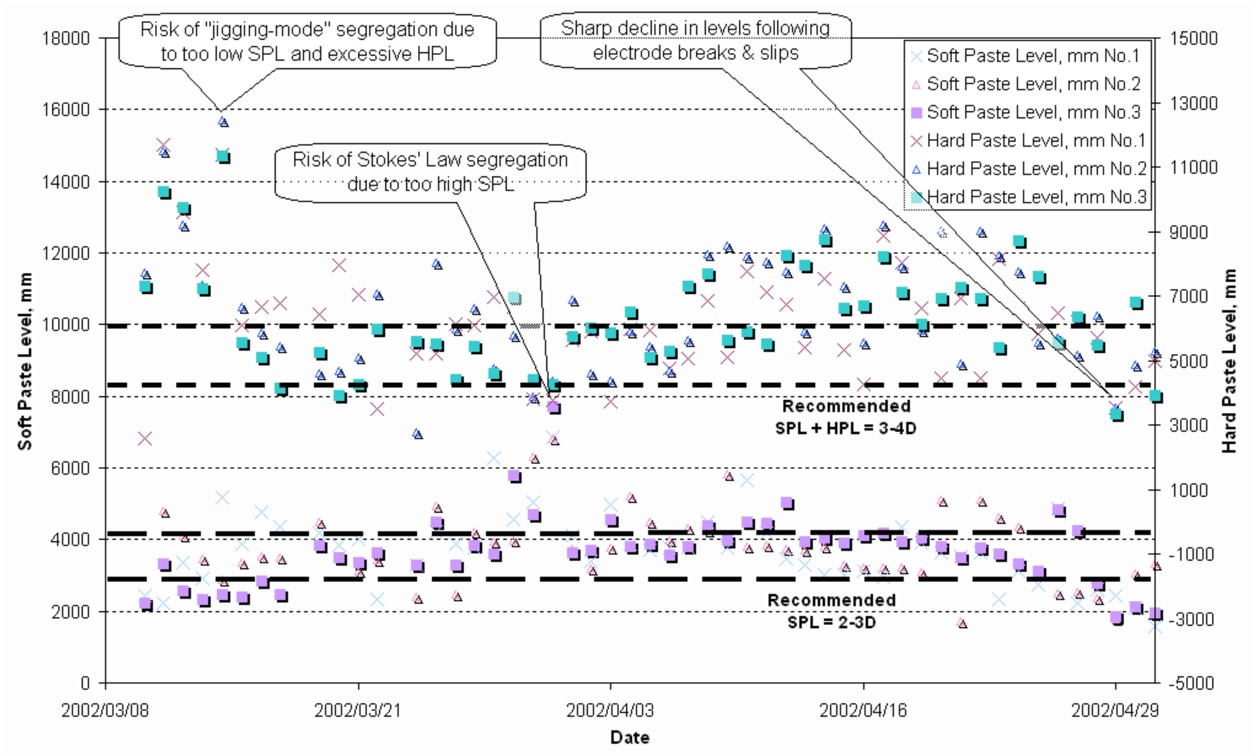

Figure 17. Plot of soft and hard paste levels on a furnace with 1.4 m diameter electrodes, showing excessive hard paste levels that correlate in time with subsequent breaks on all three electrodes.

Days	Total distance slipped before break, mm	Cumulative slip, mm	Height of the SPL before break, mm	Height of the HPL before break, mm	Downtime, min.
D-45	50	7394	2279	7739	131
D-44	400	7344	4803	11503	337
D-43	450	6944	4106	9206	95
D-42	400	6494	3453	7353	112
D-41	300	6094	2882	12432	85

Figure 18. Back calculation of the position of an actual electrode break (highlighted) relative to prevailing soft and hard paste levels under which that specific portion of the electrode was formed.

2.3 Dynamics of Paste Levels - Microwave Radar Interferometry

In one of the industrial trials, use was made of a novel Microwave Radar Interferometry technique to investigate interfaces in electrode columns (Figure 19). The equipment [1] was mounted above the electrode (Figure 20) and after some calibration, it was used to discern the hard paste level and soft paste level. An interesting result was the influence of large electrode movements on the reported HPL (Figure 21). It appeared that the hard paste had some inertia in movement in the soft paste, and the reported HPL increased with downward electrode holder movement, yet decreased when the electrode was raised. Provided that excessive electrode movement was not associated with the paste level measurements, this effect is believed to have had little impact on the paste level results presented in this study.

Figure 19. View of the top of the paste cylinder (HPL) on top of "liquid" paste (SPL) within the electrode casing column.

Figure 20. Views of sensor, electrode casing and casing measurement pointer mounted on electrode gallows.

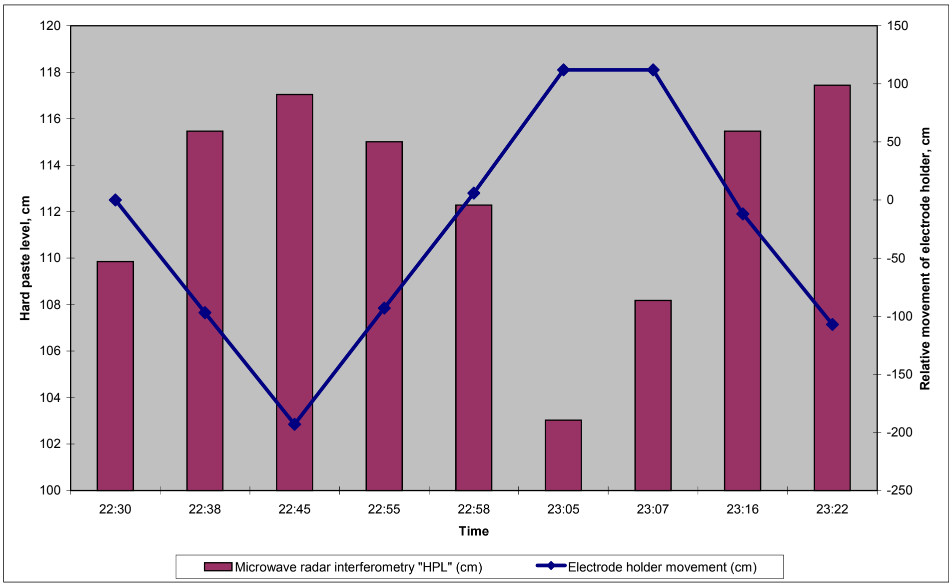

Figure 21. Inertia of HPL measured by microwave interferometry during repeated downward and upward electrode holder movement.

3. INTERPRETATION AND DISCUSSION

3.1 Segregation Literature

The key segregation mechanisms described in the literature include [2,3]:

- Stokes' Law settling of coarse particles: This involves separation of coarse aggregate (d_p < 20 mm) from the pitch binder and fine aggregate fraction (50% -64 μm) that proceeds under relatively quiescent conditions, with settling velocities (u) predicted according to [4]:

$$u = (\rho_{aggregate} - \rho_{'liquid'}) g d_p^2 / 18\mu \qquad [1]$$

where, g = gravitational acceleration

μ = 'liquid' (pitch binder and ultrafine aggregate) viscosity - both temperature and paste type dependent

ρ = densities of solid aggregate and 'liquid' (pitch binder and ultrafine aggregate).

- Loading conditions, especially on large electrodes: this involves the movement of fine aggregates and pitch binder to accumulate near the electrode casing periphery.
- Thermal accumulation of volatiles and fines: this involves accumulation of aggregate fines and volatiles near the top of the soft paste under the influences of thermally buoyant transport from hotter zones, possibly even involving fluid flow induced by rising volatile gas bubbles.
- Cavity enrichment of volatiles: this can occur if hot paste is charged and shrinks to form a cavity during carbonisation. A cold plug can develop that will be conducive to segregation by the thermal accumulation mechanism described above.

The latter two mechanisms may involve devolatilisation of pitch binder and accumulation of fine aggregate from the paste due to paste overheating, and are typically associated with low soft paste levels. This emphasises the criticality of paste temperature control to segregation, and in this regard the importance of the presence of some hard paste at all times to moderate soft paste temperatures (much like "an ice cube in a drink"). Besides the resulting coal tar pitch volatile (CTPV) health risk to the paste and casing crew, excessive generation of pitch volatile products are known to have caused numerous gaseous explosions in the electrode column, in the extreme leading to a past double fatality in Japan.

Finally, in discussions of electrode breaks in the industry, it became apparent that the term "segregation" is also loosely used by some operators to describe a layer of discontinuity in the baked electrode, caused by an inadvertent addition of a contaminant (e.g., dust or concentrate) into the paste in the electrode column. While such contaminant clearly introduces a zone of weakness between otherwise normal paste is probably falls outside of the true technical definition of segregation "to physically set apart".

All four classical segregation mechanisms described assist to explain the specific instance of paste segregation and associated concave cusp electrode breaks and regular electrode tip losses observed. However, a specific variant of the loading segregation variant is expounded to more clearly explain the potential role of this mechanism.

3.2 Control of Paste Temperature

Past tests performed on paste plasticity and slumping of "heat treated" paste (i.e., paste heated above the pitch softening point and then allowed to cool before testing), coupled with computational fluid dynamic simulations of electrode baking [5], indicate some further factors that could impede paste flow, so contributing to segregation.

These include:

- The flow characteristics of electrode pastes that have been subjected to any prior heat treatment (e.g., through any contact with higher temperature regions within the electrode column) are significantly reduced. This occurs because such in situ heat treatment may cause some devolatilisation of some low boiling point tars (added by paste manufacturers to improve paste plasticity). This raises the paste softening point and lowers paste fluidity – enhancing the risk of paste segregation.
- Low cooling water supply temperatures (below 40°C) that over-cool contact shoes, and may even cause re-solidification of an annular ring of paste adjacent to the cold contact shoes. In the extreme, a re-solidified ring can grow to the point where it bridges the electrode column, impeding downward flow of soft paste into the zone beneath the contact shoes.
- Excessive electrode slipping (e.g., following an electrode break) will contribute to the moving the baking zone downwards in the electrode column and will lower paste temperatures in the vicinity of the contact shoes. This will disrupt thermal conditions in the electrode and could potentially contribute towards conditions temporarily being more conducive to paste segregation.
- Excessive fluctuations in furnace power and freeboard temperatures can contribute to periodic heat treatment and cooling of paste already loaded into the electrode column that may impede free flow of soft paste and contribute to paste segregation.

3.3 Interpretation Of Trials And Practical Survey Of Electrode Breaks

Coupled with the classical mechanisms of segregation described above, poorly controlled addition of paste leading to a "jigging" action, is postulated to contribute to paste segregation under a combination of conditions that can include:

- Low soft paste level
- High paste temperatures
- Excessive paste addition (up to the top of the electrode column)
- High hard paste level
- Dropping of paste into the column.

It is proposed that every paste addition event, especially if the paste cylinder is dropped into the column, will lead to some "plunging" action of the hard paste through the soft paste (Figure 22). If repeated with several paste cylinders, this will conceivably lead to a "jigging" action on the soft paste, whereby some settling and separation of larger aggregate particles from the lighter pitch binder and fines fraction from the surface of the soft paste will occur. As more paste cylinders are added the hard paste progressively submerges. This could easily lead to a relatively pitch binder-enriched, or coarse aggregate-depleted soft paste developing near the surface in the annulus around the core of submerging hard paste (Figures 4-7). Clearly, multiple paste loading events, or pastes dropped with high energy into the electrode column, will magnify this "jigging" action. The presence of a core of hard paste will additionally lower the effective, now annular, area of soft paste in the electrode casing, so magnifying the force of any "jigging" action applied through movement of the column of hard paste. Contributions by classical segregation mechanisms will enhance the overall segregation effect.

The predicted undesirable consequence of the resultant segregation is that similar to cement, as opposed to concrete, the aggregate-depleted zone will be more susceptible to propagation of cracks under the action of applied stresses due to the presence of fewer "crack arrestors" – the larger aggregate (or "stones" in the concrete analog). Moreover, if the interpretation is correct, and an excess of paste cylinders are added on a regular basis (e.g., daily), a pitch binder-enriched, or aggregate-depleted, zone on the periphery of the electrode should develop at regular intervals. Under the application of applied stresses in furnace operation, such an electrode would be predicted to develop a series of circumferential cracks around the electrode periphery, spaced at fairly regular intervals (representing overloaded paste events – Figures 9 and 10).

If sufficiently severe, this could lead to electrode tip losses, or even to an electrode break, where the remaining electrode may frequently display a distinctive concave paste cusp – usually associated with an "over-baked" electrode break surface, but definitely not due to over-baking/under-slipping.

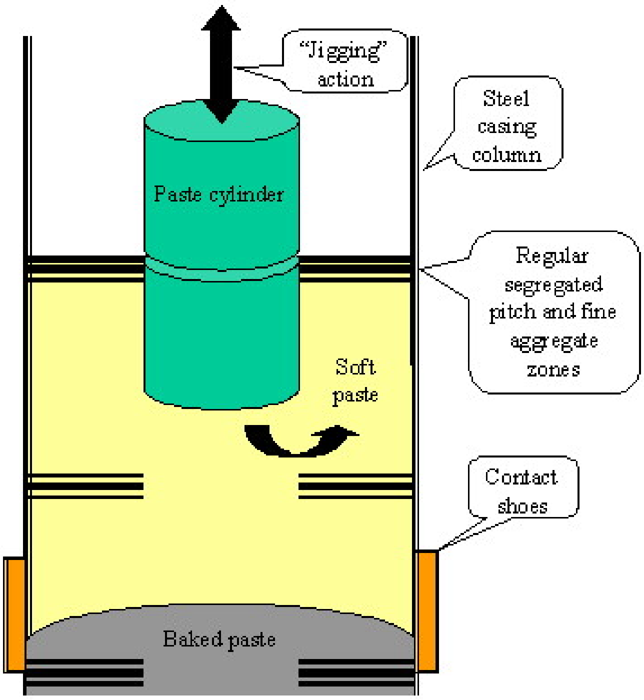

Figure 22. Mechanism of concentrated paste segregation at the electrode periphery in an annulus by a "jigging" action of paste cylinders acting vertically through the core of the electrode column.

To further support the proposed mechanism, a remarkable electrode stub in which the outline of a paste cylinder that had not even had the opportunity to melt was observed (Figure 8). This provides confirmation of the extreme case of overloading of hard paste predicted from the paste trials, where the hard paste directly interferes with paste baking, distorting the 450°C baking isotherm. This cannot be desirable to formation of a sound electrode.

4. SOME RECOMMENDED PASTE HANDLING AND LOADING PRACTICES

Discipline needs to be instilled that forces operational staff to handle paste as a precious commodity that is critical to successful furnace operation.

Specific actions recommended to improve overall electrode management through limiting undesirable effects of paste segregation include:

- Receipt of paste wrapped in plastic and supplied on pallets
- Storage of paste under-roof , where temperature and contaminants (dust and water) are controlled
- Paste cylinders should be brushed clean of dust prior to loading and any metallic paste tags should be removed prior to loading
- Electrode casings should be covered by dust covers at all times (Figures 23 and 24)
- Consistent and regular paste addition should be planned according to soft paste and hard paste levels, and electrode slipping and baking conditions that are consistent with prevailing smelting conditions. A suitable limit should be placed on the maximum number of paste cylinders to be loaded at a time (e.g., 3-4 paste cylinders have been found to be a practical number on many ferroalloys operations).

This requires the following:

- Paste levels are maintained consistent and measurable at all times, either by manual, laser (Figure 24) or microwave radar interferometry techniques (Figure 20), with special care being taken to ensure that fin baskets or other techniques are adopted to secure liquid paste measurement in the more problematic situation of paste briquette addition
- Always ensure that some hard paste is present to act as a thermal buffer and prevent overheated paste that can otherwise drive segregation by mechanisms of thermal accumulation and cavity enrichment of volatiles and fine aggregate. Resultant pitch volatilisation can pose a CTPV health risk, and even a casing column explosion risk. Consider forced convection of air through the electrode column, especially should fumes be observed, to mitigate the risk of accumulation of volatiles, CO and H_2 to above the explosive limit.
- Consider temporary use of paste briquettes to raise rapidly low soft paste levels (the greater surface area of the briquettes will accelerate softening into the liquid paste).
- Avoid excessive paste addition under conditions of low paste level, to limit the risks of:
  - Paste bridging and cavity formation, especially in the case of addition of briquettes
  - Hard paste interfering with, cooling and distorting the thermal profile of the baking zone (450°C isotherm, usually contained within the bottom third of the contact shoes), especially in the case of addition of cylinders
  - Segregation of coarser aggregates from pitch binder and fine aggregate by a “jigging” action, especially in the case of addition of cylinders.
- Avoid high soft paste levels, that otherwise can contribute to Stokes’ Law segregation of coarser aggregates from pitch binder and fine aggregate under the influence of buoyancy and viscous forces.
- Always ensure that the paste cylinders are lowered, never dropped (Figure 11), to the top of the paste level in the electrode column to:
- Avoid bridging of paste between fins in the column
- Limit segregation of coarser aggregates from pitch binder and fine aggregate by mechanical “jigging”
- Limit unnecessary mechanical stress on the electrode and column.

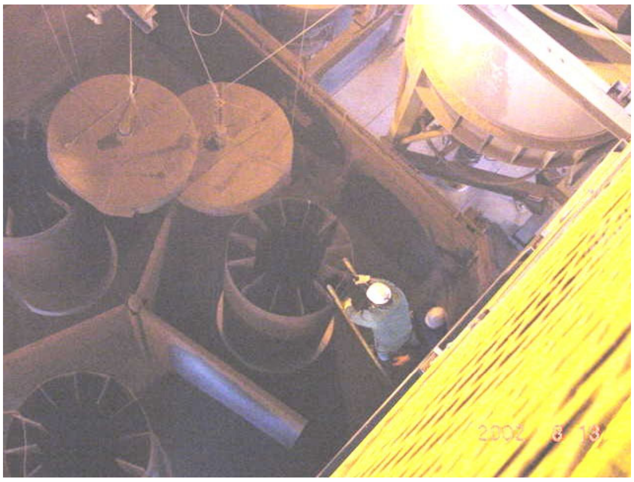

Figure 23. Electrode casing column paste covers all in place.

Figure 24. Electrode column dust covers equipped with lasers for continuous measurement of hard paste level.

In addition, through a combination of consistent paste addition, control of paste levels and temperatures, regular slipping, supply of cooling water of adequate temperature to the contact shoes (greater than 40°C), routine paste heating and through exercising tight control over the furnace operation to minimise fluctuations in furnace freeboard temperatures and power input, secure conditions that avoid unwanted paste segregation by preventing conditions that may contribute to:

- Paste heat treatment in situ that may raise paste softening points and lower paste fluidity
- Potential re-solidification of paste in an annular ring in the contact shoes that may impede downward free flow of soft paste.

5. CONCLUSIONS

A mechanism of segregation of coarser aggregates from pitch binder and fine aggregate is postulated that may explain some electrode breaks characterised by the remaining electrode displaying a distinctive concave cusp, classically categorised as an over-baked/under-slipped break surface, but where conditions physically precluded any possibility of over-baking/under-slipping.

It is believed that such breaks may result from paste segregation involving:

- Some separation of coarser aggregates from pitch binder and fine aggregate in the annulus of soft paste around the central core of hard paste in the electrode column, by a “jigging” action associated with each paste cylinder loading event. The downward “plunging” force of hard paste into the soft paste is potentially exacerbated by both:
  - any substandard practice of dropping, instead of lowering, paste cylinders down the electrode column, and/or
  - repeated overloading of paste cylinders and resultant high paste levels
- Volatilisation of pitch binder constituents due to excessive paste temperatures, particularly under conditions of low soft paste levels and especially in the absence of any hard paste level.

It is further postulated that a practice of excessive paste cylinder addition resulting in high hard paste levels may cause paste segregation into alternating pitch binder- and fine aggregate-depleted (coarse aggregate-enriched) and coarse aggregate-depleted zones, repeated at regular intervals along the length of the electrode (and associated with the timing of paste loading). These zones will not benefit from the original composite material design intent of the paste and, being more susceptible to both crack initiation and propagation, may take on an electrode appearance of a series of circumferential cracks. These would increase the incidence of electrode tip losses that detract from optimal smelting performance.

By taking cognisance of certain paste handling recommendations, and by rigorously adhering to the adage "show me your paste handling and I will tell you what your electrode performance is", it is hoped that most furnace operations will benefit, and not be exposed unnecessarily to the detrimental effects of electrode paste segregation.

6. ACKNOWLEDGEMENTS

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