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PASTE PRODUCTION AND ITS PERFORMANCE IN SØDERBERG SMELTERS

Markus W. Meier, Raymond C. Perruchoud
R&D Carbon Ltd, PO Box 362, 3960 Sierre, Switzerland

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Abstract

The evolution of the capacity of Søderberg smelters and of the pot technology over the past two decades is addressed. Today's figures of specific energy consumption and current efficiency are reviewed along with the paste performance in view of anode voltage drop, skimmed carbon and paste consumption. Bench mark performance figures are commented as a function of the technology using dry, semi-dry or wet carbon pastes.

Laboratory testing of paste and baked artefacts is overviewed and the typical worldwide ranges of the key properties are given. The impact of the pitch and fines content on the intrinsic paste properties is quantified and the effects of raw materials are illustrated. The importance of the baked paste properties for the carbon consumption is explained. The peculiarities of dry aggregate preparation and paste production in the carbon plants are discussed with their impact on the paste quality and consistency.

Modern Søderberg smelters with point feeders and hooded high amperage cells comply with severe emission limits and continue to be profitable. Modernization of the existing carbon plants is thus mandatory to keep up with the pot requirements.

Evolution of Smelter Capacity and Technology

During the last two decades the Søderberg technology has lost its importance for producing primary aluminum as it was massively surpassed by the prebaked pot technology. Søderberg smelters disappeared in China and India as well as from the African continent, while in Europe and North America the production rate decreased two to three folds. Some exceptions are the capacity increase observed in the CBA plant of Sorocaba (Brazil) and in the Russian smelters of Bratsk and Krasnoyarsk; today the latter reach both the 1 Mio tpy production level. In 1990 the 53 registered smelters have contributed 30 % (6 Mio tpy) to the world aluminum production. Today 23 smelters have survived, who represent only 12 % of the world production (5 Mio tpy).

The line current follows the same trend (see figure 1) as the percentage of low amperage potlines below 100 kA decreased from 55 % to 33 % and those for high amperage above 150 kA increased from 8 to 21 %.

The Horizontal Stud Søderberg smelters practically disappeared so that the majority of smelters use Vertical Stud Søderberg technology (VSS). In the early nineties the VSS smelters were using wet (soupy) carbon paste (no stud hole paste filling needed) and the fume emission (PAH) was a big concern for the worker's health and environment. The pots were side-breaked and not hooded so that dust emission was obviously a burden for the potline operations.

Today the state of the art potline use dry paste with stud hole paste (SHP). The pots are equipped with point-feeders and are hooded. Beside the better control and higher current efficiency of the cells the working atmosphere and the emission levels have been improved dramatically [1, 2].

Today's Pot Performance and Consumption Figures

The review of the plant data on a worldwide basis shows that in 2013 the specific energy consumption is close to 16 MWh/tAl, which is 2 to 3 MWh/tAl higher than for prebaked pots. One reason is the higher level of the carbon anode voltage drop that is more than twice the one observed in prebaked pots (more than 500 mV versus less than 250 mV), a difference representing practically an extra energy consumption of 1 MWh/tAl.

The bench mark anode voltage drop (450 mV) is 180 mV lower than the worst observed value, a difference representing already 0.6 MWh/tAl, as shown in figure 2. Beside a low baked paste anode resistivity, precise stud setting and good performance of the SHP explain the lowest levels of anode voltage drops.

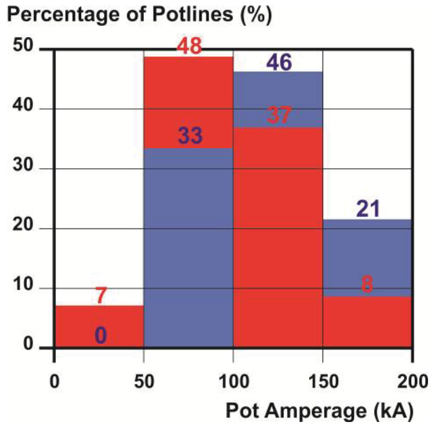

Figure 1: Line current, 1990 vs. 2013 1990 in red, 2013 in blue

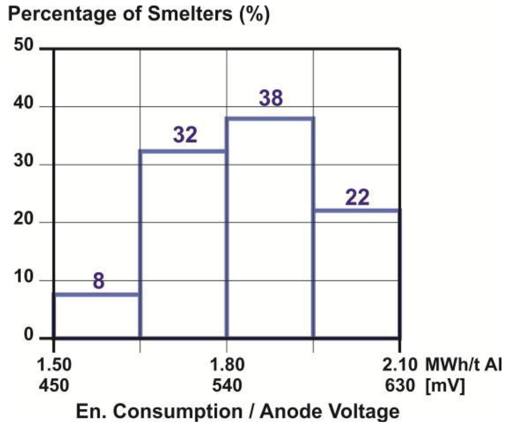

Figure 2: Voltage and energy distribution

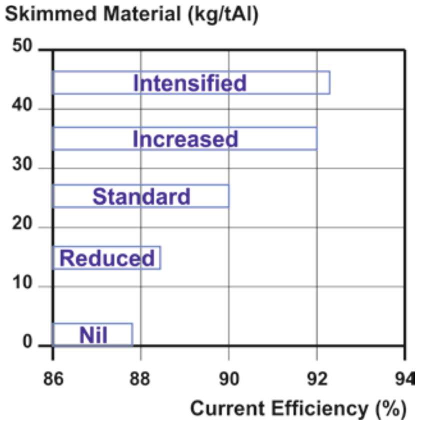

Figure 3: Skimming and current efficiency

The current efficiency (CE) depends on many factors [3], one of them is the extent of carbon dust accumulated in the bath. As shown in figure 3, the skimming of carbon dust present in the bath is an important operation for improving the metal output. The data are taken from a smelter experiment made for assessing the needed frequency of pot skimming and the corresponding crew. The current efficiency is lower than for prebaked smelters, the best being 92 % while the worst is in the range of 86 to 88 %

The need of skimming depends mainly on the paste consumption and on the dusting propensity of the working anode area. Figure 4 confirms that there is a large range of the 2013 paste consumption as the bench mark is 480 kg/tAl while many smelters operate at a level above 540 kg/t Al. The above data demonstrate the relevance of the paste quality and consistency for high metal output at low carbon and electricity consumption i.e. for low cost aluminum production, one of the basic reasons why Søderberg smelters are still in operation.

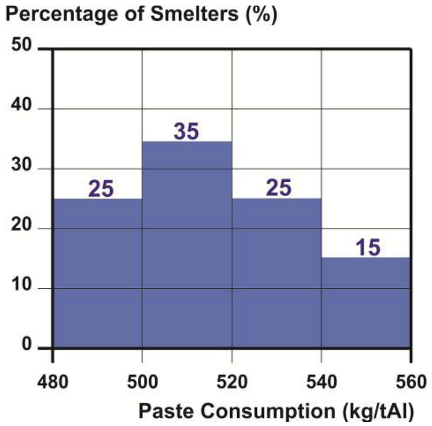

Figure 4: Paste consumption distribution

Types of Søderberg Pastes and Their Characterization

The first task of the Søderberg briquettes fed to the top of the pot is allowing smooth stud pulling operation. As the paste tends to melt through heat conduction from the hot anode bottom zone, it is important to guarantee a sufficient high flowability (wet paste) in case no stud hole paste is used. In modern pots, where SHP is used, the stud holes shall not collapse during the stud pulling operation. In this last case a so-called dry paste with low flowability is used.

For testing the melting behavior in the temperature range prevailing on the anode top area (150 to 200 °C), a shaped paste artifact is prepared and placed in a heated cabinet for a given period where after some melting a significant deformation occurs (see figure 5, left). There are different standards and options like the sloping board (where the elongation of the cylinder length is measured) or simply a horizontal plate (where the ratio of the diameter after vs. before the test is reported.

The baking of the paste under load in appropriate containers allows preparing a baked finished anode that can be core drilled for measuring the relevant properties (see figure 5, right).

Figure 5: Flowability test on the left, paste baking and core drilled baked anodes on the right

Effects of Formulation, Raw Materials and Process Parameters on Paste Characteristics

Wet paste is typically prepared by dosing about 30 to 32 % of coal tar pitch, semi-dry paste with about 28 %, while dry paste used in modern pots contains ~ 26 % as shown in figure 6.

The pitch demand for reaching a given flowability target depends also on the amount and fineness of the ball mill fines as illustrated in figure 7. A minimum of fines of 30 % is mandatory to maintain a minimum amount of binder matrix that will provide a good cohesion and therefore suitable baked anode behavior in the pot.

An optimization of fines and pitching is performed to get a high performance paste that fulfills the anode top and baked performance requirements.

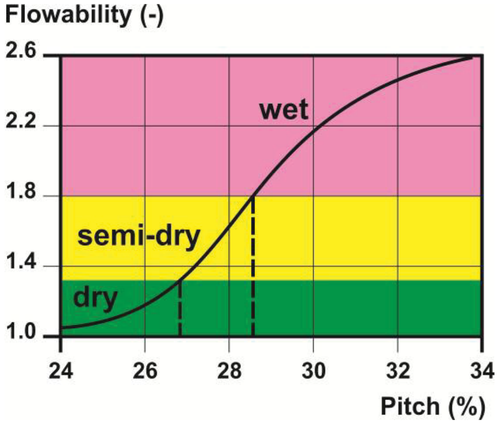

Figure 6: Flowability vs. pitch content

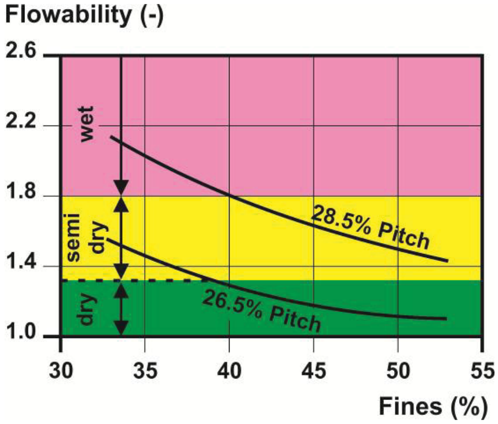

Figure 7: Flowability vs. fines - pitch content

The switch from wet to dry paste improves the basic baked paste properties such as the apparent density and the anode gas permeability (see figure 8).

With a higher level of baked density the permeation of CO_2 gas from the bottom anode working face diminishes, which reduces the carbon consumption and dust generation. The electrical consumption drops as a result of the lower electrical resistivity of the carbon in the baking zone.

Low porosity cokes with a high bulk density have the same beneficial effect (see figure 9). This is due to the reduced pitch demand [4] and the potentially lower reactivity to oxidant gases.

High primary quinoline insoluble (QI) pitches might be deleterious as the pitch requirement for reaching a given flowability is increased (see figure 10), which is a phenomenon that is not observed for prebaked anode paste.

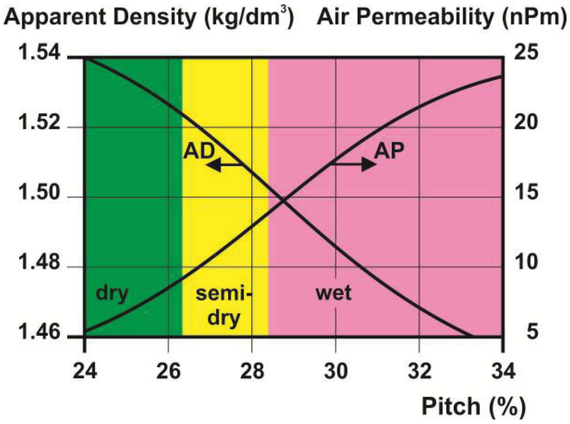

Figure 8: Density and permeability vs. pitching

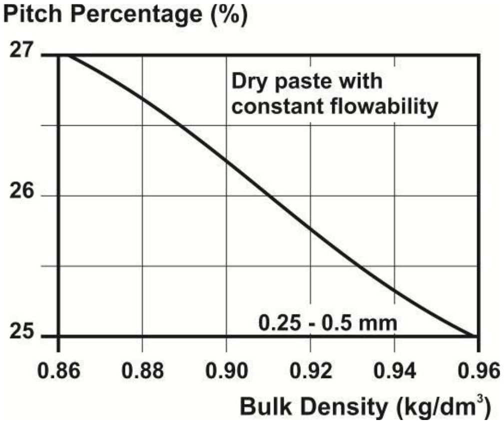

Figure 9: Coke porosity and pitching

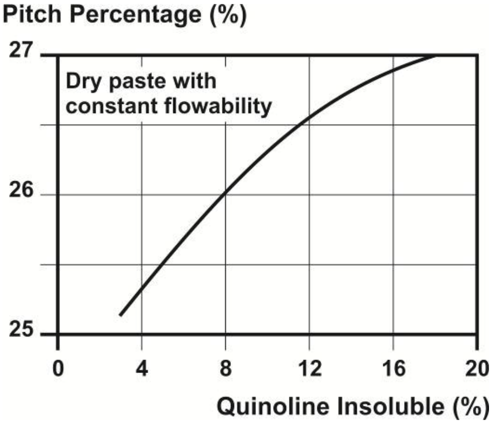

Figure 10: Effect of binder QI on pitching

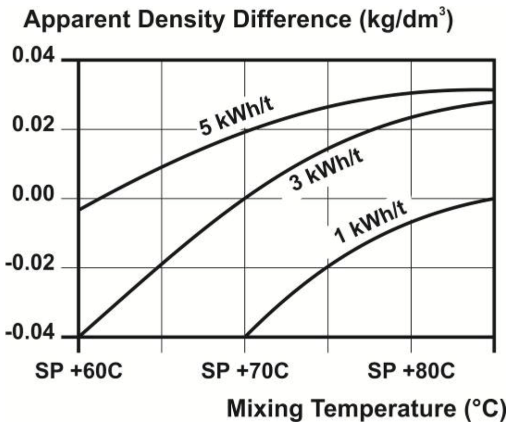

Figure 11: Impact of kneading temperature and energy

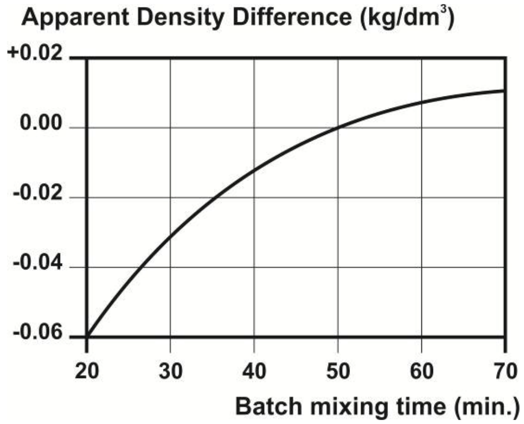

Figure 12: Impact of batch mixing time

In the paste plant, appropriate mixing conditions are a must for the baked paste quality [5]. As shown in figure 11, for continuous kneading technology, a relatively high temperature and high mixing energy provide a paste with the best performance. High mixing energy is achieved by the selection of appropriate shaft revolution speed and flap gate opening. In a batch mixer the wet mixing time and heat transfer to the paste are the key factors for efficient mixing (see figure 12).

Table I gives the typical range of the properties of dry and wet pastes resulting from the testing of more than 20 different industrial pastes at the R&D Carbon laboratories over the past 25 years. A good consistency of the flowability of the paste fed to the pots is very critical as it guarantees a smooth stud pulling operation once its level has been correctly chosen. Therefore emphasis shall be also given on the deviations of the baked laboratory paste properties and not only on their average levels.

A stable paste plant process is a must for the consistency of the baked properties as well. It should be emphasized here that one major source of short term inconsistency of the paste flowability is the variability of the fines sizing [6]. One of the most frequent paste plant design issues is the wrong option of "all fraction excess" as ball mill feed instead of a strict and single feed material that should be the excess of the finest grain fraction.

In a modern plant using a single efficient crusher with a variable size reduction ratio up to 9 (instead of 3 with the classical jaw crushers), a consistent dry aggregate preparation can be achieved with only one single crusher (see figure 13). Along with a systematic overflow approach (all grain silos always full) the ball mill feed exclusively consists of the finest grain fraction only. This guarantees an easy and good control of the ball mill circuit and hence stable ball mill fines sizing.

Table I: Typical range of the properties of Søderberg dry and wet carbon pastes (baked in laboratory)

Properties	**Method**	**Unit**	**Typical dry paste**		**Typical wet paste**	
			Mean range	**2σ range**	**Mean range**	**2σ range**
Flowability	Gost	-	1.1 - 1.3	0.05 - 0.15	1.8 - 2.4	0.10 - 0.30
Green Density	Gost	kg/dm^3	1.57 - 1.63	0.01 - 0.03	1.52 - 1.59	0.01 - 0.03
Baked Density	ISO12985	kg/dm^3	1.44 - 1.52	0.02 - 0.04	1.39 - 1.47	0.02 - 0.04
Sp. El. Resistance	ISO11713	µΩm	60 - 70	2 - 5	68 - 76	3 - 5
Flexural Strength	ISO12986	MPa	7 - 12	2 - 4	6 - 10	2 - 4
Thermal Conductivity	ISO12987	W/mk	2.6 - 3.4	0.2 - 0.4	2.2 - 3.0	0.2 - 0.4
Air Permeability	ISO15906	nPm	5 - 18	5 - 10	8 - 25	8 - 12
CO_2 Reactivity Residue	ISO12988	%	80 - 92	4 - 10	80 - 92	3 - 10
Air Reactivity Residue	ISO12389	%	60 - 90	5 - 10	55 - 90	5 - 10
Density in xylene	ISO 9088	kg/dm^3	2.02 - 2.06		2.02 - 2.06	
S		%	0.5 - 2.2		0.5 - 2.2	
V		ppm	40 - 400		40 - 400	
Si		ppm	100 - 300		100 - 300	
Fe		ppm	100 - 500		100 - 500	

Bench mark value in green

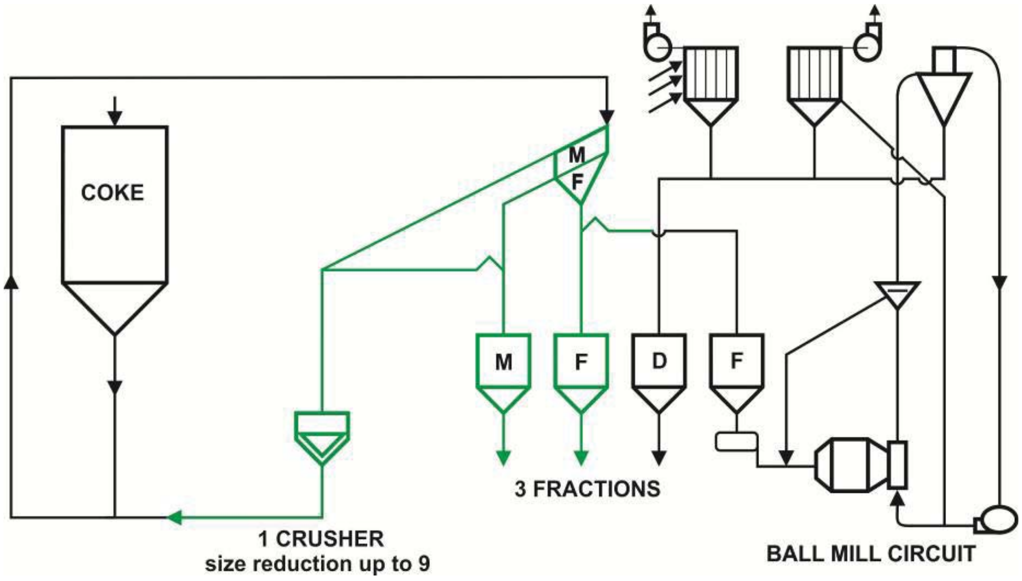

Figure 13: Modern plant: one overflow as ball mill feed

Other important aspects of the paste plant are the preheating and mixing steps. The old batch mixing approach, where first the dry aggregate was preheated in the mixer and then the paste was mixed using rotating sigma-blades, has been replaced by the continuous preheater and kneader system. Continuous twin-screw mixers may also be replaced by the latest kneader generation (enlarged shaft with reduced discharge end combined with adjustable flap gate).

This provides by far a much more efficient mixing of the pitch to the dry aggregate. This is not only related to the level of the initial temperature of the components entering into the mixing step, that is close to the final paste discharge temperature, but also to the much higher paste mixing energy [7]. With a specific mixing energy level up to 4 kWh/t of paste at an appropriate mixing temperature of 80 °C higher than the pitch softening point (see figure 11), the paste prepared in the kneader reaches an apparent density level that is up to 0.05 kg/dm^3 higher than the paste prepared in batch sigma-blade mixers.

Anode Performance in Pots

Figure 14 gives detailed visual information on the deficiencies of an anode bottom where extended cavities and practically all stud holes are visible. When the apparent density and mechanical strength of the anode are low and the resistance to CO_2 attack is minimal, a progressive formation of deep channels takes place. Inappropriate practices of stud setting together with inferior SHP quality end up in cavities below the studs that are also problematic for low Fe content in the metal as the bath can wash the stud tips.

The resulting uneven distribution of the current leads to magnetic disturbances. Combined with an increased amount of carbon dust production and accumulation, the pots tend to overheat and the potline current efficiency drops. Such an unsatisfactory performance can be detected by determining the bubble noise. This noise is the average extent of the rapid oscillation (in the range of 1 second) of the pot voltage related to the gas bubbles release from the anode bottom area. It is much lower for a problematic condition of the anode bottom (40 vs.120 mV) as the channels drain the electrolysis reaction gas towards the side of the cell. Thus the gas insulation layer is continuously eliminated and the measured pot voltage oscillation decreased [8].

The accumulation of carbon dust in the bath is a major risk with inferior Søderberg paste quality. In the past, on side-breaked pots having one anode effect per day, the cells could eliminate much more carbon dust present in the bath. Today with point-feeder technology and the massive reduction of the number of anode effects, the produced carbon dust has far less chance to burn so that it might accumulate in the bath. An indirect indicator of the amount of carbon content in the bath is the level of the pot voltage during the anode effect. The voltage can reach up to 40 V when the bath is relatively free of suspended carbon dust while in case of severe accumulation it does not reach the level of 20 V [9].

When the anode behavior is poor (low bubble noise) and the number of anode problems is on the high side, an appropriate countermeasure is the increase of the frequency of skimming as suggested in figure 3. The amount of skimmed material from the bath (typically 1/3 of it is carbon from the baked paste) depends on numerous human factors like the workforce available and its skill for such a tedious operation. It is also strongly influenced by the management strategy for reaching the higher metal output at the lower production costs. There are smelters with virtually no skimming (5 to 10 kg/tAl) and others exceeding 50 kg/tAl.

Substandard performance of the anode in the pots is commonly reported as anode problems. They include for instance stud-hole leakages, spikes formation requiring a manual removal but also fallen chunks resulting from a combination of deep vertical cracks on the casing sides with horizontal cracks. Beside the unpleasant conditions faced by the operators exposed to heat and aggressive gases, all these events create unsatisfactory electrolysis conditions with loss in current efficiency and increased energy consumption. The number of anode problems per pot and day can be as low as 0.01 [7] so that only one such event for a typical potline having about 100 pots shall be handled each day.

Figure 14: Problematic condition of anode bottom: channels and stud hole cavities

The paste consumption is an important cost factor. Today with a paste cost of 500 to 700 USD/t, the 80 kg/tAl difference (see figure 4) observed between the bench mark and the worst smelter figures results in a direct difference of 50 USD per ton of metal. Together with the reduced metal output and the extra amount of electrical energy, indirectly related with the poor anode performance and its high consumption level, the total production cost difference easily reaches 150 USD/t Al.

Therefore emphasis shall be given in the consistency of the paste flowability, in other words also in a minimum amount of the so-called correction paste, which is a must for a smooth stud pulling and setting operation. High apparent density level of paste, achieved through appropriate formulation and high mixing severity (temperature and energy), is a key property as it correlates with low gas permeability and high strength and eventually low carbon excess consumption.

Conclusions

The experience of the past two decades has shown that it is feasible not only to maintain but to expand the production of aluminum by using the low investment cost Søderberg technology in existing smelters.

The main issues that were PAH, dust, fluoride and greenhouse gas emissions were successfully abated to acceptable levels for the workforce and for the environment. With the cost of retrofit to prebaked technology being too high the right response is rather tackling the issues mentioned above along with an increase of the productivity of the potlines by higher amperage and better current efficiency [10].

In this respect the quality level of the paste plays an important role to sustain the higher current density. Continuous dry anode paste production in modern plant equipped with state of the art dry aggregate preparation, along with a powerful preheater and kneader is the right combination to respond to the challenges of the Søderberg smelters.

The last generation of Søderberg paste kneader, reaching high throughput with high mixing energy, opens new revamping opportunities for smelters using continuous paste preparation units. For large smelters, having several lines in operation using small continuous mixers with low throughput (10 to 17 t/h), the installation of one high throughput (up to 35 t/h) modern kneader can cover the paste preparation of two or three dry aggregate/preheater lines.

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