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COMPACTION OF ROOM TEMPERATURE RAMMING PASTE

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Fourteen commercial cold type ramming pastes have been characterized by using a rugged and simple but precise laboratory compactor. The results are correlated with paste formulation and plant experience. The laboratory data have been modeled mathematically and the pastes are classified quantitatively in terms of ramming criteria. Most pastes have a temperature range with satisfactory properties and these temperature windows are calculated. A visual model is presented and the paste properties are discussed in terms of quality and paste formulation.

INTRODUCTION

As stated by Franke *et al.* [1], the purpose of the rammed joints and seams of the cathode is not to weld the prebaked parts of the cathode together, but to prevent metal and bath from penetrating the lining. This requires the ramming paste to have proper characteristics with respect to:

- shrinkage and thermal expansion
- resistance towards and expansion from sodium
- mechanical strength and abrasion resistance.

The above criteria will again be influenced in a complex manner by the materials chosen, the granulometry of aggregate and amount of binder content. A more extensive discussion of ramming paste and cathodes in general will be published elsewhere [2].

The object of the present paper is to discuss a minimum requirement of ramming paste: Which properties enable tight and uniform compaction. Not only must the tamping be executed properly, but the paste must also be well formulated, with special attention to how and under which conditions the customer is likely to apply the product, *i.e.* climatic conditions, hand-ramming *versus* mechanized compaction [3].

It is, however, often experienced by the pot relining crew that the consistency or "workability" of room temperature ramming pastes may vary considerably. This variation is often found between batches or shipments of what nominally should be the same consistent product, not to mention the differences experienced in compaction behaviour between different brands. Climatic conditions at the plant site may further influence the compaction behaviour of a given paste.

One obvious problem is that such properties are difficult to specify, and later to verify. An experienced operator will almost imediately be able to tell if a given paste lot will cause problems during ramming, but a quantification of its "off-specs" properties other than "too wet" or "too dry" will be difficult to obtain, and even more difficult to use in a dialog with the paste producer. In its extreme a "wet" paste may reach a "jellyish" or "rubbery" consistency upon tamping while self adhesion may be impossible to acheive in a "dry" paste.

Binder content and paste formulation are important empirical tools for the paste producer, but are of limited value as control parameters to an end user of ramming paste. Changes in raw material supply, calcination conditions and minor short and long term variations in filler granulometry will render paste property estimates based on extraction and sieving analysis, virtually impossible. Only when all other variables can be considered constant, may the binder content be used as an indicator of paste property and rammability.

In the work which will be presented in the following, it will be shown that, with the use of a precise but simple and rugged experimental apparatus, it is possible to analyze the compactability behaviour of a given room temperature ramming paste. The method can easily be employed on-site and will almost instantly indicate in a qualitative way which paste (shipment, batch, big-bag, etc.) that may be unsuitable for compaction at a given temperature. It will also be shown that quantitative and verifiable rammability criteria can be obtained from a mathematical treatment of the compaction results. These criteria can be used in a dialog with the paste producer, either as part of ramming paste specifications or in case of specific complaints on paste quality.

EXPERIMENTAL

Compaction

All compaction experiments were performed with commercially available room temperature ramming pastes, either taken from regular shipments to aluminium plants or as samples offered for testing as part of the marketing efforts by the individual producers.

As a ramming tool a manually cranked +GF+ Sand Rammer Type PRA (George Fischer Ltd., Schaffhausen, Switzerland) was used. The compaction took place as the energy from a falling weight was transferred to the paste (180.0 g paste in a 50 mm diameter steel cylinder) through a piston resting on the paste (Figure 1). The energy of each stroke was independent of the degree of compaction, *i.e.* the height of the paste cylinder. This height (H) could be read directly to the nearest 1/10 mm after each stroke and the paste density (d_R) computed:

$$d_R = 91673.25/H \qquad (1)$$

With H given in mm, d_R is obtained in kg/m^3. The compactions were performed in a standardized manner with up to 350 strokes or number of rammings, (N). The height of the cylinder was most frequently read at low N, less frequently as the number of strokes increased.

In order to examine the temperature sensitivity of the pastes, the compactions were performed at three different temperatures: 10, 22 and 50°C (±2°C). In the former and latter cases, the paste, steel cylinder and pedestal, Sand Rammer baseplate and piston had to be cooled or heated to the given temperatures, respectively. In order to minimize the heat transfer to and from the surroundings, the steel cylinder was enclosed in thick synthetic fibre wool insulation (Figure 1).

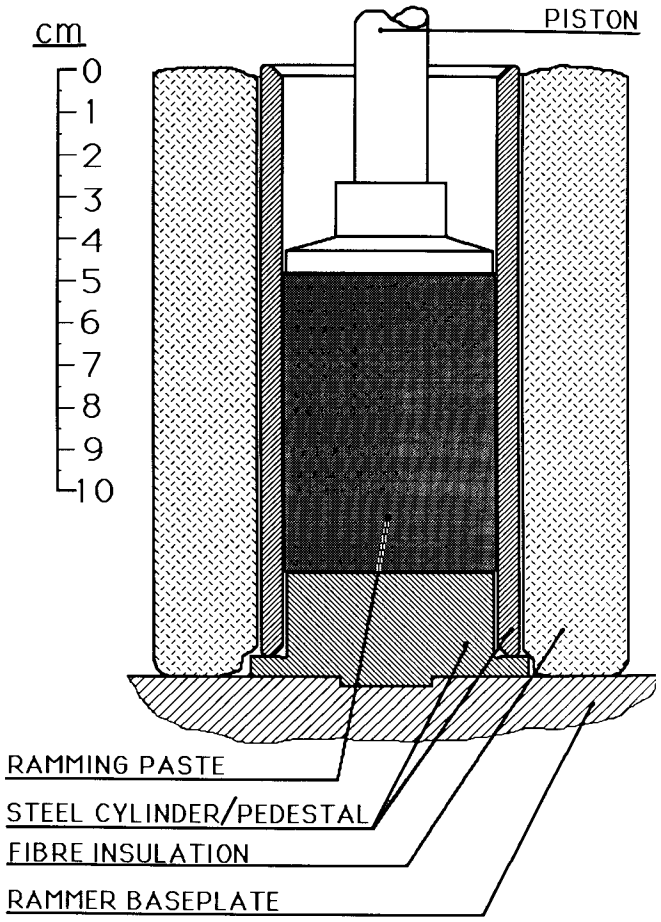

Figure 1. Sand Rammer mould (specimen tube and pedestal) with insulation.

Table 1. Characterization of the room temperature ramming pastes examined.

Paste	Filler: Type	-125+63µm (%)	-63 µm (%)	Binder: Type	Extr.loss (%)	Plant experience	Lab experience (22°C)	Temp. window (°C)
A1a (A1b)	GCA+G	13.4	17.0	CTP	15.6	Satisfactory after preheating.	Same as plant	32-41
A2	ECA	15.2	16.5	CTP	16.9	Unsatisfactory, no self adhesion in paste.	Dry	(++)
B1	ECA	10.1	20.7	CTP	15.1	Satisfactory.	Wet	10-15
B2	GCA			S	9-10		Satisfactory	19-32
B3	G	9.6	15.0	CTP	16.8	Satisfactory.	Satisfactiory	8-18
B4a (B4b)	GCA	9.3	18.4	CTP	10.5	Satisfactory.	Satisfactory	18-26
C1a	ECA	10.6	14.5	CTP	13.8		Wet	5-15
C1b	ECA	6.9	23.4	CTP	16.2	Unsatisfactory, achieves "rubbery" consistency.	Wet (+)	3-10
C2	ECA	8.5	18.2	CTP	15.9		Wet	8-14
D1a	ECA	11.5	21.0	CTP	14.6	Unsatisfactory, achieves "rubbery" consistency.	Much too wet	(++)
D1b	ECA	10.5	26.4	CTP	17.1	Unsatisfactory, achieves "rubbery" consistency.	Much too wet (+)	(++)
E1	ECA	8.5	18.5	CTP	12.0		Dry	>40

GCA: gas calcined anthracite
ECA: electrocalcined anthracite
G: graphite
CTP: coal-tar (pitch) binder
S: synthetic binder
(+): wettest in group
(++): should not be applied

Static pressure up to about 50 MPa was also used in compaction experiments with some of the pastes, using the same steel cylinder described previously. These experiments were performed only at ambient temperature (22°C), mainly for comparision with Sand Rammer densities. Paste densities obtained by applying pressure are denoted d_P.

Extraction and sieve analysis

As seen in Table 1, all ramming pastes with one exception had a coal-tar (pitch) based binder which could be extracted in quinoline. The only exception was paste B2 which had a novolak type binder, only solvable in polar solvents. The dried fillers were characterized by sieve analysis with standard ISO sieves from 8 mm openings and down to 63 μm (reduction factor 2).

RESULTS

Table 1 presents in a summary fashion the pastes studied. The different commercial pastes are identified with a letter-number code. A capital letter refers to the producer, a number to the paste type while a lower case letter refers to different shipments of the supposedly same material but with varying binder content and granulometry. In addition to the physical characterization, the suitability of the material in plant operation is listed as far as it is known, as well as a laboratory characterization. Finally, an estimate of the temperature window for each laboratory tested paste is given.

Figure 2 shows the compaction characteristics at 22°C for the materials studied. They have been classified according to plant (or laboratory) experience, *i.e.* 2A: Paste with poor self adhesion or paste which shows a high resistance towards densification; 2B: satisfactory paste; 2C: paste which obtains rubbery consistency after compaction. The materials where plant experience is not known are classified in the group that shows the closest compaction characteristics. Figure 3 illustrates the influence of temperature upon compaction while Figure 4 shows compaction of the same material but with varying binder content and temperature.

All the materials were characterized more detailed with respect to granulometry than given in Table 1. Figure 5 shows the sieve analysis for some selected materials, illustrating the differences which could be found in paste formulation.

QUANTITATIVE CHARACTERIZATION OF COMPACTION

Inspection of Figures 2-4 reveals some important criteria for classifying the ramming pastes as satisfactory or not. It is not the final density obtained during ramming, but the apparent density (or change in density) as a function of temperature and the work applied, which is important with respect to giving an estimate of the quality and compactability of a green ramming paste. It must, however, be stressed that the compaction behaviour in the Sand Rammer cannot directly be compared to densities

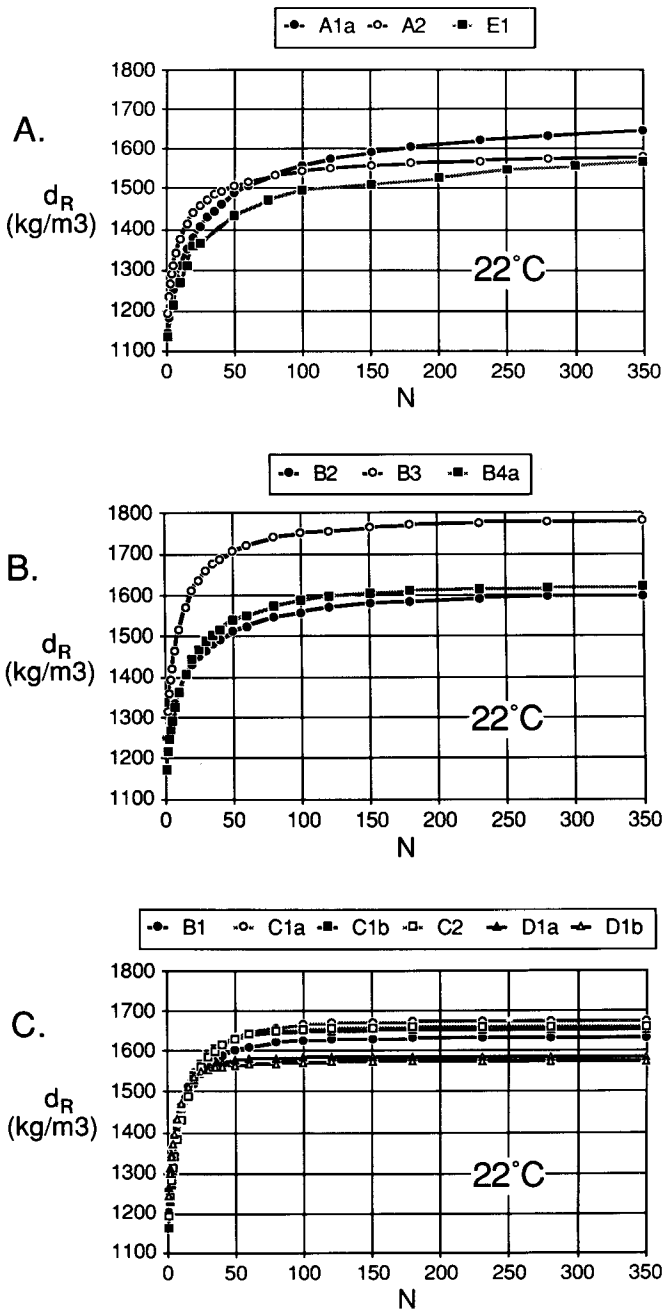

Figure 2. Compaction curves of room temperature pastes displaying roughly A: "dry"; B: "normal" and C: "wet" compaction behaviour at 22°C.
Black lines: Plant experience with paste.
Grey lines: Only lab experience with paste.

obtained in the cathode with the same paste and with similar work applied, mainly due to wall friction and flow restriction in the small specimen tube.

A "wet" paste is characterized by a rapid increase in paste density and the asymptotic upper density value, d_{max}, is reached quickly (Figure 2c). The "wetter" the paste, the more quickly this asymptotic value is reached. This is illustrated clearest in Figure 4A-C where the compaction curves for pastes C1a and C1b are compared in the region

near d_{max}. It is seen that paste C1b, which appears slightly "wetter" than paste C1a, reaches its d_{max} at a lower number of strokes, N, than paste C1a. This ranking is valid at all temperatures. A similar behaviour, and ranking, is displayed by pastes D1a and D1b.

The compaction behaviour of a "dry" paste is characterized by a slow approach towards its asymptotic density value, a value which may not be reached even after prolonged compaction in the Sand Rammer (Figures 2A and 3A). The risk of crushing filler particles upon prolonged ramming is great. A "dry" room temperature ramming paste cannot be diagnosed on its binder content only, as shown in Table1. Paste A2 has apparantly a high binder content, but is nevertheless characterized as "dry" and with a very poor compaction behaviour. It is not the lack of binder which makes paste A1a (and partly E1) hard to compact at ambient temperature and below, but a binder with a highly temperature dependent viscosity. Within a temperature window above ambient temperature the A1a paste acheives good compaction characteristics.

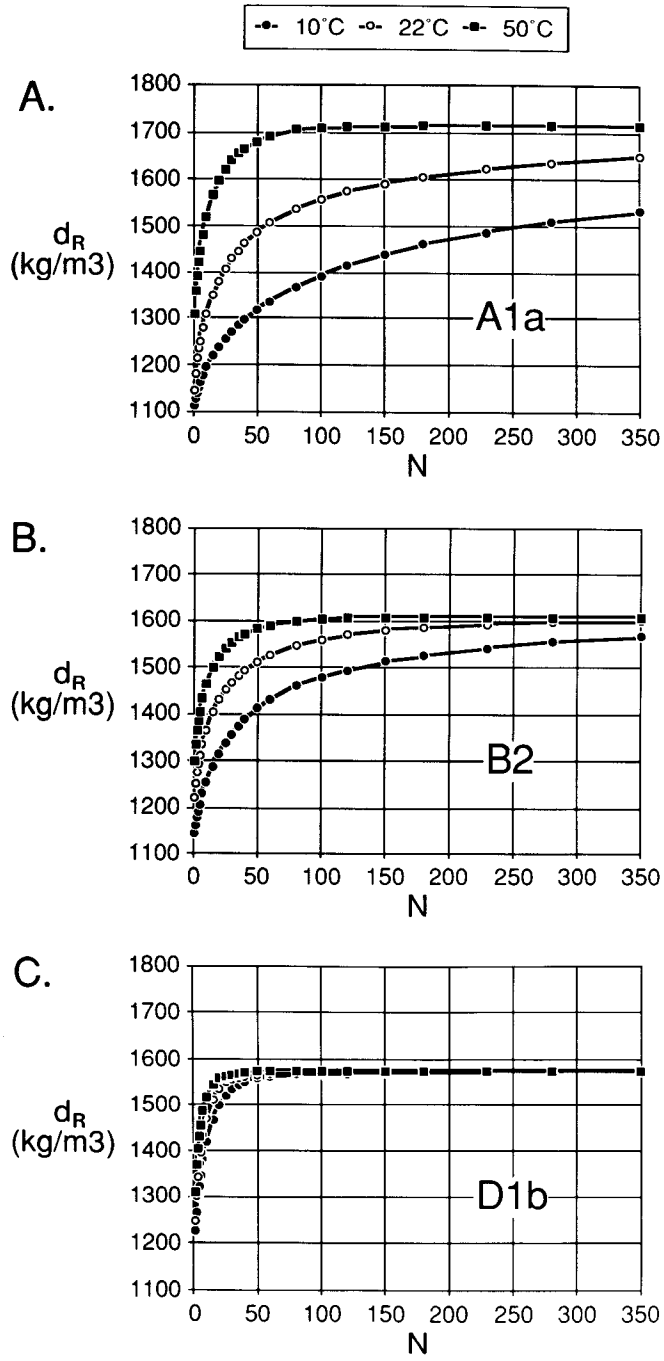

Figure 3. Compaction of three different ramming pastes at 10, 22 and 50°C.
A: The compaction behaviour is strongly dependent upon temperature (A1a); B: "Normal" compaction behaviour (B2); C: Compaction nearly independent of temperature between 10 and 50°C (D1b).

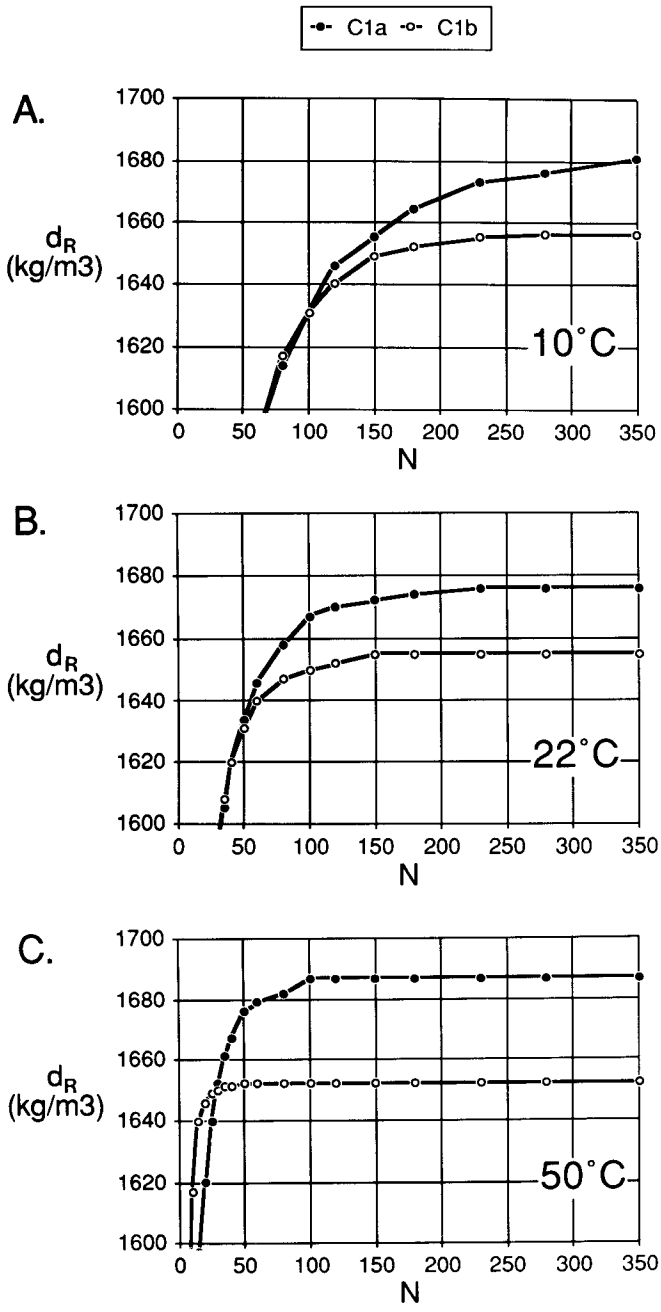

Figure 4. Compaction curves of two shipments of the nominally same paste but differing in binder content. Paste C1b has the highest binder content (Table 1).

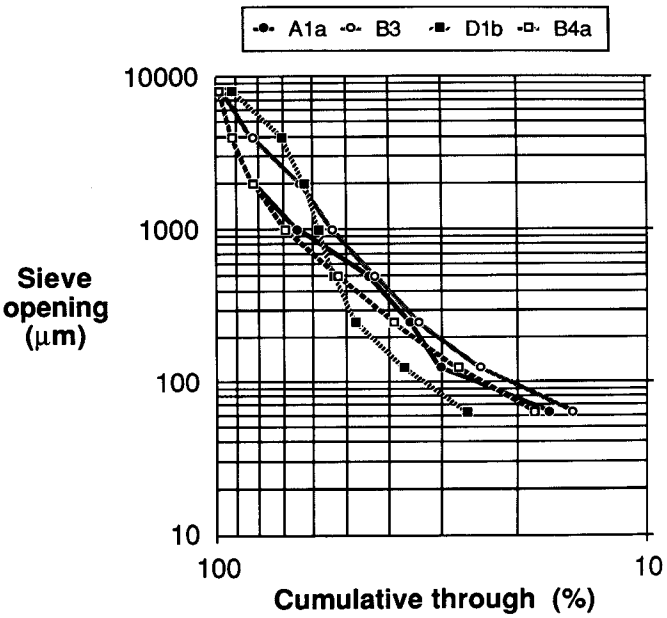

Figure 5. The curves serve to illustrate the variation which may be found in the dry aggregate formulation of room temperature ramming pastes.

In the "normal" pastes (compaction curves shown in Figure 2B and Figure 3B) the compaction characteristics are between the extremes discussed above. The density approaches d_{max}, but does not fully reach this value except after prolonged compaction in the Sand Rammer (N > 300-350) or at temperatures above ambient.

Paste B1, which was the wettest of the B pastes, is very similar to the C pastes, but nevertheless paste B1 has been found to be satisfactory in plant trials (but not necessarily this actual batch).

From the discussion above it can also be deduced that the temperature, at which a given cold type tamping paste is applied, may have a major impact on its "workability" and compaction characteristics. A paste like A1a is fully acceptable after preheating to about 30°C, while "normal" pastes like B2 or B4a may be on the border of uselessness at this temperature. A "wet" paste like C1a may yield good compaction results at 10°C, while pastes such as A2 and D1a,b are unsuitable at any reasonable temperature. Paste A2 is a special case in that it shows a nearly "normal" compaction behaviour at low N. However, as the number of rammings increases, the compaction curves fail to approach d_{max} in a normal way irrespective of temperature, as the density slowly but steadily increases. The reason for this will be discussed later.

An inspection of the paste surface, after removing the sample from the specimen tube, will also yield some diagnostic information. Figure 6 shows three room temperature ramming pastes which have been subjected to the same amount of work (at 22°C) in the Sand Rammer. Paste A1a (Figure 6A) has not reached proper compaction and a large amount of porosity can be seen at the surface. The paste cylinder in Figure 6B (B4a) has been densified close to ideal compaction, and minor pores may still be observed. Figure 6C, however, shows a paste (D1a) where the density has reached d_{max}. The surface is smooth and no open porosity can be detected.

However useful the above descriptions are for characterization of the different pastes, a quantitative mathematical description in terms of numbers will be still more satisfactory when discussing the criteria for rammability. The curves on Figures 2-4 have been curvefitted to a variety of functions, the object not only to obtain a good fit but also to obtain parameters which can express paste quality.

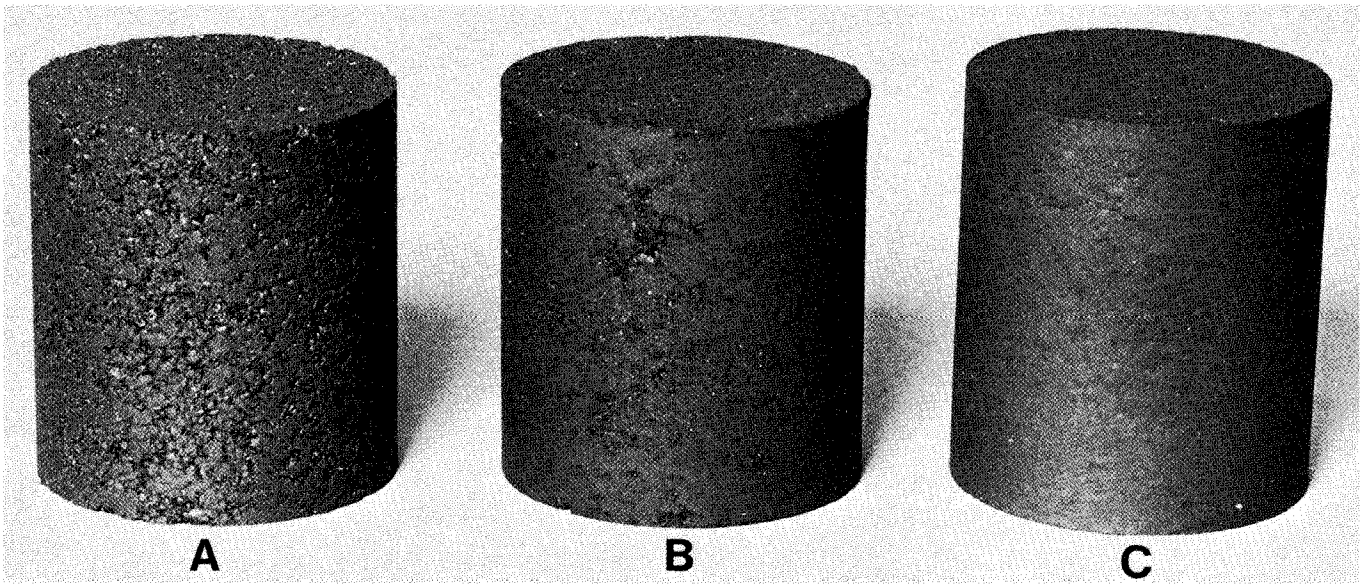

Figure 6. Three pastes with different compaction characteristics which are given the same amount of work in the Sand Rammer (22°C). A: Paste A1a compacted at a temperature below its temperature window; B: Paste B2 compacted within its temperature window; C: Paste D1a compacted at a temperature above its temperature window. Cylinder diameters 50 mm.

After trying different curvefitting procedures we were left with two models. The first gives a good fit to the experimental data but it is difficult to directly relate the parameters to physically meaningful compaction criteria. The second model yields a somewhat poorer fit but its parameters can better be used for assessing the compactability of a given paste.

The first model is based on the similarities between the compaction curves presented with a logarithmic abcissa (Figure 7) and statistical cumulative distribution functions. A general three parameter cumulative Weibull distribution function was chosen:

$$W(t) = 1 - \exp\{-[(t - \gamma)/\alpha]^{\beta}\} \qquad (2a)$$

which, transformed to the present system can be written:

$$d_R = d_{max} - \Delta d \cdot \exp\{-[(\log N - \gamma)/\alpha]^{\beta}\} \qquad (2b)$$

logN is an abbreviation for $\log_{10}N$. The pre-exponential factor Δd equals $d_{max} - d_o$ where d_o is the lower asymptotic value, which may represent a loose (gravimetric) compaction of the paste. α is the scaling or normalization parameter which determines the curve's steepness (decreases as α increases). β is the Weibull modulus or shape parameter and controls the asymmetry of the distribution. γ is the location parameter and has the effect of shifting the origin of the distribution.

The Weibull parameters (α, β and γ) and Δd were fitted to the model, while d_{max} is known from the compaction experiments or can be estimated with a high degree of accuracy. The model calculations showed that the fit was nearly independent of the Weibull shape parameter for $\beta > 3$. With $\beta = 6$ Eqn. 2b gave the results listed in Table 2.

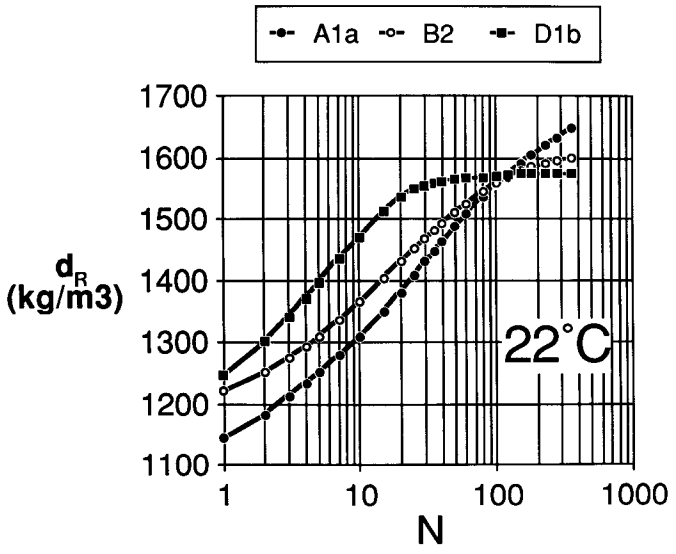

Figure 7. Graphical presentation of paste density *versus* the logarithm to the number of ramming strokes show the typical S-form of the compaction curves.

Table 2. Results from fitting data to Eqn.2b (Weibull function with ß=6).

Paste	t (°C)	d(max) (kg/m3)	Δd (kg/m3)	α	γ	s.d (%)
A1a	10	1715	616	5.288	-2.923	0.16
	22	1715	646	5.750	-4.079	0.20
	50	1715	452	3.675	-2.581	0.22
A2	10	1600	509	5.599	-3.963	0.29
	22	1600	560	6.075	-4.989	0.28
	50	1600	492	6.176	-5.247	0.14
B1	10	1636	537	4.096	-2.574	0.13
	22	1636	486	3.641	-2.576	0.13
	50	1636	449	3.397	-2.491	0.16
B2	10	1608	493	4.622	-2.851	0.13
	22	1608	427	4.402	-3.007	0.07
	50	1608	348	3.698	-2.629	0.12
B3	10	1800	681	4.765	-3.348	0.33
	22	1800	701	5.093	-4.012	0.30
	50	1800	594	4.611	-3.960	0.27
B4a	10	1634	575	5.178	-3.373	0.18
	22	1634	526	4.494	-3.204	0.15
	50	1634	422	3.900	-2.858	0.26
C1a	10	1684	511	3.924	-2.499	0.10
	22	1684	482	3.909	-2.770	0.19
	50	1684	348	3.381	-2.420	0.23
C1b	10	1655	555	3.305	-1.949	0.34
	22	1655	540	3.334	-2.298	0.33
	50	1655	375	2.708	-2.084	0.17
C2	10	1660	560	3.655	-2.164	0.32
	22	1660	498	3.237	-2.120	0.27
	50	1660	411	2.831	-1.877	0.18
D1a	10	1586	416	3.572	-2.548	0.15
	22	1586	360	3.148	-2.226	0.13
	50	1586	333	3.131	-2.385	0.22
D1b	10	1575	378	3.103	-2.063	0.18
	22	1575	390	3.289	-2.461	0.13
	50	1575	333	3.154	-2.472	0.09
E1	22	1592	509	4.959	-3.385	0.57
	50	1592	448	4.594	-3.215	0.26

The coupling of the Weibull parameters is one of the reasons why they are not easily associated with recognizable compaction criteria. Even when the value of β is fixed, the coupling between α and γ does not give a clear ranking of the paste.

The parameters in Table 2 can also be used to calculate the equivalent to the Weibull probability density function for this system, which is the 1.derivative (with respect to logN) of Eqn. 2b and gives the change in density *versus* the logarithm to the compaction work, *i.e.*:

$$d_R' = \Delta d(\beta/\alpha)[(\log N-\gamma)/\alpha]^{(\beta-1)}\exp\{-[(\log N - \gamma)/\alpha]^{\beta}\} \qquad (3)$$

This kind of presentation, especially if N is used as the abcissa, may improve the visualization of differences in compaction behaviour of various ramming pastes (Figure 8).

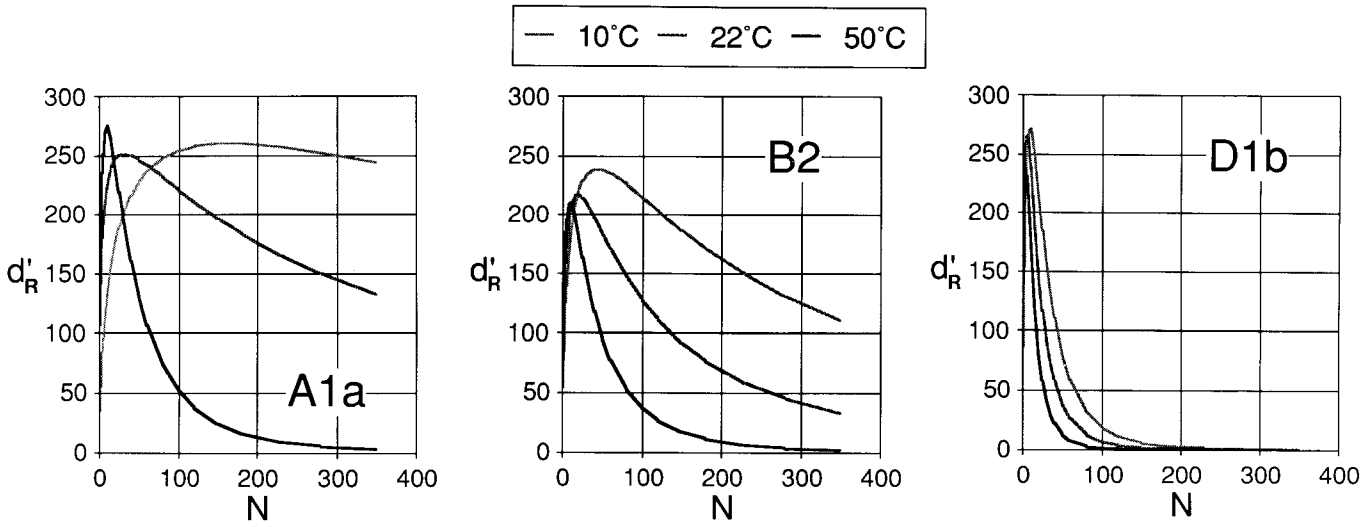

Figure 8. A graphical presentation of the first derivative, d'=∂d/∂logN (i.e. the Weibull probability density function, Eqn.3), of the compaction curves in Fig.3 may improve the visual differensiation of compaction characteristics of ramming pastes.

The second model is based on an exponential function having more recognizable and descriptive parameters:

$$d_R = d_{max} - \Delta d \cdot \exp[-(N/N_o)] \qquad (4a)$$

The advantage with this model is that N (and not logN) is the free variable and that $\Delta d/N_o$ is the limiting slope (for $N \rightarrow 0$). The parameter N_o can thus be given a discrete and recognizable physical meaning. It is immediately recognized that a low N_o value will indicate a "wet" paste while a high value of N_o will indicate a "dry" paste at the given temperature. The goodness of the fit is, however, not as good with this model (Table 3) as with the Weibull distribution function.

Another advantage with this model is that it is not strictly necessary to use the advanced type of non-linear parameter estimation program [4] which have been employed in this work. A simple transformation of Eqn. 4a:

$$\ln(d_{max} - d_R) = \ln(\Delta d) - N/N_o \qquad (4b)$$

makes it possible to estimate N_o (although with different weight assigned to the individual experimental values) with a simple linear regression program available for most microcomputers.

Until more plant experience can be related to compaction measurement in the Sand Rammer, the definition of paste rammability with reference to N_o can only be given on an approximate scale (Figure 9). In this provisional estimate, pastes with N_o values less than 20 are considered too "wet" to be compacted while pastes with N_o values higher than 50 are estimated to be too "dry" or too hard to compact properly at a given temperature. "Normal" pastes are assigned N_o values between 25 and 40, with borderline cases on each side of this range. Based on the

Table 3. Results from fitting data to Eqn. 4a.

Paste	t (°C)	d(max) (kg/m3)	Δd (kg/m3)	N_o	s.d. (%)
A1a	10	1715	550	212	2.76
	22	1715	506	68	3.26
	50	1715	396	16	0.94
A2	10	1600	401	62	2.64
	22	1600	368	28	2.19
	50	1600	300	24	1.68
B1	10	1636	480	39	1.77
	22	1636	428	15	1.03
	50	1636	403	10	0.74
B2	10	1608	431	69	2.24
	22	1608	361	33	1.45
	50	1608	303	15	0.76
B3	10	1800	562	35	2.44
	22	1800	513	22	2.15
	50	1800	412	8	1.11
B4a	10	1634	482	79	2.95
	22	1634	433	27	1.72
	50	1634	353	15	0.99
C1a	10	1684	460	32	1.43
	22	1684	414	18	1.16
	50	1684	314	11	0.59
C1b	10	1655	532	25	1.00
	22	1655	499	13	0.94
	50	1655	380	4	0.24
C2	10	1660	523	34	1.43
	22	1660	471	15	0.80
	50	1660	412	9	0.36
D1a	10	1586	368	13	0.85
	22	1586	339	9	0.49
	50	1586	309	6	0.43
D1b	10	1575	363	12	0.53
	22	1575	356	8	0.56
	50	1575	306	6	0.35
E1	22	1592	414	51	2.69
	50	1592	381	36	1.70

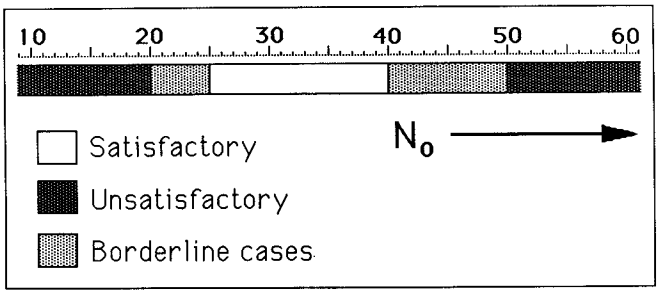

Figure 9. Provisional compaction characteristics in terms of the parameter N_o.

criteria that N_o should be between 25 and 40, the corresponding temperature window have been calculated and given in Table 1. The apparent inconsistency between the N_o values calculated for paste A2 (Table 3) and the characterization it has been given in Table 1 will be discussed later.

COMPACTION METHOD

While hand-ramming with pneumatic tools still will have to be applied in difficult accessible parts of the cathode, there are now various types of mechanized compaction equipment available. With some of these the compaction is performed by applying pressure instead of repeated ramming [2]. This, however, may give a given paste compaction characteristics different from those experienced with ramming. One way to clarify this dependency upon the mode of compaction is to calculate the relationship between applied pressure and ramming work upon densification of a given paste, *i.e.* under isodensity conditions.

Plots of paste density (d_P) *versus* the logarithm to the applied pressure gave curves with some similarities to those obtained through ramming. One distinct difference from the ramming curves (with logarithmic abcissa, Figure 7) was that the S-form of the latter was not observed, probably due to lack of data for very low pressures (Figure 10). Pressure compaction data for four different pastes were fitted to 2.order polynomials:

$$d_P = a_0 + a_1 \log P + a_2 (\log P)^2 \qquad (5)$$

with acceptable accuracy (Table 4). By combining Eqns. 2b and 5, *i.e.* setting $d_R = d_P$, this isodensity relationship between applied pressure and ramming work can be obtained, and the pressure, P, solved explicitly as a function of the number of rammings, N.

This isodensity relationship has been calculated and plotted for four different ramming pastes in Figure 11. It is seen from the curves that different types of paste may behave differently when various compaction equipment is used. The "dry" pastes, A1b and E1, are more effectively compacted when pressure is applied than when ramming is performed. As the pastes become more fluid the curves bend upwards ("normal" paste B4b), and compaction by means of ramming becomes increasingly more effective.

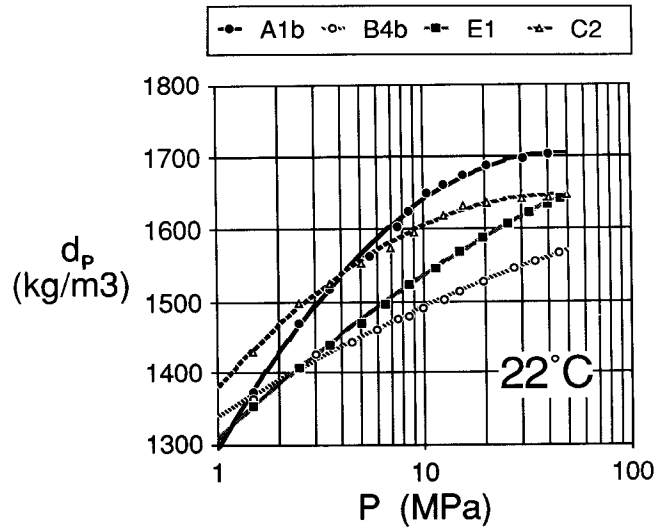

Figure 10. Pressure compaction of ramming pastes. Points are experimental values, curves are calculated from Eqn.5 (parameters in Table 4).

Table 4. Results from fitting pressure compaction data to Eqn. 5.

Paste	Temp. (°C)	Polynomial coefficients a(0)	a(1)	a(2)	Std.Err. (kg/m3)	Corr. Coeff.
A1b	22	1292.0	494.5	-147.89	6	0.999
B4b	22	1337.4	180.5	-25.22	3	0.999
C2	22	1378.5	323.8	-97.51	5	0.998
E1	22	1307.4	266.3	-38.14	2	1.000

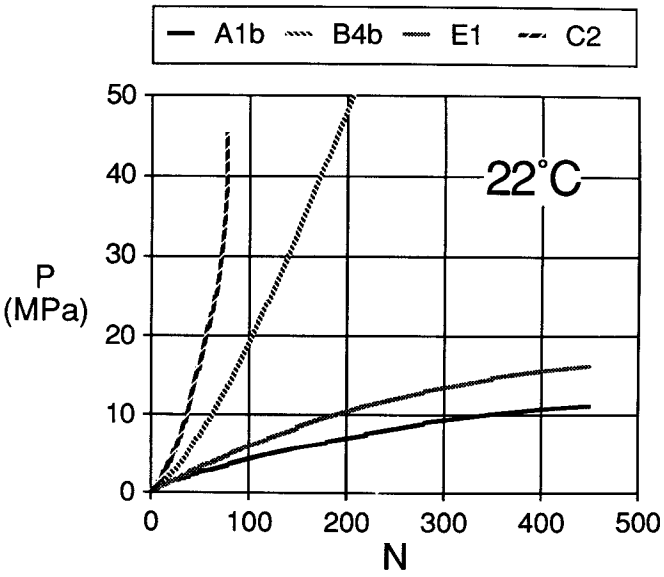

Figure 11. Calculated isodensity relationships between compaction by pressure and by ramming.

The "wettest" paste (C2) can only absorb a small number of strokes but a rather high static pressure before it turns into an incompressible "fluid".

PASTE FORMULATION

The present work has concentrated on finding experimental ramming criteria for characterization of pastes. It might be considered possible, with an intimate knowledge of the paste formulation, to estimate the compaction behaviour of a given ramming paste. This is, however, only practically possible in those cases where one has a detailed empirical knowledge of the process variables, *i.e.* mixing time and temperature, coke porosity, surface area, granulometry and binder requirement and characteristics, among others. Although the granulometry of a given paste aggregate may be based on packing theory, it is virtually impossible to produce a satisfactory cold type ramming paste based solely on a theoretical formulation.

The binder content might be an indicator, but minor short and long term variations in coke aggregate properties and granulometry, especially in the fines fraction, will make this an unreliable quality indicator for an end user of the paste. It has absolutely no value in comparing different brands of paste, its only informative value is in the comparision of different shipments of the same type of paste (Table 1), and only if the filler granulometry and physical properties can be considered constant over time.

The various paste granulometries illustrated graphically in Figure 5 may all, although not included in this work, yield acceptable ramming pastes with the right binder content. A complete extraction and sieve analysis is, however, time consuming and may be very difficult to interpret in terms of paste quality and compactability.

The correlation between optimum binder content and paste quality is illustrated in Table 1 with reference to type B1 and B4. The extraction loss (in quinoline) for B4 with a less porous GCA filler coke is 4.4 % lower on an absolute scale than B1 which contains a more porous ECA aggregate. Although paste B1 is characterized as "wet" compared to paste B4a, only a part of the difference in binder content is related to this.¶

Within the same material it can, however, be found correlations between compactability and the content of binder and fines/dust (particles less than about 100μm, Table 1). For the C and D materials we have the ranking

$$C1b \rightarrow C2 \rightarrow C1a$$

$$D1b \rightarrow D1a$$

with respect to improved rammability, decrease in fines and decrease in binder content. The increase in apparent binder demand is a direct result of the increase in the dust fraction. In the mixing stage the higher dust content will, due to the increased coke surface area, require a higher binder amount in order to give a similar apparent paste consistency. This, however, may only worsen the paste properties as the amount of binder matrix may increase more than intended.

The unsatisfactory compaction characteristics of paste A2 are caused by a poor match between the amounts of fines and binder in the paste formulation. Although the paste apparently has a high binder content (Table 1), it is not enough to satisfy the demand caused by the relatively large content of dust and fines. The result is a paste that appears to display a "normal" densification behaviour during the first stage of compaction, but which becomes increasingly "dry" as the compaction proceeds. This is most easily spotted in its inability to reach d_{max} even at high temperatures and after prolonged compaction in the Sand Rammer. This may be read directly from the experimental compaction curves or, perhaps more illustrative, from plotting d_R' *versus* N (or logN) from Eqn.3.

As the N_o value is related to the limiting slope of the compaction curve for low N, the particular compaction behaviour of paste A2 is not readily recognized from Figure 9 and the numbers given in Table 3. The anomalous compaction behaviour caused by this paste formulation is nevertheless indicated in the small reduction of the relatively high N_o values by increasing the ramming temperature from 22 to 50°C. In other words, the binder matrix is not fluid enough to allow a proper ramming.

The amount and viscosity of this binder matrix is, for a given aggregate, of substantial importance to the rammability and compaction behaviour of a room temperature paste. The binder matrix acts as lubrication and adhesive between the coarser particles. The distinction between the various compaction categories for a given paste in terms of binder content can be narrow and highly dependent on the amount and properties of the fines and dust fractions.

As a visualization of the above discussion a schematic representation of some characteristic compaction behaviours are shown in Figure 12. The paste is represented by three distinct phases: filler particles, pores and binder matrix.

Figure 12A represents a loose compaction, either not worked enough or compacted at a too low temperature. It needs further densification.

The paste in Figure 12B requires more binder. The filler is close to its maximum bulk density and further work applied to it will result in crushing of filler particles.

An ideal compacted paste is shown in Figure 12C. It still contains a small amount of open porosity which makes it marginally compactible if more work is excerted upon it. The coarser filler particles are locked into a three-dimentional semi-rigid network or "structure" which enables the paste to withstand reasonable compressive

¶ Confirmed by recent measurements on another shipment of B1 paste which was characterized as satisfactory in laboratory experiments.

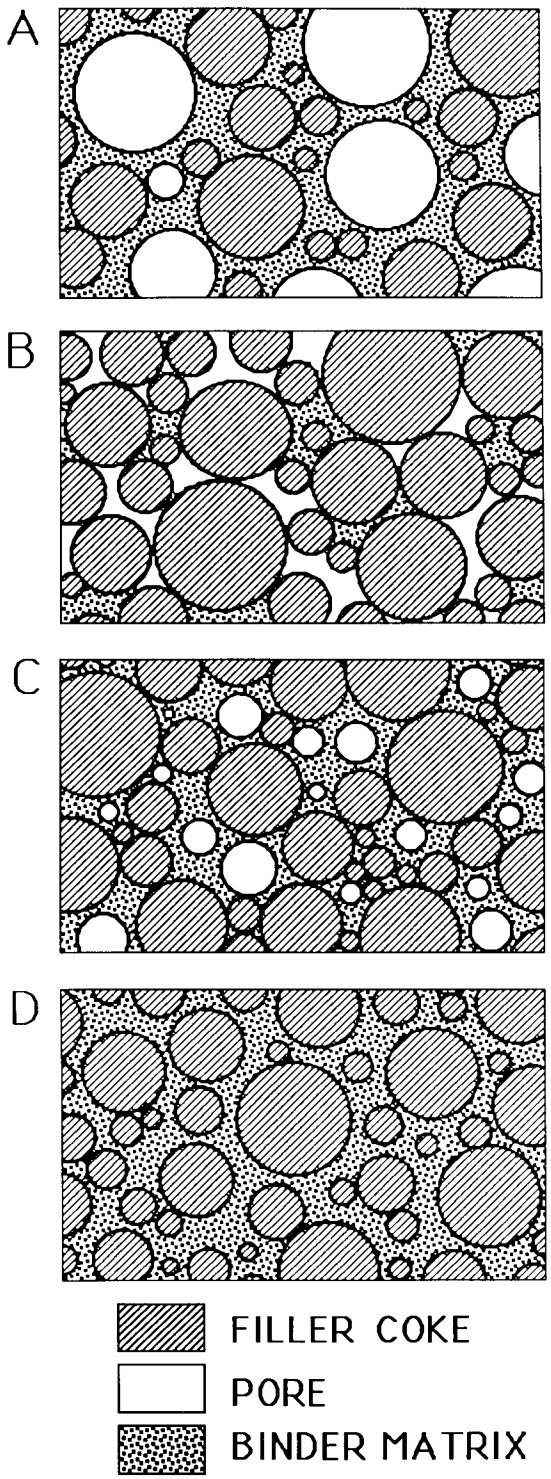

Figure 12. Schematic representation of pastes with different compaction characteristics.
A: Poorly compacted or compaction attempted below temperature window; B: A "dry" paste with not enough binder matrix. Can not be compacted satisfactorily at any temperature; C: Ideally compacted paste; D: A paste with too much binder or compaction attempted above its temperature window.

and shear stresses without further deformations.

Figure 12D represents a "wet" paste which has been compacted at a higher temperature than supposed or which have a too high binder matrix content. At a certain point during the compaction, d_{max} is reached as all open porosity dissappears. Excess binder matrix replaces the porosity and the paste is suddenly converted to an uncompressible fluid. The rigid filler network breaks down as fluid binder matrix forces the particles apart. The paste appears "jellyish" or "rubbery" and can no longer withstand minor compressive or shear stresses without being deformed.

CONCLUSION

The main recommendations that can be given for obtaining a satisfactory ramming of cathode joints and seams can be summarized as follows:

- A compaction parameter as the presently employed N_o can be used to control the paste quality.

- The paste producer has to keep accurate control of the dust fraction in the coke aggregate. Compensation of excess dust content with more binder may easily worsen the ramming characteristics of the paste.

- Most pastes have a temperature window that they should be applied within. An otherwise good paste may yield poor results outside this window.

- A satisfactory ramming paste should still be marginally compactible when the ramming operation is finished.

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