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DENSIFICATION OF RAMMING PASTE IN CATHODES

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Cold type carbonaceous ramming mixes are now used for refractory purposes in several metallurgical and electro-metallurgical industries. Green density measurements of these pastes are easily performed on the spot during and after installation, by using a simple impact penetrometer. Used in the cathode repair shop, it serves as a quality assurance tool with respect to improved density, compaction uniformity and installation procedure of the rammed parts. Four commercial room temperature ramming pastes, differing widely in quality and compaction characteristics, have been used in this work. Penetrometer measurements during relining of cathodes have established optimal installation practices for the various pastes.

INTRODUCTION

Glued semi-monolithic cathode designs have been tried out at aluminium smelters for several years with acceptable performance, and test pots with wettable TiB_2-containing cathodes have shown promising results. However, the most important cathode construction in the aluminium industry will, in the foreseeable future, continue to be based on prebaked cathode bottom blocks with rammed joints and seams.

Ease of handling combined with environmental considerations and regulations have been the driving forces behind the conversion from hot to cold type ramming pastes during the last decade. Despite improvements in paste quality and paste testing techniques [1], the rammed joints and seams and the interface between paste and prebaked carbon bodies remain weak parts of the cell lining and can often, directly or indirectly, be linked to premature cell shutdown or poor cell performance.

The quality of the rammed parts is dependent on paste quality, as well as installation practice [2]. Final green density and density distribution achieved during ramming are important parameters for control of the installation procedure. While direct control of hot ramming paste installations can be made relatively simple by drilling out a core after cooling, similar removal of room temperature paste for density control and inspection may be more difficult as the sampling procedure itself may influence the results. In this case it is more relevant to use indirect methods.

In the present report we will discuss the calibration of a simple, reproducible and operator independent penetrometer for measurement of room temperature ramming paste density. Its use in the pot repair shop for controlling the quality of rammed cathode parts and improving paste installation practices will also be discussed.

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EXPERIMENTAL

Laboratory

Pastes. Four different pastes were chosen for the calibration experiments. All were commercial room temperature ramming mixes from ordinary shipments to aluminium smelters or introductory samples received from paste producers for test lining purposes. Some selected paste properties are listed in Table 1. Three pastes had aggregates based on electrically calcined anthracite (ECA) while one consisted of gas or kiln calcined anthracite (GCA) and synthetic graphite (G). All four had coal tar based binders. The table further illustrates that the amount of binder found (quinoline extraction) in tamping pastes has no relation to their performance if their formulation otherwise differs.

Table 1. Some selected ramming paste properties.

Paste	Aggregate type	Max.green density* (kg/m3)	Binder content (%)	Paste characterization/ plant experience
A	ECA	≈1620	16.9	Dry
B	GCA+G	≈1700	15.6	Satisfactory after preheating
C	ECA	≈1650	15.1	Satisfactory
D	ECA	≈1675	16.2	Wet

*) Under experimental conditions given

All four pastes were tried out in the pot repair shop in full scale relining tests. Two pastes, A and D, were judged unacceptable due to their quality. Paste A did not contain enough binder matrix (binder and fines) which resulted in a low densification rate and excessive aggregate particle degradation during compaction and a poor baked strength. Paste D contained too much binder with respect to its aggregate formulation and reached a 'rubbery' or 'jellyish' state during compaction. Pastes B and C were satisfactory when compacted within their temperature windows [1].

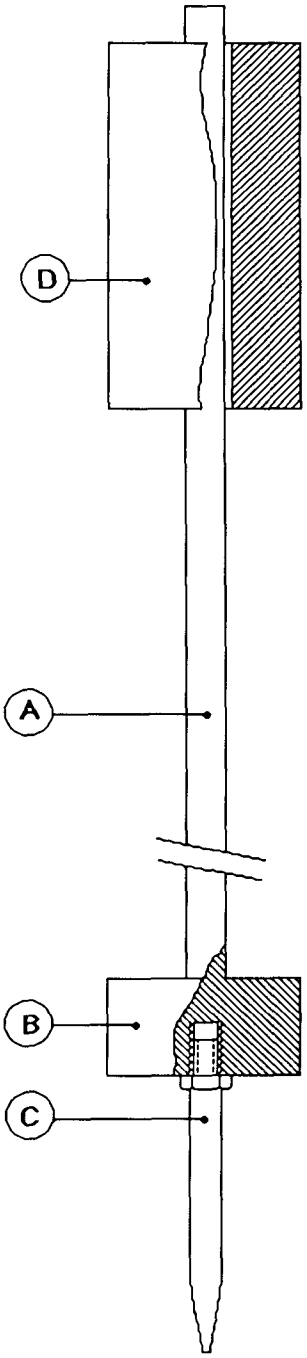

Figure 1. Impact penetrometer. All parts are made of steel. A) Handle. B) Stopper. C) Cone-tipped pin. D) Drop-weight.

Penetrometer. A simple impact penetrometer for measuring densities of compacted cold type ramming pastes in industrial cathodes was built according to Figure 1 [3]. It consisted of a steel handle (A) which ended in a stopper (B) welded to the handle. A threaded hole in the stopper allowed a cone-tipped pin (C) to be fastened underneath. The final part of the penetrometer was a cylindrical drop-weight (D) which could slide along the handle bar.

Penetration measurements were performed by resting the cone-shaped tip of the penetrometer at the spot where a paste density reading was found necessary and the drop-weight released from a given height. The penetration of the pin into the paste was measured to the nearest mm and the density found using a calibration chart of penetration *versus* temperature and density for the given ramming paste. The temperature of the paste was usually measured in the hole left after removal of the penetrometer.

Only a minimum of operator training was necessary for satisfactory use of the penetrometer during ramming of cathodes. The most important requirements were to drop the weight from the predetermined height and to keep the penetrometer in a vertical position during measurement. The drop-weight will then transfer the same reproducible amount of impact energy to the paste during each stroke and will be nearly totally operator independent. A good calibration of the penetrometer is therefore essential for a satisfactory control of the rammed density. Due to slight wear and occational damage to the cone-tipped pin during use, the pin had to be replaced from time to time.

In order to simplify the penetration measurements a vertical slot, wide enough for a ruler, was cut into the stopper (Figure 2). By making the ruler the exact length of the pin (H) plus the height of the stopper (A), the

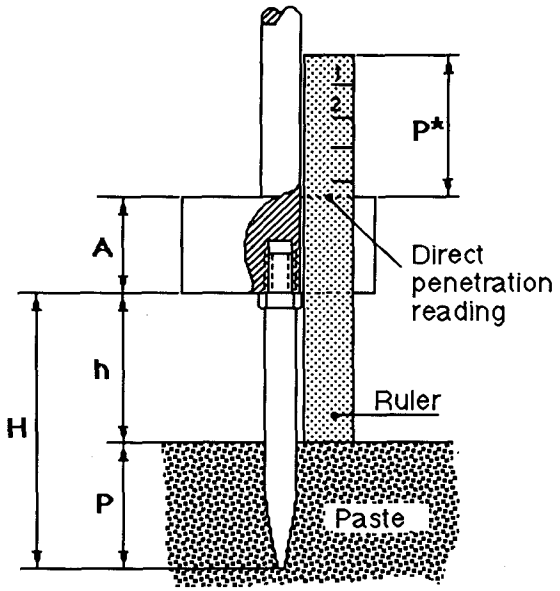

Figure 2. Penetration readings (P* = P) are simplified by using a ruler with exactly the length of the pin plus the height of the stopper (H + A).

penetration (P) could be directly read (P* in mm) at the top of the stopper.

Calibration. The three important variables for control of a given paste using the impact penetrometer are penetration depth (P [mm]), paste temperature (t [°C]) and density (d [kg/m^3]). As the compaction behaviour may show large variations between different paste brands [1], it is necessary to make calibration runs of each new type of paste. The compaction behaviour may also vary between batch or shipments of what nominally should be the same product, the magnitude generally depending on the control the producers have with their formulation and mixing variables.

The first step in the calibration procedure is to choose a ramming paste with 'satisfactory' behaviour within the expected operational temperature window. The criteria described by Sørlie and Øye [1] can be used. This eliminates the inadvertent use of off-specs pastes in the calibration runs.

Densifications for calibration purposes took place in 200 mm diameter cylindrical moulds by using a 600 kN (max) universal test machine. The maximum pressure that could be applied to the paste was thus about 19 MPa. This was sufficient as this maximum pressure gave green densities higher than those obtained for the same paste during manual or mechanized installation in the cathode. Polished mould walls, a relatively large amount of paste (6 kg) and a large diameter to paste height ratio (>1) minimized the 'wall' effect, *i.e.* achieved green density became virtually independent of mould geometry.

The weighed amount of paste at a known temperature was added to the mould and the pressure, evenly distributed over the entire cross-section, was increased linearly to a predetermined set-point, kept at isostatic conditions for 1 minute and reduced to zero pressure again at the same linear rate. The green density was calculated from the height of the paste cylinder. Measurements were usually performed at temperatures ranging from about 5 to 35°C. Samples tested below ambient temperature (20-22°C) were temperature equilibrated in a refrigerator prior to compaction, while samples tested at higher temperatures were equilibrated in a hot air oven. Each experimental point was the average of at least three penetration measurements at a given density and temperature.

Narrow joints. The 'wall' effect that is experienced when tamping paste into the narrow joints between bottom blocks limits the practical use of the impact penetrometer to the rather broad peripheral border between the bottom blocks and the sidewall carbons. This is caused by the friction between the paste and the solid carbon block and the joint geometry, *i.e.* volume to width ratio. The peripheral border is, however, where most paste-related problems are experienced. The penetrometer can, in principle, be used for controlling paste densification in the narrow joints between the bottom blocks, but this requires the introduction of another calibration variable; the width of the joint. This problem is more easily dealt with by introducing, and being able to control, the right standard practice.

This was done by making a 1:1 model of a part of a bottom block joint using two sidewall carbons (of similar type as the bottom blocks) supported by a rigid steel frame. The height of the 'joint' was made equal to the height of the bottom blocks in the cathode and the width could be varied within the joint widths experienced in the pot repair shop. Joints were rammed using pot repair shop equipment. The frame could easily be taken apart for visual inspection and measurement of compacted paste density.

Pot repair shop.

Potlining equipment. Compaction of the rather broad peripheral border was performed using a mechanized potliner [4]. The densification tool was a wheel that was rolled back and forth over the paste. The pressure that the wheel exerted on the paste could be controlled by the operator. Hand-ramming by means of pneumatic hammers was limited only to parts where potliner wheel access was difficult.

Densification of the narrow joints between the bottom blocks was performed using a different type of mechanized equipment. This tool was a piston exerting a downward stroke.

RESULTS AND DISCUSSION

Laboratory investigations

Density measurements. One way of presenting the calibration results is to plot the green density obtained by applying isostatic pressure (d_p) versus penetration depth at one or more temperatures. This have been done in Figure 3 for paste A. A number adjacent to each experimental point represents the measured temperature

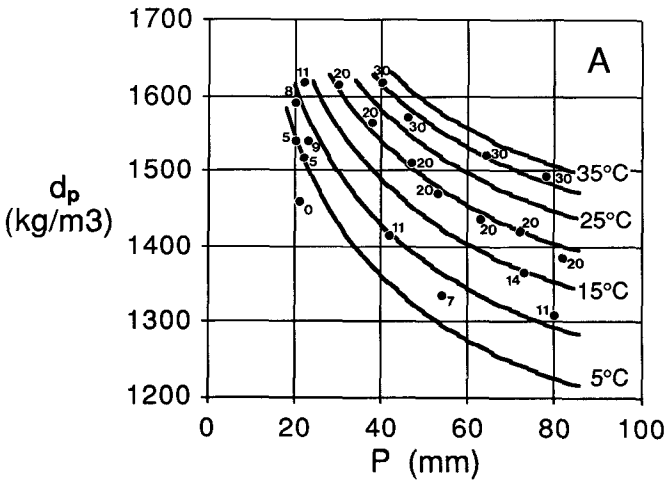

Figure 3. Experimental (●) and calculated (—) green density *versus* penetration depth and temperature for paste A. Standard deviation of fit is 12 kg/m^3, correlation coefficient is 0.99.

to the nearest °C. The lines drawn in the figure are the results from a polynomal fit (d_p = f(P, t)), plotted at temperatures from 5 to 35°C with 5°C intervals.

Paste characterization. The isotherms in the d_p = f(P, t) diagram yield important information on some compaction characteristics of a given paste. Figure 4 shows the penetration calibration results for paste B. The fact that this paste needs some preheating in order to be installed satisfactory is reflected in the spread and steepness of the isotherms. It is readily seen from this figure that the behaviour of paste B is very temperature dependent. Furthermore, the steepness of the low temperature isotherms makes the penetrometer less suited for use at temperatures below about 15°C with this particular paste. In such a case precision may not be satisfactory as small variations in penetration depth will correspond to large fluctuations in calculated green density.

The calibration results for paste C (Figure 5) yield isotherms more grouped together, indicating that the density measurements and ramming characteristics of this paste are much less dependent on installation temperature. This paste showed satisfactory compaction behaviour at ambient temperatures without the need for preheating.

Paste D is characterized as 'wet' (Table 1) and this property is reflected in its d_p = f(P, t) diagram (Figure 6).The paste displays a 'normal' behaviour at low temperatures and/or low green densities, but as the maximum density (d_{max}) is approached the penetration depth increases again. This is another manifestation of the characteristic behaviour Sørlie and Øye [1] pointed out for 'wet' pastes:

". . . 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 incompressible 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. . ."

In the paste D example (Figure 6) the increase of the penetration depth near and at d_{max} is caused by the above described 'fluidization' of aggregate particles.

Control of ramming. The d_p = f(P, t) diagram contains all information that is needed for control of ramming. It is, however, practical to simplify it when used by the pot repair crew for control during paste installation. This is done by setting a target for minimum green density allowed with a given paste and by substituting this constant with the density variable in the d_p = f(P, t) equation. For lack of enough experience this minimum allowable or setpoint density (d_s) is set equal to $0.9 \cdot d_{max}$. This is a provisional and practical arrangement and may be subjected to corrections as more experience and potroom feedback is obtained.

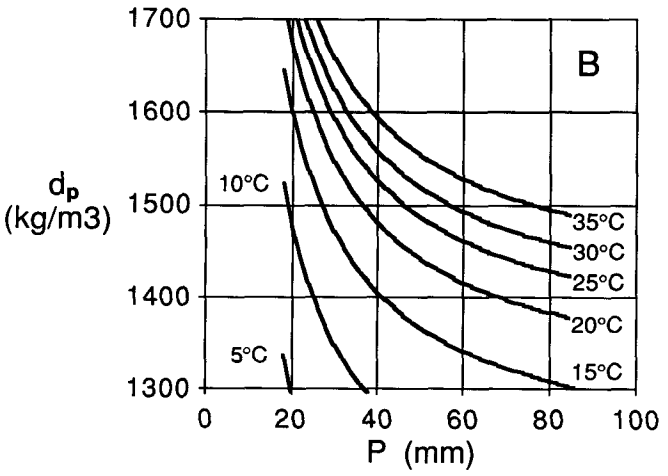

Figure 4. Green density *versus* penetration depth and temperature for paste B. Standard deviation of fit is 17 kg/m^3, correlation coefficient is 0.98.

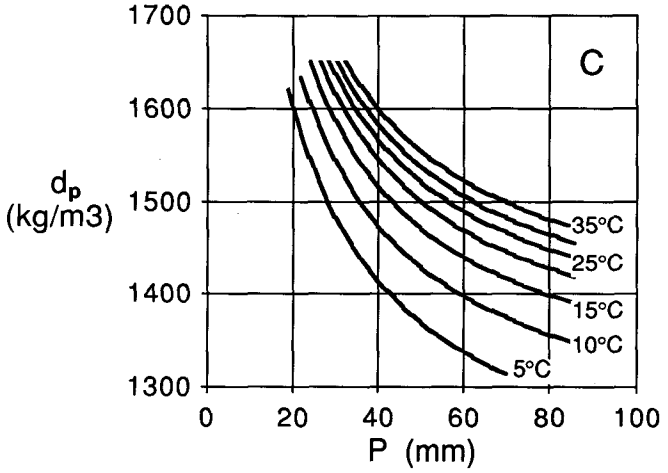

Figure 5. Green density *versus* penetration depth and temperature for paste C. Standard deviation of fit is 14 kg/m^3, correlation coefficient is 0.98.

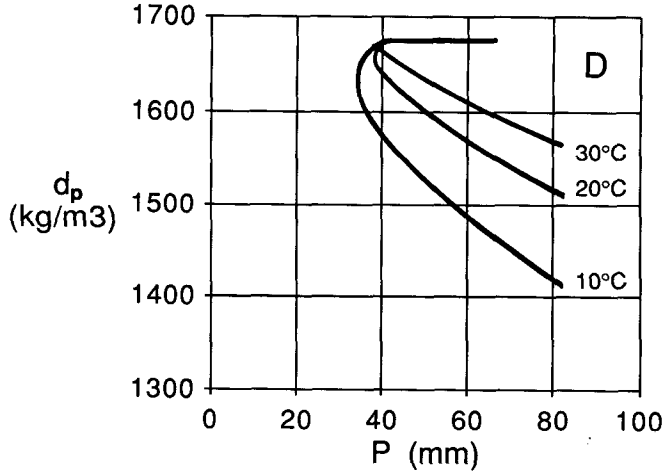

Figure 6. Green density *versus* penetration depth and temperature for paste D.

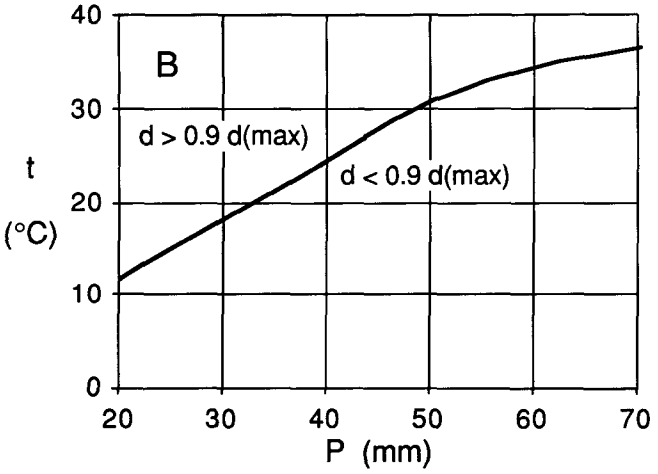

Figure 7. Paste temperature *versus* penetration depth at d_s = 90 % of d_{max} in paste B.

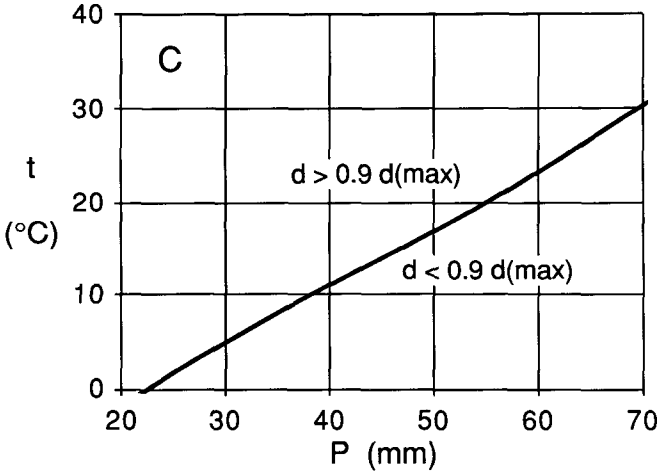

Figure 8. Paste temperature *versus* penetration depth at d_s = 90 % of d_{max} in paste C.

Figures 7 and 8 show examples of such ramming control diagrams, the curve corresponding to d_s = 90 % of d_{max} for paste B and paste C, respectively. If, during paste installation in the cathode, the coordinates of penetration depth and corresponding temperature rises above the line a satisfactory compaction has been acieved. Otherwise, if the coordinates fall below the line, further densification is required. This kind of testing is performed throughout the build-up of the rammed parts.

Cathode relining

Narrow joints. The amount of paste that was added to the joint initially and between each compaction cycle was found to be the variable that influenced the final density and vertical density distribution most. The density of joint samples had to be measured more directly. In order to minimize the influence the sample procedure had on the final results it was found to be most convenient to measure the baked density (d_b) in this case. Figure 9 shows baked density values achieved before and after practice improvement in the pot repair shop using paste B. Green density is typically 10 % higher than the given values.

Peripheral border. Wheel (roller) dimensions, the pressure it excercises on the paste (through the calibrated wheel force manometric reading, F_w [kp]), the number of passes (n) and paste volume (layer thickness) are usually the variables with which the operator may influence the compaction by using the mechanized compaction equipment [4]. Keeping the roller dimensions and layer thickness constant, compaction control experiments showed that high (near maximum) wheel force was inefficient with respect to rate of densification. It could even be harmful with respect to the quality of the border, as the roller might crush filler particles at or near the surface. This new aggregate surface exposed did not have the binder coating to give it the necessary baked strength, thus resulting in severe stratification between compacted layers. A too high densification pressure could also reduce compacted paste quality due to the effect of the curved roller/paste contact surface as the horizontal pressure component might exceed compacted paste shear strength and move it sideways in front of the roller.

The net compaction pressure that the mechanized potlining equipment excercises on the paste is not readily obtained. One way to quantify the 'work' that has been transfered to the paste on a relative scale is the cumulative sum of manometric readings with the number of passes ($\Sigma(F_w)$). By defining one 'pass' as the wheel traversing back and forth over the paste, the way this work is applied can be studied in terms of densification. This is shown in Figure 10 for paste B. Horizontal bars above the figure indicate the manometric readings during compaction.

In one example the manometric wheel force is increased from 400 *via* 600 to 750 kp while in a second example a constant manometric reading of 400 kp is maintained throughout the compaction procedure. The results are

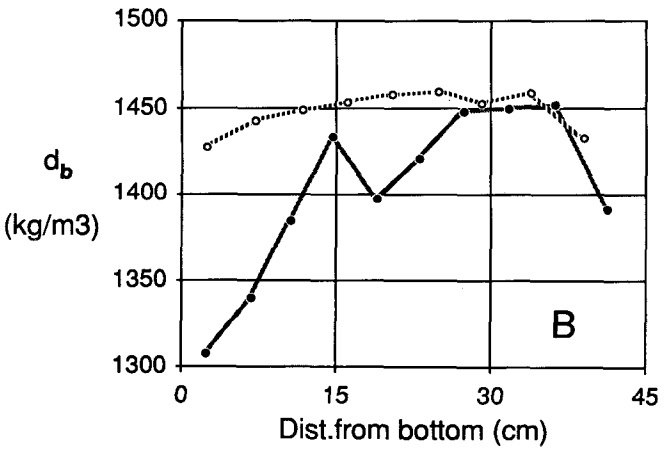

Figure 9. Baked density distribution in joint between bottom blocks before (●) and after (o) improvement of tamping practice. Paste B.

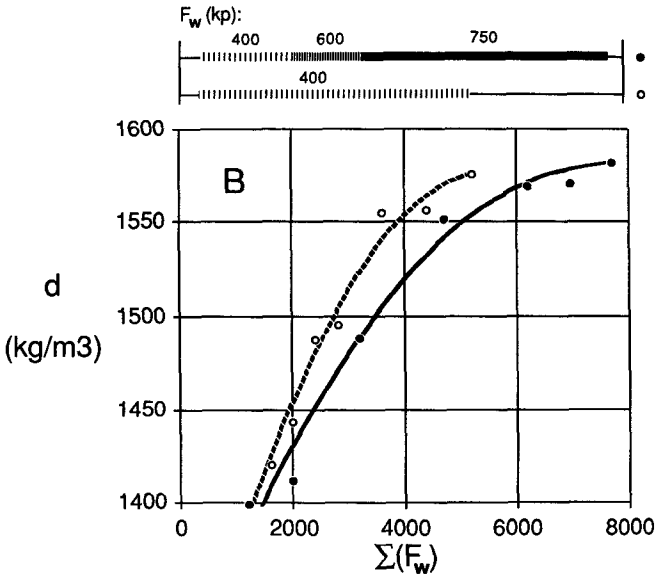

Figure 10. Measured border density *versus* cumulative manometer readings during densification. Horizontal bars indicate the manometer readings during compaction.

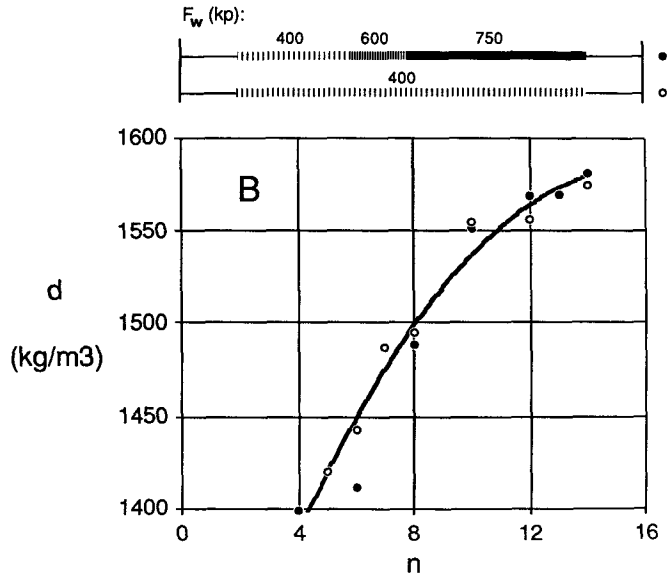

Figure 11. Measured border density *versus* number of potliner (wheel) passes during densification. Horizontal bars indicate the manometer readings during compaction.

obtained under otherwise comparable conditions and in similar parts of the lining . It is seen that a rapid increase of the manometric pressure does not result in a better compaction. In fact, a more rapid increase in paste density with respect to cumulative manometric pressure readings ($\Sigma(F_w)$) is obtained by employing a moderate but constant wheel force.

The number of passes made with the roller is more important than high manometric readings during densification. This is shown in Figure 11. The same experimental data plotted *versus* the number of passes (n) gives almost identical densification 'rates'.

The importance of establishing separate densification practices with different tamping pastes is illustrated in Figure 12. The figure shows the relationship between the fraction of setpoint density achieved (d/d_s) *versus* compaction work expressed in terms of cumulative manometric readings for pastes B and C. The results were obtained using the same constant wheel force (400 kp) and in similar parts of the lining. Each paste was compacted within its ideal temperature window [1]. It is seen that a compaction practice giving satisfactory results for paste B may lead to unsufficient densification of paste C.

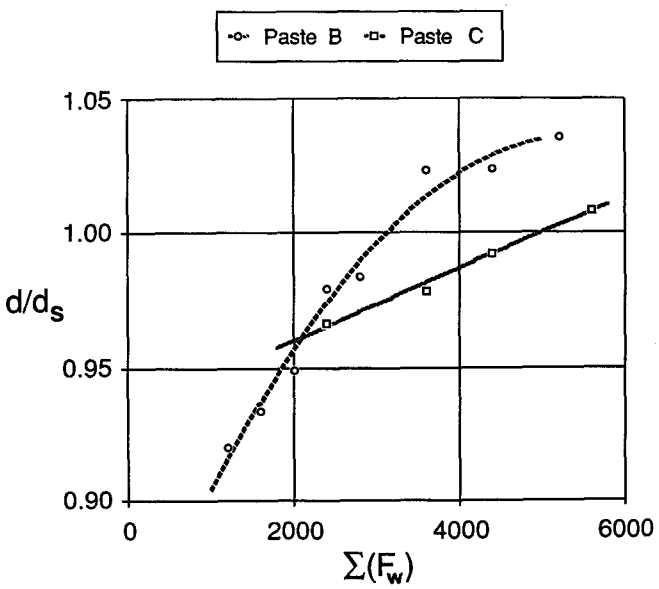

Figure 12. Fraction of setpoint density obtained with pastes B and C *versus* potliner compaction work.

CONCLUSIONS

- A simple but reproducible impact penetrometer can be used for control of density during and after cold type ramming paste installation in cathodes.
- Compaction quality can be controlled over the whole practical temperature range.
- Penetrometer calibration curves yield information related to paste quality and densification characteristics.
- Paste installation practices with special emphasis on mechanized compaction has been established.
- Different pastes will need different compaction practices for optimum performance.

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