MODELLING AN INVERTED BELT FILTER

R.O. Weber[1], L.R. White[2] and N.D. Fowkes[3]

This project report describes the attempts to model the adhesive forces relevant to the manufacture of products such as fibre cement board. As they are made with an inverted belt filter, the mixture must adhere to the underside for a considerable time for the manufacturing process to work. Fluid mechanical, chemical and physical mechanisms were all considered by the MISG team working on this problem during the week long study group. Although it was impossible to determine the mechanism involved, the MISG team were able to make a number of observations and suggestions for further study. Specifically, the mositure content of the fibre and paste ensemble needs to be carefully monitored during the manufacturing process and a statisical study of the process needs to be undertaken, including drop off times.

1. Introduction

The James Hardie products, such as fibre cement board, consist of a mixture of cement powder, ground sand and cellulose. To produce the board these constituents are mixed with water and drawn off as a thin paste on the external surface of a rotating drum. Subsequently the paste is transferred to a belt. Several of these operating units work in series and rollers are used to join the sheets together, thereby producing boards of the required thickness. The transfer of the paste from the rotating cylinder to the belt passed across the top of the cylinder is achieved by the apparatus shown in Figure 1 (on next page). The rotating rubber wheel shown squeezes the belt and paste against the cylindrical drum, and because the paste adheres more strongly to the belt than the drum, attachment may occur. It is desirable to produce thicker paste sheets and this can be achieved by using larger drums rotating more slowly. However, the resulting heavier sheets, hanging as they do underneath the belt, are more likely to separate from the belt. To a certain extent this tendency can be countered

[1]University College ADFA, Department of Mathematics, Canberra ACT, Australia 2600. Email row@harpo.ma.adfa.oz.au.

[2]Department of Mathematics, University of Melbourne, Parkville VIC, Australia 3052. Email lrw@maths.mu.oz.au.

[3]University of Western Australia, Department of Mathematics, Nedlands WA, Australia 6907. Email fowkes@maths.uwa.edu.au.

by using a vacuum box to improve adhesion. To find an optimum arrangement will require an understanding of the physics of adhesion and detachment.

Given the lack of experimental evidence the MISG was not in a position to decide on which of the competing mechanisms primarily caused attachment, but it is hoped that the results obtained from an analysis of possible mechanisms will enable an experimental determination to be made. There were two basic attachment mechanisms suggested by the group: surface tension induced suction and chemical or physical adhesion.

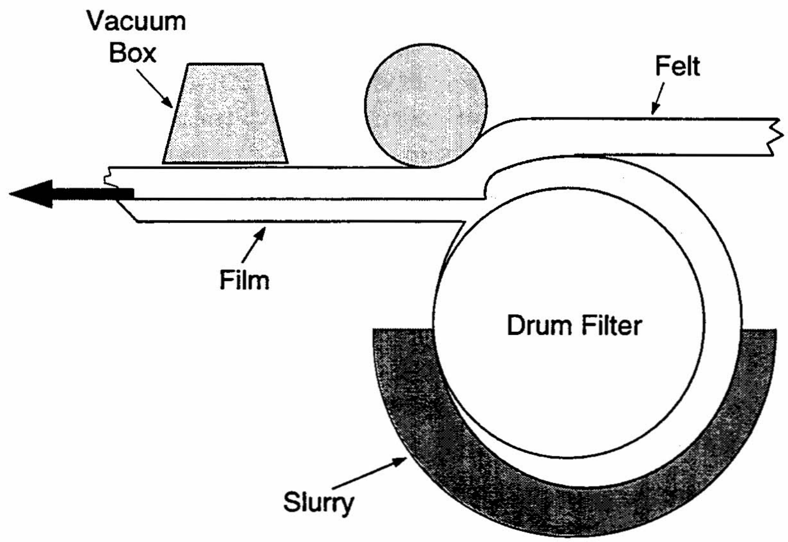

Figure 1: Fibre cement board production.

2. The process and problems

The system, as shown in Figure 1, is essentially an inverted belt filter adapted for use from the paper industry where it has been used for over a century. It is noteworthy that Taylor (1956, 1957, 1960) examined the dynamics relevant to the papermaking process. Unfortunately, the MISG team found significant differences between the papermaking study and the present situation.

The belt is a permeable membrane made up of woven nylon fibres, under which hangs a film of paste. When the belt enters the nip point it is partially compressed and the thickness decreases from the initial value. The upper nip point roller is a rubber roller, while the lower nip point roller is covered in an open steel mesh to allow de-watering. Upon exiting from the nip point the belt regains its initial thickness, which is approximately 6 mm when new, but reduces to approximately 3 mm when old after 200 hours use. As the thickness of the belt decreases, so does its permeability. The belt then travels under a vacuum box, within which the pressure may vary from −20 kPa to −80 kPa relative to atmospheric pressure. From the vacuum box the belt continues on into the rest of the process.

The film of paste which hangs underneath the belt is composed of cement, ground sand, cellulose fibre and water, not necessarily homogeneously mixed. For example, the side of the film of paste which is furthest from the belt can be rich in cellulose fibres while the side in contact with the belt can be rich in cement and ground sand. As the film enters the process the initial thickness is reduced at the nip point and some water is removed. Further moisture is removed as the film of paste passes under the vacuum box, and may continue to be removed beyond this point due to a partially saturated belt.

James Hardie requested a model which would:

- include the physical dynamics of the process;
- estimate the maximum thickness of the paste which will adhere to the belt;
- determine the optimal vacuum box pressure to control the process;
- determine a method for verifying the thickness of the film of paste; and
- determine whether the segregation of ingredients in the film of paste influences the maximum thickness that will adhere to the belt.

3. General modelling considerations and possible mechanisms

Clearly the key element of any model of this process will be an understanding of the mechanisms which are responsible for the adhesion of the film of paste to the permeable belt. These may change at different stages of the process. The MISG team came up with various possible mechanisms, each of which will be considered in turn.

3.1 Hydrostatic adhesion

A simple experiment with two smooth, non-wetting surfaces, such as glass slides, with a thin layer of water between the surfaces will demonstrate the remarkably large adhesive force that can be produced by a thin layer of liquid. It is the surface tension at each edge of the layer of liquid that causes this phenomenal adhesion: it is practically impossible to pull the surfaces apart with purely normal forces applied to the large flat surfaces. However, any small shear will easily slide the surfaces over each other, the layer of liquid acting as a lubricant. Note that some of the calculations pertinent to viscous adhesion can be found in textbooks, such as Acheson (1990).

Any estimation of the magnitude of the adhesive force from such a layer of liquid of given density, viscosity and surface tension yields an enormous force far in excess of that required to adhere the film of paste to the permeable belt.

3.2 Wicking experiments and model

Several samples of the permeable belt were subjected to 'wicking' tests. In these tests the samples were held vertically with one end soaking in a beaker of water containing dye (an impromptu modification also used coffee). The capillary action of the permeable belt caused liquid to be drawn up and the final equilibrium height was of the order of 200 mm. This gives an estimate of the adhesive pressure due to the capillary action of the permeable belt as being approximately 200 mm of H_2O. Note that the group considered the use of the so called 'Washburn equation' (see Bear, 1972) to model the wicking process from start to finish, and while this was fairly successful as a curve fitting exercise, it did not reveal any additional insight; but it provided a valuable number in the permeability of the belt, estimated to be $1.38 \times 10^{-8}\ \mathrm{m^4N^{-1}s^{-1}}$. The adhesive pressure of 200 mm of H_2O is a substantial force and more than sufficient to hold the weight of the film of paste. It could be altered by drying or increasing the saturation of the system. Consequently, the total amount of moisture needs to be between the levels at which only the belt is saturated and at which both the belt and paste is saturated, providing upper and lower moisture bounds. We note that this argument predicts permanent adhesion in the absence of drying.

4. Action of the vacuum box

The previous section naturally raises the question of the role of the vacuum box, where a pressure reduction of 20 to 80 kPa is applied to the upper side of the paste and belt ensemble. Clearly the vacuum box acts as a drying agent. The question which could not be answered during the study group was whether the moisture reduction results in the correct moisture bounds being achieved, or whether it dries out the ensemble more thoroughly and introduces a new, possibly mechanical, mechanism for adhesion. This mechanical mechanism is considered in Section 7.

4.1 Capillary necks or fluid layer

A thermodynamic view of capillary action relates the Gibb's Free Energy of an unsaturated medium to the contact angle between microscopic particles in the porous medium, which in turn is related to the pressure difference generated by such action. This insight prompted considerable debate about whether the liquid in an unsaturated medium exists as a 'water table' or a single layer in the lower portion that fills up all the available cavities in the lower portion before filling those higher up. Alternatively, there could be necks of water distributed throughout the unsaturated medium and running from top to bottom with consequent dry patches at a microscopic level. This aspect could be crucial to understanding the action of the vacuum box, as it would more readily remove water from a situation where there are capillary necks. Without doubt, there needs to be extensive moisture monitoring during the entire process, particularly after the paste is attached to the belt and beyond the vacuum box. An estimate of the adhesive force due to capillary necks was carried out, including an additional estimate of the total number of contacts between capillary necks and the paste and belt ensemble. The result suggested that a force of up to 1.4×10^4 Nm^{-2} could be generated by this mechanism; more than ample to support a paste weight of around 36 Nm^{-2}. The nature of these estimates means that our result is necessarily inconclusive, except to say that this could be a viable adhesion mechanism.

5. Surface tension models

Wet sponge models

If a suction cap with a heavy handle is pressed against the ceiling and then released it will stick to the ceiling, providing the force applied to the handle is sufficiently large and the edge of the cap is sealed with grease so that air doesn't readily leak back into the partial vacuum inside the cap. After sufficient time air sucked past the seal will reduce the cap suction pressure to such a level that the handle weight can't be supported, and the cap and handle will drop off the ceiling.

If a kitchen washing sponge full of water is placed on a bread board and the board inverted, the sponge will sometimes adhere to the board and will sometimes drop off immediately. If the combination is inverted with care so that the edges of the sponge are not allowed to peel away, then the sponge will adhere for a long period, but eventually drop off.

If the same sponge is initially carefully squeezed to expel some of the water before the board is inverted, then the sponge will again adhere; seemingly more strongly than before.

In all the above cases once the seal is broken the surfaces separate dramatically. This is to be expected from 'squeeze film' lubrication analysis, see 'Wet gum labelling of wine bottles' in Proceedings of the 1996 MISG. The suction pressure p developed within the thin fluid layer is very strongly dependent on the thickness δ of that layer with p inversely proportional to δ^5. Once separation occurs at an edge, the gap thickness will increase rapidly at that location. Thus, if care is not taken when the bread board is inverted, the sponge peels away from the board immediately.

In the Hardie problem, we ask the following questions. What is it that causes the integrity of the squeeze film between the paste and the belt to be lost, and is it possible to 'set up' the squeeze layer more carefully? Surface tension effects are likely to determine the effective surface area of contact between the paste and the belt and thus the extent of the suction layer. The presence of unwanted particles on the belt and also the presence or generation of air bubbles at the interface could be major issues. One would also anticipate the texture of the belt surface to be important. In practice this has been seen to be the case.

6. Physical model description

The rubber roller squeezes the paste and belt thereby removing air pockets from the belt, extracting excess water from the paste, and compressing the 'elastic' belt and paste structure; its role seems crucial to the process, and the nip pressure is an important parameter in the problem. Observationally one sees excess water flowing back down the face of the drum away from the narrow gap between the rubber cylinder and the drum. Also water passes through the drum, which has holes in it, confirming that the paste is permeable at the pressures of interest. At the smallest gap location one can therefore assume the belt and paste are saturated with water and the felt belt is in a compressed state. Assuming the 'unobstructed' removal of water by the nip, one would expect the pores and cells of the belt and paste to be fully filled with water at atmospheric pressure. The implication of this is that all the compression applied by the cylinders at the nip is taken up by the elastic structure of the belt and paste. If the water removal rate at the nip is obstructed, the water pressure in the gap will be greater than the atmospheric pressure by an amount that could be determined by simple models, and the elastic structure of the belt would not absorb as much of the external load. The process would not be as efficient. Once past the gap the elastic structures 'relax' and expand. This produces the suction mediated by water generated surface tension effects in the now unsaturated belt which enables the paste to detach from the drum and hang upside down under the belt past this point. This description suggests that both the surface tension properties of the belt's surface and its elastic or non-elastic behaviour are important. After leaving the gap a redistribution of moisture across the belt and paste layers brings about reductions in suction potential levels at the paste and belt interface. If and when this level reaches $-w$, where w is the weight per unit area of the paste, the paste drops off. It is thus the moisture diffusion time scale δ^2/D where δ and D are the appropriate thickness and diffusion scales that is seen to govern the problem.

The question arose: Is there a thin layer of water separating the paste and the belt? Such a layer would exist for example if both the paste and belt were impermeable, or both remained saturated past the nip as would happen without the nip and which we observe with the kitchen sponge. It seems that the presence or absence of such a layer is not important as far as moisture transfer within the system is concerned, basically because the surface tension induced pressure within such a layer would be equal to the suction potential in the adjacent paste and belt; the dynamics of flow would thus be unaffected.

6.1 Mathematical formulation

The scalar potential formulation greatly simplifies the mathematical treatment of flow through porous media. The total scalar potential measures the work necessary to move a unit weight of water from a reference point $x = 0$ at atmospheric pressure to a specified location within the material, and *it is measured directly* using a probe with a U tube attached. By doing this one avoids the necessity of detailing and describing the microscopic origin of the forces that cause water movement; one simply uses data obtained from samples under the prescribed conditions. Herein lies both the strength and weakness of the approach. Bear (1972) and others have derived macroscopic Darcy Law like equations by averaging the microscopic fluid flow and solid movement equations, but we will use the approach of defining potentials for each of the moisture distribution mechanisms. The total potential Ψ within a normal, swelling porous medium is composed of three independent components; the gravitational ψ_g, moisture content ψ_w, and overburden potentials ψ_o, with

$$\Psi = \psi_g + \psi_w + \psi_o.$$

The flux of water within the material is assumed to be proportional to the total potential gradient. Three macroscopic characteristic functions are necessary to describe the conditions within a porous medium that determine macroscopic flow behaviour; the suction potential function $\psi(\iota)$, the conductivity $K(\iota)$ and the void ratio $e(\iota)$, depend on the *moisture ratio* ι, defined to be the volume of liquid water per unit volume of *solid medium*. Again these functions need to be measured experimentally, and the use of ι rather than the water content θ per unit volume of space in this swelling medium context is important. In the units of length used we set $\psi_g = -x$ where x is measured vertically upwards, and the overburden potential is

$$\psi_o = \frac{de}{d\iota}\left(P + \int_0^x \gamma dx\right),$$

where γ is the apparent specific gravity and P the pressure at the nip point.

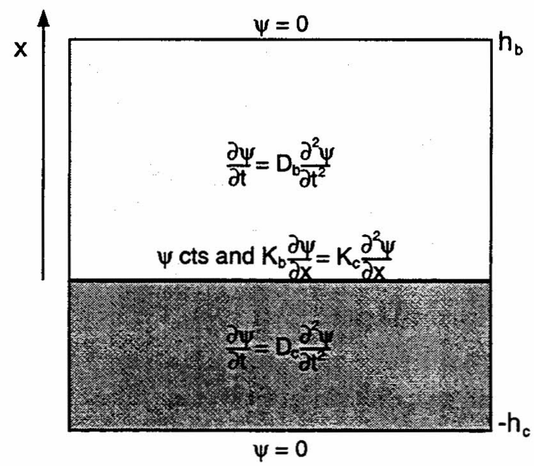

Figure 2: Moisture redistribution equations; subscripts 'b' for belt and 'c' for paste.

At the nip, since both paste and belt are saturated with water at atmospheric pressure, $\psi_m = 0$ throughout. As stated earlier, the pressure P applied by the rubber roller is taken up by the cellular structure within the belt and paste, and this determines the overburden potential. Conditions are close to saturation so $de/d\iota \approx 1$, and since $P \gg gh_b$, variations of the overburden pressure and gravitational potential across the belt and paste can be ignored; the total potential Ψ will be effectively uniform across the belt and paste and equal to pressure P applied at the nip. Just past the nip the pressure applied at the surface goes to zero and the belt and paste structure relaxes. In this way the potential built up by the application of P externally is stored in the form of suction and elastic potential within the paste and belt. All the forces involved, primarily surface tension and elastic forces, are conservative so that, before flow is initiated, there is no loss of potential for work and $\Psi = -P$. Flow within the structure then ensues. Once flow occurs within the belt and paste the pore size within the structure will change and this will effect a change in ψ_w and e through their dependence on ι. Also, the total thickness of the paste and belt will alter. By using material coordinates the implications of such geometric changes on potential levels is accounted for, and contained within the characteristic functions. It is also assumed that over the likely range of interest of ι, we can take K, D as constant. The modifications required to cope with variations of ι are minor, and not relevant at this stage of the investigation.

The equations governing the redistribution of water within the belt are thus,

$$\frac{\partial \Psi}{\partial t} = D_b \frac{\partial^2 \Psi}{\partial z^2}, \text{ in } 0 < x < h_b \tag{1}$$

$$\frac{\partial \Psi}{\partial t} = D_c \frac{\partial^2 \Psi}{\partial z^2}, \text{ in } -h_c < x < 0 \tag{2}$$

$$\Psi(x, 0) = -P, \quad -h_c < x < h_b,$$

$$\Psi(h_b, t) = 0, \quad \Psi(-h_c, t) = 0, \quad t \geq 0,$$

$$\text{with } K_b \frac{\partial \Psi(0)}{\partial x} = K_c \frac{\partial \Psi(0)}{\partial x}. \tag{3}$$

The paste will drop off the belt at time t^* given by

$$\Psi(0, t^*) = -w. \tag{4}$$

An exact, though not particularly informative solution is available for this problem in Carslaw and Jaeger (1959) p. 322. More informative approximations can be obtained using the fact that the belt is a much better conductor of moisture than the paste, so $K_c \gg K_b$ and $D_c \gg D_b$. Under these circumstances there will be a relatively quick initial adjustment of potential within the belt on a time scale $t_b = h_b^2/D_c$, followed by a much slower adjustment on a time scale of order $t_c = h_c^2/D_c$ associated with moisture flow from the paste to the belt. Thus the paste will either drop off after a short time of order t_b, or it will take a much longer time, of order t_c, to drop off.

6.2 Solutions

For time $t < t_c$ the paste effectively presents a nonconducting face to the belt, so the flux condition can be replaced by the zero flux condition $\frac{\partial \Psi(0)}{\partial x} = 0$.

The first term of the Fourier series solution accurately determines the solution behaviour and, for times not very close to 0, is given by

$$\Psi(x,t) \approx -\frac{2P}{\pi}\cos(\frac{\pi x}{2h_b})e^{-D_b(\pi/2h_b)^2 t},$$

so that the potential at the paste and belt interface will be $-\frac{2P}{\pi}e^{-D_b(\pi/2h_b)^2 t}$. Thus, if the paste drops off during this early period, it will drop off at

$$t^* = -\frac{4h_b^2}{\pi^2 D_b} ln(\frac{w\pi}{2P}), \quad \text{where } \frac{\text{w}\pi}{\text{2P}} < 1.$$

If the paste survives long enough, the moisture distribution within the belt will be approximately linear, and moisture transfer within the paste will determine the suction potential at the interface. The relevant approximate problem will be the moisture transfer within the paste subject to the radiation condition approximation in equation (3)

$$K_c\frac{\partial\Psi(0)}{\partial x} = K_b\frac{\Psi(h_b)-\Psi(0)}{h_b}.$$

The RHS is small so that replacing it by 0 will provide a first estimate. The non-conducting boundary condition problem again provides first estimates. A perturbation procedure can be used to determine the small effect of the moisture transfer across the interface. Thus we get

$$t^* \approx -\frac{4h_c^2}{\pi^2 D_c} ln(\frac{w\pi}{2P}), \quad \text{where } \frac{\text{w}\pi}{\text{2P}} < 1.$$

Of course refinements to these expressions can be made, where a multi-scaling solution would be particularly appropriate, but seem unwarranted at this stage of the investigation. The general picture is clear from the above. The suction model predicts

- a logarithmic dependence of the drop off time on the ratio P/w
- $t^* \propto \delta^2/D$,

where D is the appropriate diffusion coefficient and δ the appropriate thickness. These results should be checked experimentally before proceeding further. It will be seen that the physical adhesion predictions are *very* different.

6.3 Other suction related mechanisms

Recalling that if the edge of the paste peels away from the belt then the whole paste will follow, we can see that changes in suction levels at the edges of the belt may be important. The inevitable vibrations of the apparatus may also cause the edge to peel away. Air penetration through the belt could also interfere with the suction layer. However the process appears robust in practice so it seems unlikely such destabilizing effects are important. There is no evidence that random collapse events occur in the process.

7. Adhesion models

Physical and chemical mechanisms mediated by the presence of water acting like a glue may cause the paste to adhere to the belt. For example, fibres may intertwine, the charged ends of the bipolar water molecules may re-orientate and electrostatically attach to the two surfaces. The precise mechanism is irrelevant for the crude model set up here. Eventually the surfaces separate, which must mean that either the number or average strength of attachment points reduces as time goes on. The presence of water is obviously necessary because the dry surfaces don't stick to each other, but it is not necessarily the critical feature as far as separation is concerned. This model simply assumes that weak attachment points break leaving the burden to be borne by fewer attachment points and an accelerating failure mechanism is set in motion that will eventually result in separation. Alternative models still need investigation. We assume that the failure strength of connections S is normally distributed about an average value $\bar{S}$, with standard deviation Σ, so that the probability distribution function is given by

$$p(S, \Sigma, \bar{S}) = \frac{1}{\sqrt{2\pi}\Sigma} e^{-\frac{1}{2}(\frac{S-\bar{S}}{\Sigma})^2}.$$

The distribution is shown in Figure 3. The general results obtained are not special to this distribution.

If there are initially N_0 attachment points per unit belt area, then the average load borne by each attachment point will be $w/N_0 = S_0$, where w is the weight of paste per unit belt area. This will exceed the 'snapping strength' of attachment points lower in the distribution than S_0, so that after snapping at time τ there will be

$$N_1 = N_0 \int_{S_0}^{\infty} p(S, \Sigma, \bar{S}) dS$$

points left to support the paste; the average load borne now being $S_1 = w/N_1$.

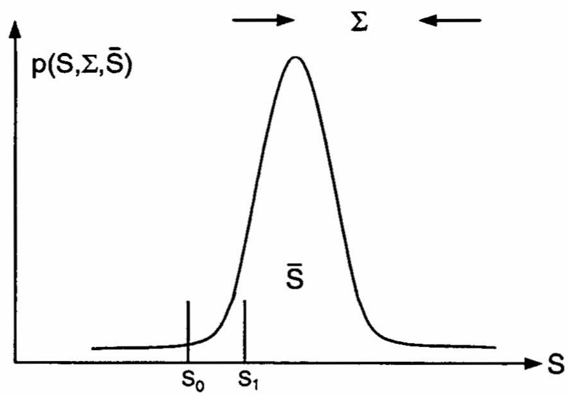

Figure 3: The attachment point strength distribution.

The iterative scheme

$$N_{k+1} = N_0 \int_{S_k}^{\infty} p(S, \Sigma, \bar{S})dS, \quad \text{with } S_k = \frac{w}{N_k} \quad k \geq 0,$$

thus describes the collapse of the adhesive layer according to this model. Evidently $N_{k+1} < N_k$. Introducing convenient scales

$$N_k = N_0 n_k, \; S = \bar{S}s, \; S_0 = s_0\bar{S}, \tag{5}$$

we get the description

$$n_{k+1} = \int_{s_k}^{\infty} p(s', \sigma)ds', \quad \text{with } s_k = \frac{s_0}{n_k}, \quad k \geq 0, \; n_0 = 1, \tag{6}$$

where

$$p(s, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} \exp(-\frac{1}{2}(\frac{s-1}{\sigma})^2),$$

and

$$s_0 = w/(N_0\bar{S}) \text{ and } \sigma = \Sigma/\bar{S}$$

are the two dimensionless groups defining the problem; the first measuring how relatively strong the initial attachment is compared with the load to be supported and the second measuring the relative variability of the strength of attachment points on the same scale. For the normal distribution equation (6) reduces to

$$s_0/s_{k+1} = \text{erfc}\left(\frac{s_k - 1}{\sigma}\right),$$

and in the usual way, by plotting the LHS and RHS functions, as in Figure 4, one can determine the evolution of the solution. The intersection of these curves determines possible equilibrium points (n_E, s_E), i.e.

$$s_0/s_E = \text{erfc}\left(\frac{s_E - 1}{\sigma}\right), \; n_E = s_0/s_E,$$

and it is clear from Figure 4 that there will be either 2 solutions or none, depending on the parameters. Recalling that only increasing s solutions are allowed by the physics (reattachment is impossible), and noting that at $s = s_0$ the LHS curve is at 1, and so above the probability integral associated with the RHS, one can see that the possible scenarios are:

Case 1: If the curves intersect, only the smallest equilibrium solution s_E^1 is stable, and $s_k \to s_E^1$; some of the attachment points break leaving a stable situation in which the remaining stronger points remain intact supporting the paste.

Case 2: No equilibrium solutions: eventually the paste drops off.

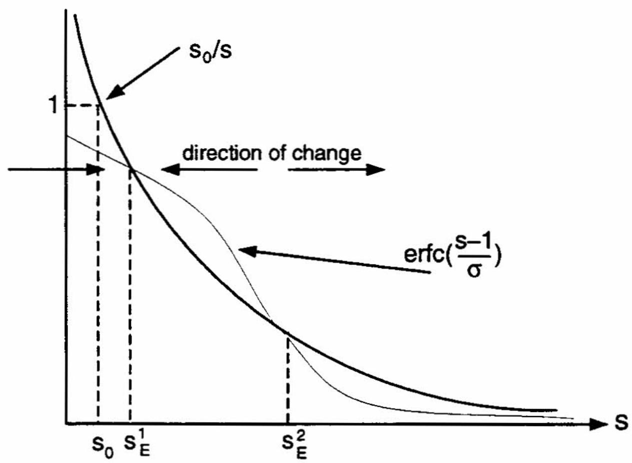

Figure 4: Equilibrium solutions (Case 2).

This difference equation can be explored numerically to determine the dependence of adhesive collapse on (s_0, σ), however, it is more instructive to process the equation further by noting that

$$n_{k+1} - n_k \approx p(s_k, \sigma)\delta s_k \;=\; p(s_k, \sigma)(\frac{s_0}{n_k} - \frac{s_0}{n_{k+1}}),$$

which can be approximated by

$$n_{k+1} - n_k = \frac{s_0 p(s_k, \sigma)}{n_k^2}(n_k - n_{k-1}),$$

providing the fractional change in n is small over the time interval τ; this relates the rate of change of $\frac{Dn}{Dt}$ to the height of the probability distribution curve. The implication is that the collapse of adhesion will be very slow until p is significant.

Collapse situations can occur for:

- $s_0 \ll 1, \sigma \ll 1$ Collapse very slow initially, then rapid;
- $s_0 \ll 1, \sigma \approx 1$ Collapse is steady;
- $s_0 > 1$ Collapse is immediate.

These situations are illustrated in Figure 5.

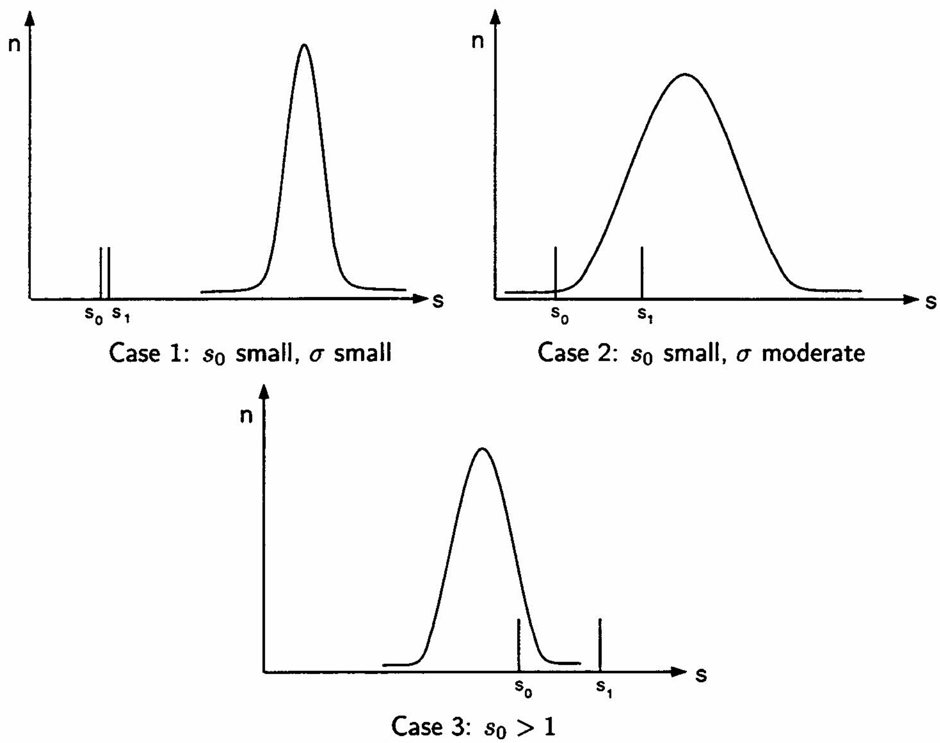

Figure 5: Collapse situations.

The time required for failure is evidently strongly and non-linearly dependent on two basic parameters related to the relative size of the load to be supported *and* the width of the strength distribution. This is very different from the surface tension model results. One would expect the number of attachment points to increase with the effective nip pressure; experiments would be necessary to determine this dependence.

It should be a simple matter to distinguish experimentally between suction based adhesion and physical attachment, using the above results and simple sponge squeezing experiments.

8. Other considerations

8.1 Thickness and water measurements in situ

There was some discussion about ways to measure the thickness of the paste and the water content of the paste in situ. Ultrasonic techniques were suggested to be accurate in the determination width to 0.1 mm, but the feasibility would need to be the subject of a detailed study.

8.2 Rotational effects

As there are periods during which the belt and paste ensemble experience considerable rotation, it was thought necessary to calculate the acceleration experienced to see if this could be a factor in the loss of adhesion. Careful estimates of the speed and radii revealed this to be a small effect and unlikely to play any role.

8.3 Flocculation

The addition of some as yet unknown ingredient (prosaically referred to as 'Pixie Dust') to the cement paste prior to application was suggested as a possible way of increasing surface tension effects and consequently adhesion. While this may be effective, it would require further study to determine a suitable additive and success depends upon the determination of the main mechanism of adhesion.

8.4 Resonant vibrations

As the ensemble travels through the process, there are many vibrations experienced due to inexact alignment and other factors. These could result in a resonant effect which causes disruptions to the paste and subsequently lower adhesion. The calculation or experimental investigation of these effects could be valuable.

8.5 Suggestions for further investigation

To obtain further useful information on the mechanism for adhesion and assist in the modelling and improved control of the process, the following were suggested.

1. The total amount of moisture needs to be between the levels at which only the belt is saturated and at which the system of the belt and paste is saturated. Hence there needs to be extensive moisture monitoring during the entire process and particularly after the paste is attached to the belt and after the vacuum box.

2. A statistical study of failure could assist in identifying the key factors which are responsible for the loss of adhesion. This could also assist in determining the physical or chemical mechanisms.

3. Check whether the compression applied by the cylinders at the nip point is taken up by the elastic structure of the belt and paste ensemble.

4. Investigate the predictions of the suction model used in Section 6.2 to determine if

   - there is a logarithmic dependence of the drop off time on the ratio of nip point pressure to the weight per unit area of paste; and if
   - the fall off time is proportional to thickness squared over moisture diffusivity.

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