

Innovative procedure for automatic measurement of specific filtration resistance and electrostatic charge

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ABSTRACT: *An on-line technique has been developed to monitor streaming potential and specific filtration resistance (SFR). The technique was validated on a hardwood furnish, where SFR and charge were varied by refining and by application of a high-charge-density, low-molecular-weight polymer. The technique performed as anticipated. The SFR was compared with a maximum drainage parameter and against Schopper-Riegler freeness. All of these approaches track the observed trends, but SFR seems to be more sensitive. SFR also has a theoretical basis and can be used to predict drainage on the paper machine. It is time for the paper industry to adopt this new fundamental parameter to monitor drainage and relegate pulp freeness to a role of historical significance.*

KEYWORDS: *Procedures, on line measurement, monitoring, electrostatic charge, filterability, drainage, polymers.*

Papermakers have long known that the paper machine is a dynamic, changing system. While it gives the illusion of being a steady-state process, a close examination of the water quality shows that it is always slowly changing. The reason for this is the long times to equilib-

rium because of the high-residence-time recycle loops in the process.

Much fundamental understanding exists about retention and drainage on the paper machine, but attempts to apply this knowledge have been unsuccessful because of the changing system. A fundamental property

important to retention on the paper machine is the state of the charge on the fiber surface, and a fundamental property important to drainage is specific filtration resistance.

The trend for measurement of both drainage and retention has been away from the laboratory and toward on-line continuous measurement. Early attempts to apply zeta potential were often unsuccessful because the system conditions would be different by the time the measurement was taken in the laboratory. This difficulty led Paper Chemistry Laboratory to develop the Zeta Data™ instrument, the only commercially available on-line device for measuring streaming potential. Another company has also developed an instrument, but it is not yet available. These devices should greatly help us understand the role of electrokinetic charge in the papermaking system.

A similar evolution has taken place in the field of drainage measurement. The industry measures drainage in terms of Canadian standard freeness (CSF) or Schopper-Riegler freeness (SR). Both are empirical tests that measure the drainage time of a fixed volume of pulp stock. They give a qualitative picture of how a stock drains, but there is no existing theory that can extrapolate their values to drainage on the paper machine.

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Retention/Drainage

A fundamental measurement that characterizes stock drainage—and has a theoretical underpinning—is specific filtration resistance (SFR). The idea to use SFR to characterize stock drainage was introduced in the 1950s by Ingmanson (1) and refined into a workable concept by Springer and Pires in 1989 (2, 3). The current paper is the latest in a series that has advanced the concept of SFR from a theoretical concept to a practical, realistic parameter for use in predicting machine drainage. The basis for the technique is discussed in detail in the literature (2). Its usefulness in predicting the drainage profile on a machine is established in another work (3). The desirability of doing this was recognized as far back as 1950, but it was not accomplished until 1989. It is now possible, in 1994, to make these predictions on a real-time basis as the machine is running.

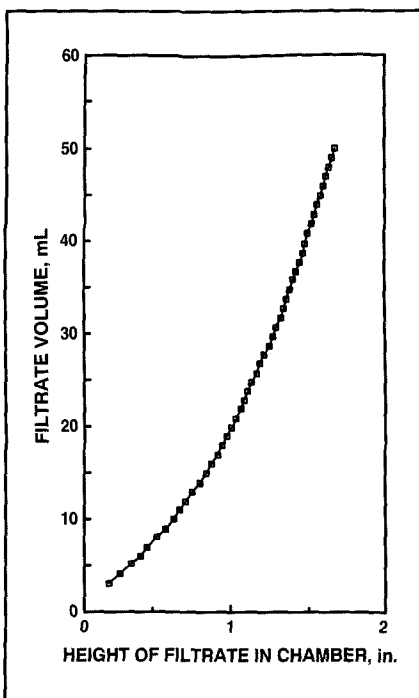
This paper describes the procedure for monitoring SFR on a real-time basis. Experimental data are then presented to validate the procedure. With such a parameter as SFR available, it is time for the industry to phase out its dependence on freeness.

The need for some type of on-line freeness testing is apparent, since several companies market such devices and mills use them. SFR has not been used as the basis for an on-line device because of unfamiliarity with the theory and the lack of a user-friendly apparatus. The latter difficulty has now been overcome. To understand the theory, read two previous works in the literature (2, 3) and consult a good fluid mechanics text that covers flow through continuously forming porous media. SFR is a property of the slurry and the conditions under which the pad is formed. It is a basic, inherent property of the material being drained.

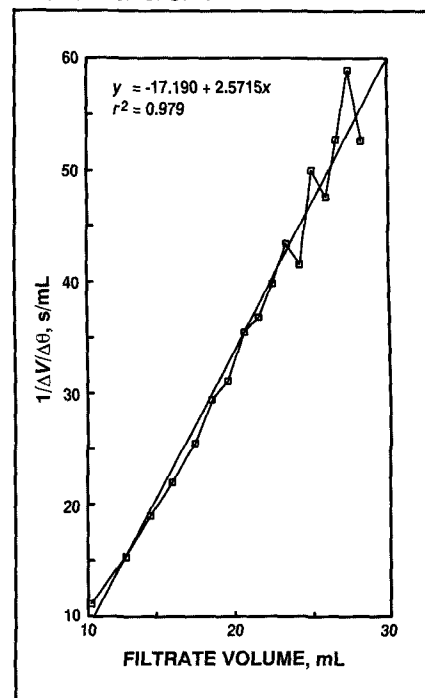
Value of SFR measurement

Measurement of SFR should enable the papermaker to ascertain the

1. Correlation between measured height of filtrate in collection chamber and the inferred volume of filtrate within the chamber



2. Least-squares fit of key data from Table I (pulp freeness of 50 SR, no polymer addition) to obtain slope m (2.5715 s/mL^2) used in calculation of SFR



I. Spreadsheet transformation of data for pulp at constant freeness (50 SR) and no polymer addition

	Time (T), s	Filtrate height, in.	Filtrate volume (V), mL	ΔV , mL	$1/\Delta V/\Delta(\theta)$, s/mL
1	1.000	0.117	3.233	0.233	...
2	2.000	0.350	5.208	0.295	...
3	3.000	0.645	10.350	0.089	11.236
4	4.000	0.734	12.481	0.064	15.625
5	5.000	0.798	14.179	0.052	19.231
6	6.000	0.850	15.662	0.045	22.222
7	7.000	0.895	17.019	0.039	25.641
8	8.000	0.934	18.250	0.034	29.412
9	9.000	0.968	19.366	0.032	31.250
10	10.000	1.000	20.452	0.028	35.714
11	11.000	1.028	21.431	0.027	37.037
12	12.000	1.055	22.400	0.025	40.000
13	13.000	1.080	23.319	0.023	43.478
14	14.000	1.103	24.183	0.024	41.667
15	15.000	1.127	25.104	0.020	50.000
16	16.000	1.147	25.887	0.021	47.619
17	17.000	1.168	26.723	0.019	52.632
18	18.000	1.187	27.493	0.017	58.824
19	19.000	1.204	28.192	0.019	52.632
20	20.000	1.223	28.984	0.096	...
21	21.000	1.319	33.177	...	...

drainage of the stock before it enters the headbox and then adjust the electrochemical conditions with an ap-

propriate polymer if there are going to be drainage problems that would slow down the machine. Such a drain-

age-measuring device might even be useful for monitoring and controlling refining conditions. The instrument also should prove to be useful for monitoring the new microparticulate techniques that are aimed at optimizing both retention and drainage.

Description of instrument

The Zeta Data on-line streaming-potential instrument is a well-developed, rugged, proven instrument that can operate in a mill environment with little operator attention. For details of the instrument and specifications, consult the manufacturer's literature (4). The operating principle is that furnish is drawn through a screen to form a pad. White water is drawn through the pad while measuring the electrical potential across the pad. This electrical potential is the streaming potential. Through use of appropriate equations, this potential can be related to the zeta potential of the fiber. The amount of white water drawn through the screen and pad is monitored as a buildup of height in the measuring chamber. This enables measurement of the volume drained as a function of time. The conductance and temperature are also monitored. All data are electronically recorded and stored in a microcomputer. The microcomputer also operates all functions on the instrument.

The procedure for getting streaming potential from such data has been discussed previously (5) and appears to be reasonably well accepted. The current work focuses on how to obtain SFR, since this is the new addition to the established instrument.

Theoretical background— procedure for measuring SFR

The total drainage resistance, which is a function of the flow pattern and stock composition, is the sum of the effects of resistance to the flow imposed by the wire and by the fiber

mat. Thus, the filtration equation can be written as

$$dV/d\theta = A \, dP/[\mu(R_f + R_w)] \quad (1)$$

where

V = filtrate volume, m^3

θ = time, s

$dV/d\theta$ = drainage flow rate, m^3/s

A = cross section of the flow, i.e., area of the fiber mat, m^2

dP = pressure gradient across the fiber mat and wire, Pa

μ = filtrate viscosity, Pa·s

R_f = drainage resistance of the fiber web, m^{-1}

R_w = drainage resistance of the wire, m^{-1}

The fiber resistance, R_f , can be written in terms of the mass of fiber deposited on the web per unit area and an SFR coefficient:

$$R_f = (W/A)SFR \quad (2)$$

where

W = mass of the fiber web, kg

SFR = specific filtration resistance, m/kg .

For a given instant θ , the mass of fiber in the web is

$$W = C \, V \, \S \quad (3)$$

where

C = concentration of fibers in the slurry, kg/m^3

V = accumulated volume of slurry filtrate, m^3

$\S$ = retention, i.e., fraction of stock retained in fiber web

Thus, in incremental form, the combination and simplification of Eqs. 1–3 yields (in inverted form)

$$\Delta\theta/\Delta V = [\mu \, \S \, C \, V \, SFR/(A^2 \Delta P)] + [\mu R_w/(A \Delta P)] \quad (4)$$

If Eq. 4 is valid for the flow through the fiber mat and wire, then a graph of the ratio $\Delta\theta/\Delta V$ as a function of the accumulated volume should result in a straight line. Experiments performed during this

work showed that a linear relationship can be used to describe the measured points, as assumed. The slope and the intercept of the line are used to evaluate the SFR and the wire resistance (R_w), respectively.

Implementing the procedure

A special sensor was added to the Zeta Data device to determine the height of the liquid interface in the exit chamber after the pad-formation screen. This height was translated into a drainage volume by the correlation shown in Fig. 1. The height-vs.-time data were automatically recorded and stored in the computer. These data were printed out and manually transferred to a spreadsheet program, which transformed the data to volume and then calculated the change in volume and the reciprocal of change in volume per unit time. This is the transformation necessary to use the theory described under the heading "Theoretical background." Table I is an example of this transformation for a pulp of 50 SR with no polymer addition. These data were plotted in appropriate form, and a least-squares fit line was applied to the data, as shown in Fig. 2. These results are representative of most data observed in this study. The theoretical model seems to be a good fit to the data, and this was found to be true over the complete range of data collected in this study.

The specific filtration resistance is obtained from the slope, m .

$$SFR = (m \, A^2 \, \Delta P)/(\mu \, \S \, C) \quad (5)$$

where

m = slope, $2.57 \, s/mL^2$

A = area, $1.266 \times 10^4 \, m^2$

ΔP = pressure difference across the fiber mat and wire, $4.13 \times 10^{-4} \, Pa$

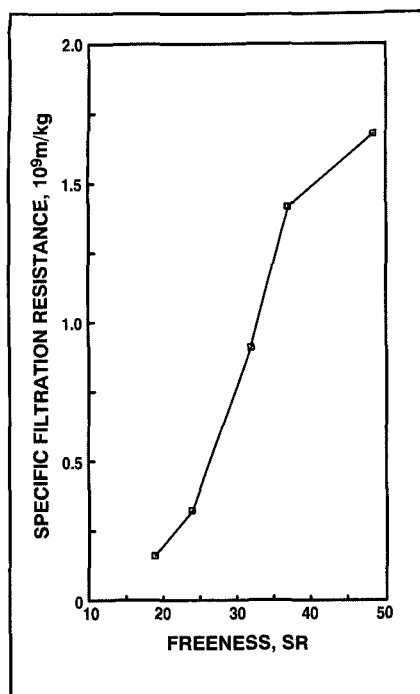
μ = viscosity, $6.56 \times 10^{-4} \, Pa \cdot s$

$\S$ = retention, 0.8

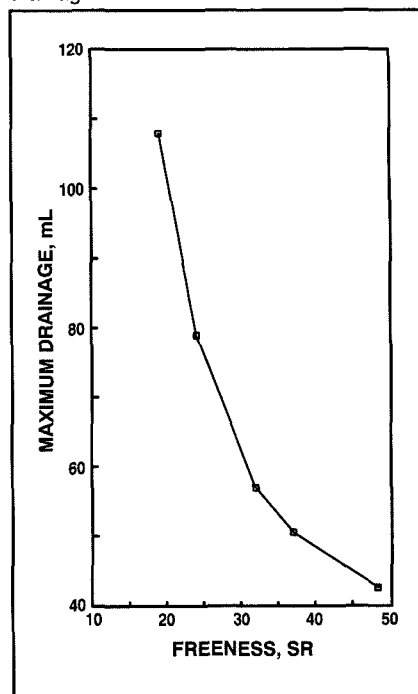
C = concentration, $2 \, kg/m^3$

Retention/Drainage

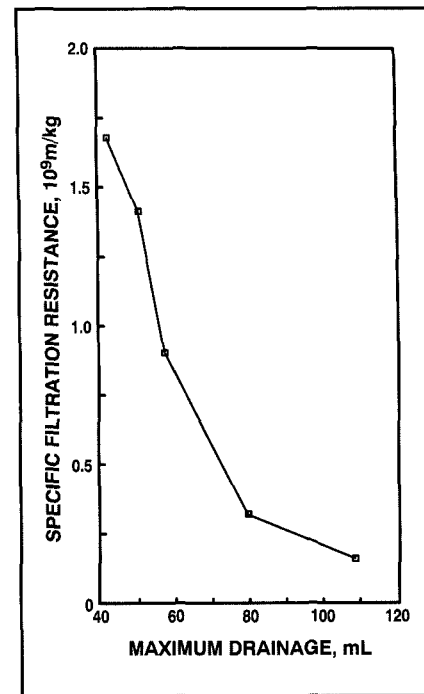
3. Correlation of SR freeness and SFR



4. Correlation of SR freeness and maximum drainage



5. Correlation of maximum drainage and SFR



Thus

$$\begin{aligned} \text{SFR} &= m \times 0.63 \times 10^9 \text{ m/kg} \\ &= 1.62 \times 10^9 \text{ m/kg} \end{aligned}$$

Since the procedure looked good, a study was designed to see if the SFR calculated by the procedure made sense and behaved in a manner that was consistent with a papermaker's knowledge of the system.

Study plan

The main papermaking variables that affect the way a stock drains are its degree of refining and the chemical additives put into the furnish. A bleached hardwood kraft pulp from Champion Paper Co. (Quinnesect, MI) was refined from 19 SR to 48 SR, with samples taken at 19 SR, 24 SR, 32 SR, 37 SR, and 48 SR. This provided a wide range of freeness over which to test the procedure. The stock samples at each level of freeness were then treated with a high-charge-density, low-molecular-weight polymer (Cypro 516™) in incremental dosages of 0.005%

II. Summary of results at variable freeness and no polymer addition

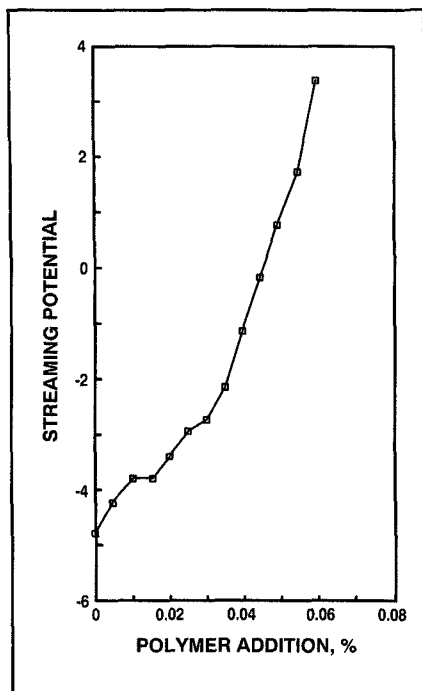
	Freeness, SR	Maximum drainage, mL	SFR, 10 ⁹ m/kg	Zeta potential, mV
1	19.000	108.400	0.162	0.000
2	24.000	79.300	0.325	0.000
3	32.000	57.200	0.910	-0.900
4	37.000	50.500	1.420	-0.165
5	48.000	42.600	1.670	-2.150

from none (control) to 0.06% by weight of the stock. The samples were then run through the Zeta Data on a batch basis in a recirculating mode. This paper presents data for (a) stock refined to five levels of freeness with no polymer addition and (b) stock at initial freeness of 50 SR treated with various levels of polymer addition.

Discussion of results

The streaming potential, freeness (SR), SFR, and maximum drainage were determined for all samples tested. The maximum drainage is the volume drained at the end of the measurement cycle and is a quick indication of how the stock will drain. Table II is a summary of the results

6. Influence of polymer addition on streaming potential



for the pulp samples containing no polymer. The measurements all show the expected trend for a pulp subjected to increasing levels of refining.

Figure 3 illustrates the relationship between Schopper-Riegler freeness and SFR. As expected, they track each other but do not correlate to each other in a linear fashion. This is because they are distinctly different measurements, with SFR providing much more useful information, since it has a theoretical basis. Figure 4 shows the relationship between the maximum-drainage number and the Schopper-Riegler freeness parameter. Again, they track each other, but it is apparent that they are different measurements. Figure 5 shows the relationship between maximum drainage and SFR, and again the result is a curve.

One might think that the differences between Schopper-Riegler freeness and either maximum drainage or SFR reflect the differences in the devices used to monitor these properties. One might also suppose

III. Summary of results at variable polymer addition to pulp of 50 SR freeness

	Polymer addition,* %	SFR, 10^9 m/kg	Maximum drainage, mL	Freeness, SR	Streaming potential
1	0.000	1.67	38.600	48.000	-4.810
2	0.005	1.35	38.600	48.000	-4.230
3	0.010	1.40	40.200	45.000	-3.780
4	0.015	1.28	40.900	44.000	-3.780
5	0.020	1.30	41.200	43.000	-3.390
6	0.025	1.18	42.000	42.000	-2.950
7	0.030	1.15	42.100	41.000	-2.730
8	0.035	1.28	42.600	40.000	-2.150
9	0.040	1.28	41.900	40.000	-1.160
10	0.045	1.28	41.700	41.000	-0.190
11	0.050	1.31	41.400	42.000	0.730
12	0.055	1.31	41.000	42.000	1.730
13	0.060	1.33	40.600	42.000	3.320

*Cypro 516™

that maximum drainage and SFR should correlate linearly, since they are measured using the same device. However, maximum drainage and Schopper-Riegler freeness are just qualitative measures of stock drainage that provide a qualitative indication of how a stock will drain on a paper machine. Neither can quantitatively predict machine performance. Only SFR has this ability. Since all three methods were developed to monitor the same phenomenon—and since they do track each other—it seems reasonable to recommend that papermakers shift to SFR, the parameter with a theoretical basis.

Table III summarizes the changes that occurred when a 50-SR pulp sample was subjected to various doses of retention aid. The polymer has sufficient effect on drainage to be equivalent to a shift of one level of refining chosen in this study. Figure 6 shows the stock's response to polymer addition as far as streaming potential is concerned, and the expected pattern of rise to a more positive state of charge is observed.

As expected, the cationic polymer neutralizes the negative charges on the cellulose and then makes the pulp positively charged. The effect one might expect on drainage would be low drainage when the fines are dispersed, then good drainage around the zero charge on the positive side.

Figure 7 shows what happens to the different drainage parameters as polymer is added. All three of the monitored drainage parameters go through an optimum. The optimum for SFR occurs before the optimum for SR freeness and maximum drainage. The optimum for SFR is also more sharply defined than for SR freeness. All of the optimums occur before the occurrence of zero streaming potential. It is not possible to state which measurement best predicts optimum drainage, since the stock was not run on a machine. It appears that the minimum point for SR freeness and maximum drainage are very close, so when data are accumulated on a commercial machine with the Zeta Data device, this question will be answered. The pattern observed for the maximum-drainage

Retention/Drainage

number is more consistent than the SR freeness pattern, so the technique may be more sensitive. The SR freeness values often did not change with polymer addition, and this was attributed to lack of sensitivity.

Table IV lists the individual SFR measurements obtained during the polymer study. All SFR data were calculated from duplicate measurements. The standard deviation calculated from the average range is 0.035. Thus a confidence interval for measurement of two standard deviations would be 0.07, indicating that the procedure is reproducible and reasonably sensitive.

Future work

The procedure of determining SFR and streaming potential together is a breakthrough, and it would be even more powerful if the charge per surface area could be determined. What one is principally doing by changing the SFR is changing the surface area per volume of the clumps of particles. Applying the Kozeny-Carman theory to the fiber slurry, one finds that

$$\text{SFR} = (S_v^2 / \rho_{\text{pad}}) [(1 - E_{\text{pad}}) / E_{\text{pad}}^3] \quad (6)$$

where

S_v = surface area/volume, m^2/m^3

ρ_{pad} = pad density, kg/m^3

E_{pad} = pad porosity

for

$$S_v = S_p / V_p \quad (7)$$

where

S_p = surface area/particle

V_p = volume/particle

and for

$$E_{\text{pad}} = 1 - [W_{\text{pad}} / (A_{\text{pad}} T_{\text{pad}} \rho_{\text{pad}})] \quad (8)$$

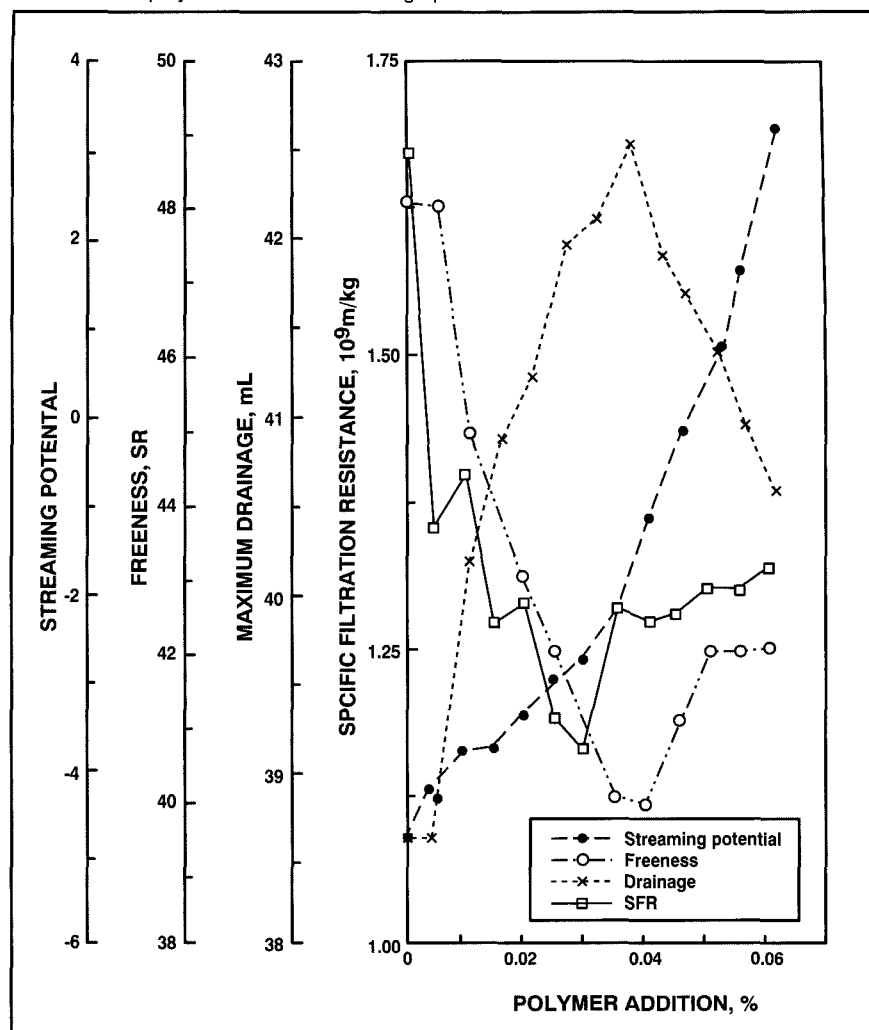
where

W_{pad} = pad weight

A_{pad} = pad area

T_{pad} = pad thickness

7. Influence of polymer addition on drainage parameters



IV. SFR reproducibility at variable polymer addition to pulp of 50 SR freeness

	Polymer addition, %	SFR, 10^9 m/kg			
		1st measurement	2nd measurement	Range	Average
1	0.000	1.62	1.73	0.11	1.68
2	0.005	1.34	1.38	0.04	1.36
3	0.010	1.34	1.46	0.12	1.40
4	0.015	1.27	...	...	1.27
5	0.020	1.30	...	...	1.30
6	0.025	1.18	1.20	0.02	1.19
7	0.030	1.17	1.16	0.01	1.17
8	0.035	1.26	1.32	0.06	1.29
9	0.040	1.29	1.26	0.03	1.28
10	0.045	1.27	1.30	0.03	1.29
11	0.050	1.31	1.30	0.01	1.31
12	0.055	1.29	1.32	0.03	1.31
13	0.060	1.33	1.30	0.03	1.32

*Cypro 516™

Solving for the surface area/volume, S_v ,

$$S_v = \{(SFR \rho_{pad} E_{pad}^3) / [k(1-E_{pad})]\}^{1/2} \quad (9)$$

where

$k = 5$ for isotropic cakes of $E_{pad} = 0.3-0.6$

For fibrous materials with $E_{pad} > 0.6$, k would be higher. Ideally, k should be determined for each material. A representative value might be $k = 8$.

This shows that measurement of pad thickness at the end of the filtration cycle would make it possible to calculate the surface area per volume of material in the slurry. However, it is difficult to measure pad thickness on a continuous basis.

The apparatus was disassembled, and pads were measured for weight, area, thickness, and density. These measurements were then used to calculate E_{pad} , pad porosity. The calculated value of E_{pad} was then inserted into Eq. 9 to calculate S_v , as seen in the following example.

$$E_{pad} = 1 - [W_{pad} / (A_{pad} T_{pad} \rho_{pad})]$$

where

$$W_{pad} = 0.082 \text{ g} = 8.2 \times 10^{-5} \text{ kg}$$

$$A_{pad} = 1.266 \times 10^{-4} \text{ m}^2$$

$$T_{pad} = 0.104 \text{ in.} = 2.64 \times 10^{-3} \text{ m}$$

$$\rho_{pad} = 1250 \text{ kg/m}^3$$

Thus

$$E_{pad} = 1 - \{8.2 \times 10^{-5} / [(1.266 \times 10^{-4})$$

$$(2.64 \times 10^{-3}) (1.25 \times 10^3)]\}$$

$$= 1 - 0.196 = 0.804$$

Assuming

$$SFR = 6.7 \times 10^9 \text{ m/kg}$$

$$k = 8$$

then

$$S_v = \{(SFR \rho_{pad} E_{pad}^3) / [k(1-E_{pad})]\}^{1/2}$$

$$= \{[(6.7 \times 10^9) (1.25 \times 10^3) (0.804^3)] / [8 (0.196)]\}^{1/2}$$

$$= (2.78 \times 10^{12})^{1/2}$$

$$= 1.67 \times 10^6 \text{ m}^2/\text{m}^3$$

The value for S_v in the preceding example seems reasonable. What one is doing by either refining or polymer flocculation is changing the surface area per unit volume (S_v). SFR is a strong function of this, but it is not solely a function of this, since it also depends on the pad's compressibility characteristics, which relate to its structural characteristics. If pad-thickness data could be obtained on a continuous basis, then surface area per volume would be available. This, coupled with the streaming potential, would give charge per surface area, which probably controls a lot of the wet-end chemistry phenomena that occur on the machine.

Conclusions

A new, realistic, reproducible, continuous method of monitoring specific filtration resistance (SFR) on-line is available. SFR tracks changes in drainage and is related to pulp freeness in a nonlinear fashion. However, SFR is a more satisfactory measurement than freeness because it is grounded in theory that can predict drainage on the paper machine.

The maximum drainage as measured on the Zeta Data™ device is different from SFR (measured on the same device) or Schopper-Riegler freeness. While all three relate to the same phenomenon, they are distinctly different measurements. SFR appears to be a more sensitive indicator of drainage. The position of fastest drainage for polymer addition is predicted earlier by SFR than either Schopper-Riegler freeness or maximum drainage.

If pad thickness in the Zeta Data device could be monitored during drainage, it would be possible to predict specific surface area per unit volume and then charge density per unit surface area. ■

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