On-line soft-nip calendering and supercalendering: Effects of coating formulation and operating variables

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ABSTRACT: *On-line soft-nip calendering was studied on the pilot scale using a lightweight-coated paper grade. An extensive test matrix was carried out to quantify the response of sheet optical properties to calender temperature, pressure, and coating-formulation variables. Paper webs were also treated in an off-line mode and in a conventional supercalender. One of two coating colors—an all-mineral pigment control and a system containing synthetic pigment—was applied using a high-speed short-dwell coater. Gloss and smoothness were more easily developed on-line than off-line. In general, the gloss and smoothness of the on-line hot soft-nip calendered sheets approximated that of the supercalendered controls, with indications of better brightness and opacity. The synthetic pigment improved gloss response, allowing use of lower temperature and/or nip load to achieve target gloss.*

KEYWORDS: *Calendering, calenders, coated papers, coatings, formulations, light weight papers, off line processing, on line processing, optical properties, paper grades, physical properties, process variables, processing, soft nip calenders, supercalendering, surface finishing, variables.*

The potential of hot-soft-nip or soft-nip calendering is exciting. As experience is gained and some of the perceived problems are addressed, solved, or discounted, new doors will continue to open for this relatively young technology.

Several factors affect the sheet's response to hot soft-nip calendering. The furnish and the coating formulation, including binder and pigment system, have a significant effect on sheet response. For hot soft-nip calendering to be effective, a reformulation of the entire system must be considered *(1, 2)*. Simply trying to force-fit an existing sheet to this different finishing method will not produce optimal results. Redesign is key to success. While the validity of this observation is beyond doubt, a total system approach is not feasible for everyone. In such cases, it is incumbent on participants in each phase of the field to gain a solid understanding of how their components affect system response.

The aim of this study was to examine the response of a trial paper to a wide range of on-line hot soft-nip calendering conditions in a comprehensive test matrix with two coating formulations. The two formulations had shown significant differences in thermal response in the laboratory. In addition, crossover evaluations were performed in an off-line mode, where more data have been published, and with a traditional supercalender. The objective was to gain perspective on the relationships between operating variables and sheet properties for all three modes. An added-value aspect was in establishing meaningful correlations with laboratory data, which will expedite further studies with binders, other pigments, and other basestocks.

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Experimental design/ background

Operating parameters included roll temperature, pressure (nip load), line speed, sheet moisture, and number of nips. Earlier pilot work with wood-free grades on a different pilot line had clearly shown the advantage of a second nip for smoothness and gloss. **Table I** shows the results from this earlier work. The data represent an average of nine pairs of results (three coating formulations at three nip loads).

The improvement of sheet properties with two nips is in agreement with recent works, which show that the superior gloss and smoothness associated with supercalendering are best approached when hot soft-nip calendering is carried out using two nips per side *(1, 3, 4)*. Therefore, in this study, the number of nips was held constant at two. Line speed was maintained at 1000 m/min (3280 ft/min), which represents a reasonable speed that fits within the operating limits of the pilot equipment. The on-line variables were thus temperature and nip load. A separate segment of the design dealt with sheet moisture.

Three coat weights were run for each calender condition to increase the robustness of the design, so that scatter or spurious points would not weigh unduly in the interpretation. Each roll represented nine data points—three coat weights at three nip loads—at a single temperature. Temperatures were increased sequentially, and formulations were reversed at succeeding temperatures for efficiency. Coat weight was established, and then the three nip loads were run from low to high. When the coat weight was changed for the next set of runs, the process was reversed (nip loads were run from high to low) to avoid two changes at once, i.e., both coat weight and nip load.

I. Gloss and smoothness for wood-free grades after treatment in one or two nips *

	Gloss (75°), %		*Smoothness (PPS-5), µm*	
	Average	*Avg. std. dev.*	*Average*	*Avg. std. dev.*
1 nip	73.8	1.6	1.37	0.08
2 nips	79.4	1.1	1.10	0.06

* Data for each nip mode are based on nine runs (three coating formulations at three nip loads).

II. Pilot-plant operating conditions [a]

	Temp., °C	*Nip load, kN/m*	*Line speed, m/min*	*No. of nips*	*Coat weight, g/m²*
On-line test matrix [b]	50	50, 200, 340	1000	2	6, 8, 10
	100	50, 200, 340	1000	2	6, 8, 10
	150	50, 200, 340	1000	2	6, 8, 10
	200[c]	50, 125, 200	1000	2	6, 8, 10
Off-line	150	200	1000	2	6, 8, 10
	175	250	1000	2	6, 8, 10
Supercalender	70	200	450	9	6, 8, 10

[a] Basic coating formulation: 10 parts carboxylated SBR [T_g (DSC) = –8°C]; 4 parts ethylated starch; 0.5 parts lubricating agent; 0.2 parts crosslinker
Pigment:
Coating A: 80 parts No. 1 clay; 20 parts ultrafine calcium carbonate
Coating B: 75.2 parts No. 1 clay; 18.8 parts ultrafine calcium carbonate; 6 parts synthetic pigment [1-µm hollow sphere *(5)*]
Base sheet: European LWC (33.5 g/m²)
Moisture (exit): 4.5% (beta gauge)
[b] Coated on one side
[c] Trials at this temperature were abandoned because of picking and loss of gloss.

The experimental design is summarized in **Table II**.

Results

On-line test matrix

The test matrix proceeded without evidence of picking or dusting through the 150°C point. However, the data point for 150°C and 340 kN/m was lost for Coating B when the basestock roll ran out.

The experiment ended prematurely at 200°C (actual running temperature was 180°C). Application of Coating A at 6g/m² ran without incident at this temperature. However, at 8 g/m², slight picking was observed at 125 kN/m, and significant sticking occurred at 200 kN/m. Gloss measurements for Coating A at 8 g/m²

III. Response of gloss and brightness in the on-line test matrix for Coatings A and B at three levels of coat weight

Coating	Coat weight, g/m^2 [a] Avg.	Coat weight, g/m^2 [a] Std. dev. [b]	Basis weight, g/m^2 [c]	Gloss, % [d] Min.	Gloss, % [d] Max.	Brightness, % [e] @ min. gloss	Brightness, % [e] @ max. gloss
A	6	0.4	45.5	18	50	72.8	70.4
B	6	0.6	45.5	21	59	74.1	71.5
A	8	0.6	49.5	25	59	73.4	70.4
B	8	0.4	49.5	31	65	75.6	71.6
A	10	0.3	53.5	31	61	74.3	71.0
B	10	0.3	53.5	33	(65) [f]	76.0	(73.3) [f]

[a] Average standard deviation = 0.1 g/m^2 for any given sample/condition
[b] Across the array of nine samples, i.e., three temperatures at three nip loads
[c] Paper coated on one side, but basis weight calculated as if coated on two sides.
[d] Average standard deviation = 1; confidence limit (95%) = ±0.44
[e] Average standard deviation = 0.2; confidence limit (95%) = ±0.09
[f] Values observed at maximum-condition run at 150°C and 200 kN/m. Because there are no data for Coating B at 150°C and 340 kN/m, these values may not represent the maximum gloss achievable.

indicated that there was picking and a loss of gloss even at the 50-kN/m load. Since all of the data points for the 6-g/m^2 application of Coating A at 200°C showed higher gloss than their 150°C counterparts, it is assumed that there was no sticking under these conditions. When Coating B exhibited dusting and roll buildup even at the lowest nip loads and coat weight, the run at 200°C was aborted. No rebalance of the line conditions was attempted.

Given the breadth of calender parameters, a wide range of optical properties would be anticipated. Since paper grades are closely tied to gloss and brightness values, the observed range is summarized in **Table III**. The reported brightness values are those associated with minimum and maximum gloss and do not represent actual brightness minima or maxima *per se*.

Since the design encompasses 58 samples, no attempt will be made to deal with all of the data. The focus here will be on the highest coat weight (10 g/m^2 or 6.75 lb/3300 ft^2), where the normal, relatively small variations in coat weight would cause the least disruption. However, the trends are consistent at each of the studied coat weights.

Response to temperature

Figure 1 shows the response of sheet optical properties to temperature for Coatings A and B at three levels of nip pressure. The temperature range studied was 50–150°C.

The increase in gloss over this temperature range averaged 15 points for any given nip load, as seen in Fig. 1A. At the same time, smoothness improved about three-quarters of a point for a given nip load, as seen in Fig. 1B. The slopes of the plots and the absolute magnitude of the changes were very similar for both formulations. There is no indication that the response is leveling out. However, at higher temperatures, runnability issues become a real concern.

The data for brightness and opacity, presented in Figs. 1C and 1D, respectively, are not quite as well behaved, and there are some inversions and other aberrations within individual series. The lines are not parallel, so that slopes vary more. Ignoring this scatter, the loss in brightness across the temperature range for a given formulation and nip load averaged about 1.5 points and seems relatively similar for both formulations.

Opacity shifts for Coating B are on the order of 2–3 points over the temperature range studied, while the opacity of Coating A appears constant from 50°C through 150°C. Parallel performance was observed with the set coated at 8 g/m^2 as well. There is no logical explanation for this anomaly. Since finishing of the paper was being achieved, opacity should have been lost as temperature increased. Presumably, the problem is one of scatter. Laboratory calendering of pilot-coated paper from another trial did show the expected decrease in opacity with increasing temperature.

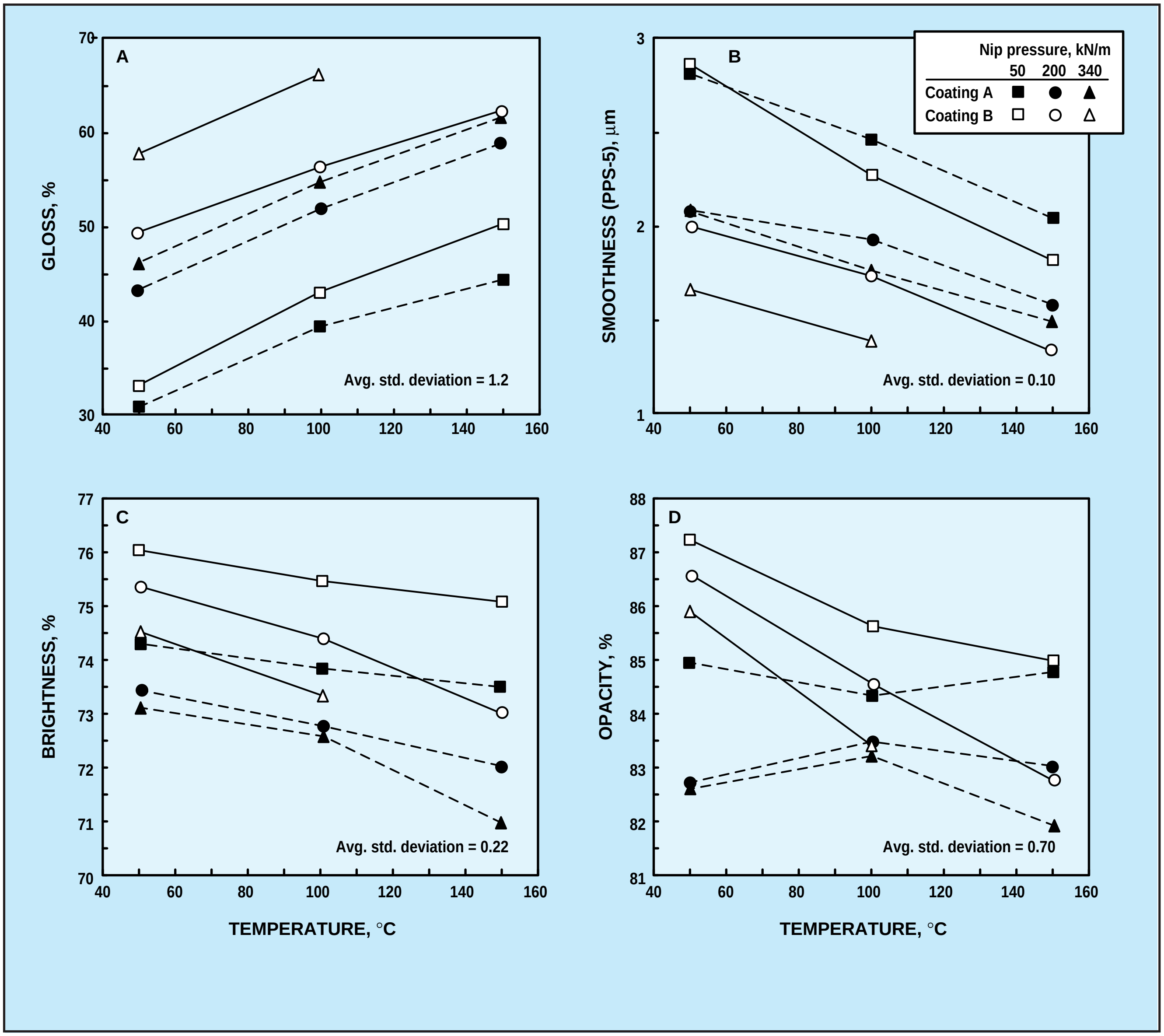
Influence of nip load

Figure 2 shows the response of sheet optical properties to changing nip load for Coatings A and B at three levels of temperature. The nip-load range studied was 50–340 kN/m.

At the lowest nip load, the gloss data in Fig. 2A are clustered more tightly across the temperature range, since relatively little finishing has taken place at 50 kN/m. Therefore, the change in gloss along the isotherm (Fig. 2A) is somewhat greater than for the analogous isobars (Fig. 1A). Figures 2B–2D show the expected changes in other optical properties in response to pressure.

The three gloss curves for Coating A show a noticeable reduction in

1. Effect of temperature on sheet optical properties for on-line hot soft-nip calendering at three levels of nip load (coat weight = 10 g/m²)



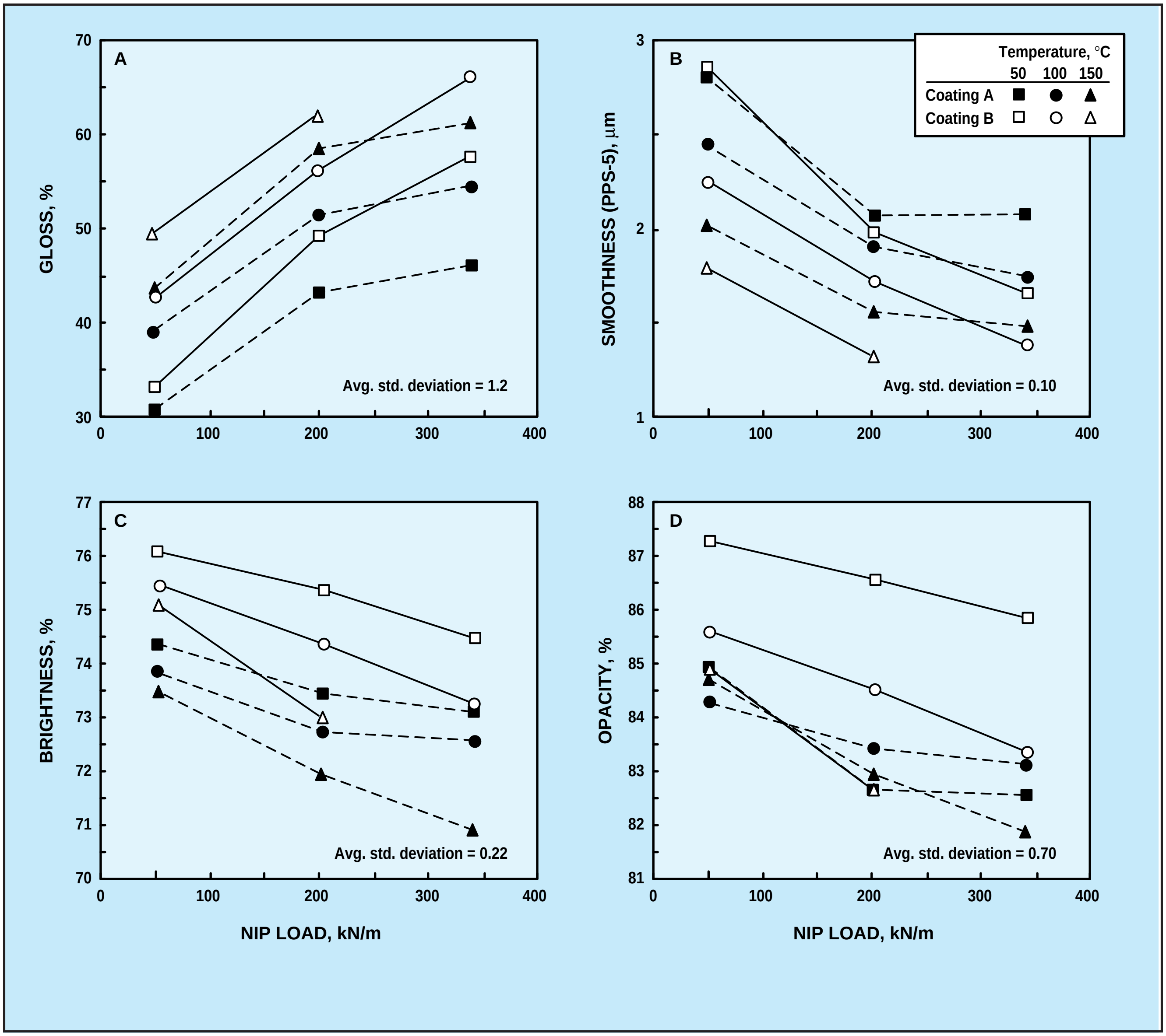
slope as the nip load increases (Fig. 2A). This carried through appropriately in other optical properties (Figs. 2B–2D). There is a similar indication—although not quite as strong—in the two full curves for Coating B. Examination of all the data for both formulations at all three coat weights confirms the trend of diminishing response as nip load increases from 200 kN/m to 340 kN/m in at least 10 out of 12 cases at the other coat weights. This is somewhat a reflection of the three nip loads selected, but it also suggests that the response is not linear across the range.

One way to assess the relative effects of temperature and nip load is to compare performance at different combinations, e.g., lower temperature/higher nip load vs. higher temperature/lower nip load. **Figure 3** presents such a head-to-head comparison of the runs at 100°C–340 kN/m and 150°C–200 kN/m. The response is rather similar for both conditions. The few apparent differences suggest that the higher temperature/lower nip load is somewhat more effective in finishing the sheet. This is more apparent in the gloss and smoothness data for Coating A, as seen in Figs. 3A and 3B, respectively.

Role of moisture

Sheet moisture influences development of optical properties, and it is also a significant factor in runnability. The experimental design included a module to study sticking phenomena. This subset was carried out at midpoint parameters of 125°C at 200 kN/m and a constant coat weight of 8 g/m², so that the only on-

2. Effect of nip load on sheet optical properties for on-line hot soft-nip calendering at three levels of temperature (coat weight = 10 g/m^2)



line change was moisture. The onset of picking problems was very precipitous when safe moisture levels were exceeded, even briefly. Sticking is quite formulation-dependent and would have to be studied for each set of moisture conditions. Data for optical properties are included here, since moisture does contribute positively to gloss and smoothness.

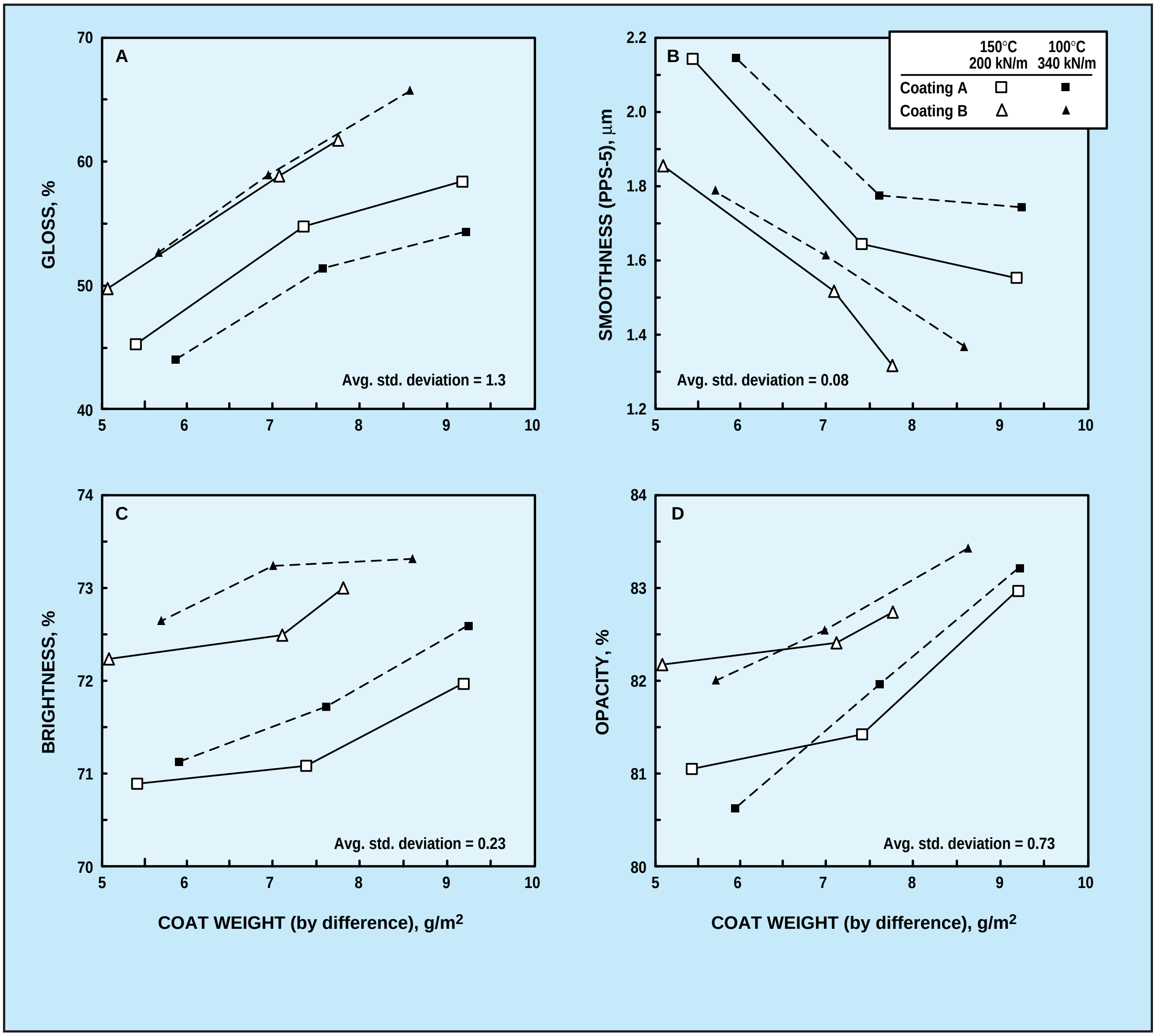
Figure 4 demonstrates the effect of sheet moisture on the development of sheet properties for Coatings A and B. The challenge is to reap the benefits of increasing gloss by increasing sheet moisture without compromising runnability by introducing roll buildup.

Formulation effects

Across the board, Coating B exhibited higher gloss, greater smoothness (lower Parker print–surf), and higher brightness and opacity. The magnitude of the change along the individual isotherms is quite similar for both Coatings A and B. The major difference is that the Coating B sheet glosses up more easily, resulting in a higher starting point under minimum finishing conditions. That advantage is maintained throughout the matrix. Other optical properties follow this pattern as well. The key point is that changes in coating formulation can significantly influence response to calendering conditions.

Of particular interest is the potential for obtaining targeted gloss at significantly reduced temperatures. For example, Fig. 1A shows that a 60% gloss can be obtained at any of the following conditions: Coating A at 140°C and 340 kN/m; Coating B at 130°C and 200 kN/m; Coating B at 62°C and 340 kN/m.

3. Sheet optical properties after on-line hot soft-nip calendering at two combinations of temperature and nip load



Equal smoothness is achieved in each case. Better brightness and opacity are associated with reduced temperatures. In the three cases cited, the reduced conditions with Coating B resulted in brightness and opacity increases of 2–3 points at equal gloss and smoothness.

These significant reductions also produce other benefits as by-products. Lower temperature means longer roll life and lower energy bills. The ability to operate at less harsh conditions should make it possible to achieve a desired level of gloss for equipment running at its operating limits *(3)*. The ability to achieve a given gloss at lower temperature should also translate to fewer runnability problems resulting from roll buildup. Overall, reformulation can represent a viable approach.

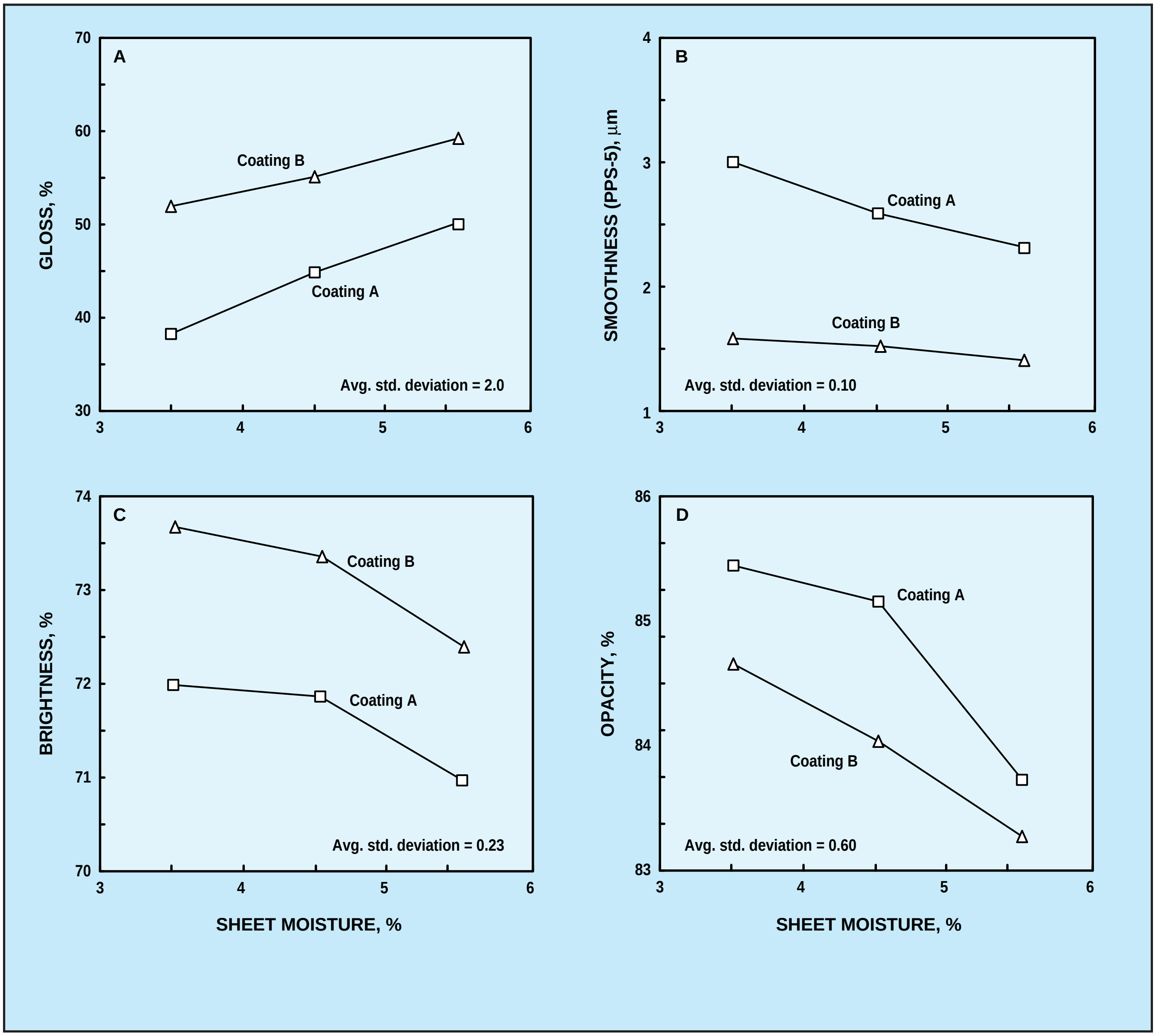
Comparison with other calendering modes

Results from the on-line test matrix were compared with two other relevant calendering modes:

- Conventional supercalendering
- Off-line soft-nip calendering.

On-line calendering offers the greatest potential for achieving significant economies. Realistically, this is not without justifiable concerns for machine shutdown because of roll buildup by dusting, picking, stick-

4. Effect of sheet moisture on sheet optical properties for on-line hot soft-nip calendering at 125°C and nip load of 200 kN/m (two nips, coat weight = 8 g/m²)



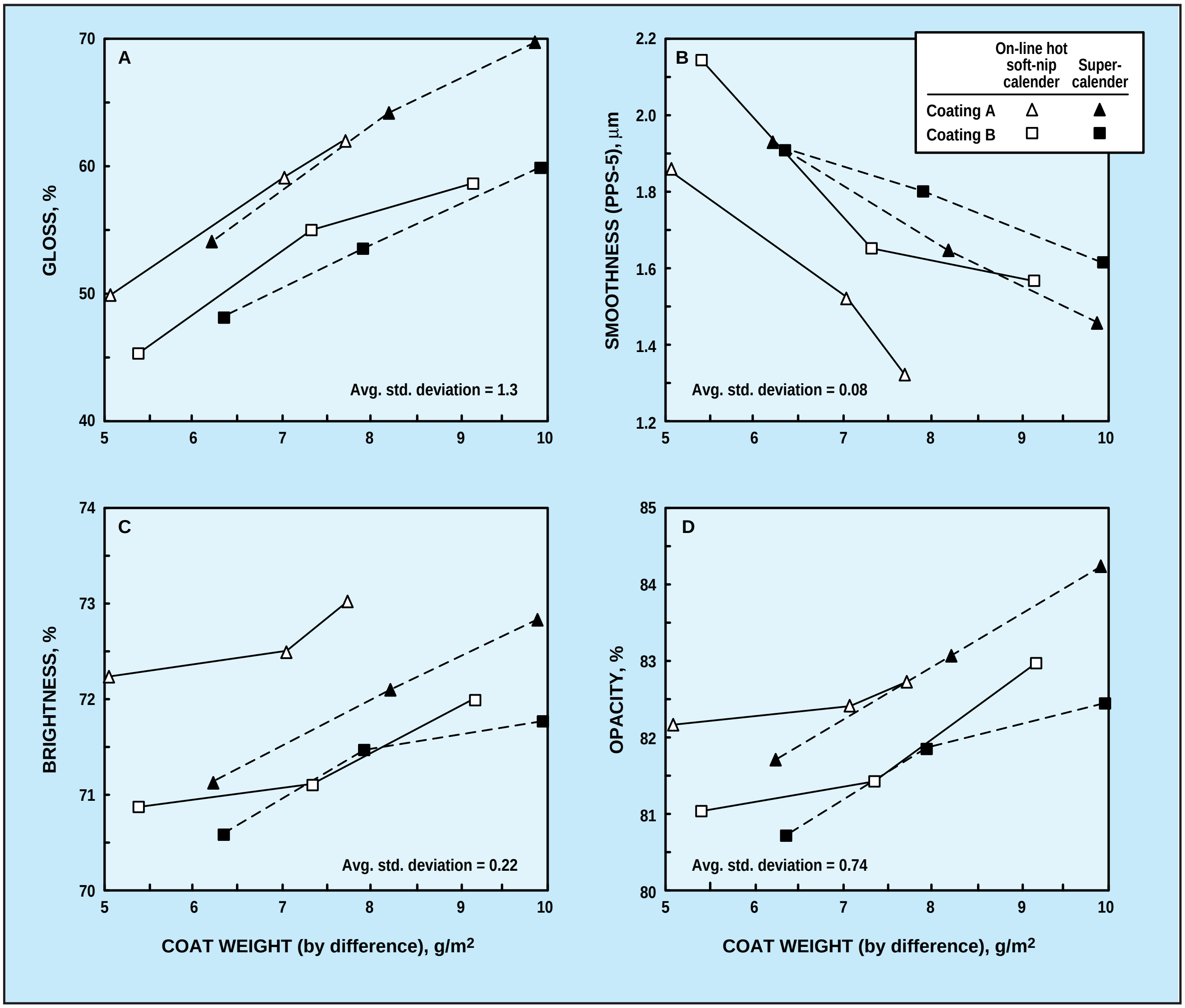
ing, etc. Temperature, nip load, coat weight, and moisture all have an impact on this problem. However, the performance data presented in this section indicate that it is well worth the effort to gain a solid understanding of runnability parameters and identify feasible operating conditions.

Running on-line is the most efficient way to achieve optimum gloss. The paper coming from the dryers is already warm, so that the maximum benefit is derived from dwell time in the nip. Using cold paper, it was not possible to maintain the targeted temperatures in the off-line mode. Temperature rapidly drifted down and settled at about 135°C for the 150°C runs and hovered around 150°C for the 175°C runs. By comparison, during the on-line runs, the temperature equaled the targets of 50°C and 100°C and rebounded very quickly to 145–146°C for the 150°C runs.

On-line hot soft-nip calender vs. supercalender. The response of sheet optical properties to supercalendering (70°C, 200 kN/m) and on-line hot soft-nip calendering at 150°C and 200 kN/m is shown in **Fig. 5**.

The gloss and smoothness of paper finished on-line approximate those of their supercalendered counterparts, as seen in Figs. 5A and 5B, respectively. Brightness and opacity are also within range, as seen in Fig. 5C and 5D, respectively. With the scatter in the data, this is a reasonable conclusion. Considerably more experience would be needed to

5. Sheet optical properties after on-line hot soft-nip calendering (150°C and 200 kN/m) and supercalendering (70°C and 200 kN/m)



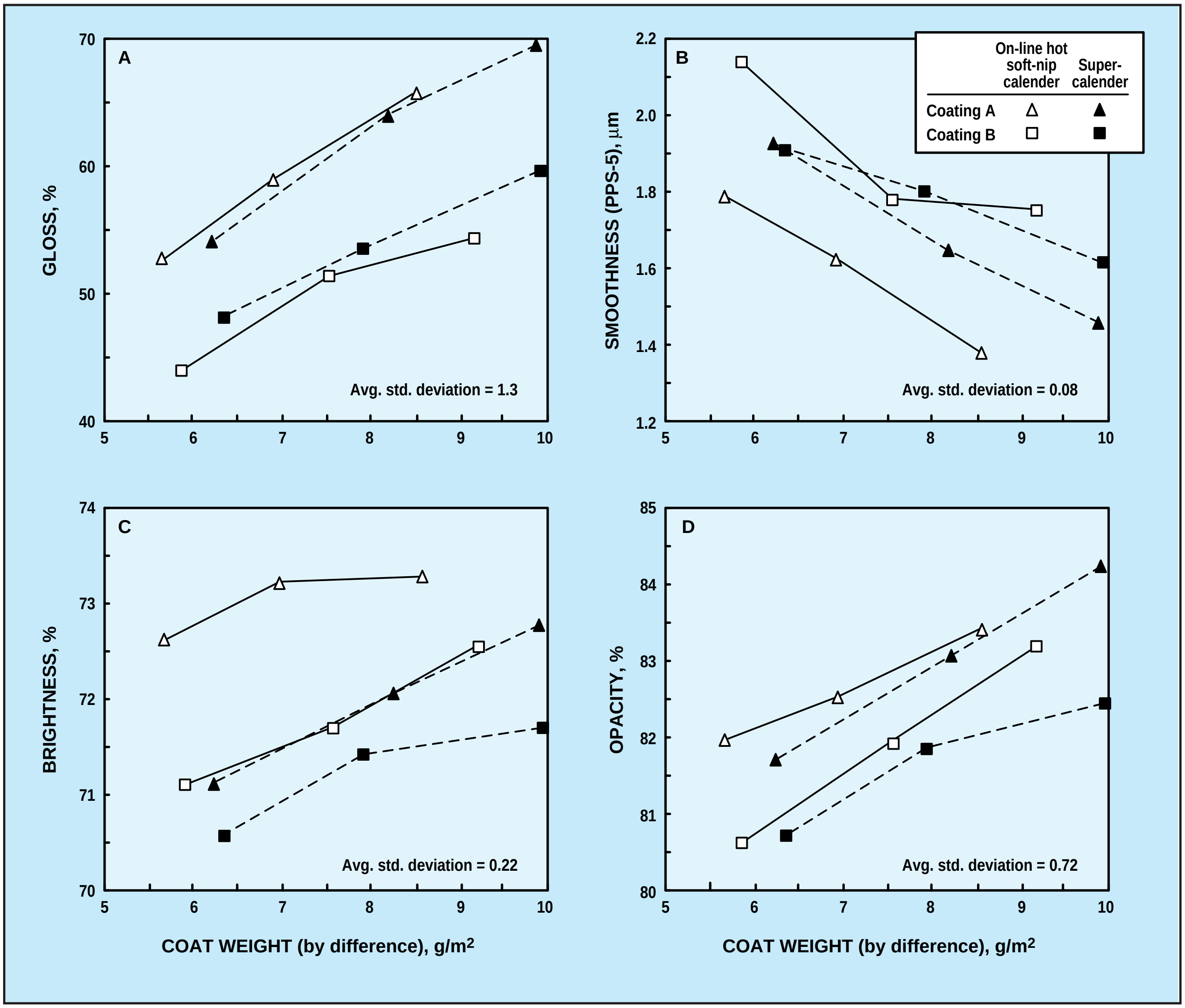
push the interpretation any further. The significant difference in the response between Coatings A and B reinforces the premise that changes in formulation should also be considered as an important option. Differences between formulations may be greater than any differences between calender techniques.

Alternative hot-soft-nip calendering conditions are also worthy of examination. The 150°C–200-kN/m option was selected to maximize gloss and smoothness. However, the 100°C–340-kN/m combination examined earlier is also worthy of consideration. **Figure 6** shows that the entire set of optical properties is fairly well matched, even at this more moderate temperature. However, more data would be necessary to get better definition. The main point is that it appears possible to match optical properties with various calender and/or formulation balances. This is somewhat of a departure from previously reported experience—primarily in the off-line mode—where it was sometimes difficult to achieve the gloss and smoothness of a supercalendered sheet while maintaining brightness and opacity *(3, 4)*.

On-line vs. off-line hot soft-nip calendering. The response of sheet optical properties to the two modes of hot soft-nip calendering—on-line and off-line—are presented in **Fig. 7**.

On-line calendering was far superior to off-line in gloss development. The average difference in gloss was about ten points under the same calendering conditions, as seen in Fig. 7A. Smoothness was also superior in the on-line mode by approximately three-quarters of a point, as seen in Fig. 7B. Brightness and opacity were better off-line, as would be expected given the loss in gloss and smoothness, as seen in Figs. 7C and 7D, respectively.

6. Sheet optical properties after on-line hot soft-nip calendering (100°C and 340 kN/m) and supercalendering (70°C and 200 kN/m)



The plots included the response to on-line and off-line calendering at 150°C–200 kN/m and to off-line calendering at 175°C–250 kN/m. The incremental change in properties for the harsher calendering conditions was rather minimal, indicating that the practical limit had been reached from a response point of view. In addition, the operating limits of the pilot unit had essentially been reached.

Printability

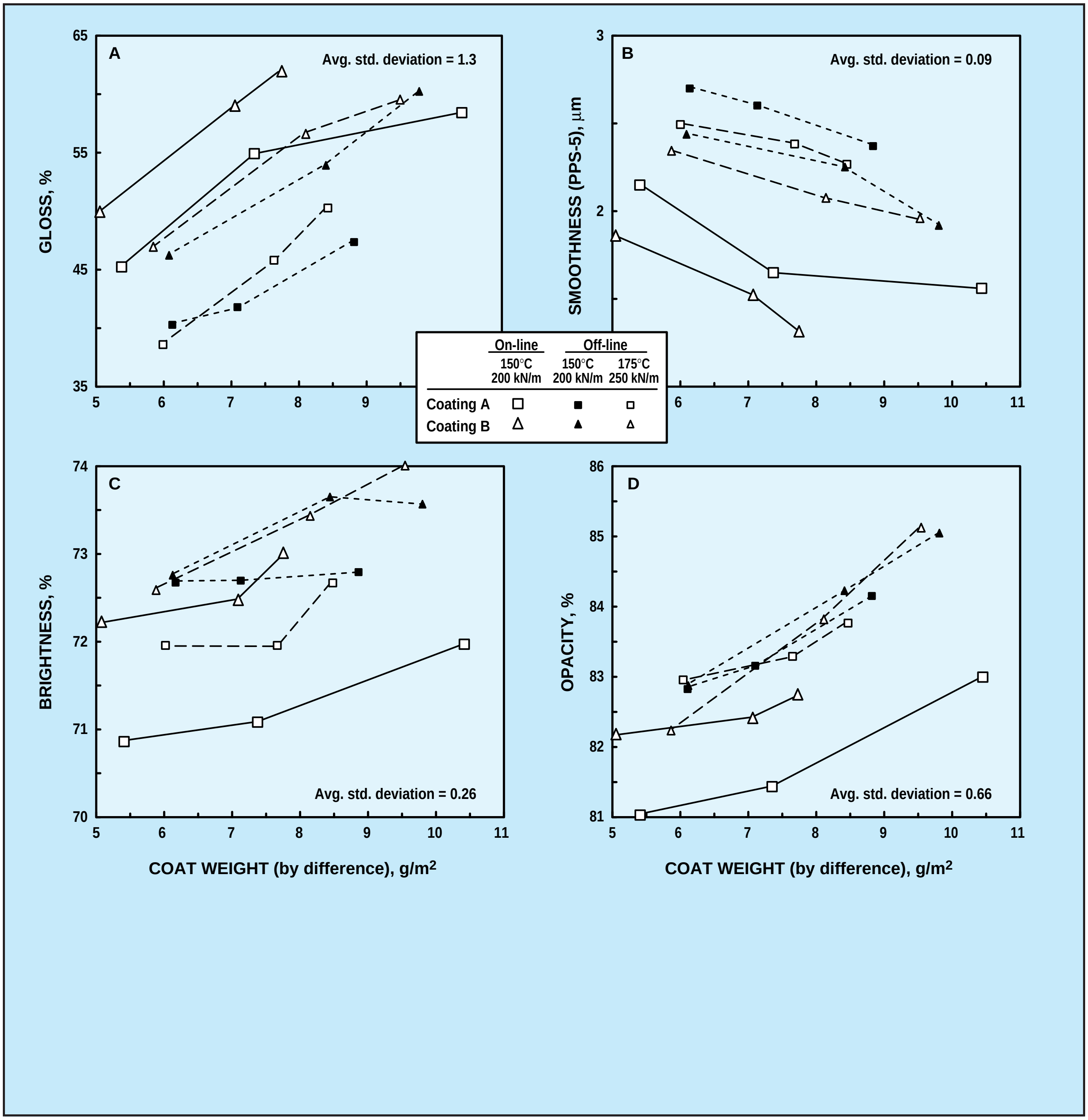
The primary thrust of the current work was to quantify the response of optical properties to calender modes and operating parameters. However, the real issue is printability, since that is the reason for coating paper in the first place. Print gloss was evaluated in the laboratory using a Prufbau press, and representative results are shown in **Figs. 8 through 10**. No glaring deficiencies were observed, but this issue was not definitively addressed here and remains unresolved for us in the context of lightweight-coated (LWC) grades without further work including print trials. [Previous, unpublished work of ours with wood-free coated grades, which included print trials, gave satisfactory results. This topic is addressed in the literature *(1, 3, 4)*].

Conclusions

Hot soft-nip calendering can produce the gloss and smoothness commonly associated with a conventionally supercalendered LWC grade while matching brightness and opacity properties. The on-line mode provides maximum performance. When operating off-line, a prime way to achieve supercalender optical targets is by reformulating the coating.

Redesign is pivotal to achieving optimum potential in either an on-

7. Sheet optical properties after on-line and off-line hot soft-nip calendering at different combinations of temperature and nip load



line or an off-line mode. Coating B, which contained a hollow-sphere synthetic pigment, exhibited easier gloss response, thus allowing a reduction in operating temperature/pressure while achieving or surpassing gloss targets. Such a reduction in the harshness of the operating conditions yields a favorable balance of brightness and opacity, since less work goes into the sheet. The ability to calender at milder conditions represents an area of potential cost savings. TJ

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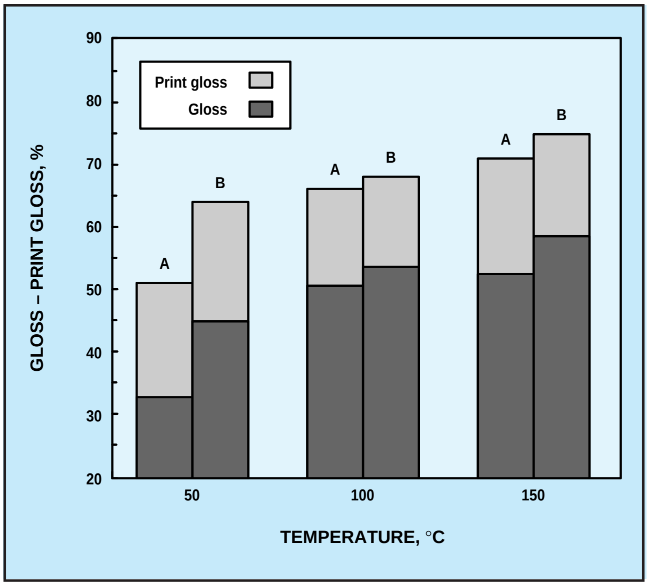
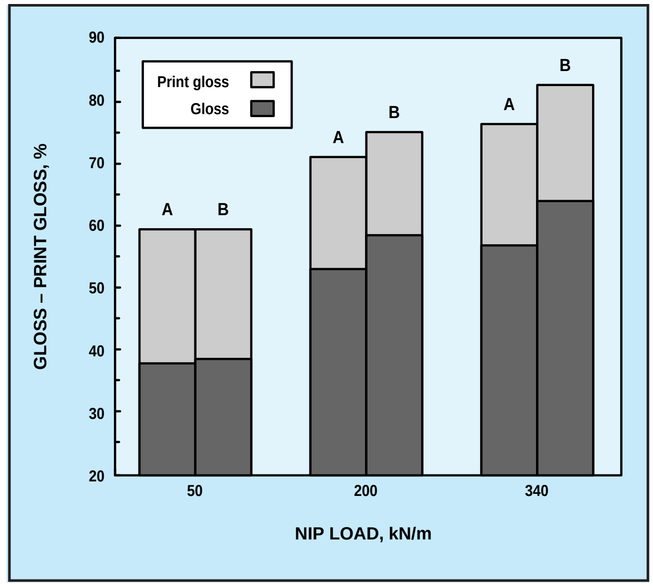
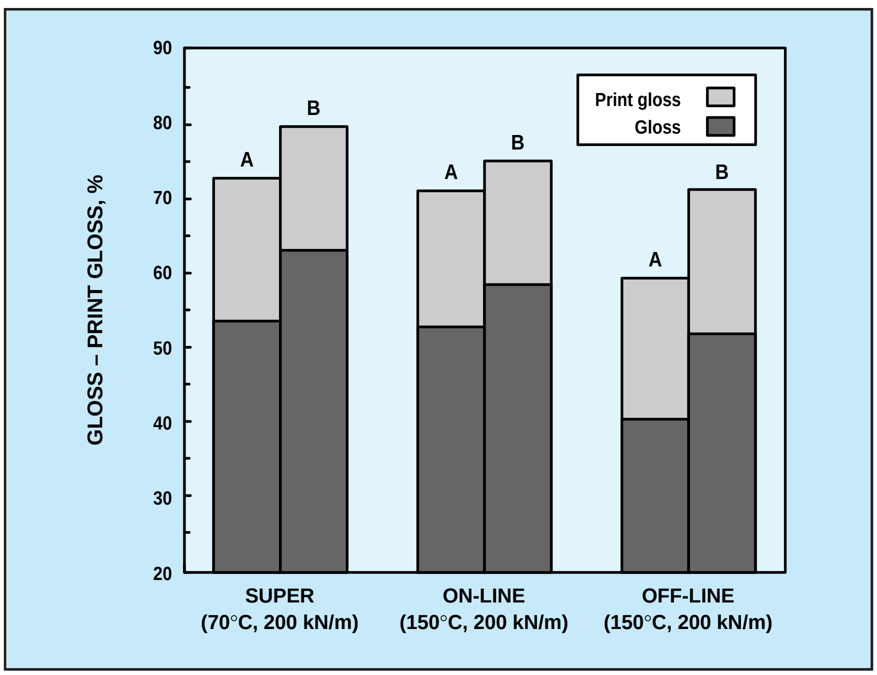
8. Gloss and print gloss as a function of temperature for Coatings A and B after on-line hot soft-nip calendering at 200 kN/m (coat weight = 8 g/m²)



9. Gloss and print gloss as a function of nip load for Coatings A and B after on-line hot soft-nip calendering at 150°C (coat weight = 8 g/m²)



10. Gloss and print gloss for Coatings A and B as a function of finishing method (coat weight = 8 g/m²)



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