

6 Steam Explosion Pulping

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INTRODUCTION

Explosion pulping is an ultra-high-yield pulping process based on short time vapor-phase cooking at temperatures in the range of 180 to 210°C, followed by explosive decompression. The process has been studied extensively by many researchers. This chapter reviews work relating to explosion pulping and some work concerning conventional CMP and CTMP to clarify different points of agreement and disagreement among the scientists. The influence of pulping operating conditions on the resulting pulp yield, specific refining energy, pulp resistance, and optical properties are discussed. The effects of the concentration of impregnating chemicals, liquor-to-wood ratio, and cooking temperature and time on the resulting hardwood and softwood explosion pulps are also reviewed.

Chemimechanical pulps (CMP) with pulp yields ranging from 80 to 95% were developed in the mid 1970s. Ultra-high-yield chemimechanical (CMP) pulps and chemithermomechanical (CTMP) pulps represent excellent alternatives and complements to the rather weak mechanical pulps and the rather expensive chemical pulps of low yield (45-50%). CMP and CTMP pulps combine high yield, low cost, and fewer pollution problems while achieving good mechanical properties. The only major drawback of CMP/CTMP pulps is their relatively high defibrillation energy (Leask and Kocurek, 1987). The production of CMP/CTMP generally requires two important steps: (1) chip sulfonation with a sodium sulfite mixture ($\text{NaHSO}_3/\text{Na}_2\text{SO}_3/\text{NaOH}$) and (2) high-consistency refining at atmospheric or higher pressure (Garceau, 1989).

It is generally accepted that the chemical treatment is mainly responsible for permanent fiber softening and increases in long fiber content, fiber specific surface, and conformability (Heitner and Atack, 1983). Treatment of chips with steam at high temperature, followed by explosive decompression, also contributes to the softening of the fibers (Kokta et al., 1991a). Moreover, the explosive decompression of treated chips leads to a reduction in energy consumption in subsequent refining stages (Ahmed et al., 1994).

Steam explosion pulping (SEP) was suggested as an alternative to CMP/CTMP processes in the early 1990s because of the reduced refining energy required for the SEP pulp. A much higher temperature is used (180-210°C), as compared with that used in conventional CTMP/CMP processes (120-150°C), and a shorter time. Moreover, the cook is terminated by a sudden pressure release. This relatively new process is fully described in recent literature (Vit and Kokta, 1986; Kokta et al., 1992; 1987; Kokta, 1989). The objective of the present review of explosion pulping process is to update and discuss the various technical information.

DEVELOPMENTS IN STEAM EXPLOSION PULPING

Explosion pulping was invented by Mason (1928) in the early 1930s. In this process, the chips are fed from a chip bin through a screw loading valve in a masonite gun. The chips are then steam heated at a very high temperature, about 285°C, and at a pressure of 3.5 MPa for about 2 min. The pressure is increased rapidly to about 7 MPa for about 5 s, and the chips are then discharged through restricted orifices (slotted port) and explode at atmospheric pressure into a pulp. Two stages of low-consistency atmospheric refining result in a dark pulp of about 75% yield suitable for the manufacture of high-density fiberboard. This process is very effective as a means of fiber separation with low energy consumption. However, Koran and co-workers (1978) concluded that masonite pulp is very coarse in texture and dark in color. The fibers are mostly uncollapsed, rigid, and degraded and display a highly lignin-rich surface structure, which is unsuitable for papermaking.

Asplund (Asplund et al., 1953) refined chips at elevated temperature and pressure to produce a coarse, dark fiber for board manufacturing. They attempted to avoid the fiber degradation, inherent in high-temperature processes, through the application of different chemicals. Thus, steam was replaced with ammonia (O'Connor, 1972) and liquid sulfur dioxide (Mamers and Grave, 1973). The pulp produced was of acceptable quality, but the technical and economic problems associated with the recycling of the liquefied gases precluded any commercial applications (Mamers et al., 1981).

An alternative approach to explosion defibration was used with aqueous systems at a relatively moderate temperature of 200°C with further pressurization of the digester to 13.8 MPa by injection of compressed nitrogen. The fibrous material was explosively discharged through a specially designed multiple bar nozzle (Mamers et al., 1976, 1979, 1981). The pulp properties obtained were comparable to those of conventional CTMP and CMP processes but had lower brightness. As pointed out by Stamm (1965), the major problem to overcome is oxidation and hydrolytic degradation of fibers, which leads to brightness and yield losses.

Vit and Kokta (Vit and Kokta, 1986; Kokta and Vit, 1987) were able to produce ultra-high-yield pulps suitable for papermaking. The process consists of chemical impregnation of chips, short-duration saturated steam cooking at a temperature varying from 180 to 210°C sudden pressure release, refining, and bleaching. Later, Kokta (1987, 1989) modified and improved this explosion process, referred to as the steam explosion pulping process (SEP). The negative effect of wood hydrolysis

and oxidation on yield and brightness owing to high temperature cooking was minimized by optimizing the impregnation and cooking conditions (Kokta, 1989). Kokta and his co-workers conducted many studies on explosion pulping (Vit and Kokta, 1986; Kokta, 1987; Kokta et al., 1987, 1987, 1988, 1989, 1990, 1990, 1991, 1992, 1993), particularly with aspen (Kokta et al., 1988, 1989; Barbe et al., 1990; Ahmed et al. 1991). They have also published results related to black spruce (Kokta and Didwania, 1990), Douglas fir (Kokta and Didwania, 1990), and various types of nonwood fibers (Kokta et al., 1992, 1993, 1993). Law and co-workers have studied black spruce (Law and Bi, 1989) aspen (Law and Valade, 1990), and other wood species (Law et al., 1990). Chaudhuri (1989) has studied spruce. and Heitner et al. (1991) have done comparative studies on explosion and conventional chemimechanical pulping of aspen.

Explosion Pulping Equipment

The heart of the explosion pulping process is the reactor, which allows the use of high pressure during heating and cooking (Figure 6.1). The reactor can be of either the batch or continuous type. The continuous reactor is equipped with special feeding and discharge valves.

To promote defibrillation during the digester release in the masonite process, the pulp is passed through a masonite gun (Mason, 1928). Mamers and co-workers (1981) designed an eight-bar digester discharge nozzle. The commercial Stake Technology reactor is also equipped with a Kamyr discharge valve to promote partial chip defibrillation.

Barbe and co-workers (1990), O'Connor (1972), Mamers and co-workers (1979), and Kokta and co-workers (1990b) have attributed the partial liberation of fibers from chips mainly to the sudden pressure release. The extent of chip defibrillation obtained by explosively terminating the cooks was found by Mamers et al (1973) to vary directly with applied pressure. the higher pressure giving the better defibrillation. However, Law and co-workers (1989, 1990) have suggested that the chip impacts in the discharge vessel affect mainly fiber separation. High-pressure steam cooking contributes to additional fiber swelling, followed by partial defibrillation during the pressure release (Kokta et al., 1987). This partial defibrillation after steam cooking was shown by Saddler (1987).

The influence of the nature of pressure release (either explosive discharge or slow pressure release) following Na_2SO_3 impregnation and steam cooking (190°C. 3-4 min) of spruce chips has been studied by Kokta et al. (1990) and Law et al. (1989). Explosion pressure release was found to result in higher tear strength for the same breaking length or in higher breaking length at a given freeness, as well as a lower brightness, as compared with slow pressure release. However, Kokta et al. (1990) and Law et al. (1989) reported different results when they compared breaking length at a given energy consumption. This could be attributed to different wood characteristics and/or impregnation conditions and refining modes.

A standard press with a compression ratio of 4:1 was used for chip impregnation (Kokta, et al., 1991; Law and Valade, 1990). Atmospheric pressure refining was

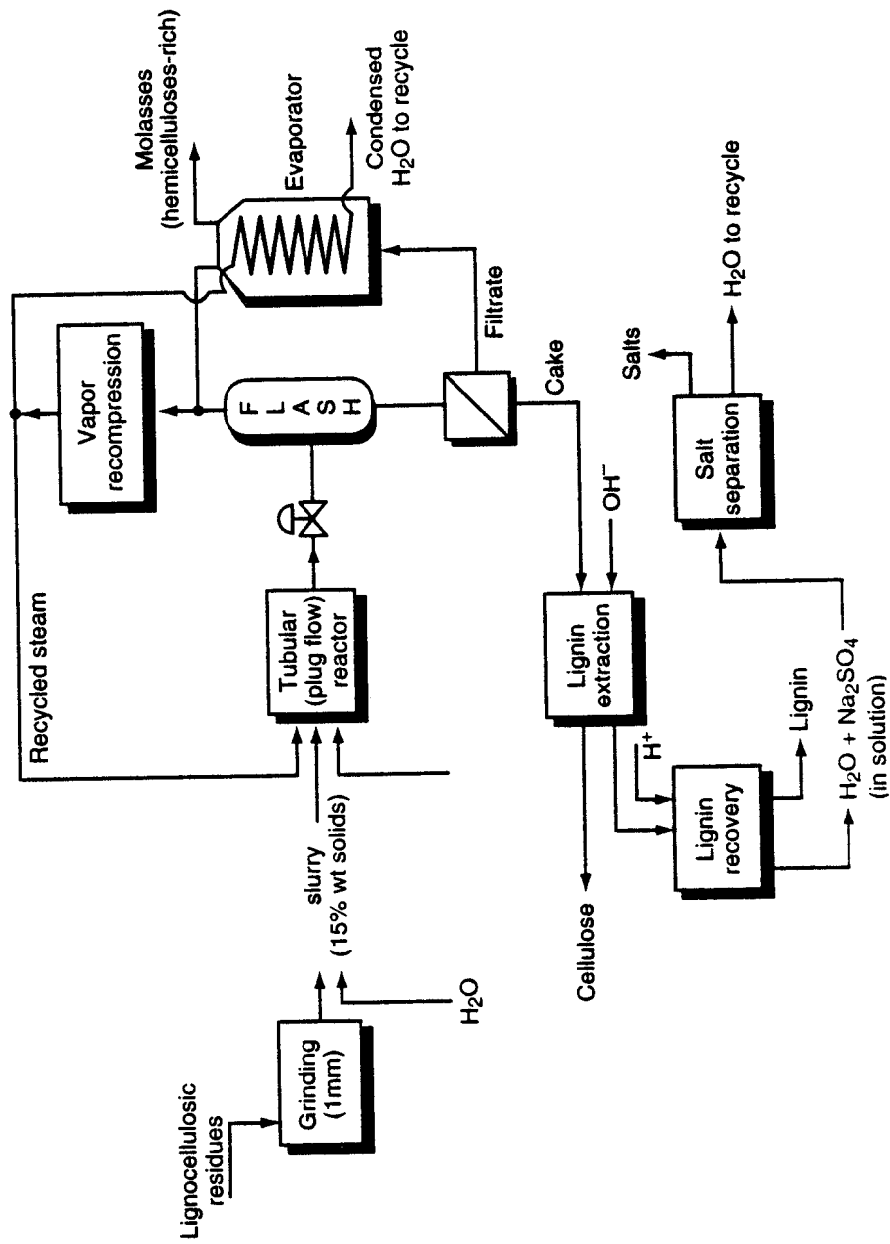


Figure 6.1 Process diagram for a typical aqueous/steam explosion system (Chornet and Overend, 1991).

found to be adequate for chip refining. The low amount of refining energy required makes it difficult to justify economically a pressurized refiner with steam recovery. All the peripheral equipment can be of the standard type.

Chip Impregnation

In the early work on explosion pulping, the pulp produced had a relatively low yield and dark color. This degradation was caused by wood autohydrolysis during high-temperature treatment. Acetic and formic acids, which are released from the wood with steam treatment, lower the pH to below 4 and are responsible for this degradation (Stamm, 1965). This negative effect is directly related to steam cooking temperature and time.

To protect the chips against oxidation during the high-temperature cooking stage and to simultaneously develop hydrophilic groups on the fiber surface and hydrogen bond-forming capacity during the steam treatment, the wood chips were impregnated with antioxidant products like DTPA and/or Na_2SO_3 , as well as with swelling agents such as NaOH and other sodium salts (Kokta and Zhan, 1987). The pores or pits present in fiber walls allow liquid or gas to pass between the fibers. This is the basis for the chemical impregnation process (Law and Valade, 1990). Uniform impregnation of chips with the cooking liquor is essential to produce good-quality pulps in vapor phase cooking where the impregnated chips are treated in the absence of free liquor (Kokta et al., 1989). Most investigators use Na_2SO_3 and $\text{Na}_2\text{SO}_3 + \text{NaOH}$ for impregnation of softwoods and hardwoods, respectively.

The importance of chemical impregnation instead of water pretreatment has been discussed by Mamers and co-workers (1981) and Chaudhuri (1989). Mamers and co-workers (1976) studied the explosion pulping of *Pinus elliotii* wood chips with high-pressure carbon dioxide solutions. They stated that the use of 50 g/L Na_2SO_3 instead of water results in 3 to 12 points higher pulp yield. The chemical is more efficient at high temperatures and short cooking times. Chaudhuri (1989) made a comparison of spruce chips impregnated at 20°C over 30 min with water and with sodium sulfite prior to laboratory explosion pulping. For a given freeness, the pulp prepared with sulfite-impregnated chips required many more PFI revolutions, but produced a much stronger pulp with higher brightness than that made with water-impregnated chips.

Law and Valade (1990) studied the effect of time and temperature of chip impregnation with sodium sulfite liquor on pulp characteristics. Raising the temperature from 40 to 60°C almost doubled the pulp sulfonate content. The content was practically unaffected by increasing treatment time from 12 to 48 h. The rate of carboxylate formation was also higher at 60°C than at 40°C. Variation of the impregnation time of aspen chips from 12 to 48 h with 8% Na_2SO_3 , followed by explosion pulping at 190°C for 4 min, was studied (Kokta et al., 1989). Paper properties, including brightness, increased with impregnation time, but there was a sharp decrease in yield at 48 h impregnation. At this chemical concentration, 24 h was suggested as optimal to retain pulp yield at 90% and obtain good paper properties.

Kokta and co-workers (1989) have run two semi-industrial impregnation trials

with sulfite and caustic liquors. In the first, they used a full-scale Hymac screw press. Chips were presteamed at 85°C using atmospheric steam for 20 min before spray impregnation. In the second trial, chips were press-impregnated in a CE Bauer press and then submerged in chemical solutions. Both presses have a compression ratio of 4:1, but the liquor-to-wood ratio was 2 and 3 for the first and second trials, respectively. The total ionic concentration increased from 174 to 210 mmol/kg, which resulted in 10% higher paper properties and 30% refining energy reduction. They attributed this behavior to better chip impregnation in the second trial.

Cooking Temperature and Time

Cooking temperature and time are interdependent when a given pulp yield must be reached. Kokta and co-workers (1989) have suggested the use of the product time-temperature for combining the two effects. They recommended for laboratory studies that the multiple be kept under 1,000 (°C · min) to avoid a sharp loss in yield and brightness (Kokta et al., 1990b). Optimum values of the product for industrial cooks should be far lower (under 400) (Kokta, 1987). The physical pretreatment of chips in pilot plant operation (i. e., compression and decompression during impregnation and further compression before steam cooking) leads to considerable fiber deformation and partial fiber separation. This allows semi-industrial steam cooking to be carried out at considerably shorter times (Kokta et al., 1989). The time-temperature sequence for steam cooking must be sufficiently long to lead to the softening and partial defibrillation of the chips without leading to hydrolytic degradation (Kokta et al., 1987).

Aspen chips impregnated with solutions containing sodium sulfite and sodium hydroxide have been subjected to vapor phase cooking with explosive pressure release at temperatures ranging from 150 to 200°C (Barbe et al., 1990; Kokta et al., 1989; Law et al., 1990). Law and co-workers (1990) investigated cooking times from 3 to 40 min, and Barbe and co-workers (1990) increased the cooking temperature of a semi-industrial reactor from 190 to 195°C and reduced the cooking time from 2 to 1 min. Many workers (Kokta and Zhan, 1987; Kokta et al., 1989, 1990b, 1991a; Mammers et al., 1981; Barbe et al., 1990; Law and Valade, 1990) have shown an increase in strength properties when using higher temperatures. For all wood species under various pulping conditions, breaking length increased with higher cooking temperatures. Tear index was reported not to be significantly affected by a temperature variation from 170 to 200°C.

The increase in breaking length and the lack of variation of tear index when cooking temperature is increased might be explained by a simultaneous increase of long fiber content and handsheet density. A rise in cooking temperature from 180 to 200°C results in an increase in the long fibers, L_{48} (i. e., $R_{14} + R_{28} + R_{48}$, where R signifies the fibers retained on the mesh, identified by the subscript number of holes/sq in, and L expresses the sum of the fibers retained on the identified mesh screens), from 50 to 58% (Kokta et al., 1989), and handsheet density was increased about 10% when the temperature was increased from 190 to 195°C (Barbe et al., 1990). As is known, a fiber length increase has a positive effect on both strength properties

(Garceau, 1989), but a density increase suggests greater flexibility and conformability, which have a positive effect on breaking length and a negative one on tear index (Heitner and Attack, 1983). The two effects apparently compensate each other and keep the tear index relatively constant.

The refining energy is reduced with an increase in cooking temperature. The refining energy required to reach a given freeness depends on the equipment used; however, it is valuable to compare the relative energy consumed at different cooking temperatures. As shown in Table 6.1, pulps produced at higher cooking temperatures require less energy for a given freeness (Barbe et al., 1990; Kokta et al., 1991; Law and Bi, 1989).

By increasing cooking temperature of aspen chips from 170 to 200°C while decreasing cooking time from 17 to 1 min. Kokta and co-workers (1991a) have been able to reduce refining energy by about 50% for pulps of similar freeness and breaking length. The sulfonate and carboxylate content was reduced by 14% when the temperature was increased from 170 to 200°C. Pulp yield, strength properties, and brightness were similar at all temperatures. They have attributed the energy saving to the corresponding increase in steam pressure, which promotes chip softening during cooking. Generally, an increase in cooking temperature also has some negative effects, particularly on pulp yield and optical properties, including brightness.

Law and co-workers (1990) have noted the sensitivity of aspen to an increase in cooking temperature. Pulp yield drops from 94 to 74% when the cooking temperature is increased from 150 to 200°C for a 10 min cooking period. They concluded that under their operating conditions, (10% Na₂SO₃ + 1% NaOH, L/W= 5, 10 min), it was not possible to obtain a 90% pulp yield at a temperature higher than 170°C. This seems to be in agreement with other authors (Barbe et al., 1990; Kokta et al., 1989) who have reduced cooking times to 2 min or less and Na₂SO₃ concentration to 8% to obtain a pulp yield of 90% with a cooking temperature of 190°C or more. A similar conclusion was also obtained for softwoods (Kokta et al., 1987; Law and Bi, 1989). Law and Bi (1989) found that pulp yield obtained from vapor phase cooking (9 min) of black spruce with explosive discharge decreased from 93 to 85%

TABLE 6.1 Effect of Cooking Temperature on Energy Consumption to Obtain a Given Freeness.

References	Wood	Particularity	Temperature, ° C	Energy
Law and Bi, 1989	Spruce	CSF = 200 ml	170	5.1 × 10 ⁴ Rev.
		Cooking Time:	190	5.0
		t = 9 min	200	3.8
Kokta et al., 1991b	Aspen	CSF = 200 ml	170	6.9 MJ/kg
		Yield = 90%	180	5.5
		t = 1 to 11 min	190	5.1
			200	3.6
Barbe et al., 1990	Aspen	CSF = 300 ml	190	3.0 MJ/kg
Kokta et al., 1991b		t = 1 to 2 min	195	2.5

when the cooking temperature was increased from 170 to 200°C. A brightness loss of up to 11% was attributed to the increase in cooking temperature (Mamers et al., 1981; Barbe et al., 1990; Kokta et al., 1989; Law and Bi, 1989). The influence of cooking temperature on pulp brightness is shown in Table 6.2.

To promote explosion defibrillation, and probably some internal fibrillation, when wood chips are sufficiently softened with chemicals, maintain 90% yield range, and take into consideration pulp strength, refining energy, and pulp brightness, *some* authors have recommended a cooking temperature of about 190°C as an optimum (Kokta et al., 1987, 1989, 1990; Law and Bi, 1989). But, as mentioned, this temperature is quite sensitive to chip size, moisture, and previous compression and decompression treatments (Kokta et al., 1989; Law et al., 1990). At such a high temperature, the cooking time is restricted to 4 min or less.

The influence of cooking time on pulp yield and properties was also investigated by a number of scientists (Kokta et al., 1987; Mamers et al., 1976; Law and Bi, 1989; Law et al., 1990). Carbon dioxide explosion pulping of *Pinus elliottii* impregnated with Na₂SO₃ at 200°C was performed at cooking times of 0, 5, 10, and 15 min. pulp yield dropped from 89% to 68% (Mamers et al., 1976). Similar results were found for explosion pulping of aspen chips at a temperature of 195°C at 1, 2, and 3 min cooking times. pulp yield dropped as much as 5 points, depending on the percentage of Na₂SO₃ used for chip impregnation (Kokta et al., 1987). The fibrillation, as measured by the water retention value, increased with increasing cooking time (Kokta et al., 1989). The sulfonate and the carboxylate contents in the pulp also increased with increasing cooking time at 150°C, but the opposite relation was found at 200°C (Kokta et al., 1990).

In general, the pulp properties followed the expected trend of increasing strength and decreasing refining energy with a decrease in pulp yield. Studies of the effect of increasing cooking temperature or time should take into consideration the possi-

TABLE 6.2 Effect of Cooking Temperature on Pulp Brightness.

Reference	Raw Material	Particularity	Temperature, °C	Brightness, %
Mamers et al., 1981	Bagasse	CSF = 200 ml	174	27
		t = 3 and 30 min	200	26
Kokta et al., 1989	Aspen	Soda cooking		
		CSF = 350 ml	180	59
		Na ₂ SO ₃ = 8%	190	57
		t = 1, 4, 10 min	200	54
Law and Bi, 1989	Spruce	CSF = 150 ml	170	55
		t = 3 min	190	49
		Na ₂ SO ₃ = 10%	200	44
Law and Bi, 1989	Spruce	CSF = 150 ml	170	50
		t = 9 min	190	42
		Na ₂ SO ₃ = 10%	200	40

ble pulp yield variation. For example, Mamers and co-workers (1976) reported an increase in burst and tear indexes, as well as in breaking length, with increasing cooking time from 0 to 10 min at a constant temperature of 200°C; however, pulp yield was also reduced from 89 to 77%.

Chemical Impregnation

In the pioneer work on explosion pulping, only steam was used to soften the chips (Mason, 1928; Koran et al., 1978; Asplund, 1953). Australian authors (Mamers and Grave, 1973; Mamers et al. 1981, 1976, 1979) have explored the possibility of using many different pulping chemicals. In the more recent studies, the authors have selected Na_2SO_3 for softwood and a mixture of Na_2SO_3 and NaOH for hardwood pulping. They performed vapor phase cooking by removing the excess chemical solution used for chip impregnation.

Caustic and sulfite are known to greatly influence the pulp yield, refining energy, pulp strength, and brightness of aspen chemimechanical pulps (Barbe et al., 1990). It was also found that at least 6% Na_2SO_3 concentration is necessary to protect the brightness (Kokta et al., 1989).

In explosion pulping of aspen at 190°C at 4 min, Kokta and co-workers (1989) have shown that an increase in Na_2SO_3 concentration from 3 to 8% produces an increase in sulfonate content from 20 to 48 mmol/kg. The concentration adjustment results in an increase in the long fiber content (L_{48}) from 35 to 54% and an increase in tear and burst indexes and breaking length. The Na_2SO_3 concentration was increased from about 3 to 12% for explosion pulping of spruce chips at 235°C and a retention time of 5 to 30 s (Chaudhuri, 1989). At a given freeness value, tensile strength, elongation, burst and tear indexes, and density were increased with higher chemical concentrations. A reduction in refining energy was also reported with an increase in initial sulfite concentration (Barbe et al., 1990). It has been shown that the breaking length increases with the chemical concentration for aspen chips with (Barbe et al., 1990) or without (Kokta et al., 1989) the addition of 1% NaOH. Similar results were obtained for spruce at a freeness of 600 mL (Chaudhuri, 1989).

Production of long fibers at two given freeness values with the variation of Na_2SO_3 from 2 to 16% was also investigated (Kokta et al., 1992). Aspen chips were pulped at 190°C for 4 min with a $L/W=3$. The percentage of long fibers, L_{48} (i. e., $R_{14} + R_{28}$), first decreases and levels out at a concentration of about 8% and subsequently increases with increasing Na_2SO_3 concentration up to 14%. The drop of long fibers at 16% concentration remains unexplained. At a freeness of 100 mL, the variation of Na_2SO_3 concentration from 2 to 16% results in an increase of total ionic content (117 to 205 mmol/kg), breaking length (4.9 to 7.8 km), burst index (2.1 to 4.2 kPa.m²/g) and brightness (47 to 60%). Tear index is not significantly affected, and specific refining energy is significantly reduced (7.6 to 2.6 MJ/kg). Pulp yield is reduced from 94 to 89%.

NaOH is used in CTMP pulping in order to increase fiber swelling and accelerate the physico-chemical process leading to chip softening as well as internal morphological changes. Consequently, NaOH treatment contributes to the decrease in refin-

ing energy and, possibly, to the increase in paper properties (Kokta et al. 1989, Law and Bi 1989).

Explosion pulps produced in a pilot plant at 195°C for 1 min from aspen chips impregnated, respectively, with 8% Na₂SO₃ and with 8% Na₂SO₃ + 1% NaOH were compared (Barbe et al., 1990). Breaking length and scattering coefficient increased with refining energy for both impregnation solutions. The treatment with NaOH resulted in an increase in breaking length by about a factor of 2; however, the scattering coefficient was negatively affected. The pulp from the 1% NaOH impregnation had about 10% greater total ionic content, higher strength properties (burst, tear), and similar fiber length and bulk. However, brightness dropped by about two points. It was also shown, for the conventional CMP and CTMP and explosion pulps studied, that the NaOH addition reduces the energy required in a pilot plant refiner to produce a pulp at a given freeness (Barbe et al., 1990). Kokta and co-workers (1989) prepared pulp from aspen chips preimpregnated at 50 to 60°C for 24 h with 8% Na₂SO₃ plus 0, 1, or 2% NaOH. All explosion cooks were made at 190°C for 4 min. The long fibers (L_{48}) increased from 54 to 69% with the addition of 2% NaOH. The sulfonate content rose from 47 to 58 mmol/kg, and the carboxylate content increased from 123 to 133 mmol/kg with this addition. The addition of 2% NaOH to an impregnation liquor containing 8% Na₂SO₃ led to explosion pulps of higher burst, breaking length, stretch, and density. For a given freeness, the refining energy was also reduced. Unfortunately, the 2% NaOH addition had a negative effect on opacity and pulp yield. The brightness was reduced by about 15% (Kokta, et al., 1987).

Breaking length increased with freeness reduction and NaOH addition. It was reported that the best paper properties were obtained with 8% Na₂SO₃ and 2% NaOH, but with some brightness and yield loss (Kokta et al., 1989).

The addition of 1% Na₂SO₃ or NaHCO₃ to an 8% Na₂SO₃ solution resulted in the production of pulps requiring 60% less refining energy. Pulp strength was also significantly increased. The specific refining energy and paper properties are correlated to some fiber properties by means of multiple linear regression analysis. It was found that two measurements, such as sulfonate content and pulp yield, were needed to predict the energy requirements as well as mechanical and optical properties (Carrasco et al., 1993).

The effects of different forms of chemical treatment during impregnation and cooking on the pulp lignin content and pulp yield have been discussed by Ben et al. (1993). The highest lignin contents (20% and 20.4%) were found in the pulp using 8% Na₂SO₃ + 1% NaOH and 3% NaOH + 1% MgCl₂, respectively. Pulp yields were highest for 8% Na₂SO₃ + 1% MgCO₃ and 8% Na₂SO₃ + 1% NaHCO₃ (93% and 90.5%, respectively), whereas pulp lignin contents were the lowest (18.3% and 18.5%, respectively). The highest pulp yield (93%) produced with 8% Na₂SO₃ + 1% MgCO₃ at pH 10.8 (which is 6% higher than the level attained with 8% Na₂SO₃ + 1% NaOH) can be related to the protective effect of MgCO₃ against carbohydrate hydrolysis, oxidation, and degradation. Breaking length was found to be a function of chemical treatment in conjunction with freeness (CSF) and yield.

Breaking length in all CSF ranges increased in the presence of NaOH, NaHCO₃, or MgCO₃ in comparison with Na₂SO₃ alone. Breaking length is not always a function of yield, because the pulp from the system with MgCO₃ with a yield of 93% had strength similar to that with NaOH with an 87% yield.

The presence of swelling agents (i. e., NaOH) along with Na₂SO₃ results in a considerable decrease in specific refining energy as compared with the use of Na₂SO₃ alone (Ben et al., 1993). This finding is in agreement with results obtained from semi-industrial trials with or without NaOH (Kokta et al., 1989, 1991). What is important to consider is that the specific energy decrease is similar with the use of NaHCO₃, MgCO₃, and NaOH, even though the yields are 3 to 6% higher with the first two chemicals.

Liquor-to-Wood Ratio

From a pilot plant study in which an industrial press was used, Kokta and co-workers (1989) found that an *L/W* ratio increase from 2 to 3 resulted in about a 10% increase in strength properties and a 35% reduction in refining energy. A CD-300 Sunds defibrator refiner (60 cm, 2 t/d) was used, and the pulps were compared at a freeness of 100 ml.

Kokta and co-workers (1992) have conducted a systematic laboratory investigation of the influence of *L/W* ratios of 3, 4, and 6 for impregnation of aspen chips with 8, 12, and 16% Na₂SO₃, followed by steam cooking at 190°C for 4 min. The refining energy consumed to reach a freeness of 100 mL was reduced when the *L/W* ratio was increased, and generally the strength properties were significantly improved. However, brightness was negatively affected. It is noteworthy that breaking length, at the same total chemical charge, is higher for a lower *L/W* ratio. It was also reported that an increase in the *UW* ratio from 3 to 6 at sodium sulfite concentration of 16% has a negative influence on the tear-breaking length relationship for explosion pulping of black spruce chips at 190°C for 4 min (Kokta et al., 1991). It appears that with an extremely high chemical charge (16% Na₂SO₃, *L/W* = 6), the release of explosion pressure causes some fiber damage, which results in lower strength properties. Macleod and co-workers (1987) have reported a similar effect for softwood kraft pulping with a sudden pressure release.

Refining Energy

For comparison of the specific refining energy to a given freeness, the equipment used for refining has to be taken into consideration. Valley beater and PFI are normally used for laboratory evaluation of chemical pulp. To evaluate the various types of mechanical pulp, many authors have extended their use to the new mechanical pulp grades. Protection of PFI equipment from very rough mechanical pulps is maintained by a preliminary disintegration in a British disintegrator or a blender.

Refining of explosion pulps has been evaluated in a Lampen mill (Mamers et al., 1981, 1979) and a PFI mill (Kokta et al., 1987, 1987; Mamers et al., 1976; Law et

TABLE 6.3 Comparison of Laboratory and Pilot Plant Refiners

Property	Laboratory Blender	CD-300 Sunds Defibrator, UQTR Pilot Plant	Bauer Paprican Pilot Plant
CSF, mL	704	702	687
Refining energy, MJ/kg	3.6	4.0	4.0
Breaking length, km	3.7	4.4	3.7
Tear index, mN.m ² /g	14	14	14
Bulk, cm ³ /g	3.5	3.3	2.8
Brightness, %	47	52	52

al., 1989, 1990; Chaudhuri, 1989), and others made a preliminary disintegration in a domestic blender (Kokta et al., 1989; Law et al., 1989, 1990). Based on the work published by Shaw (1984), Kokta and co-workers (1988, 1989, 1990b) adopted a domestic blender for explosion pulp.

By comparing the energy consumed to refine aspen pulp in a laboratory blender and in a pilot plant CD 300 Sunds-defibrator refiner, Kokta and co-workers (1989) concluded that the energy recorded in the laboratory blender is similar to the energy required in the pilot plant for explosion pulp and CMP/CTMP, respectively. Explosion pulp produced from a mixture of spruce and balsam fir chips was refined in a laboratory blender and two pilot plant refiners: the CD 300 Sunds-defibrator at UQTR (Université du Québec a Trois-Rivières) and the Sprout-Bauer at Paprican (Pulp and Paper Research Institute of Canada). Pulp properties and energy consumption were comparable, as shown in Table 6.3. To reach a given freeness for aspen explosion pulp, it was found that the CD 300 Sunds-defibrator pilot refiner required from 0 to 30% more energy than a laboratory blender. For softwood, the blender consumed about 10% less energy than pilot plant and industrial Bauer refiners (Kokta, 1987, 1987 Kokta and Zhan).

It was reported that specific refining energy of ultra-high-yield pulp is independent of yield (Ben et al., 1993). This is in complete agreement with other work (Carrasco et al., 1993; Kokta, et al. 1992). The higher specific refining energy for SEP resulting from Na₂SO₃ treatment without a swelling agent can be related to the lower total ionic content (Kokta et al., 1991 a). The presence of NaOH, NaHCO₃, or MgCO₃ substantially increases the paper strength at a constant specific refining energy. The same paper strength can be achieved with substantially lower specific refining energy when a swelling agent is present. These results are in agreement with semi-industrial trials carried out with Na₂SO₃ alone or in combination with NaOH (Barbe et al., 1990). The presence of swelling agents enables faster chemical diffusion and fiber softening and facilitates higher total ionic content on fiber surfaces. As a consequence, this leads to easier defibration, along with lower specific refining energy, and to higher long-fiber content expressed as *L*-factor.

FUNDAMENTAL CHARACTERISTICS OF PULP

The fundamental characteristics of various types of pulp produced under different operating conditions are discussed in the literature. Ionic content of pulp: lignin content: fiber length; fiber flexibility and conformability as measured by sheet density: and specific surface of pulp fibers (measured by S-factor or WRV) are compared to characterize the pulps. The pulps were also characterized by means of FTIR and ESCA (electron spectroscopy for chemical analysis) techniques (Barry et al., 1990; Dorris and Gray, 1978). The characteristics of explosion pulps were compared with conventional CMP and CTMP pulps, as well as with industrial semibleached kraft pulp from hardwood.

Ionic Content of Pulps

Important pulp and paper properties, such as breaking length, tear index, density, shive content, dewatering capacity, and conformability of the long fiber fraction, can be partly attributed to the degree of sulfonation for CMP/CTMP processes (Atack et al., 1988; Engstrand et al., 1989). Sulfite pretreatment is also essential to protect the chips against oxidation and to develop hydrophilic ionic groups on the fiber surface during cooking at explosion pulping conditions.

Aspen chips were pretreated in an 8% sulfite solution and cooked at various temperatures (180-200°C) for different periods of time (0.5-8 min) to allow a study of the kinetics of sulfonation and formation of carboxylate groups (Ahmed et al., 1994). The maximum sulfonate content of the chips, in the temperature range of 180 to 200°C was about 75 mmol/kg. Beatson and co-workers (1987) obtained substantially lower sulfonate contents when a lower-treatment temperature (140°C) was used for a longer time. The rate of sulfonation at 180 to 200°C increased sharply within the first minute of treatment. The amount of sulfonate groups formed during this initial period was about 50 to 60% of the maximum sulfonate groups formed under these treatment conditions. The rate of sulfonation was greatly affected by the treatment temperature. Under very severe conditions, such as 200°C, the degree of sulfonation reached about 73 mmol/kg within 1.5 min, and then dropped with time. The treatment time necessary to raise the sulfonate content to a maximum level increased at lower temperatures. It appears that the high temperature process accelerates the sulfonation reaction in available sites and that some probable sites disappear or change with prolonged treatment time, owing to selective dissolution of the most highly-sulfonated lignin fragments. The sulfonation reaction proceeds in three stages: the first stage shows a sharp increase in sulfonate rate, the second stage shows a slow increase, and the third stage shows a decrease in the sulfonate group content. The apparent activation energy value of the sulfonation reaction was about 57 kJ/mol.

Aspen chips pretreated with a Na_2SO_3 solution, with a concentration varying from 2 to 16%, were treated with saturated steam at 190°C for various amounts of time (0.5-8 min) to facilitate study of the effect of the sulfite concentration on the degree of sulfonation and carboxylation (Ahmed et al., 1994). A change in the

Na_2SO_3 charge from 2 to 8% increased the sulfonate content by about 30 mmol/kg. A further increase in the Na_2SO_3 from 8 to 16% increased the sulfonate content by only 6%. The increase in the sulfite charge beyond 8% is not very beneficial. A similar conclusion was drawn previously by others (Kokta et al., 1989). The breaking length increases and the refining energy decreases almost linearly with the rise of sulfonate content (Kokta et al., 1991). The addition of NaOH from 0 to 6% to a 8% Na_2SO_3 solution was shown to increase the sulfonate groups from 44 to 64 mmol/kg. The content of sulfonate groups levels off with 2% NaOH. The carboxylate groups are not significantly affected by the NaOH addition (Kokta et al., 1991a).

The formation of sulfonate groups was very sensitive to the addition of a second impregnation of chemicals, especially when the addition was at a concentration below 1% in the presence of Na_2SO_3 . The sulfonate content of $\text{Na}_2\text{SO}_3 + \text{Na}_2\text{CO}_3/\text{NaHCO}_3$ -pretreated pulps was as much as 100% higher than that obtained when chips were impregnated only with Na_2SO_3 (Carrasco et al., 1994).

Carboxylate groups are formed mainly from the hydrolysis of uronic acid esters in the hemicelluloses, which are very sensitive to high temperature treatment (180–200°C). High temperatures and prolonged treatment time reduce the amount of carboxylate groups in the chips because of the degradation of hemicellulose and of the carboxylate groups formed during the initial stages. Carboxylate group formation is sensitive to the pH of the pretreatment solution (Ahmed et al., 1994). The formation of carboxylate groups was almost constant when NaHCO_3 was added, but it was very sensitive to the addition of Na_2CO_3 for chips cooked at 190°C (Carrasco et al., 1994). Paper strength properties are related to sulfonate and total ionic contents (sulfonate + carboxylate groups). A total ionic content was 169 mmol/kg for Na_2SO_3 treatment alone and 184 or 180 or 178 mmol/kg for the treatment systems with $\text{Na}_2\text{SO}_3 + \text{NaOH}$ or $\text{Na}_2\text{SO}_3 + \text{NaHCO}_2$ or $\text{Na}_2\text{SO}_3 + \text{MgCO}_3$. For 3% NaOH + 1% MgCl_2 or for untreated samples, the total ionic contents were 163.8 and 79 mmol/kg. The higher breaking lengths with the use of NaOH, NaHCO_3 or MgCO_3 were correlated to the higher ionic content.

Explosion pulps, at a given freeness, are stronger and consume less refining energy than CMP and CTMP, with the use of Douglas fir chips under the same impregnation conditions (Kokta et al., 1990a). The explosion pulp contains about 10% less ionic groups content than the two others. Similar results were obtained by other workers for aspen pulped at comparable yield (Law et al., 1990). The conventional CMP produced by liquid-phase cooking had about 25% higher ionic content than explosion pulp resulting from vapor-phase cooking. Kokta and coworkers (1990a) also reported a reduction in sulfonate and carboxylate contents for a cooking temperature above 170°C SEP.

A study conducted by Barbe and co-workers (1990) did not show any significant differences in the ionic content of CMP, CTMP, and explosion pulp produced at 195°C for 1 min from aspen chips impregnated with $\text{Na}_2\text{SO}_3 + \text{NaOH}$. All authors agree that the higher strength reported for explosion pulp cannot be explained by an higher ionic content as compared with to that of conventional CMP and CTMP

Sheet Density

The transition of the crystalline structure of cellulose to an amorphous state (i. e., breakdown of the crystallinity of the cellulose structure in the original fibers into smaller crystalline zones contained within numerous dislocated zones, which are amorphous) controls the flexibility of the pulp (Barbe et al., 1990). Barbe and co-workers (1990) confirmed that the lower temperature (128°C) used for CTMP as compared with 150°C for CMP and 190 to 195°C for explosion pulp, is responsible for the production of CTMP pulps that form lower-density sheets. This suggests greater flexibility and conformability of the explosion pulp fibers produced at higher temperatures. The higher sheet density of explosion pulp, as compared with that of CMP and/or CTMP, was confirmed by other authors (Kokta et al., 1989).

Scanning electron micrographs and microscopic studies of fibers produced by explosion pulping have demonstrated a clear separation in the middle lamella (O'Connor, 1972; Mamers et al., 1976; Law et al., 1989). A unique relation between tensile strength and sheet density for explosion pulp and CTMP obtained from spruce chips has been reported (Chaudhuri, 1989). Pulp yields were between 82 and 96%.

Fiber Length

The excellent strength properties of explosion pulp are partly attributed to the high content of long fibers, L_{48} (i. e., $R_{14} + R_{28} + R_{48}$). Breaking length reported at a freeness of 100 mL was correlated with the percentage of long fibers (L_{48}) of explosion pulp, CTMP, and CMP. Significant correlation was established for pulps prepared from aspen (Kokta et al., 1989, 1991, 1990), Douglas fir (Kokta et al., 1990), and black spruce chips (Kokta et al., 1990). For mechanical pulps, the variation of the long fiber fraction normally explains more than 50% of the tear index variations. But for explosion pulp, it seems that tear is not significantly related to the percentage of long fibers (Barbe et al., 1990; Kokta et al., 1990a, 1991, 1992).

The presence of NaOH, NaHCO₃, or MgCO₃ along with Na₂SO₃ in the impregnation solution substantially increased paper strength at a constant specific refining energy. The presence of swelling agents enables faster chemical diffusion and fiber softening and facilitates higher total ionic content on the fiber surfaces. This leads to easier defibrillation along with lower specific refining energy, and to higher long fiber content expressed as L -factor. The L -factor is directly correlated with paper strength and can at least partially explain the breaking length increase when NaOH, NaHCO₃, or MgCO₃ is present in the impregnation solution (Kokta et al., 1989).

Specific Surface and Porosity

Water retention value (WRV) and S -factor (CSF 48/100 or CSF 28/200) are often used as an indirect measure of the specific surface of fibers (Garceau, 1989). The water retention value of exploded and unexploded pulps increases with increasing cooking temperature, which suggests a better fibrillation at higher temperatures

(Law et al., 1989). It was also found that explosion pulp (195°C, 1 min) has, at a given freeness, a lower S-factor than CMP pulp (150°C, 30 min), which also suggests a better defibrillation and/or flexibility of the explosion pulp (Kokta et al., 1991a, 1990a). Other authors have also reported a lower S-factor for explosion pulps (Kokta et al., 1990a).

Delignification as well as enzymatic hydrolysis of SEP were extensively studied to verify indirectly the increase in specific area and surface accessibility (Kosik, 1993). Some delignification agents (nitric acid, 2-chloro-ethanol) were able to delignify steam explosion pulp at atmospheric conditions with an acceptable rate and extent: for example, 2-chloro-ethanol could extract almost all lignin at 110°C during 40 min. Specific surface areas of all dried samples, measured by the nitrogen sorption method, were lower than 10 m²/g. The value for SEP pulp was approximately twice that for any commercial pulp. After solvent extraction of SEP pulp, a drop in the nitrogen sorption was observed at a low value of pressure.

It is known that the surface of explosion pulp contains numerous large pores with evidence of considerable ultrastructural rearrangements (Donaldson et al., 1988; Brownell and Saddler, 1987). Fragments of cell wall form more or less spherical particles, primarily from lignin. During the action of organic solvents or other delignifying agents, the lignin particles swell, then their structure is destroyed, and finally they move from the liquid phase and disappear from the fiber structure. The extracted SEP pulp can have an even more compact structure, with decreasing specific area/volume and pores of about 1.5 to 2.5 μm diameter. The porosity of steam-exploded wood is thus enhanced by a combination of lignin redistribution as a result of melting and agglomeration owing to surface tension effect, the removal of hemicelluloses, and fragmentation of the wood to form cell wall fragments (Donaldson et al., 1988).

Cellulose Crystallinity

A four-component model of structure definition of cellulose material was recently proposed from an extensive study by means of FTIR and Raman Spectroscopy (Sukhov et al., 1991). It has been shown that Cellulose I (CI) leads to higher degree of interfiber bonding than Cellulose II (CII), and, in consequence, sheets made of CI exhibit tensile strength more than twice the value of those made from mercerized cellulose of CII. The increase in cooking temperature leads to a CI ordered increase and a CI disordered decrease in the resulting pulp. The increase in cooking temperature leads also to a CII disordered decrease. At a cooking temperature of 200°C, the cooking time of 1 min seems to be sufficient for an increase in pulp properties because it leads to the required CI increase and CII decrease.

Using classical X-ray evaluation, crystallinity index and crystallite sizes were compared for aspen fibers, CTMP, CMP, and SEP, all prepared in semi-industrial trials (Table 6.4) (Barbe et al., 1990).

It has been shown (Donaldson et al., 1988) that CTMP and CMP aspen treatment increases CI crystallinity from the 56% level to 71.5% and 71.3%, respectively. In the case of SEP with temperature above the glass transition temperature of lignin, crystallinity CI increases to 75.9%, irrespective of chemical treatment. It seems that

TABLE 6.4 X-Ray Diffraction Parameters.

	CTMP 128°C, 30 min 8% Na ₂ SO ₃ + 1% NaOH	CMP 150°C, 30 min 8% Na ₂ SO ₃ + 1% NaOH	SEP 194°C, 1 min 8% Na ₂ SO ₃	SEP 194°C, 1 min 8% Na ₂ SO ₃ + 0.5% NaOH
Crystallinity Index (Cr I)%	56.0	71.5	71.3	75.9
Crystallite Sizes (002) Å	21.4	27	27	31.5

crystallite sizes, being 21.4 angstroms for aspen, 27 angstroms for both CTMP and CMP, and 31.5 angstroms for SEP, are a function of temperature rather than chemical treatment. As in Table 6.4, cooking temperature increase leads to both an increase in crystallinity CI as well as crystal size increase.

Electrical Surface Properties

The electrical **surface** properties of various pulp fibers, produced by refiner mechanical pulping (RMP), CTMP, and SEP process, from aspen wood were investigated by continued potentiometric base-acid titration and microelectrophoresis in aqueous electrolyte solutions. The results of the study show that electrical surface properties of the explosion pulp fibers differ from the properties of typical high-yield CTMP and RMP pulps (Sukhov et al., 1992). It was confirmed through the experiments that SEP fibers contain a relatively high concentration of dissociated surface functional groups. Electrical surface properties of SEP fibers have a relatively more acid character. In addition, the SEP fibers have a more fibrillated capillary-porous structure of the surface, which results in higher ion exchange capacity and lower specific refining energy. The SEP sample is also characterized by relatively high and stable values of specific surface charge in the wide range of pH (5.0-8.5), whereas re-charge of the surface of the CTMP and RMP fibers starts at pH = 5.0 and the stability is lost at pH = 6.5.

The increase of D₂O absorption of SEP pulp at 190°C indicates changes in morphological structure above the lignin glass transition temperature, leading to better surface accessibility and higher hydrophilic surface characteristics (Sukhov et al., 1992). Similar results, confirming higher porosity and water accessibility of SEP, were obtained by measuring water retention values. Values found for CMP or CTMP were within 115 to 118 g/100g range, as compared with SEP at 138 to 151 g/100g (Focher et al., 1991).

NMR(C13) Spectroscopy Evaluation of Pulp

Extensive evaluation of ultra-high-yield aspen pulp by CP-MAC ¹³C-NMR spectroscopy has been recently published (Focher et al., 1991; Hua et al., 1993). The results are summarized and compared in Table 6.5 for aspen fibers, CTMP, CMP, and SEP, all prepared in semi-industrial trials (Kokta et al., 1991a, 1992; Barbe et

TABLE 6.5 CP-MAS ^{13}C -NMR Spectroscopy.

	CTMP	CTMP	CMP	SEP	SEP
Aspen Fibers	128°C, 30 min 8% Na_2SO_3 + 1% NaOH	128°C, 10 min 5% Na_2SO_3 + 5% NaOH	150°C, 30 min 8% Na_2SO_3 + 1% NaOH	194°C, 1 min 8% Na_2SO_3	194°C, 1 min 8% Na_2SO_3 +0.5% NaOH
Cellulose	No remarkable modifications in respect to the spectrum of original wood	No remarkable modifications in respect to the spectrum of original wood	No remarkable modifications in respect to the spectrum of original wood	C_4+C_8 increase in ordered region	Complete disappearance of acetyl, lignin degradation, unsaturated carbonyl group, new lignin structure (140-160 ppm relaxation), increase in ordered regions.
Hemicellulose					
Acetyl					

al., 1990.) The steam explosion treatment of aspen chips with Na_2SO_3 and $\text{Na}_2\text{SO}_3 + \text{NaOH}$ led to a loss in hemicellulose and an increase in cellulose crystallinity. No lignin dissolution occurred during explosion pulping, although the spectrum was modified as compared with that in the original wood samples. The decrease or complete disappearance of acetyl groups resulting from SEP treatment has also been confirmed by IR spectroscopy.

ESCA Evaluation of Pulp

In comparative semi-industrial trials, Barbe and co-workers (1990) showed that SEP exhibited much higher strength than CMP at a comparable total ionic content and yield. To explain the fundamental factors that may contribute to the higher strength level of SEP, the pulp samples taken from semi-industrial trials were examined by ESCA (Hua et al., 1993). Kraft aspen pulps were compared with water-exploded aspen chips and CMP; the results are presented in Table 6.6.

SEP (8 + 1) revealed a higher O/C content on the surface than CMP (8 + 1), which indicates better surface bonding characteristics. The lower percentage of C_1 and O_1 (found mostly on lignin and noncellulosics) for SEP, as opposed to CMP, also indicates a lower amount of lignin in SEP (Hua et al., 1993). Finally, the higher S/C found for SEP, as compared with CMP, indicates a higher level of surface lignin sulfonation for steam explosion pulps. It seems that a higher percentage of carbohydrates and a lower percentage of sulfonated lignin on the fiber surface of SEP (as compared with CMP) can partially explain its superior bonding in relation to strength properties.

The higher O/C ratio correlated extremely well with bonding properties such as breaking length and burst, but did not correlate to tear values to any great extent. The C_1 peak area function can be found only in lignin and extractives present on the surface. Extractives, as well as lignin, have at least three times lower hydrogen bonding potential (OH groups) as compared with cellulose, which negatively influences bonding strength. It is well known that sulfonation of lignin improves the

TABLE 6.6 ESCA Spectroscopy of Ultra-High-Yield Aspen Pulps.

Pulp	Yield (%)	Total Ionic Sulfonic Content, Group,		O/C	C_1 , %	O_1 , %	S/C	Specific Breaking Refining Length. Energy,	
		mmol/kg	mmol/kg					km	MJ/kg
Kraft	—	—	—	0.59	20.0	7.7	—	—	—
SEP (8 + 1)	92	174	43	0.52	33.9	10.3	3.08	7.2	3.0
CMP (8 + 1)	89.9	190	53	0.41	43.1	14.3	2.22	4.7	9.7
SEP (H_2O)	91	85	—	0.34	55.6	22.7	—	4.1	—

Note: 8 + 1 (8% Na_2SO_3 + 1% NaOH); SEP (195°C, 1 min); CMP (150°C, 30 min); O/C = oxygen/carbon; C_1 (level of energy of C_1 component in carbon peak; O_1 (level of energy of O_1 component in oxygen peak; S/C (sulfur/carbon).

interfiber forces; therefore, it is not surprising that the increase in S/C atomic ratio leads to higher breaking length.

EXPLOSION PULPING OF NONWOOD FIBER

Although wood constitutes the major part of the world's pulp and papermaking materials, nonwood plant fibers remain an important source of papermaking materials in many countries where wood forests are limited or nonexistent. Bagasse, bamboo, straw, and reeds are presently the dominant raw materials among nonwood fibers used in the production of pulp, paper, and boards. In addition, kenaf fiber represents a potential source of raw material for pulp and papermaking (Young, 1996). The suitability of the explosion pulping process to convert bagasse (Kokta et al., 1992, 1993), kenaf (Kokta et al., 1991a, 1993), flax straw (Kokta et al., 1993), and rice straw (Ray et al., 1992) into paper has been reported.

The characteristics of explosion pulp obtained from bagasse, kenaf, and flax pretreated with 8% Na₂SO₃, 16% Na₂SO₃, or 8% Na₂SO₃ + 1% NaOH solution are presented in Table 6.7. Explosion pulping of bagasse yields pulp with excellent paper properties. The strength of explosion pulp from bagasse pretreated with 16%

TABLE 6.7 Characteristics of Explosion Pulp Obtained from Bagasse, Kenaf and Flax.

	Pulp					
	Bagasse	Bagasse	Bagasse	Kenaf	Kenaf	Flax
Pretreatment chemicals						
Na ₂ SO ₃ (%)	16	8	8	8	8	8
NaOH (%)	0	0	1	0	1	0
Liquor/chips ratio	4	6	4	3	3	3
Cooking time, min	4	4	4	4	4	4
Cooking temp., °C	190	190	190	190	190	190
CSF, ml	100	100	107	118	97	200
Sp. refining energy, MJ/kg	1.15	2.85	0.36	1.65	0.87	—
Bulk, cm ³ /g	2.4	2.88	3.3	2.9	1.78	3.4
Burst index, kPa.m ² /g	3.6	1.9	3.5	2.8	5.5	1.1
Breaking length, km	6.3	3.9	5.8	5.8	8.8	2.4
Stretch, (%)	2.2	1.8	2.2	2.0	—	—
Tear index, mN.m ² /g	7.3	6.0	7.7	10.4	7.9	10
Brightness, (%)	38	40	37	63	55	45
Opacity, (%)	91	96.7	91	94	87	96
Light sct. coefficient, cm ² /g	225	350	252	534	292	438
Porosity, mL/min	50	460	97	182	5.5	—
Drainage time, sec	12	6.0	8.5	7.7	22.7	—
Sulfonate content, mmol/kg	93	138	61	47	86	—
Carboxylate content mmol/kg	99	110	84	170	168	—
Yield, %	70	81	72	73	67	76

Na_2SO_3 or 8% Na_2SO_3 + 1% NaOH is similar to that of low-yield bagasse chemical pulp. Bagasse explosion pulp requires low-refining energy to reach a 100 mL CSF level. The tear values of explosion pulp, CMP, and CTMP are controlled by the long fiber fraction of the pulp, whereas their breaking lengths seem to be controlled by the cooking temperature. Cooking time shows a significant effect on pulp yield and breaking length, and no effect whatsoever on pulp tear values. The brightness of bagasse explosion pulp can be increased from an initial 37% to a final 65% level by applying 4% H_2O_2 in a single-stage bleaching process (Kokta et al., 1992, 1993).

Kenaf fibers represent a potential source of raw materials for pulp and papermaking in many parts of the world. The stalk consists of two basic fiber components, the bark and the core fibers, which possess different pulp and papermaking characteristics. The pulp derived from the whole stalks tends to be slow in drainage characteristics and limits the paper machine speed (Young, 1996; Clark and Wolff, 1965).

Explosion pulping of kenaf leads to excellent pulp and paper properties. As compared with conventional CMP or CTMP, SEP results in superior pulp and paper properties and lower specific refining energy. The brightness of kenaf bleached with 4% H_2O_2 was in the 80% range. Paper properties of kenaf SEP were even higher than those found for aspen SEP (Kokta et al., 1991a, 1993).

Flax is an annual plant grown for fiber in the production of linen and for seed in the production of linseed oil. The stems of the flax plant have a woody core with a hollow center, and bast fibers are located in the bark. Steam explosion pulping of flax (whole stalk) gives a yield of about 70%. The strength properties of flax SEP, such as burst index and breaking length, are considerably greater than equivalent RMP and CTMP. The strength of explosion pulp from flax is similar to that of RMP and TMP from spruce pulps, but the tear values are considerably higher ($17 \text{ mN} \cdot \text{m}^2/\text{g}$ as compared with only $5 \text{ mN} \cdot \text{m}^2/\text{g}$ for RMP or $11 \text{ mN} \cdot \text{m}^2/\text{g}$ for CTMP) (Kokta et al., 1993, Kokta and Ahmed, 1993).

CONCLUSIONS

Chip impregnation in explosion pulping is critical for control of the ionic concentration of the pulp and, consequently, its properties. Generally, an increase in cooking temperature has a positive effect on pulp strength and refining energy reduction, but a negative effect on pulp yield, brightness, and other optical properties. For a given freeness, an increase in Na_2SO_3 or Na_2SO_3 + NaOH concentrations (impregnation solutions) leads to an increase in total ionic content and strength properties and a reduction in specific refining energy and pulp yield. Sodium hydroxide addition is responsible for a significant brightness loss. A high chemical concentration of the impregnating solution seems to be responsible for some fiber damage.

The relative pulp strength derived from the various pulp processes cannot be explained by the ionic content alone. The high sheet density and specific surface (as measured by S-factor) of explosion pulp, which suggests high fiber flexibility and conformability, might explain the high pulp strength reported. A high percentage of long fibers was also reported for SEP.

The X-ray study has shown an increase in crystallinity as well as crystal size for SEP. The phase studies have shown an increase in CI ordered and decrease in CII disordered for SEP, and these structural changes were most pronounced at temperatures higher than 190°C and cooking times of 2 min or more, or 1 min at 200°C and higher. The increase in CI ordered may partially explain the superior bonding characteristics of SEP, because CII provides poorer interfiber bonding.

Steam explosion pulp has higher porosity, higher specific surface area, and higher hydrophilic character than RMP and CTMP, as documented by D₂O absorption, surface electrical properties, and water retention, as well as extraction and enzymatic hydrolysis studies. The surfaces of steam explosion pulp have a higher O/C ratio, which indicates a higher percentage of surface carbohydrates, less lignin, and a higher S/C ratio, indicating a higher level of surface lignin sulfonation.

The analysis by ¹³C NMR confirmed that pronounced changes occurred for SEP, leading to an increase in the inter- and intramolecular hydrogen bonding environment, as well as to structural reorientation leading to higher crystallinity.

SEP cooking at temperatures well above lignin glass transition temperature leads to additional permanent fiber softening through internal structural changes and, as a consequence, results in lower specific refining energy, higher surface porosity, and higher fiber specific surface. The higher fiber length combined with better bonding characteristics, owing to the more hydrophilic fiber surface characteristics, results in better bonding of the flexible fibers, as documented by lower light scattering coefficient, higher density, and superior paper properties.

ACKNOWLEDGEMENTS

We wish to thank the National Science & Engineering Research Council, Canada, Fond College d' Avancement de la Recherche, Canada, and Stake Technology Ltd. for their financial support.

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ENVIRONMENTALLY FRIENDLY TECHNOLOGIES FOR THE PULP AND PAPER INDUSTRY

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Library of Congress Cataloging-in-Publication Data

Environmentally friendly technologies for the pulp and paper industry /

edited by Raymond A. Young, Masood Akhtar.

p. cm.

Includes index.

ISBN 0-471-15770-8 (cloth : alk. paper)

1. Wood-pulp industry-Environmental aspects. 2. Green technology-Industrial applications. 3. Industrial ecology.

4. Paper industry-Environmental aspects. I. Young, Raymond Allen, 1945- . II. Akhtar, Masood. 1959- .

TS1176.E86 1997

676—dc21

97-12777

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1