# ENVIRONMENTALLY FRIENDLY AND COST-EFFECTIVE METHOD FOR MANUFACTURING ABSORBENT GRADE PAPER

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Absorbent paper is characterized by some of its important specific properties like water klemn, castor oil penetration and wet strength. An absorbent grade pulp was manufactured from a mixture of *Eucalyptus tereticornis* and veneer waste of poplar (15:85) by three distinct processes: (a) delignification at high alkali dose and longer cooking time (at 170 °C), followed by enzyme treatment (method-I), (b) delignification under normal pulping conditions, followed by semi-bleaching ($CE_{OP}$) (method-II), and (c) delignification under normal pulping conditions, followed by oxygen treatment (method-III). Method-I required 7.15 h for pulp processing and the cost of pulp was US$ 2481.72/digester. The cost of pulp produced by method-II was comparatively lower (US$ 2272.69/digester). However, it required a longer time (9.45 h) and was not environmentally benign because of generation of chloro-organic compounds. The pulp produced by method-III was environmentally friendly, required a cooking time of 12.45 h, and was also economical (US$1936.32/digester), compared to the other methods.

***Keywords***: *Eucalyptus tereticornis*, veneer waste of poplar, pulping, semi-bleaching, oxygen delignification, cost effectiveness, absorbent grade paper

## INTRODUCTION

Broadly, papers are classified into four categories, namely writing and printing, packaging and wrapping, tissue papers, and specialty papers. Specialty papers have certain special properties above and beyond the basic properties shown by the three preceding grades. Absorbent grade is a highly specialized paper due to the introduction of certain special properties like uniform thickness, toughness, tear strength and fire retardant in wax match paper,[1] opacity and brightness in barrier paper,[2] demarcation in top and bottom sides in padding paper,[3] laying of 25 µm thin copper film as a top layer in pictorial circuit board,[4] fire retardant in dark brown Turkish (DBTU) paper,[5] ivory colour in ivory base paper,[6] toxicity in seed germination paper,[7] pore size and filtering rate in car and industrial filter paper,[8] resistance to flow, filtration efficiency, and dust holding capacity in beer, coffee, beverage, and tea bag filter paper.[9]

Absorbent paper especially is a normal kraft, hydrophilic, porous medium with a high degree of water absorption. It is made of clean, low kappa kraft pulp, and has to have a good uniformity. The paper must have maximal unbound fiber surface area, porosity, bulk, pore volume, wet strength, castor oil penetration value, and water klemn.[10] However, softness is a subjective property, which depends on thickness (bulk), and flexibility, and can be induced by treating with plasticizers, such as diethylene glycol, polyethylene glycol or dipropylene glycol.[11] Normally, semi-bleached kraft pulp of permanganate number 10 with average COP (Castor Oil Penetration) value of 25 s and water klemn of 27 mm is required for unbleached absorbent kraft paper.[10]

In order to survive in a competitive international market in the midst of tough competition owing to imports, the Indian pulp and paper industry has been compelled to enhance product quality and reduce costs. The best option is therefore to bring down the production cost by augmenting in-house research and development activities. Indian pulp and paper industries manufacture absorbent kraft paper by the semi-bleaching process. This method is not environmentally benign due to generation of adsorable organic halides. Against this background, two more methods were developed for the production of absorbent grade pulp in laboratory and followed by plant trials. The absorbent grade pulps produced by three distinct methods were studied as to total pulp production cost and time required per digester, pollution load generated and paper properties.

## EXPERIMENTAL

### Pulping

The whole debarked *Eucalyptus tereticornis* logs and veneer waste of poplar (*Populus* species) were disintegrated into chips using a Vecoplan Chipper (Vecoplan LLC, High Point, North Carolina, USA). Screened chips of eucalyptus, and veneer waste of poplar were blended in the ratio of 15:85. Mixed wood chips were digested in a cylindrical digester of 85 $m^3$ capacity (Larsen & Toubro) heated indirectly with medium pressure steam by the kraft pulping process, using 20% active alkali (as $Na_2O$), 18.95% sulphidity, 120 min time from ambient temperature to 162 °C (max. temp.), 90 min time at max. temp., 7.5 $kg/cm^2$ digester pressure and 3:1 liquor to wood ratio. The pulp was blown in a blow tank, screened through a knotter screen **(**Voith, GmbH [Germany]**)** and finally washed through four stage counter current brown stock washers (Dorr-Oliver, Ahlstrom model DD3040.3 MCV). The pulp of brown stock washer number four was washed with condensate collected from the blow tank and fresh water. The unbleached pulp was prebleached with xylanase enzyme (Advanced Enzymes Co., Mumbai) at a dosing of 0.5 kg/MT of pulp for a retention time of 60 min. Enzyme was added in a drum washer where there was no need of adding extra water.

Likewise, in another set of experiments, blended wood chips were digested with 16% active alkali (as $Na_2O$), 18.95% sulphidity, 120 min time from ambient temperature to 162 °C (max. temp.) and 75 min time at max. temp., while keeping the other conditions constant, as mentioned above. The cooked pulp was passed through a knotter screen and washed through four stage counter current brown stock washers. The washed unbleached pulp was subjected to chlorination using 5% molecular $Cl_2$ at ambient temperature, 3% consistency, pH 2.6±1 and a retention time of 60 min. The chlorolignin formed in the pulp during the chlorination stage was extracted during the alkali extraction stage, using 3.6% NaOH (as such) reinforced with 1% $H_2O_2$ and 0.45% $O_2$ at 10% consistency, initial pH 11.5, end pH 10.5, temperature 70 °C and retention time 120 min.

In the 3$^{rd}$ set, blended wood chips were digested and delignified pulp was washed as per method described in the 2$^{nd}$ set of experiments. Further, the unbleached pulp was subjected to extended delignification with 1.8% $O_2$, 2% NaOH (as such) and 0.5% $MgSO_4$ at a consistency of 11%, temperature of 65-70 °C during the I$^{st}$ stage and 90-100 °C during the II$^{nd}$ stage, a retention time of 30 min during the I$^{st}$ stage and 60 min during II$^{nd}$ stage, a pressure of 7.5 $kg/cm^2$ during the I$^{st}$ stage and 3.5 $kg/cm^2$ during the II$^{nd}$ stage and end pH 10.4 to 10.8.

In all the three cases, the pulps were washed and passed through a fine screen (Voith, GmbH [Germany]) to separate shives and slivers. The pulp was evaluated for permanganate number (TAPPI T 214 su 71 "Permanganate number of pulp), brightness (TAPPI T 452 om-02 "Brightness of pulp, paper, and paperboard [directional reflectance at 457 nm]") and viscosity (TAPPI T 206 os-63 "Cupprammonium disperse viscosity of pulp").[12]

### Effluent analysis

The effluents generated during the three distinct sets of experiments were analyzed for COD (IS 3025: Part 58 [1984] "Chemical oxygen demand"), suspended solids (IS 3025: Part 17 [1984] "Non-filterable residue [total suspended solids]"), dissolved solids (IS 3025: Part 16 [1984] "Filterable residue [total dissolved solids]"), total solids (IS 3025: Part 15 [1984] "Total residue [total solids - dissolved and suspended]"), pH (IS 3025: Part 11 [1983] "pH value"), chlorides (IS 3025: Part 32 [1988] "Chloride")[13] and AOX by column method[14] with an AOX Analyzer Dextar ECS 1200.

### Pulp refining and sheet making

The pulp was refined in a double disk refiner (Parason Machinery, India) at 3% consistency to get a Schopper–Riegler degree ($^0$SR) of 27±1. The pulp was mixed with 1% melamine formaldehyde in order to develop crosslinking and machine finished paper of basis weight 70 $g/m^2$ was manufactured on a paper machine (Bentley and Jackson, England), having a Fourdrinier wet end part equipped with table rolls and hydrofoils, bi-nip presses and steam dryer cylinders. The paper taken from the pope reel was conditioned at a relative humidity of 65±2% and temperature of 25±1 °C and evaluated for grammage (T 410 om-02

"Grammage of paper and paperboard [weight per unit area]"), castor oil penetration (TAPPI T 462 om-01 "Castor-oil penetration test for paper"), wet strength (TAPPI T 456 om-03 "Tensile breaking strength of water-saturated paper and paperboard [wet tensile strength]"), and water klemn (TAPPI T 432 cm-99 "Water absorbency of bibulous papers").[12]

## RESULTS AND DISCUSSION

Table 1 reveals that the screened chips of *E. tereticornis* and the veneer waste of poplar, mixed in the ratio of 15:85, cooked at a high alkali dose (20% as $Na_2O$) and an increased cooking time (time at temperature 90 min), which was then followed by an enzymatic treatment, produced a screened pulp yield of 8.35 MT or 44.16% (on oven dry chips basis) of permanganate number 10.1. The screened pulp yield (method-I) was reduced by 3.24%, compared to method-III, where normal pulping was followed by oxygen delignification (Table 1). The decrease in pulp lignin content was due to the extension of delignification up to a residual delignification phase. The bulk delignification corresponded to the removal of easily assessable lignin present in the middle lamella, and the residual delignification corresponded to the removal of lignin present in the primary wall, the secondary wall layers, and the central interconnection cavities. The delignification of wood in alkaline pulping was also associated with the solubilization of significant amount of hemicelluloses.[15] A lower screened pulp yield was obtained at a high alkali dosing and an increased cooking time due to the peeling reactions, alkaline hydrolysis (depolymerization) of the polysaccharide chains occurred and was subjected to further degradation reactions (secondary peeling).[16,17] Further, a decrease in pulp yield was due to the release of lignin-carbohydrates complexes (LCC) as a result of enzyme attack on the pulp, because reducing sugars would continue to be generated by xylanase hydrolysis of the soluble oligosaccharides. These oligosaccharides were released by the initial depolymerization of the xylan coating on the fiber surface.[18] The bonds between carbohydrates and lignin would be partly cleaved by enzymes. In addition, Hortling and Tamminen[19] and Jääskeläinen *et al.*[20] also reported a high yield of residual lignin in enzymatic isolation procedures. The brightness of unbleached pulp mitigated by 8.8% (ISO) and contrary to this, the pulp viscosity improved by 27.3%, compared to method-III (Table 1). The increase in the brightness (7.2% ISO) of the pulp obtained after pulping followed by enzyme treatment might be due to disrupting of xylan chain which, thus, facilitated the removal of LCC. Xylanase removed the low degree polymer, i.e. xylan, from the pulp and thus, improved the viscosity of the treated pulp.[21] Bajpai *et al.*[22] also reported that the viscosity of bamboo kraft pulp after treatment with different commercial enzymes was increased. Table 2 shows the characteristics of black liquor separated from the pulp by washing and sent to the kraft recovery system, where the inorganic pulping chemicals were recovered for use, while the dissolved organics were used as a fuel to make steam and power.

Table 1
Comparison of methods I, II and III for producing absorbent kraft pulp

| Parameters | *Method-I | **Method-II | Method-III |
|---|---|---|---|
| Total time required, h | 7.15 | 9.45 | 12.45 |
| Total cost in US$/digester | 2191.77 | 1848.29 | 1936.32 |
| Total screened pulp yield produced by one digester, MT | 8.35 (44.16%) | 8.13 (43%) | 8.89 (47.04%) |
| Cost of pulp due to shrinkage, compared to pulp yield obtained by method-III, US$/digester | 289.95 | 424.40 | — |
| Total cost of pulp, US$/digester | 2481.72 | 2272.69 | 1936.32 |
| Permanganate number | 10.1 | 10.4 | 8 |
| Brightness, % (ISO) | *(29.2) **36.4 | 39.4 | 45.2 |
| Viscosity, cps | 28 | 20.8 | 22 |

* = pulp brightness after pulping
** = pulp brightness after pulping followed by enzyme treatment
US$ 1.0 = Indian Rupee 46.56 on September 11, 2011

Table 2
Comparison of combined effluents generated via different methods

| Parameters | Method-I | Black liquor generated during brown stock washing | Black liquor generated during bleaching and $O_2$ delignification | |
|---|---|---|---|---|
| | | | Method-II | Method-III |
| pH | 11.2 | 11.4 | 10.2 | 10.5 |
| COD, mg/L | 53584 | 50584 | 2697 | 3176 |
| Suspended solids, mg/L | 28400 | 26750 | 952 | 52 |
| Dissolved solids, mg/L | 14235 | 13885 | 15235 | 5782 |
| Total solids, mg/L | 42635 | 40635 | 16187 | 5834 |
| Chlorides, mg/L | — | — | 6400 | 100 |
| AOX, kg/T of pulp | — | — | 2.1 | — |

High total solids in black liquor gave a high fuel value, while less chloride had a minimum negative impact on the kraft chemical recovery process (Table 2).

A total time required to produce absorbent grade pulp was 7.15 h, which was mitigated by 5.30 h, compared to method-III (Table 1). The total cost of absorbent grade pulp produced (per digester) was US$ 2191.77. Adding the cost of pulp due to shrinkage to the total cost was increased to US$ 2481.72 and enhanced by US$ 545.40 compared to the cost of pulp produced by method-III. The electricity required for chip loading was 9 kWh/MT of chips and it was common to all the three methods. Therefore, the power required for chip loading was not taken into calculation. Cost analysis by method-I is reported below.

**Description of process**
Pulping process = Kraft
Batch digester capacity = 85 $m^3$
Raw materials ratio = Eucalyptus: Veneer waste of *Populus* species = 15:85
Method-I: cooking at high alkali dose and maximum cooking time followed by enzyme treatment

**A. Time consumed during pulping, screening and washing process:**
Time taken for digester loading = 60 min
Time from ambient temp. to 162 °C = 120 min
Time taken to temp. 162 °C = 90 min
Time taken for blowing of digester = 75 min
Time taken for screening and washing of pulp (48 MT unbleached pulp) = 90 min
(Dorr-Oliver 4 stage brown stock washers)
Total time ≈ 7.15 h

**B. Steam consumption:**
Medium pressure steam requirement during pulping = 1.52 MT/MT of wood chips
Amount of wood chips in one digester = 18.90 MT (Bone dry)
Cost of steam = US$ 12.89/MT
Total cost of steam required for one digester = 12.89 x 1.52 x 18.90
= US$ 370.30/digester

**C. Cost of chemicals and water during pulping:**
Active alkali charged in digester = 20% (as $Na_2O$)
Active alkali in white liquor = 106.5% (as $Na_2O$)
Sulphidity of white liquor = 18.95%
Ratio of NaOH:$Na_2S$ in white liquor = 86.32:20.18

100 MT of wood chips require 20 MT of active alkali (as $Na_2O$)

18.90 MT of wood chips require $\frac{18.90 \times 20}{100}$ of active alkali (as $Na_2O$)

= 3.78 MT of active alkali (as $Na_2O$)

106.5 MT of active alkali consists of 86.32 MT of NaOH (as $Na_2O$)

3.78 MT of active alkali (as $Na_2O$) consists of 3.063 MT of NaOH (as $Na_2O$)

Cost of NaOH (as $Na_2O$) = US$ 429.55/MT of NaOH (as $Na_2O$)

= US$ 3.063 x 429.55

= US$ 1315.71

106.5 MT of active alkali consists of 20.18 MT of $Na_2S$ (as $Na_2O$)

3.78 $\frac{20.18 \times 3.78}{106.5}$ ≈ 0.72 MT (as $Na_2O$)

≈0.91 MT (as $Na_2S$)

Cost of $Na_2S$ (as $Na_2O$) = US$ 392.69/MT of $Na_2S$

= US$ 0.91 x 392.69

= US$ 357.35

Bath ratio maintained at 1:3

Water required for pulping: 56.7 MT or 54.6 MT (excluding moisture in wood chips)

Cost of water = US$ 0.03/MT (according to water cess charged by pollution control board)

= US$ 1.64 for one digester

Enzymatic prebleaching:

Time required for enzymatic prebleaching = 60 min

Cost of enzyme = US$ 10.74/kg

One MT of pulp required enzyme dose = 0.5 kg

9.072 MT of pulp required enzyme dose = $\frac{9.072 \times 0.5}{1}$ kg = 4.54 kg

Cost of enzymes = US$10.74 x 4.54 = US$ 48.72

Total cost of chemicals = US$ 1315.71+ US$ 357.35+ US$ 1.64+ US$ 48.72

= US$ 1723.42 pulp produced by one digester

**E. Power consumption:**

Cost of electrical energy required during chip loading, pulping, screening washing:

Electricity consumed for pulping 18.90 MT of chips = 170 kWh (9 kWh/MT of chips)

Electricity consumed for screening 9.16 MT of pulp = 302.37 kWh (33 kWh/MT of pulp and pulp yield 48.48%)

Electricity consumed for washing 9.072 MT of pulp = 344.74 kWh (38 kWh/MT of pulp excluding screening rejects 1%)

Total power consumed = 817.11 kWh for pulp produced by one digester

Cost of electricity = US$ 0.12/kWh

Total cost of electricity = US$ 98.05

Total cost of absorbent pulp per digester produced by method-I

B+C+D= US$ 370.30 + US$ 1723.42 + US$ 98.05

= US$ 2191.77/digester

The screened chips of *E. tereticornis* and the veneer waste of poplar, cooked at the normal alkali dose (16%, as $Na_2O$) and a time at temperature (162 °C) of 90 min, were subjected to chlorination after brown stock washing and screening followed by $O_2$ and $H_2O_2$ reinforced alkali extraction stage. A total screened pulp yield of 8.13 MT per digester or 43% (on oven dry chips basis) of permanganate number 10.4 was obtained. In comparison to method-III (Table 1), a drastic reduction in pulp yield (4.04%) was observed in order to get a pulp suitable for absorbent grade papers. The loss in pulp yield was due to the detrimental effect of HOCl formed in the chlorination stage and to the peeling reactions that occurred during the $O_2$ and $H_2O_2$ reinforced alkali extraction stage. Hypochlorous acid reacted less selectively with lignin than with chlorine, and the loss of pulp quality and yield might have been due to the attack on carbohydrates. HOCl was less selective to lignin than $Cl_2$ and resulted in loss of pulp quality and yield.[23-24] The total cost of pulp produced by method-II after adding the cost of yield loss due to shrinkage was US$ 2272.69, and the cost increased by US$ 336.37 (compared to method-III). The cost difference between methods-II and I was of US$ 209.03. However, method-II was not environmentally friendly due to the generation of chlorinated organic compounds, which were recalcitrant to degradation.[25] Many of them were acute or even chronic toxins and could induce genetic changes in exposed organisms.[26] It was observed that the chlorination stage of pulp bleaching was normally the first point in which 2,3,7,8-TCDD, 2,3,7,8-TCDF and 1,2,7,8-TCDF congeners were always present.[27] The filtrate of the alkali extraction stage was found to have the highest concentrations of dioxins[28] known for changing the blood chemistry and causing liver damage, skin disorders, lung lesions and tumour within the body.[29] The use of such chemically treated papers for direct body contact was quite significant, since it was associated with chlorinated compounds including the animal carcinogen dioxin.[30] AOX formed in the effluent of $CE_{OP}$ stage was 2.1 kg/MT of pulp. COD, suspended solids, dissolved solids, total solids and chlorides were found to be higher. The black liquor generated by method-I would be sent to chemical recovery, but the removal or destruction of chlorinated pollutants from the bleached kraft process through end-of-pipe treatment was difficult due to their persistence and low concentration in the effluents. Conventional treatment technologies were relatively ineffective in destroying such compounds and, instead, might result in their transfer to other environmental media (e.g., wastewater treatment sludge), or even their partitioning into final products.

A cost calculation for producing absorbent grade pulp by pulping followed by semi-bleaching (method-II) is given below.

**Method-II: Semi-bleaching process**

**A. Time consumed during pulping, screening, washing and semi-bleaching processes:**

Time taken for digester loading = 60 min
Time from ambient temp. to 162 °C = 120 min
Time taken to temp. 162 °C = 75 min
Time taken for blowing of digester = 75 min
Time taken for screening and washing of pulp (48 MT unbleached pulp) = 90 min
(Dorr-Oliver 4 stage B. S. washers)
Time taken during chlorination of pulp = 30 min
Time taken during extraction of pulp = 120 min
Total time = 585 min
≈ 9.45 h

**B. Steam consumption:**

Pulping
Medium pressure steam requirement during pulping = 1.52 MT/MT of wood chips
Amount of wood chips in one digester = 18.90 MT (Bone dry)
Cost of steam = US$ 12.89/MT
Total cost of steam required for one digester = 18.90 x 1.52 x 12.89
= US$ 341.07/digester
Low pressure steam requirement during semi-bleaching (CE)
Steam requirement during chlorination (C) = 0.4 MT/MT of pulp
Cost of low pressure steam = US$ 8.59/MT of steam
Amount of pulp produced by one digester = 48.0% ≈ 9.072 MT (Bone dry)
Cost of steam = 9.072 x 0.4 x 8.59
= US$ 31.17 per digester
Steam requirement during extraction stage (E) = 0.3 MT/MT of pulp
Cost of steam = 9.072 x 0.3 x 8.59
= US$ 23.38

Total cost of steam = US\$ 341.07+ US\$ 31.17+ US\$ 23.38
= US\$ 395.62
Cost of water during pulping = US\$ 1.64 for one digester
Total cost of steam + water = US\$ 395.62 + US\$ 1.64 = US\$ 397.26

**C. Cost of chemicals during pulping and semi-bleaching:**
Pulping process:
Active alkali charged in digester = 16% (as $Na_2O$)
Sulphidity of white liquor = 18.95%
Ratio of $NaOH:Na_2S$ in white liquor = 86.32:20.18
100 MT of wood chips require 16 MT of active alkali (as $Na_2O$)
18.9 MT of wood chips require $\frac{18.9 \times 16}{100}$ MT of active alkali (as $Na_2O$)
= 3.02 MT of active alkali (as $Na_2O$)
106.5 MT of active alkali consists of 86.32 MT of NaOH (as $Na_2O$)
3.02 MT of active alkali consists $\frac{3.02 \times 86.32}{106.5}$
Cost of NaOH (as $Na_2O$) = US\$ 429.55/MT of NaOH (as $Na_2O$)
= US\$ 2.45x429.55
= US\$ 1051.44
106.5 MT of active alkali consists of 20.18 MT of $Na_2S$ (as $Na_2O$)
3.02 MT of active alkali consists of 0.57 MT of $Na_2S$ (as $Na_2O$)
≈ 0.72 MT (as $Na_2S$)
Cost of $Na_2S$ (as $Na_2O$) = US\$ 392.69/MT of $Na_2S$
= US\$ 0.72 x 392.69
= US\$ 282.74
Cost of $Cl_2$, NaOH and $H_2O_2$ during semi-bleaching:
100 MT of unbleached pulp of permanganate no 16 require 0.056 MT of $Cl_2$
9.072 MT of unbleached pulp of permanganate no 16 require $\frac{9.072 \times 0.056}{100}$ MT of $Cl_2$
= 0.0051 MT of $Cl_2$
Cost of $Cl_2$ = US\$ 214.77/MT
= US\$ 0.0051x215.61
= US\$ 1.10
100 MT of chlorinated pulp require 0.035 MT of NaOH
9.072 MT of chlorinated pulp require $\frac{9.072 \times 0.035}{100}$ of NaOH
= 0.0032 MT of active alkali (as NAOH)
Cost of NaOH = US\$ 429.55/MT
= US\$ 0.0032 x 429.55
= US\$ 1.37
100 MT of chlorinated pulp require 0.012 MT $H_2O_2$ per MT of pulp
9.072 MT of chlorinated pulp require $\frac{9.072 \times 0.012}{100}$ MT $H_2O_2$ per MT of pulp
= 0.0010 MT $H_2O_2$
Cost of $H_2O_2$ = US\$ 966.49/MT of $H_2O_2$
= US\$ 0.0010 x 966.49
= US\$ 0.97

One MT of pulp required $O_2$ 0.004 MT of $O_2$
9.072 MT $\frac{9.072 \times 0.004}{1}$ = 0.36 MT of $O_2$
Cost of one MT of $O_2$ = US\$ 0.17

0.32 = $\frac{0.36 \times 0.17}{1}$ = US$ 0.061

Cost of water during chlorination (Consistency 3%)

3 MT of pulp required 97 MT of water

9.072 MT $\frac{9.072 \times 97}{3}$ = 293.33 MT of water

0.03 x 293.33 = US$ 8.80

Cost of water during alkali extraction stage (Consistency 12%)

12 MT of pulp required 88 MT of water

9.072 MT $\frac{9.072 \times 88}{12}$ = 66.53 MT

66.53 x 0.03 = US$ 2.00

Total cost of chemicals = US$ 1051.44 + US$ 282.74 + US$ 1.10 + US$ 1.37 + US$ 0.97 + US$ 0.061 + US$ 8.80 + US$ 2.0 = US$ 1348.48

**D. Power consumption:**

Power consumption during pulping screening and washing = 817.11 kWh for pulp produced by one digester

Cost of electricity = US$ 98.05

Power consumption during chlorination and $O_2$ and $H_2O_2$ reinforced extraction stage

= 37.5 kWh for pulp produced by one digester

= 37.5 x 0.12 = US$ 4.5

Total = US$ 98.05 + US$ 4.5 = US$ 102.55

Total cost of absorbent pulp per digester produced by method-II

B+C+D = US$ 397.26 + US$ 1348.48 + US$ 102.55 = US$ 1848.29

Oxygen delignification provided an additional way to extend the pulp cooking process, thereby lowering the kappa number of pulp prior to bleaching and the amount of pollution associated with chlorine-based bleaching stages. With this concept, the mixed chips of *E. tereticornis* and veneer waste of poplar were cooked according to method-II and the brown stock pulp from the digester was first washed and then mixed with oxygen and sodium hydroxide as it entered the pressurized reactor. A pulp yield of 8.83MT per digester (or 47.04%) of permanganate number 8 and pulp brightness of 45.2% (ISO) was obtained. Molecular oxygen was a specific oxidizing agent for lignin in alkaline medium, which allowed the extended delignification of chemical pulps without a serious loss in pulp yield and with positive environmental impacts in the presence of carbohydrate stabilizer, i.e. Epsom salt ($MgSO_4$).[30] The use of 0.5% magnesium sulphate (a carbohydrate stabilizer) was found to protect the cellulose fibers from oxidative degradation, which might occur in pockets of high oxygen concentration inside the reactor. Oxygen delignification was used to reduce the kappa number of the pulp by 50% without affecting much the viscosity of the pulp.[31,32] The total cost of the pulp suitable for absorbent grade pulp was US$ 1936.32 per digester, which is economical compared to the other two methods. However, it requires a longer cooking time (12.45 h). The cost calculation is given as under.

**Method-III: Oxygen delignification process**

**A. Time required during pulping, screening, washing and $O_2$ delignification**

| | |
|---|---|
| Time required for pulping, screening and washing | = 9.45 h (as per method-II) |
| Time required for filling of $O_2$ tower | = 45 min |
| Time required for reaction in tower ($I^{st}$ stage, 65-70 °C) | = 30 min |
| Time required for reaction ($II^{nd}$ stage, 90-100 °C) | = 60 min |
| Time required for emptying of $O_2$ tower | = 45 min |
| Time required during pulping and $O_2$ delignification | = 12.45 h |

**B. Steam required during pulping screening, washing and $O_2$ delignification**

Cost of steam during pulping, screening and washing = US$ 370.30 (as per method-II)

Steam consumption (medium pressure) during $O_2$ delignification = 0.4 MT/MT of pulp

$= \frac{9.072 \times 0.4}{1}$ MT

= 3.63 MT

Cost of steam = 3.63 x US$ 12.89/MT

= US$ 46.79

Total cost of steam = US$ 417.09

**C. Cost of chemicals, $O_2$ and water during pulping and $O_2$ delignification**

NaOH and $Na_2S$ required during pulping = US$ 1334.18 (as per method-II)

NaOH required during $O_2$ delignification = 0.02 MT/MT of pulp

9.072 MT of pulp required = 0.18 MT of NaOH

Cost of NaOH = 0.18 x 429.55/MT

= US$ 77.32

$O_2$ required per MT of pulp during $O_2$ delignification = 0.016 MT

9.072 MT of pulp required = 0.15 MT of $O_2$

Cost of $O_2$ during $O_2$ delignification = 0.15 x 0.17 US$/MT of $O_2$

= 0.026 US$

10 MT of pulp required = 90 MT of water

9.072 MT $= \frac{9.072 \times 90}{10}$

= 81.65 MT of water

Cost of water = 81.65 x 0.03 US$/MT of $H_2O$

= 2.45 US$

Total cost = US$ 13334.18 + US$ 77.32 + US$ 0.026 + US$ 2.45 = US$ 1413.98

**D. Power required**

Power consumption during pulping screening and washing = US$ 98.05

Power required during $O_2$ delignification = 60 kWh

Cost of power = 60 x 0.12 kWh

= US$ 7.2

Total cost of power = US$ 105.25

Total cost (B+C+D) = US$ 417.09 +79.80 + 105.25

= US$ 693.01

Table 2 shows the characteristics of black liquor separated by brown stock washers. Total solids in the black liquor generated during normal cooking were comparatively lower. The black liquor produced during oxygen delignification was mixed with the black liquor separated from brown stock washers and sent to chemical recovery.

A comparison was made among absorbent grade papers made by methods-I, II and III with specifications formulated by the Association of Decorative Laminates Manufacturers of India. The absorbent grade papers manufactured by all the three methods satisfied the specifications (Table 3).

Table 3
Comparison of absorbent grade paper properties with specifications

| Particulars | Specifications | Method-I | Method-II | Method-III |
|---|---|---|---|---|
| Basis weight, $g/m^2$ | 170 (+ 2.5, -5) | 171 | 173 | 172 |
| Bulk, $cm^3/g$ (minimum) | 1.65±0.05 | 1.66 | 1.69 | 1.67 |
| Water klemn, mm/4 min, | | | | |
| MD (minimum) | 30 | 28 | 25 | 31 |
| CD (minimum) | 23 | 24 | 18 | 26 |
| Average (minimum) | 26.5 or 27 | 21 | 21.5 or 22 | 28.5 or 29 |

| | | | | |
|---|---|---|---|---|
| Wet strength, g/cm (minimum) | 150 | 155 | 167 | 165 |
| COP at 35±1 °C, s | | | | |
| TS (minimum) | 32 | 34 | 34 | 32 |
| WS (minimum) | 18 | 20 | 22 | 21 |
| Average (minimum) | 25 | 27 | 28 | 26.5 or 27 |
| Hot extract pH | 7-8 | 7.6 | 7.7 | 7.5 |

## CONCLUSION

It is difficult to survive in a globally competitive market with a high selling price and a poor quality of the end-product, therefore the manufacturer is compelled to cut down the manufacturing cost and improve the quality of the product. The price of the end-product is constantly increasing due to soaring environmental costs, high manufacturing expenses and declining profits. Although method-III requires a longer cooking time (12.45 h), the absorbent grade paper manufactured by normal cooking followed by oxygen delignification is environmentally friendly and cost-effective (US$ 1936.32/per digester), compared to the other methods, while also strictly meeting the specifications.

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