CHARACTERIZATION OF THERMOMECHANICAL PULP MADE FROM PINE TREES INFECTED WITH NEMATODES[1]

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Abstract. Pine wilt is a lethal disease caused by the nematode *Bursaphelenchus xylophilus*. It causes tree death by blocking water and nutrient uptake in pine trees. Pine trees infected by these nematodes are used as fertilizer or fuel for thermal power plants, but their utilization is still only about 37%. To increase the utilization of the infected trees, this study investigated whether the shredded wood chips prepared from them could be used as raw materials for manufacturing thermomechanical pulp (TMP) and chemithermomechanical pulp (CTMP). TMP and CTMP prepared from the infected pine chips showed fewer pitch contents and better strength properties than those made from domestic pine. After refining, the infected chip could reduce the sacrifice of fiber length more than the normal chip, and there was no remarkable difference between the two chips in terms of optical properties.

Keywords: Pine wilt, nematode disease, thermomechanical pulp, chemithermomechanical pulp, pulp strength.

INTRODUCTION

Pine wilt leads to a dramatic disease that typically kills infected pine trees within a few weeks to a few months. The causal pathogen is known to be a thread-like nematode, *Bursaphelenchus xylophilus* that blocks the passage of water and nutrients and consequently kills the pine tree (Lee 2021). Also, when the infected pine trees die, the insect vectors move to other trees, so it is necessary to

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cut down all surrounding trees to prevent the spread of the wilt worms (Rajotte 2017). A relationship between pine nematode and pine wilt disease was first reported by Japanese forest researchers (Mota and Vieira 2008). Pine wilt disease was evident only in East Asian countries in the early days following its discovery. However, it is currently occurring mainly in East Asia, North America, and Western Europe; Australia and South America are classified as areas at risk of pine wilt disease (Ikegami and Jenkins 2018).

It is difficult to use nematode-damaged pine because it must be fumigated, heat-treated, or chipped to kill the pine nematode or its vectors (Moon 2007; Donald et al 2016). Damaged trees are crushed and supplied as fuel for combined heat and power plants, or used as fertilizer after composting (Kim 2015). The tree loss due to pine wilt disease reaches 10^6 m^3 annually, which has become a serious disaster for the coniferous forest ecosystem (Chen et al 2021).

The pulp and paper industry, which consumes more than 40% of the world's industrial wood, is considered to harm the environment (World Wildlife Fund 2021). As of 2020, the wood self-sufficiency rate in Korea is about 16%, of which the self-sufficiency rate of wood for pulp production is 9% including pine and oak trees, which was $2125 \times 10^3 m^3$. In particular, the amount of pine trees obtained through nematode control and logging operations in areas affected by forest fires is 1873×10^3 m^3 and most of these pines are usually used for fuel.

There are various demands for domestic pine trees for different purposes. And as a major source of raw material for mechanical pulp in Korea, there has been shortage in its supply (Lee et al 2016b). Currently, there is one company in Korea that manufactures about 67,000 tons of thermomechanical pulp (TMP) annually using domestic pine. Considering the yield of TMP, more than 70,000 tons of pine logs are needed every year.

In Korea, the area of pine forests continues to decrease due to infection by wilt worms, climate change, and forest transition. As it is becoming increasingly difficult to secure raw materials for TMP, it is now necessary to use not only pine trees obtained from regular forestry management activities but also those harvested from wilt disease-affected areas.

The use of the nematode-damaged pine trees in the pulp and paper mills will be relatively free from raw material competition and environmental impacts, and the virtuous cycle of resources will lead to sustainable cyclical economic development and value enhancement.

Paper is manufactured by using pulps prepared through a mechanical or chemical pulping process for wood chips, either separately or by mixing them according to the final uses. TMP is a method of mechanical pulping in which pressurized steam is applied to raise the temperature of the wood to soften the lignin, whereas chemithermomechanical pulp (CTMP) also uses alkaline chemicals such as NaOH and Na_2SO_3 during the pulping process to soften wood chips and then refines them to produce pulp with high yields while reducing energy consumption and severe fiber damage (Fiber lab 2013). These mechanical pulps have higher yields than chemical pulps and have the advantage of reducing pulp manufacturing costs (Sundholm 1999; Illikainen 2008; Lee et al 2016b; Lee et al 2016c). During the manufacturing process of TMP, high-pressure steam treatment at 90-140°C and mechanical grinding treatment such as refining are applied to pine chips manufactured from wilt-damaged trees. It is possible to kill nematodes under such harsh manufacturing conditions, so it will be possible to dispel the concern about the spread of these nematodes to the surroundings by the vector in the infected pine chips.

In this study, TMP and CTMP were prepared from *Pinus densiflora* obtained from forest regions damaged by wilt nematodes, and the properties of TMP and CTMP made from normal pine chips were compared with evaluate the suitability of nematode-infected pines as raw materials for TMP and CTMP.

MATERIALS AND METHODS

Raw Material

For the preparation of TMP and CTMP, pine chips manufactured at Jeseoksan Mountain in Geoje-si, Gyeongnam Province, were used. In this area, more than 60% of pine trees were infected with the wilt nematodes, and after clear-cutting, they were chipped at the site (refer to Fig 1). The control chips were provided by Jeonju Paper Co.

Pretreatment of Wood Chips

Before manufacturing TMP and CTMP, the wood chips were washed with water to remove contaminants and impurities. The washed wood chips were impregnated at 40°C for about 12 h and then placed in an autoclave (DS-PAC 40, Lab house Co., Pocheon, Korea) and steam-treated at 90°C for 30 min. To further soften the preheated wood chips, a laboratory digester (Duko, Daejeon, Korea) was used to heat them at a liquid-to-wood ratio of 4:1 and 120°C for 60 min.

To manufacture CTMP, NaOH and Na_2SO_3 were further added to the digester at 3% based on the oven-dried weight of the wood chips representatively. Na_2SO_3 used in the CTMP process was impregnated during pretreatment to soften the chip, and NaOH maintained pH 9-10. This pretreatment caused less destructive separation of fibers, with long fiber and a much lower shive content. The pretreated TMP and CTMP raw materials were refined under the same.

Refining

As shown in Fig 2, the pretreatment wood chips were fed into a single disk refiner (KOS1, Kimhae, Korea) and refined several times at 1500 rpm until there was little change in freeness. Stock throughput was measured through the amount of the stock discharged during refining, and the pulp production efficiency was compared with the power consumption. After refining, a small bundle of wood fibers (shives) was removed using the Sommerville Screen (DM-850, Daeil Machinery Co., Daejeon, Korea) fitted with slots of a width of 0.15 mm and a length of 45 mm. The percentage of shives to TMP and CTMP remaining on the slot plate was calculated as follows:

$$\text{Shives content}(\%) = \frac{\text{Dried fiber weight left on screen (g)}}{\text{Dried fiber weight (g) before screening}} \times 100 \quad (1)$$

After removing shives, the pulps were further refined using a valley beater (DM-822, Daeil Machinery Co., Daejeon, Korea) up to the target freeness, which was 150 mL CSF according to ISO 5264-1.

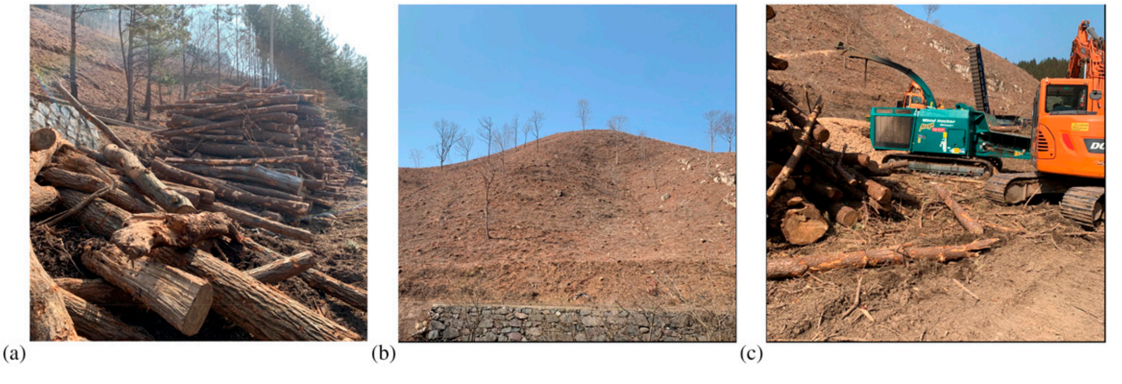

Figure 1. (a) Piles of cut pine trees infected with the wilt nematodes, (b) pine wilt disease-disturbed forest after clear-cutting, and (c) chipping of the infected pine trees.

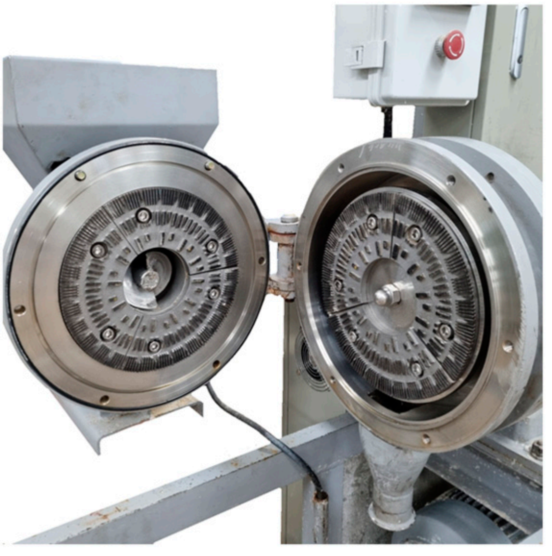

Figure 2. Single disk refiner fitted with thermomechanical pulp (TMP) plate.

Measurement of TMP and CTMP Properties

A fiber quality analyzer (FQA-360, Optest Equipment Inc., Hawkesbury, Canada) was used to measure the mean fiber length and fines contents. For the measurement of physical and optical properties of pulps, handsheets with 60 g/m^2 were produced. Tensile strength and tear strength were measured based on ISO 1924-1 and ISO 1974, respectively. Brightness and opacity were measured using the Elepho Spectrophotometer (Lorentzen & Wettre, Kista, Sweden).

Pitch Analysis

To analyze the pitch in TMP and CTMP, the analysis method applied by Nam et al was used (2015a). Sudan IV dye was used to selectively stain the hydrophobic pitch in TMP. Images of the selectively stained pitches were acquired using a stereomicroscope (Olympus BX51TF, Tokyo, Japan). Pitch analysis was performed using image analysis software (Axiovision, Carl Zeiss, Oberkochen, Germany).

RESULTS AND DISCUSSION

Chemical Characteristics of Infected Wood Chips

Table 1 compares the chemical properties of the control chips and the pine chips produced in the wilt disease-disturbed region. The infected chips had more cellulose and ash, and less lignin than the control chips, although their hemicellulose and extractives contents were similar.

Shives Content

Shives are fiber bundles that are not separated into individual fibers during the mechanical pulping process and can cause paper quality and productivity problems. In making paper using mechanical pulps, shives can lead to machine breaks, coater scratches, pick-out, and poor print quality (Pulmac International 2020). Unfortunately, refining during the TMP process does not break down all of the wood chips into individual fibers.

Figure 3 is a graph comparing the shive contents of TMP and CTMP prepared under the same conditions using normal and infected chips. In both TMP and CTMP, there was almost no difference in the content of shives according to the type of raw material. It is considered that the nematodes simply block the passage of moisture and have little effect on the structure of the pine tree itself. Therefore, this means that the presence of pine wilt disease rarely affects the formation of shives.

Fewer shives were detected in the CTMP samples than in the TMP samples due to the lignin

Table 1. Chemical characteristics of pine chips.

	Cellulose (%)	Extractives (%)	Hemicellulose (%)	Lignin (%)	Ash (%)
Wood chip	48.21 ± 3.62	5.95 ± 1.39	21.70 ± 1.29	23.85 ± 3.72	0.29 ± 0.12
Infected chip	53.89 ± 0.29	4.36 ± 0.27	20.29 ± 0.11	20.90 ± 0.14	0.56 ± 0.04

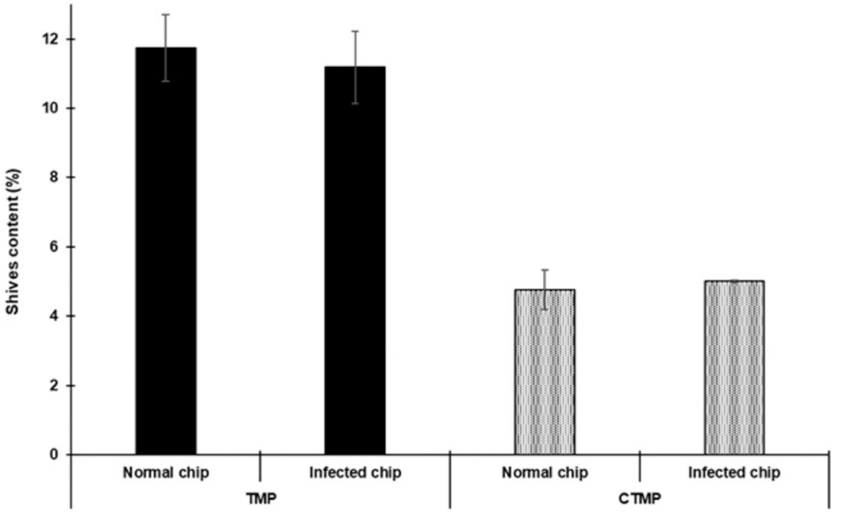

Figure 3. Shives contents of thermomechanical pulp (TMP) and chemithermomechanical pulp (CTMP) manufactured from the normal chip and the infected chip.

softening effect of alkaline chemicals such as NaOH and Na_2SO_3 (Lee et al 2016a).

Pitch Analysis

Pitch and stickies problems are the most common issues in mechanical pulping and papermaking (Guéra et al 2005). The pitch formed in the papermaking process directly affects the end products, such as reduced productivity and sheet break, and also shortens the lifespan of wire or felts, refiners, and other processing equipment (Hoekstra et al 2009). Therefore, it is preferable to avoid including tacky materials in the raw material as much as possible.

Figure 4 shows the number and area of pitches per unit area in TMP and CTMP manufactured from two different raw materials. TMP and CTMP prepared from the infected wood chips showed 27.7% and 9.5% fewer pitches per unit area, and 39.0% and 44.4% smaller pitch areas, respectively, than the normal chips. Lipophilic extractives containing pitches are known to cause problems in pulp and paper mills, mainly in the form of deposits and specks. As shown in Table 1, more contents of extractives were detected in the normal chips than in the infected chips, and it was considered that more pitches and a larger area of pitches were quantified in the TMP and CTMP prepared from the normal chips. The pitch content of softwoods varies depending on the species, age, and region, but there is no direct relationship between the wilt-damaged trees and the pitch content. Nevertheless, it was confirmed that the infected trees used in this study contributed to some extent in alleviating the pitch problem in the manufacturing process of TMP and CTMP.

Stock Throughput

Figure 5 is a graph comparing the stock throughput (g/s) and the refining time consumed up to the target freeness (150 mL CSF) when TMP and CTMP were manufactured using the two types of pine chips. In both TMP and CTMP, the amount of pulp discharged within a certain period of time was greater in the infected chips than in the normal ones. As shown in Table 1, the infected chips contained a lower amount of lignin than the normal chips, and thus were considered to be more easily refined, resulting in greater throughput. There is no direct relationship between the wilt nematodes and the lignin content, and it is known that the lignin content varies depending on the environment in which the infected tree grew.

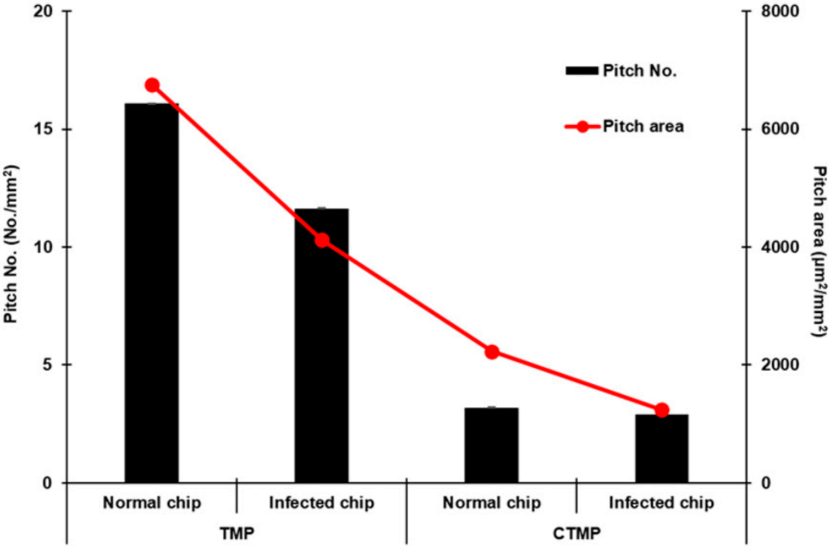

Figure 4. The number and area in a unit area in thermomechanical pulp (TMP) and chemithermomechanical pulp (CTMP) manufactured from the normal chip and the infected chip.

The more lignin the wood chips have, the more slowly the softening occurs. As a result, the swelling of the wood tissue is also slower, requiring more time for refining (Eriksson et al 1991).

Fiber Properties

Figure 6 is a graph comparing the mean fiber length and fines contents of TMP and CTMP prepared from normal and infected chips. Before refining, the infected chips had shorter mean fiber lengths than the normal chips. However, the infected chips after refining, had longer mean fiber lengths and fewer fines than the normal chips. TMP made with the infected chips had 12.7% longer fiber length and 6.7% fewer fines than TMP made using normal chips. CTMP made with the infected chips had 21% longer mean

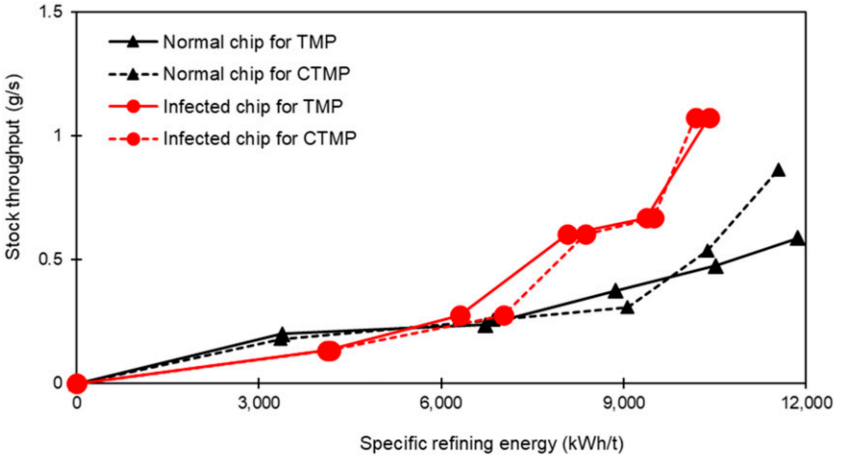

Figure 5. Stock throughput during refining of thermomechanical pulp (TMP) and chemithermomechanical pulp (CTMP) manufactured from the normal chip and the infected chip.

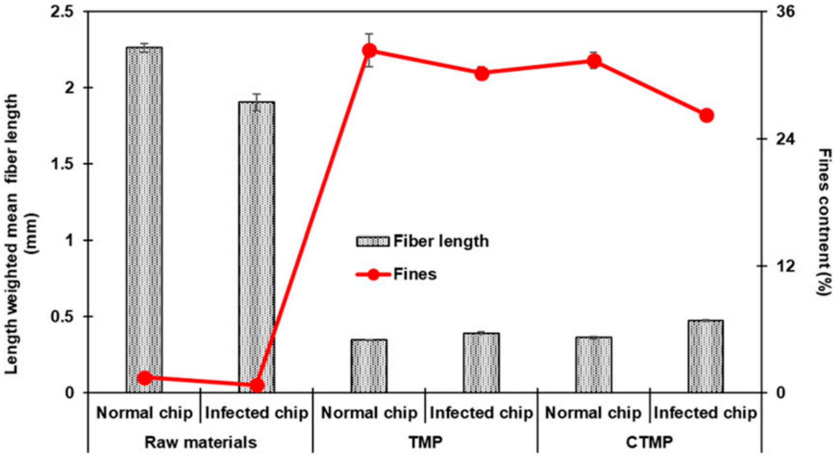

Figure 6. Mean fiber length and fines content of thermomechanical pulp (TMP) and chemithermomechanical pulp (CTMP) manufactured from the normal chip and the infected chip.

fiber length and 13% fewer fines than CTMP made with normal chips. The normal chips with longer fiber length during the manufacturing process of TMP and CTMP seemed to be refined more coarsely than the infected chips, resulting in shorter fiber lengths and more fines.

Fiber coarseness is an index that can indicate fiber flexibility, and if the coarseness is low, the tensile strength is improved due to the high flexibility of the thin-walled fiber (Nordström and Hermansson 2018). Figure 7 is a graph comparing fiber coarseness of TMP and CTMP made with the normal and infected chips. Fiber coarseness of TMP manufactured from the infected chip was 11.5% lower than that from the normal chip. Fiber coarseness of CTMP manufactured with the infected chip was 13.6% lower than that with the normal chips.

In conclusion, it was confirmed that the infected chips from TMP and CTMP could reduce the fiber length loss and contribute to the production of fibers with low coarseness.

Strength Properties

Figures 8 and 9 show the tensile strength and tear strength of TMP and CTMP manufactured from two different raw materials. TMP prepared with infected chips showed 12.7% and 2.6% higher tensile and tear strength, respectively, than TMP prepared with normal chips. CTMP made with

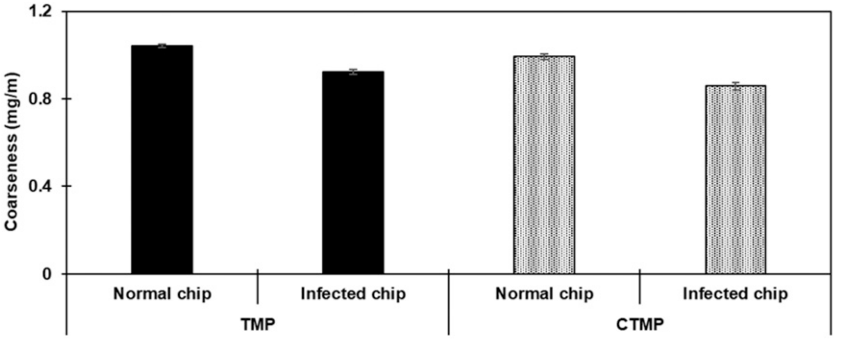

Figure 7. Coarseness of thermomechanical pulp (TMP) and chemithermomechanical pulp (CTMP) manufactured from the normal chip and the infected chip.

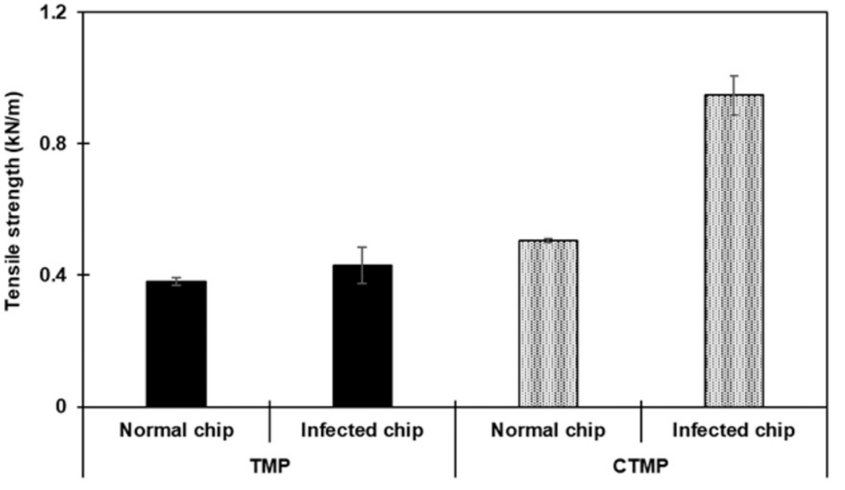

Figure 8. Tensile Strength of thermomechanical pulp (TMP) and chemithermomechanical pulp (CTMP) manufactured from the normal chip and the infected chip.

the infected chips showed 87.1% and 10.3% higher tensile and tear strengths, respectively, than CTMP made with the normal chips. It was considered that the infected chips could induce more fiber-to-fiber bonding because they had longer fiber lengths than the normal chips even after mechanical treatment such as refining.

Unlike other mechanical pulps, TMP requires higher refining energy but can produce pulp with longer fiber lengths and fewer shives and fines, resulting in paper with higher strength. Although this depends on the type of wood species used as raw material, it was greatly encouraging that the pine nematode-infected chips used in this study showed higher tensile and tear strength in TMP and CTMP compared with normal pine chips.

Optical Properties

Table 2 shows the brightness and opacity of TMP and CTMP manufactured from the two different raw materials. There was little difference in the

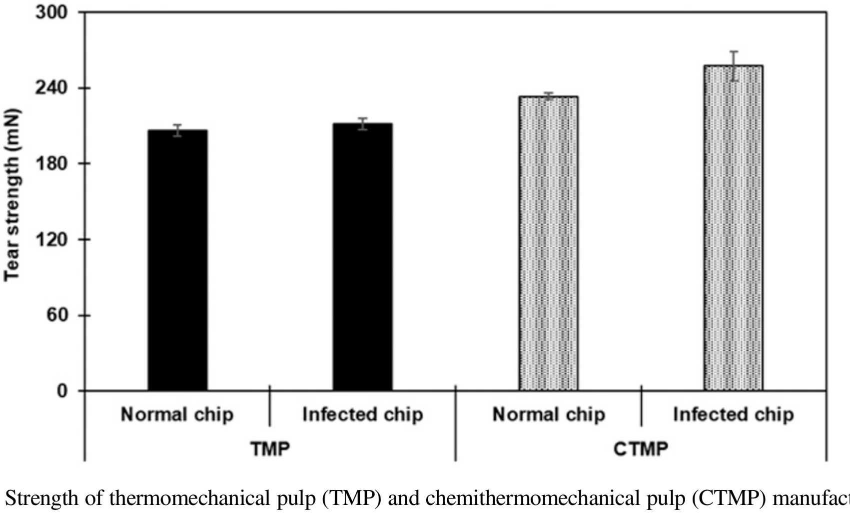

Figure 9. Tear Strength of thermomechanical pulp (TMP) and chemithermomechanical pulp (CTMP) manufactured from the normal chip and the infected chip.

Table 2. Optical properties of TMP and CTMP manufactured from infected pine tree.

	Raw material	Brightness (%)	Opacity (%)
TMP	Wood chip	34.48 ± 0.09	99.46 ± 0.09
	Damaged tree	34.49 ± 0.28	98.95 ± 0.22
CTMP	Wood chip	27.41 ± 0.09	98.96 ± 0.17
	Damaged tree	28.76 ± 0.30	98.09 ± 0.49

CTMP, chemithermomechanical pulp; TMP, thermomechanical pulp.

whiteness and opacity of TMP and CTMP prepared from the infected and the normal chips, respectively. Factors affecting the optical properties of mechanical pulp are very diverse. It is known that these properties are greatly influenced by the qualities of the raw materials, pulping, refining, and chemical treatment eg bleaching (Nam et al 2015b). In particular, the content of lignin and extract and the ratio of heartwood have a great influence on the brightness of mechanical pulp (Mishra 1990) However, the infected chips had slightly less lignin and extract content than the normal chips, but there was no remarkable difference in the brightness of TMP and CTMP.

CONCLUSIONS

After TMP and CTMP were prepared from wilt-nematode-infected pine chips and normal pine chips, their pulping properties were compared. The infected chips had lower amounts of lignin and extractives than the normal chips, leading to the refining energy saving. The fiber lengths of TMP and CTMP prepared under the same conditions were longer and there were fewer fines in the infected chips, and the shives content was also lower in the infected chips. TMP and CTMP prepared from the infected pine chips showed fewer pitch contents than those from the normal chips. Strength properties of the TMP and CTMP showed better values in the infected chips than in the normal chips, and there were no remarkable differences in optical properties.

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