Influence of CTBN content on fracture toughness of PF particleboard

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Abstract. The study investigated whether the single-edge-notch bending method could be used in quantitative determining the fracture toughness of the particleboard. Also, carboxyl-terminated poly (butadiene-co-acrylonitrile) liquid rubber was chosen to improve the fracture toughness of the particleboard. Critical energy release rate $G_{IC}$ and critical stress intensity factor $K_{IC}$ were measured in different directions with sandwich structure and common specimens. The study shows that it is a feasible method to compare the fracture performance of different particleboard by the single-edge-notch bending. The liquid rubber can toughen the particleboard when the addition amount is less than 12% when PF resin was used. More addition can lead to dispersion problem which will decrease the ductility of particleboard.

1. Introduction
Phenolic resin (PF) has many excellent properties, such as adhesion performance, heat resistance, water tolerance, flame retardance, corrosion stability, relatively low price and so on [1-3]. So, it has been widely used in various industrial fields, especially in the wood based composites production. However, PF resin solidifies into a highly cross linked structure making it very brittleness [4-8]. The addition of rubber which has been studied by a lot of researchers can toughen many thermo-set and thermoplastics polymers owing to the crazing, yielding and interface de-bonding mechanism [9-18].

The objectives of this study were (1) to study the feasibility of using single-edge-notched bending to measure the fracture toughness of the particleboard, (2) to compare the varying liquid rubber contents in the resin on the tested fracture performance and (3) to explore the toughening mechanism of particleboard.

2. Materials and methods

2.1. Materials
The wood particles used for the particleboard production were manufactured from poplar (Populus sp.). The average thickness of the wood particles was 0.25 mm. The moisture content of the dried particleboard was 4%. The viscosity of phenolic resin which was made in the laboratory is 255 mPa·s with pH 10.1 (25°C). The solid content of the resin was 45.15%. Carboxyl-terminated poly (butadiene-co-acrylonitrile) (CTBN) was purchased from Jingjiang Tonggao chemical co.LTD.
2.2. **Particleboard manufacture**

Single factor experiment was designed to study the influence of the CTBN loading on the fracture toughness of the particleboard. The target density of the particleboard was 0.65 g/cm$^3$. The resin content was 8%. The dispersion of PF adhesive on the wood particles was carried out by a spraying device combined with a blender. Prior to the adhesion spraying, the PF resin was mixed with different weight CTBN. The CTBN weight percentage of 4%, 8%, 12% and 16% was uniformly mixed with PF resin by a high speed mixing plant. The hot pressing temperature was 180°C and pressing time was 40 s/mm. The thickness of the particleboard was 10 mm controlled by two thickness gages between the hotpress boards.

2.3. **Fracture toughness test method**

A sandwich three point bend specimen was chosen for the fracture toughness test with the crack opening direction parallel to the board surface (P style). And also, the fracture performance with crack opening perpendicular to the board surface was also studied by the common three point bend specimen (C style) with pre-crack length a. The two crack opening directions are shown in Figure 1. The thin particleboard is sandwiched by two pine bars in the P style test (Figure 2). The test specimen width ($W$) is 60mm. The test specimen thickness ($h$) is 10mm. The total length of the sample is 300 mm with 240 mm span between rollers. A micro-band saw was used to machine the first 28 mm depth notch with 0.65 mm thickness band saw blade. The top-most 2 mm was made by a sharp razor to ensure the crack would be sharp enough so that an even sharper crack will not result in significantly lower values of the measured properties. So the total length of the pre-crack is 30 mm which is 50% of the specimen width. All the fracture toughness test procedure was operated according to ISO 13586-2018 with the single-edge-notch bending (SENB). Displacement corrections were also operated accordingly and then the three point bending displacements were corrected for indentation effects. The determination of the applied load at the initiation of crack growth was determined by the method shown in Figure 3 on the condition that the $F_{\text{max}}/F_0$ was less than 1.1. The energy $W_B$ to break was calculated by the integral of force and displacement.

**Figure 1.** The two directions (C and P styles) of the crack opening on fracture toughness test.

**Figure 2.** The SENB test specimens of C and P styles under three point bending.
Figure 3. The load-displacement curve for the SENB test and the determination of $F_Q$ and $W_B$. $s$ is the original slope of the curve and another line with 95% of $s$ is also drawn. $F_Q$ is the intersection between the curve and the 0.95$s$ line. When $F_{max}/F_Q$ is less than 1.1, $F_Q$ is valid.

2.4. Statistical analysis

Unpaired two sample t-tests and one-way analysis of variance (ANOVA) were conducted on Excel 2016 (Microsoft, USA). Factors influences were considered to be significant if the P value was less than 0.05.

3. Results and discussion

3.1. Effects of test directions on the fracture toughness

To compare the different fracture toughness by the sandwich and general three point bend specimen between the pre-crack surface parallel or perpendicular to the board surface in the opening mode (mode I), the results are shown in Table 1. $K_{IC}$ ranged from 43 to 81 kPa $\cdot \sqrt{m}$ and $G_{IC}$ ranged from 167 to 299 J/m$^2$ when the particleboards were manufactured without CTBN. The measured fracture toughness expressed by $K_{IC}$ and $G_{IC}$ with SENB method was close to the results studied by Rathke et al. with DCB method [4-7]. The size criteria and cross check of the results were also done according to ISO 13586:2018. All the criteria were met and the results of the test were valid. So, the SENB test can be used to quantitatively characterize the particleboard toughness.

Table 1. The measured $K_{IC}$ and $G_{IC}$ in the two directions of particleboard with different amount of CTBN.

| CTBN | Type | $K_{IC}$ (kPa $\cdot \sqrt{m}$) | SD | $G_{IC}$ (J/m$^2$) | SD |
|------|------|-----------------|----|-----------------|----|
| 0    | C    | 68              | 7.6| 267             | 32 |
|      | P    | 55              | 7.5| 198             | 28 |
| 4    | C    | 72              | 8.7| 280             | 35 |
|      | P    | 61              | 7.5| 223             | 28 |
| 8    | C    | 80              | 7.6| 316             | 35 |
|      | P    | 66              | 6.5| 243             | 29 |
| 12   | C    | 86              | 8.1| 331             | 38 |
|      | P    | 70              | 8.2| 265             | 34 |
| 16   | C    | 82              | 7.3| 325             | 31 |
|      | P    | 70              | 8.9| 257             | 29 |
From Table 1 above, we can see that the fracture toughness of pre-crack opening perpendicular to the board surface under three point bending test was higher than parallel. There were significant differences in $K_{IC}$ and $G_{IC}$ between the two directions ($P > 0.05$) studied by t-test with independent samples, no matter CTBN was added or not. As we know, the density of the near surface of particleboard is higher than the middle. Because the wood particles size of the entire board were the same, the density improvement could contribute to the fracture toughness.

The variability of the test results were also calculated. It can be seen from the data in Table 1 that the dispersion of the $K_{IC}$ and $G_{IC}$ is very similar with variable coefficient located between 8.9% to 12.83%.

### 3.2. Effects of CTBN on the fracture toughness

In one-way ANOVA analysis result manifestation, the CTBN content in the PF resin in the range from 0 to 16% had significant influence on the final fracture toughness of particleboard in both the two test directions. Both $K_{IC}$ and $G_{IC}$ increase ratio compared to the control group without CTBN were shown in Figure 4 and 5. As you can see from Figure 4, the $K_{IC}$ starts with an increase and then goes down. The maximum increase ratio reached 26% and 27% in the two direction respectively when the CTBN content was 12% in the PF resin. The relationship between the increase ratio and the CTBN content display the same pattern. The 16% loading content of CTBN in PF resin more or less would reduce the fracture toughness of the particleboard. When CTBN content was lower than 12%, the disperse was good making the fracture toughness improve. When CTBN content was higher than 12%, the disperse become worse and the aggregation had an adverse influence on the fracture toughness.

![Figure 4. Increase ratio of $K_{IC}$ compared to the control group.](image)

![Figure 5. Increase ratio of $G_{IC}$ compared to the control group.](image)

### 4. Conclusions

The single-edge-notch bending (SENB) with a sandwich structure is a useful way to measure the fracture toughness of the particleboard. The measured results of $K_{IC}$ and $G_{IC}$ by SENB are very close to DCB test. CTBN can significantly improve the fracture toughness of the particleboard in the two directions of the pre-crack opening. The optimized addition amount in the PF resin is about 12% and the fracture toughness can be improved by about 25%.

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