The Influence of Consistency and Fibre Length on the Yield Stress of OCC Pulp Fibre Suspensions

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The effect of fibre length on the yield stress of recycled old corrugated containers (OCC) pulp fibre suspensions was investigated. Two types of OCC pulps were divided into four fractions based on the fibre length with a Bauer-McNett classifier. The yield stress of each fraction was measured using the shear stress ramp method at pulp consistency ranging from 0.5% to 2.5% (w/v). The results showed that both pulp consistency and fibre length had significant effects on the yield stress of OCC pulp suspensions, and the yield stress was greater with increasing fibre length and pulp consistency. Moreover, the effect of consistency in OCC pulp suspension with long fibres on the yield stress was stronger than in the slurry with short fibres.

Keywords: Yield stress; OCC pulp fibre suspensions; Consistency; Fibre length; Classifier

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INTRODUCTION

The flow of pulp suspensions is an important parameter in manufacturing various products, such as polymeric composites (Advani 1994), composite materials (Papthanasiou and Guell 1997), food (Piteira *et al*. 2006), textiles (Umer *et al*. 2007), and pulp and paper (Bousfield 2008). The pulp and paper industry is a significant part of the global economy, and it provides a variety of commercial consumer products, including communication papers, packaging boxes, tissue papers, and hygiene products. Due to the shortage of wood fibres and the increasing market demand for packaging products, recycled old corrugated container (OCC) has been widely used by most linerboard manufacturers to produce boards of various grades and corrugating mediums of different specifications for different industrial packaging purposes (Kang *et al*. 2017). Within this context, it is of great importance to study the flow of OCC pulp suspension in the papermaking industry to improve the OCC pulp papermaking process.

During the papermaking process, the large aspect ratio of pulp fibres induces significant fibre-fibre contacts, which greatly affects pulp suspension rheology. In addition, as the pulp consistency increases, the fibre-fibre contacts will transfer from occasional collisions to forced contacts or even continuous contacts (Derakhshandeh *et al*. 2011). The degree of fibre-fibre contacts has been described as a crowding number, N, which is defined as the number of fibres in a volume swept out by the length of one fibre (Kerekes *et al.* 1985). It can be expressed in terms of a mass consistency C_m (%), fibre length L (m), and coarseness ω (weight per unit length of fibre, kg/m) (Kerekes and Schell 1992) (Eq. 1),

$$N \approx 5.0 C_{\mathrm{m}} \frac{L^2}{\omega} \tag{1}$$

where N is crowding number (kg/m^3).

Previously, Mason (1950) identified N as a "critical concentration" in which occasional collisions occur among fibres in a shear pulp suspension. Soszynski and Kerekes (1988) and Kerekes and Schell (1992) found that fibre flow has approximately three contacts per fibre at $N \approx 60$. This is a critical value in that fibres are restrained by three-point contacts. Martinez *et al*. (2003) identified another critical N value of about 16 and named this as a "gel crowding number". A fibre suspension behaves as essentially dilute when it is below this N value. With N values between 16 and 60, fibre suspensions correspond to the fibre networks of "connectivity threshold" to "rigidity threshold" (Celzard *et al*. 2009). To initiate motion throughout the suspensions, the shear force should be high enough to deconstruct the connectivity threshold network strength, which is called the yield stress of the pulp suspension (Derakhshandeh *et al*. 2010).

As it is the most important rheological property of the fibre suspension, yield stress was measured for virgin wood pulp, recycled pulp, and synthetic fibre suspensions at low and medium consistencies (Bennington *et al*. 1990). There are substantial definitions and methods for the measurement of yield stress. Two methods normally used for the measurement of yield stress of pulp suspension are "quasi-static" shear strength, which employs a conventional rheometer-like device to rupture the fibre network at rest, and "dynamic surface" strength, obtained from the disintegration of the fibre network in flowing pulp suspensions (Daily and Bugliarello 1961; Mih and Parker 1967; Duffy and Titchener 1975; Bennington *et al*. 1990). To determine the yield stress experimentally, several studies have been carried out with wood pulps (Kerekes *et al*. 1985; Bennington *et al*. 1990). The correlation of the experimental results with the volumetric concentration is represented with the following equation,

$$\tau_y = a C_V^b \tag{2}$$

where τ_y is the yield stress (Pa), a and b are constants that depend on test conditions and fibre properties, and C_V is the volumetric concentration of the pulp fibre suspension (%).

Dalpke and Kerekes (2005) studied the effect of fibre properties on the yield stress of pulp suspensions and found that longer fibres had a greater yield stress than shorter fibres. Similar results were also reported by Ventura *et al*. (2007), who measured the yield stress of long-fibre and short-fibre bleached kraft pulp suspensions and established a mathematical model describing yield stress as a function of fibre length, consistency, and temperature. OCC, as an important source of secondary fibres, continues to play an increasing role in the pulp and paper manufacturing process. However, compared with virgin wood pulp, the paper strength obtained from OCC is much lower due to the existence of short fibres and the variability in the collection process (Minor and Atalla 1992). Fractionation, which separates fibres based on the fibre length, is a promising strategy to improve paper strength and reduce process energy during the utilization of OCC pulp in the papermaking industry (Pekkarinen 1985; Musselmann 1993).

In this study, two types of OCC pulps were fractionated into four fractions based on the fibre length. The stress ramp method was used to obtain the yield stress of different pulp suspensions with different fibre lengths at pulp consistencies ranging from 0.5% to 2.5% (w/v). This study could be a guide in the application of OCC pulp for the production of various commercial products including linerboard, corrugating medium, and folding boxboard.

EXPERIMENTAL

Raw Materials and Fractionation

Two types of recycled OCC, American old corrugated container (AOCC) and Chinese old corrugated container (COCC), were provided by the Lee & Man Co. Ltd., Jiangsu, China. The obtained commercial AOCC and COCC were torn into pieces with a size of 10 mm to 15 mm in width and 12 mm to 17 mm in length and soaked in distilled water for 24 h. The soaked materials were refined for 15 min at 10% pulp consistency using a Valley Beater (ZQS2-23L, Machinery Factory of Shanxi University of Science & Technology). After refining, the obtained pulp was centrifuged and homogenized for fractionation. For one fractionation run, 24 g of oven dried (o.d.) OCC pulp was fractionated for 20 min with a Bauer-McNett classifier (PTI, Laakirchen, Austria) following TAPPI T233 cm-95 (1995). Screens with four different sizes, 30-mesh, 50-mesh, 100-mesh, and 200-mesh, were used for the fractionation. The fractionated pulps were collected and kept at 4 °C until subsequent experiments. The weight percentage of each fraction (based on original raw material) was determined by drying the sample at 105 ± 2 °C to a constant weight. All experiments were performed at least in triplicate.

Yield Stress Determination

The yield stress of each pulp suspension was measured using a RST-SST rheometer (Brookfield Inc., Middleboro, MA, USA) at a constant temperature of 26 °C. A standard four-bladed rotor with 20 mm in width and 80 mm in height was used for these tests. To obtain a uniform initial pulp sample, all samples were pre-sheared at 200 s^{-1} for 3 min and allowed to settle for 5 min. A stress ramp yield stress method was used to determine the yield stress (Møller *et al*. 2006). Pulp suspensions with the consistency of 0.5% to 2.5% (w/v) were used during this method. All measurements were conducted at least in triplicate.

Analytical Methods

The fibre morphology was observed with a light microscope (SK2000Digital, Motic, Xiamen, China). Pulp properties of length weighted fibre length, coarseness, fibre width, curl index, and fines content were determined with a Fibre Quality Analyzer (FQA; OpTest Equipment Inc., Hawkesbury, Canada). A total of 2 to 5 mg o.d. pulp samples were diluted with 600 mL distilled water and mixed for 5 min before the measurement with the FQA.

RESULTS AND DISCUSSION

Fibre Length Distribution

Normally, COCC pulp has a shorter fibre length and lower pulp strength than AOCC pulp, probably due to the higher number of recycled times (Kang *et al*. 2017). To improve the papermaking properties of COCC pulp, such as by increasing paper strength and making the comparison with AOCC pulp, fibre length distribution of the two pulp samples (COCC and AOCC) was investigated by fractionating into four different fractions according to fibre length. Figure 1 shows the results of the fractionated fibre mass distribution of AOCC and COCC pulps. The fibres retained on the 30-mesh screen are defined as long fibre. Approximately 60% of fibres of AOCC pulp were long fibres, which was higher than that of COCC pulp (35%) (Fig. 1). The fibre fraction between 50-mesh and 200-mesh wire was normally called the short fibre fraction. Figure 1 shows that the short fibre fraction of COCC pulp was 42%, which was about twice the value of the fibre fraction obtained from AOCC pulp. The fines are defined as the fibres that can pass through the smallest mesh screen (Mooney *et al*. 1999). The fines content (< 200 mesh) of COCC pulp was still about 2.5 times that of AOCC pulp. These results provide an opportunity for improving the papermaking process with the use of OCC as the raw material, for example, increasing the paper strength or reducing the cost by changing the ratio of AOCC to COCC in the pulp preparation (Hunt and Vick 1999).

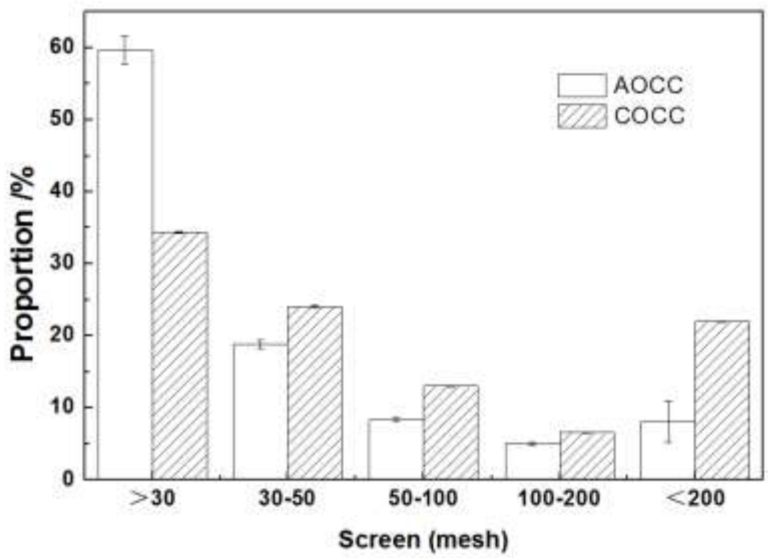

Fig. 1. The distribution of AOCC and COCC pulp fibre length using Bauer-McNett (30-mesh, 50-mesh, 100-mesh, and 200-mesh, respectively). (AOCC: American Old Corrugated Container; COCC: Chinese Old Corrugated Container)

Fiber Properties

Figure 2 shows microscopic images of AOCC and COCC pulp fibres before and after fractionation with 30-mesh, 50-mesh, 100-mesh, and 200-mesh screens. The length of fibres from both AOCC and COCC pulps gradually decreased with increasing screen mesh under the same magnitude ratio. In addition, the length of COCC pulp fibres was generally shorter than that of AOCC pulp from the same pulp fraction (Fig. 2).

To further evaluate the differences between the two pulp fibres, pulp analysis with the FQA was conducted. Triplicate experiments were performed to minimize experimental errors.

Table 1 shows the different fractions of the two pulp fibres (AOCC and COCC). The average weighted length was recorded, as it shows the effect of short fibre fragments in the pulp suspension. The average weight length decreased with increasing the screen mesh due to the presence of a large amount of short fibre fractions. Similar to the results obtained from microscopy imaging experiments, the AOCC pulp had a larger average weight length compared to COCC pulp, showing that AOCC pulp might be taken as a feedstock of long fibres in the papermaking industry. Fibre coarseness, the fibre mass per unit fibre length of the sample, was initially decreased with the decrease of fibre length for both AOCC and COCC pulps; thereafter it increased (Table 1).

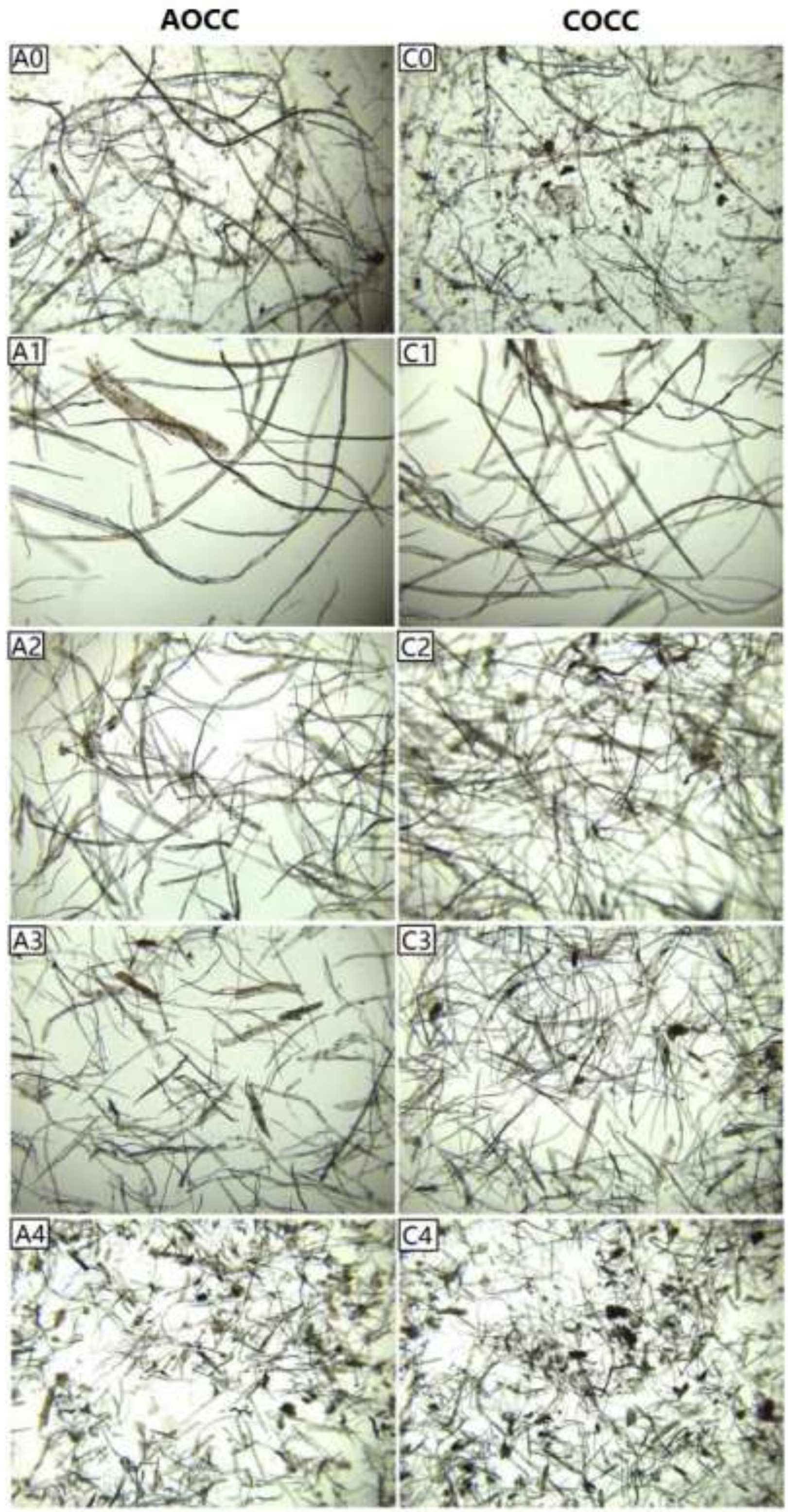

Fig. 2. Fiber morphology of AOCC and COCC pulp fibres before and after fractionation. A0 and C0 (unfractionated pulp) shows the morphology of unsized AOCC and COCC pulp fibres. AOCC A1, A2, A3, and A4 at 30-mesh, 50-mesh, 100-mesh, and 200-mesh screens, respectively; COCC C1, C2, C3, and C4 at 30-mesh, 50-mesh, 100-mesh, and 200-mesh screens, respectively. Scale bar 50 μm

One possible explanation might be that the amount of low aspect ratio tiny fibres collected from A4 and C4 increased considerably, thereby increasing the pulp coarseness (Seth 1990; Karlsson 2006). The fibre curl index, which is the real fibre length to projected length ends minus one, is an assessment of the straightness of the fibre (Gion *et al*. 2011). The curl index of both AOCC and COCC pulps was initially decreased with the decrease of fibre length, but it increased thereafter (Table 1). One likely reason might be that the irregular impurities (such as sand) in the pulp might have an increasing effect on the fibre curl index with decreasing fibre size (Fig. 2). According to data shown in Table 1, AOCC pulp might be a better pulp for high strength packaging paper. For example, the fibre length, one of the most important parameters to evaluate pulp properties, of AOCC was longer than that of COCC pulp during screening under the same sieve mesh. At 2.5% significance level, there is sufficient evidence that the fibre length of AOCC is larger than that of COCC (under 30-mesh, 50-mesh, 100-mech, respectively).

Table 1. Properties of Fractionated OCC Pulp Samples (all values are expressed as mean ± SD)

Samples	AOCC				COCC			
Fractionation	A1	A2	A3	A4	C1	C2	C3	C4
Screen mesh	30	50	100	200	30	50	100	200
Mean Length Weighted (mm)	2.483 ±0.029	1.147 ±0.002	0.728 ±0.003	0.440 ±0.007	2.195 ±0.021	1.001 ±0.003	0.658 ±0.001	0.444 ±0.026
Coarseness (mg/m)	0.176 ±0.007	0.122 ±0.001	0.115 ±0.003	0.121 ±0.001	0.173 ±0.003	0.107 ±0.001	0.102 ±0.001	0.178 ±0.001
Average Fibre Width (μm)	28.1 ±0.2	21.4 ±0.1	19.1 ±0.1	18.8 ±0.1	26.0 ±0.3	19.1 ±0.1	17.6 ±0.1	18.8 ±0.4
Mean Curl Index (%)	11.9 ±0.9	8.1 ±0.1	7.6 ±0.2	11.7 ±0.3	9.8 ±0.4	8.1 ±0.1	7.6 ±0.1	13.7 ±2.6
Fines Content (%)	2.46 ±0.11	0.74 ±0.04	1.02 ±0.05	10.50 ±0.14	1.06 ±0.07	0.61 ±0.01	1.12 ±0.05	9.05 ±0.19

Effect of Pulp Consistency and Fibre Length on the Yield Stress

During the measurement of yield stress with the consistency ramp method, pulp consistencies of 0.5%, 1%, 1.5%, 2%, and 2.5% (w/v) were used. Figure 3 shows the results of yield stress of each fibre fraction for both AOCC and COCC pulps. The yield stress of both AOCC and COCC pulp suspensions increased non-linearly with the increase of pulp consistency. For example, with the same pulp fibres (> 30 mesh), the yield stress of a pulp suspension at 0.5% was 2.25 Pa, while it increased to 58.65 Pa when the pulp consistency was increased to 2.5% (A1 line in Fig. 3). This result was attributed to the fact that there were more fibres per volume of suspension at a high pulp consistency; this increased the fibre-fibre interactions, resulting in a higher yield stress (Sha *et al.* 2015). Moreover, the yield stress for each fraction of AOCC pulp was slightly higher than the corresponding fraction of COCC pulp under the studied fibre concentrations (Fig. 3). For example, at the pulp consistency of 2.5%, the yield stress of > 30 mesh fibres fractionated from AOCC pulp was 58.65 Pa, while it was 53.03 Pa for > 30 mesh fibres from COCC pulp (Fig. 3). One likely reason might be that fibres obtained from COCC pulp had a shorter average fibre length than those fractionated from AOCC pulp, resulting in much weaker fibre-fibre interactions and a lower amount of contacts in COCC pulp.

In addition, the yield stress of pulp suspension also increased with the increase of fibre length (Fig. 3). For example, the yield stress of A1 pulp was 45.10 Pa at the pulp consistency of 2.0%. In contrast, at the same pulp consistency (2.0%), the yield stress decreased to 5.65 Pa for the A4 pulp. This could be due to the strong fibre-fibre interactions, such as twists, formed by long fibres, which thereby increase the stress required to initiate the flow. Moreover, the effect of pulp consistency was found to be much stronger on long-fibre suspensions than on short-fibre suspensions. This is different from the results obtained by Ventura *et al*. (2007), who investigated the fibre suspension rheology of bleached kraft softwood and hardwood pulps. This distinction can be explained by the differences of the fibre structure between the two kinds of pulps.

Figure 3 also illustrates that the yield stress of original AOCC pulp, ranging from 1.46 Pa to 44.55 Pa (A0 in Fig. 3), was generally higher than the original COCC pulp (0.74 Pa to 17.37 Pa) (C0 in Fig. 3) under the studied pulp suspension consistencies. This result suggests that original AOCC pulp contained higher amounts of long fibres compared with COCC pulp, which was confirmed in Fig. 1. Moreover, the results in Fig. 3 further indicated that the effect of pulp consistency on yield stress for both AOCC and COCC pulps was not very significant from 0.5% to 1.5% (w/v); thereafter, the increase in the yield stress started to increase rapidly. Thus, a pulp consistency of less than 1.5% (w/v) is an option to reduce the energy required for the pulp flow.

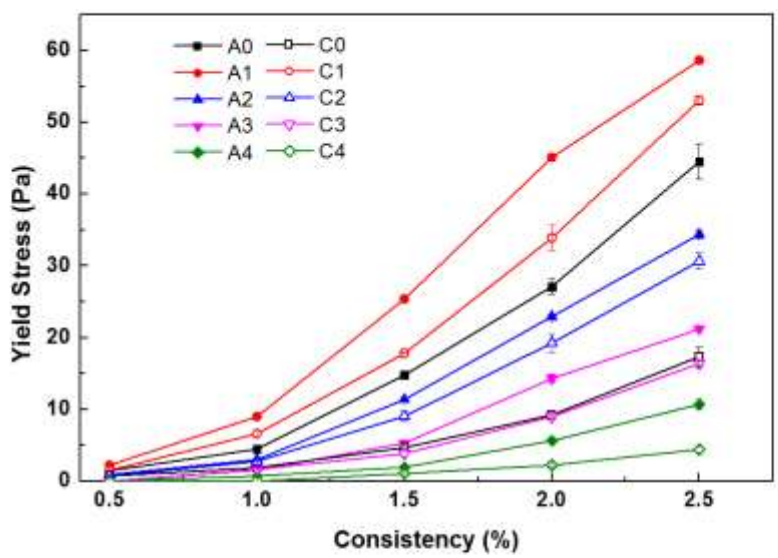

Fig. 3. Yield stress versus consistency for AOCC and COCC pulp suspensions. A0 and C0 (unfractionated pulp) shows morphology of unsized AOCC and COCC pulp fibres. AOCC A1, A2, A3, and A4 at 30-mesh, 50-mesh, 100-mesh, and 200-mesh screens, respectively; COCC C1, C2, C3, and C4 at 30-mesh, 50-mesh, 100-mesh, and 200-mesh screens, respectively.

CONCLUSIONS

1. Compared with American Old Corrugated Container (AOCC) pulp, Chinese OCC (COCC) pulp contained higher contents of short fibres and fines content and lower contents of long fibres.
2. Over the range of consistencies studied, the yield stress of both AOCC and COCC pulp suspensions increased non-linearly with increasing consistency.

3. The yield stress of fibre suspension increased with the increase of fibre length for both AOCC and COCC pulps. The yield stress of AOCC pulp was generally higher than COCC pulp due to the differences in long-fibre content.
4. The effect of pulp consistency in long-fibre OCC pulp suspensions is stronger than in short-fibre suspensions.
5. Pulp fractionation is a suitable strategy to study the rheology of pulp fibre suspensions of OCC pulp, which could improve the pulp flow system of a commercial papermaking mill.

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