The Impact of Fiber Dispersion on Filtration and Tensile Properties of Glass Fiber Filter Paper

Min Tang, Yun Liang, Jian Hu

South China University of Technology, Guangzhou, Guangdong CHINA

Correspondence to:
Yun Liang email: liangyun@scut.edu.cn

ABSTRACT

Air quality control has become increasingly important in many industrial areas. Glass fiber filter paper is widely used for the collection of airborne particulate matter. Since glass fiber is fragile, fiber dispersion is believed to be important for controlling filter paper properties. In this paper, the impact of fiber dispersion on filtration performance and tensile properties was studied. Two types of glass fiber filter paper prepared from six different dispersing methods were used to analyze the impact of dispersion on filtration and tensile properties. Rotational viscosity was used to characterize the fiber dispersion process. Dispersing strength and time had no significant effect on filtration properties, namely the pressure drop, penetration and figure of merit. The fiber composition should be the determining factor of filtration properties. Dispersing strength and time had little effect on the virgin tensile strength of glass fiber paper, while the tensile strength retention after folding was highly affected by dispersion. It is suggested that fiber cutting should be reduced in the fiber dispersion process for higher tensile strength retention.

INTRODUCTION

Particulate matter control in the air is becoming crucial where requirements of air cleanliness are increasingly stringent. The food, biotechnology, pharmaceutical, semiconductor, micro-electronics industries and fields involving sensitive micromechanical work are among those industrial areas that demand air cleanliness as a prerequisite in everyday production [1]. Filters and other particle air cleaners are used extensively in buildings to remove particles from incoming outdoor air and from recirculated air to protect products, process equipment and personnel from being adversely affected by airborne contaminants [2, 3, 4].

For air filters, a crucial property is penetration or filtration efficiency, which represents the ability to capture particles. During the life cycle of a filter, the operating cost is considerably affected by pressure drop. Lower pressure drop means less energy consumption by air filtration systems [5, 6], which in turn leads to lower operating cost and longer service life. An ideal filter should have a low pressure drop and high capture efficiency [7]. The performance quality of filter media is typically characterized by figure of merit [8], which can be calculated by Eq. (1)

$$Figure\ of\ Merit = \frac{-\ln(P)}{\Delta p} \quad (1)$$

where P is the penetration ratio of the particle number concentration downstream of the filter media to the particle number concentration upstream and Δp is the pressure drop or filtration resistance, Pa.

Mechanical properties of filers are also important. Good mechanical properties lead to good filtration performance. Mechanical property development in filtration media results from random and non-linear interactions between large numbers of fibers [9]. Tensile strength of a filter is defined as the maximum load it can endure without breaking when subjected to uniaxial tensile loading [10].

The pleating process is crucial to the development of filtration properties during the manufacturing of air filters. Pleating of filter media produces an increase in the filtration surface, and thus the particle collection efficiency. It also reduces the pressure drop, which increases filter life [11]. However, the pleating process may damage the filter media and cause leakage in the pleated part. The Institute of Environmental Sciences and Technology, IEST, recommends measuring the virgin tensile and creased tensile properties of filters as a means of evaluating the effect of pleating on the tensile strength [12]. In this study, these concepts are used to analyze the tensile properties for filter paper.

Fibrous filters have proven to be useful in aerosol filtration [7]. Glass fiber filter paper is widely used for the collection of airborne particulate matter, and this kind of filter paper is both inexpensive and highly efficient [13]. Glass fiber filter paper is manufactured using the papermaking process with fibers bonded together with a suitable resin. The fibers are blended in a slurry or pulp stock containing water and acid, and then transferred to a series of machine chests that are equipped with agitation [14]. Fiber dispersion is crucial in order to obtain uniform fiber suspension and make the manufacturing process consistent. Since glass fiber is more fragile than cellulose fiber and synthetic fiber, the dispersion process could damage the glass fibers by cutting them. The reduction of fiber length could affect the filtration and tensile properties. There is little research on this topic, so this research studies the impact of fiber dispersion on filtration performance and tensile properties of the filter media.

EXPERIMENTAL METHODS

Fiber Specification

Chopped glass fiber and glass microfiber were dispersed together to prepare the filter paper. Chopped glass fiber #1 was E-glass with uniform diameter of 6 μm and length of 6 mm. Glass microfiber #2 and #3 were flame attenuated from commercial 475 glass with polydisperse fiber diameter and length. The average diameter of glass microfiber #2 and #3 was 2.6 μm and 1.0 μm, respectively according to the manufacturer (Shenyang Dongxiang Glass Fiber Ltd, Shenyang, China). Two types of filter paper, with fiber compositions shown in *Table I*, were prepared by the wet-laid method in the lab. Filter paper A was dominated by coarser fibers, while filter paper B was dominated by finer fibers.

TABLE I. Weight percentage of fibers in the filter paper.

No.	Filter paper A	Filter paper B
Chopped glass fiber #1	40%	10%
Glass microfiber #2	40%	10%
Glass microfiber #3	20%	80%

Fiber Dispersion Methods and Characterization

A standardized fiber disintegrator (according to ISO 5263-1 [15], PTI Austria GmbH) and a compact blender (model: HR2024, Philips) were used to disperse the fibers. The compact blender with a serrated blade provided higher shear force in fiber suspension than the standardized fiber disintegrator. The dispersion methods are shown in *Table II*. Dispersion times of 200 seconds in standardized fiber disintegrator and 60 seconds in compact blender were required to obtain well-dispersed fiber suspension based on observation. Before dispersion, the addition of acid, e.g. sulfuric acid, was necessary in order to keep the pH of fiber suspension in the range of 2.5 to 2.8. Acid was beneficial for dispersing glass fiber and keeping fibers from entangling. The mass concentration for dispersion in this study was 0.1 percent.

TABLE II. Fiber Dispersion Methods.

Dispersion method	Fiber dispersion device	Dispersion time (seconds)
a-1	Standardized fiber disintegrator	200
a-2	Standardized fiber disintegrator	600
a-3	Standardized fiber disintegrator	1000
b-1	Compact blender	60
b-2	Compact blender	180
b-3	Compact blender	300

Glass fibers, particularly glass microfiber, were rather fragile and easily broken, so the dispersion process can decrease the fiber length. Since the glass microfiber is very fine, conventional devices, e.g. Kajaani FS300 fiber length analyzer, do not measure the fiber length reliably. In this study, the length of dispersed fibers was characterized by rotational viscosity. The large aspect ratio of fibers (40–100) induces significant contact among fibers and has a strong effect on suspension rheology [16]. There is a unique positive relation between fiber length and viscosity [17, 18]. The rotational viscometer (Model: DV-II+, Brookfield Engineering) with a vane spindle (V-72) was used. The use of the vane spindle resulted in reliable and repeatable data. The spindle speed was 100 rpm. The viscosity tests on the fiber suspensions temperature were carried out at room temperature.

Filter Paper Preparation

The glass fiber filter paper handsheet was prepared according ISO 5269-1:2005 [19]. The basic weight target of filter paper was 70 ± 2 g/m^2. The fibers were weighed by electronic balance with 0.001g accuracy based the ratios in *Table I*. The fibers were dispersed according to methods in *Table II* and transferred to the standard handsheet former (PTI Austria GmbH). Five liters of water with a pH of 2.5 to 2.8 was added into the handsheet former to decrease the fiber consistency and improve the handsheet formation. After drainage and formation, glass fibers were retained on the metallic wire and thus a wet handsheet was formed. Finally, the wet handsheet was carefully transferred to the dryer and dried under 105^{o}C for 20 minutes. Five samples of each type of paper were prepared.

Reinforced acrylic resin (HY26120, Lubrizol Corp.) was applied to the dried paper. The mass concentration of resin was diluted to 0.8 percent. The paper supported by a Teflon wire was fully immersed into the resin for 1 minute. Then the wire and paper were taken out and put into the air-circulating oven (Model: DHG-9070B, Shanghai Shenxian Plant, China) at 120^{o}C for 15 minutes. After drying, the weight percentage of resin in paper was 5 ± 0.7 percent. The dried papers were used for further testing.

Filtration Performance Test

The pressure drop and penetration were measured using automated filter testers (Model 8130, TSI Inc., USA). In this study, 2% NaCl solution was used to generate solid particles for filtration test. The NaCl solution was atomized by clean and dry compressed air in the aerosol generator. The generated solution droplets flowed out to the impactor. The impactor removed large particles and made the particle size distribution sharper. The remaining droplet went to a mixing chamber, in which the solution droplets mixed with hot air, evaporating the water. The particle surface was charged by the drying process. The air from the neutralizer was ionized by high voltage. The dried particles were exposed to the ions in the mixing chamber and the particle charges became Boltzmann Charge Equilibrium, which was close to the particles charging state in the ambient air. After charging the solid NaCl particles were tested for filtration performance. According to the specifications from TSI Inc., the mass mean diameter of the generated NaCl particles is 0.26 μm with geometric standard deviation less than 1.86. Since this diameter is near the Most Penetration Particle Size of mechanical filter, the filtration test results represent the worst filtration performance as a function of particle size. The particle concentration is 12~20 mg/m^3.

The filter papers were mounted in the filter holder with the test area of 100 cm^2. The upstream and downstream of the filter holder were connected to a pressure transducer and two photometers. The pressure transducer measured the pressure drop across the filter paper. The photometer tested the overall particle concentration of sampling air from upstream and downstream. The upstream concentration, N_{up}, and downstream concentration, N_{down}, were used to calculate the penetration, P, as shown in Eq. (2). The face velocity for the filtration test was 5.3 cm/s, is close to the operating velocity in real filter applications.

$$P = \frac{N_{\mathrm{down}}}{N_{\mathrm{up}}} \tag{2}$$

Tensile Property Testing

The tensile strength test was based on TAPPI T494 [20]. The tensile tester in this study was a horizontal tensile tester (Frank-PTI GmbH, Germany) with a test span of 100 mm and an elongation rate of 25 mm/min. Ten test specimens from each type of filter paper were cut. The width of test specimen was 25 ± 1 mm with sides parallel within 0.1 mm.

Since the glass filter paper was pleated, it is important to evaluate the tensile strength after pleating. In this study, the pleating process was mimicked by folding the test specimen 180^o once to induce a crease. The tensile strength of creased paper, f_{creased}, was measured and compared to the tensile strength of virgin paper with no crease, f_{virgin}. The tensile strength retention, λ, was calculated by Eq. (3).

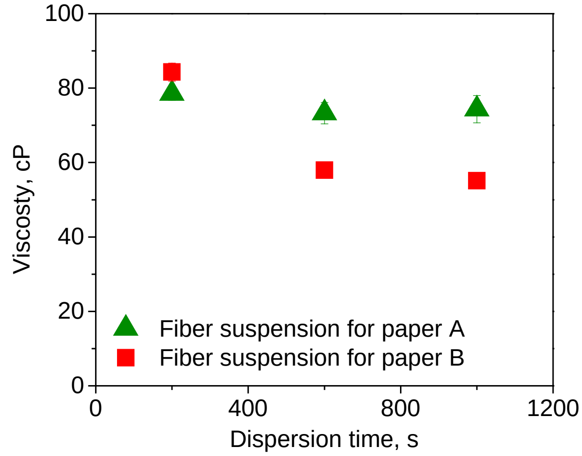
$$\lambda = \frac{f_{\mathrm{creased}}}{f_{virgin}} \times 100\% \tag{3}$$

RESULTS AND DISCUSSION

Fiber Dispersion and Characterization

The rotational viscosity as a function of dispersion time for paper A and B were shown in *Figure 1*. The viscosity value reflected the change in fiber length with increasing dispersion time. In the case of papers made using standardized fiber disintegrator, the viscosities of papers made using 600 and 1000 seconds dispersion were very close. The fiber length was hardly shortened after 600 seconds dispersion for both paper A and B. The compact blender was more powerful than the standardized fiber disintegrator. The viscosity of fiber suspension dispersed in compact blender was lower, which meant that the glass fibers are cut more effectively by the compact blender. For both the standardized fiber disintegrator and compact blender, the viscosity of fiber suspension for paper A was higher than paper B. The finer glass fiber used in paper B fiber suspension were easier to cut.

In glass fiber paper manufacturing, the fiber dispersion process is difficult to monitor and control batch to batch. For example, the water viscosity can vary with seasonal temperature changes, which may lead to different shear forces and dispersion results using the same dispersing method. For high-end specialty papers like glass fiber paper, it is very important to maintain the consistency of fiber dispersion. Rotational viscosity can be a good indicator of monitoring fiber dispersion and thus a useful tool in improving manufacturing process consistency.



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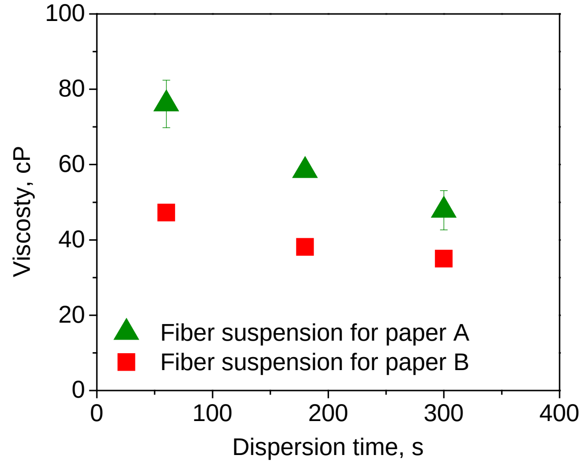

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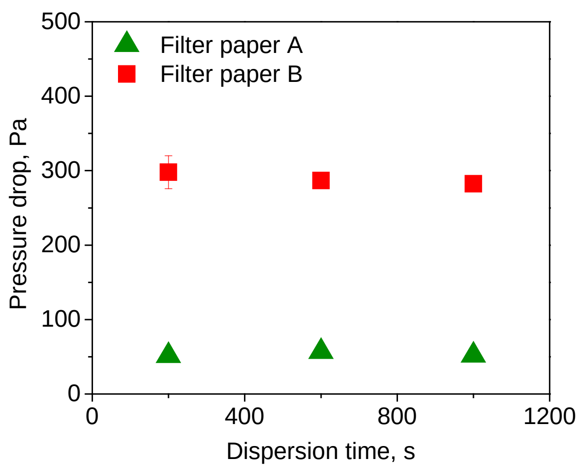
FIGURE 1. The rotational viscosity of fiber suspension dispersed in: (a) standardized fiber disintegrator; (b) compact blender.

Filtration Performance under Different Dispersion Method

The pressure drop, penetration and figure of merit data resulting from the two dispersion methods are shown in *Figures 2, 3* and *4*. Since paper A was composed of coarser fibers, paper A had a lower pressure drop and higher penetration than paper B. This demonstrates the advantage of using finer fiber in filtration. The figure of merit of paper A was slightly lower than paper B. For both paper A and paper B, the dispersion method has little effect on filtration performance and the dispersing strength and time had no significant effect on the filtration performance. Thus the fiber composition should be the determining factor for filtration properties.



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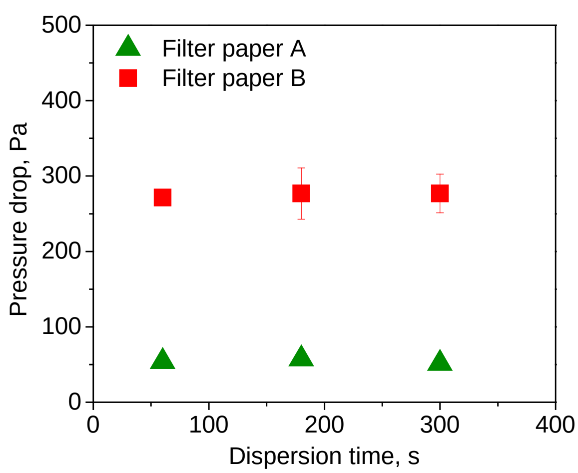

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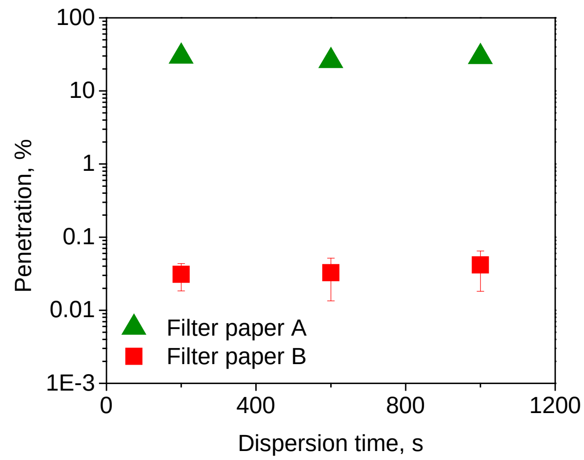
FIGURE 2. The pressure drop of filter paper prepared from: (a) standardized fiber disintegrator; (b) compact blender.



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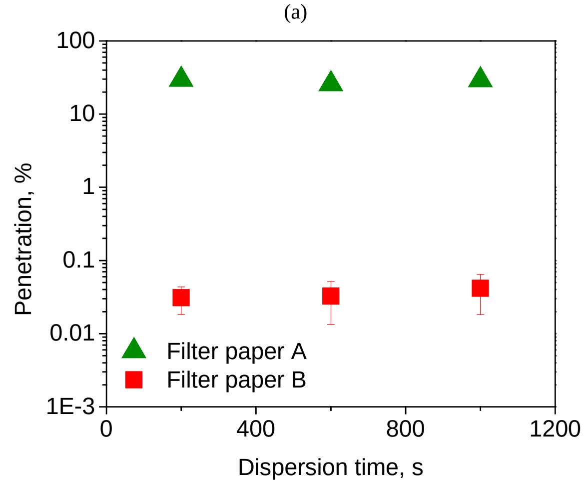

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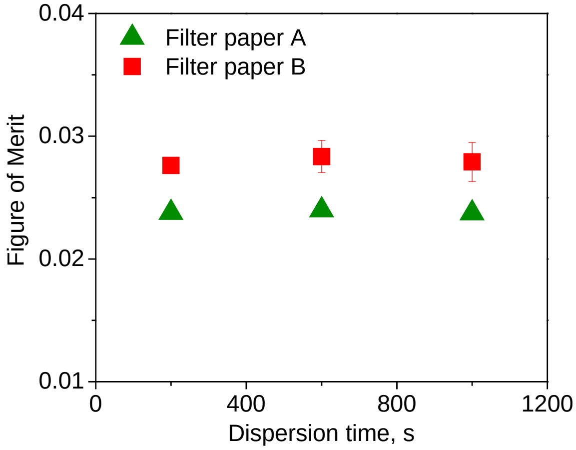
FIGURE 3. The penetration of filter paper prepared from: (a) standardized fiber disintegrator; (b) compact blender.



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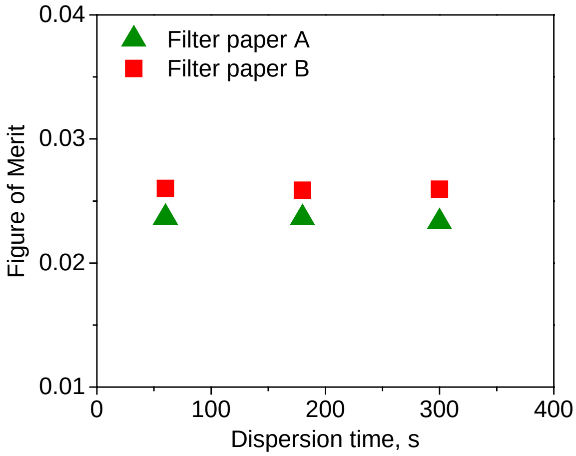


(b)

FIGURE 4. The figure of merit of filter paper prepared from: (a) standardized fiber disintegrator; (b) compact blender.

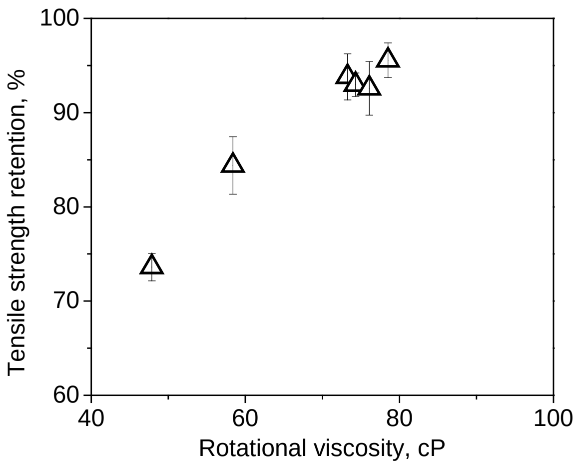
One concern about fiber dispersion was that the fiber length reduction in the dispersing process could lead to more fine fiber loss in the wet-laid process. The fine and short fibers near the forming wire could go through the pores of forming wire during the drainage and forming process. Filtration performance is very sensitive to fine fibers as a percentage of total fibers. Lower levels of fine fibers can lead to lower pressure drop and higher penetration. From the results in this study, the fine fiber loss had only a minor impact on the filtration performance, which meant that the fine fiber percentage didn't change significantly as a function of dispersion method.

Tensile Property under Different Dispersion Method

TABLE III. Virgin and creased tensile strength, and tensile strength retention under different dispersion methods for filter paper A and B.

Filter paper	Dispersion method	f_{virgin}, kN/m Mean	f_{virgin}, kN/m STD	$f_{creased}$, kN/m Mean	$f_{creased}$, kN/m STD	Tensile strength retention λ, %
A	a-1	1.04	0.02	0.99	0.04	95.55
	a-2	1.05	0.03	0.98	0.05	93.8
	a-3	1.02	0.05	0.95	0.03	92.96
	b-1	1.03	0.02	0.95	0.04	92.57
	b-2	1.01	0.02	0.85	0.05	84.39
	b-3	1.02	0.04	0.75	0.05	73.6
B	a-1	1.08	0.03	1.03	0.03	95.19
	a-2	1.05	0.03	0.83	0.05	78.9
	a-3	1.06	0.01	0.86	0.04	80.79
	b-1	1.07	0.04	0.8	0.05	75
	b-2	1.03	0.02	0.69	0.04	67.28
	b-3	1.06	0.05	0.71	0.06	66.99

The virgin tensile strength f_{virgin}, creased tensile strength $f_{creased}$ and tensile strength retention λ resulting from each dispersion method are shown in *Table III*. For both paper A and paper B, the virgin tensile strength varied little with dispersion method. This indicates that dispersing strength and time had little effect on the virgin tensile strength of glass fiber paper. Unlike cellulose fibers, which contain hydrogen bonds, there are only weak Van der Waals forces among glass fibers. Since the resin bonded the glass fibers and provided the tensile strength, shortening the fiber length didn't affect the virgin tensile strength. The fiber composition and resin played a more important role in virgin tensile strength. However, the tensile strength retention after pleating was highly affected by the dispersion method. The relationship between tensile strength retention and rotational viscosity is shown in *Figure 5*. For both paper A and B, lower viscosity led to lower tensile strength retention. Since lower viscosity of fiber suspension resulted from shorter fiber length, it is suggested that fiber cutting should be reduced during the fiber dispersion process for higher tensile strength retention.



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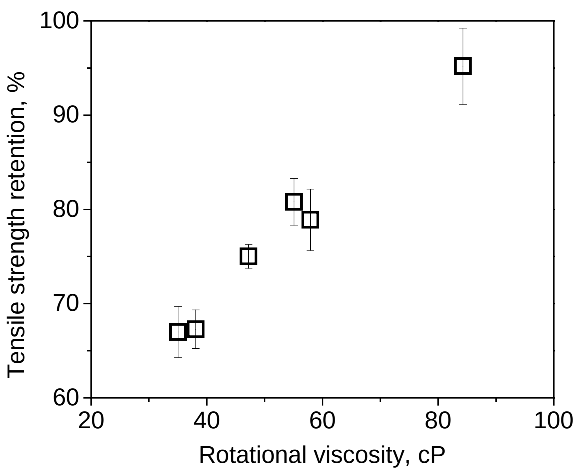

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FIGURE 5. The relationship of tensile strength retention and rotational viscosity: (a) filter paper A; (b) filter paper B.

During the paper folding process the inner part of the paper crease is compressed and outer part is stretched. When glass fiber paper is folded, the weaker points either on the glass fibers or bonds between fibers in the creased region tend to break due to compression or stretching. For weaker points on the glass fibers, fibers from lower viscosity fiber suspensions could have developed more surface flaws due to the dispersion force, resulting in flawed fibers that were easier to break during folding. For weaker points on bonds between fibers, the bonds could break during folding if they were not strong enough. Longer fibers have more bonding points with other fibers than short fibers and the load can be transferred to the unbroken bonding points. Thus, the paper was less susceptible to rupture at resin bond points. For those reasons, reducing fiber cutting during the dispersion process was beneficial for higher tensile strength retention.

CONCLUSION

In this study, two types of glass fiber filter paper prepared from six different dispersing methods were studied. Rotational viscosity was used to characterize the dispersion process. The impact of dispersion on filtration and tensile properties was analyzed. The rotational viscosity was a good indicator of fiber dispersion. Dispersing strength and time had no significant effect on pressure drop, penetration and figure of merit of glass fiber paper. Fiber composition should be the determining factor of filtration properties. Dispersing strength and time had little effect on the virgin tensile strength of glass fiber paper, while the tensile strength retention after folding was highly affected by dispersion. Lower viscosity as a result of fiber cutting through increased dispersing force or longer dispersion time can lead to lower tensile strength retention. It is suggested that fiber cutting should be reduced during the fiber dispersion process for higher tensile strength retention.

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AUTHORS' ADDRESSES
Min Tang
Yun Liang
Jian Hu
South China University of Technology
No. 381, Wushan Rd.
Guangzhou, Guangdong 510640
CHINA