Apparel Performance of Flame Retardant Silk Fabrics

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ABSTRACT

Many countries enacted flame retardant legislation for apparel such as evening dress, and pajamas. But durable and formaldehyde free flame retardant finishing for silk is necessary and challenging. In this paper, three kinds of silk fabrics with different weaving styles for apparel uses were treated with a vinyl phosphorus monomer dimethyl-2-(methacryloyloxyethyl) phosphate (DMMEP) by a graft copolymerization technique using potassium persulfate as an initiator. The treated silk fabrics can be self-extinguished after being ignited with a candle like fire, can pass the vertical flammability test, and. show some decrease in permeability. Fabric bending, shear, compression, and drape were tested so that possible problems in garment manufacturing could be predicted, because these properties not only affect the appearance of silk products but also influence the garment making process. The sewing properties of the treated silk fabrics are also discussed.

Keywords: silk, mechanical property, FAST, flame retardancy

INTRODUCTION

Silk, known as "the queen of fibers", was once an exclusive material of the Chinese imperial family for its luster, wearing comfort ability, and special scrooping [1]. Now, silk is used ordinary people's homes as pajamas, shirts, evening dress, furnishings, and wall coverings. These products need different level of flame retardancy according to the fire regulations. Because textiles are easier to ignite than others, they account for 20% of dwelling fires and 50% of fatalities [2].When fire accidents occur, the primary hazard is ignition of clothing by contact with hot surfaces or small open-flame sources. So fabric with good flame retardant character should be chosen for garments to reduce unreasonable risk of burn injuries and deaths from fires associated with clothing.

It is also important for people, especially the children and the elderly, to have more time to escape. Presently, many related regulations have been enacted around the world to state the flammability performance and standardize testing methods for flammability of textiles such as S.I.1985 No 2043 Nightwear (safety) Regulations of United Kingdom [3] and CFR 1610 Standard for the flammability of clothing textiles in the United States of America [4].

Flame retardancy treatment of silk fabric by immersion in a mixture of borax and boric acid solution can be traced back some 200 years [5]. Crosslinking by introducing N-hydroxymethyl (3-dimethyl phosphono) propionamide and trimethylolmelamine (TMM) or hexamethylol melamine (HMM) onto silk fabric can improve laundering durability to 30~50 hand wash cycles, and the LOI of treated silk fabric were above 30%. But the treated silk fabrics would become stiff and yellow and had the problem of formaldehyde releases [6-7]. Developing a durable flame retardancy and formaldehyde-free process for silk fabric is still a challenge. Recently, we successfully synthesized a series of phosphorous-based flame retardants and applied them to silk fabrics to produce durable and formaldehyde free effects [8-10]. However, little research on the properties of apparel and sewing ability for silk fabrics after being treated with flame retardant has been reported in the literature. Such parameters are very imperative for garment manufacturers. This paper reports detailed research to explore the mechanical properties and sewing ability of flame retardant silk fabrics.

EXPERIMENTAL

Materials

Three kinds of silk fabrics with different densities were commercial purchased. Detailed information of is shown in *Table I*. Flame retardant dimethyl l-2-(methacryloyloxyethyl) phosphate (DMMEP), *Figure 1*, was synthesized in our lab as reported elsewhere [9]. Other chemicals were commercial reagent grade and used as received.

TABLE I. Fabric information.

Silk	Density (g/m^2)	Fabric count (ends/10cm)		Fiber finiess (denier)	
		warp	weft	warp	weft
Georgette	51.67	497	421	3/20/22	3/20/22
Satin	53.82	1403	560	1/20/22	2/20/22
Habotai	51.67	517	410	2/20/22	2/20/22

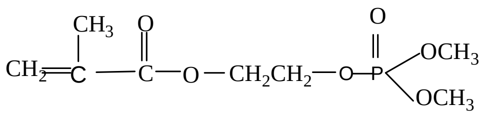


FIGURE 1. Dimethyl 1-2-(methacryloyloxyethyl) phosphate (DMMEP).

Fabric Treatment Procedure

Silk fabrics were immersed into the finishing solution containing 200% DMMEP (on the weight of fibers) and 1.0% potassium persulfate (on the weight of DMMEP). The pH value of the mixture was adjusted to 4.5 with ammonium hydroxide. The liquor ratio was 1:30. Then the flask was sealed with a rubber-stopper and put into water bath under oscillating at 90℃ for 60 min. Then the sample was rinsed with methanol followed by water, and finally dried at room temperature under vacuum to a constant weight. The weight gain was calculated as following Eq. (1):

$$weight\ \ gain(\%) = \frac{W_2 - W_1}{W_1} \times 100 \qquad (1)$$

Where W_2 and W_1 are the weight of grafted and original silk fabric respectively.

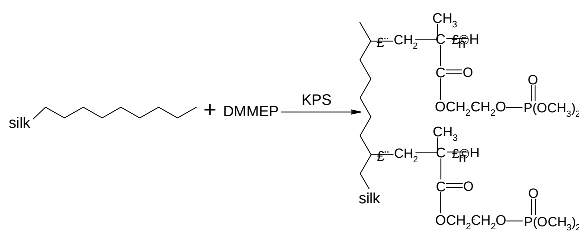
Measurements

Limiting oxygen index (LOI) was measured according to ASTM Standard Method D 2863-97 on a Fire Testing Technology Oxygen Index Instrument. Char length was measured according to ASTM Standard Method D6413-99. Permeability of the fabrics was tested by a Digital Fabric Permeability Testing Instrument YG [B] 461D according to GB/T5453-1997 (eqv. ISO9237：1995). The mechanical properties of flame retardancy fabric was evaluated by a FAST (Fabric Assurance by Simple Testing) system by testing the fabric thickness, fabric bending length, bending rigidity, extensibility, shear rigidity, and dimensional stability. Fabric drape was tested by a Drape Performance Testing Instrument YG811 according to GB/T23329-2009 (eqv. ISO9073-9：2008). Model YG026B an Electronic Table Fabric Strength Tester was used for testing the breaking strength and breaking elongation according to GB/T13773-2008 (eqv. ISO13935 1:1999).

RESULTS AND DISCUSSION

Flammability and Permeability

Table II shows the flammability and permeability of silk fabrics. Flame retardant grafted Silk fabrics showed different weight gain, although they have similar fabric density and the same DMMEP add on. This is mainly because the different weaving style has different absorption and inner diffusion for flame retardant in the finishing solution. Treated silk fabrics showed good self-extinguishing property and could pass vertical flammability testing when ignited with a candle like fire, while control silk fabrics could not. This is because materials will be self-extinguish when the LOI is above 28% [11], and char length lower than 178 mm will be considered to successfully pass the vertical flammability test [12]. Three original silk fabrics with the similar fabric density showed a little difference of LOI for the different weaving styles. This treatment is a kind of formaldehyde free process because DMMEP is a kind of vinyl monomer, and it can be grafted onto silk fabrics by graft copolymerization initiated by potassium persulfate (KPS) seen as *Scheme 2*.



Scheme 2. Graft polymerization of silk with DMMEP.

Treated silk fabrics showed excellent flame retardancy mainly because phosphorus based flame retardant DMMEP can catalyze silk dehydrate to form nonflammable char hence decrease flame volatility during combustion [13]. *Table II* also shows that the permeability of treated silk fabrics had some decrease in different level compared with the control silk fabrics. Georgette showed a very slightly decrease of permeability due to its looser yarn structure, while satin and habotai decreased by 22.5% and 35.4% respectively.

TABLE II. Flammability and permeability of silk fabrics treated with DMMEP.

Samples		Weight Gain (%)	LOI (%)	Char Length (mm)	Perme-ability (m/s)
Control Silk	Georgette	-	24.5	BEL	40.75
	Satin	-	25.1	BEL	60.99
	Habotai	-	25.4	BEL	5.28
Flame retardant silk	Georgette	8.3	29.7	6.8	36.07
	Satin	13.4	31.9	5.6	47.29
	Habotai	15.3	32.6	4.5	3.41

Note: BEL= Burn Entire Length

Mechanical Properties

The mechanical properties of fabrics will affect the wearing and tailoring performance and the making up of the tailored garments in wear. [14]

*Table III s*hows the fabric thickness tested by FAST-1 and bending length and bending rigidity tested by FAST-2. Thickness, bending length and bending rigidity are the main factors which represent the compression and bending properties of the fabric. *Table III* shows the difference in fabric thickness measured at two different pressures $2gf/cm^2$ and $100gf/cm^2$. After DMMEP treatment, the surface thickness of three silk fabrics increased. This can be attributed to the grafting process and chemical deposit which largely occurred on the fabric surface. Increased fabric thickness will yield firm fabric handle. Bending length and bending rigidity are the two parameters which affect the stiffness or conversely, the flexibility of fabric.

The larger the bending length value; the stiffer the fabric will be. Fabrics with low bending rigidity may exhibit seam pucker and are prone to problems in cutting, while fabrics with a higher bending rigidity may be more manageable during sewing, which results in a flat seam but may cause problems during molding because of its stiffness. From *Table III*, it can be seen that bending length and bending rigidity of DMMEP treated silk all became somewhat higher compared to the control fabrics, especially in the warp direction. This shows that the flame retardant treated fabrics became stiffer, which is helpful for flat seam appearance.

Table IV shows the fabric extensibility, shear rigidity measured by FAST-3 and fabric dimensional stability, including both the relaxation shrinkage and the hygral expansion measured by FAST-4.

Shear rigidity can predict whether fabric can be distorted at the loads in bias direction, which is directly related to fabric relaxation. Much higher or lower shear rigidity is not desirable in garment making. Fabric with low shear rigidity will be easily distorted during laying-up, making, and cutting. While Fabric with high shear rigidity will be difficult to form into smooth 3-dimensional shapes with problems in molding and sleeve insertion. Formability is an indication of possible seam pucker during or after sewing. Fabric with low formability causes seam pucker more easily. In the FAST system, hygral expansion and relaxation shrinkage are defined as the percentage change in dimensions of the relaxed fabric from wet to dry and in dry dimensions after release in water at room temperature respectively [15]. Fabric with high levels of hygral expansion and relaxation shrinkage will result in sizing difficulties, seam pucker and pleating problems during sewing and final pressing process.

TABLE III. Compression and bending properties of silk fabrics treated with DMMEP.

		Surface Thickness mm	Bending Length mm		Bending Rigidity μN/m	
			Warp	Weft	Warp	Weft
Control Silk	Georgette	0.016	16.33	15.00	2.08	1.61
	Satin	0.007	18.33	17.33	3.18	2.69
	Habotai	0.011	18.00	18.00	3.13	3.13
Flame retardant silk	Georgette	0.051	18.67	16.50	3.39	2.34
	Satin	0.032	18.83	18.17	4.07	3.65
	Habotai	0.016	19.33	18.00	3.88	3.13

Table IV shows that the shear rigidity of fabric treated with DMMEP becomes higher, which means that flame retardant silk fabrics are not easy to distort during laying up, panel cutting, and making processes. And treated silk fabrics possess higher formability compared with control silk fabric. Decreased relaxation shrinkage and hygral expansion means that treated silk fabrics should have higher dimensional stability during the sewing, wearing and pressing process.

Drape Property

Drape is the ability of a fabric to fall under its own weight into wavy folds of different nature. It plays significant role in providing graceful aesthetic effects in garment. Here it is characterized by drape coefficient which is defined as percentage of the shadow configuration of the draped fabric sample and the support disk [16]. Lively rate (LR) is defined as the difference of the stable and dynamic drape coefficient, seen as formula Eq. (2):

$$LR = [(FS-Fd)/(1-Fd)]\times 100\% \quad (2)$$

Where F_s and F_d are the static and dynamic drape coefficient respectively.

Aesthetic coefficient (AC) can be got as Eq. (3):

$$AC = F\,(6/R_m)[1-1/(n+1)^2]\times 100\% \quad (3)$$

Where F is the drape coefficient, n is the node numbers and R_m is the average radius of the shadow configuration. Drape coefficient, LR and AC results are shown in *Table V*. From *Table V*, it can be seen that the drape coefficient of treated georgette and satin increased a little which means the drape property of the two kinds of silk fabrics decreased a little. While treated habotai has improved drape property with lower drape coefficient compared with original habotai. The decrease of drape property is mainly because treated silk fabrics become a little bit stiff. Except habotai, the other two silk fabrics are livelier after being treated with flame retardant which further shows that treated georgette and satin have lower drape property. The aesthetic coefficient of treated silk fabrics shows very slight improvement which shows that flame retardancy treatment had slightly affect on aesthetic appearance of silk fabrics.

TABLE IV. Tensile extension and dimensions properties of silk fabrics treated with DMMEP.

Samples		Shear Rigidity	Formability mm^2		Relaxation Shrinkage %		Hygral Expansion %	
		N/m	Warp	Weft	Warp	Weft	Warp	Weft
Control Silk	Georgette	7.24	0.26	0.38	2.53	1.60	3.28	1.76
	Satin	17.57	0.21	0.18	2.00	1.33	2.31	1.76
	Habotai	23.21	0.14	0.15	0.67	0.53	1.48	1.07
Flame retardant silk	Georgette	8.31	0.38	0.49	1.73	1.20	2.31	1.75
	Satin	18.64	0.26	0.25	1.20	1.07	1.62	1.48
	Habotai	23.21	0.17	0.15	0.53	0.53	1.21	0.94

TABLE V. Drape property of silk fabrics treated with DMMEP.

Samples		Drape Coefficient %		Liveliness Rate %	Aesthetic Coefficient %
		Static	Dynamic		
Control Silk	Georgette	26.87	53.52	26.87	19.59
	Satin	31.85	50.96	28.04	22.31
	Habotai	39.19	59.97	34.18	25.83
Flame retardant silk	Georgette	27.06	59.31	44.22	19.93
	Satin	33.17	56.64	35.12	23.00
	Habotai	38.88	52.14	21.69	25.88

Sewing Properties

Fabrics are sewn with or without fusible interlining along warp, weft and oblique directions. The results are shown in *Figure 1* and *Figure 2*.

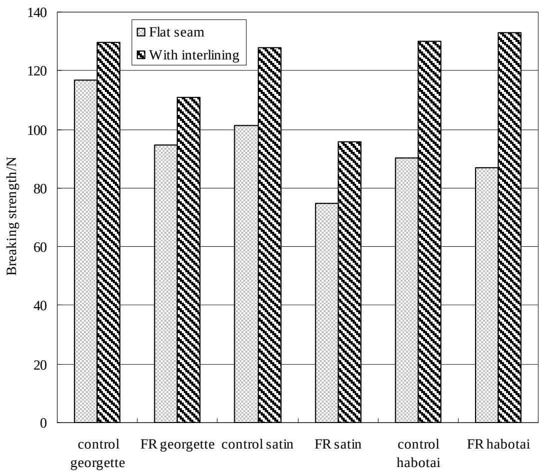


FIGURE 1. Breaking strength of silk fabrics (FR means flame reatardant treated).

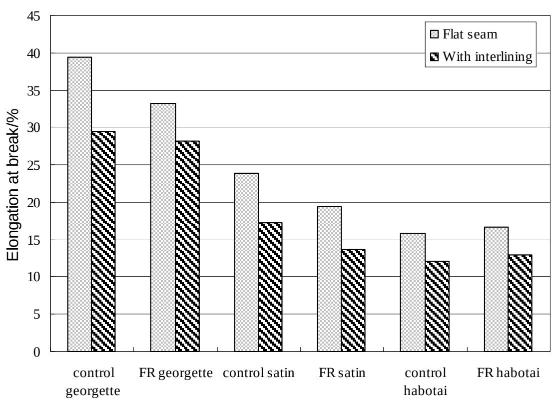


FIGURE 2. Breaking elongation of silk fabrics (FR means flame reatardant treated).

The breaking strength reflects the seam strength, the greater the breaking strength, the better the seam fastness. For flat seam, breaking strength dropped by 26% for satin and 19% and 4% for georgette and habotai respectively. The decrease of break strength below 20% is considered as allowable in our finishing industry. After adhering with interlining, the breaking strength of treated silk fabric improved and was even better than the control silk fabric itself.

The breaking elongation of DMMEP treated silk fabrics and fabrics with fusible interlining both decreased compared with the control silk fabrics. The seams of garment made by treated silk fabrics are stronger than that with original fabrics. So the shape retention property and life-span of the flame retardant garment can be prolonged.

CONCLUSION

The flame retardant dimethyl-2-(methacryloyloxyethyl) phosphate (DMMEP) treated silk fabric can pass the vertical flammability test and can be self-extinguish once ignited by candle like fire. Permeability of silk fabrics dropped slightly. The flame retardant silk fabrics became a little bit stiff which is helpful for flat seam appearance and are more difficult to distort in fabric laying up, panel cutting, and making. The formability and sizing stability during sewing, wearing, and pressing process was improved. The flame retardancy treatment had different affects on the drape property of silk fabrics with different weaving styles. The seam strength decreased for different weaving styles after being treated with flame retardant. Adhering with interlining improved seam strength to levels even better than that of the original silk fabrics.

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