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# Mechanical and Thermal Properties of Industrial Protective Fabric with Recycled m-Aramid and Natural Fiber

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**Abstract** As consciousness of safety becomes an important social issue, the demand for protective clothing is increasing. Conventional flame-retardant cotton working wear has low durability, and working wear with m-aramid fibers are stiff, heavy, less permeable, and expensive. In this study, recycled m-aramid and cotton have been blended to produce woven fabric of different compositions to enhance high performance and comfort to solve aforementioned problems. The fabrics were analyzed according to constituents and various structural factors. Mechanical properties were measured using KES-FB system. The measured thermal properties are TGA, $Q_{max}$, TPP and RPP. Fabric with polyurethane yarn covered by m-aramid/cotton spun yarn is observed to have good wearability. The fabric of open end spun yarn showed more stiffness than that of ring spun yarn. The sample with the high count of yarn has more smooth surface. In addition, high m-aramid content fabric is considered to have relatively high stiffness when using as clothing. In TGA the fabric with higher m-aramid content showed more stable decomposition behavior. The fabric having rough surface showed lower heat transfer properties in $Q_{max}$. The influence of the fabric thickness was important in convection and radiant heat test.

**Keywords** *recycled m-aramid, cotton, polyurethane, KES-FB system, thermal properties, industrial safety protection*

## 1. Introduction

Due to frequent occurrence of industrial accidents, substantial effort is being given to protect workers and minimize the damage of accidents. Accordingly, it is necessary to supply protective clothing to all industrial fields in preparation to reduce the fatalities of accidents[1]. Unlike casual wear, protective clothing has a major purpose in protecting workers from various hazards, such as intense flames and hot fumes, when workers are exposed to industrial heat or extreme environments. Among various kinds of protective clothing, flame retardant fabric is a kind of functional fabric that is treated to protect the wearer from heat and flame spreading at high temperature[2,3]. The m-aramid fiber is typical flame retardant and synthetic fiber in which aromatic rings are linked by amide bond (-CONH-). The m-aramid has several thermal advantages. Tg of m-aramid is 260 to 270℃ and Td of m-aramid is 430℃ under a nitrogen stream. It is also known that it has a strength of 70% or more even at 1,000 hours exposure at 250℃. In terms of long-term heat resistance, m-aramid is excellent in dimensional stability and physical properties. It also has high elongation and spinnability compared to other high performance fibers. Because of these properties, m-aramid fiber is used as fire fighting suit, flame retardant clothing, chemical protective clothing, and military uni-

**Table 1.** Characteristics of blended yarn

| Blend yarn | Materials | Blending ratio(%) | Spinning | Yarn count(Nm) |
|---|---|---|---|---|
| BY1 | Cotton /Re. m–aramid | 85/15 | Ring | Ne30 |
| BY2 | | 85/15 | Ring | Ne40 |
| BY3 | | 70/30 | Ring | Ne30 |
| BY4 | | 85/15 | Open–end | Ne30 |

form[4,5]. The m-aramid protective clothing is used to prevent harmful elements from reaching the wearer. But fabric made of 100% m-aramid is not convenient to wear for its heavy weight and poor permeability[6]. Therefore, attempt was taken to develop functional and comfortable clothing. On the other hand, because of increased use of m-aramid, including protective clothing, waste has also increased proportionately. Consequently, super fiber such as m-aramid need to be recycled not only for the utilization of resources but also for environmental aspects. In this study, recycled m-aramid and cotton have been blended to produce woven fabric of different compositions to enhance high performance and comfort to solve aforementioned problem. Blended fabrics have been studied in terms of mechanical and thermal properties by various factors. In order to reduce the waste of m-aramid used in the production of protective clothing and to reduce the cost, we used the byproducts produced during the production of m-aramid and used them as raw material. In the previous research, it was confirmed that the recycled m-aramid/cotton blended fabric exhibits intermediate properties between m-aramid and cotton. Therefore, in order to develop and commercialize the recycled m-aramid/cotton blend fabric, their characteristics were studied based on the influence of various weaving factors. This study established data base for the development of long-term protective clothing.

## 2. Experimental

### 2.1 Samples

The samples used in this study are flame retardant blended fabrics composed of recycled m-aramid and cotton. Table 1 and Table 2 shows the characteristics of each blended yarn and sample. Polyurethane covering yarns mean that polyurethane yarn covered with m-aramid/cotton blended yarn. Figure 1 shows the SEM image of polyurethane covering yarn. Ring spun yarn is indicated by CM and open-end spun yarn is indicated by OE. R/S fabric is a ripstop fabric, which is strong in tearing by putting a strong thread in square

**Table 2.** Characteristics of sample fabrics

| Sample | Materials | | Thickness (mm) | Density(threads/in) | | Weave type | Weight(g/m²) |
|---|---|---|---|---|---|---|---|
| | Warp | Weft | | Warp | Weft | | |
| A | BY1 PU covering | BY1 | 0.75 | 80 | 52 | 1/3 twill Rip–stop | 297.7 |
| B | BY2 PU covering | BY2 | 0.58 | 71 | 63 | Rip–stop Nano | 310.6 |
| C | BY3 | | 0.49 | 94 | 50 | Honeycomb | 281.7 |
| D | BY2 | | 0.62 | 80 | 37 | 2/2 twill | 241.4 |
| E | BY4 PU covering | BY4 | 0.52 | 83 | 42 | 1/3 twill Rip–stop | 235.8 |

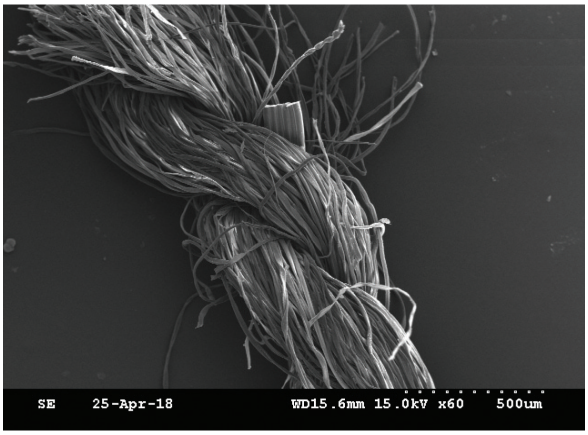



**Figure 1.** SEM image of polyurethane covering yarn.

shape. Honeycomb fabrics are based on a twill line of various honeycomb types. The fabric surface has twill shape or square shape[7]. The cotton used was PIMA cotton, which has a long fiber length, good spinnability and yarn quality. The used recycled m-aramid was non-graded product of virgin m-aramid. Recycled m-aramid staple fiber is a non-graded product that shows non-uniform properties in fiber length and firmness. This affects the strength, uniformity and productivity of the yarn, so it can not be used directly as a raw material for yarn. Therefore, pretreatment is required. Recycled m-aramid sliver was produced through the blowing and the carding process to adjust the firmness and remove foreign substances. The produced sliver was re-cut by rotary cutter to a constant fiber length of 38mm. Before drawing and roving processes, staple fibers were prepared by oiling to prevent curling. Then, during blended yarn spinning process, recycled m-aramid and cotton staple fibers are blended in the blowing process. For uniform blending of the staple m-aramid and cotton fiber, the blowing process was changed to sandwich method. In sandwich method, the raw material is layered on the conveyor belt according to the blending ratio, and then blended into the automatic blowing machine to make more uniform blended yarn. Then fabrics were woven in various conditions. The characteristics of the blend yarn are shown in Table 1. The woven fabrics were treated with THPC(tetrakis hydroxymethyl phosphonium chloride)-Urea flame retardant, which is one of the representative organophosphorus flame retardants. Then, through the ammonia curing process, an insoluble polymer containing phosphorus and nitrogen is formed in the fibrils of the cotton to produce a flame retardant polymer.

### 2.2 Experimental

**Mechanical Properties**: The tensile, shear, bending, surface, and compression properties of the fabric were measured using the KES-FB system(Kawabata Evaluation System for Fabric, Kato Tech Co., Ltd., Japan). Each sample was prepared to size of 20cm×20cm. Then they were measured after being conditioned for 24 hours under the standard condition(room temperature 20±2℃, relative humidity 65±5% RH).

**TGA**: To investigate the thermal decomposition properties of the recycled m-aramid blended fabric, fabric was heated from room temperature to 800℃ at 30℃/min under air stream using TGA(STA6000, Perkin Elmer, USA).

**$Q_{max}$**: $Q_{max}$ of the fabric was measured using the KES-FB7 system. $Q_{max}$ is a method of measuring the maximum heat flow rate when instantaneously touching the sample surface with a T-box maintained at 10℃ higher than room temperature.

**Thermal Protective Performance**: TPP was tested using FPT-30A(DAIEI KAGAKU SEIKI MFG. Co., Ltd., Japan) according to KS K ISO 9151. When a thermal flux density of 80kW/m$^2$ is applied from the flame located below the fixed sample, the heat passing through the sample is measured with a small copper calorimeter at the top of the tester. Then, the time in seconds was recorded until the calorimeter reaches 24±0.2℃.

**Radiant Protective Performance**: RPP was tested using HPS-2000(PIMACS Co., Ltd., Korea) according to KS K ISO 6942. In this test, the sample is fixed to the front of the calorimeter and exposed to radiant heat. Then, the time in seconds is recorded until the calorimeter reaches 24±0.1℃. In this experiment, the incident heat flux density $Q_0$ is set to a medium level of 40kW/m$^2$. The heat flux density $Q_c$(kW/m$^2$), was calculated using the following equation (1).

$$Q_c = \frac{M \cdot C_p \cdot 12}{A \cdot (t_{24} - t_{12})} \quad \cdots\cdots (1)$$

where,

M : Mass of the copper plate in kg

$C_p$ : Specific heat of copper 0.385(kJ/kg·℃)

A : Area of the copper plate in $m^2$

$12/(t_{24}-t_{12})$ : Rate of rise of the calorimeter temperature in ℃/s, in the region between a 12℃ and a 24℃ rise

## 3. Results and discussions

### 3.1 Mechanical properties

**Tensile Properties**: Tensile properties indicate the extent to which the fabric is stretched and restored in a direction of warp or weft. It is a characteristic that influences body movements when wearing clothes and affects the comfort.

Tensile linearity(LT) is the degree of initial tension by external force, which is related to the pressure sensation of the garment. If the LT value is small, the elongation resistance is reduced at the beginning of tension, and drapeability is good[8,9]. LT values were generally similar. However, in the fabric which used polyurethane covering yarn showed the lower LT value in the warp direction compared with weft direction. It is thought that the polyurethane covering yarn improved the elasticity and comfort. Tensile energy(WT) is the amount of work at tensile strain when subjected to the maximum load and it is proportional to the degree of elongation. If the value is large, it means that the initial stretching and deformation are performed well. The WT of sample A and B was high in the warp direction. Resilience(RT) indicates recovery after tensile and is related to dimensional stability. Therefore, when the RT value is large, the fabric is not sufficiently stretched and the recovery is high, so that the fabric has good dimensional stability. Most samples showed similar values (Figure 2).

**Shear Properties**: Shear properties occur when the crossing angle of warp and weft changes. Shear properties are related to the handle, drape, and dimensional stability of the fabric that adapts well to the surface of the human body and drapes well when the fabric is used as clothing[10,11].

Figure 3 shows the value of shear stiffness(G) and shear hysteresis at 5° of shear angle(2HG5). The shear stiffness(G) represents the average of the forces required for deformation. The larger the value of G, the more difficult for shear deformation. The hysteresis (2HG5) is a characteristic related to deformation and recovery during initial shear deformation. The 2HG5 value of sample E was high. It was thought that the energy loss in recovery after shear deformation was increased due to the friction between rough surface of open-end yarn during shear deformation(Figure 4).

In previous studies, Skelton has found that the shear stiffness increases with the number of constituent

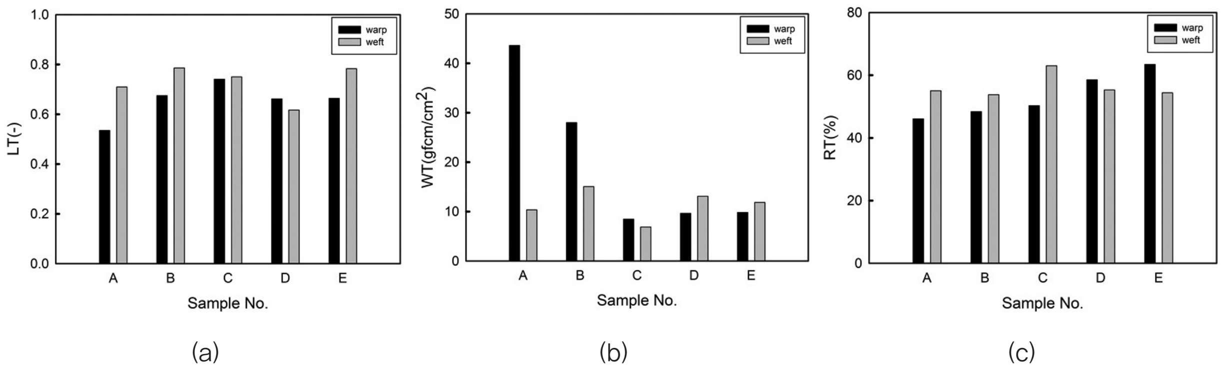
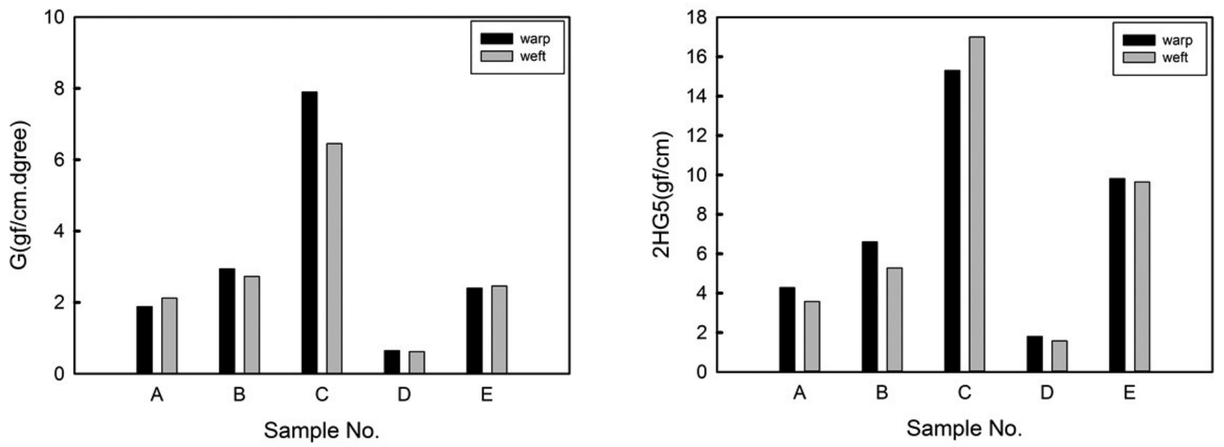



**Figure 2.** Tensile properties of sample fabrics; (a) Tensile linearity, (b) Tensile energy, (c) Resilience.




(a) (b)

**Figure 3.** Shear properties of sample fabrics; (a) Shear stiffness, (b) Shear hysteresis at 5°.

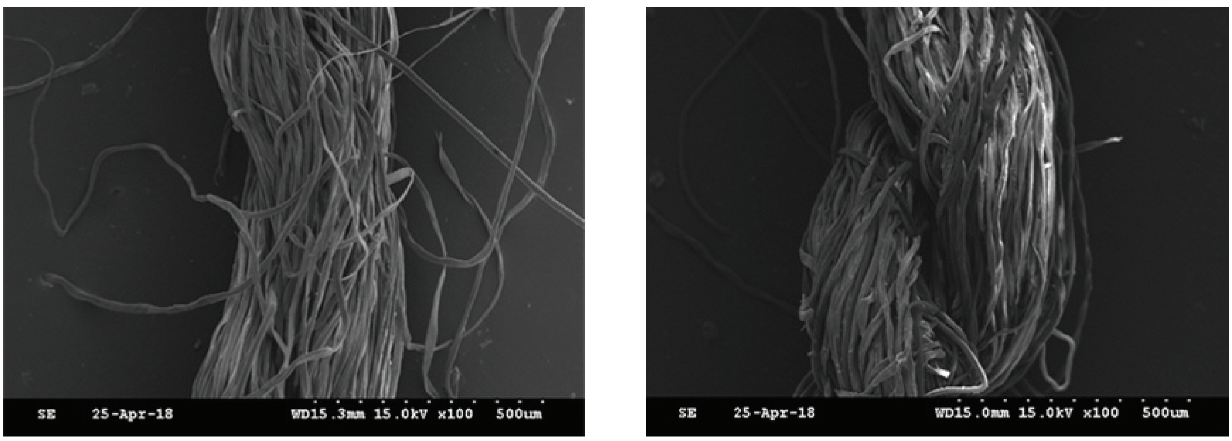
yarns of the fabric as shown in the following equation (2)[12,13]. It is considered that the sample C, having a relatively high number of constituent yarns and a high content of m-aramid fibers, has higher values in both G and 2HG5. In other hand, sample D, which has a relatively small number of constituents, shows low G and 2GH5 values.

$$G = \frac{0.12Ed(d/p)^2}{N^5} \quad \cdots\cdots\cdots\cdots (2)$$

where,
G : Shear stiffness of fabric
E : Young's modulus
d : Yarn diameter
p : The space between yarn and yarn in the fabric
N : The number of filament within yarn

**Bending Properties**: The bending properties are related to the flexibility and drapeability. It is a characteristic that shows easiness to adapt to the human body. The bending properties are affected by bending resistance of the warp and weft, the interaction of yarns, and the frictional resistance of fibers and yarns.

Figure 5 shows the values of bending rigidity(B) and bending hysteresis(2HB). The bending rigidity(B) of the fabric is influenced by the contact pressure, contact




(a) (b)

**Figure 4.** SEM image of (a) ring spun yarn and (b) open-end spun yarn.

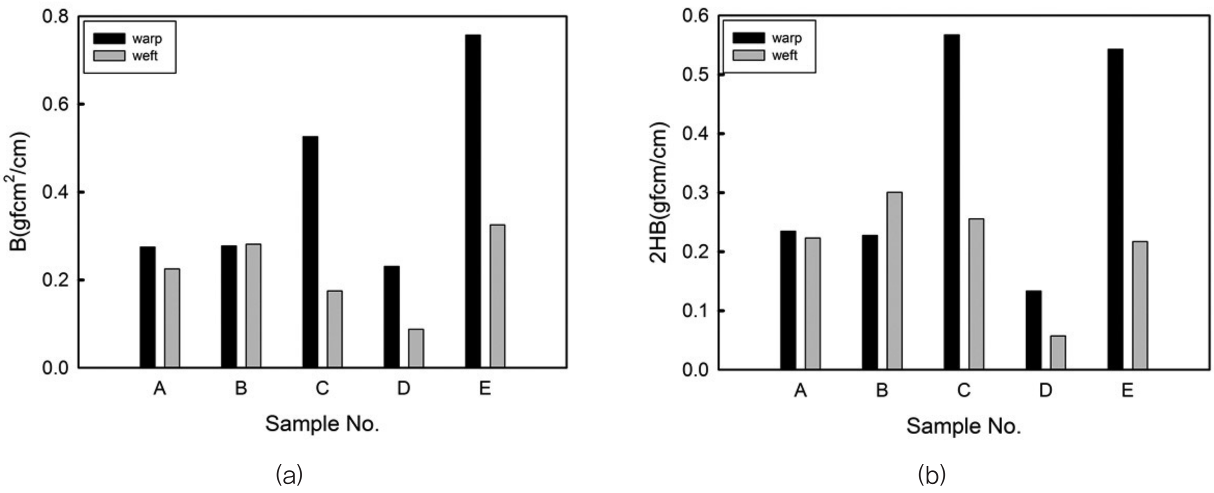



**Figure 5.** Bending properties of sample fabrics; (a) Bending rigidity, (b) Bending hysteresis.

length, density, and the thickness of the yarn in addition to the fiber characteristics. A larger value of bending rigidity means higher stiffness, on the contrary, a smaller value means better drapeability. The bending hysteresis(2HB) is related to the energy loss that occurs during the bending deformation and recovery[14,15]. Sample C and E showed high B and 2HB values. Sample C is considered to be stiff due to the relatively high proportion of firm m-aramid. The larger the difference in the number of constituent yarns between the warp and weft, the greater the difference in the bending rigidity values between the warp and weft directions. Unlike the shear properties which are influenced by the intersection of warp and weft, the bending properties have less influence between warp and weft. Therefore, the difference between the warp and weft direction is considered to be large. Sample E is considered to have a large energy loss in recovery after bending due to the increase in friction between fibers during bending deformation due to the rough surface of OE yarn.

**Compression Properties**: Compression properties are closely related to the thickness and bulkiness of the fabric. In particular, the compression properties of fabrics directly affect the characteristics such as softness, comfort, and warmth[16].

Figure 6 shows the values of compression linearity (LC), compressional energy(WC), and resilience(RC). If the LC value is large, the resistance to initial compression is large and the compression deformation is hard .

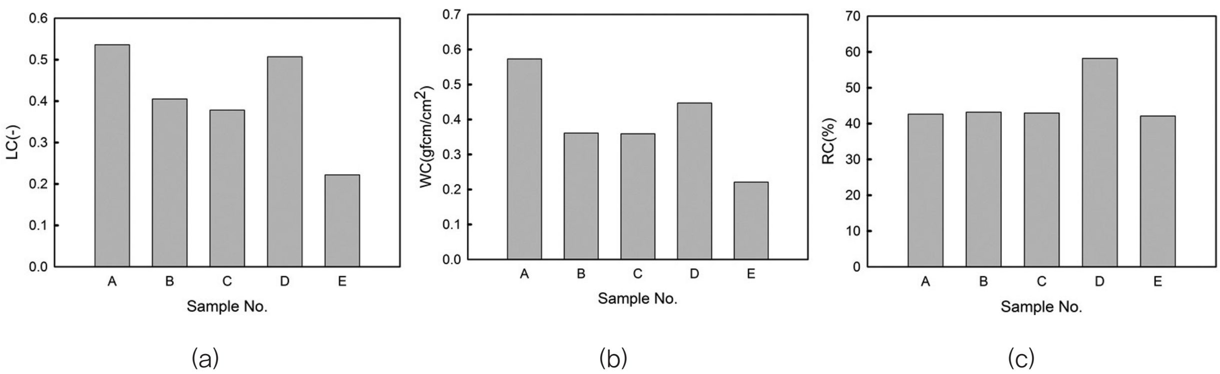
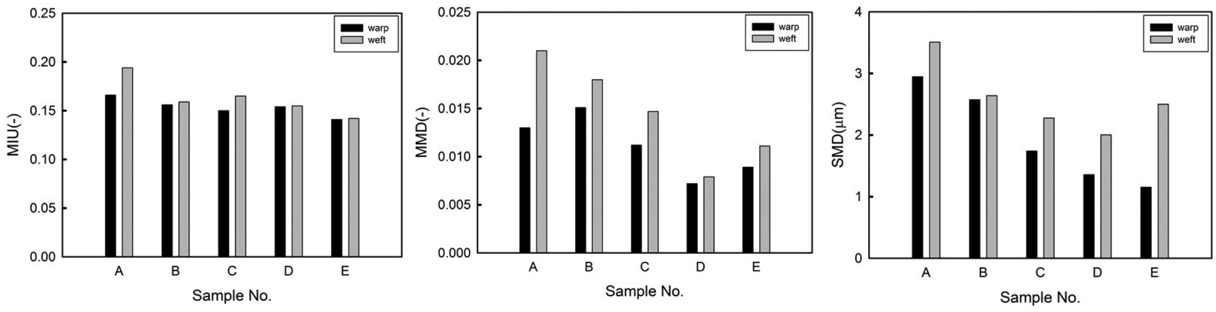



**Figure 6.** Compression properties of sample fabrics; (a) Compression linearity, (b) Compressional energy, (c) Resilience.




(a) (b) (c)

**Figure 7.** Surface properties of sample fabrics; (a) Coefficient of friction, (b) Mean deviation of MIU, (c) Geometrical roughness.

WC represents the energy required for compressive deformation. WC value showed the same tendency as LC value. It was similar to the tendency of sample thickness. Then higher the thickness, the greater the resistance to compression.

**Surface Properties**: The surface properties are related to the smoothness of the fabric. The surface properties directly affect not only the contact area but also the touch including cold/warm sensation[13].

Figure 7 shows the values of coefficient of friction (MIU), mean deviation of MIU(MMD), and geometrical roughness(SMD). The results of MIU, which is the frictional coefficient of fabric surface, show similar value for all samples. Low MMD value signifies more uniform surface friction. The SMD is related to the roughness of the fabric surface, and a smaller value symbolizes the smoothness of surface. In case of surface properties, sample D using the higher count of yarn showed lower surface roughness. This result is considered to be related to the radius of curvature of the yarn.

### 3.2 Heat transfer properties

**TGA**: TGA is a method of analyzing the weight change of samples with temperature change. The temperature-weight loss curve shows the thermal stability of the samples and the composition ratio of used materials. It also shows the amount of residue after heating.

Td(decomposition temperature) was observed to be slightly higher having with high cotton content, indicating sample A 307.12℃, sample B 310.49℃, sample C 285.84℃, sample D 307.06℃ and sample E 298.37℃.

Figures 8-9 show the TGA and DTG thermograms. It is considered that the flame retardant polymer con-

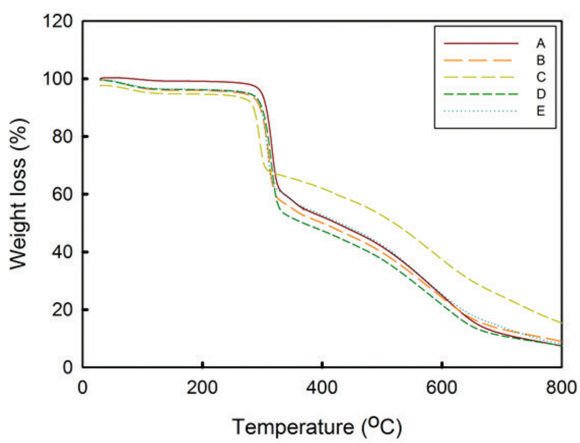



**Figure 8.** TGA curve of fabrics.

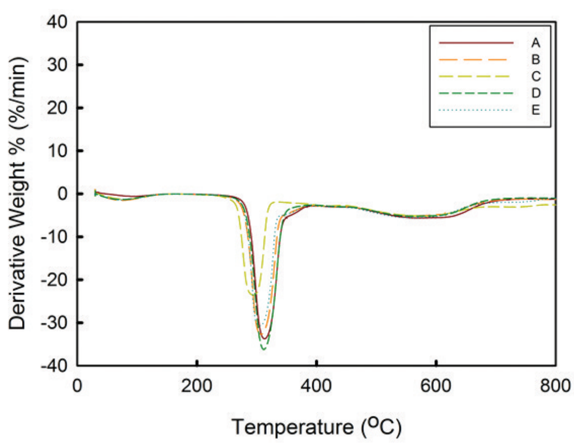



**Figure 9.** DTG curve of samples.

taining phosphorus and nitrogen was formed in the fibrils of the cotton through the ammonia curing process[17]. However, after decomposition started, sample C with higher m-aramid content showed more stable decomposition behavior. There were also more char yields.

**$Q_{max}$**: $Q_{max}$ is the maximum value of the initial heat flux and is the absorbed heat by the fabric while getting contacted with body. The larger the $Q_{max}$ value, the stronger the cold feeling, and the smaller the $Q_{max}$ value, the stronger the warmth.

Figure 10 shows the $Q_{max}$ results of samples. The results are considered to be related to the surface properties. The fabric with rough surface has higher amount of the stagnant air layer on the fabric surface. Therefore, it is considered that the maximum value of the initial heat flux is lowered because the stagnant air layer reduces the heat transfer from the heat plate to the external environment[18].

**Thermal Protective Performance**: Convection heat test is a method of measuring the ability to delay heat transfer from the flame. Table 3 shows the convection heat test results. As the results, the thicker the thickness, the greater the heat resistance.

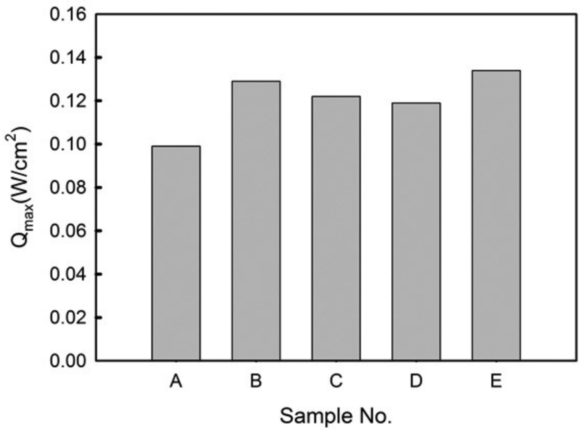



**Figure 10.** $Q_{max}$ of sample fabrics.

The values of sample A and B were large. During the convection heat test, pressure is applied to the test samples by the copper disk calorimeter, so that the air layer between the fabrics becomes similar[19].

Therefore, when the influence of the air layer is excluded, it is considered that the moisture of each fabric reduces the heat transfer rate by losing the transferred

**Table 3.** Convection heat test result of sample fabrics

| Sample | Thickness (mm) | $l_{Q12}$ (s) | $l_{Q24}$ (s) | $l_{Q24}-l_{Q12}$ (s) |
|---|---|---|---|---|
| A | 0.75 | 3.5 | 5.3 | 1.8 |
| B | 0.58 | 3.1 | 4.9 | 1.8 |
| C | 0.49 | 3.1 | 4.3 | 1.2 |
| D | 0.62 | 3.1 | 4.6 | 1.5 |
| E | 0.52 | 2.7 | 4.2 | 1.5 |

**Table 4.** Radiant heat test result of sample fabrics

| Sample | Thickness (mm) | $t_{12}$ (s) | $t_{24}$ (s) | $t_{24}-t_{12}$ (s) | $Q_c$ (kW/m$^2$) | TF ($\frac{Q_c}{Q_0}\times 100$) (%) |
|---|---|---|---|---|---|---|
| A | 0.74 | 10 | 16.4 | 6.4 | 10.42 | 26.05 |
| B | 0.58 | 9.4 | 15.7 | 6.3 | 10.59 | 26.47 |
| C | 0.51 | 9.2 | 15.2 | 6 | 11.12 | 27.79 |
| D | 0.67 | 9.5 | 15.6 | 6.1 | 10.93 | 27.34 |
| E | 0.53 | 9.2 | 15.4 | 6.2 | 10.76 | 26.90 |

heat as evaporation heat. As a result, it can be claimed the thick fabric is good for protective performance because of containing large amount of moisture.

**Radiant Protective Performance**: Radiant heat test is a method of measuring the ability to delay heat transfer from the radiant heat. Table 4 shows the radiant heat test results. From results, it was concluded that the thickness of the sample had a greater effect on the protective performance than the difference in the structure of the fabric. TF(transfer factor) is the ratio of the heat transmitted through the samples exposed to the radiant heat source. As the values of $t_{12}$ and $t_{24}$ decrease, the time required to raise the temperature get shortened. So that, the heat transfer ratio and the TF value tends to increase.

## 4. Conclusions

In this study, mechanical and heat transfer properties of recycled m-aramid/cotton flame retardant fabric for industrial safety protection were analyzed according to constituents and various structural factors.

As a result of mechanical properties, fabric that use polyurethane yarn covered by m-aramid/cotton spun yarn as warp is considered to have good wearability. Because it showed low shear stiffness(G) and bending rigidity(B). The fabric of open-end spun yarn showed higher shear hysteresis(2GH5) and bending rigidity(B) than ring spun yarn. In the effect of the count, the sample with the high count of threads showed lower mean deviation of MIU(MMD) and geometrical roughness (SMD). In addition, high m-aramid content fabric showed high tensile linearity(LT), shear stiffness(G), and bending rigidity(B), depicting relatively high stiffness when using as a clothing.

In TGA analysis of thermal properties, the fabric with higher m-aramid content showed more stable decomposition behavior and more residual was also observed. Due to the stagnant air layer existing on the surface, the fabric having rough surface showed lower heat flux in $Q_{max}$. In case of convection and radiant heat test, the influence of the fabric thickness on the protective performance was important due to the fact that the moisture of fabric reduces the heat transfer rate by losing the transferred heat as evaporation heat.

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