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Investigating the Functional and Comfort properties of a Face Mask Based on a Coolmax® Blended Cotton Fabric

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Abstract
As the spread of Covid-19 has created a fatal threat to human survival, a comfortable and virus-deactivated functional face mask is extremely necessary. Herein, an appropriate thermally comfortable and highly breathable as well as virus-protecting functional knit fabric face mask was developed that consisted of multichannel PE Coolmax® yarn with cotton yarn. Due to the multichannel structure (four and six channels) of PE Coolmax® yarn with cotton yarn blended fabric, the fiber showed good filtration efficiency, air permeability, water vapour permeability and moisture management properties. In addition, the thermal conductivity and absorptive properties of the blended fabric based on the properties of PE Coolmax® yarn with cotton yarn make the face mask more comfortable for the user.

Keywords
Coolmax® blended cotton fabric, air permeability, water vapour permeability, moisture management.

1. Introduction

Information about the spread of the COVID-19 virus fluctuates every minute. Although COVID-19 is primarily a respiratory disease, the symptoms of infection with the virus can vary from very mild, non-respiratory signs to severe critical respiratory illness or dysfunctions of some vital organs and even death [1, 2]. Some people have also been reported to be infected without any symptoms at all [3, 4]. According to most of the research, the virus is transmitted mainly among society via respiratory droplets . Droplet exchange usually occurs if someone is in close contact (within 3 feet) with infected people. Exposure to infectious respiratory droplets may occur through sneezing, coughing or very near personal contact by way of the nose, mouth or eyes [5, 6]. Infection can also take place through the surface of materials in the environment near infected people. Consequently, the spread of the COVID-19 virus can take place directly by interaction with infected persons, or indirectly through touching surfaces. The WHO also advises policymakers to prepare regulations to decide where, when and what type of masks should be used [3, 8, 13]. The primary intention for utilising a face mask is to prevent the infection of others or for providing safety to the wearer against transmission. The face mask generates a corporal obstruction between the nose and mouth of the wearer against possible infections in the immediate environment [7, 14]. Face masks should be used not only by health care personnel but also by common people to prevent the transmission of the COVID-19 virus. Various types of face masks are considered to control the virus and limit the spread of the COVID-19 virus [13, 15]. Surgical masks and N95 masks are usually used in hospitals and are not available to common people. These types of masks are also costly and not suitable to wear in daily activities [2, 5, 16]. On the other hand, the most common face masks do not have functional and comfort properties for wearers [2, 3]. Since masks obstruct comfortable breathing during use, the wearer may touch the outside area of the mask, and consequently there is a chance of being infected due to the contaminated outer surface. Face masks also have to go through a lot of wear and tear during use. After using and washing, most masks may not function properly nor have the ability to protect against COVID-19. However, the face masks currently available in the market may not reduce the transmission of the virus in the community because they are not manufactured effectively [2, 8, 15]. Furthermore, the most current face masks have the problem of discomfort during use [8]. It would be better if the face mask were comfortable to wear and, at the same time, could reduce the transmission of the virus by itself. Taking into account all the factors, knitted fabric masks must be developed in such a way that includes PE Coolmax® yarn with cotton yarn, so that fabric masks with increased comfort ability and functional properties can be used [17, 18]. Thus, the fabric masks proposed herein can be used in an effective way to increase the comfort capacity of the wearer as well as reduce the transmission of COVID-19 immediately.

2. Experimental

2.1. Materials

In this study, cotton and modified polyester, that is, PE Coolmax® yarn of 18.5 tex (Figure 1), were selected as the basic material, and cotton yarn (30 Ne) was produced in three differential ratios, that is, 100% cotton fiber, 50% cotton and

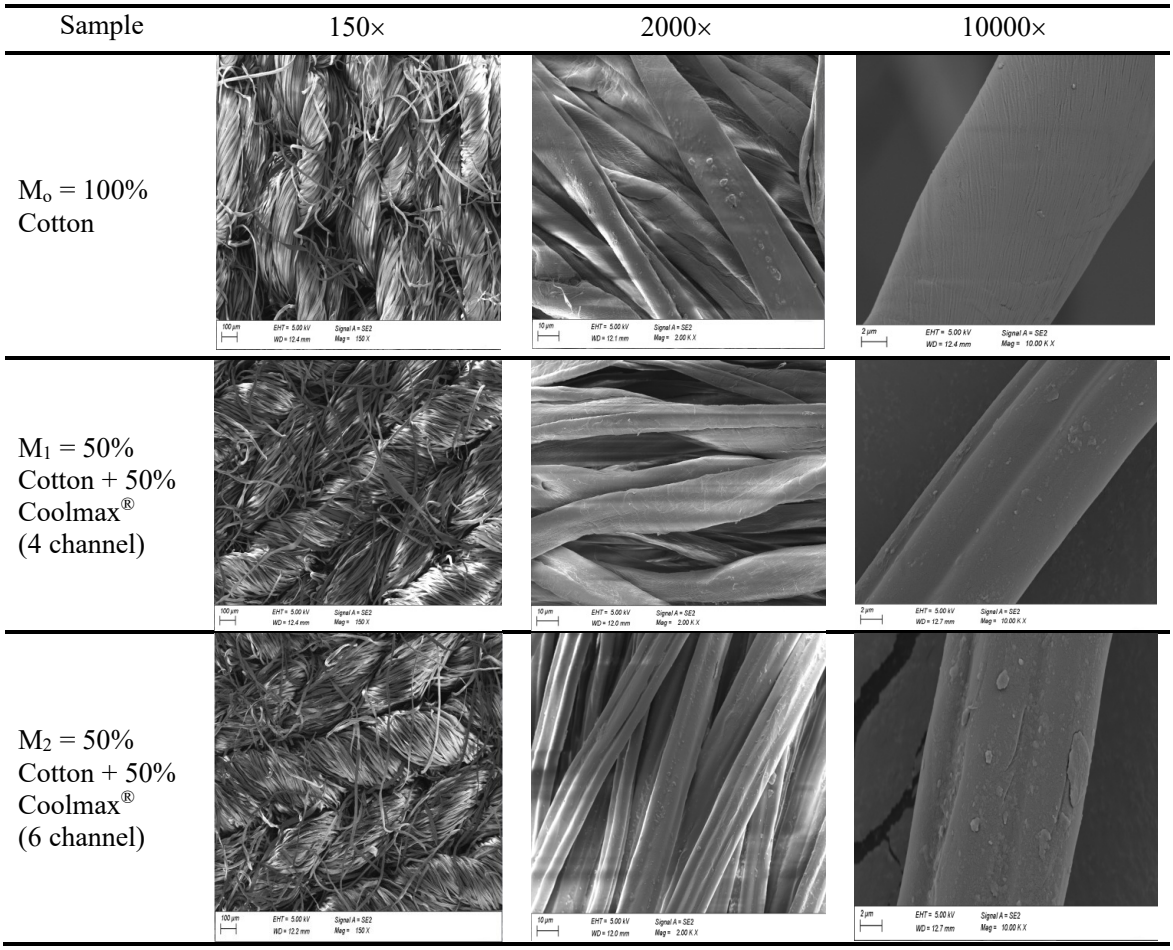

Fig. 1. Microphotos of the different face mask knit fabrics

Fabric Sample	Fibre Composition	Fabric Structure	Thickness (mm)	GSM (g/m²)	Pore size (m)	
					Mean	Max
M_o	100% cotton	Single jersey fabric	0.5217	149.760	31.72	92.12
M_1	50% cotton + 50% coolmax (4 channel)	Single jersey fabric	0.542	150.234	35.06	87.74
M_2	50% cotton + 50% coolmax (6 channel)	Single jersey fabric	0.5637	150.864	41.00	106.60

Table 1. Comparison of structural difference of the various fabric masks

50% PE Coolmax® yarn (4 channel), and 50% cotton and 50% PE Coolmax® yarn (6 channel). The fibers of PE Coolmax® yarn (4 channel and 6 channel), shown in Figure 2, were modified by the use of different spinnerets. A 24-gauge single jersey circular knitting machine of 30-inch diameter (Fukuhara, Japan), was used to make the face mask fabric samples. Three types of knitted fabrics were developed with the yarn produced while keeping the different GSM and stitch length. The face mask fabric samples were abbreviated as M_o = 100% cotton, M_1 = 50% cotton and 50% Coolmax® (4 channel), and M_2 = 50% cotton and 50% Coolmax® (6 channel), respectively. The GSM and thickness of the knitted fabrics are shown in Table 1.

The GSM and stitch length of all the knitted fabrics were almost 150 and 2.58 mm, respectively. The thickness of the manufactured fabrics was around 0.54±0.02 mm. The knitted fabrics were scoured and bleached with H_2O_2 (4 g/L) and NaOH (2 g/L) together with other accessories at 95°C for 60 minutes to remove impurities (oil, wax, fat, natural colour). To improve antimicrobial properties, the fabrics were also treated with a functional chemical - dimethyltetradecyl-(3-trimethoxysilyl)-propyl ammonium salt (Sanitized AG, (Switzerland) at 40°C for 20 minutes. The functional properties of all the fabrics were evaluated after conditioning them for 24 hours under standard atmospheric conditions: 20±2°C temperature and 65±2% relative humidity.

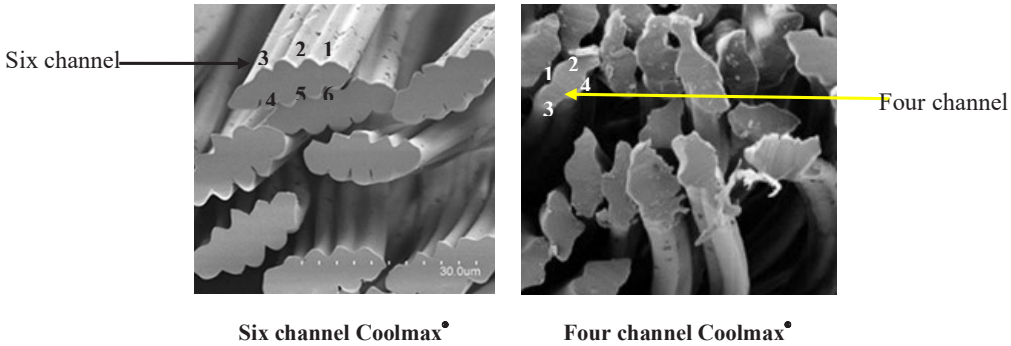

Fig. 2. Structure of Coolmax® fiber used to produce face mask knit fabrics

2.2. Methods

2.2.1. Filtration efficiency

The experimental apparatus consists of an aerosol generation chamber, mixing chamber, and downstream collection chamber [19]. Air flows from the generation chamber to the collection chamber through the cloth sample which is mounted on a tube connecting with the two chambers. Aerosol particles are generated using a commercial sodium chloride aerosol generator, producing particles in the range of a few tens of nanometers to approximately 10 µm. Tests were carried out according to the NIOSH 42 CFR Part 84 test protocol.

2.2.2. Air permeability measurement

Air permeability properties of the face mask knit fabrics were measured according to Standard ISO 9237:1995 using a head area of 20 cm^2 and differential pressure of 100 Pa. Air permeability is the rate of air passing perpendicularly through a known area under a prescribed air pressure between the two surfaces of a material. Air permeability was measured by an SDL Atlas M021A air permeability tester under standard test conditions.

2.2.3. Water vapour permeability measurement

Water vapour permeability was determined using an SDL Shirley water vapor permeability tester STM-473 according to Standard BS 7209-1990. As per the British standard, the sample knit fabric under test was sealed over the open mouth of an appropriate plate containing water, and the assembly was placed in a standard atmosphere of 20°C and 65%RH. Following a period of time to establish equilibrium of the pressure gradient of water vapour across the fabric sample, successive weighing of the dish was performed, and the water vapour transfer rate through the fabric sample was calculated comparing with a reference fabric. All experiments were replicated ten times and data were reported as a mean of the results.

2.2.4. Drying capacity

The drying capacity of the face mask fabric was determined by the drying rate of the sample. To measure the evaporating characteristics of the fabric, the sample weight taken in a dry state is W_f , and the initial weight with water is W_o. The variation in weight is W_i, which was evaluated after every minute for the first 5 minutes and then after every 5 minutes until 30 minutes. The residual water ratio (%) was calculated using Equation 1.

$$\text{The remaining water ratio} = (W_i - W_f) / (W_o - W_f) \times 100\% \quad (1)$$

The residual water ratios were taken into account to reveal the drying ability of the face mask fabrics. To evaluate the dry capability of the face mask fabric, it was measured at 35°C. All tests were repeated five times, and the data are reported as means of the results.

2.2.5. Vertical wicking test

A face mask fabric sample of 20×2.5 cm was cut along the course-wise and wale-wise directions and then suspended perpendicularly with the bottom end immersed in a reservoir of water. The bottom end of every face mask fabric was fastened with a 5 g clip to confirm that the bottom end was dipped perpendicularly at a depth of 3 cm in water. The wicking lengths of the face mask fabric were measured every minute for 10 minutes.

2.2.6. Thermal and moisture management properties

The thermal properties (thermal conductivity and thermal absorptivity) of the face mask knitted fabrics were evaluated on an Alambeta instrument according to EN ISO 31092-1994. The quantity of heat power transmission from the dry skin of the human body through the test fabric sample was given by the temperature difference between the top measuring head (32°C) and bottom measuring plate (22°C). The hot plate came in contact with the face mask fabric at a pressure of 20 Pa. The moisture management properties of the samples were also determined using the SDL moisture management tester (M-290 SDL Atlas, UK) according to the AATCC test method 195-2009.

2.2.7. Flexural rigidity (bending stiffness)

Face mask fabric stiffness can be evaluated by calculating the flexural

rigidity. The flexural rigidity of the mask fabric samples was determined for flexural rigidity as per ASTM D1388-08 using a Shirley stiffness tester. The principle of the stiffness of the fabric was based on the principle of cantilever bending of the fabric under its own mass. A specimen 20×2.5 cm was cut from the fabric sample in the wale and course directions. Five readings were reported for each mask fabric sample in both the wale and course directions.

Equation 2 was used to evaluate the flexural rigidity of the face mask fabric:

$$\text{Flexural rigidity (G)} = W \times C^3 \times 10^3 \text{ mg-cm}, \quad (2)$$

Where, C is the bending length in cm, and W is the weight of the fabric in g/cm^2.

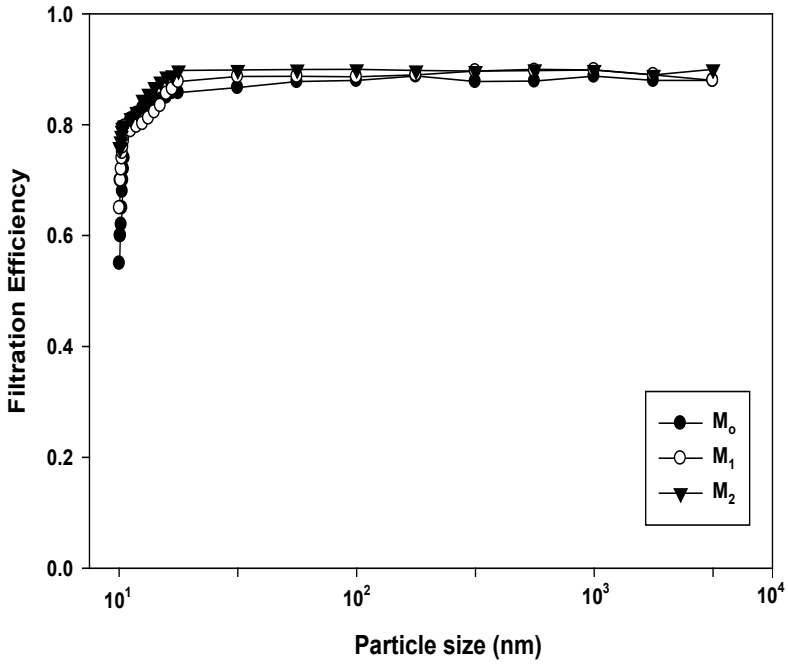

Fig. 3. Filtration efficiency of the functional finished Coolmax® and cotton blended fabrics at a flow rate of 1.2 CFM (without gap)

3. Results and Discussion

3.1. Filtration efficiency against droplets

The results shown in Figure 3 are the filtration efficiencies for cotton (the most common material used in cloth masks) with different PE Coolmax® yarns and cotton yarn. When comparing the three different fabrics, PE Coolmax® yarn with six channels is clearly superior with >85% efficiency at < 300 nm and >90% efficiency at > 300 nm. In comparison, the four-channel PE Coolmax® yarn with cotton yarn shows rather lower filtration efficiencies with >85% efficiency at < 300 nm. However, only single cotton fiber reveals a similar filtration efficiency across the range of particle sizes (<80% for <300 nm and >85% for >300 nm). In all of these cases, the performance in filtering nanosized particles < 300 nm is superior to that for the 300 nm to 6 µm range, and is particularly effective below ~30 nm, which is consistent with the expectations of the electrostatic effects of these materials.

3.2. Air permeability of face mask fabric

Air permeability is measured to establish the rate of the air pressure difference between the surfaces of a fabric. The key factors affecting the air permeability of knitted fabrics are the loop length, yarn linear density, and the course and wales density per inch of the fabric. Fibre morphology appears to be the main dominating factor preventing the passage of air through knitted fabric. PE Coolmax® yarn with cotton yarn face mask fabric gives higher air permeability (245 cc/cm^2/s) due to the extra pore channels present in PE Coolmax® yarn with a cotton yarn surface, which helps air flow through the knitted fabric. Air permeability increases with an increase in channels in PE Coolmax® yarn with cotton yarn in face mask fabric as more channels make the fabric structure less compact. The lowest air permeability (145 cc/cm^2/s) is observed in the case of cotton face mask fabric. PE Coolmax® yarn with polyester yarn blended with cotton fabric has good porosity and, thus, a great impact on air permeability properties.

3.3. Water vapour permeability of face mask fabric

The transmission of water vapour through a face mask fabric signifies the ability of comfort to humans. Two processes are usually related when water vapour passes through a textile fabric: sorption–desorption and diffusion. In the diffusion of fiber, moisture vapour diffuses from the innermost surface of the textile fabric, then passes through the central area of the fiber and to the outer part of the fabric surface. The diffusivity of the fiber increases with increasing moisture regain. Similarly, the transmission of moisture vapour through sorption–desorption will increase with the hygroscopicity of the material. Various studies have established that there is no link between fabric vapour permeability and air permeability [19, 20]. Results of the water vapour permeability of PE Coolmax® yarn with knitted cotton fabrics are shown in Figure 5. The higher water vapour permeability of PE Coolmax® yarn (240 mg/cm^2 h) with cotton yarn blended face mask fabrics can be ascribed to lower areal mass. The fabric produced with cotton fiber showed the smallest water vapour permeability (140 mg/cm^2 h), whereas the six channel PE Coolmax® yarn with cotton yarn gave the highest water vapour permeability due to the cross-section of the fiber, giving hydrophobicity to PE Coolmax® yarn with cotton yarn blended fabrics.

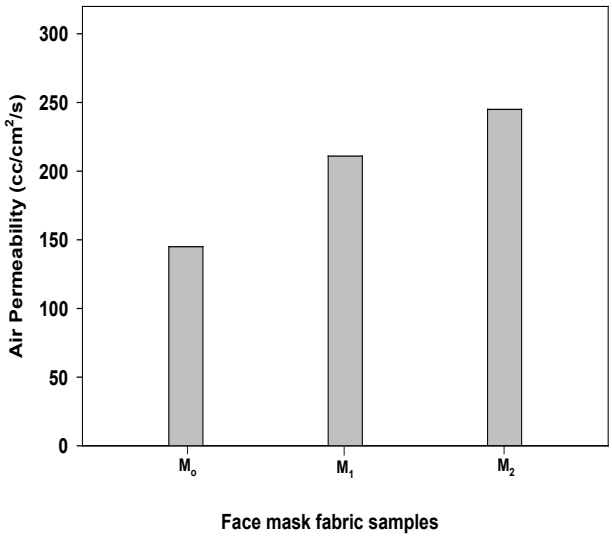

Fig. 4. Effect of Coolmax® fiber structure: M_o = 100% cotton, M_1 = 50% cotton and 50% Coolmax® (4 channel), and M_2 = 50% cotton and 50% Coolmax® (6 channel)) on the air permeability of face mask fabric

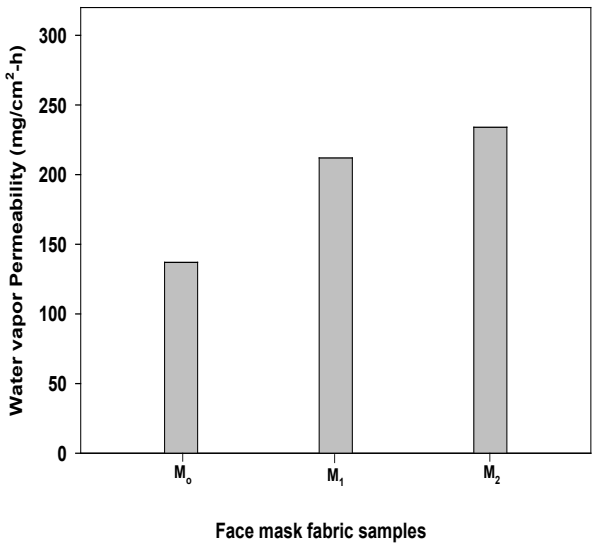

Fig. 5. Effect of fiber structure: M_o = 100% cotton, M_1 = 50% cotton and 50% Coolmax® (4 channel), and M_2 = 50% cotton and 50% Coolmax® (6 channel) on the water vapour permeability of the face mask fabrics

3.4. Transfer wicking results of face mask fabric

Wicking is the property of the intermolecular forces at the surface of the fabric material, which is measured from the effective capillary pathways as well as surface tension and pore distribution. The yarn-wicking behaviour of knitted fabrics is also affected by surface irregularity and the dispersion of fluid into the fabric by the capillary action of the yarn assemblies. Knitted fabrics are based on natural fibers, such as cotton, which is hydrophilic; therefore, it shows higher moisture absorption ability. However, the swelling of fabric is the result of wetting, which changes the position of the capillary space and moisture vapour absorbed bonds greatly, as well as raises the weight of the fabric and affects the wicking behavior. On the other hand, wicking will not occur for most synthetic fabrics due to their high contact angles. Synthetic fibers, such as PE Coolmax® yarn, are hydrophobic; they are not able to absorb a large amount of moisture. The wicking height of 100% cotton fabric is the lowest due to its hydrophilic nature, which negatively affects capillarity more than for blended fabrics. Furthermore, Figure 6 indicates that the wicking ability of PE Coolmax® yarn with cotton yarn blended fabric has the highest value (14 cm) in the wall direction compared to the course direction (12 cm). It is clear that the wicking ability of the face mask fabrics is more influenced by the geometry of PE Coolmax® yarn with cotton fiber used during blending.

3.5. Drying capacity of face mask fabric

The drying capacity is mainly related to the density of knitted fabrics, and drying times are lower for light weight and thinner fabrics of similar fabric construction. Light weight knitted fabrics were investigated here to establish the drying ability of blended fabric with various structures of PE Coolmax® yarn and cotton yarn. The evaporation curves presented in Figure 7 reveal that all the knitted fabrics exhibited differential behaviour at 35°C from the very first minute. After 15 minutes the drying ability of the 6 channel PE Coolmax® yarn with cotton yarn face mask fabrics was higher than that of the 4 channel PE Coolmax® yarn with cotton yarn fabric and 100% cotton fabric. 100% cotton knit fabric demonstrated the maximum residual water ratio even after 30 minutes. In cotton fabric, water is readily soaked inside the fiber structure due to the hydrophilic nature of the material. Due to the higher number of hydroxyl groups available in cotton fiber for bonding with water, its moisture content is much higher than that of other blended fabrics with PE Coolmax® yarn and cotton yarn. Therefore, PE Coolmax® yarn and cotton yarn blended fabric becomes dry faster than for 100% cotton fabrics, and the level of heat loss may also be higher during the evaporation due to the presence of a continuous water evaporating channel by means of thermal conductivity. The wicking ability and drying capability of PE Coolmax® yarn and cotton yarn blended knitted fabric will play an important role in producing a comfortable face mask for the wearer.

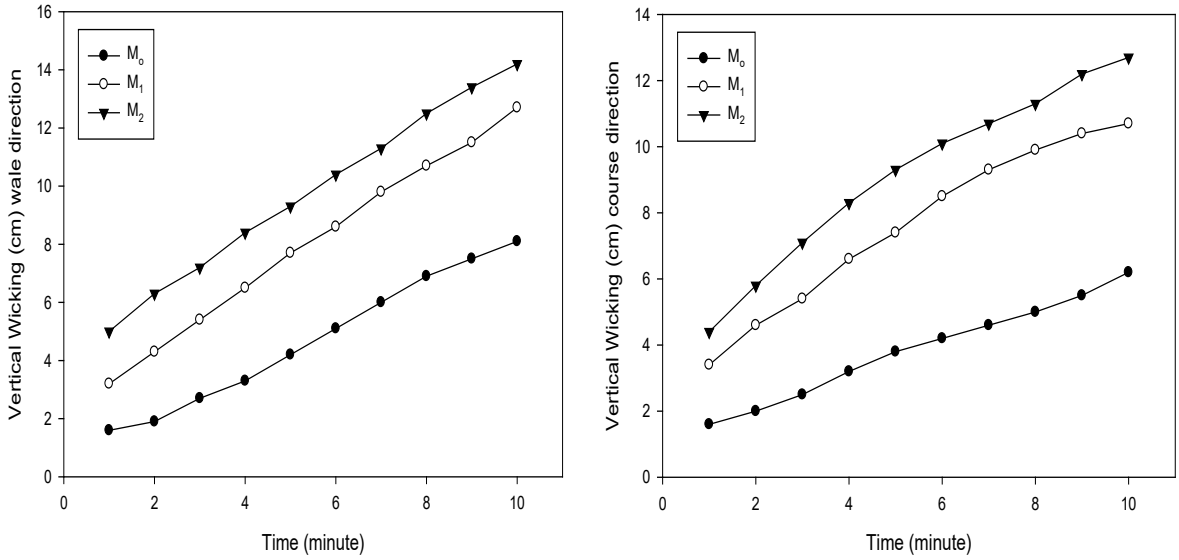

Fig. 6. Wicking property results of face mask knitted fabric: M_o = 100% cotton, M_1 = 50% cotton and 50% Coolmax® (4 channel), and M_2 = 50% cotton and 50% Coolmax® (6 channel)

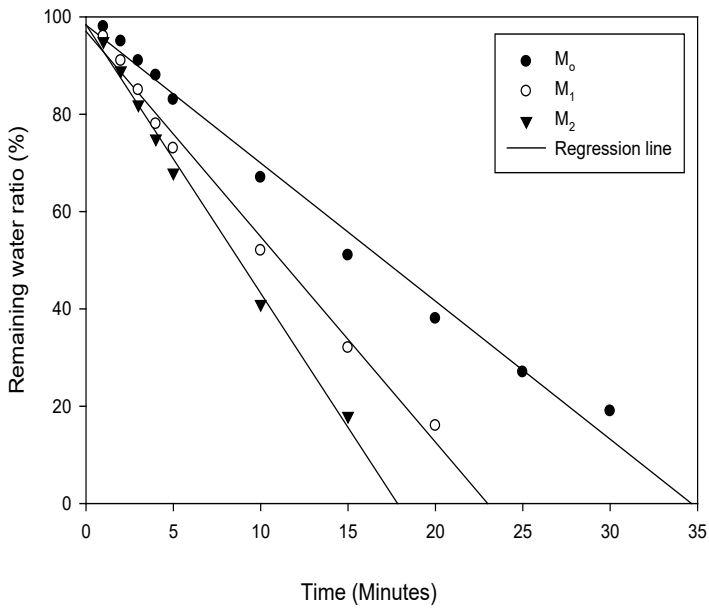

Fig. 7. Remaining water ratio values at 35° C of Coolmax® blended face mask fabric: M_o = 100% cotton, M_1 = 50% cotton and 50% Coolmax® (4 channel), and M_2 = 50% cotton and 50% Coolmax® (6 channel)

3.6. Thermophysiological comfort properties of the face mask fabrics

Figure 8 shows results of the thermal conductivities. Thermal conductivity is an intensive property of a textile fabric that characterises the heat transmission process through fiber. Thermal conductivity (λ) can be evaluated using Equation 3:

$$\lambda = Qh / A\Delta Tt, \quad (3)$$

Where λ is the thermal conductivity (W/mK), Q the amount of heat (J), A the area through which heat is conducted (m^2), t the time of conduction (s), ΔT the drop in temperature; and h is the thickness of the fabric (m).

The thermal conductivity of the face mask fabric can be defined as the quantity of heat transmitting through the unit fabric at a 1°C heat difference. According to the test results, the PE Coolmax® yarn with cotton yarn fabrics in this study have a similar thermal conductivity, with the exception of the 100% cotton knit fabric, which showed the highest value (55×10^{-3} (W/m K)), probably due to the higher areal mass of this fabric. There exists a direct correlation between thermal conductivity and fabric areal mass in the case of knitted fabric. When the mass of the fabric area increases, the thermal conductivity also increases. Because the amount of air in the structures increased in the case of PE Coolmax® yarn with cotton yarn fabric, the fabric provides higher thermal insulation with lower thermal conductivity values. However, PE Coolmax® yarn (six channels) with cotton yarn imparts lower thermal conductivity (41×10^{-3} (W/m K)).

3.7. Thermal absorptivity of face mask fabric

The thermal absorptivity of the fabric is a surface-related property that affects the warm-cool feeling for the wearer. Therefore, the thermal absorptivity of knitted fabric is the characteristic associated with the thermal insulation of the material. Thermal absorptivity is interrelated with fabric density, conductivity, and specific heat capacity, and can be measured using Equation 4:

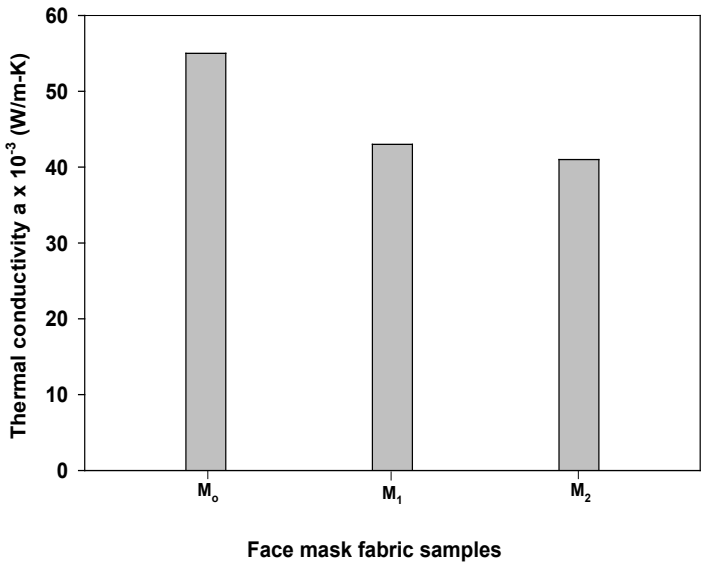

Fig. 8. Thermal conductivity of face mask fabric (M_o = 100% cotton, M_1 = 50% cotton and 50% Coolmax® (4 channel), and M_2 = 50% cotton and 50% Coolmax® (6 channel))

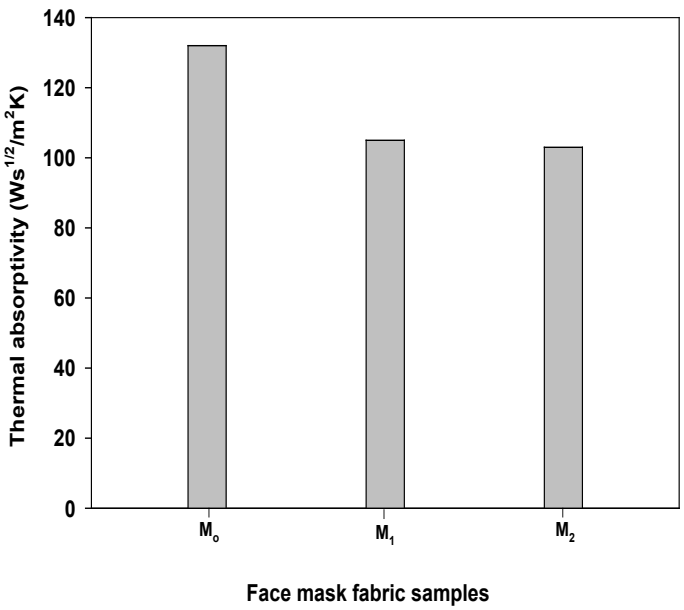

Fig. 9. Thermal absorptivity of face mask fabrics: M_o = 100% cotton, M_1 = 50% cotton and 50% Coolmax® (4 channel), and M_2 = 50% cotton and 50% Coolmax® (6 channel)

$$r = \sqrt{\lambda \rho c} \quad (4)$$

Where r is the thermal absorptivity ($Ws^{1/2}/m^2K$), λ the thermal conductivity (W/mK), ρ the density of the fabric density (Kg/m^3); and c is the specific heat capacity ($JKg^{-1}K^{-1}$). 100% cotton face mask fabric displays the highest thermal absorptivity values, providing the coolest feeling at the beginning of human skin contact (Figure 9). The thermal absorptivity value (103 $Ws^{1/2}/m^2K$) decreases when PE Coolmax® yarn is added with cotton yarn. The heat transfer mechanism through knitted fabrics may comprise conduction through fibers and air radiation and convection inside the fabric. Higher thermal conductivity is the result of higher heat flux. It can be observed that 100% cotton knit fabric has the highest thermal absorptivity (132 $Ws^{1/2}/m^2K$) and the highest heat flow, indicating a relatively cooler feeling when it touches human skin just for a few seconds. But it does not give a more pleasant feeling compared to PE Coolmax® yarn with cotton yarn fabric for a longer time due to the lowest thermal insulation properties. However, four-channel PE Coolmax® yarn with cotton yarn has less pore size than six-channel PE Coolmax® yarn, with cotton yarn; thus, the thermal insulation area is slightly higher in six channel Coolmax® fiber. The lowest thermal conductivity (41 W / mK) is shown by six-channel PE Coolmax® yarn with cotton yarn fabric due to the thickness of the fiber and thermal conductivity.

3.8. Flexural rigidity of face mask fabric

The stiffness of face mask fabric can be evaluated by measuring the flexural rigidity of the fabric. The stiffness of the mask fabric affects the properties of drape and comfort. Face mask fabric with a higher value of flexural rigidity will be stiffer, may not be comfortable to wear, and cannot bend according to the surface of body contours. The flexural rigidity, as shown in Figure 10, is lower in the course direction due to the loop formation mechanism of knitted fabric in the weft direction. The flexural rigidity of the knit fabrics is observed to increase with an increase in PE Coolmax® yarn with cotton yarn content both in the wale (251 mg-cm) and course (95 mg-cm) directions. The filament structure of PE Coolmax® yarn with cotton made the yarn stiffer, which eventually led to an increase in the stiffness of the fabric. Although PE Coolmax® yarn and cotton blended knit fabric shows a higher flexural rigidity compared to 100% cotton knit fabric, the flexural rigidity values of all the knitted fabrics are lower compared to woven fabrics [23]. Therefore, the use of PE Coolmax® yarn with cotton in the wale and course directions does not create a negative impact on the face mask fabric.

4. Conclusion

A protective functional mask can reduce the spread of COVID-19 infection, but it will not reduce the risk of transmission;

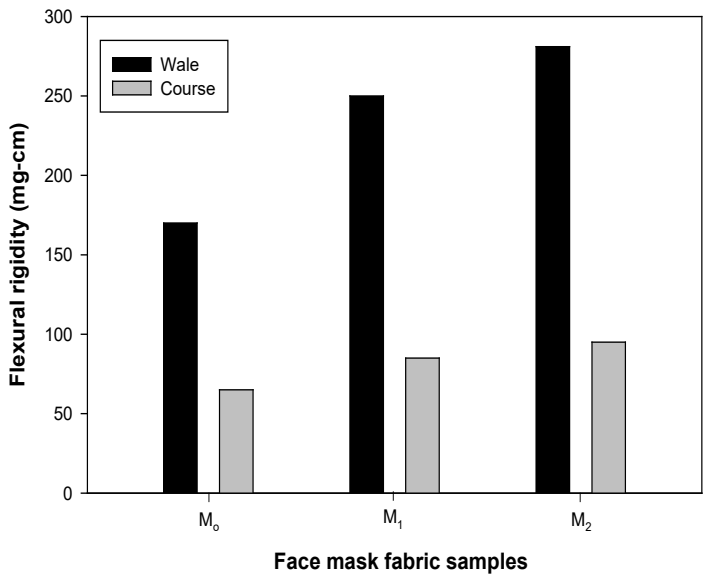

Fig. 10. Effect of Coolmax® fiber content on flexural rigidity properties of face mask fabric: M_o = 100% cotton, M_1 = 50% cotton and 50% Coolmax® (4 channel), and M_2 = 50% cotton and 50% Coolmax® (6 channel)

particularly when a mask does not create comfort ability during use. The results show that the PE Coolmax® yarn (6 channel) with cotton yarn face mask shows higher filtration efficiency than PE Coolmax® yarn (4 channel) with cotton yarn fabric and only cotton yarn face mask fabric. The air permeability and water vapour permeability of the PE Coolmax® yarn (6 channel) with cotton yarn face mask fabric produced the best comfortability among the other samples. The wicking ability of PE Coolmax® yarn (6 channel) and cotton yarn blended fabric showed the highest value in the wale-wise direction compared to the course-wise direction. Additionally, PE Coolmax® yarn (6 channel) with cotton yarn blended fabric showed the highest drying efficiency than any other face mask fabric sample. Moreover, PE Coolmax® yarn (6 channel) with cotton yarn fabric provides lower thermal conductivity and absorptivity, and higher flexural rigidity. This kind of face mask can be used to minimise the transmission of COVID-19.

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