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Protective and Comfort Performance of Fire Protective Clothing

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Article

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ABSTRACT

The study examined the fire protection performance of several woven products. Given that the comfort and fire protection properties of fire protective clothing (FPC) are opposite, it is important to consider the specific needs of firefighters when selecting the most suitable structure from various plain-woven derivatives, such as plain, basket, and ripstop. The yarn used was Nomex IIIA, which is a type of meta-aramid fibre. To achieve different thread densities, the pick density was adjusted while keeping the end density constant. The physical characteristics, thermal protective performance, thermal resistance, thermal conductivity, water vapour transmission rate and air permeability of all samples were assessed according to the appropriate standards. The goal was to identify the weave structure with the highest performance and the most optimal thread density. The basket weave structure was proposed as a fire protective clothing (FPC) having comfort qualities at a moderate level. Furthermore, increased density provided enhanced fire resistance, however, comfort must be sacrificed. Thus, to achieve a balance between fire protection and comfort, it was recommended to choose a thread density that is of an average level and the suggestion made by this research is to use the fabric as a basket weave design with an ends per inch of approximately 42, it is recommended to retain the pick density within the range of 46 with 44 tex Nomex IIIA yarn. The results of this study may be replicated in other designs using Nomex IIIA and comparable types of cloth and weave specifications.

KEYWORDS

fire protective clothing, weave structure, fabric density, comfortability, fire resistance

INTRODUCTION

Within the field of occupational safety, especially in settings with thermal dangers, the design and effectiveness of fire protection clothing (FPC) are of utmost significance in protecting the welfare of those who are exposed to these risks. The outer layer of FPC functions as the main barrier against radiant heat, flame, and other dangerous materials, playing a crucial role in guaranteeing the wearer's safety [1]. The ongoing advancement of textile technology has generated a greater interest in maximizing the efficiency of FPC. Researchers and industry professionals are increasingly investigating the intricate connection between fabric construction and desired performance results on FPC. Woven fabric structures play a crucial role in determining the effectiveness of fire protection outer layers [2]. The intricate designs and weave arrangements, as well as the density of threads, are important aspects that greatly impact their thermal and comfort overall efficacy [3]. Although the main goal is to protect the wearer from heat-related dangers, it is crucial to prioritize comfort. Prolonged pain can undermine the efficacy of protective equipment and, consequently, the wearer's safety.

High-performance fibres such as Meta aramid fibres [4], para-aramid fibres [5,6], FR Modacrylic fibres [7], Flame-Resistant Cotton [8], Carbon Fibre [9], FR Rayon fibres [10] are used by researchers to see their fire protective performance. Among all these fibres, Nomex IIIA comprises inherent properties of flame retardancy from its molecular structure [11]. Moreover, it has excellent protection capabilities against flash fires, and it can withstand its basic fire-retardant properties even after multiple washes. Apart from that, Nomex IIIA also shows extraordinary resistance towards various chemicals [12,13].

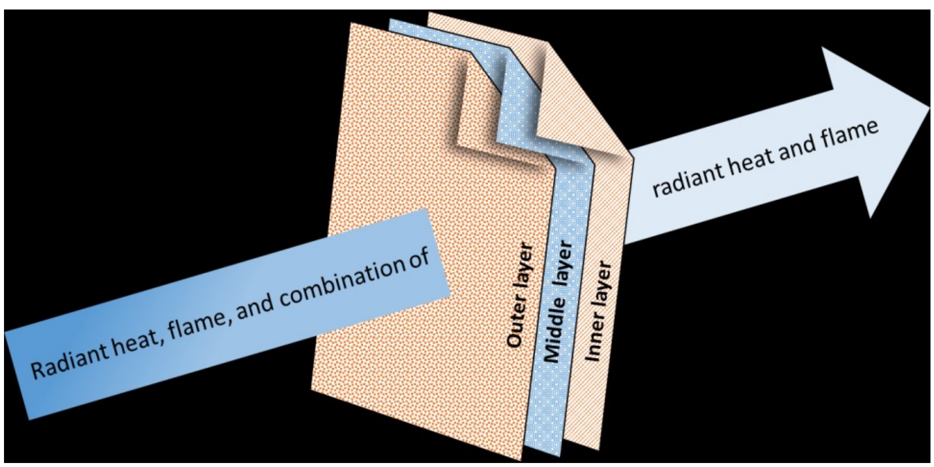


Figure 1. Schematic diagram of fire protective clothing (different layers)

The outer layer of FPC is exposed to the initial impact of intense heat in fire situations, necessitating the adoption of fire-resistant materials in that area [14]. In addition, the performance of the FPC can be balanced by considering the fibre types, weave structure, and thread density of its outer layer. A study was commenced to examine the plain weave structure using Nomex IIIA fibre where the Box-Behnken experimental method was employed to forecast the radiative thermal protection performance. A greater distance between the heat source and the cloth resulted in a better level of protection, and the model showed a substantial impact [15]. Plain, ripstop and twill architectures were used for another research to determine the effective thermal ageing of FPC on mechanical performance. They employed various models and conducted extensive research to achieve a high level of concurrence with multiple models to support their predictive assertions [16]. Rare focus was devoted to the pick density of different weave structures by the researchers to assess thermal protection capabilities. R. Rathour et al. examined the protection against heat and comfort performance of meta-aramid fabrics with various weave structures (plain, twill, sateen, honeycomb) and thread densities (two and three-plied) [15,17]. These four structures are not only distinct from one other, but they also exhibit a certain degree of predictability, indicating the presence of differences. However, the design of a basket is a variation of a plain design, and the rip-stop design is created by combining many plain derivatives, such as warp rib, weft rip, and basket design. Given that plain structure has already been shown to produce the most compact fabric and that fabric tightness is a significant factor in achieving higher protection performance [4], choosing plain construction and its derivatives may offer some quantifiable insights into the comfort and thermal protection characteristics.

Numerous studies have indicated that the thickness of the fabric significantly influences its capacity to provide thermal protection. Higher thermal resistance was the result of increased fabric thickness; additionally, the significance of fabric thickness varied with different radiative heat rates, particularly at low radiative heat flow, where thickness value was critically important. At higher radiative heat flow, however, other fabric parameters—such as pick density, yarn type, and so forth—became more important than fabric thickness [18–20].

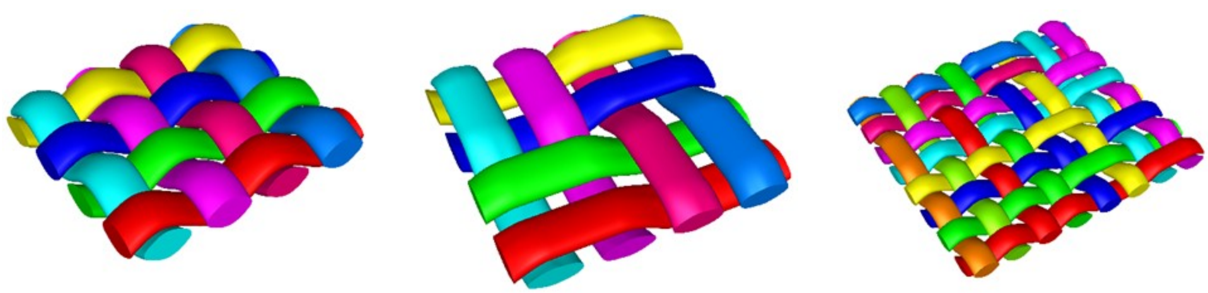
Every fire incident undergoes two basic and essential challenges; firstly, skin burn injuries due to exposure to heat and flame and secondly, stress caused by metabolic heat generated inside the clothing. Unluckily, these two phenomena are completely inverse in characteristics. Protection against burn injury increases the risk of metabolic heat stress and vice versa [15]. Therefore, along with the heat protection of FPC comfort qualities are also highly essential phenomena. During battling against fire occurrences, fighters had to be exposed to a wide range of hazardous situations such as carcinogenic gases, heated and melted chemicals, smoke and so on. Due to the high degree of temperatures and carcinogenicity of the gases FPC garments are normally manufactured with high density so that heat, liquid, and gases cannot travel from fabric to skin [21]. While keeping this architecture of the fabric, the heat generated within clothing remains retained and boosts the sweating rate. As a result, firefighters suffer from dehydration and often fall during firefighting. For this reason, air permeability, water vapour transportation rate, thermal blockage and thermal conductivity measurement are very crucial to measuring the comfort properties of clothing. It is noteworthy that clothing comfort is a very complex term which not only depends on the objective materials but also on subjective content. Apart from fibre and fabric constructional parameters, comfort phenomenon vastly depends on the wearer's psychology and his attitude towards the clothing item and desire performance [22].

This article thoroughly analyzes the complex relationship between the structure of woven materials and the density of threads. It examines how these factors together affect the ability of fire-protective outer layers to provide both protection and comfort. By accumulating all the discussion above, to accomplish this project, a plain weave structure along with its two impactful derivatives basket and ripstop design was selected. Three different thread densities of the fabrics were maintained by changing the pick density for the same end density. First and foremost, the physical properties of all the samples were measured and compared. Later, the Thermal protective performance of all samples was measured and analyzed. Air permeability, thermal conductivity, water vapour permeability and thermal resistance properties were evaluated for comfort performance evaluation.

MATERIALS AND METHODS

Materials

Samples of woven cloth were created on a handloom with 42 ends per inch as a constant. The Nomex IIIA yarn was bought from a nearby yarn store and utilized as the foundation for the fabric prototypes. Depending on the required areal density of the fabric, 44 Tex was chosen as the linear density of Nomex IIIA. For each design, the plain (2 × 2), basket (4 × 4), and ripstop (8 × 8) weave structures were used to create fabric with 40, 46, and 52 pick densities. Table 1 provides details on the fabric specifications.



a) b) c)

Figure 2. Type of weave: a) plain weave [$\frac{1}{1}$]; b) basket weave [$\frac{2}{2}(2)$]; c) ripstop weave [$\frac{1\ 1\ 2}{1\ 1\ 2}$ $(1+1+1+1+2+2)$]

Basic plain weave $\left(\frac{1}{1}\right)$ the structure was selected along with the basketweave design of the formula number $\frac{2}{2}(2)$ and ripstop weave design of [$\frac{1\ 1\ 2}{1\ 1\ 2}$ $(1+1+1+1+2+2)$]. Both basket and ripstop designs were the simplest derivatives of plain fabric belonging to basket and ripstop designs. Other derivatives of plain weave structures consist of more floating on fabric that will increase the pore size of the fabrics with reduced fire protection performance.

Methods

Physical properties

Following ASTM D 3775-12(6) standard, thread density of all plain, basket and ripstop fabric were measured. End density in terms of inch (EPI) and pick density in terms of inch (PPI) were measured with the help of ordinary counting glass manually. For precise values of EPI and PPI total average values of ten measurements were counted. Moreover, the thickness of the fabrics was determined respecting ASTM D 1777-96(7) where the standard pressure of 20 gf/cm^2 was maintained. Like thread density, for precision, twenty thickness values were averaged out for each sample. In addition to that, areal density and fabric weight were measured using ASTM D 3776-09 standard. In brief, for measuring the areal density, a sample of size 10 × 10 cm was considered and an electronic weighing scale was employed. The average value of five samples was taken as the final areal density (gram/m^2).

Equation 1 was implemented to determine the bulk density of all the fabric samples [3]. This is the amount of material per unit volume which relates thickness and areal density of the fabric samples.

$$\text{Bulk density}\left(\frac{kg}{m^3}\right) = \frac{\text{Areal density}\left(\frac{gm}{m^2}\right)}{\text{Thickness}\ (mm)} \tag{1}$$

Fabric porosity is another term used for FPC items. Having a higher pore size means there may have to be more probability of heat and mass transfer through the fabric. Fabric porosity of the fabric was measured through the below equation 2 [3]. The density of Nomex IIIA fibre is 1380 kg/m^3.

$$\text{Fabric porosity} = 1 - \frac{\text{Bulk density}\left(\frac{kg}{m^3}\right)}{\text{Fiber density}\left(\frac{kg}{m^3}\right)} \tag{2}$$

Comfort characteristics

Thermal conductivity

A dry contact KES-F7 thermolabo tester was employed to determine the thermal conductivity of the samples. A 20 × 20 cm size specimen was placed on the hot plate maintaining a constant air temperature of 10 °C above ambient temperature. With that, a constant air blow was maintained. The amount of heat loss was calculated and tabulated following the below formula:

$$k = q\frac{L}{\Delta T} \tag{3}$$

Where, L = Thickness of the specimen, ΔT = Temperature (°C), and q = Heat flow rate (W/m^2), K = amount of heat loss (W/m°C).

Thermal resistance

The thermal conductivity of textiles was measured using the KES-F7 Thermolabo tester. By applying a steady heat source through the cloth and measuring the quantity of heat lost through it, the thermal conductivity of the material was determined. The following formula was used to determine the thermal resistance based on the sample thickness and thermal conductivity [23].

$$Thermal\ resistance\left(m^2\frac{°C}{W}\right) = \frac{Thickness\ of\ specimen\ (m)}{Thermal\ conductivity\left(\frac{W}{m°C}\right)} \tag{4}$$

Air Permeability

Air permeability refers to the ability of different types of textiles, including woven, blanketed, airbag, knitted, napped, layered, and pile fabrics, to allow airflow to pass through them perpendicularly. It is measured by determining the rate of airflow through a specific area of the fabric under a defined air pressure difference between its two surfaces. The essential air permeability tester was used in combination with the ASTM D737-96 methodology. The SI unit cm^3/s/cm^2 was used.

Water Vapor Transmission Rate

Fabric breathability is directly related to the comfort performance of cloth. The water vapour transmission rate (WVTR) is the term used to determine the breathability of fabric to check whether the fabric is capable of transmitting moisture or not. WVTR of the fabrics was measured by satisfying the standard ASTM E 96 using the WVTR instrument [24]. The testing temperature was 38 ˚C and the relative humidity was 80 %.

Thermal protective performance

Based on the NFPA 1971 standard, the Thermal Protective Performance (TPP) rating was determined. This approach employed a heat flux value of 83_+4 kW/m^2 with 50% radiative and 50% conductive exposure. Here, nine quartz T-150 infrared tubes and two Merker or Fisher burners positioned at a 45-degree angle from the vertical were used.

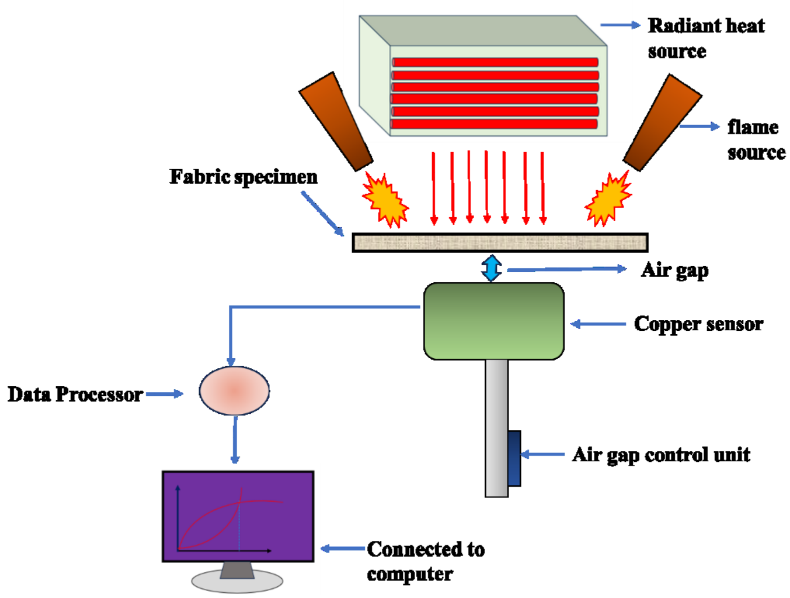


Figure 3. Thermal protective performance (TPP) tester

A 40 mm diameter and 1.6 mm thickness copper calorimeter were used to measure the heat transmission through cloth. The heat flux and burn duration were multiplied to get the thermal protection performance rating [25].

RESULTS AND DISCUSSION

Physical Properties

Figure 2 reveals that the plain fabric has the smallest repeat size of 2×2, while the basket and ripstop designs have repeat sizes of 4×4 and 8×8, respectively. Figure 2 demonstrates that the ripstop design is a composite of plain weave, warp rib, weft rib, and basket design. Increasing the number of floats in the weave design enhances the likelihood of float yarns overlapping with each other, leading to a higher areal density compared to designs with fewer floats. According to that reasoning, the ripstop design exhibited a greater areal density (ranging from 125.9 to 143.9 grams per square meter) compared to the basket (ranging from 117.4 to 140) and plain (ranging from 106.1 to 120.35) weave designs. Additionally, the plain weave structure exhibited a smaller thickness (0.442 mm to 0.466 mm) compared to the basket design (0.472 mm to 0.490 mm), which can be attributed to the overlapping caused by extra floats. However, the ripstop design is a hybrid of the plain and basket designs, resulting in a thickness that is less than that of the basket design (0.438 mm to 0.448 mm) but more than that of the plain fabric. Furthermore, it was observed that as the number of picks per inch elevated, the thickness value was similarly raised for all fabric designs.

Table 1: Fabric specifications of different woven fabrics

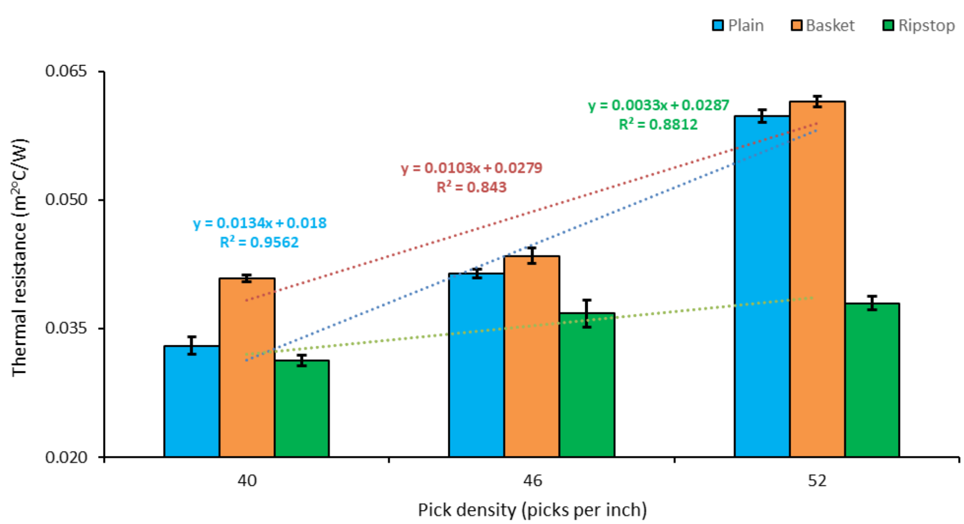
Sample Code	Weave	Ends per inch	Picks per inch	Areal density (g/m²)	Thickness (mm)	Bulk density (kg/m³)	Porosity
S1	Plain		40	106.1	0.442	240.11	0.82
S2	Plain		46	112.16	0.452	248.14	0.82
S3	Plain		52	120.35	0.466	258.26	0.81
S4	Basket		40	117.4	0.472	248.77	0.82
S5	Basket	42	46	133.2	0.488	272.97	0.80
S6	Basket		52	140	0.490	285.69	0.79
S7	Ripstop		40	125.9	0.438	287.49	0.79
S8	Ripstop		46	133.2	0.441	302.15	0.78
S9	Ripstop		52	143.9	0.448	321.32	0.77

The pick density of the woven fabrics exhibited a direct correlation with the bulk density. As the pick density spiked the bulk density of the textiles also increased, like the way areal density increases. Nevertheless, the ripstop design exhibited the highest bulk density (ranging from 287.49 to 321.32) while having a lower thickness. This occurred due to the greater areal density of the ripstop textiles compared to plain and basket designs. The porosity of the fabric samples was measured following equation 2. With the rising tendency of areal density and bulk density of all the samples, porosity decreased. It means that higher bulk density lowers the porosity, which already has been shown by several researchers [17,26]. The same trend was found in this research. Nonetheless, though basket designs showed less thickness than ripstop designs, due to higher areal density and bulk density, porosity was a bit higher. It means that bulk and areal density have more impact on porosity than the thickness of the fabric, though indirectly bulk density is dependent on thickness, however, bulk density also depends on areal density. Therefore, finally, it can be confirmed that the primary factor for the porosity of fabric is areal density and the secondary factor is bulk density.

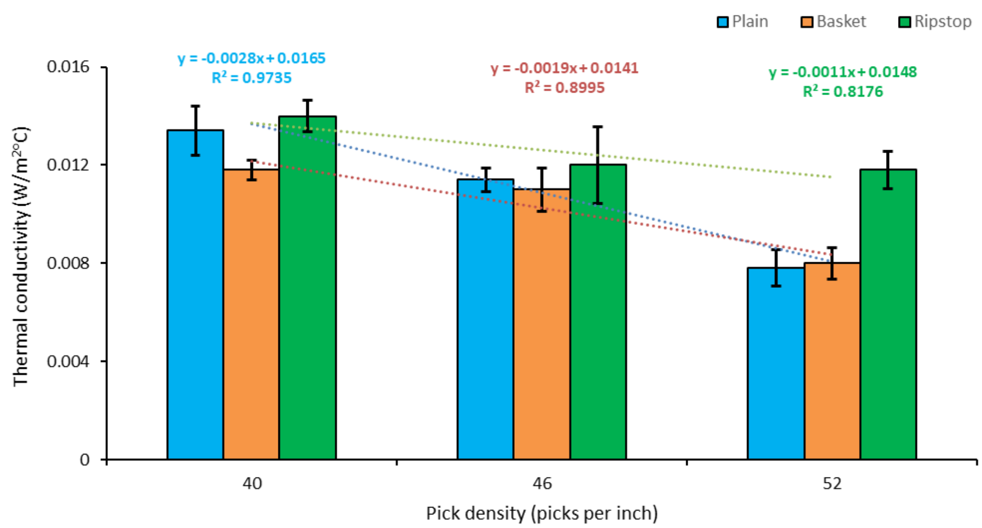
Comfort or transmission characteristics

Thermal conductivity and thermal resistance

Figure 4 depicts the thermal conductivity and thermal resistance characteristics of plain, basket, and ripstop textiles. Given that thermal conductivity and thermal resistance are reciprocal phenomena, a similar relationship appeared in both Figure 4 (a) and 4 (b). Despite having a higher bulk density, the ripstop design exhibited lower thermal resistance compared to alternative structures with higher thermal conductivity values.



a)



b)

Figure 4. The plain, basket and ripstop weave structures: a) thermal resistance, b) thermal conductivity

From Table 1, it is visible that ripstop fabric has the lowest thickness and plain consists of the second lowest among the three samples. For this reason, being thicker, basket fabrics showed greater thermal resistance (0.041-0.062 m^2°C/W). For the lowest thickness value, ripstop design fabric showed (0.031-0.038 m^2°C/W) thermal resistance value. The reason for this is, that higher thickness means there are higher amounts of air in the medium which reduces thermal conductivity and increases the resistance capability. Due to weave structure differences among the samples, within the same thread densities, the thickness and bulk density of the samples were revealed different (table 1). That stands for that, thread density is not the only factor to change the areal and bulk density of fabric, weave structure is also an important factor by which the thermal properties can be modified and adjusted to the desired outcome. At the same time, the highest coefficient of determination (R^2) was obtained for plain fabric for both thermal conductivity (0.9735) and thermal resistance (0.9562) which meant that the relation between thermal conductivity and thermal resistance with thread density could explain 97.35% (thermal conductivity) and 95.62% (thermal resistance) variation of the entire data.

Air Permeability

Compact fabric structures prohibit the flow of air through it [27]. Bulk and area densities both rise in response to an increase in pick density. Because of this, the fabric compactness will also be enhanced. Thus, as seen in Figure 5, the air permeability of all samples reduced dramatically as the pick density increased.

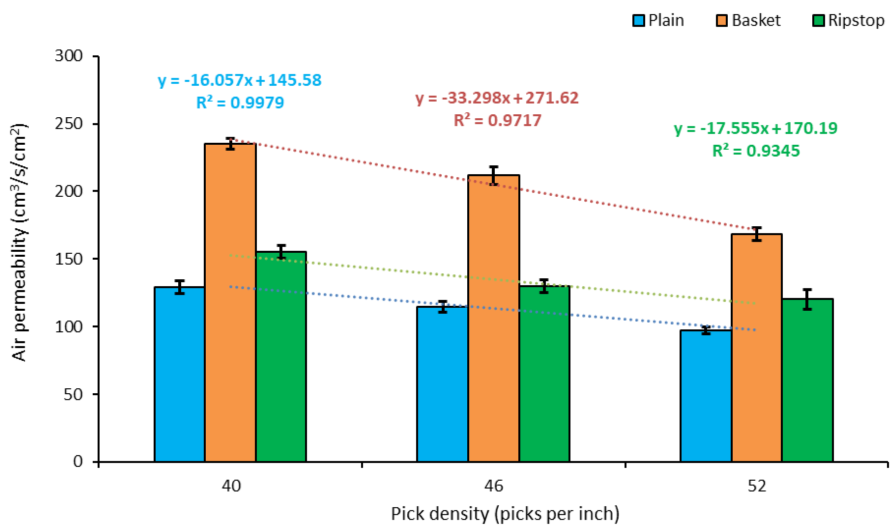


Figure 5. Air permeability of plain, basket and ripstop weave structures

Moreover, since the ripstop design is a combination of plain and basket design (figure 1), it can be suspected that the compactness of the ripstop design may be laid in between the other two designs. Following that, ripstop design experienced less air permeability value (155.314 $cm^3/s/cm^2$ - 120.204 $cm^3/s/cm^2$) than basket fabric (235.036 $cm^3/s/cm^2$ -168.44 $cm^3/s/cm^2$) and higher than plain (129.1 $cm^3/s/cm^2$ - 96.96 $cm^3/s/cm^2$). The R^2 value was higher for plain fabric (0.9979) than basket (0.9717) and ripstop (0.9345) structures, though the data variation of all the constructions is within the acceptable range (>0.9).

Water Vapor Transmission Rate

The WVTR values are displayed in Figure 6. Across all the samples, it was seen that increasing the pick density led to a decrease in the WVTR values. This occurrence occurred as a result of the heightened density of fabrics due to higher pick density.

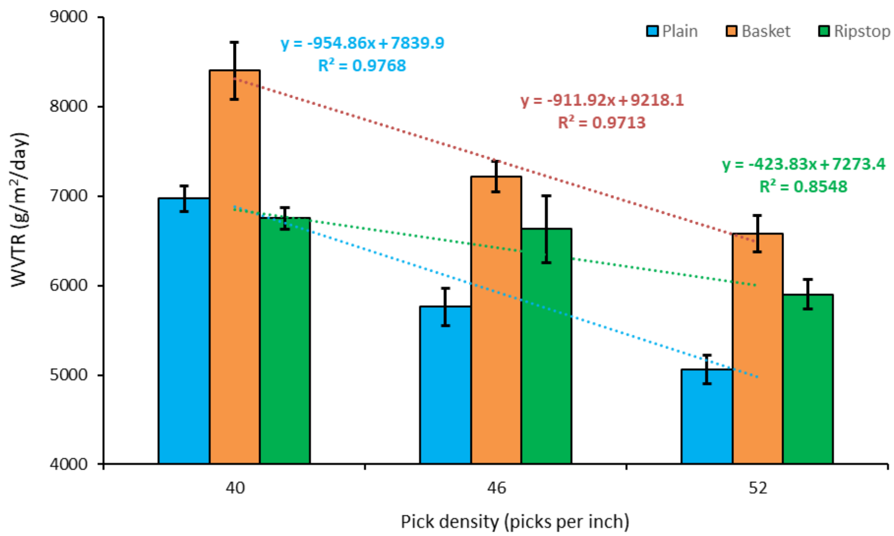
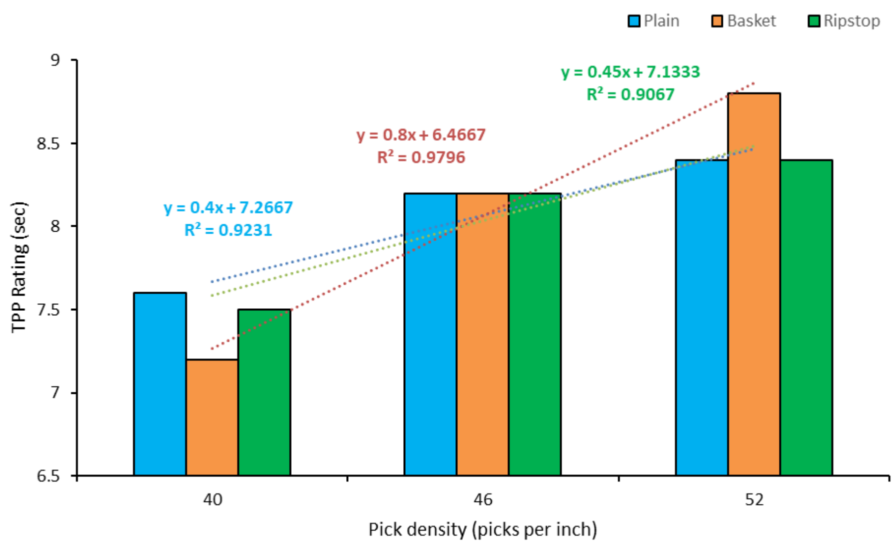


Figure 6. WVTR of plain, basket and ripstop weave structures.

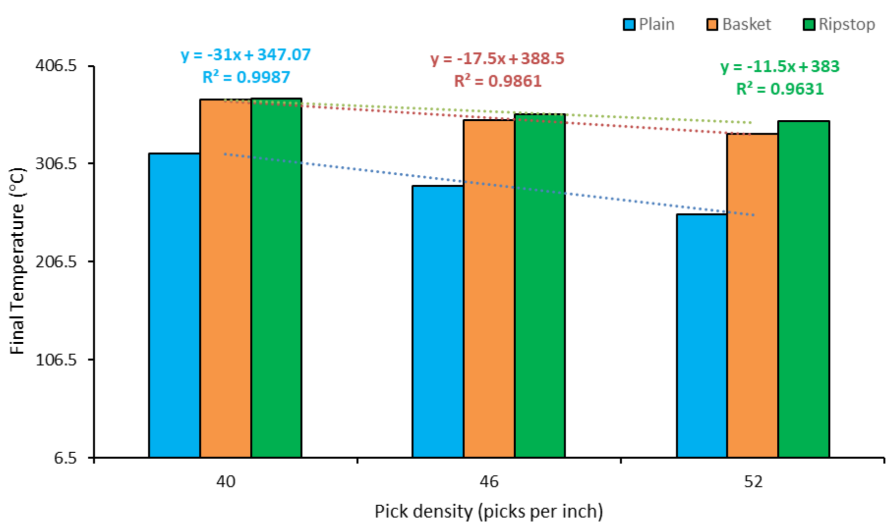
More specifically, plain fabrics showed the least WVTR properties though they had mediocre thickness values (table 1) than ripstop and basket. It is generally accepted that water vapour might pass quickly through less thick fabrics. But, from Table 1, it is also seen that plain fabrics porosity is maximum (0.82-0.81) among all samples. Due to having greater pores in the sample, water vapour molecules were supposed to move through the fabric. However, the interlacing field plays the main role in this case. Porosity equation 2 does not take the interlacing field into concern. Having more interlacing fields means fabric becomes tighter and less space between warp and weft yarn which provides extra spaces for water vapour molecules to transport from one surface to another. The same fact works for basket design where larger floats provide more scope for water vapour transport (6572.87 gm/m^2/day – 8396.71 gm/m^2/day) that value was seen in Figure 5. Plain (0.9768) and basket (0.9713) exhibit higher R^2 values than ripstop design (0.8548), which indicates WVTR has a better relationship with plain and basket structure than ripstop design.

Thermal Protective performance

Figure 7 expresses the thermal protection performance and final temperature measured by the sensor on the other side of the heat flux source. The thermal protection performance at 52 picks per inch for all the weave structures was found maximum because of greater fabric areal and bulk density. In addition to that, almost the same type of TPP rating value was obtained for each pick density from all samples. Basket fabrics at 52 pick density showed maximum TPP rating though temperature sensed at the opposite of heat flux source was high. It means that its thermal conductivity was higher than others which was observed in figure 3.



a)



b)

Figure 7. The plain, basket and ripstop weave structures: a) thermal protective performance, b) final temperature

Likewise, results obtained in Figure 3 support the final temperature at the sensor side of Figure 7 a). As plain fabric thermal conductivity was lowest that meant less temperature would be sensed at the sensor and the same thing was found in figure 7 b). Plain fabric showed (316.7 °C for 40 picks - 254.4 °C for 52 picks) the minimum temperature at the sensor side that stood for the least thermal conductivity of plain fabric. From the TPP rating point of view, plain fabric exhibited comparatively higher thermal resistance, better thermal protection performance and less temperature at opposite heat sources. TPP rating and final temperature at the sensor side have a good correlation (all samples exhibited R^2>0.9) with all the construction of fabrics; however, the basket structure showed higher R^2 (0.9796) against the TPP rating and the plain design exhibited higher R^2 (0.9987) against the final temperature at the sensor side.

Coefficient of correlation analysis in terms of bulk density

Bulk density is a term which is directly related to pick density, fabric thickness and areal density. Meanwhile, it is also related to the porosity of the fabric. Therefore, the correlation of bulk density with thermal protection and thermal properties can provide some key information. The coefficient of correlation of any dependent variables can give an idea about its independent variables on which it depends more or has a significant impact [17]. For this reason, the coefficient of correlation of bulk density with the thermal protection and thermal properties was measured and tabulated as below:

Table 2. Coefficient of correlation values for linear equation between bulk density and thermal protection and thermal properties

Fabric type	TPP	AP	WVTR	TC	TR
Plain	0.8841	0.9996	0.9524	0.9906	0.9793
Basket	0.9988	0.8845	0.9999	0.77	0.695
Ripstop	0.8574	0.8915	0.9045	0.7547	0.8272

Figure 6 has previously demonstrated that the basket weave construction has a better TPP rating compared to other structures. Additionally, it was shown that an increased bulk density of the cloth corresponded to a higher TPP rating. In Table 2, the coefficient of correlation of TPP for the basket design was greater (0.9988) than the plain (0.8841) and ripstop (0.8574) design. It appears like the basket weave pattern substantially corresponds with bulk density than other designs like plain and ripstop. A similar sort of solution was developed for WVTR performance. However, the coefficient of correlation of plain fabrics for thermal resistance (0.9793) and thermal conductivity (0.9906) is significantly greater than basket and ripstop designs in terms of bulk density. This speaks for increased reliance on thermal characteristics on bulk density in the case of plain structures. Likewise, air permeability also revealed a greater coefficient of correlation value (0.9996) for plain fabric.

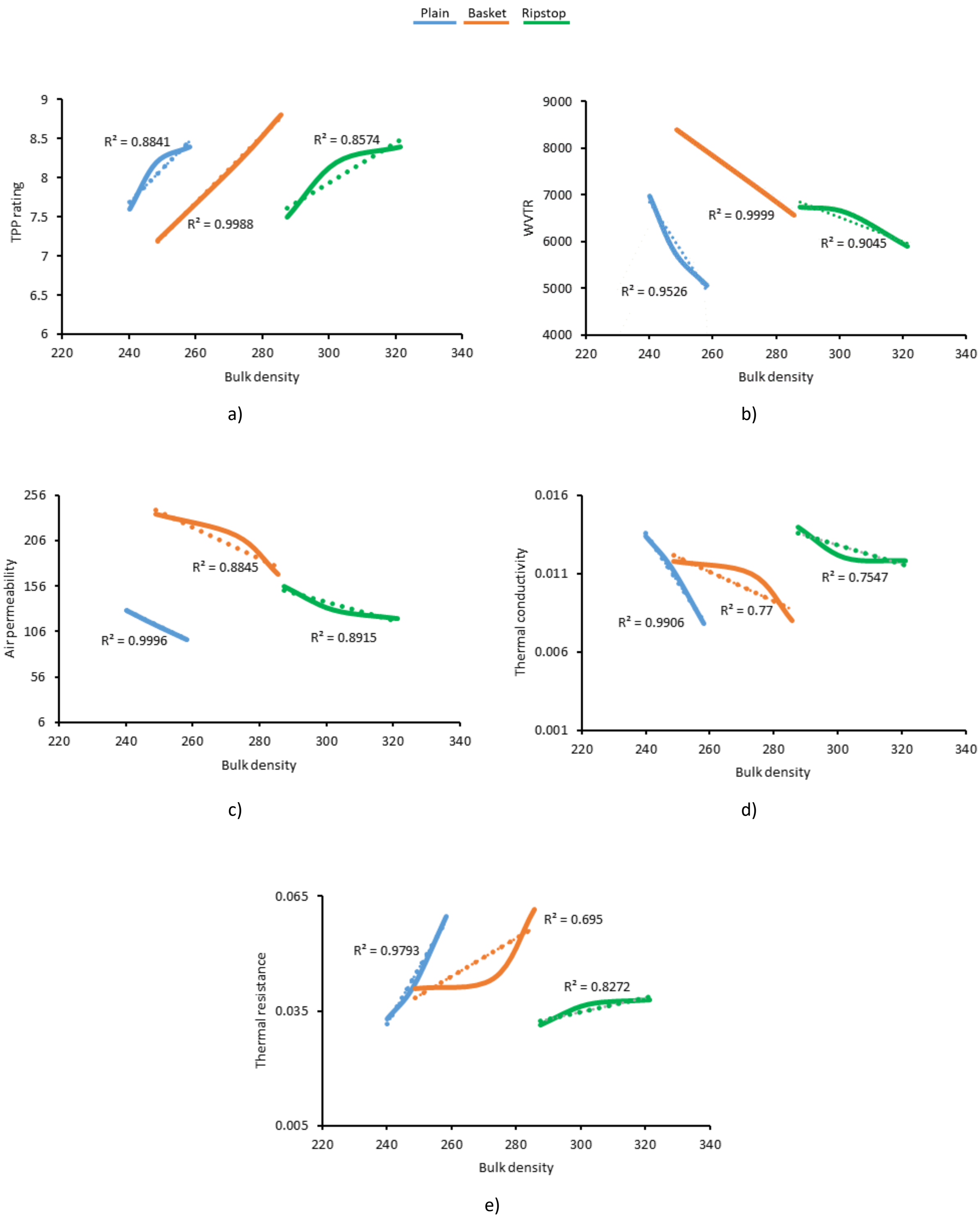


Figure 8: Coefficient of correlation of bulk density with thermal protection and thermal comfort properties: a) bulk density vs TPP, b) bulk density vs WVTR, c) bulk density vs air permeability, d) bulk density vs thermal conductivity and e) bulk density vs thermal resistance

Correlation among the samples compared to bulk density is clearly illustrated in Figure 8. Apart from the coefficient of determination (R^2), it is also clear that TPP (figure 8 a)) and thermal resistance (figure 8 e)) performance of the samples is directly proportional to the bulk density of the fabrics. On the other hand, WVTR (figure 8 b)), air permeability (figure 8 c)), and thermal conductivity (figure 8 d)) properties are inversely proportional to bulk density. It is also visible that basket fabric performs better than all other samples; in brief, higher TPP performance with air and water permeability may uplift the comfort properties. At the same time, thermal resistance values lay at higher range and conductivity at lower range.

CONCLUSION

Since the outer layer of FTC experiences the most heat during a fire incident, it becomes essential to examine its characteristics thoroughly, that is what researchers are doing all around the globe. According to the study mentioned above, the basket weave structure had a somewhat better fire protective rating than the plain, and ripstop weave structures. Additionally, greater thread densities demonstrated superior protection against fire than lower densities. However, plain and ripstop designs with more interlacement points provide a bit more heat protection than basket designs at lower thread densities. Comparing basket woven fabrics to plain and ripstop patterns, the former demonstrated superior water vapour transmission rate and air permeability. When it came to thermal resistance and conductivity, the basket design outperformed the other plain and ripstop designs, showing greater resistance values and lower thermal conductivity values. The coefficient of correlation of the study showed bulk density of the fabrics closely relates with TPP and WVTR of basket design and for the other properties plain fabric relates with AP, TC, and TR. This study suggests that for balanced FTC in terms of fire protection and comfort, Nomex IIIA yarn be woven at 42 ends per inch and 46 or more picks per inch at basket weave pattern for safety against second-degree burn time and mediocre comfort level.

Author Contributions

Conceptualization – Das A and Alagirusamy R; methodology – Rathour R, Das A and Alagirusamy R; formal analysis – Rathour R, Islam MA and Ibn Amin MJ; investigation – Rathour R, Islam MA and Ibn Amin MJ; resources – Rathour R, Islam MA and Ibn Amin MJ; writing-original draft preparation – Rathour R, and Islam MA; writing-review and editing – Rathour R, Islam MA, Ibn Amin MJ, Das A and Alagirusamy R; visualization – Islam MA; supervision – Das A and Alagirusamy R. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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