Influence of Multilayer Fabric Construction on Thermal Conductivity of Protective Fabrics

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Abstract:
The effect of layering on properties such as air and water vapor permeability, and thermal conductivity is crucial for materials meant to be worn as clothing. The majority of these multi-layered assemblies are three-layered, as each layer performing a specific function and working together to achieve of thermal physiological equilibrium. One of the main factors that contribute to thermal resistance is the still air trapped in the fabric. Thermal protective clothing is primarily designed to provide protection from thermal hazards such as exposure to high temperature sources and hot gases. Heat transfer from the thermal hazards can be by radiation, convection or conduction. This study identifies the relationship between the construction of multilayer fabrics used in the production of protective fabrics, and their thermal conductivity property by using 3 layers and 4 materials. The results show that there are opportunities to control protective fabric thermal conductivity. Further, thermal management attributes of Protective Fabrics materials can also be significantly improved to reduce thermal loss.

Keywords:
Technical Textiles, Protective Textiles, Thermal Protective Textiles, Multilayer Fabrics, Thermal Comfort

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1. Introduction:

Technical Textiles:

Technical textiles definition which published by the textile Institute, and adopted by the authoritative textile terms and definitions, is “textile materials and products manufactured primarily for their technical and performance properties rather than their aesthetic or decorative characteristics”. The definition of European Union is that: “technical textiles are technical fibers, materials, and support materials meeting technical rather than aesthetic criteria” [1], [2].

Technical textiles can be used for a variety functions, these can be divided into four categories:

- Mechanical functions: These include reinforcement of the materials, mechanical resistance, elasticity, tenacity, etc.
- Functionalities for living beings: such as antidust mites, antimicrobial, biodegradability, biocompatibility, etc.
- Protective functions: These include protection against chemicals, flame, electro-magnetic fields, infrared and ultraviolet rays, environment, etc.
- Exchange functions: including as filtration, insulation and conductivity, drainage, absorption, permeability, etc. [3], [4].

Technical textiles are produced using a wide range of methods, from basic processes as weaving and knitting to much advanced processes as stitch bonding, needle punching, thermal bonding, and many more [5].

Protective Textiles:

Protective textiles are becoming an essential component of technical textiles. These textiles are intended to protect the wearer from extreme environmental influences that might cause harm or even death [6].

According to the end-use functions, protective textiles can be categorized, like thermal protective, electrostatic protective, flame protective, biological protective, chemical protective, mechanical impact protective, radiation protective [7].

Multi-layer Fabrics:

Multilayer fabric is a type of fabrics which are composed of one or more layers. Multilayered fabrics consist of various layers of the fabrics which have the ability to complement and enhance the essential comfort and protective properties for a specific end application [10], [11]. The effect of layering on properties such as air and water vapor permeability, thermal resistance, and thermal conductivity is crucial for materials meant to be worn as clothing. [9]. The majority of these multi-layered assemblies are three-layered, with each layer performing a specific function and working together to achieve of thermal physiological equilibrium [12].

The purpose of layering textile is to achieve synergy during the transfer of heat and humidity in each layer of textile and to prevent the occurrence of unpleasant feelings whether it is hot, cold, or humid. Better vapour permeability through textile, or reduced vapour resistance, can be achieved with lower number textile layers. On the other hand, higher number of textile layers leads to better thermal insulation property of textile [13].

Thermal Comfort:

The balance of heat and moisture between the body and the environment determines the level of thermal comfort for the human body. Survival depends on the body's ability to adapt to heat and cold. If environmental conditions become too severe, the body cannot adapt and death may result [14].

Two aspects of clothing wear comfort can be distinguished:

- Skin sensational wear comfort, which considers the fabric's mechanical contact with the skin, how it moves softly and pliably.
- Thermo physiological wear comfort, which concerns clothing heat and moisture transport properties, as well as how clothing helps to keep the body's temperature balanced during varying levels of activity.

The Textile properties may be considered under the following categories: thermal conductivity, air permeability, and water vapour resistance.

Thermal Conductivity:

Heat transfer from the body through fabrics to the environment is a complex, physical process, it includes four mechanisms that allow the body to lose heat to the environment to keep its thermal balance. The external environment determines how the heat loss is distributed across the mechanisms:

Conduction: In this mechanism heat loss is accomplished through direct contact with another substance.

Convection: A moving fluid (liquid or gas) transfers heat during this mechanism.

Radiation: This is the electromagnetic wave-based method of transferring heat.

Evaporation: If the water on the skin's surface evaporates, then the required energy is removed from the skin, which cools it.

Air Permeability:

The air permeability of textiles is a measure of how well it allows the passage of air through it. The ease or otherwise of passage of air is of importance a variety of fabric end uses such as tents, industrial filters, parachutes, sailcloths, shirtings, raincoat materials, downproof fabrics and airbags. Air permeability of textiles is dependent on their thickness, construction, finishing, gauge, and on the different laminates, membranes and coatings and provides a good guide to the extent to which textiles are able to pass water vapor through them, and makes it easier for sweat to evaporate from the skin surface, which enhances the provision of better thermal comfort [15], [16].

2. Experimental:

Fabric Production:

The produced fabrics are multi-layer fabrics that consists of woven fabrics for the outer layers and non-woven fabrics for the filling layer.

Woven Fabric Produced Specifications:

Four materials were used in the six produced woven fabrics as shown in table 1:

Two looms were utilized to produce the fabrics, loom 1 with a cotton warp, and loom 2 with a polyester warp.

Table (1): Types of Produced Fabric

Serial	Type	Warp material	Weft material
1	Cotton	Cotton 100%	Cotton 100%
2	Polyester	Polyester 100%	Polyester 100%
3	Cotton – Acrylic	Cotton 100%	Acrylic 100%
4	Cotton – Viscose	Cotton 100%	Viscose 100%
5	Polyester – Cotton	Polyester 100%	Cotton 100%
6	Polyester – Acrylic	Polyester 100%	Acrylic 100%

Yarn Count:

Cotton 80/2 Ne (266/2 Denier) was utilized for warp yarns of loom 1, and polyester 150/1 Denier (36/1 Ne) was utilized for warp yarns of loom 2.

30/1 Ne (177/1 Denier) was utilized for weft yarns.

Fabric Set:

All woven fabrics have the same number of warp, which were 66 ends per cm, and the same number of picks, which were 30 picks per cm.

Fabric Structure:

Canvas 2/2 structure was utilized to produce the fabrics.

Nonwoven Fabric Produced Specifications

Polypropylene was utilized for producing nonwoven fabrics.

Nonwoven fabrics weight is 110 gm/m².

Nonwoven fabrics were produced by thermal bonding process, these utilized as filling (Middle) layer.

Bonding Process:

Stitching method was used to bond the layers to produce multi-layer fabrics. Single needle sewing machine was utilized to bond the layers as shown in figure 1.

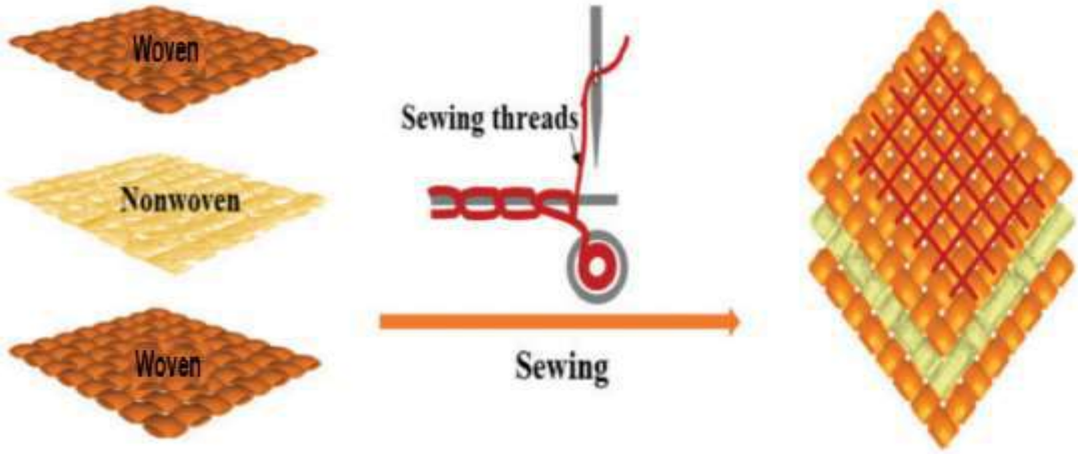

Figure (1) Bonding the Fabric Layers [17]

Polyester yarn (210/3 denier) was utilized for sewing.
Sewed squares were formed by the size of, 3x3 cm, 4.5x4.5 cm, and 6x6 cm.

Stitching design of multilayer fabrics is shown in figure (2):

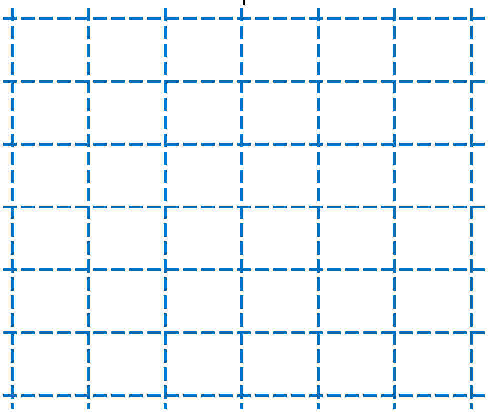

Figure (2) Stitching Design of Multilayer Fabrics

Layering Process:

Samples were prepared utilizing three layers of fabric (Sandwich): two outer layers (woven fabric) and one filling layer (nonwoven fabric), bonding them by stitching at different distances, 3 cm, 4.5 cm, and 6 cm.

Multi-layer fabrics arrangement is shown in table (2):

Table (2): Types of Produced Multilayer Fabric

Serial	Outer layer	Filling layer	Outer layer
1	Cotton	Polypropylene	Polyester
2	Cotton		Polyester - Cotton
3	Cotton		Cotton – Acrylic
4	Polyester		Polyester - Cotton
5	Polyester		Cotton - Viscose
6	Polyester		Cotton - Acrylic
7	Polyester		Polyester - Acrylic

Fabric Testing:

Fabric air permeability test, was carried out according to the standard method ASTM D 737[18].

Fabric thermal conductivity test, was carried out according to the standard method JIS L 1927[19].

3. Results and Discussion:

Fabric Air Permeability

Table (3) and figure (3) represent the effect of multilayer fabrics construction on fabric air permeability of produced fabrics, with different stitching distances.

Table (3): The Effect of Multilayer Fabrics Construction on Fabric Air Permeability of Produced Fabrics

Samples		**6x6 cm**	**4.5x4.5 cm**	**3x3 cm**
		(Cm³/Cm²/S)		
Outer Layer	Cotton	4.586	5.014	6.018
Filling	Polypropylene			
Outer Layer	Polyester			
Outer Layer	Cotton	4.89	5.521	6.106
Filling	Polypropylene			
Outer Layer	Polyester - Cotton			
Outer Layer	Cotton	5.833	5.95	6.395
Filling	Polypropylene			
Outer Layer	Cotton – Acrylic			
Outer Layer	Polyester	3.61	4.192	4.633
Filling	Polypropylene			
Outer Layer	Polyester - Cotton			
Outer Layer	Polyester	4.339	4.645	5.498
Filling	Polypropylene			
Outer Layer	Cotton - Viscose			
Outer Layer	Polyester	4.48	4.837	5.599
Filling	Polypropylene			
Outer Layer	Cotton – Acrylic			
Outer Layer	Polyester	3.54	3.851	4.292
Filling	Polypropylene			
Outer Layer	Polyester - Acrylic			

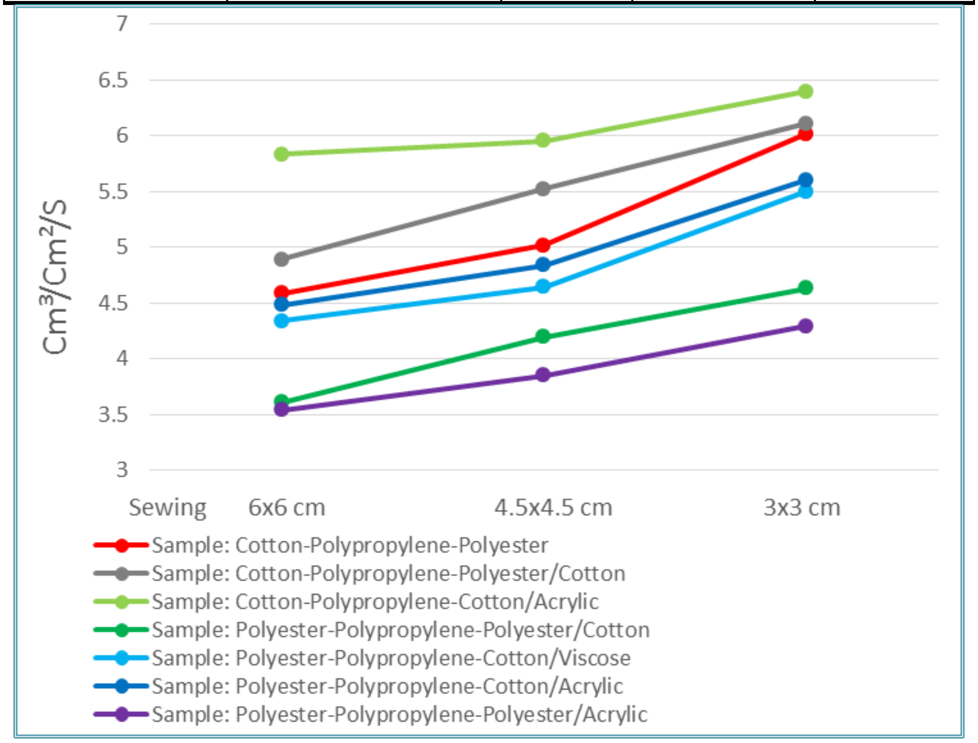

Figure (3): The Relationship between Multilayer Fabrics Construction and Fabric Air Permeability for Produced Fabrics with different stitching distances

From table (3) and figure (3) which represent the relationship between multilayer fabrics construction and fabric air permeability for produced fabrics, it is clear that there is an increase in the fabric air permeability for both samples 4.5x4.5 cm and 3x3 cm respectively, and the use of larger squares leads to decrease in fabric air permeability.

The above figure indicates that sample (cotton-polypropylene-cotton/acrylic) with stitching 3x3 cm has the highest value for fabric air permeability, and sample (polyester- polypropylene-polyester/ acrylic) with stitching 6x6 cm has the lowest value for fabric air permeability.

From the above figure it is found that multilayer fabrics which include cotton yarn in both of their outer layers have the highest values for fabric air permeability.

Fabric Thermal Conductivity:

Table (4) and figure (4) represent the effect of multilayer fabrics construction on fabric thermal conductivity of produced fabrics.

Table (4): The Effect of Multilayer Fabrics Construction on Fabric Thermal Conductivity of Produced Fabrics

Samples		6x6 cm	4.5x4.5 cm	3x3 cm
		(W/Cm*C)		
Outer Layer	Cotton	0.00442	0.00467	0.00491
Filling	Polypropylene			
Outer Layer	Polyester			
Outer Layer	Cotton	0.00477	0.00492	0.00515
Filling	Polypropylene			
Outer Layer	Polyester - Cotton			
Outer Layer	Cotton	0.00519	0.00536	0.00586
Filling	Polypropylene			
Outer Layer	Cotton – Acrylic			
Outer Layer	Polyester	0.00395	0.00404	0.00425
Filling	Polypropylene			
Outer Layer	Polyester - Cotton			
Outer Layer	Polyester	0.00427	0.00435	0.00457
Filling	Polypropylene			
Outer Layer	Cotton - Viscose			
Outer Layer	Polyester	0.00438	0.00463	0.00486
Filling	Polypropylene			
Outer Layer	Cotton – Acrylic			
Outer Layer	Polyester	0.00391	0.00408	0.00417
Filling	Polypropylene			
Outer Layer	Polyester - Acrylic			

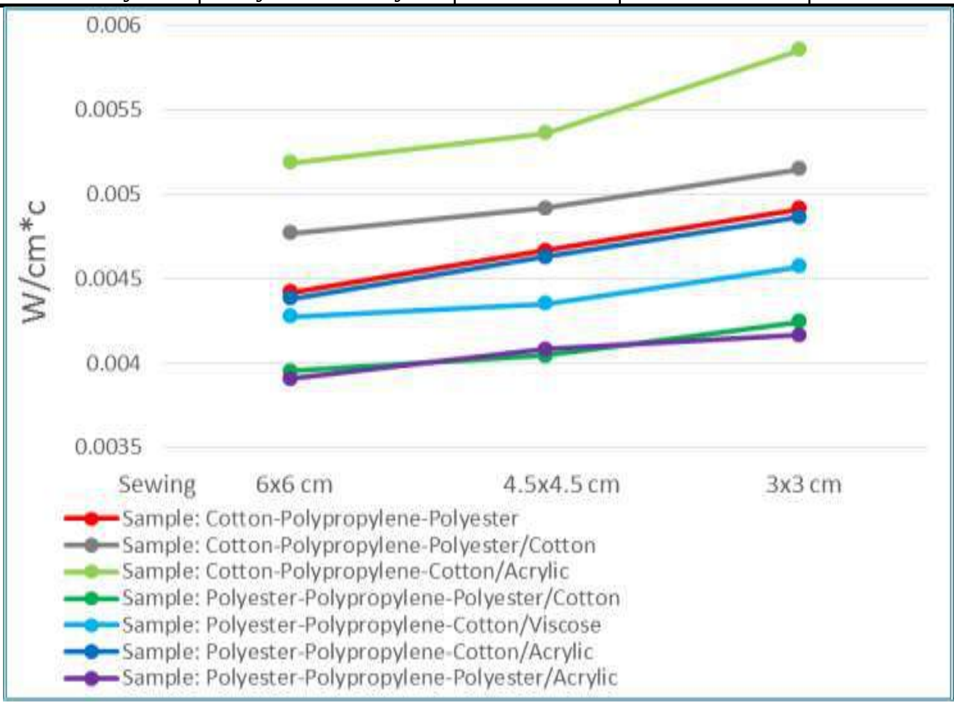

Figure (4): The Relationship between Multilayer Fabrics Construction and Fabric Thermal Conductivity for Produced Fabrics with different stitching distances

The test device measures heat loss, then the thermal conductivity of fabrics was obtained by the equation: "Heat conductivity (K) = Average heat loss (Ave. W) x Sample thickness / (BT Plate area x Delta-T)".

From table (4) and figure (4) it is noted that the fabric thermal conductivity of samples 3x3 cm is higher than samples 4.5x4.5 cm, and samples 4.5x4.5 cm is higher than samples 6x6 cm, and the use of larger squares leads to decrease in fabric air permeability.

The above figure indicates that sample (cotton-polypropylene-cotton/acrylic) with stitching 3x3 cm has the highest value for fabric thermal conductivity, and samples (polyester-polypropylene-polyester/acrylic), with stitching 6x6 cm has the lowest value for fabric thermal conductivity.

From the above figure it is found that multilayer fabrics which include highest percentage of cotton have the highest values for fabric thermal conductivity.

Conclusion:

This study was conducted to determine the influence of multilayer fabrics construction (from different materials, and bonding fabric layers by stitching at different distances) on thermal conductivity of these fabrics produced for utilizing as protective fabrics.

- Fabric air permeability has been found as a key fabric characteristic influencing thermal conductivity and is directly proportional to it, samples with higher fabric air permeability allow more heat to pass through fabric, that the transfer (loss) of heat in this case is transmitted by convection.
- Multilayer fabrics which include highest percentage of cotton have the highest values for fabric air permeability and fabric thermal conductivity, this may be due to that cotton fibers appear under a microscope looks like a twisted ribbon, these twists are called convolutions, this convolutions do not allow the fibers to be stacked next to each other in a compact manner, which allows the creation of inter-spaces and gaps between the fibers within the yarn that allow amount of heat to pass greater than other materials like polyester which gives lowest thermal conductivity, due to the compact structure of polyester fiber.
- There is an increase in the fabric air permeability and fabric thermal conductivity for samples 4.5x4.5 cm and samples 3x3 cm respectively, this is may be due to that using sewing threads for stitching larger squares (samples 6x6) leads to create larger air gabs between fabric layers that acts as a barrier against air and heat transmission, results in to decrease in fabric thermal conductivity.
- The influence of multilayer fabrics construction on thermal conductivity of protective fabrics is clear, as the ability of multi-layer fabrics to conduct heat can be increased by using cotton fabrics and bonding the layers using stitching at smaller distances, and their ability to thermal conductivity can be reduced by using polyester fabrics and bonding the layers using stitching at larger distances.

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