DECEMBER 2018 M.Sc. inTextile Engineering HİLALYILDIRIM

REPUBLIC OF TURKEY
UNIVERSITY OF GAZİANTEP
GRADUATE SCHOOL OF
NATURAL & APPLIED SCIENCES

# PERFORMANCE OF WEFT KNITTED FABRICS FROM GLASS YARN IN TERMS OF ARCHITECTURE, CAM SETTING AND NUMBER OF YARN PLY

M.Sc.THESIS
IN
TEXTILE ENGINEERING

BY
HİLAL YILDIRIM
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**M.Sc. Thesis**

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**University of Gaziantep**

**Supervisor**

**Asst. Prof. Dr. Mehmet Erdem İNCE**

**by**

**Hilal YILDIRIM**

**December 2018**

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This is the certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of master of Science.

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**This thesis is written according to the academic and ethical rules and I declare that all used literature information takes place with giving reference.**

**Hilal YILDIRIM**

# ABSTRACT

## PERFORMANCE OF WEFT KNITTED FABRICS FROM GLASS YARN IN TERMS OF ARCHITECTURE, CAM SETTING AND NUMBER OF YARN PLY

**YILDIRIM, Hilal**

**M.Sc. in Textile Engineering**

**Supervisor: Asst. Prof. Dr. Mehmet Erdem İNCE**

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In recent years, weft knitting is used to produce technical textile and composite dry preforms due to their rapid, low-cost and versatile fabric manufacturing technique. Different loop formations like tuck- and skip-stitches and loop length size display variable performances for physical and mechanical properties of knitted fabrics.

This study revealed the effect of cam setting and number of yarn ply onperformance of weft-knitted fabrics from glass yarn. Change in cam setting from loose to tight level increased fiber content, and stitch-density; while it decreased loop length. Fabrics knitted via tight cam setting level exhibited less air permeability, and higher bursting strength than fabrics knitted via loose cam setting. Fabrics from 3-ply yarn showed less air permeability and higher bursting strength than fabrics from 2-ply yarn. Due to their stiff and brittle nature; glass fibers can easily be broken during weft knitting process that creates broken fiber ends on the fabric surface, and deteriorates the performance of resultant fabric.

The overall conclusion is that the fabrics with tuck stitches are the thickest structure and they had the highest fiber content. Number of yarn ply is not effective parameter on fabric properties as much as cam setting is. The cam setting of the knitting machine affects loop lengths that modify fabric performance at statistically significant level.


**Keywords:** Glass yarn, weft knitted fabrics, bursting strength, air permeability, loop strength

## ÖZET

**MİMARİ, KAM AYARI VE İPLİK KAT SAYISI AÇISINDAN CAM İPLİĞİNDEN ATKILI ÖRME KUMAŞLARIN PERFORMANSI**

**YILDIRIM, Hilal**

**Yüksek Lisans Tezi, Tekstil Mühendisliği**

**Tez Danışmanı: Dr. Öğr. Üyesi Mehmet Erdem İNCE**

**Aralık 2018**

**97 sayfa**

Son yıllarda; hızlı, düşük maliyetli ve çok yönlü kumaş üretim tekniği sayesinde, teknik tekstil ve kompozit kuru preformlarını üretmek için atkılı örme kullanılmaktadır.Askı ve atlamalı ilmekler ve ilmek uzunluğu gibi farklı ilmek oluşumları, örme kumaşların fiziksel ve mekanik özellikleri için değişken performanslar sergiler.

Bu çalışma cam ipliğinden atkılı örme kumaşların performansı üzerine kam ayarları ve iplik kat sayısının etkisini ortaya koymuştur.Kam ayarında gevşekten sıkı seviyeye değişimi, ilmek uzunluğunu azaltırken, lif içeriğini ve lif yoğunluğunu arttırmaktadır. Sıkı kam ayar seviyesi ile örülen kumaşlar, gevşek kam ayarı ile örülen kumaşlardan daha az hava geçirgenliği ve daha yüksek patlama mukavemeti sergilemiştir. 3 katlı ipliklerden elde edilen kumaşlar, 2 katlı ipliklerden daha az hava geçirgenliği ve daha yüksek patlama mukavemeti göstermiştir. Kumaş yüzeyinde kırık lif uçları oluşturan atkı örme işlemi sırasında, cam lifleri kolayca kırılabilir ve sonuçta elde edilen kumaşın performansını bozar.

Genel sonuç, askı ilmekli kumaşların en kalın yapıda olması ve en yüksek lif içeriğine sahip olmalarıdır. İplik kat sayısı, kumaş özelliklerinde kam ayarı kadar etkili bir parametre değildir. Örgü makinesinin kam ayarı, kumaş performansını istatistiksel olarak anlamlı düzeyde değiştirecek şekilde ilmek uzunluklarını etkiler.

**Anahtar kelimeler:** Cam ipliği, atkılı örme kumaş, patlatma mukavemeti, hava geçirgenliği, ilmek mukavemeti

***Anneme ve Babama…***

***(Fatma & Fatih)***

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# CHAPTER 1

# INTRODUCTION

Technical textiles are not used for our daily needs as conventional textiles; therefore it is desired them to perform properly to their production purpose before fashion factors. In contradistinction to conventional textiles, technical fabric products are produced with superior features for a specific target. Properties of technical textiles alter according to needs and expectations of area of use. These needs and expectations can be achieved by combining different basic textile skills of fibers, fabrics and finishing techniques with understanding their properties correctly.

Technical textiles have entered many areas of our lives as medicine, transportation, protection, agriculture, sports, packaging, civil engineering and industry. In 2005 technical textiles was consumed about 20 million ton per year, the majority of this consumption was from protective textiles. Increase rate of protective textile market was between 3,3 and 4% per annum; and between 2005-2010 years consumption of protech was reached from 280000 to 340000 tons. According to the data in 2009, consumption percentages of fibers in the technical textile field are shown in Figure 1.1. Polyester, polyolefin and glass fiber are the most widely used fibers. (Mecit D., 2007) (Rigby, 2002)

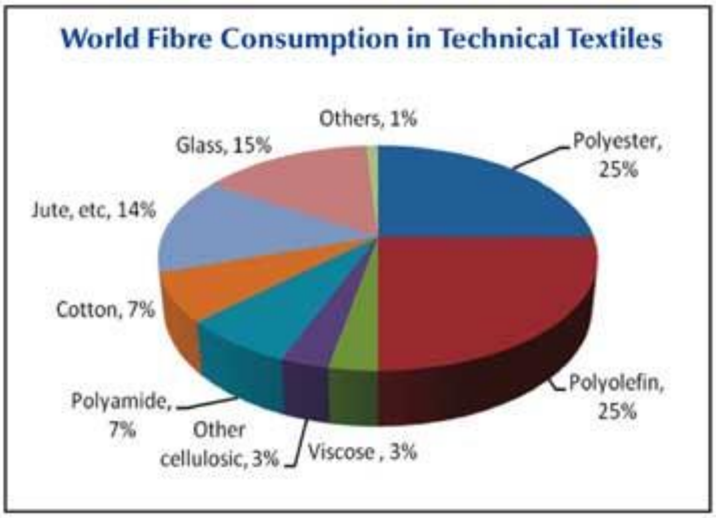



**Figure 1.1** Consumption percentages of fibers in the technical textile field in 2009 (Pakistan Textile Journal, 2009)

Protective textiles have been designed to protect our bodies from hazards and death risk (Figure 1.2). Aim of production of these textile materials are protection of ballistic, against sharp materials, against low-speed effects, fire, waste, nuclear effects, biological and chemical hazards, high voltage and static electricity. Today protective clothes have specialized to use area because of hazards that are exposed have not just a single type. According to kind of hazards fabric properties will be changed. Selection of raw materials, fabric type (weaving-knitting etc.), fabric design, thickness etc. affects properties of fabric. (Adanur, 1995) (Bajaj, et al., 1992) (Holmes, 2000)

**Figure 1.2** Example of technical fabrics - fire blanket (Kıvanç Group, 2016)

Technical textiles have not only grown industry sector. Their development has progressed in various directions at different speeds and success levels. The textile composites have made a great progress with gaining new characteristics to the fabric or expanding the scope of the textile. Textile materials have broadly been classified as flexible and non-stretchable. Examples of flexible composites are cloth, automobile tires and seat belts. Textile reinforced composites are example of non-elastic composites. (Adanur, 1995)

Woven, knitted, nonwoven and braided fabrics produced from different yarns (glass, carbon, aramid, organic polymers) are used as technical textiles in the composite sector. In recent years, knitted fabrics have been used more often in composite materials. Knitted surfaces are divided into two main classes according to the type of stitch formation: (MEB, 2011)

- Weft knitting: According to single yarn feeding system, fabric surface is formed with making a connection by moving loops in the transverse direction.

- Warp knitting: According to multi-yarn feeding system, fabric surface is formed with making a connection by moving loops in the longitudinal direction.

Weft knitting method which is preferred due to cheaper than other methods is classified into two groups as flat knitting and circular knitting. In weft knitting production via flat knitting machines, the needles are fixed, yarn and systems are movable (Figure 1.3).

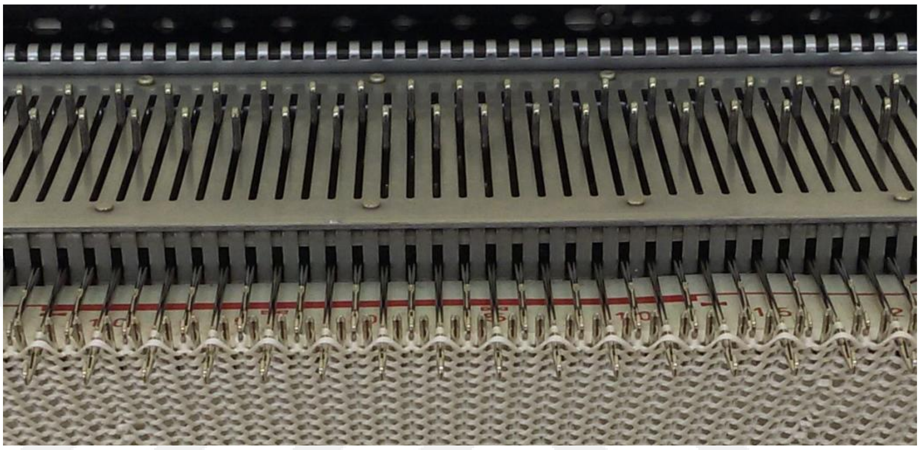


**Figure 1.3** Needle plate of flat weft knitting machine

In weft knitting different surfaces of fabric which consist of various stitches can be created by changing position of needles according to tracking of cams. Tuck stitch and miss (skip) stitch are commonly used to pattern knitted fabrics (Figure 1.4). Performance of fabrics with tuck stitches or skip stitches are different from single jersey fabrics in view of fabric properties like weight, thickness, porosity, air permeability, bursting strength. (Uyanik, et al., 2016)

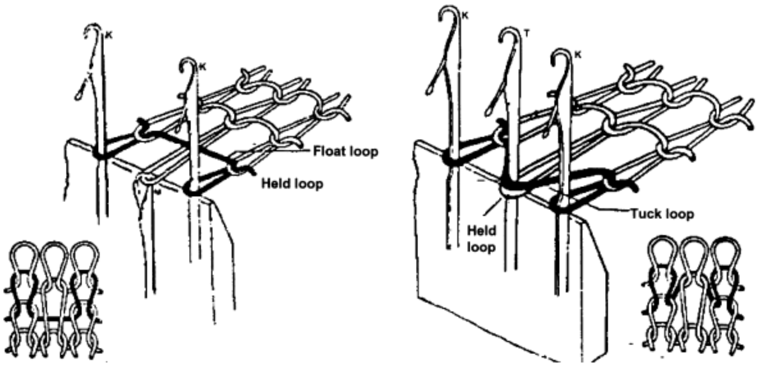



**Figure 1.4** Schematic needle diagrams of miss (skip) stitch and tuck stitch respectively (Leong, et al., 2000)

The use of knitted reinforced composites has been rising due to the ability to easily design complex patterns, near-net-shape preforming, drapeability and easy to shape formation. Advantages of knitting technology can be summarized as follows; (Berhe, 2015) (Horrocks, et al., 2000)

- Very flexible structure (especially weft knitted fabrics)
- No need to yarn preparation process
- Easy to produce 2D and 3D fabrics
- Easy to design like tuck stitch, laid yarns etc.– quick set up and adjustment of the knitting machine
- Gaining novel properties to composite due to the structural nature of knitted fabrics–having desired shapes without sewing process (examples; shapes of artificial vein, helmet, pipe etc.)
- Having drape-ability property - Forming complex shapes (examples; easily mold processing)

Glass types which are used in production of textile fiber are generally soda-lime-silicates or borax silicates. E-type of glass in production of filament fiber and C-type of glass in production of staple fiber is mostly used ones. (Özdemir, et al., 2006) Glass yarns are brittle than other conventional textile yarns. Because of in textile processing glass yarns break easily; inter-fiber friction is minimized by using suitable size material. Besides, glass yarns used as protective clothes or a mask should be worn to prevent skin irritation and to supply inhalation of skin. (Horrocks, et al.,

2000) Properties of strength and numbering of E-type and S-type of glass fibers and carbon fiber are shown in Figure 1.5.

| Capability | Carbon fiber | E-glass fiber | S-glass fiber |
|---|---|---|---|
| Tensile strength, MPa | 3500~6000 | 3100~3800 | 4020~4650 |
| Elastic modulus, gPa | 230~600 | 72.5~75.5 | 83~86 |
| Elongation at break, % | 1.5~2.0 | 4.7 | 5.3 |
| Diameter of filament, mµ | 5~15 | 6~21 | 6~21 |
| tex | 60~2400 | 40~4200 | 40~4200 |
| Temperature of application, °Ñ | -50~+700 | -50~+380 | -50 +300 |
| Price, USD/kg | 30 | 1,1 | 1,5 |

**Figure 1.5** Strength and numbering values of E-type, S-type and carbon fibers (Next Big Future, 2010)

Glass which has high tenacity and is an incombustible textile fiber is used generally in insulation of building and applications for needs of fire resistance (Figure 1.6). Glass fiber is commonly used in composite applications as reinforcement because of its low cost and other characteristic properties like resistance to fire, electricity, heat etc. Also it is used in the reinforcement of synthetic fibers and in the areas which are required high strength and electrical strength. (Özdemir, et al., 2006) The fibers used in composites are expected to have high elastic stiffness and high dimensional stability, but the fibers are damaged during production of the knitted composite material. (Epstein, et al., 1991) (Andersson, et al., 1994)However, it has been found that the loop strength of the glass yarn exponentially increases with knitting needle diameter. (Lau, et al., 1994)


**Figure 1.6** Examples of fire blankets made from glass yarns (Tedex) (Piyasadan)

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Literature Review about Performance of Knitted Fabrics

This study is about the effects of cam setting, number of yarn ply and knit architecture on physical properties, air permeability and bursting strength of weft-knitted fabrics from glass yarn, and the literature review within this context is given below.

Mikucioniene et al. studied (Mikučionienė, et al., 2012) determination of the correlation between air permeability and flammability until knit structure variables were changed i.e. loop length, linear density of yarns and tightness factor of knits. They investigated to improve the safety of fire-fighters with preserved comfort properties of wears as breathability, lightness and ventilation.

They used to knits from Nomex Delta TA 18 tex×2 yarns and four groups of knits were constituted different linear densities of yarns. The 11 different knits that combined with various loop length and linear density of yarns were produced on a circular 14E gauge one-bed knitting machine. These knits comprised 3 combinations for variant I, 6 combinations for variant II and 1 combination for variant III, IV were shown in Table 2.1.

**Table 2.1** Characteristics of tested knitted fabrics

| Variants | Yarn linear density, tex | Course density $P_v$, $cm^{-1}$ | Wale density $P_h$, $cm^{-1}$ | Loop length l, mm | Surface density M, $g/m^2$ | Tightness factor TF |
|---|---|---|---|---|---|---|
| I-1 | 18.5 × 2 | 9.5 | 8.25 | 5.10 | 147.89 | 11.93 |
| I-2 | 18.5 × 2 | 7.0 | 6.50 | 6.32 | 106.40 | 9.64 |
| I-3 | 18.5 × 2 | 6.0 | 6.00 | 6.90 | 91.91 | 8.83 |
| II-1 | 18.5 × 2 × 2 | 10.5 | 8.50 | 4.80 | 317.02 | 17.92 |
| II-2 | 18.5 × 2 × 2 | 9.5 | 8.50 | 5.01 | 299.37 | 17.17 |
| II-3 | 18.5 × 2 × 2 | 10.0 | 8.25 | 5.10 | 311.36 | 16.87 |
| II-4 | 18.5 × 2 × 2 | 8.5 | 7.50 | 5.72 | 269.84 | 15.03 |
| II-5 | 18.5 × 2 × 2 | 7.5 | 7.00 | 6.32 | 245.53 | 13.61 |
| II-6 | 18.5 × 2 × 2 | 6.5 | 6.50 | 6.90 | 215.73 | 12.46 |
| III-1 | 18.5 × 2 × 3 | 11.0 | 8.00 | 5.10 | 498.17 | 20.66 |
| IV-1 | 18.5 × 2 × 4 | 12.0 | 7.25 | 5.10 | 656.68 | 23.85 |

The study showed influence of knit structure on fabric flammability and permeability to air by changing linear density of yarns and loop length parameters. When linear density of yarns (fabric density) increased, fabric of permeability to air decreased and burning time increased. In Figure 2.1 illustrates the coefficient of exponential curve determined equal to 0.9442, which means sufficiently a correlation between burning time and permeability to air.

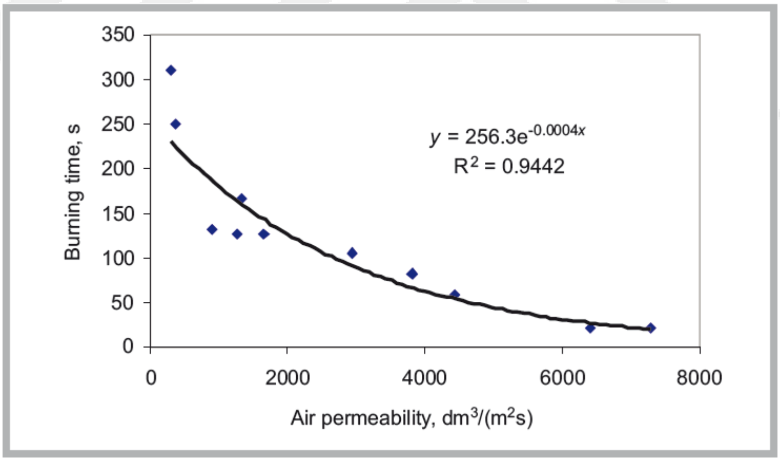



**Figure 2.1** Correlation between the burning time and permeability to air of knitted fabric

Linear density of yarns affected thickness of the knits so it increased, comfort and possibility of personal comfortable feelings decreased due to lower permeability to air. Air permeability of knits was affected by loop length; when loop length increased, permeability to air increased and comfort of wearer increased. Tightness factor was influenced by alterations of loop length and linear density of yarns. In looser knit fabrics tightness factor had small change and air permeability had marked change; in thicker knitted fabrics had great change in tightness factor and lower variation in permeability to air. Therefore correlation between tightness factor and burning time of knits existed.

In conclusion high correlation between air permeability-burning time and tightness factor-permeability to air was observed. Increasing permeability to air indicated when loop length increased or linear density of yarns decreased. When tightness factor of knits was known, potential burning time could be predicted without additionally investigations due to correlation between burning time-tightness factor. (Mikučionienė, et al., 2012)

Later Mikucioniene et al. (Mikučionienė, et al., 2011) investigated comparison between number of yarns in a loop and multilayer packet on flammability of garment which manufactured by knitting of Nomex Delta TA 18 tex×2 yarns. Protective clothing of fire-fighters demanded excellent heat protection and good moisture comfort. Multilayer fabrics provided higher thermal protection than single layers but they prevented good ventilation because of thicker structure. Thermal resistance of clothing was increased mainly by material thickness rather than changes in porosity of clothing fabrics.

The study indicated that number of yarns in the loop increased burning time than influence of number of layers in packet. Moreover fabrics which had very different air permeability values showed the same flammability properties. It was possible increasing comfort properties of clothing not to decreasing burning time. The correlation between burning time and air permeability shows in Figure 2.2.

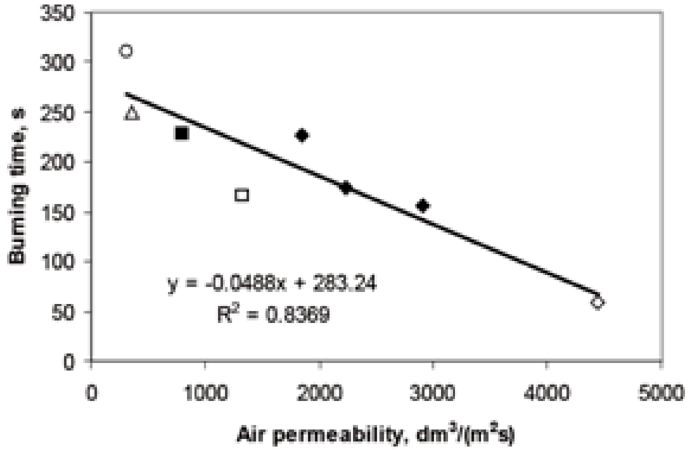



**Figure 2.2** Correlation between air permeability and burning time

**Note:** ◊ - single fabric and ♦ - packets from variant I knits (2,3 and 4 layers), □ – single fabric and ■ – packet from variant II knits (2 layers), Δ – single fabric of variant III, ○ – single fabric of variant IV

Burning time achieved similar results with increasing number of layers of knits and using folded yarns. In Figure 2.3 indicates that two layers of the knit had only 5.5% lower burning time value than the knit made by two folded single yarns. (Mikučionienė, et al., 2011)

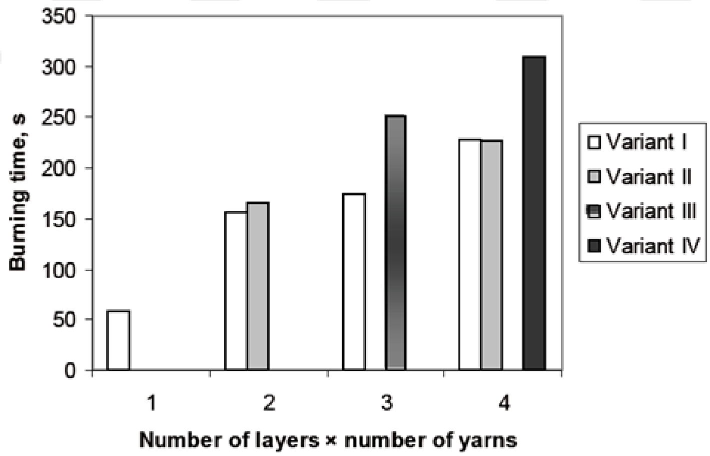



**Figure 2.3** Influence of the number of layers of knits and number of yarns in the loop on the burning time

Mikucioniene's another study (Mikučionienė D., 2014) is about the same subject that influence of knit structures on flammability and comfortability. The main characteristics of knitted fabrics show in Table 2.2.

**Table 2.2** The main characteristic of knits

| Sample variant | Yarn linear density (tex) | Loop length (mm) | Area density (g/m²) | Tightness factor (tex1/2/cm) |
|---|---|---|---|---|
| *A1* | 18.5 × 2 | 4.80 ± 0.03 | 135 ± 3 | 12.67 |
| *A2* | 18.5 × 2 | 5.01 ± 0.02 | 126 ± 5 | 12.16 |
| *A3* | 18.5 × 2 | 5.72 ± 0.04 | 111 ± 6 | 10.65 |
| *A4* | 18.5 × 2 | 6.32 ± 0.06 | 106 ± 8 | 9.64 |
| *A5* | 18.5 × 2 | 6.90 ± 0.07 | 92 ± 7 | 8.83 |
| *B1* | 18.5 × 2× 2 | 4.80 ± 0.02 | 317 ± 3 | 17.92 |
| *B2* | 18.5 × 2× 2 | 5.01 ± 0.03 | 299 ± 3 | 17.17 |
| *B3* | 18.5 × 2× 2 | 5.72 ± 0.03 | 270 ± 5 | 15.03 |
| *B4* | 18.5 × 2× 2 | 6.32 ± 0.02 | 246 ± 4 | 13.61 |
| *B5* | 18.5 × 2× 2 | 6.90 ± 0.02 | 216 ± 3 | 12.76 |

They researches especially effects of loop length on permeability to air and bursting strength in the study. Increasing loop length increases permeability to air (Figure 2.4) and decreases burning time of fabrics (Figure 2.5). Therefore number of layers in packet increases, permeability to air decreases and burning time increases. (Mikučionienė, et al., 2011)

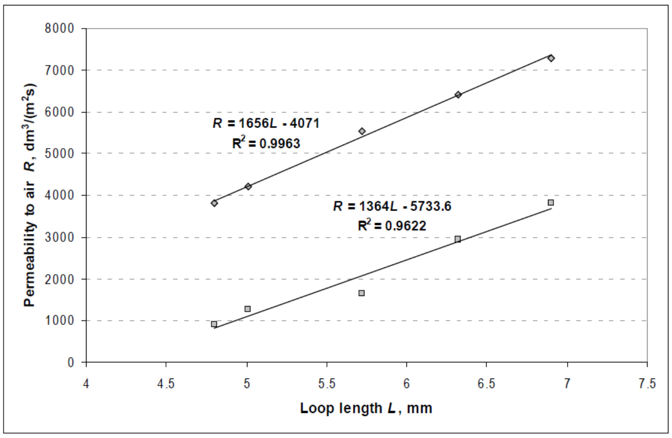



**Figure 2.4** Correlation between permeability to air and loop length (upper line for the variant A and lower line for the variant B)

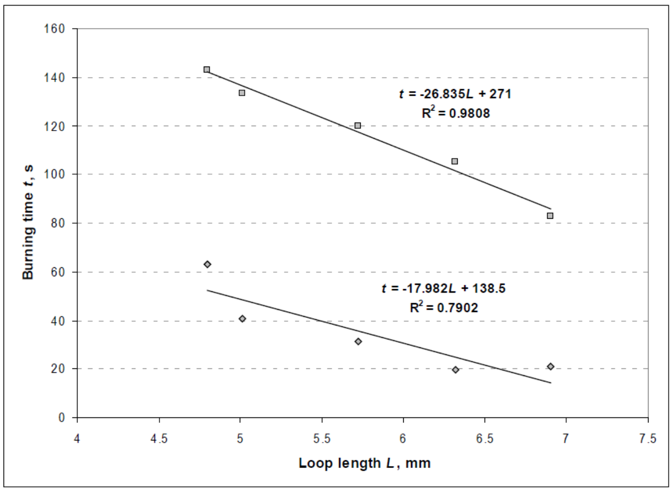



**Figure 2.5** Correlation between burning time and loop length (lower line for the variant A and upper line for the variant B)

In conclusion increasing number of yarns in the loop had greater effect on burning time than increasing number of layers of knits. Burning time will be achieved the same possibly with alteration of air permeability and/or surface density. Using with different number of layers and folded yarns in knits increased burning time but causes lower air permeability and higher rigidity on knit properties. Manufacturing enhanced number of yarns of one knit was cheaper method than manufacturing multilayer packet knits from single yarns. (Mikučionienė, et al., 2011) (Mikučionienė D., 2014)

Kane et al. studied (Kane C. D., 2007) on performance of dimensional, comfort, mechanical and other properties of tuck-knit and plain fabrics that were produced cotton 30 Ne ring and compact yarns with different structural cell stitch length (SCSL). There were three variables in the study; fabric architecture, kind of yarn and varied SCSL.

Fabric architectures were designed single jersey (plain), single pique, double pique, honeycomb as shown in Figure 2.6. Tuck stitches were positioned different orders in the structures. They proved that performances of the fabrics were adjusted with these architectures. Thickness, grams per square meter, water absorbency, thermal insulation and abrasion resistance properties of double pique fabric were higher values than other structures. Air permeability and bursting strength properties of single jersey fabric were better performance than other structures. Bursting strength performance of single jersey fabrics was better than other structures due to higher elongation value of them.

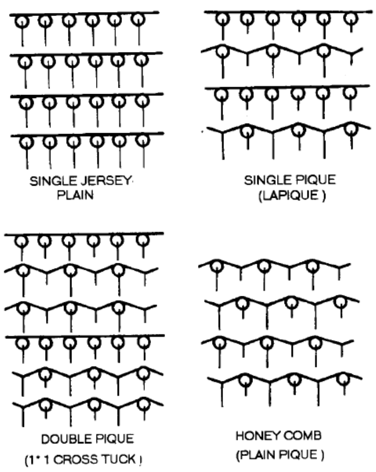



**Figure 2.6** Fabric architectures (single jersey (plain), single pique, double pique, honeycomb)

In the study yarn properties affected the performance of knitted fabrics. Performance of compact yarn fabric combinations was better in all structures than ring yarn fabrics. However air permeability and thermal insulation resistance of compact yarn fabrics due to less hairiness were lower than ring yarn fabrics. Thickness, grams per square meter, water absorbency, bursting strength, abrasion resistance, etc. properties were higher than ring yarn fabrics.

Structural cell stitch length (SCSL) affected signally performance properties of knitted fabrics. They used three different level of SCSL in the study as shown in Figure 2.7. SCSL changed lengths of loops to make loose or tight structure of knitting. SCSL was increased; CPI, WPI, SD, tightness factor, thickness and grams per inches were decreased due to looser structure. Air flow, thermal and abrasion resistance, bursting strength of fabrics were lower value but water absorbency property was higher value to increase SCSL.

| Sample no. | Fabric structures | SCSL (mm) |
|---|---|---|
| 1 | single jersey | 2.50 |
| 2 | single jersey | 2.85 |
| 3 | single jersey | 3.05 |
| 4 | single pique | 2.50, 2.40 |
| 5 | single pique | 2.85, 2.75 |
| 6 | single pique | 3.05, 2.95 |
| 7 | double pique | 2.50, 2.40 |
| 8 | double pique | 2.85, 2.75 |
| 9 | double pique | 3.05, 2.95 |
| 10 | honeycomb | 2.40 |
| 11 | honeycomb | 2.75 |
| 12 | honeycomb | 2.95 |

SCSL, structural cell stitch length.

**Figure 2.7** SCSL levels of specimens

In conclusion compact yarn fabric properties had higher performance than ring yarn fabrics except air flow and thermal resistance. Fabric properties as dimensional, comfort, mechanical and handle; were affected alteration of SCSL. Tuck-knit stitch fabrics had better performance in abrasion resistance, air permeability, water absorbency, thermal insulation, mechanical properties and total handle values but lower performance in surface properties. The study indicated that double pique fabrics had better performance for summer outer wear and single jersey fabrics had better performance for summer inner wear. (Kane C. D., 2007)

Due to dependence of warmth and coldness feeling on fabric's permeability to air, and damp and dryness feeling on fabric's capability to absorb/evaporate sweat; Bivainyte et al. researched (Bivainyte, et al., 2011) influence of fiber type, yarn properties and knitting structure on air and water vapor permeability of double-layered knitted fabrics. In double-layered fabrics (Figure 2.8); one layer (outer) was made from natural (cotton) or man-made (bamboo) yarns and the other layer (inner) was made from synthetic yarns (polyester, polypropylene, polyamide). Different fiber combination of yarns and knitting structure affected significantly air and water vapor permeability of double-layered weft-knitted fabrics.

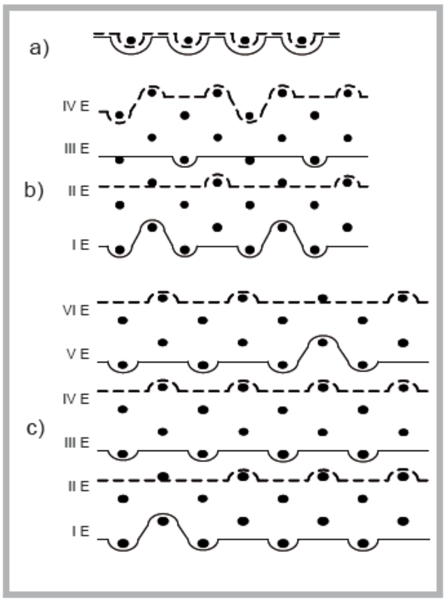



**Figure 2.8** Pattern of the knitted fabrics investigated

**Note:** a) plain plated single jersey, b) combined I (pique), c) combined II; ——— cotton C or bamboo B yarn, - - - -PP, PA, PES, or Coolmax yarn

Air permeability property depends on size and number of pores in the fabrics. When loop length increases, permeability to air increases significantly in statistical analyses due to rising porosity of the knitted fabrics (Figure 2.9). In different patterns, loop length of the fabrics cannot be used to determine the common rate for comparison of air permeability.

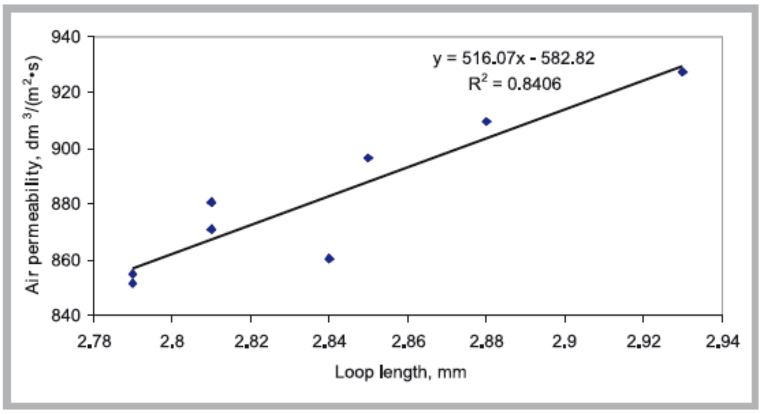



**Figure 2.9** Influence of loop length on the air permeability of fabrics knitted with a plain plated LS pattern

Water vapor permeability of the fabrics was not affected from loop length like air permeability so coefficient of determination of the dependence of water vapor permeability had a lower value ($R^2$=0,1592). The fabrics which were produced with cotton/polypropylene or bamboo/polypropylene blends had the lowest water vapor permeability as LSI-4, LSII-4, KI-4 and KII-4 shows in Table 2.3.

**Table 2.3** Characteristics and notification of the knitted fabrics tested

| Pattern | Sample code | Linear density of yarns and composition percentage | Course density $P_v$, $cm^{-1}$ | Wale density $P_h$, $cm^{-1}$ | Loop length l, mm | Area linear filling rate E | Air permeability, $dm^3/(m^2 \cdot s)$ | Water vapour permeability, $mg/(m^2h$ |
|---|---|---|---|---|---|---|---|---|
| Plain plating | LSI–1 | Cotton, 20 tex, 71%<br>PA, 7.8; 29% | 24.5 | 12.5 | 2.84 | 1.817 | 860 | 3562 |
| | LSI–2 | Cotton, 20 tex, 71%<br>Coolmax, 7.8; 29% | 24.5 | 12.5 | 2.79 | 1.701 | 852 | 4058 |
| | LSI–3 | Cotton, 20 tex, 71%<br>PES, 8.3; 29% | 24.5 | 12.5 | 2.79 | 1.701 | 855 | 3693 |
| | LSI–4 | Cotton, 20 tex, 71%<br>PP, 8.4; 29% | 25 | 12 | 2.88 | 2.045 | 899 | 3560 |
| | LSII–1 | Bamboo, 20 tex, 71%<br>PA, 7.8; 29% | 24 | 12.5 | 2.85 | 1.696 | 896 | 4141 |
| | LSII–2 | Bamboo, 20 tex, 71%<br>Coolmax, 7.8; 29% | 24 | 12.5 | 2.81 | 1.589 | 871 | 4773 |
| | LSII–3 | Bamboo, 20 tex, 71%<br>PES, 8.3; 29% | 24 | 12.5 | 2.81 | 1.589 | 881 | 4274 |
| | LSII–4 | Bamboo, 20 tex, 71%<br>PP, 8.4; 29% | 24.5 | 12 | 2.93 | 2.016 | 927 | 4008 |
| Combined (piquè) | KI–1 | Cotton, 20 tex, 71%<br>PA, 7.8; 29% | 16 | 12 | 3.11 | 1.753 | 863 | 3887 |
| | KI–2 | Cotton, 20 tex, 71%<br>Coolmax, 7.8; 29% | 16 | 12 | 3.10 | 1.867 | 882 | 4338 |
| | KI–3 | Cotton, 20 tex, 71%<br>PES, 8.3; 29% | 16 | 12 | 3.10 | 1.867 | 877 | 3905 |
| | KI–4 | Cotton, 20 tex, 71%<br>PP, 8.4; 29% | 16 | 11 | 3.21 | 1.820 | 920 | 3862 |
| Combined | KII–1 | Cotton, 20 tex, 76%<br>PA, 7.8; 24% | 15 | 11.5 | 3.24 | 1.688 | 788 | 3999 |
| | KII–2 | Cotton, 20 tex, 76%<br>Coolmax, 7.8; 24% | 15 | 11.5 | 3.26 | 1.566 | 779 | 4358 |
| | KII–3 | Cotton, 20 tex, 76%<br>PES, 8.3; 24% | 15 | 11.5 | 3.26 | 1.566 | 772 | 3888 |
| | KII–4 | Cotton, 20 tex, 76%<br>PP, 8.4; 24% | 15 | 11 | 3.35 | 1.758 | 876 | 3832 |

In the study influence of loop length and fiber blends of yarns on air and water vapor permeability of double-layered knitted fabrics were observed. While air permeability was affected from loop length; water vapor permeability was affected from fiber blends of yarns significantly according to the study (Bivainyte, et al., 2011).

Ciobanu et al. investigated (Ciobanu, et al., 2016) influence of knitting structure and raw material type on mechanical properties of weft-knitted sandwich fabrics. Two types of raw materials were used in the fabrics: Kevlar and linen yarns (Table 2.4). Three levels of positions of quality cam (NP:12, 13.5, 15) were used in the study.

**Table 2.4** Fabric variants according to the position of raw material in the structure architecture

| Raw materials | Position of the yarn type in the structure architecture | Variant code |
|---|---|---|
| Kevlar® | Outside layers 1 & 2 and connecting yarns from Kevlar® ·(***Figure 1.a, 1.b***) | SK |
| Kevlar® | Outside layers 1 & 2, connecting yarns and weft in-lay yarns from Kevlar® (***Figure 1.c, 1.d***) | SB-K |
| Kevlar® with linen | Outside layers 1 & 2 from Kevlar®, connecting yarns and weft reinforced yarns from linen (***Figure 1.c, 1.d***) | SB-I |

Bursting strength of sandwich fabrics were tested with two stages: the bursting behavior of single layer fabrics firstly and secondly the bursting behavior of more layers of sandwich fabrics were observed. Four different velocity levels used for testing all single layer variants as 100, 300, 500 and 1000 mm/min. Principle of creating sandwich knitted fabrics is shown in Figure 2.10.

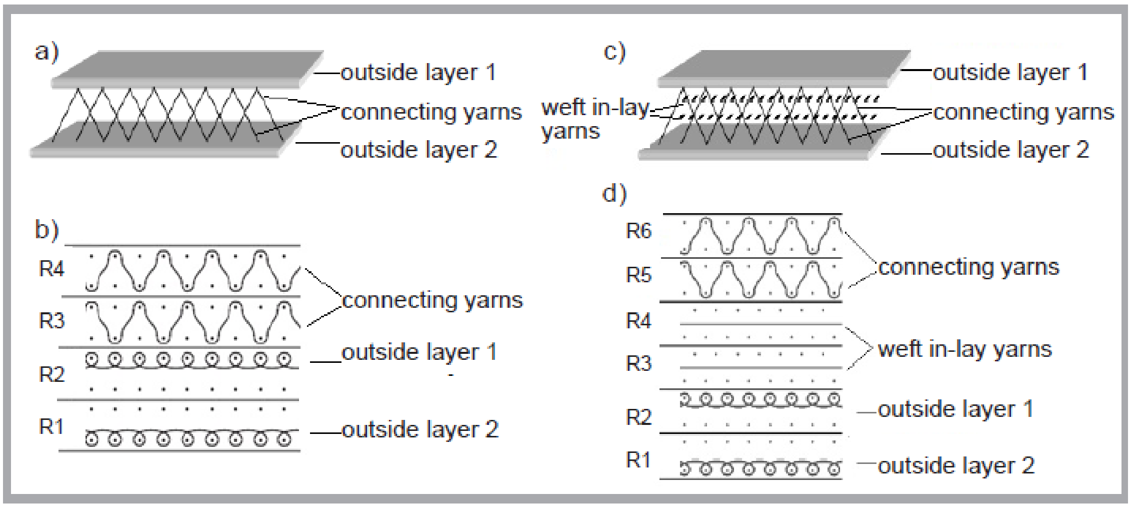



**Figure 2.10** Principle of creating sandwich knitted fabrics

**Note:** a) technical representation, b) knitting sequence, c) reinforced with weft in-lay yarns-technical representation, d) knitting sequence

The fabrics made from Kevlar yarns had better bursting strength than those with linen for the first velocity level. Also bursting strength of SK fabrics is the lowest for the other three velocity levels. The fabrics which include weft in-lay yarns (variants SBK and SBI) had better fabric behavior and lower differences in strength caused by velocity test. Linen yarns did not affect the fabric behaviors except for the first velocity test. Value of deflection of velocity test increased up to 500 mm/min, but decreased at 1000 mm/min (Figure 2.11).

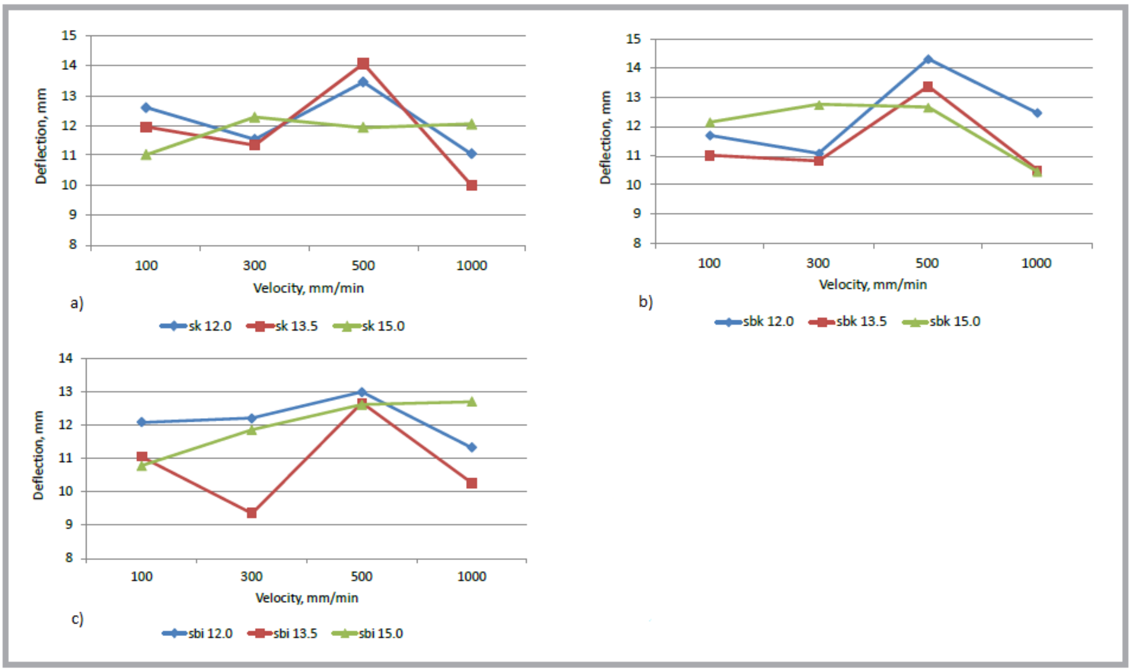


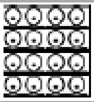
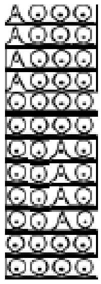
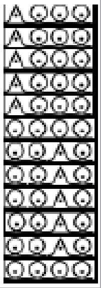
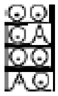
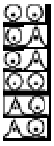
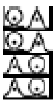
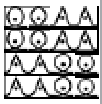

**Figure 2.11** Variations in bursting deflection with the testing velocity

**Note:** a) for SK variants, b) for SBK variants, c) for SBI variants

In conclusion most compact fabrics (NP=12) had better bursting strength for all cases because of having smaller stitch length and higher rigidity. Bursting strength of fabrics decreased with the test velocity because of the fabrics do not respond to the strain for longer time. Bursting strength increased with presence of weft in-lay yarns which indicated similar values as both types of yarns at higher velocities. (Ciobanu, et al., 2016)

Uyanık et al. investigated (Uyanik, et al., 2016) effect of number and location of tuck stitches in knitted fabric combinations which produced by circular knitting machine on fabric properties. Knitted fabrics having tuck stitches increases some fabric properties as thickness, width and weight and makes the fabric more porous than fabrics having loop stitches. In the study, bursting strength of 12 different greige and dyed fabrics which have number and location of tuck stitches was examined. Table 2.5 shows pattern properties and needle diagrams of 12 specimens.

**Table 2.5** Pattern properties and needle diagrams of fabrics

| Sample No | Pattern properties | Needle diagram | Sample No | Pattern properties | Needle diagram |
|---|---|---|---|---|---|
| 1 | This sample is named single jersey" and it has no tuck stitch. |  | 2 | This sample is a combination of sample 4 with 48 courses and sample 1 with 36 courses. | |
| 3 | This sample is a combination of sample 6 with 54 courses and sample 1 with 30 courses. | | 4 | This sample is named 'honeycomb' and it has 4 tuck stitches and 2 plain stitches in the same needle. This type is known as a zigzag pattern. |  |
| 5 | This sample has 2 tuck stitches and 1 plain stitch in the same needle. |  | 6 | This sample has 4 tuck stitches in the same needle |  |
| 7 | This sample is named 'honeycomb' and it has 5 tuck stitches 1 plain stitch in the same needle. This type is known as a zigzag pattern. |  | 8 | This sample is named 'single lacoste' and it has 1 tuck stitch and 1 plain stitch in the same needle. This type is known a as zigzag pattern. |  |
| 9 | This sample is named 'double lacoste' and it has 2 tuck stitches and 1 plain stitch in the same needle. This type is known as a zigzag pattern. |  | 10 | This sample has 2 tuck stitches in the adjacent needles for the 1st and 2nd courses and then 1 tuck stitch in the other needles for the 3rd and 4th courses. This type is known as a zigzag pattern. |  |
| 11 | This sample is named 'English pique' and it has 2 tuck stitches but no plain stitch in the same needle. This type is known as a zigzag pattern. |  | 12 | This sample has 2 tuck stitches in the adjacent needles for the 1st and 2nd courses and then 1 tuck stitch in the other needles for the 3rd and 4th courses. This type is known as a zigzag pattern. |  |

Tuck stitch formation changes structure and properties of fabrics. Tuck stitches pull yarn from adjacent loops also making them smaller. Fabric length and elasticity in lengthwise of fabrics having tuck stitches reduce due to pulled and held yarns. Strength and elongation of yarn and fabric structure parameters influence bursting strength of knitted fabrics. Contrary to general belief the weakest yarns is not broken firstly, the stronger yarns have less elasticity and reach their elastic limit fast then break. Test results of the specimens show that bursting strength values increases when number of tuck stitches decreases. Tuck loops make the fabric more porous, it causes decreasing fabric resistance to pressure. The yarns which are under pressure break easily and bursting strength decreases.

Location of tuck stitches is significant parameter which affects fabric performance. Zigzag and not zigzag formations have different results in bursting strength test shows in Figure 2.12. The patterns are not zigzag like samples 3, 5 and 6 (Table 2.5 illustrates their needle diagrams) have loose structure than zigzag patterns. Due to lower tightness, decreasing in resistance to air pressure occurred and the samples have low bursting strength values. Honeycomb patterns like samples 4 and 7 have more compact structure so their bursting strength results are higher than samples 3, 5 and 6. While zigzag patterns like samples 8, 9, 10, 11 and 12 are extremely tough than other structures, their bursting strengths which are very close to single jersey structure (Sample 1) have the highest values within all structures. Dyeing process decreases yarn strength due to extracts waxes and oil from yarn so bursting strength of fabrics decreases.

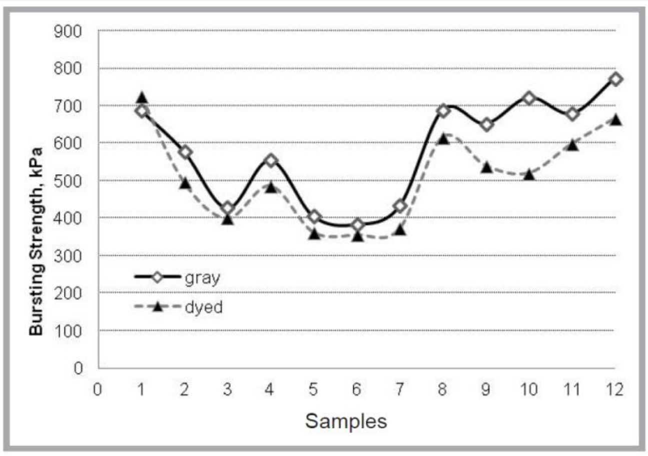



**Figure 2.12** Effects of dyeing on bursting strength

In conclusion when stitch length increases, bursting strength value decreases. Location of tuck stitches are more determinant parameter than number of tuck stitches in bursting strength property. In zigzag patterns bursting strength of samples which have tuck stitches form in adjacent needles are higher than others like samples 10 and 11. Dyeing process reduced the bursting strength because of extracting waxes from yarns. (Uyanik, et al., 2016)

Uyanık et al. investigated (Uyanik, et al., 2017) effects of knitted fabrics having tuck stitches which have different number and location in the fabrics, on to pilling property of fabrics. Tuck stitch formation achieve higher porosity, thickness and weight than single jersey fabrics. Needle diagrams of fabrics which were tested in the study indicated in Figure 2.13.

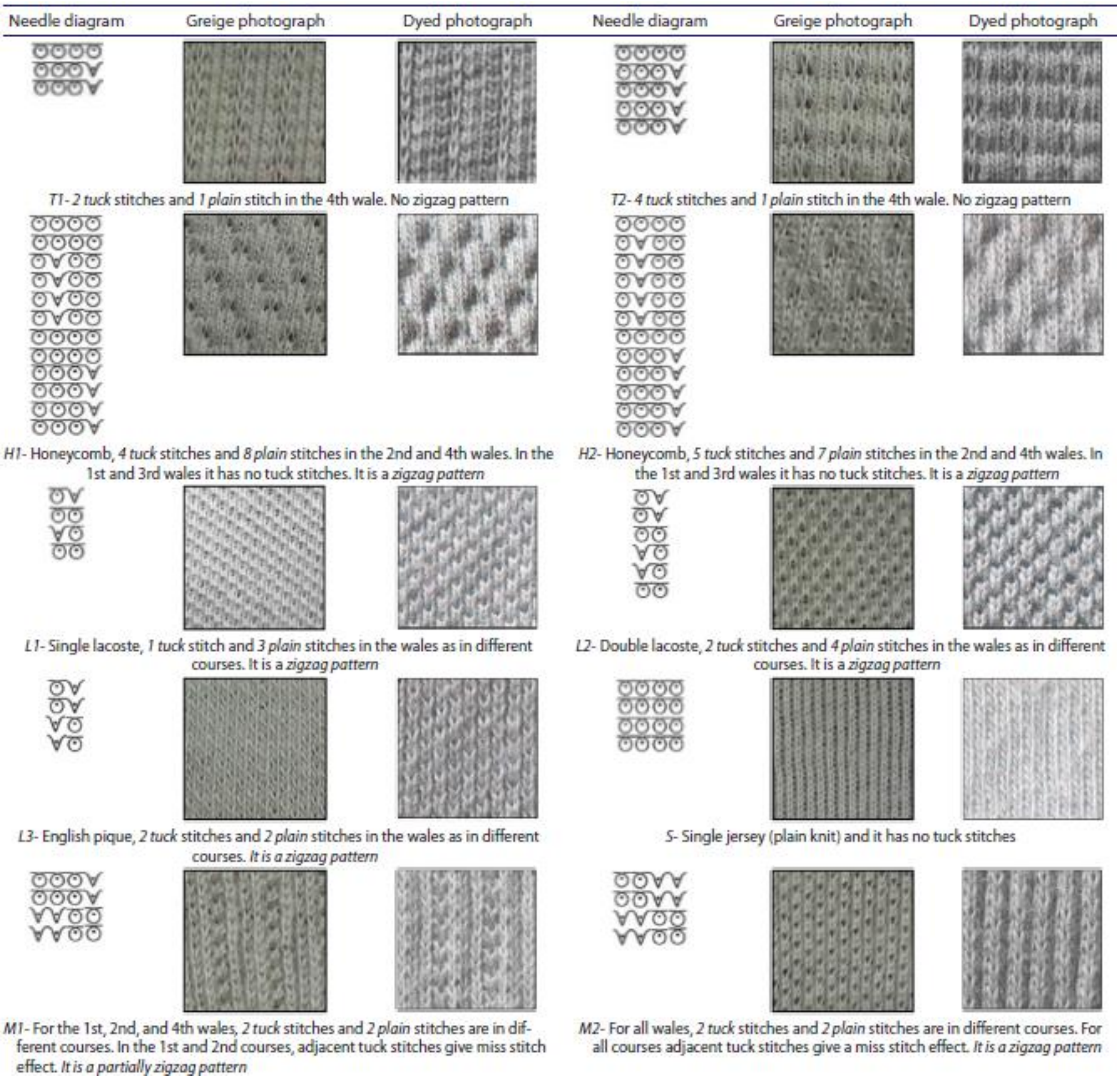



**Figure 2.13** The fabric codes, pattern descriptions, needle diagrams and photographic views

Location of tuck stitches is decisive on properties of fabrics. When number of loop stitches which are between tuck stitches (separating them) increases, the fabric is seen more relief. When number of tuck stitches increases; stitch density descends and porosity, thickness and weight of fabric enhances that shows in Table 2.6.

**Table 2.6** The structural and physical properties of studied knit fabrics

| Fabric code (LTS) | NTS/48 stitch | SCSL mm | Courses/cm cpc ± .5 | | Wales/cm wpc ± .5 | | Stitch density cpc × wpc/cm² | | Porosity % | | Weight gsm ± 5 | | Thickness mm ± .3 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Greige | Dyed | Greige | Dyed | Greige | Dyed | Greige | Dyed | Greige | Dyed | Greige | Dyed |
| S | 0 | 2.7 | 21 | 20 | 12.5 | 15.5 | 262.5 | 310 | .30 | .17 | 130 | 153 | .44 | .44 |
| T1 | 8 | 2.7 | 17 | 17.5 | 11.5 | 12.5 | 195.5 | 218.75 | .57 | .50 | 138 | 159 | .54 | .51 |
| T2 | 9.6 | 3.01 | 20 | 19.8 | 11 | 11.7 | 220 | 231.66 | .49 | .42 | 137 | 152 | .56 | .52 |
| H1 | 8 | 2.7 | 17 | 17.5 | 11.5 | 13.5 | 195.5 | 236.25 | .57 | .49 | 146 | 172 | .53 | .54 |
| H2 | 10 | 3.15 | 13 | 14.5 | 12 | 11.5 | 156 | 166.75 | .60 | .59 | 132 | 150 | .54 | .56 |
| L1 | 12 | 2.6 | 14 | 14.5 | 11 | 12 | 154 | 174 | .67 | .65 | 142 | 180 | .53 | .56 |
| L2 | 16 | 2.65 | 17 | 17.5 | 11 | 11.5 | 187 | 201.25 | .69 | .64 | 168 | 184 | .69 | .64 |
| L3 | 24 | 2.6 | 15 | 15.5 | 10.5 | 11.7 | 157.5 | 181.35 | .71 | .67 | 145 | 174 | .62 | .63 |
| M1 | 18 | 2.54 | 13.5 | 13.5 | 11 | 12.6 | 148.5 | 170.1 | .73 | .69 | 137 | 161 | .60 | .61 |
| M2 | 24 | 2.26 | 15 | 14 | 12 | 14 | 180 | 196 | .70 | .70 | 137 | 166 | .59 | .65 |

Pilling resistance of fabrics with tuck stitches are higher compared to single jersey structures because of more porous structure of fabrics having tuck stitches. While size and number of pores increases, increasing pilling and abrasion resistance are observed. In Figure 2.14 shows the number of pills/cm² of fabrics in cycles.

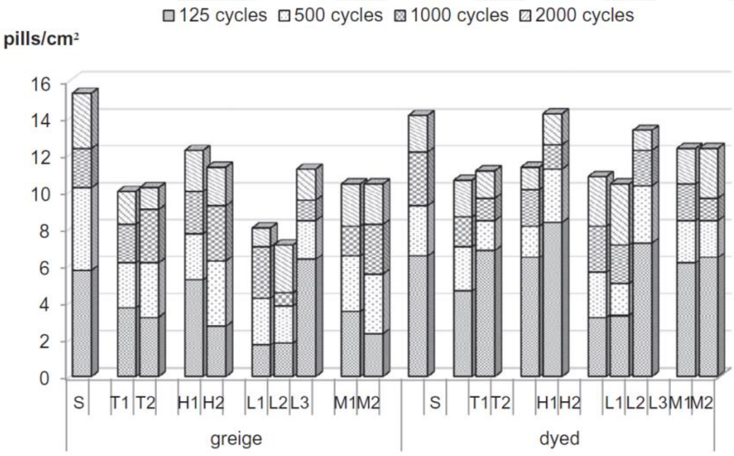



**Figure 2.14** The number of pills/cm² of fabrics in cycles

In conclusion when number of tuck stitches enhances; stitch length decreases and fabric properties as thickness, porosity and weight improves. Adjacent tuck stitches formation give float stitch effects to knitted fabrics. Therefore thickness and weight of fabric is lower than expected. When tuck stitches are located in the same wale more than two stitches, fabric is tough, thick and heavy. Dyeing process descends pilling resistance due to slack structure of fabrics. (Uyanik, et al., 2017)

Çoruh (Çoruh, 2015) investigated performance of mechanical and comfort properties of single jersey knitted fabrics which were produced by four different blends of cotton, viscose and polyester fibers. Fiber types, yarn properties, loop length, knitting structure, and tightness factor caused significant changes on performance of the properties. In the paper, performance of different loop lengths and fiber blends of single jersey fabrics were studied in view of comfort and mechanical properties. Twelve different types of single jersey fabrics were produced with different blends (cotton 50%: polyester 50%, cotton 40%: polyester 60%, cotton 30%: polyester 70%, cotton 50%: viscose 50%) and tightness (loose, medium, tight).

Bursting strength, air permeability and water vapour permeability of the fabrics were tested and the results of the tests were significant according to statistical analysis were made by "Design Expert Analysis 6.06." in the study. When loop lengths increased; bursting strength decreased, air and water vapour permeability increased. If the amount of polyester increased in the structures, the bursting strength of them increased (Figure 2.15). Therefore wales per cm, course per cm and tightness factor decreased while loop length increased.

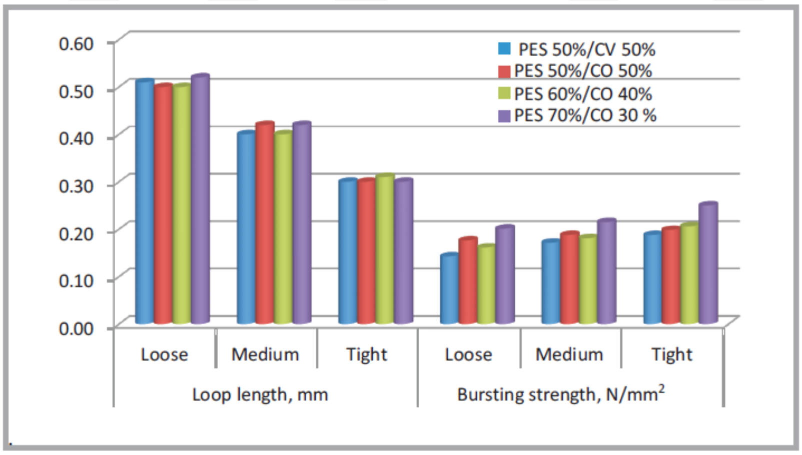



**Figure 2.15** Influence of the loop length and fiber blend on the bursting strength of the knits

Looser structures of the fabrics had small changes in tightness factor. But there was a marked change in air permeability. Air permeability increased when loop length increased so comfort of wearer raised (Figure 2.16). Thick structures had a great change in the tightness factor. Therefore air permeability had low variation according to statistical analyses.

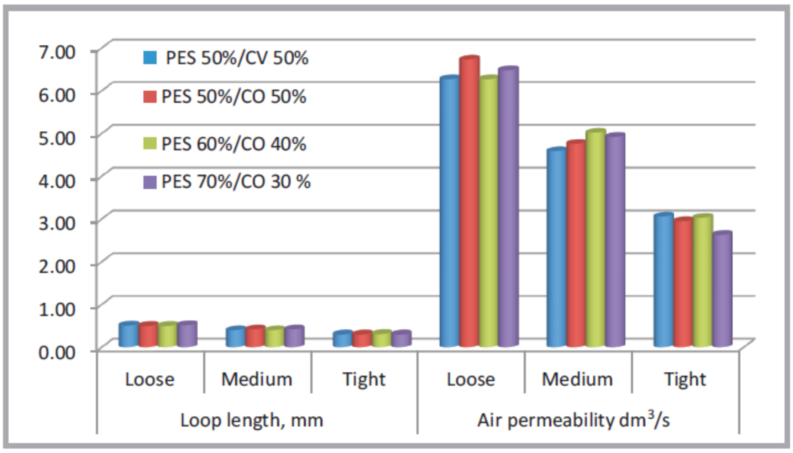
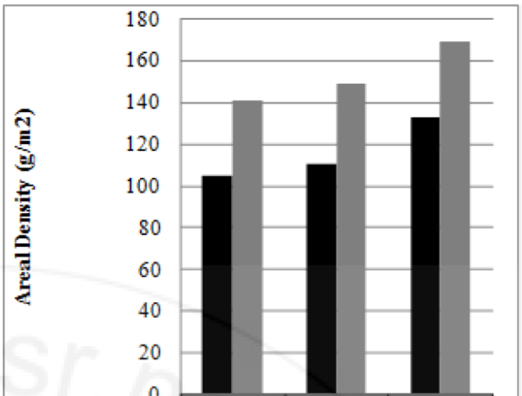



**Figure 2.16** Influence of the loop length and fiber blend on the air permeability of the knits

In conclusion different loop length and blend ratios carried out significant changes in mechanical and comfort properties of the fabrics. The changes are statistically significant on performance of the properties of single jersey knitted fabrics. (Çoruh, 2015)

Asif et al. investigated (Asif, et al., 2015) effect of three different weft knitted structure on properties of fabric as dimensional stability, spirality, fabric width, areal density, pilling resistance and color fastness to washing/light/rubbing. Knitted structures as plain jersey, single lacoste and double lacoste which produced from %100 cotton yarns of count 30 Ne were selected for the study.

Tuck stitches gained a thicker structure to knitted fabrics due to robbing yarn from adjacent loops so tuck stitches in fabric enhanced areal density property. Areal density of fabrics ordered from higher to lower as double lacoste, single lacoste and plain jersey that show in Figure 2.17.




| | Plain Jersey | Single Lacoste | Double Lacoste |
|---|---|---|---|
| Grey GSM | 105.2 | 110.9 | 132.9 |
| Finished GSM | 140.7 | 148.8 | 169.3 |

**Figure 2.17** Areal density of samples of different structures

In conclusion increasing tuck stitches of fabrics improves resistance to pilling, width shrinkage, and fabric diameters and descends spirality, length shrinkage. Color fastness to washing/light/rubbing does not influence knitted structure when dyeing and finishing parameters remain same. (Asif, et al., 2015)

Rashed et al. analyzed (Rashed, et al., 2014) effect of tuck stitch on bursting strength of single jersey fabrics which are produced with 30/s and 40/s Ne card yarns by 24 gauge circular knitting machine. Bursting strength does not influence directly increasing or decreasing percentage of tuck stitches, it depends on sequence of tuck stitches in the same wale or course.

In Figure 2.18 tuck stitches are ranged in wale direction as percentage of 10%, 20%, 30%, 40%. Average of bursting strength values are between 210-294,4 kPa in knitted fabrics which produced with 30/s yarns. When tuck stitches in wale direction enhances, bursting strength diminishes as in Figure 2.19.

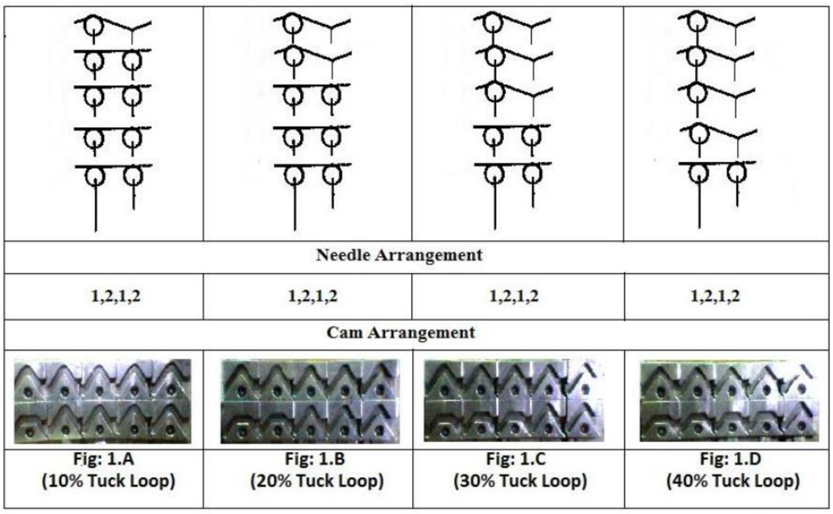



**Figure 2.18** Use tuck loop in same wales by maintaining percentage (%) of the fabrics (N.B. 30/s yarn) notation diagram

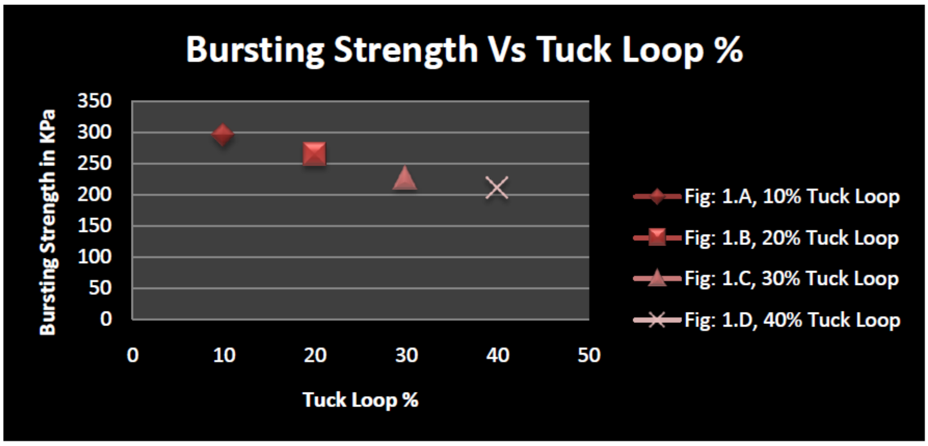



**Figure 2.19** Bursting strength test for 10%, 20%, 30% and 40% tuck loop

Figure 2.20 shows that presence of tuck stitches increases in course direction as percentage 25%, 33,3% and 37% of knitted fabrics which produced with 30/s yarns. Therefore increasing tuck stitches in course direction causes decreasing bursting strength values as in Figure 2.21.

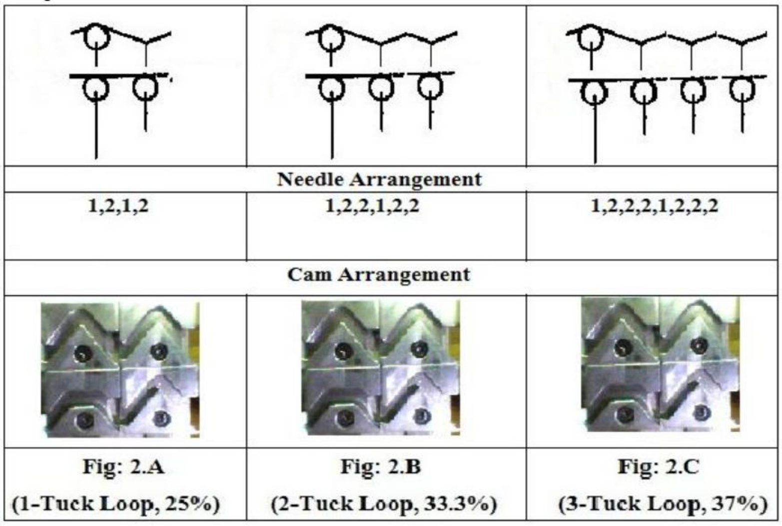



**Figure 2.20** Use tuck loop in same course without maintaining percentage (%) of the fabrics (N.B. 30/s yarn) notation diagram

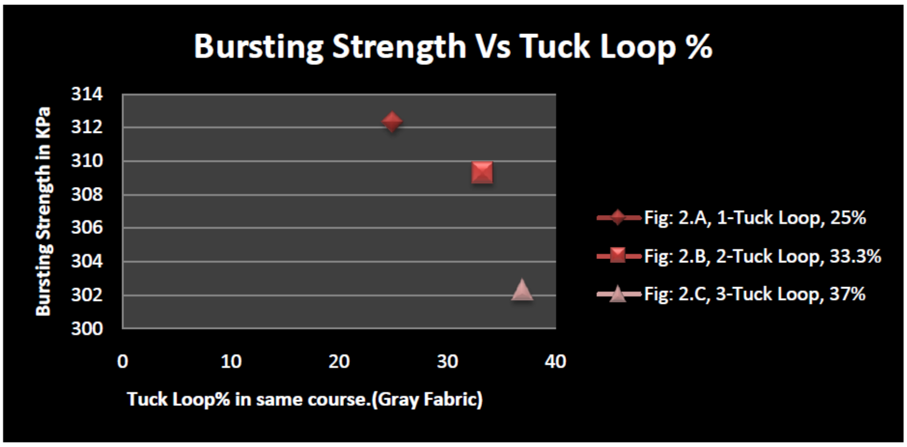



**Figure 2.21** Bursting strength test for 1, 2 and 3 tuck loop in same course

In Figure 2.22 knitted fabrics which were produced with 40/s yarns have tuck stitches as percentage of 10%, 20%, 30%, 40% and 50%. Results of the fabrics indicated linear decrease on bursting strength except percentage of 30% (Figure 2.23). There are two explanation of decreasing bursting strength of percentage of 30% with tuck stitches fabric. One explanation is the fabric which has 30% tuck stitches has fewer wales and tuck in 15*15 cm² samples. Because of GSM of the fabric with %50 tuck stitches was less than 30% has more wales and tuck in width, so it had contained more yarn. When the fabrics had more yarn in the wale direction, they had become more resistant to bursting force. For this reason, bursting strength of 30% was lower than 50% and 40%. Another explanation is fabric with 30% tuck stitches had consisted one of wales has tuck loops and the adjacent wale has totally loop stitches shown in Figure 2.24. Therefore tuck loops has lower elongation capability than loop stitches; also tuck loops tends to break firstly during bursting strength test. Lack of tuck stitches in the adjacent wale had reduced endurance to bursting. (Rashed, et al., 2014)

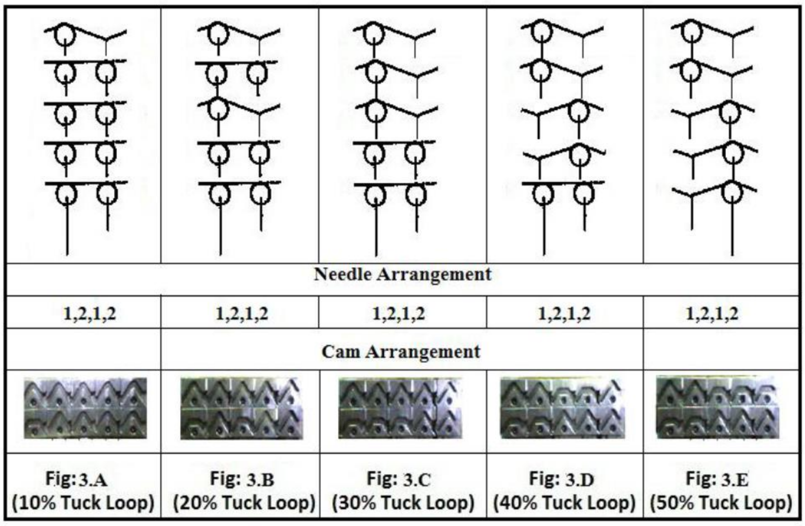



**Figure 2.22** Use tuck loop in various course & wales to complete design by maintaining percentage (N.B 40/s yarn) notation diagram

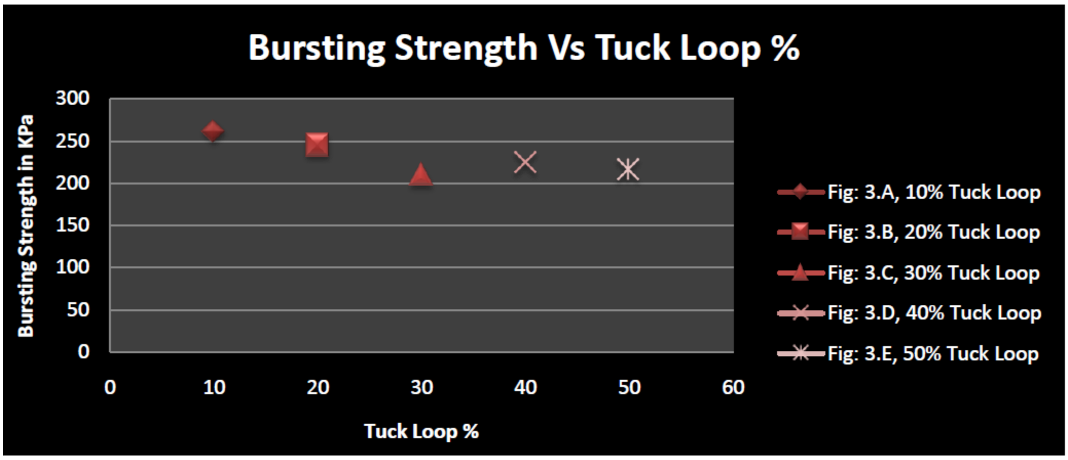



**Figure 2.23** Bursting strength test for 10%, 20%, 30% 40% and 50% tuck loop

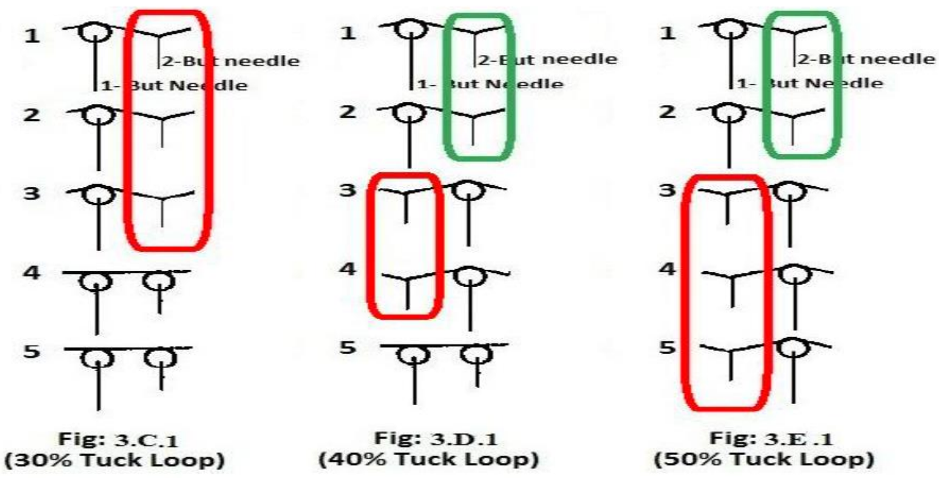
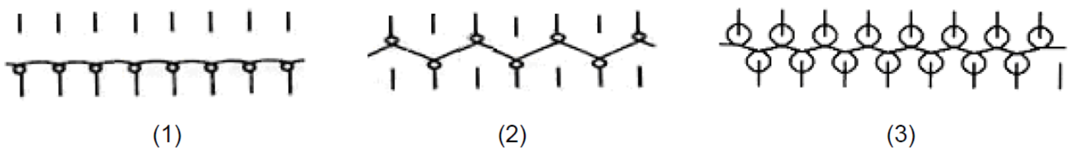



**Figure 2.24** Notification of fabrics of 30%, 40% and 50% tuck loop

In the literature review, the previous studies about the technical and mechanical properties of knitted fabrics were investigated. We observed that air permeability and bursting strength properties are significantly influenced by the loop length of fabrics. The effect of tuck stitches from conventional textile fibers on fabric thickness, areal density, and porosity were clearly revealed in the previous studies. However, in the literature about weft knitted fabrics; it was determined that there is not enough research on the glass yarn weft knitted fabrics.

## 2.2 Literature Review about Yarn Strength

Hu et al. investigated performance of glass yarns which were unraveled from knitted fabrics. Knit structures, cam settings and yarn parameters were changed in weft knitted fabrics and degree of breakages of the yarns were analyzed. Three different types of knit patterns (single jersey, 1x1 rib half needle in action, 1x1 rib all needle in action, indicated in Figure 2.25) and two types of glass yarns whose fiber diameters and twists/m were different from each other (type A and type B) were used in the study. Stitch cam settings in the flat knitting machine could not be clearly indicated, so very tight and very loose settings were used in the study. (Hu, et al., 2005)




(1) Single Jersey, (2 ) 1×1 Rib I (half needles in action), (3) 1×1 Rib II (all needles in action)

**Figure 2.25** Knitted structures used

The breakage degree of glass filaments was obtained via measuring strength of the yarns which were unraveled from knitted fabrics. The minimum and the maximum values of loop length in knitting structure were determined by adjusting the stitch cam settings. The positions of minimum and maximum values were referred as lower and upper limits in cam settings. (Hu, et al., 2005)

When loop lengths were increased, degree of filament breakages firstly decreased then increased for all knit patterns and type of glass yarns (Figure 2.26). Higher frictional actions occurred between yarn and machine parts (yarn/yarn, yarn/needle and higher yarn tension in old loops just the knitted fabric). Therefore in longer loop lengths, degree of filament breakages increased during the loop formation step. Knit patterns were ordered higher to lower in degree of breakage of filaments as single jersey, 1x1 rib stitch (all needle in action) and 1x1 rib stitch (half needle in action) respectively. (Hu, et al., 2005)

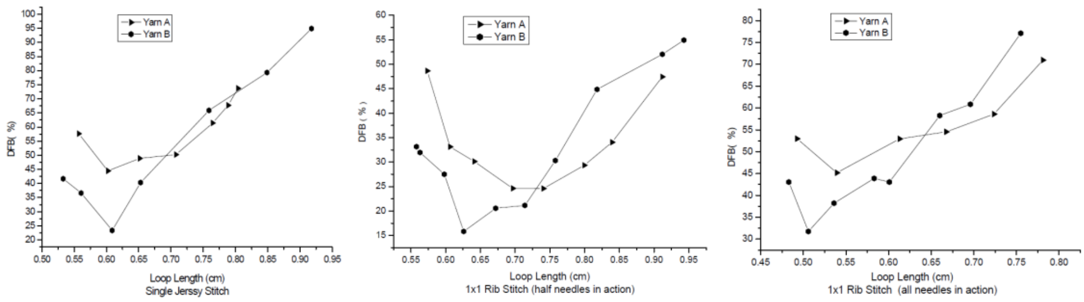



**Figure 2.26** Variation of DFB in term of the loop length for single jersey, 1x1 rib stitch (half needles in action) and 1x1 rib stitch (all needles in action)

In the study, (Hu, et al., 2005) to confirm performance of glass fiber filaments; same tests that applied glass yarns were also applied to two types of other yarns (a cotton yarn and a wool/acrylic blend yarn). The other yarns have very small damages than glass yarns during knitting process (Figure 2.27). Therefore knitting with glass yarns were more difficult than that with common yarns and choosing a proper cam setting was very important in knitting of glass yarns.

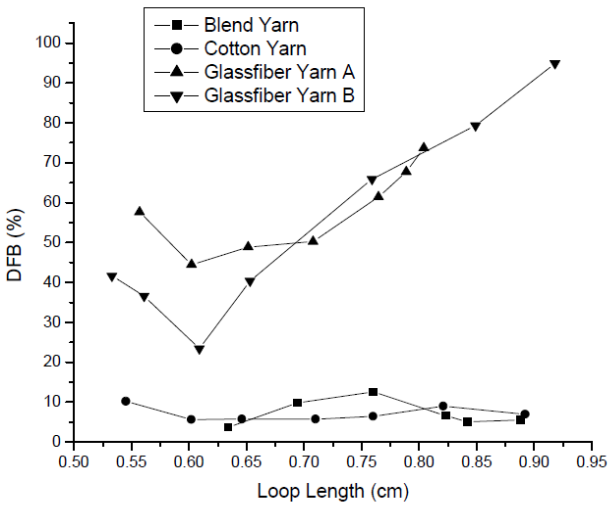



**Figure 2.27** Comparison of DFB between commonly used yarns and glass yarns

In conclusion, fiber damages of glass fiber filaments were higher in single-faced knitted fabrics than double-faced fabrics. When cam settings were in optimum values, degree of breakages of glass filaments decreased. Finally commonly used the other yarns have lower fiber damages in knitting process than glass fibers. (Hu, et al., 2005)

Liu et al. studied on the knittability of glass yarn. Knitting process was simplified by separating yarn-needle hook systems and evaluating breakages of the yarns was carried out with designed experiments under tensile, bending and abrasive actions. The whole yarn path which the yarns moved on them linearly and circular segments in knitting area could be simplified (Figure 2.28). (Liu, et al., 2009)

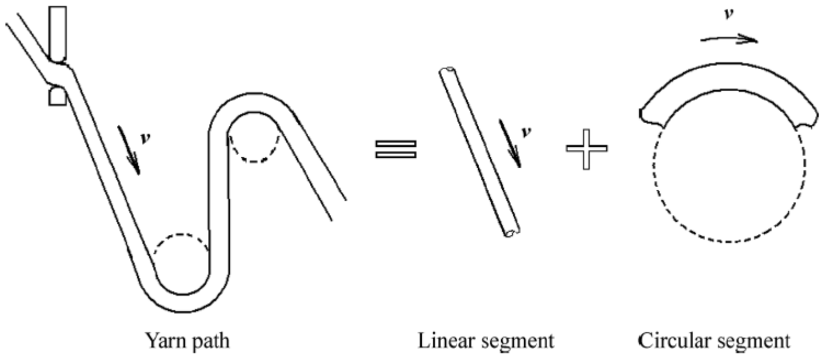



**Figure 2.28** Sketch of yarn path simplification

Results of straight tensile and loop strength tests were compared in the study. Loop efficiency was calculated with dividing loop strength by straight tensile strength of the yarns. Straight tensile strength of the yarn was much more than loop strength. Loop efficiency was lower than 50% and loop efficiency increased when diameter of needle hook increased (Figure 2.29). Yarn modulus of the tested yarns did not change in both types of strength tests (Figure 2.30). (Liu, et al., 2009)

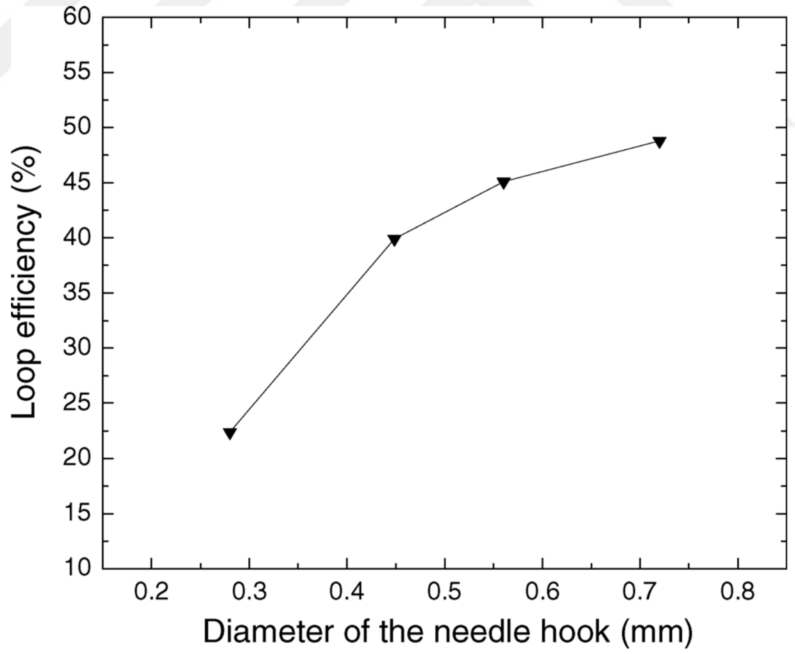



**Figure 2.29** Yarn loop efficiency with different hook diameters

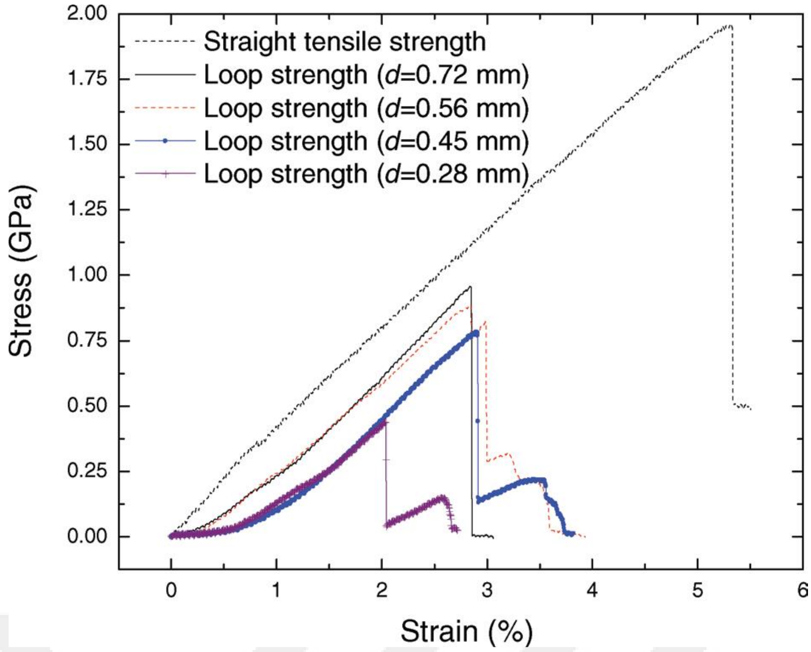



**Figure 2.30** Tensile curve comparison between straight tensile test and loop strength test (d = 0.28 mm~0.72 mm)

As conclusion, needle hook diameter and loop efficiency had positive relationship. If needle hook diameter decreased, load carrying capacity of glass yarn under bending status decreased according to loop strength test. (Liu, et al., 2009)

Savcı et al. observed knittability of glass fibers and relationship between machine settings and physical properties of the weft knitted preforms made from glass yarn. Machine limits, yarn source and knit pattern were adjusted to produce the tightest structure. Yarn feeding system was shown in Figure 2.31. (Savcı, et al., 2001)

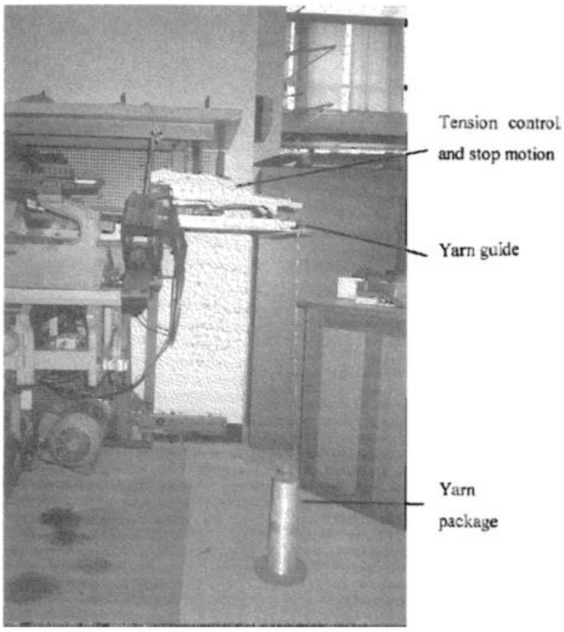



**Figure 2.31** Modified path of the yarn feed

Degree of fiber damage and needle wear was assessed with image processing and electron microscopy techniques. Image analyses of the fabric structures are shown in Figure 2.32. Working with glass fibers was difficult in weft knitting process due to architecture of the knits and also high fiber stiffness and friction, and low fiber strain. The number of needle breakages was noted approximately twice times higher than observed number of breakages in manufacture of conventional textile fabrics.

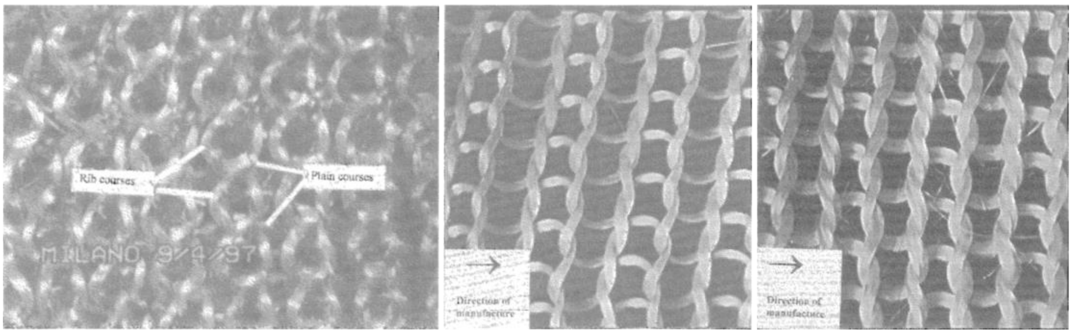



**Figure 2.32** Image analyses of the full milano, single jersey using Z twist yarn, single jersey using S twist yarn (technical face) structures, respectively

In the study, limits of knitting machine and relaxation states of glass fiber knits were investigated. Knittability of glass yarns were assessed with the number of needle breaks. Adjusting with fabric tightness and specific stitch cam setting, the knittability property provided to establish for full milano structure. The results indicated that high correlation between loop lengths and stitch cam settings. (Savcı, et al., 2001)

Koo measured yarn tension variations with a newly developed test rig. Simulated knitting conditions were used in order to assess yarn tension variations. Yarn feeding system were arranged to control yarn tension so knitting faults were reduced and good quality knitted fabrics were manufacturedfor the study (Figure 2.33). (Koo, 2004)

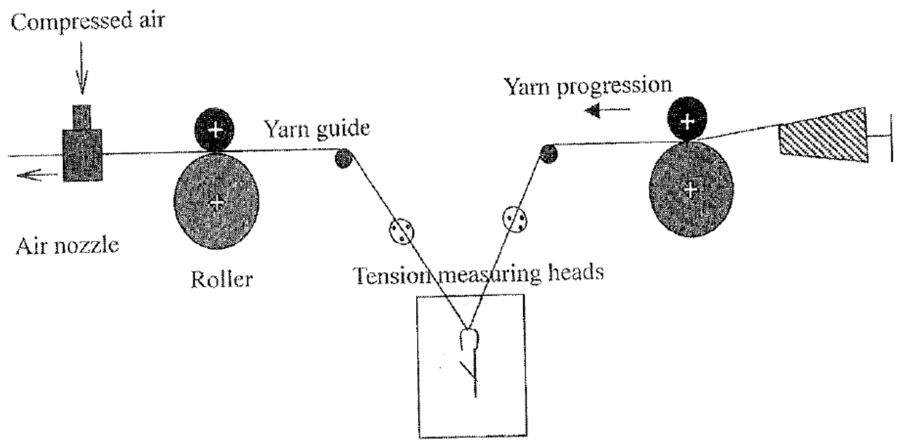



**Figure 2.33** Schematic diagram of a test rig

Results of yarn feeding speed showed that nodistinct correlation between yarn tension and yarn feeding speed (Figure 2.34). Another compared parameters were needle type and tension variations based on yarn feeding speed and angle. E28 needles had higher tension variation than E18 (Figure 2.35). When the friction between yarn and needle hook increased, yarn tension also increased. (Koo, 2004)

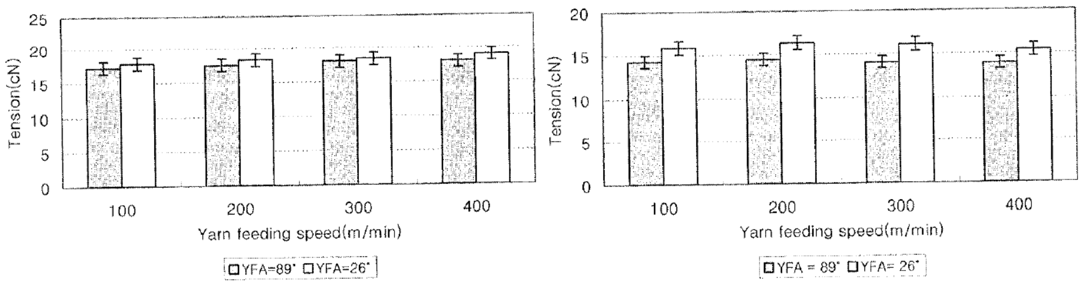



**Figure 2.34** Variation of yarn tension with E28 and E18 needle, respectively

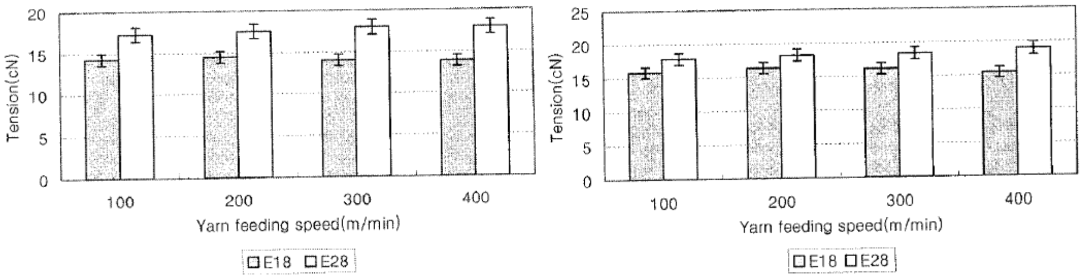



**Figure 2.35** Tension variation with 89˚ and 26˚ yarn feed angle, respectively

In the study, tension mechanism of knitting process was investigated so yarn tension variations were observed in the simulated test rig. As a conclusion yarn tension may not be continuously controlled during the knitting process. Needle changes showed a distinct difference on yarn tension variation. Needle selection and yarn feed angle were important factors to determine tension variations. (Koo, 2004)

Literature review that is about glass yarn strength does not have comprehensive results in the knitting activities of glass yarn. The strength of unraveled yarns was measured or the tension conditions of the knitting mechanism were applied and the evaluations were made in the studies. When the optimum cam settings were applied, it had been observed that working with the glass yarn can be achieved without any high damage to the fibers/filaments. Furthermore, it was concluded that the yarns were more damaged as the friction between the yarn and needle was higher in the single bed knitted fabrics.

# CHAPTER 3

# OBJECTIVES

Knitting is a manufacturing technique that creates flexible and versatile fabric structure that cannot be achieved by other techniques. This method which does not require any preparations like weaving process also provides fabrics with low costs. One of the most unique features of knitting fabrics is their stretch-ability towards multi-axial direction. Usage of knitting fabrics in technical areas has increased in recent years because of their multidirectional damage resistance. Drapeability of knitted fabrics provides them to take the shape of the desired mold. So the specific advantage of knitted fabrics is adapting easily into molded shapes that cannot be achieved by other fabrics cannot. Producing one-pieced fabrics used in technical areas can be provided by knitting technology.

Glass is a fiber which is incombustible, brittle and has high tenacity. Different featured kinds of glass fibers provide protection from fire, electricity, heat etc. They are cheaper than other aramid fibers (like Kevlar and Nomex etc.) which are incombustible, but it is not possible to produce clothes from glass fibers because of uncomfortable feeling. In recent years usage of glass fibers increased in area of technical textiles and composites are one of them. Because of being cheap, filament and easy to find, E-glass yarn was used in this study. Other good properties of glass yarns which preferred in this study were written above.

Aim of this study is to evaluate air permeability and bursting strength performances of weft knitted fabrics produced from glass yarns on single bed flat knitting machine. Advantages and lower costs of knitting process and glass yarns are thought as significance of this study. Previous studies examined performances of knitted fabrics which were produced by natural fibers or produced with technical fibers by double bed machine. There was not enough knowledge about knitted fabrics that were produced from glass yarns by single bed flat knitting machine is noticed after literature review.

The second goal of this study is to measure and compare structural properties (course/wale density, loop length etc.), thickness and areal density of different fabrics which are obtained through changing knit pattern, number of yarn plies and machine parameters. When knit pattern, number of yarn plies and cam settings are changed, revealed values of air permeability and bursting strength showed the importance of choosing fabrics that have desired properties according to use area.

The third aim is observing strength evolution of glass yarns before and after knitting process. Due to various aggressive forces experienced by the glass fibers during loop formation; lower unraveled yarn strength than virgin yarn was expected. Realizing how these changes in glass yarns and measurements of loop strengths are another conclusion of this study.

CHAPTER 4

# MATERIALS AND METHODS

## 4.1 Materials

We utilized E-glass filament yarn provided by “Puran Dış Ticaret Tekstil Makine Sanayi Ltd.Şti.” to manufacture fabrics on Brother KH-864 manual and flat weft knitting machine (Figure 4.1). The nominal count of E-glass yarn is 133 tex (Figure 4.2).

**Figure 4.1** KH-864 manual flat weft knitting machine

**Figure 4.2** E-glass fiber yarns

### 4.2 Methods

The knitting machine Brother KH-864 available in our laboratory consists of front and rear needle beds and their carriages. The beds have five needles per inch and each has two hundreds needles in total.

We considered three variables; fabric architecture, cam setting and number of yarn ply. Table 4.1 indicates the experimental plan of this study. Four different fabric architectures including loop-, tuck-, and skip-stitch and weft-in-lay yarn separately were determined. Fabric architecture settings were made by cam buttons and weaving pattern lever on the carriage. While cam buttons were controlling tuck or skip stitch formation, weaving pattern lever provided to insert weft-in-lay yarn. Tuck-stitch, skip-stitch and weft-in-lay architectures were created by punch card number one which patterns one of the needles is in front position, the adjacent needle is behind position.

**Table 4.1** Experimental plan

| **Variables:** | **Knit Architecture** | **Cam setting (three- or eight-tension)** | **Yarn ply number (2- or 3-ply yarn)** |
|---|---|---|---|
| **Levels** | Loop stitch (single jersey) | Eight-tension (loose fabric) | 2 ply |
| | Tuck stitch | Three-tension (tight fabric) | 3 ply |
| | Skip stitch | | |
| | Weft-in-lay | | |

The size of loops that determines tightness of the fabric is controlled by the tension dial on the carriage. (Brother Industries, 1990) The tension dial is graduated from zero to ten; while zero-tension creates the smallest loop size (the tightest fabric); ten-tension creates the largest loop size (the loosest fabric). As we rotate the tension dial from zero to ten while looking at the needle track on the cam, the lowest position of the needle descends that growths the size of the forming loop (Figure 4.3). Two different tension levels; high (three-tension) and low (eight-tension) was selected in this study. Tension levels were adjusted with tension dial on to the carriage (Figure 4.3).

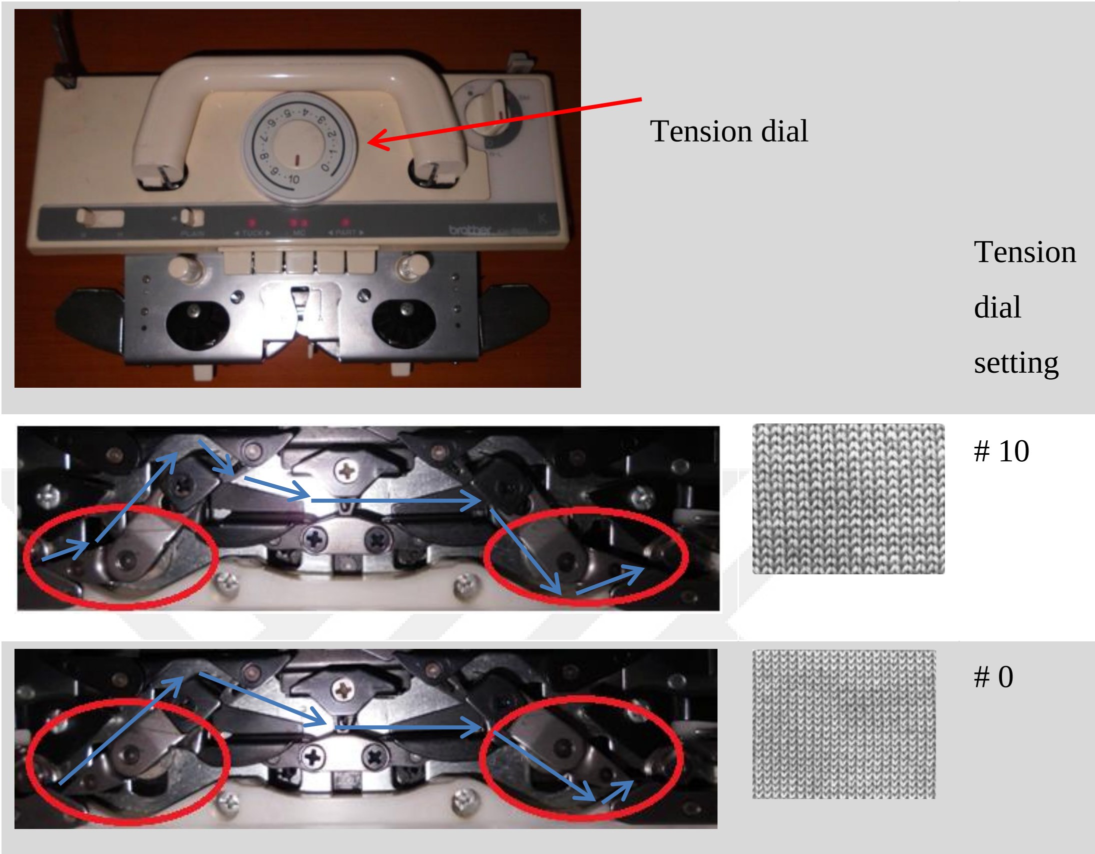
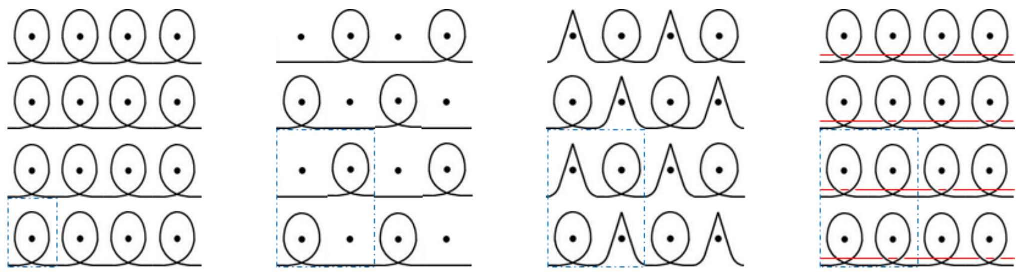



**Figure 4.3** Tension dial of the knitting machine (top row) and cam tracks followed by needles and fabric structures manufactured by different tension dial numbers (middle and bottom rows)

The third variable was number of yarn ply. Fabrics were knitted with 2-ply and 3-ply yarns. Yarns were feed together from the same yarn guide except extra yarn in weft-in-lay fabric. Weft-in-lay architecture included the extra yarn to pass middle of knitted fabric in addition to 2-ply or 3-ply yarns forming the ground loops.

We only used rear needle bed of weft knitting machine and its carriage to knit our fabrics. We selected the 4 different architectures to observe loop, tuck, skip and weft-inlaid. Technical notations (needle diagrams) of each architecture shows in Figure 4.4.



: loop stitch : skip stitch : tuck stitch : weft-inlay : knit repeat boundaries

**Figure 4.4** Technical notations of the weft-knitted fabrics

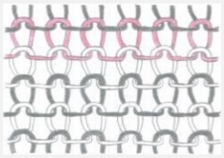
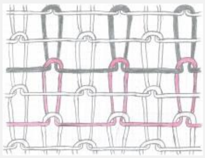
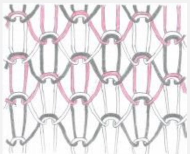
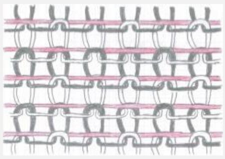
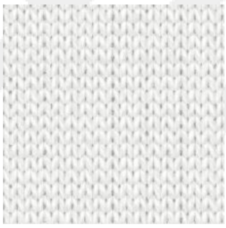
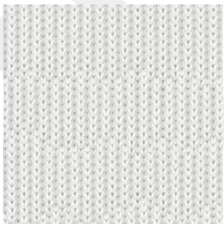
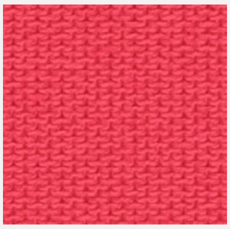
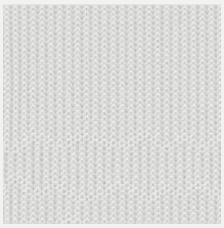
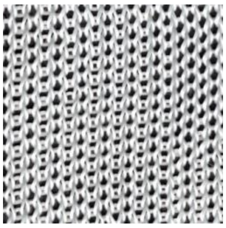
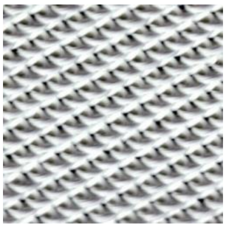
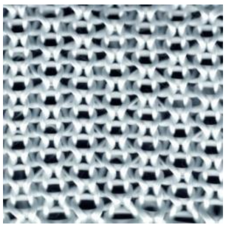
| | **Knit architectures:** | | | |
|---|---|---|---|---|
| | loop stitch | skip stitch | tuck stitch | weft inlay |
| Hand-draft schematic view of the 2D knitted fabrics |  |  |  |  |
| Front face simulation of the knitted fabrics from filament yarn |  |  |  | - |
| Back face simulation of the knitted fabrics from filament yarn |  |  |  |  |
| Actual images scanned from front faces of the fabrics after they were removed from the machine. |  |  |  |  |

**Figure 4.5** Hand-draft drawings, simulations, and actual images of knit architectures

Figure 4.5 shows hand-draft drawings, simulations, and actual images of knit architectures.

Physical (as thickness, areal density, stitch density, course/wale density, loop length) and mechanical properties (as bursting strength, air permeability, yarn strength) of weft knitted preforms were tested. Table 4.2 indicates physical and mechanical tests which applied the specimens in this study.

**Table 4.2** Physical and mechanical tests

| **Properties** | **'hysical:** | **Mechanical:** |
|---|---|---|
| | Thickness | Bursting strength |
| | Areal density | Air permeability |
| | Course/Wale density | Yarn strength |
| | Loop length | |

### 4.2.1 Physical Properties Analyses

#### a. Thickness

We measured thickness of weft knitted fabrics by Wira Digital Thickness Gauge Serial No. G161/15 (Figure 4.6). This test instrument was designed for carpets but we measured with the tester because of technical textile materials was exposed to high pressure level. There were 8 pressure weights (2-5-10-20-50-100-150-200 kPa) to adjust compression pressure. The presser foot was 2 kPa, other weights were movable. Diameter of the presser foot was 21.15 mm.

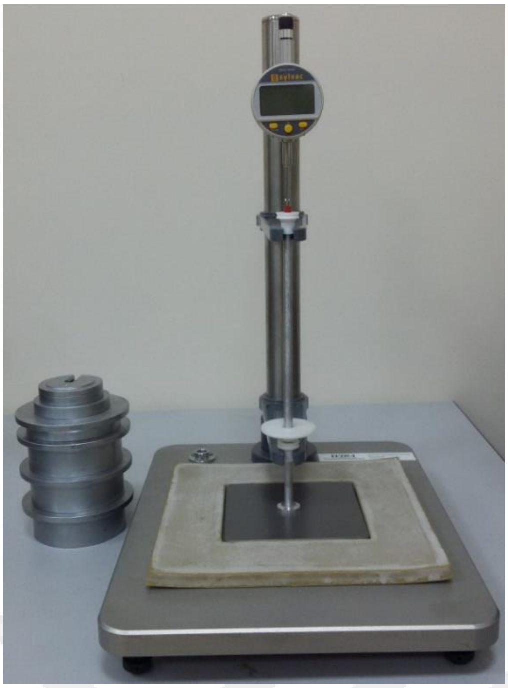


**Figure 4.6** Wira Digital Thickness Gauge

We selected 4 different compression pressure values that were 50-100-150-200 kPa. We placed the tested specimen under the presser foot on to the reference plate. The weights were put respectively on to the presser foot. We recorded the indicator reading half a minute after removing each weight for 4 different compression values to 16 specimens. We measured thickness from 5 different places of the specimens. Tested area had to comprised more than one repeat of pattern illustrates in Figure 4.7. Tests were made randomly selected.

**Figure 4.7** An example of the tested fabric during thickness measurement

### b. Areal density

Areal density measurement of weft knitted fabrics was preformed according to ASTM D3776 "Standard test methods for mass per unit area (weight) of fabric". (ASTM, 2013) Thickness of the specimens measured totally 150 $cm^2$ because of standard approved the total area of small swatch fabrics was at least 130 $cm^2$. We procured a die cutter as shown in Figure 4.8. The die cutter had square shape and 25 $cm^2$ area.

**Figure 4.8** Die cutter

We took 6 small swatches from different places of weft knitted fabrics by the die cutter to measure areal density shows in Figure 4.9. Wooden chopping board was used to cut specimens because of preventing specimen slippage on to the board until hammering die cutter to it. The swatches were weighted precision balance and recorded the readings illustrates in Figure 4.10.

**Figure 4.9** A measurement of areal density with die cutter


**Figure 4.10** Precision balance during a swatch weighed

**c. Course/Wale density**

ASTM D8007-15 “Standard test method for wale and course count of weft knitted fabrics” was utilized to assess course and wale density of weft knitted fabrics. (ASTM, 2016) We counted course and wale per inch and converted course and wale counts to per cm. We counted from 5 different places of the specimens for each course and wale.

Loops of wale direction were counted in Figure 4.11 shows single jersey fabric, course density was found as 10. Loops of course direction were counted, wale density was found as 7. Densities were counted course/wale per inch, after converted counts to per cm.

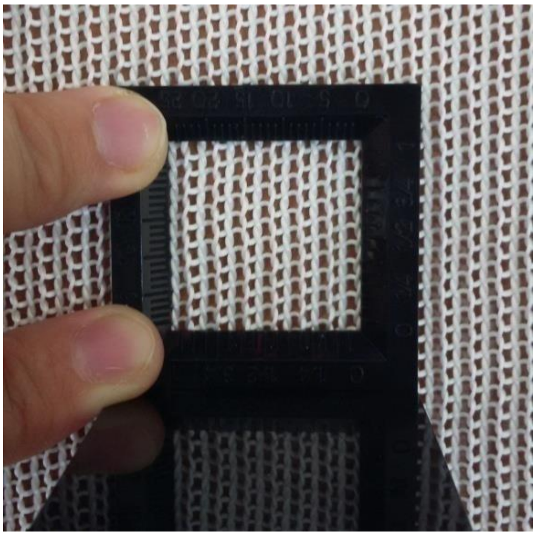


**Figure 4.11** Course and wale density of single jersey fabric

### d. Loop length

BS 5441 "British standard methods of test for knitted fabrics" was used to measure loop length. (BSI, 1991) Loop length was calculated to count loops in course direction from determined length. We counted loops in 5 cm length as shown in Figure 4.12.

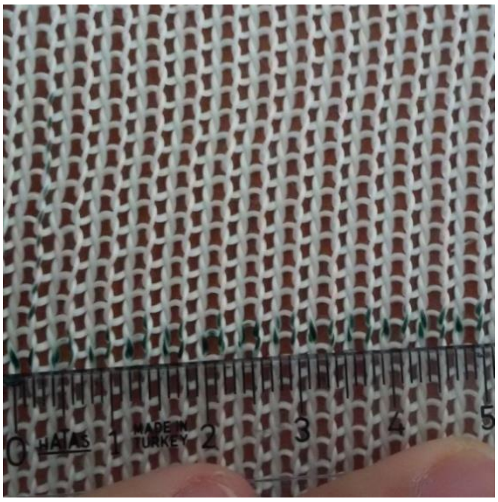



**Figure 4.12** Counting loops in 5 cm length

Then we unraveled yarns from knitted fabric in the 5 cm length and yarn lengths were measured by ruler is shown in Figure 4.13. The yarn lengths were divided to the loop counts to calculate loop lengths. We calculated 10 times for all the specimens.


**Figure 4.13** Measured loop lengths by ruler

### 4.2.2 Mechanical Properties Analyses

#### e. Bursting strength

Knitted fabrics were not convenient to test tensile strength because of their pliable structure. Their strength was measured by bursting strength tester. We tested the 16 different specimens by James H.Heal TruBurst$^{2}$ Bursting Strength Tester is shown in Figure 4.14. Bursting strength was determined according to ASTM D3786 “Standard test method for bursting strength of textile fabrics-diaphragm bursting strength tester method”. (ASTM, 2013)


**Figure 4.14** TruBurst$^{2}$ Bursting Strength Tester

Principle of the test diaphragm was inflated by air pressure until bursting tested fabric. (James H.Heal, 2007) Test area was chosen 50 cm² (79,8 mm diameter). Pressure unit was kPa and distention unit was mm. Time to burst were 20±5 seconds. Tests were repeated 5 times. We adjust some regulations to test glass weft knitted fabric. Tests were applied technical fabrics so diaphragms were selected specially that has 1,5 mm thickness. Clamp pressure was adjusted 800 kPa to prevent slippage of the specimens under dome.

The fabric was placed under the dome for testing. Then test was begun, diaphragm was inflated by air until bursting the fabric. Figure 4.15 illustrates a tested specimen when diaphragm was inflated.

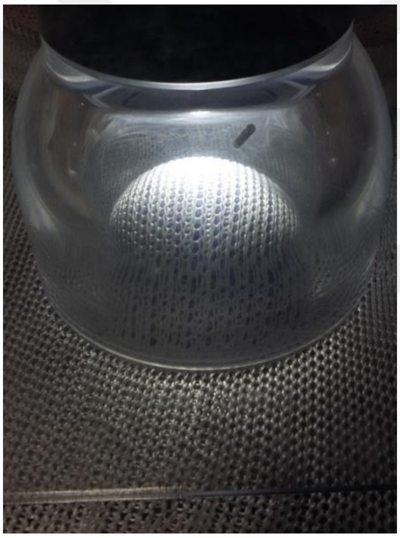


**Figure 4.15** Tested specimen for bursting strength when diaphragm was inflated

**f. Air permeability**

Air permeability tester was SDL ATLAS M021A as shown in Figure 4.16. We tested specimens according to ASTM D737-04 “Standard test method for air permeability of textile fabrics”. (ASTM, 2016) The principle of this test was measuring air flow through fabric test area according to controlled variables. (SDL Atlas) There were 5-20-25-38-50-100 cm² heads available for testing. We tested 16 specimens for area 20 cm² and pressure 200 kPa. We selected cm³/cm²/s unit from options display for readings.


**Figure 4.16** SDL ATLAS air permeability tester

Fabric was placed under the arm and pressed down to begin test as shown in Figure 4.17. Air passing through the testing area and air flow was measured. Then readings were recorded.

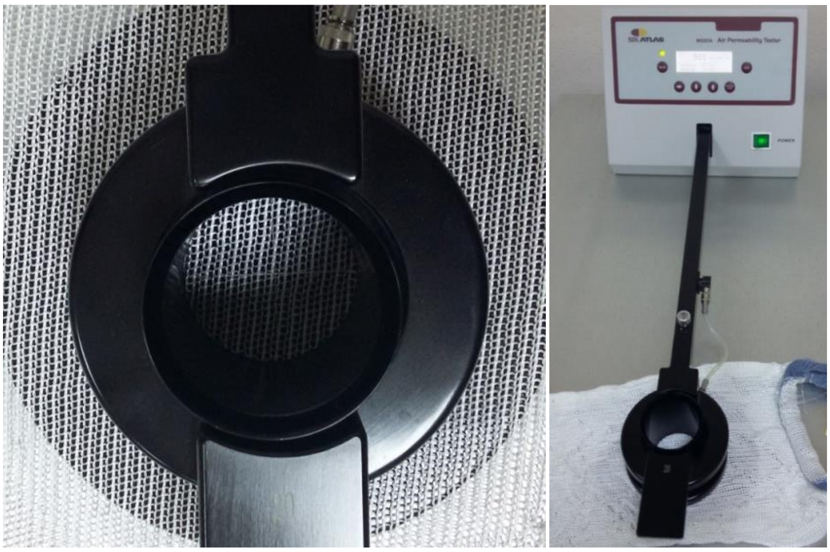


**Figure 4.17** An example of air permeability measurement

### g. Yarn strength

Yarn strength test was made according to ASTM D2256 “Standard test method for tensile properties of yarns by the single-strand method”. (ASTM, 2015) We tested unraveled and virgin yarns by James H.Heal Titan² Universal Strength Tester Model 710 (Figure 4.18). (James H.Heal, 2006)


**Figure 4.18** James H.Heal Titan² Universal Strength Tester

We selected ASTM D2256 250 mm/20 second option of Titan² program on to computer. It means jaw separation was 250 mm, time to break was 20 second. Linear density option indicated yarn count; for example when we tested 2 ply of yarn, 2*133 tex = 266 tex was entered linear density box. Titan² was enabled to adjust variables about testing; pretension, rate of extension, break detection, max load as shown in

Figure 4.19. We determined pretension 0.5 cN/tex, rate of extension 50 mm/min, break detection 95 % and maximum load 600 N. Rate of extension specified rate of jaws moving, the value was given as 150 mm/min for this standard. When we tried 150 mm/min, we observed that time of break was very short. In conclusion of tries observations indicated 50 mm/min was precise for unraveled glass yarn from knitted fabric. Similarly maximum load was tried 3000 N firstly, but it is not enough sensitive for the specimens. We selected 600 N load cell. Break detection was 50 % normally but we want to ensure breaking yarn to select 95 % for break detection.

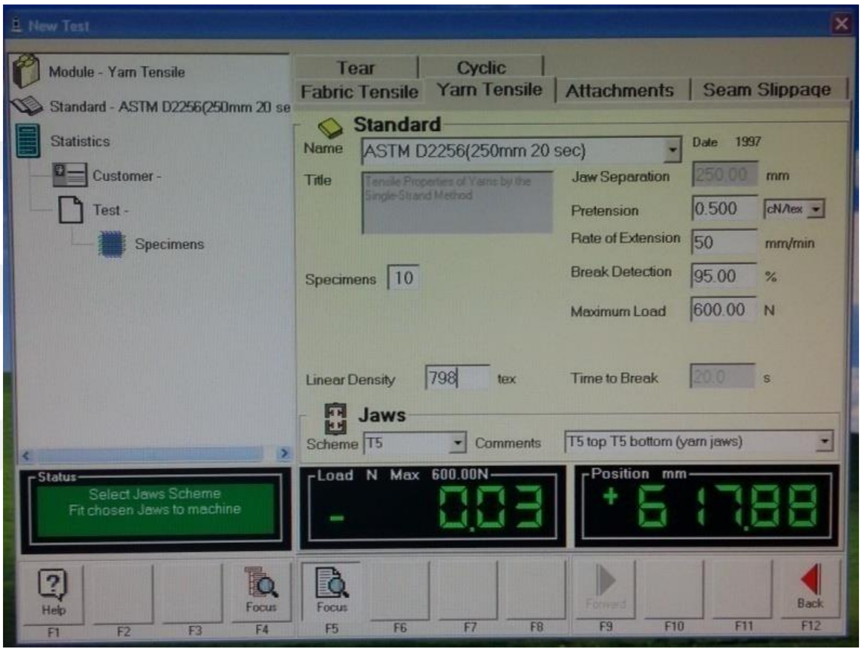



**Figure 4.19** Variables in Titan strength tester

We selected physical configuration 3: looped method in ASTM D2256 standard to test specimens. Two yarn pieces passed through each other to form as loops and ends of the same yarn were taken reverse side as shown in Figure 4.20. We simulated yarns of knitted fabric to utilize strength readings. Therefore yarns were shaped loops in knitting and they were strengthening to forces.

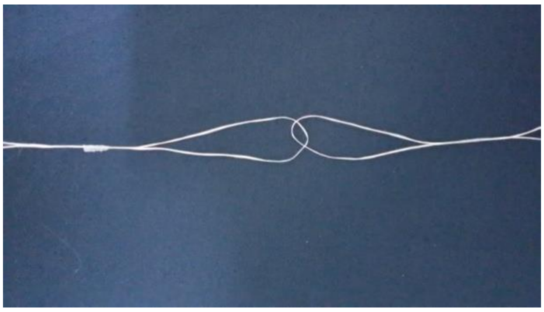


**Figure 4.20** Configuration of yarns in measurement of loop strength

We had two different variables for number of yarns, 2 ply – 3 ply. Therefore we tested loops by 2 or 3 ply of yarns illustrates Figure 4.21. We observed glass yarns slipped between jaws. We applied epoxy resin edge of the yarns under the jaws to prevent slippage until testing. The edges with epoxy resin situated between the jaws shows in Figure 4.22.

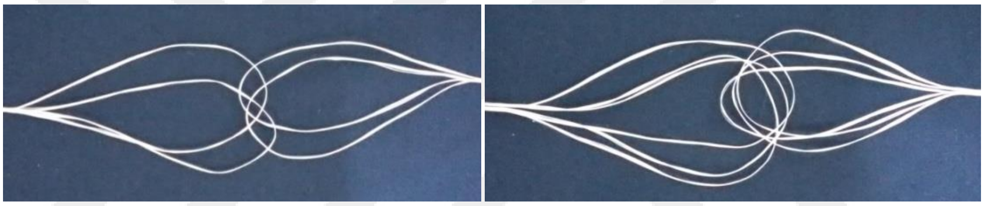


**Figure 4.21** Configuration of 2 and 3 plies of yarns in measurement of loop strength

**Figure 4.22**Situated epoxy resin in the ends of yarns

Then test was begun as shown in Figure 4.23. Readings were recorded. Tests were repeated 10 times for each specimen.

**Figure 4.23** An example of yarn strength measurement

# CHAPTER 5

# RESULT AND DISCUSSION

## 5.1 The Effect Of Cam Setting

Cam setting has two different levels that produced tight and loose fabrics. According to 640 measurements in total, thicknesses of tight fabrics were higher than loose fabrics (Figure 5.1). The shorter loop length of tight fabrics provided more compact structure that increased thickness of the fabrics. Loose fabrics with longer loop lengths spread over a wider area than tight fabrics that decreased thickness. Cam settings affected the thicknesses of the fabrics at statistically significant level (Table 5.1).

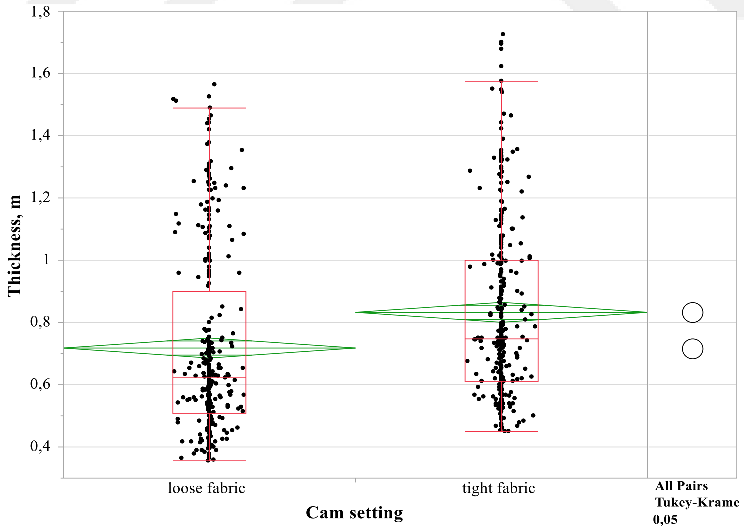



**Figure 5.1** Effects of cam setting on thickness

**Note:** The distance between top and bottom ends of green diamond represents the 95% confidence interval. Comparison circles (given on the right column) for means those are significantly different either do not intersect, or intersect slightly. The height of red box (known as interquartile range) is a quantitative indication of variation.

Figure 5.2 indicated the relationship between cam settings and areal density of the fabrics. Due to greater amount of loops per unit area of tight fabrics; tight fabrics possessed higher areal density than loose fabrics. Areal densities of loose fabrics were lower than those of tight fabrics due to longer loops were accommodated less amount of loops in the same area.

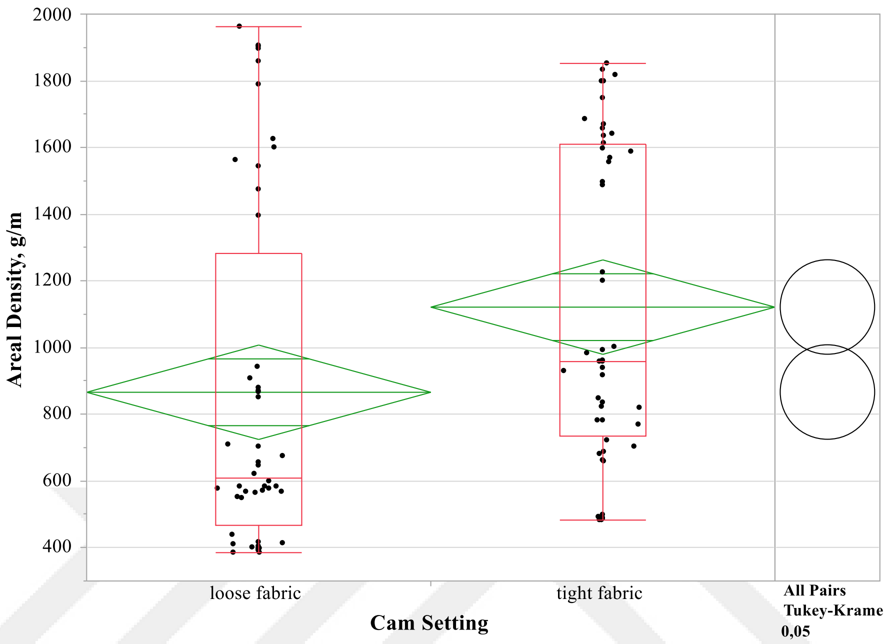



**Figure 5.2** Effects of cam setting on areal density

Cam settings affected thickness, areal density and formulized fiber volume percent at statistically significant levels (Table 5.1). Fiber volume percent defines fiber volume of one-hundred volumes of technical materials saturated by resin. Theoretical fiber volume percentage of the technical material produced by tight fabrics was higher than those produced by loose fabrics (Figure 5.3).

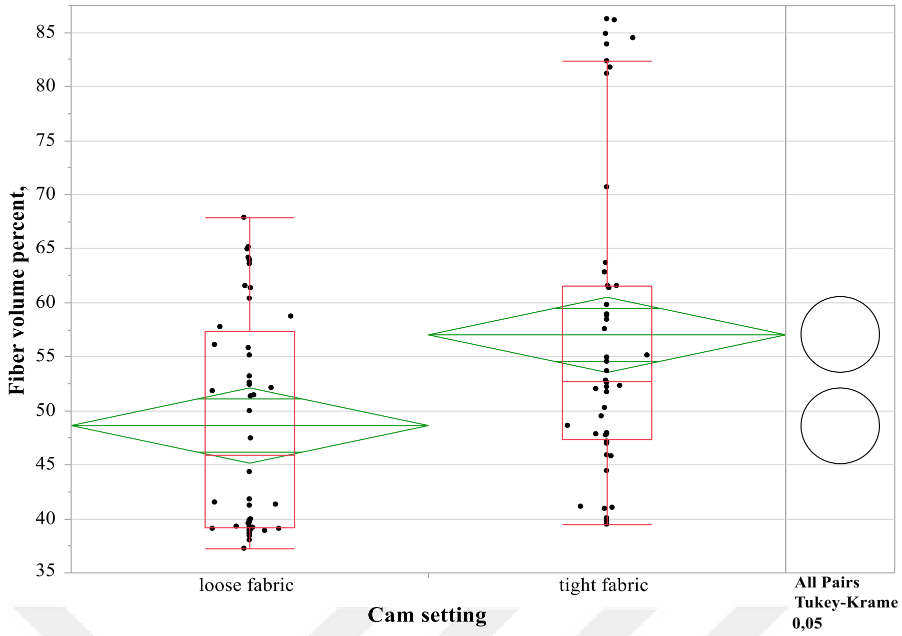



**Figure 5.3** Effects of cam setting on thickness

**Table 5.1** The effects of cam setting on fabric thickness, areal density, and fiber volume percent

| Property | Cam setting | Mean | SD | LL | UL | p-value |
|---|---|---|---|---|---|---|
| t, mm | loose fabric | 0,72 | 0,30 | 0,68 | 0,75 | <0,0001 |
| | tight fabric | 0,83 | 0,29 | 0,80 | 0,86 | |
| AD, g/m$^2$ | loose fabric | 865,90 | 522,10 | 714,30 | 1017,50 | 0,0065 |
| | tight fabric | 1121,20 | 464,11 | 986,44 | 1256,00 | |
| FVP, % | loose fabric | 48,64 | 10,01 | 45,73 | 51,54 | 0,0005 |
| | tight fabric | 57,03 | 13,97 | 52,97 | 61,09 | |

**Note: t:** thickness, **AD:** areal density, **FVP:** fiber volume percent. **SD:** standard deviation, **LL:** lower limit, **UL:** upper limit. Limits are based on 95% confidence level. Significance level, α, was determined as 0,05.p-values were based on one-sided hypothesis testing. p-values less than 0,05 were colored in red and show statistical significance.

Course and wale densities of tight fabrics were higher than loose fabrics because of tight fabrics had small loops (Figure 5.4). Therefore in tight fabrics more amounts of courses and wales were located to unit area. Loops of loose fabrics spread over a wide area that caused lower courses and wales per unit area. Cam setting caused statistically significant changes in course and wale densities of the fabrics (Table 5.2).

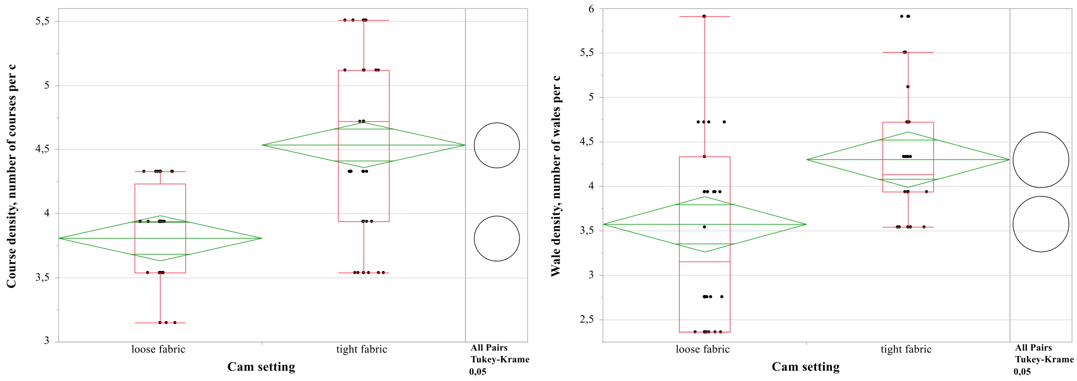



**Figure 5.4** The effect of cam setting on course- (left), wale-density (right)

Stitch density indicated similarity with figures of course and wale densities, because of it was multiplication of course and wale density. Stitch density of tight fabrics was higher than that of loose fabrics (Figure 5.5). Small loops of tight fabrics increased the number of stitches per unit area. Stitch density was reduced in loose fabrics due to slack, porous structure.

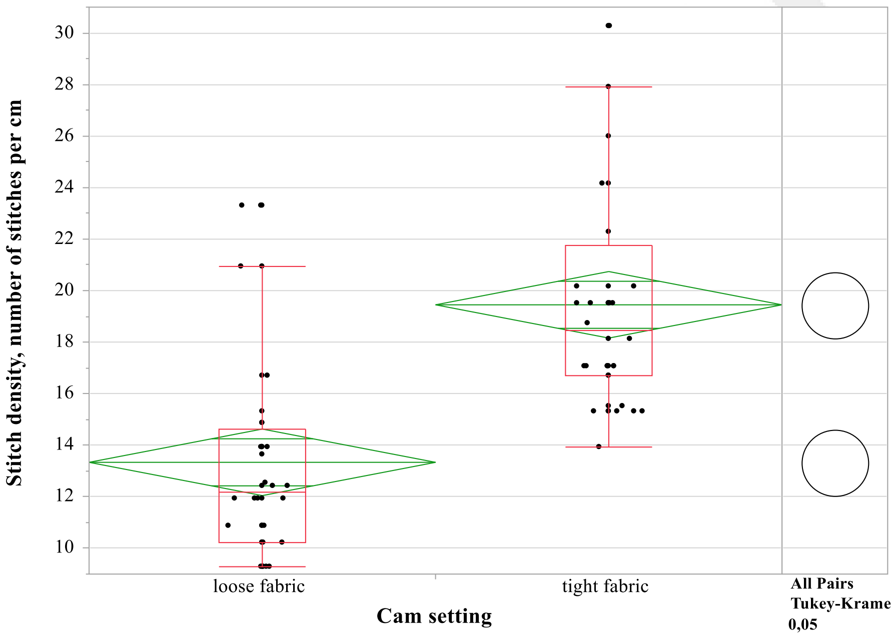



**Figure 5.5** The effect of cam setting on stitch-density

**Table 5.2** The effects of cam setting on course-, wale-, and stitch-density

| Physical property | Cam setting | Mean | SD | LL | UL | p-value |
|---|---|---|---|---|---|---|
| Course density | loose fabric | 3,81 | 0,40 | 3,68 | 3,94 | <0,0001 |
| | tight fabric | 4,54 | 0,68 | 4,32 | 4,75 | |
| Wale density | loose fabric | 3,57 | 1,21 | 3,19 | 3,96 | 0,0008 |
| | tight fabric | 4,30 | 0,70 | 4,08 | 4,53 | |
| Stitch density | loose fabric | 13,34 | 4,02 | 12,05 | 14,62 | <0,0001 |
| | tight fabric | 19,45 | 4,19 | 18,11 | 20,79 | |

**Note: course density:** number of courses per cm, **wale density:** number of wales per cm, **stitch density:** number of stitches per $cm^2$.

Loop lengths of loose fabrics were higher than tight fabrics as expected (Figure 5.6). Slack structure of fabrics increased yarn consumption for loops that raised lfa (loop fed array) value. Compact structure of tight fabrics created loops with shorter lengths. Cam settings exhibited statistically significant effect on loop length (Table 5.3).

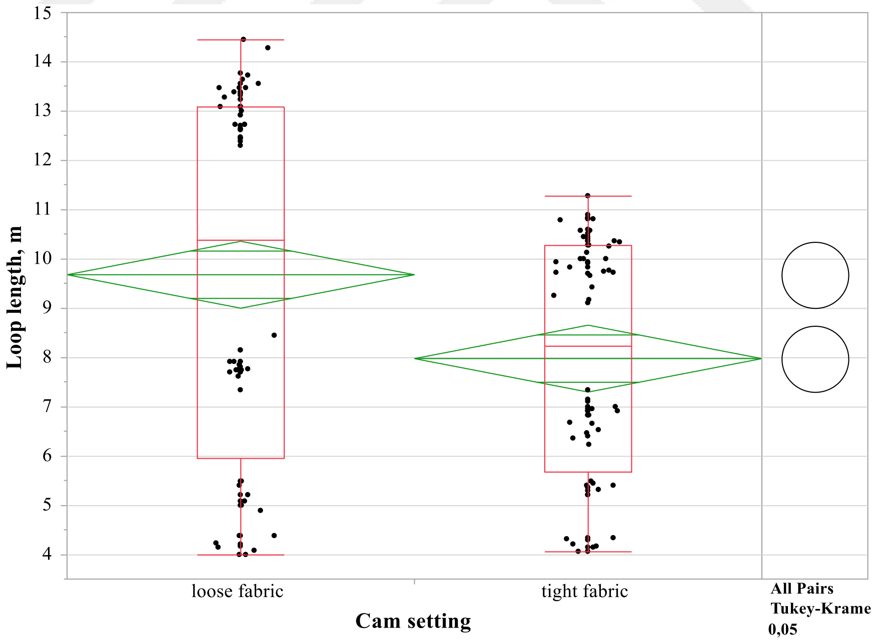



**Figure 5.6** The effect of cam setting on loop length

A negative relationship was detected between loop length and stitch density. In tight fabrics, stitch density was high and loop length was short that increased sd/l ratio.

Increasing this ratio raised tightness of fabric. Tightness and sd/l ratio has directly proportional relationship. Due to their longer loop lengths; loose fabrics exhibited lower sd/l ratio than tight fabrics (Figure 5.7).

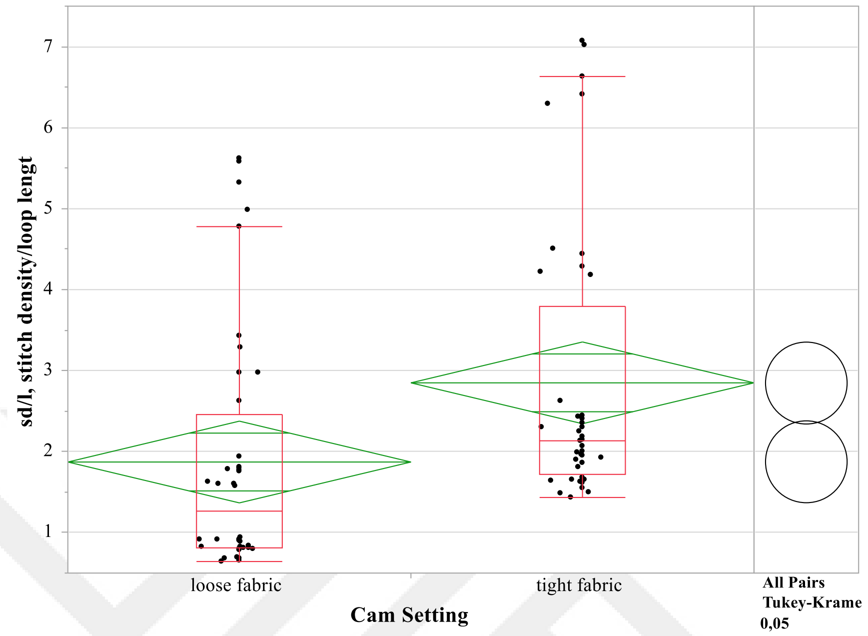



**Figure 5.7** The effect of cam setting on "stitch density/loop length" ratio

**Table 5.3** The effects of cam setting on loop length, and "stitch density/loop length" ratio

| Property | Cam setting | Mean | SD | LL | UL | p-value |
|---|---|---|---|---|---|---|
| l, mm | loose fabric | 9,68 | 3,65 | 8,87 | 10,49 | 0,0003 |
| | tight fabric | 7,98 | 2,37 | 7,45 | 8,50 | |
| "sd/l" ratio | loose fabric | 1,87 | 1,51 | 1,39 | 2,35 | 0,0039 |
| | tight fabric | 2,85 | 1,69 | 2,31 | 3,39 | |

**Note: l:** loop length in mm, **sd:** stitch density, number of stitches per cm2.

The effect of cam settings on air permeability was observed as statistically significant level (Table 5.4). Pores between loops were wide due to slack structure of loose fabrics. Inherently air has passed easily through the fabrics which had low fabric density and air permeability of the fabrics increased. Air permeability of tight fabrics was lower than that of loose fabric (Figure 5.8). As they are more compact, the intermeshing of yarns reduces air travel. Inter looping of yarns decreased permeability to air because tight fabrics had more compact structures.

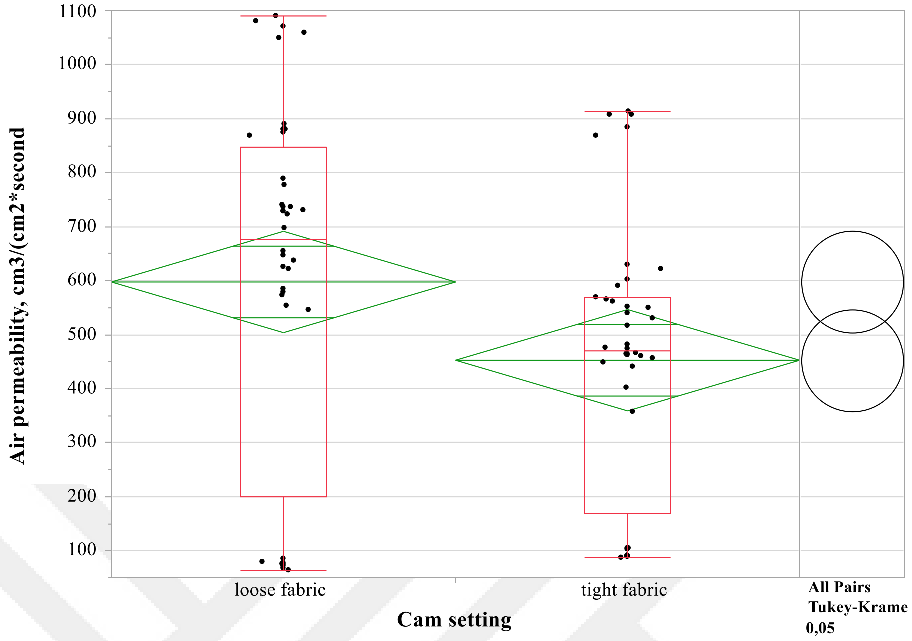



**Figure 5.8** The effects of cam setting on air permeability

Within the context of this study; it was observed that thicker fabrics were more difficult to explode in bursting strength test. Firm structure of tight fabrics increased the bursting strength by raising thickness of fabrics. In loose fabrics, loops tended to spread over a wide area, so they were thinner and could burst more easily. Therefore they had low bursting strength (Figure 5.9). Difference between bursting strengths of tight and loose fabrics reached statistically significant level as indicated in Table 5.4.

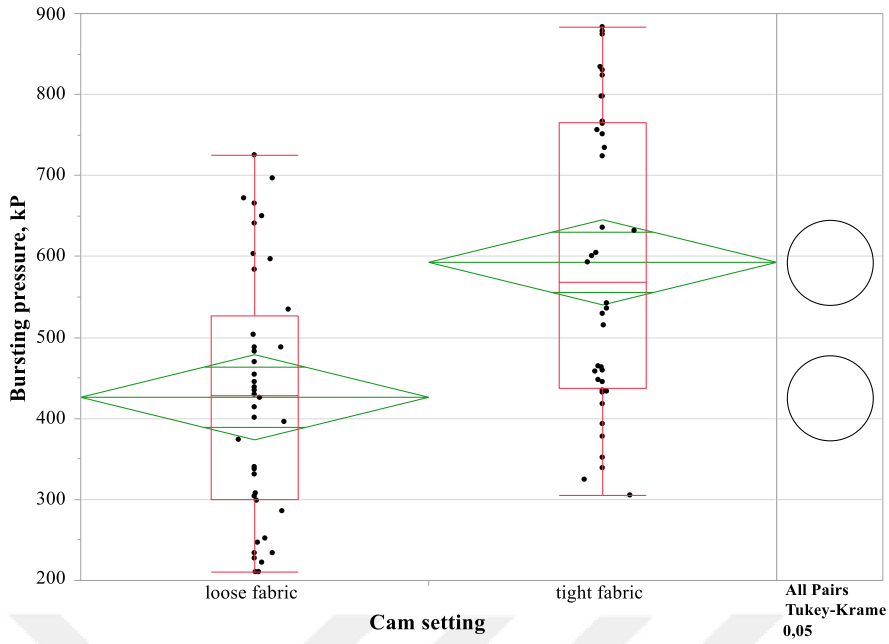



**Figure 5.9** The effects of cam setting on bursting strength

Bursting distension is the value that indicates how high the dome is during measurement of bursting strength. Tight fabrics expanded less during dome rising because of their tendency to become nested structure that lowered their bursting distension (Figure 5.10).Loose fabrics stretched more because of easy surface spread.

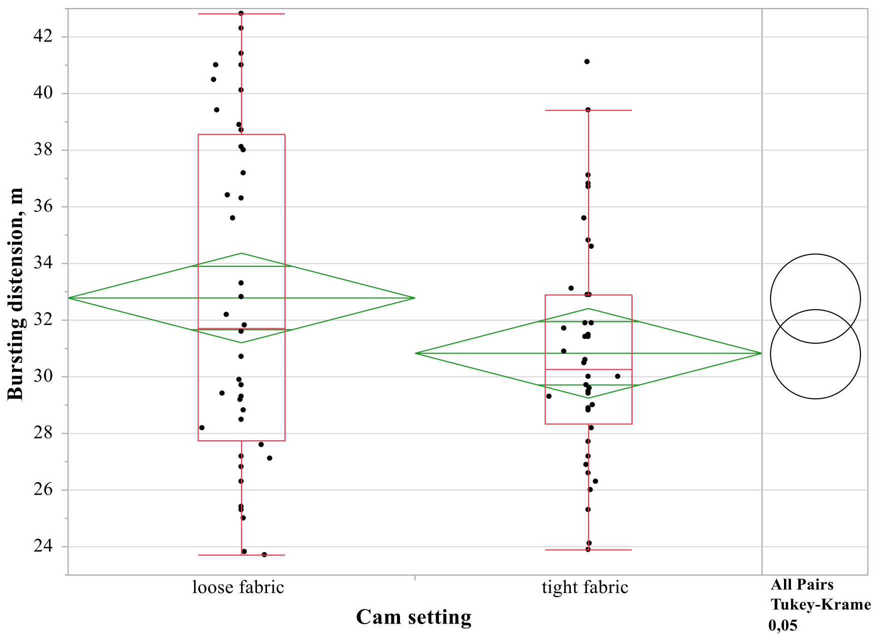



**Figure 5.10** The effects of cam setting on bursting distension

**Table 5.4** The effects of cam setting on air permeability, bursting strength and bursting distension

| **Property** | **Cam setting** | **Mean** | **SD** | **LL** | **UL** | **p-value** |
|---|---|---|---|---|---|---|
| Air permeability | loose fabric | 597,59 | 338,36 | 489,38 | 705,81 | 0,0165 |
| | tight fabric | 452,68 | 251,54 | 372,24 | 533,13 | |
| Bursting strength | loose fabric | 426,19 | 151,70 | 377,67 | 474,70 | <0,0001 |
| | tight fabric | 592,80 | 181,07 | 534,89 | 650,71 | |
| Bursting distension | loose fabric | 32,78 | 5,90 | 30,90 | 34.67 | 0,0431 |
| | tight fabric | 30,83 | 3,96 | 29,56 | 32,10 | |

**Note: air permeability**:$cm^3/(cm^2 \times s)$,**bursting strength**: kPa, **bursting distension**: mm.p-values are based on one-sided hypothesis testing.

### 5.2 The Effect of Number of Yarn Ply

In graph of number of yarn ply versus thickness, fabrics which were made by 3 plies of yarns were thicker than fabrics which were made by 2 plies of yarns (Figure 5.11). Increasing numbers of yarn plies made fabrics coarser and fluffier as expected. Therefore 3 plies of yarns raised the volume and thickness of fabrics. Thickness differences of fabrics which were produced by 2 and 3 plies of yarns were statistically significant (Table 5.5).

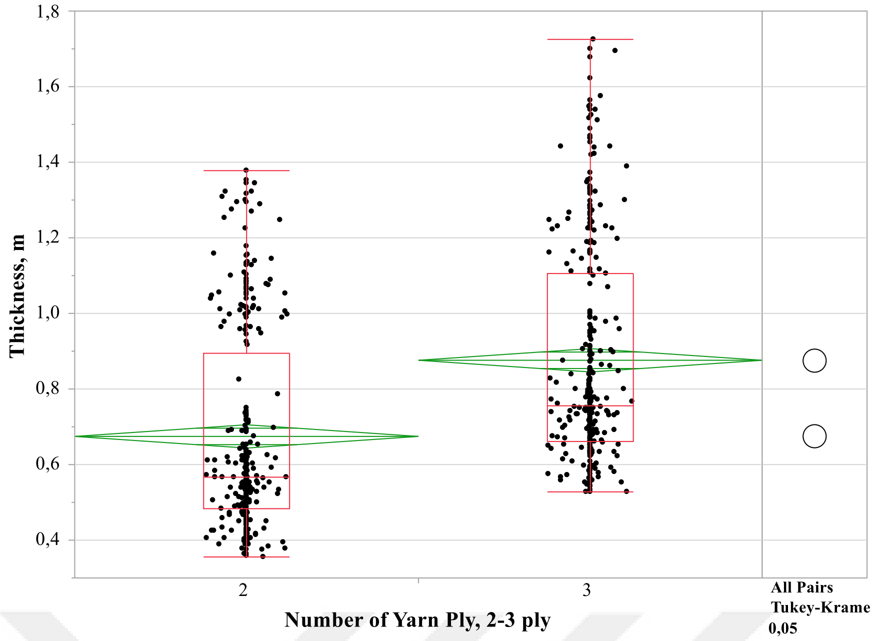



**Figure 5.11** Effects of number of yarn ply on fabric thickness

The fabrics from 3-ply yarns were thicker than those from 2 ply yarns that increased areal density of fabrics from 3-ply yarns (Figure 5.12). Weight of 3-ply yarns had more than weight of 2-ply yarns per unit area. While weight increased, areal density raised.

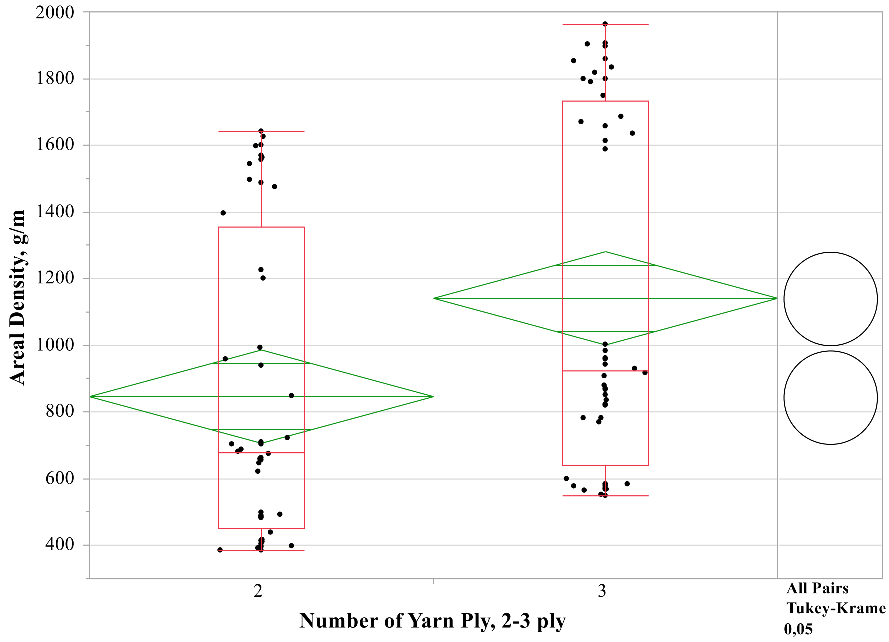



**Figure 5.12** Effects of number of yarn ply on areal density

According to fiber volume fraction results, there was not statistically difference between fabrics which were produced by 2 and 3 plies of yarns (Figure 5.13). For production of technical textile material where fiber volume fraction is critical, usage of 2 or 3 plies of yarns have not created a difference theoretically. 3 plies of yarns could be preferred when more compact fabrics are required.

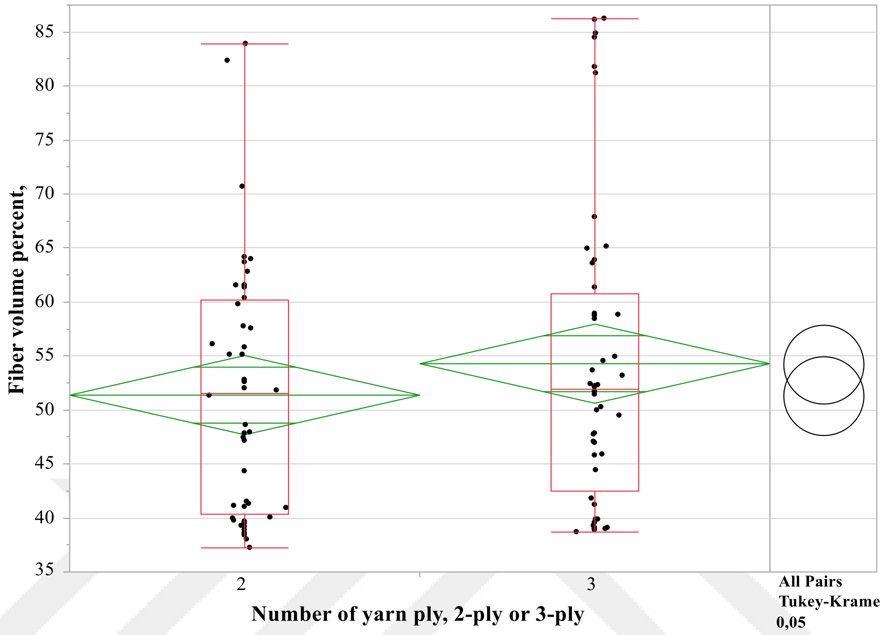



**Figure 5.13** Effects of number of yarn ply on fiber volume percent

**Table 5.5** The effects of number of yarn ply on fabric thickness, areal density, and fiber volume percent

| Property | # of yarn ply | Mean | SD | LL | UL | p-value |
|---|---|---|---|---|---|---|
| t, mm | 2-ply | 0,67 | 0,27 | 0,64 | 0,70 | <0,0001 |
| | 3-ply | 0,88 | 0,29 | 0,84 | 0,91 | |
| AD, $g/m^2$ | 2-ply | 846,14 | 454,76 | 714,09 | 978,20 | 0,0020 |
| | 3-ply | 1140,96 | 519,69 | 990,06 | 1291,90 | |
| FVP, % | 2-ply | 51,37 | 11,46 | 48,05 | 54,70 | 0,2670 |
| | 3-ply | 54,29 | 13,99 | 50,23 | 58,35 | |

Results of fabrics which were produced by 2 and 3 plies of yarns indicated that course density was affected statistically from number of yarn plies when wale density was not affected (Figure 5.14). Because of distances between needles are constant in flat knitting machine, number of yarn plies have not affected wale density at statistically significant level. Similar wale numbers were obtained in the fabrics which were produced by 2 and 3 plies of yarns. There was a considerable difference between course numbers of the fabrics. However the fabrics which were produced by 3 plies of yarns were more fluffy and compact.

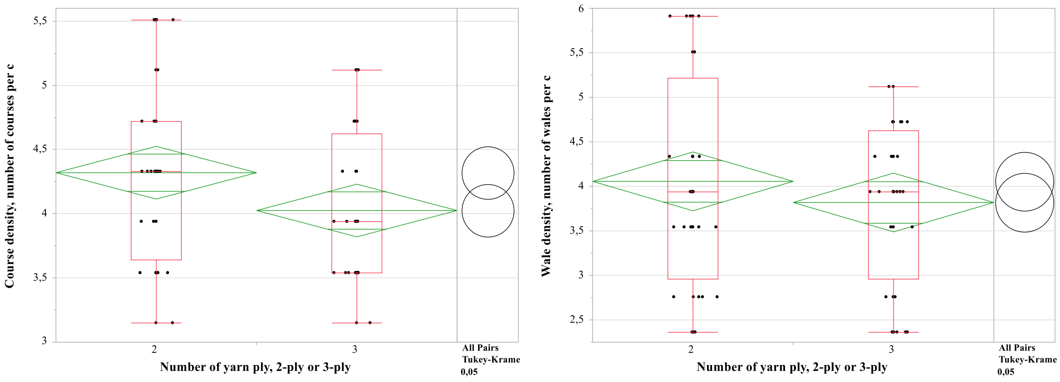



**Figure 5.14** The effects of number of yarn ply on course-, wale-density

Numbers of yarn plies had statistically significant effect on loop (stitch) density (Table 5.6). When the loops thickened, numbers of loops per unit area had decreased. So in the fabrics made from3-ply yarns; loop density had been decreased. Because of the fabrics from 2-ply yarn were thinner than those from 3-ply yarns; they had more loops per unit area. Figure 5.15 indicated that loop densities of the fabrics which made by 2 plies of yarns had rarer as 10-30 stitches/cm$^2$.

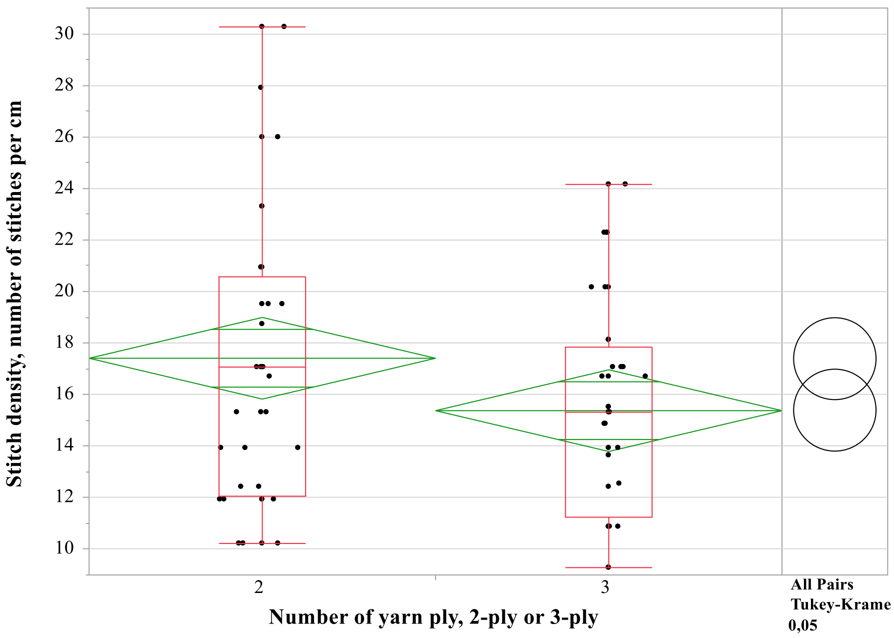



**Figure 5.15** The effects of number of yarn ply on stitch-density

**Table 5.6** The effects of number of yarn ply on course-, wale-, and stitch-density

| Property | # of yarn ply | Mean | SD | LL | UL | p-value |
|---|---|---|---|---|---|---|
| Course density | 2-ply | 4,32 | 0,69 | 4,10 | 4,54 | 0,0235 |
| | 3-ply | 4,02 | 0,61 | 3,83 | 4,22 | |
| Wale density | 2-ply | 4,06 | 1,21 | 3,67 | 4,44 | 0,1575 |
| | 3-ply | 3,82 | 0,86 | 3,54 | 4,09 | |
| Stitch density | 2-ply | 17,41 | 5,67 | 15,60 | 19,22 | 0,0375 |
| | 3-ply | 15,38 | 4,31 | 14,00 | 16,76 | |

Numbers of yarn plies had not created a statistically significant difference on loop length. Loop length of fabrics was not affected by changing numbers of yarn plies. If more compact fabrics were desired, 3 plies of yarns should be preferred in fabric production. If more loops have been desired per unit area, the fabrics which made by 2 plies of yarns should be produced; because amount of loops decreased when loop length increased (Figure 5.16).

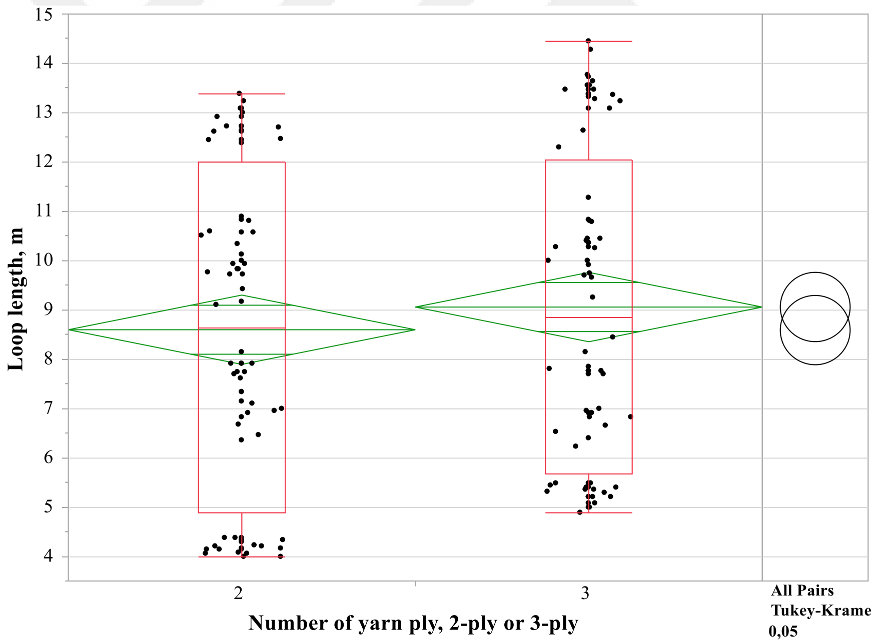



**Figure 5.16** The effects of number of yarn ply on loop length

Stitch density/loop length ratio was affected significantly from number of yarn plies (Table 5.7). Stitch density was higher in the fabrics which made by 2-plies yarns, results of loop length indicated that there was no statistically significant difference between 2- and 3-plies of yarns (Figure 5.17). Therefore sd/l ratio was higher in the fabrics which made by 2-plies yarns as expected.

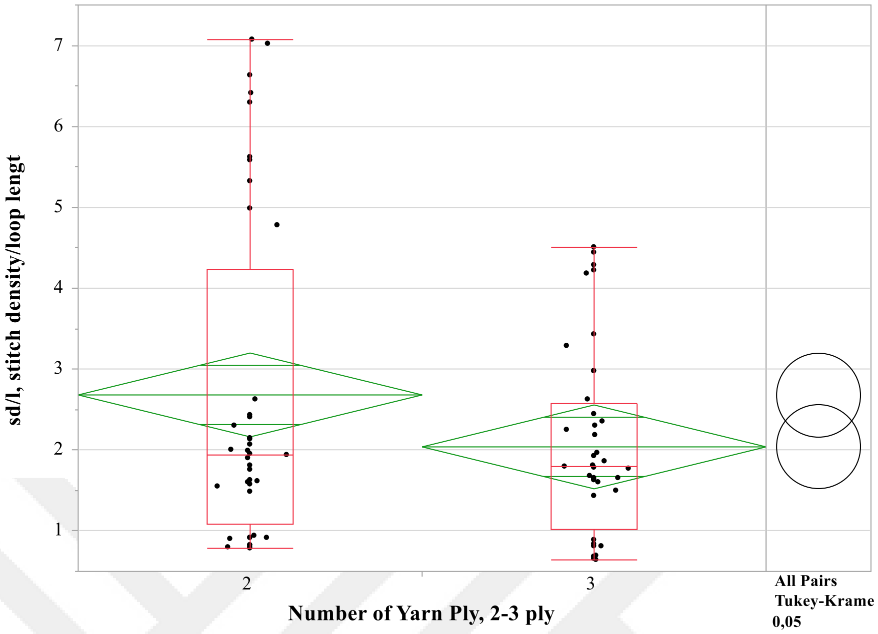



**Figure 5.17** The effects of number of yarn ply on “stitch density/loop length” ratio

**Table 5.7** The effects of number of yarn ply on loop length and “stitch density/loop length” ratio

| Property | # of yarn ply | Mean | S.D. | LL | UL | p-value |
|---|---|---|---|---|---|---|
| l, mm | 2-ply | 8,60 | 3,23 | 7,88 | 9,32 | 0,1813 |
| | 3-ply | 9,06 | 3,13 | 8,36 | 9,75 | |
| “sd/l” ratio | 2-ply | 2,68 | 2,03 | 2,03 | 3,33 | 0,0426 |
| | 3-ply | 2,04 | 1,14 | 1,67 | 2,40 | |

It was observed that number of yarn ply did not affect air permeability at statistically significant level. Despite of more air pass through the fabrics from 2-plies yarns than 3-plies ones; an important difference had not occurred (Figure 5.18). Although the fabrics which are produced by 3-plies yarns were thicker, they have not compromised with air permeability property. According to the use area in practice; it is a great advantage to set the thickness as desired while not losing in inhalation property.

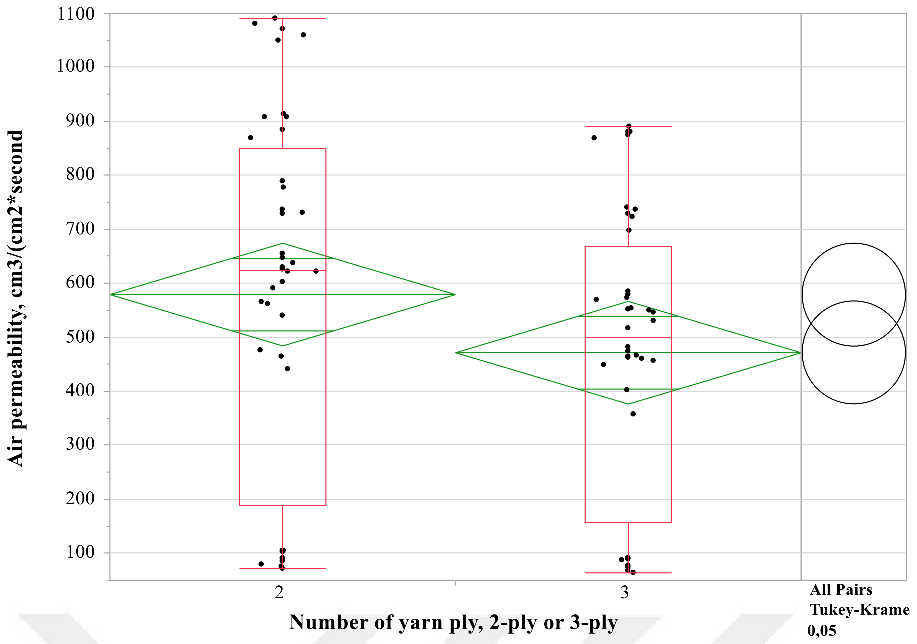



**Figure 5.18** The effects of number of yarn ply on air permeability

The fabrics from 3-ply yarns had twice higher bursting strengths than the fabrics from 2-plies yarns (Figure 5.19). Bursting strengths of the fabrics from by 2-plies yarns were between approximately 350-430 kPa, and in the fabrics from 3-plies yarns were between 560-670 kPa (Table 5.8). According to these results, numbers of yarns plies have affected bursting strength at statistically significant level. When using area of technical textile fabrics requires higher bursting strength, 3 plies of yarns should be preferred in production of the fabrics.

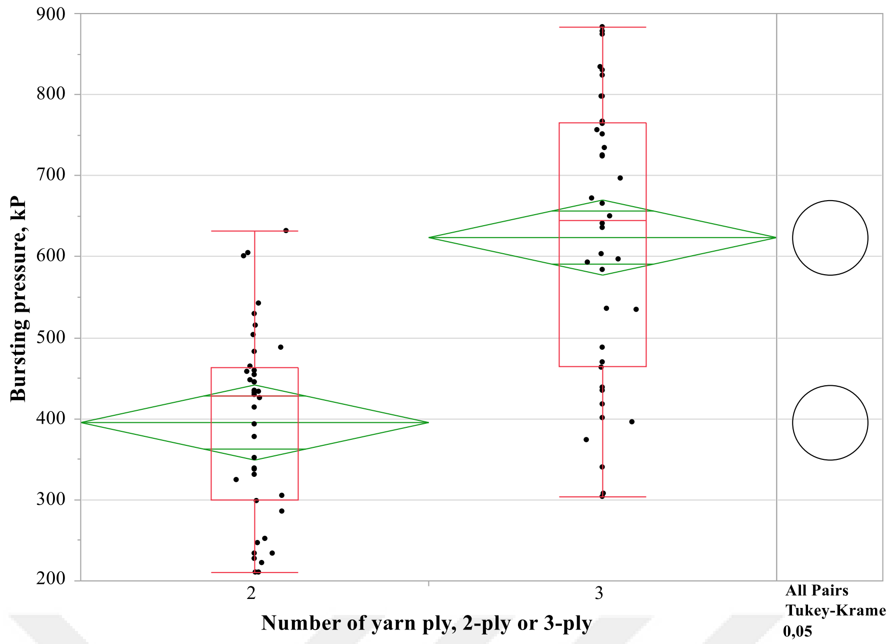



**Figure 5.19** The effects of number of yarn ply on bursting strength

Bursting distension is the parameter which was affected by number of yarn ply. Bursting distension of the fabrics which were produced by 2-plies yarns was higher than 3 plies of yarns was explained with their more flexible structures (Figure 5.20). 3 plies of yarns provided to locate nested loops in fabrics, was reduced flexibility of the fabrics; so bursting distension decreased. The fabrics which were produced by 2 plies yarns have more porous structure; have tended to stretch before bursting.

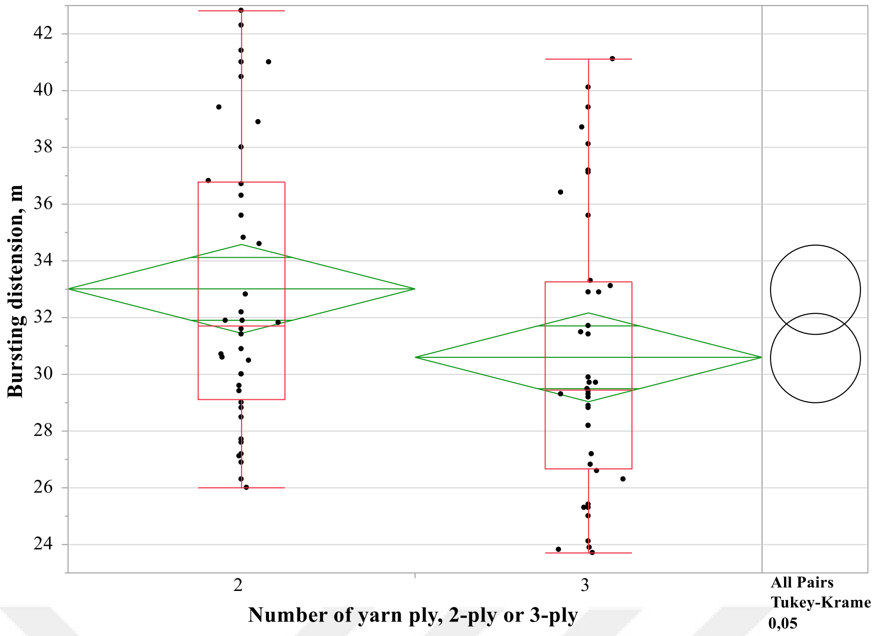



**Figure 5.20** The effects of number of yarn ply on bursting distension

**Table 5.8** The effects of number of yarn ply on air permeability, bursting strength and bursting distension

| Property | Cam setting | Mean | SD | LL | UL | p-value |
|---|---|---|---|---|---|---|
| Air permeability | 2-ply | 578,97 | 333,67 | 472,26 | 685,89 | 0,0576 |
| | 3-ply | 471,30 | 266,92 | 385,94 | 556,67 | |
| Bursting strength | 2-ply | 395,39 | 115,88 | 358,33 | 432,35 | <0,0001 |
| | 3-ply | 623,60 | 172,92 | 568,30 | 678,90 | |
| Bursting distension | 2-ply | 33,01 | 5,00 | 31,42 | 34,61 | 0,0165 |
| | 3-ply | 30,60 | 4,95 | 29,02 | 32,18 | |

### 5.3 The Effect of Knit Architecture

Pattern of fabric is an important parameter which affects performance of fabrics when the fabrics were exposed to mechanical effects. Shape and thickness of fabrics shows great difference between during knitting on machine and after removing from machine. The knitted fabrics which were produced by single needle bed knitting machine indicated curling after removing the machine. Especially the thinner fabrics as single jersey indicated much more curling. Values of thickness were observed single jersey fabrics had the lowest values with average of 0,57 mm, tuck stitch fabrics had the highest values with 1,21 mm. Accumulation of yarn plies inside the needle hook during tuck stitch formation produced extra tension in wale direction. The nested architecture of tuck stitches and the tension in wale direction caused to shorten highly the length of the fabric once it was removed from the machine. Therefore more compact and thicker fabric had been obtained. Statistically there was no difference between skip stitch and weft in-lay fabric (Table 5.9). Because of skip stitch fabrics which were formed by floats and in weft in-lay fabrics the yarns which were lied down straightly between loops; these two fabrics have similarities, the thicknesses of skip stitch fabrics and weft in-lay fabrics were comparable (Figure 5.21).

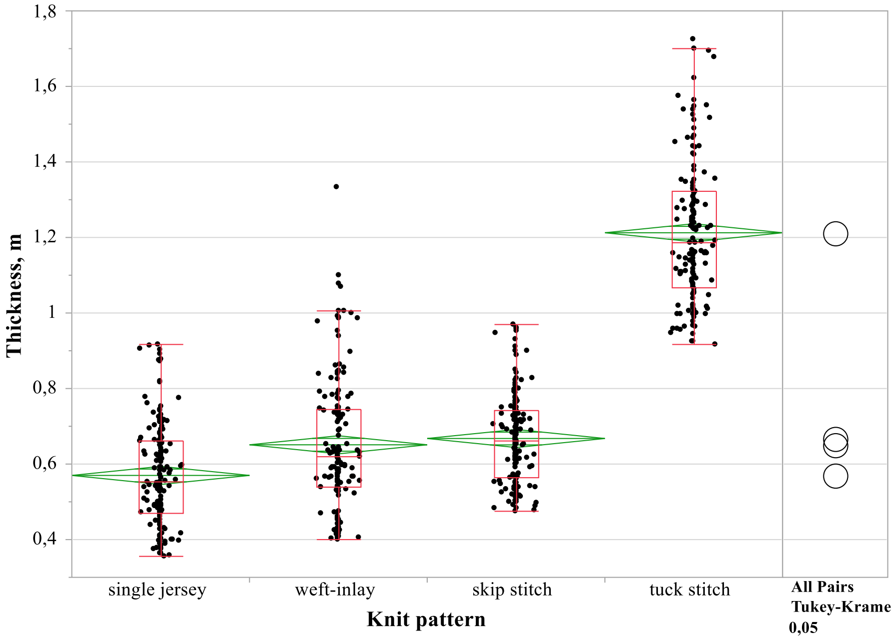



**Figure 5.21** The effects of knit pattern on thickness

Structure of tuck had much higher values than the other fabrics for areal density property like thickness. Tuck stitches which made the structure nested enhanced approximately twice number of loops per unit area compared to structures of other fabrics. Tuck stitch fabrics were followed by weft in-lay fabrics but results of weft in-lay indicated the most variations that stemmed from protrusion and irregular spread of weft inlay yarns over the fabric surface once the fabric was removed from the machine. Skip stitch and weft in-lay fabrics showed no statistically significant difference in view of thickness property. The two fabrics that had floats indicated similarities in loop density and areal density. The lowest values of areal densities were belonged to single jersey fabrics which were the thinnest structures. It is thought that single jersey structure was the main architecture of other knits, added tucks and floats increased yarn densities of other fabrics. Inherently single jersey fabric with the lowest areal density per unit area is an expected result (Figure 5.22).

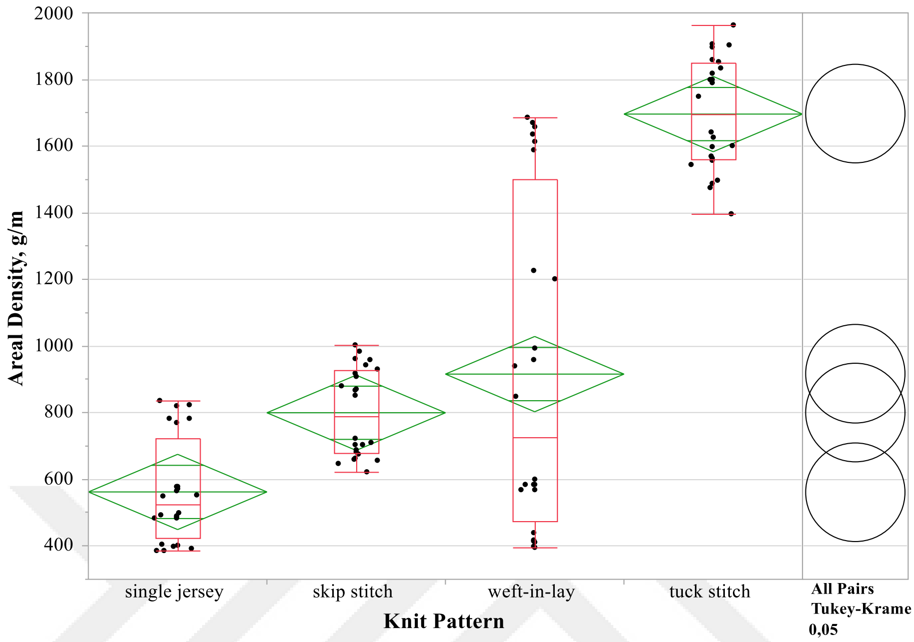



**Figure 5.22** The effects of knit pattern on air permeability

As we mentioned fiber volume percent is the value of percentage of fiber ratio when technical textile materials are molded with resin. Fabric pattern had an important role to determine the fiber ratio. Tuck stitches which were the thickest fabrics had the highest fiber ratio and single jersey which was the thinnest fabrics had the lowest fiber ratio. Fabrics with tuck stitches due to their compact and nested structure possessed the highest fiber volume percent (60,34 %) followed by weft-inlay (57,90 %), skip stitch (51,36%), and loop stitch (41,73%), respectively. Weft in-lay fabrics had protrusion and irregular spread that was observed as the highest variation in results of fiber volume percent (Figure 5.23).

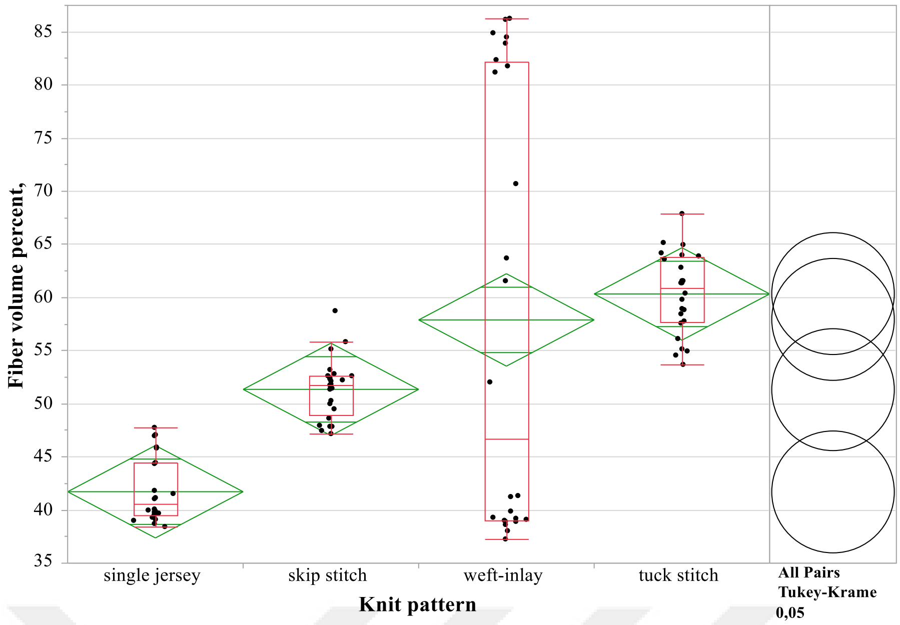



**Figure 5.23** The effects of knit pattern on fiber volume percent

**Table 5.9** The effects of knit pattern on thickness, areal density and fiber volume percent

| Property | Knit pattern | | | | mean | sd | LL | UL |
|---|---|---|---|---|---|---|---|---|
| Thickness, mm | tuck stitch | A | | | 1,21 | 0,18 | 1,18 | 1,24 |
| | skip stitch | | B | | 0,67 | 0,12 | 0,65 | 0,69 |
| | weft-inlay | | B | | 0,65 | 0,17 | 0,62 | 0,68 |
| | single jersey | | | C | 0,57 | 0,13 | 0,55 | 0,59 |
| Areal density, g/m$^2$ | tuck stitch | A | | | 1696,23 | 166,71 | 1625,80 | 1766,60 |
| | weft-inlay | | B | | 915,88 | 491,35 | 708,40 | 1123,40 |
| | skip stitch | | B | | 799,85 | 131,15 | 744,50 | 855,20 |
| | single jersey | | | C | 562,23 | 154,84 | 496,90 | 627,60 |
| Fiber volume percent, % | tuck stitch | A | | | 60,34 | 3,82 | 58,73 | 61,96 |
| | weft-inlay | A | B | | 57,90 | 20,71 | 49,15 | 66,64 |
| | skip stitch | | B | | 51,36 | 2,82 | 50,17 | 52,55 |
| | single jersey | | | C | 41,73 | 3,01 | 40,46 | 43,00 |

**Note:** Levels not connected by the same capital letter are significantly different. **sd:** standard deviation, **LL:** lower limit, **UL:** upper limit. Limits are based on 95% confidence level.

Knit pattern created a statistically significant effect on course and wale densities. Single jersey fabrics had the highest values of course density and tuck stitch fabrics had the highest values of wale density. The highest course density was exhibited by single jersey fabrics where the legs of loops intermeshed the most uniformly. Floats in skip stitch fabrics prevented the nesting of the courses after removing from knitting machine, so skip stitches had the lowest course density. There was no statistically significant difference between course densities of tuck stitch and weft in-lay fabrics (Table 5.10). As we mentioned shortening of tuck stitch fabrics after removing the machine was the most important factor that increased their wale density. Because of the tension in wale direction wales created nested structure, so they had the highest wale density. In wale density; tuck stitch fabrics were followed by skip stitch fabrics. Weft in-lay and single jersey fabrics had similar loop construction in main structure; difference between them was the yarns laid straightly between loops in weft in-lay pattern. Therefore weft in-lay and single jersey fabrics had no statistically significant difference for wale density (Figure 5.24).

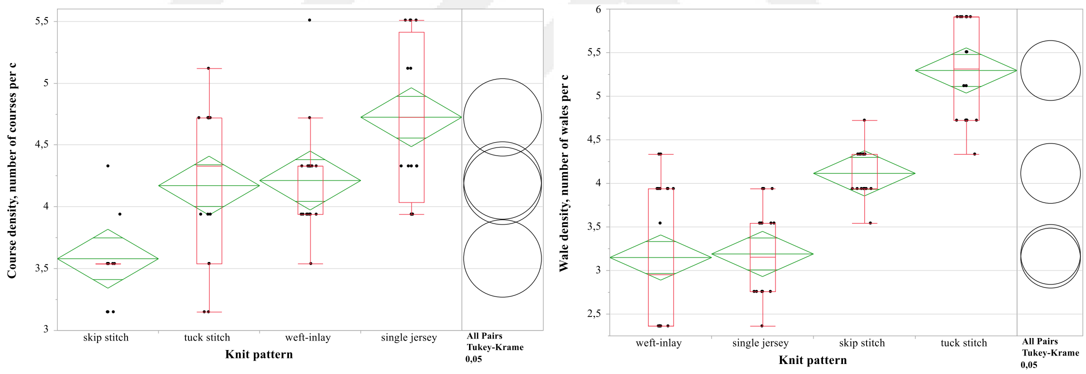



**Figure 5.24** The effects of knit pattern on course-, wale-density

Stitch density of tuck stitch fabrics had substantial difference than other patterns due to prominently different wale densities of tuck stitch fabrics. Tuck stitch pattern had the most loops per unit area because of the fabrics were more compact than other fabrics and tuck loops provided nested structure. Skip stitch, single jersey and weft in-lay patterns had no difference statistically for stitch densities (Figure 5.25).

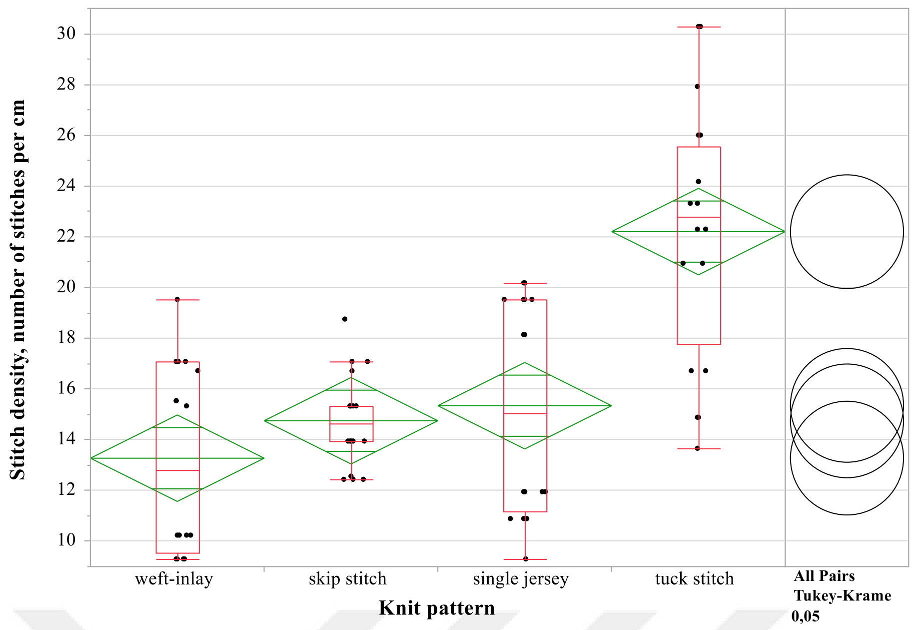



**Figure 5.25** The effects of knit pattern on stitch-density

**Table 5.10** The effects of knit pattern on course-, wale-, and stitch-density

| Property | Knit pattern | | | | mean | sd | LL | UL |
|---|---|---|---|---|---|---|---|---|
| Course density | single jersey | A | | | 4,72 | 0,64 | 4,43 | 5,02 |
| | weft-inlay | | B | | 4,21 | 0,40 | 4,02 | 4,40 |
| | tuck stitch | | B | | 4,17 | 0,69 | 3,85 | 4,50 |
| | skip stitch | | | C | 3,58 | 0,31 | 3,44 | 3,73 |
| Wale density | tuck stitch | A | | | 5,30 | 0,58 | 5,02 | 5,57 |
| | skip stitch | | B | | 4,12 | 0,27 | 3,99 | 4,24 |
| | single jersey | | | C | 3,19 | 0,51 | 2,95 | 3,43 |
| | weft-inlay | | | C | 3,15 | 0,83 | 2,76 | 3,54 |
| Stitch density | tuck stitch | A | | | 22,20 | 4,85 | 19,93 | 24,47 |
| | single jersey | | | B | 15,34 | 4,27 | 13,34 | 17,34 |
| | skip stitch | | | B | 14,75 | 1,74 | 13,93 | 15,56 |
| | weft-inlay | | | B | 13,27 | 3,72 | 11,54 | 15,01 |

No statistically significant difference was observed between the loop lengths of single jersey and weft in-lay fabrics because of their main patterns were similar except lying yarns in weft in-lay (Table 5.11). Weft in-lay patterns had the longest loop lengths, followed by single jersey, skip stitch and lastly tuck stitch respectively.

Floats in skip stitch fabrics kept constant loop lengths. Nested structure of loops in tuck stitch fabrics caused to shorten their loop lengths three times than single jersey fabrics (Figure 5.26).

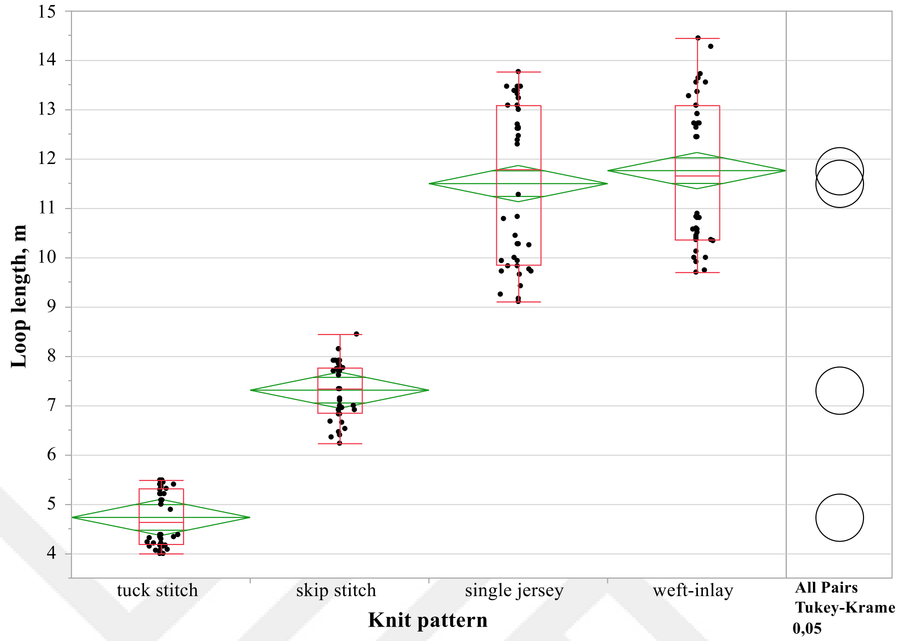



**Figure 5.26** The effects of knit pattern on loop length

Tuck stitch fabrics had the highest stitch densities and the shortest loop lengths. Therefore tuck stitch fabrics had the highest sd/l ratio. Because of sd/l ratio was directly proportional with tightness, the most compact structure was tuck stitch pattern. Sd/l ratio of patterns of skip stitch, single jersey and weft in-lay were similar to each other's. It is expected that no difference between sd/l ratios of single jersey and weft in-lay due to the fact that patterns of weft in-lay and single jersey fabrics were same except lying yarns in weft in-lay fabrics. Also the loose fabrics of skip stitch pattern and tight fabrics of these two patterns exhibited similarity. (Figure 5.27)

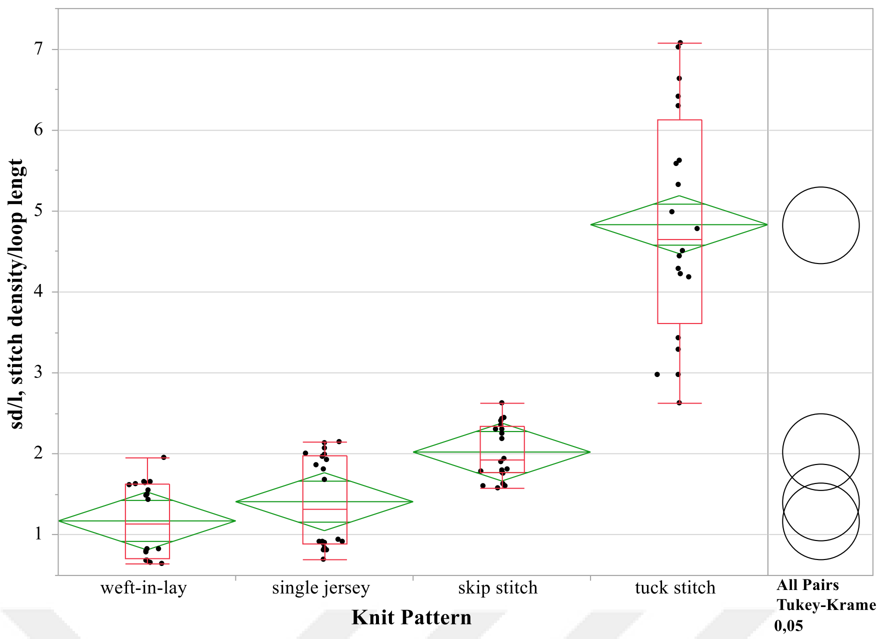



**Figure 5.27** The effects of knit pattern on “stitch density/loop length” ratio

**Table 5.11** The effects of knit pattern on loop length and “stitch density/loop length” ratio

| | **Knit pattern** | | | | **mean** | **sd** | **LL** | **UL** |
|---|---|---|---|---|---|---|---|---|
| l, mm | weft-inlay | A | | | 11,76 | 1,50 | 11,29 | 12,24 |
| | single jersey | A | | | 11,50 | 1,63 | 10,98 | 12,02 |
| | skip stitch | | B | | 7,31 | 0,58 | 7,12 | 7,50 |
| | tuck stitch | | | C | 4,73 | 0,56 | 4,55 | 4,91 |
| sd/l ratio | tuck stitch | A | | | 4,83 | 1,39 | 4,18 | 5,48 |
| | skip stitch | | B | | 2,02 | 0,34 | 1,86 | 2,18 |
| | single jersey | | B | C | 1,41 | 0,57 | 1,14 | 1,68 |
| | weft-inlay | | | C | 1,17 | 0,46 | 0,96 | 1,39 |

Single jersey had the highest permeability to air, followed by weft in-lay, skip stitch and lastly tuck stitch respectively. Therefore it could be concluded that single jersey fabrics had the most porous structure. Even single jersey and weft in-lay had basically the same pattern, lying weft yarns in course direction caused to affect negatively permeability to air. For this reason values of air permeability were between 517-1090 $cm^3/(cm^2*second)$ in single jersey fabrics and between 357-788 $cm^3/(cm^2*second)$ in weft in-lay fabrics. No statistically significant difference between air permeability of skip stitch and weft in-lay fabrics were observed (Table 5.12). Tuck stitch pattern had the lowest value of air permeability due to their compact structure as expected. Air permeability of tuck stitch fabrics was8 times lower than single jersey fabrics. Moreover cam setting and number of yarn ply did not affect air permeability property of tuck stitch which had the lowest values (Figure 5.28).

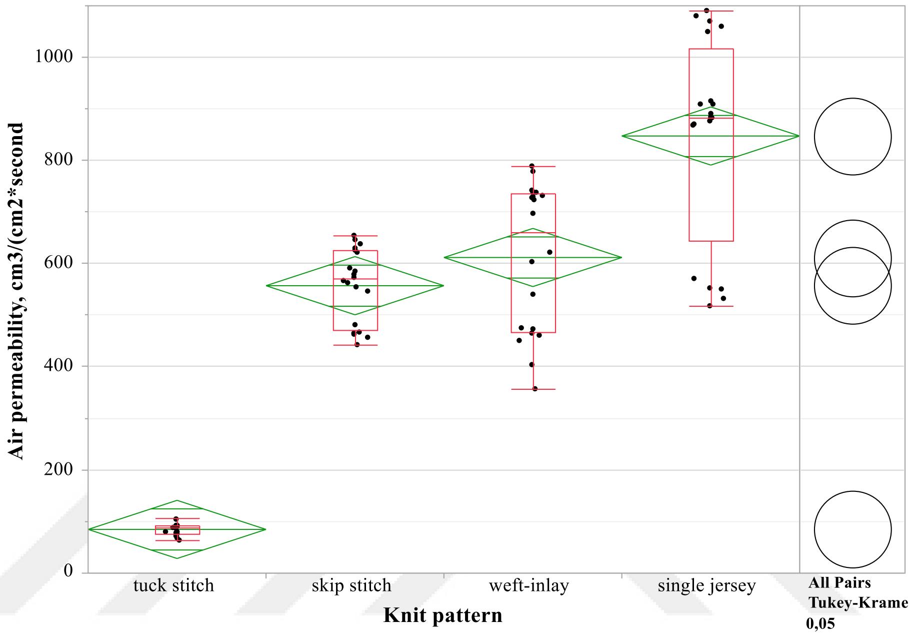



**Figure 5.28** The effects of knit pattern on air permeability

Tuck stitch fabrics had the highest values of bursting strength; there was no difference statistically between bursting strengths of skip stitch and weft in-lay fabrics (Table 5.12). Nested structure of tuck stitch patterns was the reason of higher bursting strengths. Elasticity of tuck stitch patterns which nested structure provided this property, caused to burst the fabrics in high pressure values. Straight yarns in structure of fabrics resisted to bursting force much more than other yarns which formed loops. Therefore the yarns which made floats in weft in-lay and skip stitch fabrics were the factors to burst late. Due to regular spread of loop in the case of single jersey fabrics; they could not withstand bursting force as other fabrics. Therefore, single jersey fabrics burst easily and their bursting strengths were lower other fabrics (Figure 5.29).

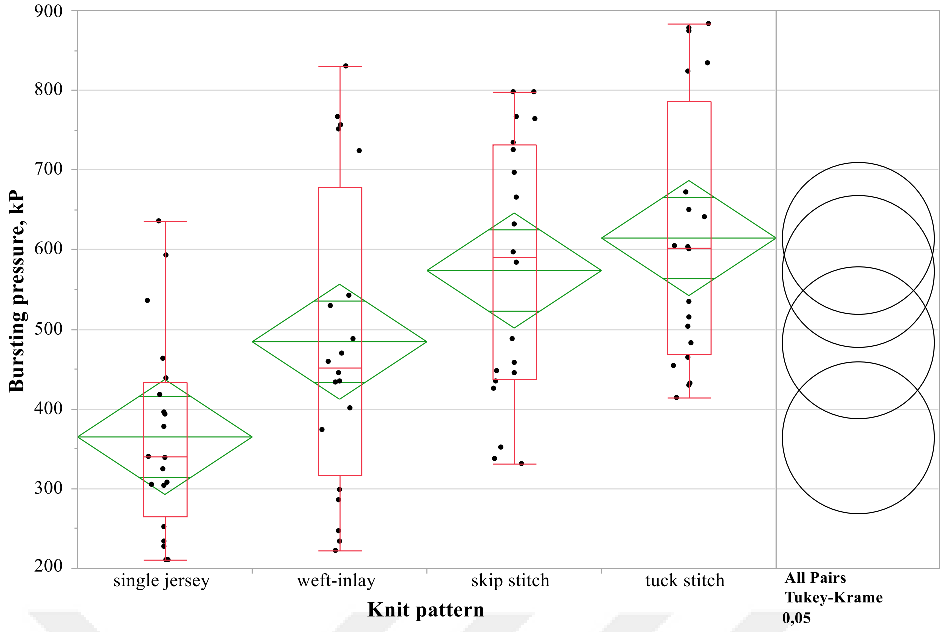



**Figure 5.29** The effects of knit pattern on bursting strength

Due to similar reasons as bursting strength was explained; elasticity of tuck stitch patterns provided higher bursting distension. While there was no statistically significant difference between bursting distensions of weft in-lay and tuck stitch fabrics, weft in-lay fabrics exhibited more irregular results. Single jersey pattern had lower values of bursting distension because of they were not tend to stretch as tuck stitch patterns. Floats of skip stitch patterns improved bursting strengths but prevented to stretch so distance of bursting distension stayed shorter than other fabrics (Figure 5.30).

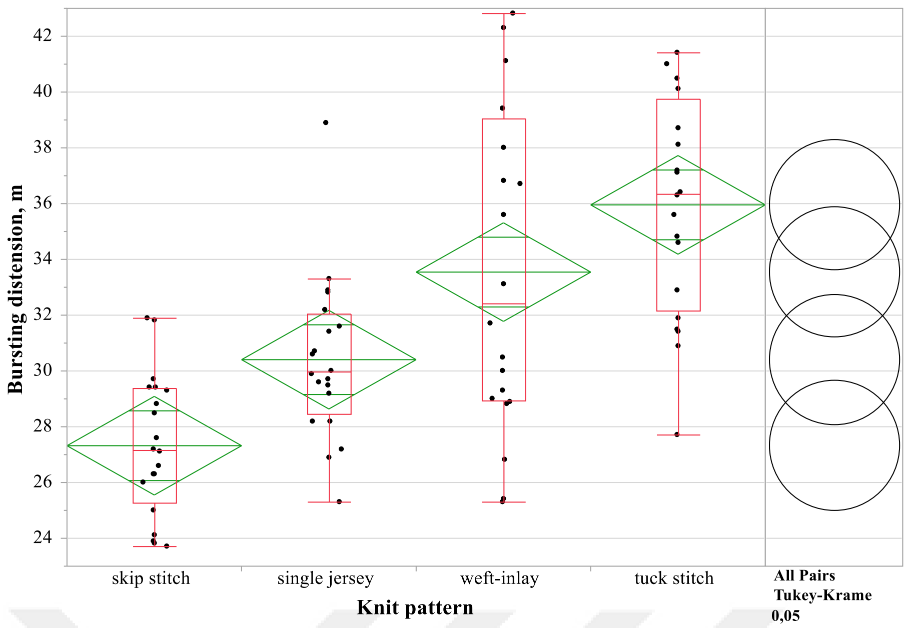



**Figure 5.30** The effects of knit pattern on bursting distension

**Table 5.12** The effects of number of yarn ply on air permeability, bursting strength, and bursting distension

| Property | Knit pattern | | | | mean | sd | LL | UL |
|---|---|---|---|---|---|---|---|---|
| Air permeability, $cm^3/(cm^2 \times s)$ | single jersey | A | | | 847,40 | 195,95 | 755,69 | 939,11 |
| | weft-inlay | | B | | 611,75 | 143,48 | 544,60 | 678,90 |
| | skip stitch | | B | | 557,05 | 71,07 | 523,79 | 590,31 |
| | tuck stitch | | | C | 84,35 | 11,69 | 78,88 | 89,82 |
| Bursting pressure, kPa | tuck stitch | A | | | 614,60 | 163,62 | 538,03 | 691,18 |
| | skip stitch | A | | | 573,86 | 163,54 | 497,33 | 650,40 |
| | weft-inlay | A | B | | 484,48 | 191,39 | 394,91 | 574,05 |
| | single jersey | | B | | 365,02 | 122,43 | 307,72 | 422,33 |
| Bursting distension, mm | tuck stitch | A | | | 35,96 | 3,95 | 34,10 | 37,81 |
| | weft-inlay | A | B | | 33,54 | 5,72 | 30,87 | 36,22 |
| | single jersey | | B | C | 30,40 | 2,91 | 29,04 | 31,76 |
| | skip stitch | | | C | 27,32 | 2,52 | 26,14 | 28,50 |

## 5.4 Multivariate Results

Correlation coefficient quantitatively indicates the strength of relationship between two numeric continuous variables, and it ranges from -1 and +1. While -1 is a sign of strong negative relationship, zero is lack of relationship, and +1 is positive strong relationship. Table 5.13exhibits symmetric correlation coefficients matrix for physical properties of the weft knitted fabrics. While strong positive relationships were observed in pairs of “areal density - thickness”, “wale density (wpc)-thickness”, and “wale density- areal density”; strong negative relationships were detected in pairs of “loop length – thickness”, “loop length – areal density” and “loop length – wale density”. No strong relationships were observed between course density (number of courses per cm, cpc) and other physical properties of fabric.

**Table 5.13** Symmetric correlation coefficients matrix for physical properties of the weft knitted fabrics

| | **t,** mm | **a,** g/m$^2$ | **cpc** | **wpc** | **l,** mm |
|---|---|---|---|---|---|
| **t,** mm | **1,00** | **0,94** | -0,06 | **0,80** | **-0,79** |
| **a,** g/m$^2$ | **0,94** | **1,00** | -0,10 | **0,80** | **-0,76** |
| **cpc** | -0,06 | -0,10 | **1,00** | -0,05 | 0,14 |
| **wpc** | **0,80** | **0,80** | -0,05 | **1,00** | **-0,94** |
| **l,** mm | **-0,79** | **-0,76** | 0,14 | **-0,94** | **1,00** |

**Note: t**: thickness, **a**: areal density, **cpc**: course density (number of courses per cm), **wpc**: wale density (number of wales per cm), **l**: loop length. Strong positive relationships are in dark blue color, strong negative relationships are in dark red color, and weak relationships are in black color.

As expected, strong and positive relationships between areal density and thickness were observed for overall, and individual knit patterns (Figure 5.31 and Table 5.14), which proved that areal density increase accompanied thickness increase, which in turn formed more compact and dense knit fabric structure. When thickness of fabrics increased, amount of yarns per unit area increased so areal density of the fabrics raised. Shortening the fabrics after removing from machine raised thickness of tuck stitch fabrics due to nested fabric structure. The relationships between thickness – areal density that was shown in Table 5.14 were strong in all patterns.

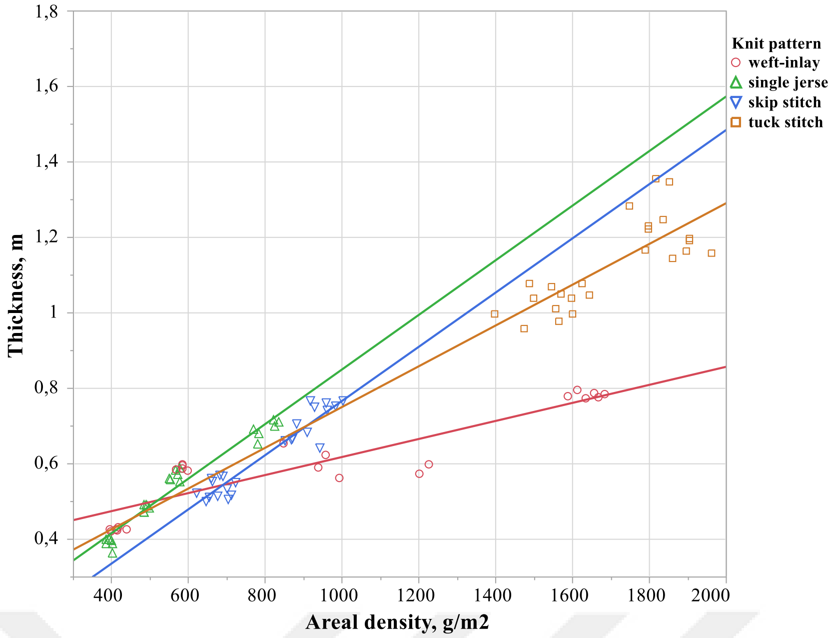



**Figure 5.31** Pairwise relationships in "thickness – areal density" (grouped by knit pattern)

**Table 5.14** Pairwise relationships in thickness - areal density (grouped by knit pattern)

| Name of linear fit | Knit pattern | $R^2$ | Linear equation | p-value |
|---|---|---|---|---|
| "areal density – thickness" | overall | 0,86 | t = 0,24 + 0,0004825*a | <0,0001 |
| | single jersey | 0,95 | t = 0,13 + 0,0007233*a | <0,0001 |
| | skip stitch | 0,90 | t = 0,049 + 0,000718*a | <0,0001 |
| | weft-inlay | 0,82 | t = 0,38 + 0,000239*a | <0,0001 |
| | tuck stitch | 0,61 | t = 0,21 + 0,0005401*a | <0,0001 |

**Note:** **t**: thickness in mm, **a**: areal density in g/m$^2$

Knit patterns of weft inlay, single jersey and skip stitches displayed a negative moderate strong relationship between loop length and thickness, while structures with tuck stitches displayed the positive strong relationship (Figure 5.32, Table 5.15). As we mentioned, fabrics with tuck stitches were knitted on the machine under tension, and on the table in relaxed state showed that these fabrics rotated clockwise more than 45 degree and shortened dramatically in both course and wale directions, once we removed them from the machine. Tuck stitches provided a nested structure with loops which placed regularly with each other. For this reason when loop lengths of tuck stitches rose, loops had filled gaps of tucks firmly so volume and thickness of the structure increased after removing from the machine. But other patterns did not show this shortening, when loop lengths increased, amount of loops per unit area decreased and the fabrics spread over a wider area than fabrics with tuck stitches. Therefore thicknesses of the fabrics decreased when loop lengths increased. (Figure 5.32)

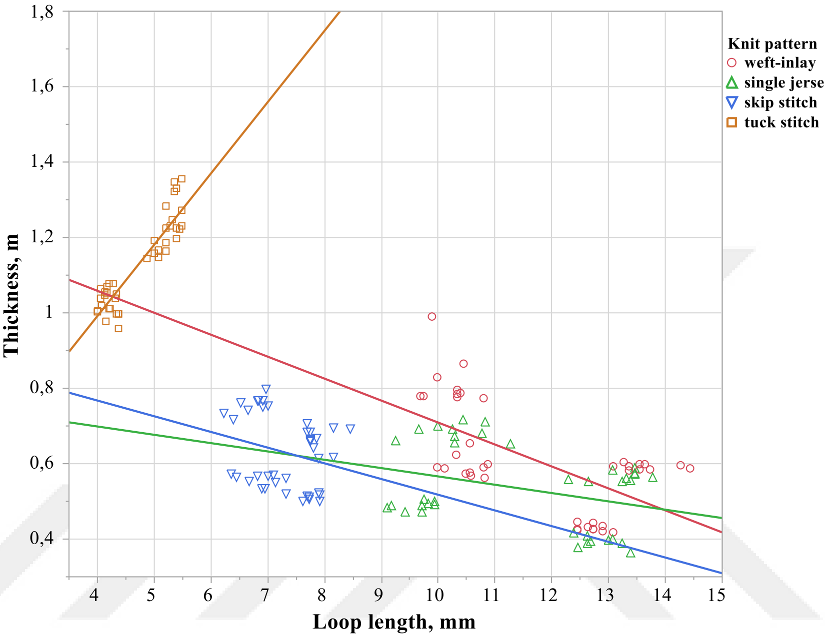



**Figure 5.32** Pairwise relationships in “thickness – loop length” (grouped by knit pattern)

**Table 5.15** Pairwise relationships in thickness - loop length (grouped by knit pattern)

| Name of linear fit | Knit pattern | $R^2$ | Linear equation | p-value |
|---|---|---|---|---|
| “loop length – thickness” | overall | 0,57 | t = 1,28 – 0,06*l | <0,0001 |
| | tuck stitch | 0,83 | t = 0,23 + 0,19*l | <0,0001 |
| | weft-inlay | 0,37 | t = 1,29 - 0,06*l | <0,0001 |
| | single jersey | 0,11 | t = 0,79 - 0,02*l | 0,0375 |
| | skip stitch | 0,06 | t = 0,93 - 0,04*l | 0,1143 |

**Note: t**: thickness in mm, **l**: loop length in mm

Fabrics with longer loop lengths exhibited higher air permeability due to their more porous structures. Determination coefficients ($R^2$) of the data grouped by 2-, and 3-

ply yarn appeared close to each other, which was the case in data grouped by cam setting. Values of $R^2$ showed that increase in loop length resulted in similar increase rate patterns for 2- and 3- ply yarn fabrics. Air permeability of fabrics from 2-ply yarns which had more porous structure was higher than fabrics from 3-ply yarns. 3-ply yarns thickened loops in the structure that decreased air permeability as expected. As we mentioned air permeability of loose fabrics was higher than tight fabrics due to slack structure of loose fabrics. Thus, modeling the relationship between air permeability and loop length provided more accurate data grouped by number of yarn ply (Figure 5.33).

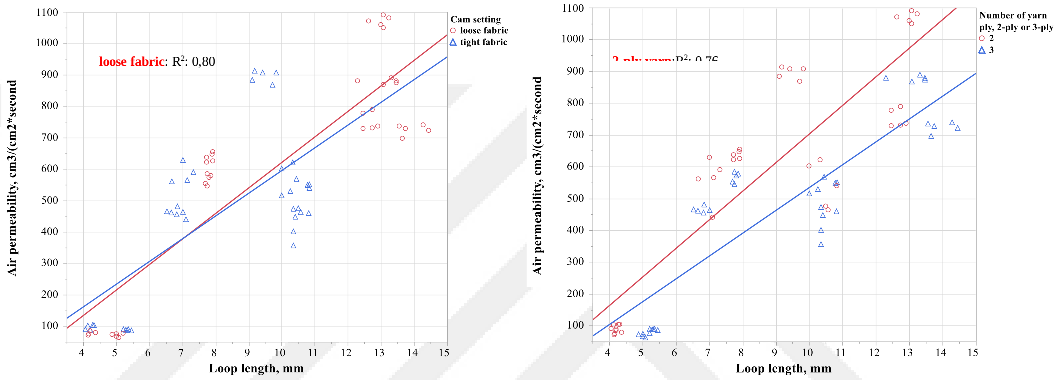



**Figure 5.33** Pairwise relationships in “air permeability – loop length” grouped by cam setting (left) and grouped by number of yarn ply (right)

Multivariate analysis revealed the strongest negative pair wise relationship in “loop length - bursting strength” (Figure 5.34). Fabrics with higher fiber content due to their tight structure exhibited higher bursting strength. Fabrics from longer loops due to their porous architecture demonstrated lower bursting strength. Relationship between bursting strength and loop length of fabrics was affected from number of yarn plies more prominently than cam setting effects. Bursting strength of fabrics with 3-ply yarns was higher than fabrics with 2-ply yarns as expected. 3-ply yarns thickened the structure so the yarns could withstand bursting force more than 2-ply yarns. But values of $R^2$ of them were similar as air permeability property.

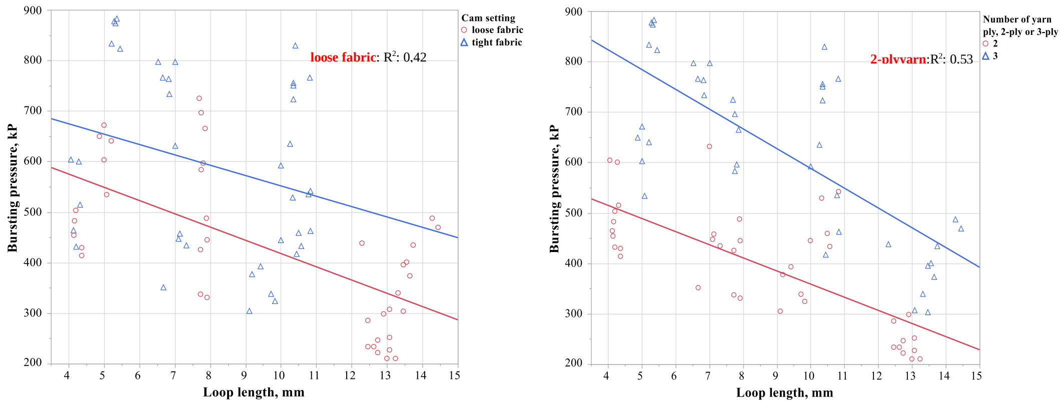



**Figure 5.34** Pairwise relationships in “bursting strength – loop length” grouped by cam setting (left) and grouped by number of yarn ply (right)

While overall relationship between air permeability and bursting strength was negative and moderately strong ($R^2$: 0,40), structures with tuck stitches exhibited positive weak relationship between air permeability and bursting strength (Figure 5.35, Table 5.16). Due to dominancy of knit pattern over other input variables (cam setting and number of yarn ply) for structures with tuck stitches, air permeability of structures with tuck stitches varied within a very small range, while bursting strength was affected by other input variables. Knit patterns except those included tuck stitches exhibited negative and strong relationships between air permeability and bursting strength.

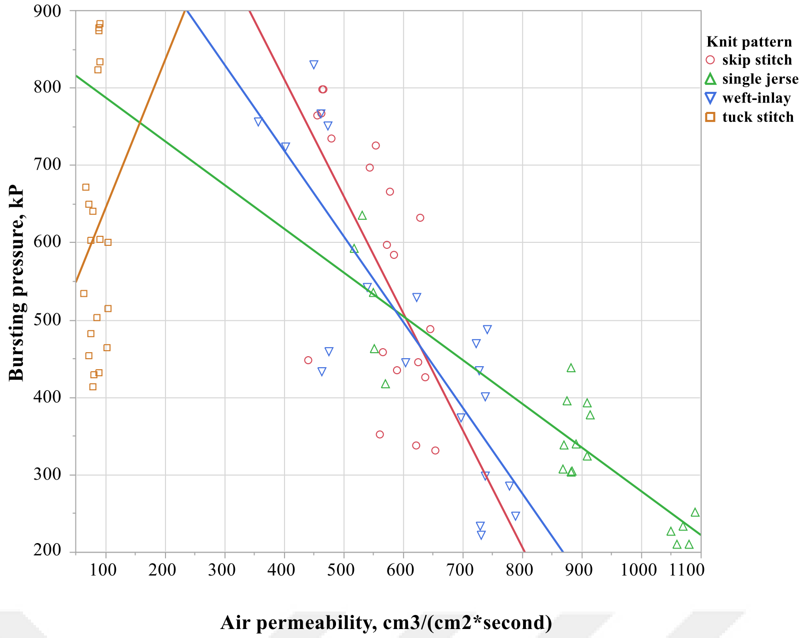



**Figure 5.35** Pairwise relationships in “bursting strength – air permeability” (grouped by knit pattern)

**Table 5.16** Pairwise relationships in bursting strength - air permeability (grouped by knit pattern)

| Knit pattern | $R^2$ | Linear equation | p-value |
|---|---|---|---|
| overall | 0,40 | b = 712,80 – 0,39*a | <0,0001 |
| single jersey | 0,82 | b = 844,38 – 0,57*a | <0,0001 |
| weft-inlay | 0,69 | b = 1162,56 – 1,11*a | <0,0001 |
| skip stitch | 0,43 | b = 1416,84 – 1,51*a | 0,0016 |
| tuck stitch | 0,02 | b = 453,00 + 1,92*a | 0,56 |

**Note: b:** bursting strength in kPa, **a:** air permeability in $cm^3/(cm^2 \times s)$

Fabrics those exhibited higher permeability to air showed less resistance to bursting pressure with a determination coefficient ($R^2$) 0,40 (Figure 5.36). Due to their dense structure, fabrics knitted by tight cam setting from 3-ply yarn showed higher resistance to air permeability and bursting strength. On the other hand, using loose cam setting and 2-ply yarn created a relaxed knit structure, that demonstrated higher permeation to air, and less resistance to bursting pressure.

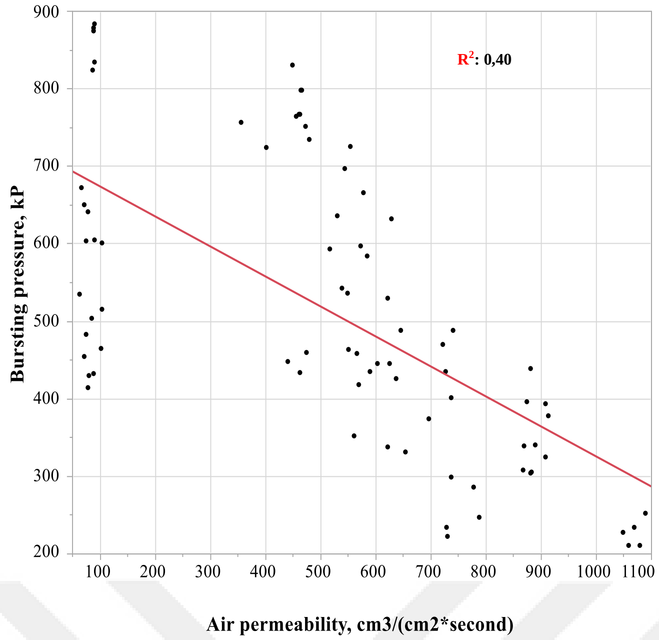



**Figure 5.36** Pairwise relationships in bursting strength – air permeability

## 5.5 Yarn Strength Results

Yarns unraveled from tightly knitted fabrics exhibited slightly higher loop strength than yarns from loosely knitted fabrics; however this difference did not reach statistically significant level (at $\alpha = 0{,}05$ significance level) (Figure 5.37, Table 5.17). Yarns in tight fabrics have shorter loop length with smaller size and greater internal tension than yarns in loose fabrics. Short loop length and higher internal tension enhanced uniform distribution of fibers in the yarn cross section that slightly improved loop strength of unraveled yarn. Virgin yarns displayed lower loop strength than unraveled yarns that again was attributed the uniform spread and distribution of fibers over yarn cross section in case of unraveled yarns from knitted fabrics (Figure 5.37, Table 5.17).

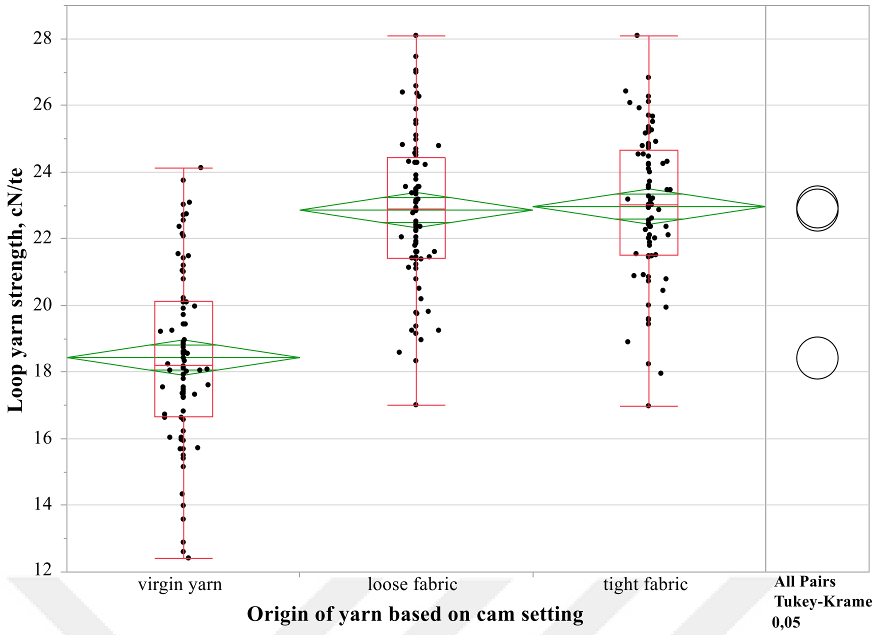



**Figure 5.37** The effect of cam setting on loop yarn strength

**Table 5.17** Cam settingversus loop yarn strength report

| **Cam setting** | | **n** | **mean,** cN/tex | **sd,** cN/tex | **LL,** cN/tex | **UL,** cN/tex |
|---|---|---|---|---|---|---|
| **tight fabric** | A | 80 | 22,96 | 2,21 | 22,47 | 23,46 |
| **loose fabric** | A | 80 | 22,86 | 2,35 | 22,34 | 23,38 |
| **virgin yarn** | B | 80 | 18,43 | 2,64 | 17,85 | 19,02 |

While number of yarn ply did not affect the unraveled yarn loop strength; it affected virgin yarn loop strength at statistically significant level. 3-plies virgin yarns exhibited better strength than 2-plies yarns. Both 2-, and 3-plies unraveled yarns displayed better loop strength than their counterpart virgin yarns (Figure 5.38 and Table 5.18). Knitting process enhanced the distribution of the fibers and promoted their load bearing capability.

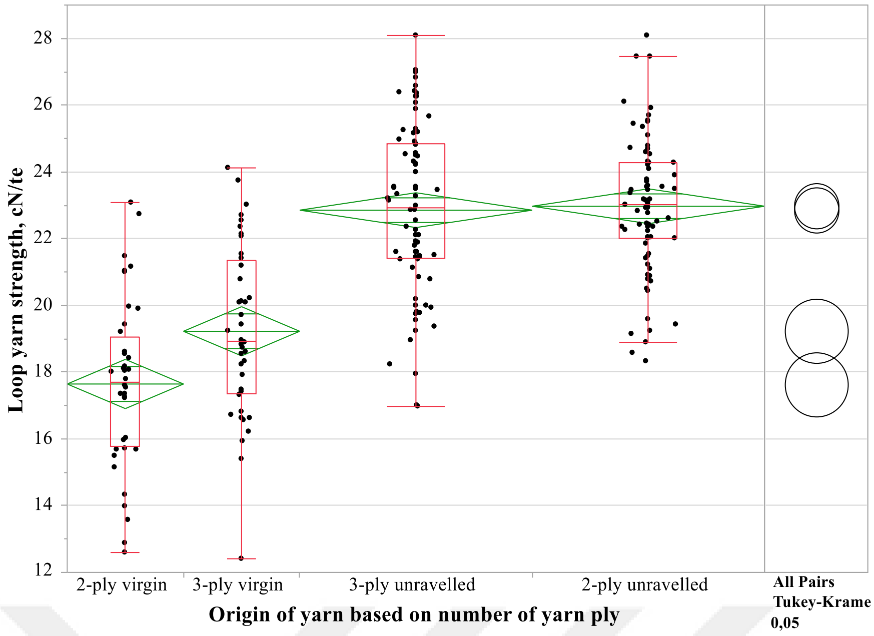



**Figure 5.38** The effects of number of yarn ply on loop yarn strength

**Table 5.18** Number of yarn ply versus loop yarn strength report

| **Number of yarn ply** | | | | **n** | **mean,** cN/tex | **sd,** cN/tex | **LL,** cN/tex | **UL,** cN/tex |
|---|---|---|---|---|---|---|---|---|
| **2-ply unraveled** | A | | | 80 | 22,97 | 2,00 | 22,53 | 23,42 |
| **3-ply unraveled** | A | | | 80 | 22,85 | 2,53 | 22,29 | 23,42 |
| **3-ply virgin** | | B | | 40 | 19,22 | 2,57 | 18,40 | 20,05 |
| **2-ply virgin** | | | C | 40 | 17,65 | 2,51 | 16,84 | 18,45 |

While unraveled yarns from skip stitch patterned fabric exhibited the highest yarn strength and unraveled yarn from weft-inlay showed the lowest unraveled yarn strength, no statistically significant difference was observed among the unraveled yarn strength of all knit pattern that proved lack of effect of knit pattern on yarn strength. Contrary to expected, unraveled yarns exhibited better strength than virgin yarn at statistically significant level (Figure 5.39 and Table 5.19). Knitting process improved loop yarn strength. Conversion of virgin yarn into the loop shape in the course of knitting process enhanced the uniform distribution of fibers in the yarn cross section that enhance the load carrying capability of unraveled yarns.

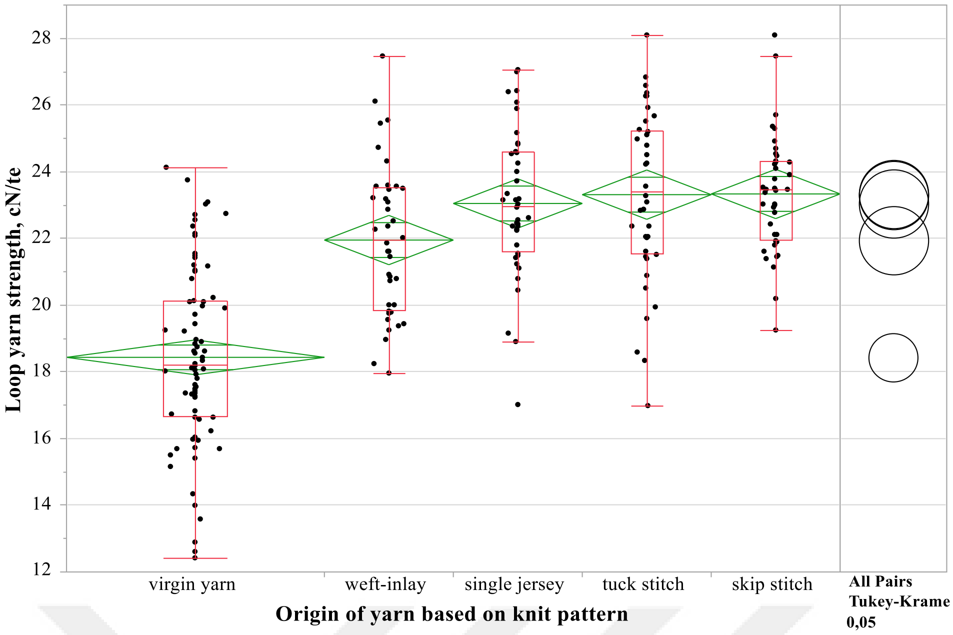



**Figure 5.39** The effect of knit pattern on loop yarn strength

**Table 5.19** Knit pattern versus loop yarn strength report

| **Knit pattern** | | | **n** | **mean,** cN/tex | **sd,** cN/tex | **LL,** cN/tex | **UL,** cN/tex |
|---|---|---|---|---|---|---|---|
| **skip stitch** | A | | 40 | 23,34 | 1,76 | 22,77 | 23,90 |
| **tuck stitch** | A | | 40 | 23,31 | 2,58 | 22,49 | 24,14 |
| **single jersey** | A | | 40 | 23,05 | 2,22 | 22,34 | 23,76 |
| **weft-inlay** | A | | 40 | 21,95 | 2,26 | 21,23 | 22,68 |
| **virgin yarn** | | B | 80 | 18,43 | 2,64 | 17,85 | 19,02 |

# CHAPTER 6

# CONCLUSION

It was observed that cam settings have an important effect on thickness and areal density. Adjustment of cam setting that varies between 1-10 levels was explained previously, our fabrics were produced as level 3-tight and level 8-loose. Tight fabrics formed a thicker and compact structure. Values of fiber volume percent of loose fabrics which have longer loop lengths were lower than tight fabrics. It can be concluded that compact fabrics have more fiber ratio in technical textile and/or composite materials.

As expected stitch densities of tight fabrics were higher than loose fabrics. In tight fabrics loops were in small and short structure, so the fabrics have more compact architecture. Having longer loops in loose fabrics decreased course and wale densities that also decreased stitch density.

Forming longer loops in loose structures affects sd/l ratio negatively and causes the ratios of loose fabrics lower. Sd/l ratio has positive relationship with areal density of fabrics. It can be commentated that density of tight fabrics will be higher than loose fabrics.

Despite number of yarn plies affected significantly some properties, it was also observed that there was no statistically significance in some properties. As expected in results of number of yarn plies; fabrics produced with 3 plies of yarns have higher values in properties of thickness and areal density. However; there was no statistically significant difference between fabrics produced with 2 and 3 plies of yarns in values of fiber volume fraction. Although fabrics with 3 plies of yarns have higher fiber ratio, difference did not reach to statistically significant level.

Values of course and wale densities of fabrics with 2 plies of yarns were higher than fabrics with 3 plies of yarns but in wale densities there was no difference between the fabrics were observed. Stitch densities of fabrics with 2 plies of yarns have higher values because of they have finer loops.

When values of loop lengths were examined; it was observed that there was no difference between fabrics with 2 or 3 plies of yarns. Sd/l ratios of the fabrics with 2 plies of yarns were higher than those with 3-ply yarns. When areal densities were compared, the fabrics with 3 plies of yarns were higher but sd/l ratios of them were lower. Reason of this situation is sd/l ratios increased because of the fabrics with 2 plies of yarns had high stitch densities and low loop lengths. In producing technical textile preforms, using 2 or 3 plies of yarns did not create a significant difference as much as cam settings created.

When effects of knit patterns on thickness and areal density properties were examined, fabrics with tuck stitch have the thickest structures and single jersey fabrics have the thinnest structures were occurred. Fabrics with tuck stitches had approximately twice thickness and areal density was observed due to changes specifically after removing fabrics from knitting machine. Importance of choosing knit pattern that can be used as technical textiles was observed in values of fiber volume percent. Fabrics with tuck stitches molded with resin as technical textile will be have 60,34% fiber ratio theoretically. Values of fiber volume percent of the weft in-lay fabrics which were tight and produced with 3 plies of yarns had an average of 84% fiber ratios.

Despite single jersey fabrics had the highest density in course direction, fabrics with tuck stitches were the most compact in wale direction. The nested structure of tuck stitches provided the most compact fabrics in view of stitch density after removing them from knitting machine. Other fabrics had no difference between each other statistically in view of stitch density. The most compact and tight structure of fabrics with tuck stitch attracted our attention due to their stitch density property.

When loop lengths were examined; weft in-lay and single jersey have the same pattern mainly, so their loop lengths were the same. The difference of these patterns (weft in-lay yarns laid though in course direction) occurred in thickness and areal density properties. Loop length of single jersey fabrics had approximately twice higher than fabrics with tuck stitches, nested structure of tuck stitches caused this situation. As expected, it was observed that sd/l ratios of fabrics with tuck stitches had the highest. Due to higher sd/l ratios; it can be remarked that areal densities of fabrics with tuck stitches will be the highest values. Results of areal densities of fabrics with tuck stitches supported truth of this thought.

It was observed that air permeability and bursting strength properties had negative relationship. Values of air permeability of tight fabrics were lower but values of their bursting strength were higher than loose fabrics. Due to thick and compact structure, tight fabrics passed smaller amount of air and needed higher forces to burst. When values of bursting distension were examined; loose fabrics had higher bursting distension than tight fabrics. It was determined that loose fabrics stretched mostly during bursting test. As we consider producing technical textiles with molded resin, it can be concluded that loose fabrics can stand the forces for longer time. We can state that tight fabrics will respond the forces short time despite their compact structure.

Number of yarn ply did not affect statistically on air permeability property. Although there was no difference in air permeability of fabrics from 2-, and 3-ply yarns; bursting strengths of fabrics produced with 3 plies of yarns were higher approximately twice than fabrics produced with 2 plies of yarns. According to using area, fabrics produced with 3 plies of yarns did not compromise performance of air permeability and providing higher bursting strengths of fabrics is an important conclusion. Also we can understand that despite of cost of fabrics produced with 2 plies of yarns is cheap; they provide the same air permeability values with 3 plies of yarns. When bursting distension of fabrics produced with 2 plies of yarns were examined, they were higher than fabrics with 3 plies of yarns. Therefore it can be said that their swellings were higher than fabrics with 3 plies of yarns.

Negative relationship of air permeability and bursting strength were observed on changes of knit pattern. When bursting strengths of fabrics with tuck stitches had the highest values, values of their permeability to air were the lowest. Single jersey pattern had the highest permeability to air (approximately 8 times higher than fabrics with tuck stitches), and the lowest bursting strengths. In bursting strength the highest values belonged to tuck stitch structures though weft in-lay and skip stitch patterns had no difference statistically. In weft in-lay and skip stitch patterns the laid and floated yarns in course direction were the most important factor provided to increase bursting strengths. During bursting tests, fabrics with tuck stitches showed the highest stretch that was observed in values of bursting distension. In producing composite preforms with resin, the material from with tuck stitches will be having the highest fiber ratios, the thickest and the most stretchable structure.

The overall conclusion is that the fabrics with tuck stitches are the thickest structure and they had the highest fiber ratios. Single jersey fabrics have the lightest structures but they stretch more than fabrics with weft in-lays and skip stitches. Number of yarn ply is not effective parameter on fabric properties as cam settings. The mechanical parameter of knitting machine affects loop lengths and significant conclusions were obtained. In future studies; working with double bed of knitting machine will enlarge our knowledge about potential of weft knitted fabrics from glass and other high performance technical yarns from aramid and carbon fibers.

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