Chapter 1
Introduction

1.1 General:

Conventional garments have become the second skin to the human for protection purposes over time it has become a sign of social as well as a cultural symbol. Clothing that protects against extreme conditions has been used by humans for ages. A person will feel comfortable in a climatic condition only when the energy produced and energy exchange with the environment is evenly balanced. And this allows the heating and cooling of the body is within the tolerable limit.

In bad weather, the outerwear must be wind and waterproof because it is always expected that the clothing protects such things. And for this purpose, a water-proof material is usually expected to guard us against rain, snow, and wind completely preventing the penetration and absorption of the liquid water from the atmosphere. Such waterproof fabrics tend to be an excellent barrier between our bodies and humidity. So, it helps to give excellent protection from this kind of element, but they are not able to transport the perspiration through the clothing to the outside causing a person to get wet from inside the clothing.

Traditionally, the fabric was made waterproof by coating it with a continuous layer of impervious flexible material, but such coated fabrics were considered to be very uncomfortable to wear, as they are relatively stiff and do not allow the escape of perspiration vapour. Water-repellent fabric is more comfortable to wear but its water-resistant properties are short-lived. To avoid this problem, the fabric is also made moisture-permeable to increase its degree of comfort.

Moisture permeable means to make the fabric breathable. In a nutshell, it can be explained as making a fabric properly ventilated. So along with making a fabric waterproof it is also made breathable. Such waterproof breathable fabric prevents the penetration of liquid water from outside to inside the clothing yet permits the penetration of water vapour from inside the clothing to the outside atmosphere. Waterproof breathable fabrics have gained huge popularity in several applicationsincluding outdoor apparel, workwear and sportswear products due to the levels of protection and comfort they provide.

Generally, the use of natural or synthetic materials or their blend to manufacture different types of clothing is done. Amongst all the fibres Polyester is one of the most common and widely used synthetic materials. It has achieved this position in the market due to its excellent properties like high strength, abrasion resistance, wash and wear, wrinkle-free characteristics and so on. Its use in apparel and technical textile is limitless.

Recently great attention has been focused on imparting waterproof breathable properties to polyester using different formulations. Therefore the aim of this study is directed toward the formulation of the chemical to provide the waterproof-breathable property of the polyester. The chemical formulation containing silk fibroin and PVP (Polyvinylpyrrolidone) is used here to impart the required functional properties.

1.2 Objective of Work:

The main objectives of the present study are as follows:

1. Modification of water-soluble PU using various agents.
2. Development of formulations for coating polyester fabric.
3. Development of waterproof breathable fabric by the application of modified PU.
4. Testing and evaluation of coated fabric for the effectiveness of its waterproof and breathable properties.

1.3 Scope of Study:

There are numerous benefits of the use of polyurethane to get a waterproof finish. First of all, it gives better protection from exteriors. But doing modification in PU using various agents may result in a change in the properties of the fabric treated with the same. The scope of the project is to achieve optimum results of waterproof and breathable coating on polyester using the modified formulation of chemicals. And achieve the specification and requirements to fit its end-use application

Chapter 2
LITERATURE REVIEW

2.1. Introduction:

Clothing as protection is also known as the second skin of human beings. Clothing that protects the wearer from external factors is been used for ages. This kind of clothing helps to prevent the wearer from certain external factors like wind, water, snowfall etc. For such kind of protection from the external factors initially, leather was used which was later replaced by fabric by providing waterproof finishing to it. So, it is expected that the clothing should behave like skin and be comfortable for the wearer.

Waterproof fabric protects the external factor by preventing the penetration of liquid whereas water-repellent fabric will only delay the penetration of the liquid. Initially, they were coated using animal fat, wax etc. but such coated fabrics are uncomfortable to wear. Comparatively, water repellent fabrics are more comfortable but at the same time, their water-resistant property is very short-lived. To overcome this breathability was introduced to this kind of fabric to make it more comfortable. The term breathable means properly ventilated. Here, breathable fabric passively allows the water vapour to diffuse and then to prevents the penetration of water through it.

During any physical activity to maintain the body temperature body perspires and if it doesn’t escape the wearers' cloth it becomes uncomfortable. A waterproof breathable material combines waterproof properties and moisture permeability in a functional fabric and it plays an important role in special protective clothing where it will not only prevent the penetration of liquid from the atmosphere but at the same time will allow the water vapour from inside the clothing to the outer atmosphere at the same time. [23]

2.2. Waterproof breathable fabric

R.Perumalraj, in his article waterproof breathable fabric, has clearly stated that Waterproof breathable fabric is designed to protect from the wind, rain and loss of body heat. The breathable fabric will passively allow the water vapour and prevent the penetration of liquid water for comfortable clothing. It allows the fabric breathe under extreme conditions by keeping the wearer dry and comfortable while performing any activity. He has clearly explained the need and requirement of such material by clearly giving the example that a normal core body temperature if exceeding the limit while performing any activity can cause adverse effects such as disorientation and convulsions. If the sufferer is engaged in a hazardous pastime or occupation then this could have fatal consequences. The author explains that how these waterproof breathable fabrics will allow the body to remain at the physiologically required temperature by permitting the passage of water vapour from perspiration during the activity. [1]

A.Mukhopadyay and V. K. Midha have stated that the breathability of such fabric is dependent on the temperature gradient across the waterproof breathable fabric, the humidity of clothing microclimate and the interaction between waterproof material and the clothing layer. They have explained how conventional waterproof fabric differs from waterproof breathable fabric due to their special property of waterproofness along with breathability. These types of fabric have been developed to minimize the wearers' heat stress by requiring moisture management while blocking the passage of the external water molecules. [4]

2.2.1. Characteristics of waterproof breathable fabric:

David A. Holmes in his article explains about characteristics of waterproof breathable fabrics in different atmospheric conditions and the difference in their behaviour in the case of different fibres. Through this work, it was stated that the performance of waterproof breathable fabric cannot be judged alone based on atmospheric conditions but also several other factors like durability, and physiology should also be considered. The results observed during the studies stated that the main variables like fabric construction and the water vapour pressure gradient which is present in between the fabric faces affect water vapour permeability. So accordingly, the tightly woven fabrics had the highest water vapour permeability values because they had a high ratio of inter-fibre and inter-yarn spaces The coated fabrics were recorded with the lowest water vapour permeability values coating thickness was very high whereas membranes have higher permeability as they are thinner as compared to the coated material. The micro-porous membranes showed higher permeability as they contain physical holes. [14]

2.2.2. Factors affecting waterproof breathability of fabric:

J. C. Gretton, D. B. Brook, H. M. Dyson, and S. C. Harlock have discussed the factors that are responsible for Water Vapour transmission through the clothing ensemble. They explained that water vapour transmission is dependent on the thermal resistance of the clothing layers as well as their water vapour transport properties. The major purpose of their experimental work was to develop a reproducible method to examine the effect of a temperature gradient on moisture vapour transport through waterproof breathable fabrics and simulated clothing systems. They used the evaporative method based on BS 7209 for exerting a temperature gradient across the sample. It was observed that when a temperature gradient was applied across the single-layer samples, the transport properties of these fabrics improved. [15]

2.3. Types of Water Breathable Fabric:

S Sakthivel, A Zaid Hamza and S D Kiruthika in their article application of waterproof breathable fabric have explained the different types of method application and in what way they are playing a very important role in designing the waterproof and breathable fabrics. They have explained different methods, which can be used to obtain fabrics that are both breathable and waterproof. These can be divided into three groups.

2.3.1. Densely woven fabrics:

In the case of closely woven fabric, the surface area and concentration of inter yarn spaces should be as high as possible to maximize water vapour transmission through woven fabrics. The woven fabric is dense with the least quantity of pores and it's treated with a durable water repellent material for making it waterproof. The pore structure does not allow water droplets to penetrate through the fabric from the outside. On the other hand, fibre fineness combined with inherent moisture absorption and the ability of the fibre to swell with increasing moisture content helps to make it both waterproof and moisture permeable or breathable. Nowadays, man-made fabrics such as polyester, polyamide, acrylic, and viscose are widely preferred for manufacturing tightly woven fabrics. The pores of these tight constructions are very small for water molecules to penetrate through but are at the same time large enough to allow water vapour to pass through.

2.3.2. Membranes:

Membranes are thin films made from polymers. Such membranes can be used to provide the waterproof-breathable properties to the fabric there are two membranes:-

2.3.2.1. Microporous membranes:

The microporous membranes have very small holes on their surface which are smaller than raindrops but are larger than water vapour molecules. Some of the membranes are made from PTFE polymer, PVDF, etc.

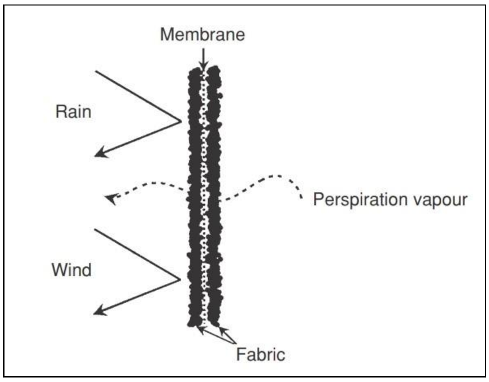

Fig 2.1 Micro Porous Membrane [14]

2.3.2.2. Hydrophilic membranes:

The hydrophilic membranes are thin films of chemically modified polyester or polyurethane. These polymers are modified by forming an amorphous region in the main polymer system. This amorphous region acts as intermolecular pores allowing water vapour molecules to pass through but preventing the penetration of liquid water due to the solid nature of the membrane.

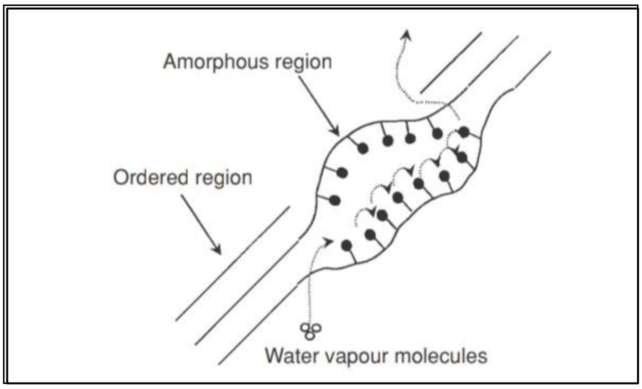

Fig 2.2 Hydrophilic Membrane [14]

2.3.3. Coatings:

Coated fabrics with waterproof breathable fabrics consist of polymeric material applied to one surface of the fabric. These consist of a layer of polymeric material applied to one surface of the fabric. Like membranes, the coatings are of two types; microporous and hydrophilic. These coatings are much thicker than membranes. Contains very fine interconnected channels, much smaller than the finest raindrop but much larger than a water vapour molecule. [2]

Supriya Pandit and Smita Bait have discussed powerful tools for the advancement of textile technology i.e., lamination and coating. It helps to produce special kinds of fabrics like water-proof resistant tarpaulins, coverings, and large tents. But Waterproof breathable fabrics are the ones that will protect the wearer from the harsh weather without hampering their efficiency. The garment is considered breathable and comfortable when it allows the passage of water vapour. Different methods of achieving the waterproof-breathable fabrics are mentioned but one of the different methods of achieving waterproof-breathable fabrics is the application of polyurethane paste by coating on the substrate. The principle behind the working of this type of coating is adsorption and diffusion and desorption of water vapour. The study made on this is an attempt to substitute current solvent-based PU emulsion coating technology with water-based PU emulsion because adverse health hazards are caused due Solvent-based emulsion coating causes due to solvent evaporation occurring during the curing stage. Here untreated polyester was taken which was padded with a water repellent finish for the conduction of the experiment. Later on, Coating technology was used for the application purpose of the water-based polyurethane to polyester fabric. Different concentration was used to make a comparative study. The performance of treated waterproof breathable coating was studied and compared with the available commercial solvent-based waterproof breathable fabric and it was observed that Water-based PU emulsions can be a good alternative to solvent-containing PU emulsions. And the effect of variation in PU concentration in coating paste on the breathability of polyester was evaluated and it was found that fabric coated with 95% PU concentration, 150°C curing temperature and 5 min curing time shows the highest breathability, air permeability and waterproof Performance. [11]

On the other hand, a group of contributors to the book entitled Active Coatings for Smart Textiles have explained in the book the topic related to coated textiles that are being used in a wide range of end applications. The durability of textile coatings must be long lasting. Conventional materials based on either microporous or hydrophilic coatings cannot have expected durability. The breathable coating materials can be termed smart in which smart technology is used to enhance the durability as well as the functionality. On the other hand, breathable fabrics based on shape memory polymers are also discussed. The evolving technology behind designing breathable fabrics is continuously achieving improved functionality which is also cost-effective manufacturing processes for a variety of applications the smart breathable coated fabrics based on biomimetic and shape memory polymers are regarded as active smart, and those based on conventional microporous and hydrophilic coatings can be called passive smart.[10]

2.3.3.1. Microporous Coating:

The microporous coating is very similar to that of a microporous membrane. This type of coating contains the very fine interconnected channels which are smaller than the finest raindrop but are much larger than the water-vapour molecule. [23]

Ilhan Ozen, in his experimental article, has discussed the work regarding the waterproof breathable fabric which consists of microporous breathable film on the plain/twill weave fabric. To work in a most cost-effective way the fabric was initially treated with a conventional fluorine-based water repellent finish and later on layer structure was generated on it by bringing the treated fabric together with the microporous breathable film. The evaluated results showed that the water-resistance achieved was dependent on weave type and the structure generated. Waterproofing requires filling the pores of the fabric, so waterproofness in densely woven plain fabrics is more as compared to that of the twill fabric. So from this work, it was clearly stated that to resist the water up to the required extent tightly woven water repellent finished fabric layered with the microporous breathable film will have more restive properties as compared to a conventional water repellent finish fabric alone.[12]

2.3.3.2. Hydrophilic coating:

The mechanism is the same as that of the hydrophilic membrane the only difference in both is that the membrane passes water vapour through the permanent air-permeable structure whereas the coating transmits the vapour by molecular mechanisms which involve adsorption-diffusion and desorption. [23]

Along with the above consideration, several diverse methods have also been explained on how to create the interconnecting course structure in solid polymer film and coating. These are some of the easiest methods of generating microporous membrane and coating and they are as follows:

- Wet coagulation process
- Thermo coagulation (only for coating)
- Foam coating (only for coating)
- Solvent extraction

- Solubilising one component within the mixture (only for coating)
- Radiofrequency (RF)/ion/UV or E beam radiation
- Melt blown/hot melt technology
- Point bonding technology.[3]

2.4. Methods of Coating:

A.K. Sen in his book titled Coated Textiles: Principles and Application Second Edition has discussed the various coating methods by which to coat polymer to textiles. They are classified based on equipment used, method of metering, and the form of the coating material used. The various methods are explained further.

2.4.1. Fluid coating:

In this coating material is in the form of paste, solution, or lattices

- Knife coaters: Wire wound bars, round bars, and so forth. These are posted metering devices.
- Roll coaters: Reverse roll coaters, kiss coaters, gravure coaters, dip coaters, etc. These are pre-metered application systems.
- Impregnators: The material to be coated is dipped in the fluid, and the excess is removed by squeeze roll or doctor blades.
- Spray coaters: The material is sprayed directly on the web or onto a roll for transfer.

2.4.2. Coating with dry compound:

In this coating technique, the dry compound could be a solid powder or film.

- Melt coating: Extrusion coating, powder coating,
- Calendaring: It is done for thermoplastic polymers and rubber compounds, Zimmer process, and Bema Coater.
- Lamination.

The choice of a coating method also depends on several factors like:

- Nature of the substrate on which coating is to be performed
- Form of the resin being used for coating and viscosity of the coating fluid
- End product to be made after coating and the accuracy of coating as per requirement
- The process should be economical

Certain important thing related to the preparation of the fabric of coating is also well mentioned. To get trouble and a defect-free coating it is necessary to prepare the fabric first. During coating and lamination, the fabric is heated so the fabric selected for coating purposes should be properly pre-treated involving a heat setting. The fabric must be well set otherwise it may lead to a non-uniform or uneven coating on it. At the same time, it is also important to remove size, waxes, oils, and other hydrophobic finishing chemicals which may cause difficulties during coating. [3]

Jianzhong Shao, Chenglong Wang, Jinli Zhou and Lili Wang experimented with using a novel waterproof and moisture-permeable coating agent by modifying a waterborne polyurethane agent with silk fibroin and polyvinylpyrrolidone and the blended agent was applied on polyester fabric using coating technology to achieve a desirable waterproof and breathable effect. Waterborne polyurethane was used due to its nontoxicity, non-flammability, excellent abrasion resistance, and flexibility another one used is polyvinylpyrrolidone or PVP it is a water-soluble polymer, which has good biocompatibility and is used applied as a biomaterial or additive to drug compositions for several years. PVP exhibits excellent transparency along with biocompatible nature. The novel coating agent was characterized by Fourier transform infrared scanning electron microscope, thermogravimetry and X-ray diffraction techniques. The evaluation of moisture permeability and water repellence of polyester coated using this novel waterproof and moisture permeable coating agent was made. The results thus obtained showed that the thermostability of the blended film was increased and the compatibility was improved by adding the PVP component, and there was a significant improvement in the moisture permeability and waterproofing of the coated polyester fabrics. An optimized recipe was used to conduct this coating process to achieve the optimum results. It was also observed that the physical and mechanical properties of the coated polyester fabric were not considerably affected. [7]

2.5. Designing Waterproof Breathable Fabric

Mukhopadhyay A. and Midha V have explained that certain considerations are needed to be considered while designing a waterproof breathable fabric. It is stated below

- Waterproofness
- Mass of the fabric
- Durability/flexibility of coating/laminating
- Comfort level
- Aesthetic property
- Water-vapour transmission
- Effectiveness of clothing against wind chill factor
- Durability: tear tensile and peel strength; flex and abrasion resistance
- Launderability
- Tape saleability with good adhesion
- Strength of coating
- Good washability/dry cleanability
- Resistance to insect repellents
- Good hydrostatic resistance [4]

Kale R. D., Vade A., Potdar T. in their article Optimization study for waterproof and breathable polyester fabric in which study was done on polyester fabric which was coated with polyurethane formulation along with chlorine with water repellent compound for making water breathable fabric. The water repellent properties of the coated fabric were analyzed by measuring water vapour permeability status contact angle hydrostatic pressure and rain test along with the physical characteristics of the coated fabric like its mechanical strength stiffness and crease recovery. And after making a comparative study in regards to that the performance and the durability of waterproof breathable fabric they got satisfactory results. And on this basis of the study, it was easy to decide on the end-use application as there was a certain limitation of conventional waterproof breathable fabrics. So to overcome the limitation of the conventional waterproof breathable fabric they coated the material by optimizing the concentration of the chemicals and the other auxiliaries for getting the optimum result. [5]

2.6. Need of waterproof breathable material

Desai A. in her article related to medical textiles has mentioned the need for waterproof breathable material in certain products which require repellency and comfort for the user at the same time. The major requirements for fabrics that are used in the medical field should resist the penetration of liquids, particularly blood and at the same time be sterile, breathable, flexible, inexpensive, comfortable, effective, and repellent to stains. And to fulfil the requirement of lighter, comfortable, more protective clothing protection coating and lamination techniques are used. [19]

2.7. Limitation of the conventional waterproof breathable fabric

Kanjana S. And Nalankilli G. In the review article smart waterproof breathable sportswear: A review has explained in detail the limitation of the conventional waterproof breathable fabric and how we can overcome these limitations for designing the waterproof-breathable fabrics. Further explanation was made on the smart coating for sportswear to enhance the efficiency of the wearer without causing any stress Trending technology of smart coating involves the application of PCMs, SMPs, and SRPs which improves the functionality of the material used for the sportswear is mentioned. The future trend for smart coating for sportswear is more likely to be adopted as there is a variety of conventional textile fabrics and novel coating substances thus doors for the innovation remain to be opened for such things. [6]

2.8. Various Branded fabrics:

Chaudhari S. S., Chitnis R.S. and Ramakrishnan R. in their review paper have discussed the development of waterproof, breathable materials for sportswear textiles.

The moisture transport properties and various factors affecting it also are discussed for sportswear fabrics using different fibres. They have also explained the different natural and synthetic fibres characteristics concerning waterproofness and breathability and also mentioned the solution through which they can be made applicable for breathable sportswear to fulfil specific needs of the sports activity without effect the efficiency of the wearers' activity and prove to be comfortable. The various branded fibres and fabrics are described alongside their constitutional elements and special characteristics. And they are as follows:

- **Hygra**: Hygra was launched by Unitika Limited which was made from water-absorbing polymer and nylon. It also shows superior antistatic properties under low wet conditions. They are used for making athletic wear, skiwear, golf wear etc.
- **Lumiac**: Lumiac is also a produced by Unitika. It is a collection of polyester of different fineness. It is used along with Hygra to manufacture athletic wear.
- **Dryarn**: Dryarn is a new fibre from Aquafil. It is usually very lightweight and comfortable, soft handle and has a high thermoregulatory capacity and also dries quickly. Bacteria are unable to settle on the smooth surface of the fibre which thus avoids the unpleasant odour which is associated with the decomposition of bacteria.
- **Killat N**: Killat N is a nylon hollow filament. It gives good water absorbency and warmth retentive property.
- **Triactor:** was developed as a perspiration absorbing/quick-drying polyester filament. They exhibit good sweat absorption and fast-drying property.
- **Lycra:** It has a good stretch and recovery, so it is used particularly in gymnastics and swimwear where body skin flexing and stretching is an important aspects.
- **Roica and Leofeel: Roica** is a polyether type of spandex and Leofeel is a soft nylon-66 yarn which is developed by Asahi Chemical. Fabric made out of a blend of these gives a soft touch and excellent stretch. It is mainly used for making swimwear.

- **Different types of other fibres like** Elite, Linel Ac, Elastil and Sens etc. also have good stretchability and thus they are effectively used in swimwear.[8]

2.9. Recent developments:

2.9.1. Development of waterproof breathable by applying electrospun web of polyurethane

Yun Kyung Kang, Chung Hee Park, Jooyoun Kim, and Tae Jin Kang developed waterproof breathable by applying an electrospun web of polyurethane directly to the substrate fabric. And for this purpose, all the condition required for electrospinning was checked based on the concentration, applied voltage and tip-to-collector distance. Polyester/nylon blended fabric was used for this purpose and a 0.02 mm thickness of electrospun web was applied to it. For comparison purposes, the coated polyester/nylon fabrics with the same thickness of the coating were used. An increase in weight was recorded for the coated fabric as compared to the electrospun web applied fabric. Higher air permeability, vapour transmission, and thermal insulation properties were observed in The electrospun web applied fabric as compared to that of resin-coated fabrics. based on the characteristics of electrospun PU web/ fabric recorded it can it is acceptable that the electrospinning application also shows great potential for making waterproof-breathable fabric with optimum results.[16]

2.9.2. Preparation of Double-layer membrane by electrospinning

Jingge Ju, Zhijie Shi, Nanping Deng, Yueyao Liang, Weimin Kangab and Bowen Cheng studied the double-layer membrane that was prepared by electrospinning in which a direct combination of TPU-NMs inside and TPU/TBACTLNMs outside was made. Different microporous structures and performance were observed on the double layer membrane like the inside (TPU-NMs) were hydrophobic and the outside was hydrophilic Moreover, the double-layer electrospinning membrane offered obvious advantages compared with a commercial PU waterproof breathable membrane. The double-layer membrane along with moisture unidirectional transport and good shielding properties was used as waterproof breathable material. The results evaluated showed better water resistance, mechanical, waterproof, moisture permeability, air permeability, air filtration and moisture unidirectional transport performances as compared to the existing ones. This development in the manufacturing of waterproof breathable fabric is an approach toward further development. [17]

2.9.3. Eco-friendly waterproof breathable coating:

Jassal M., Khungar A., Bajaj P., Sinha T. J. M. studied the performance of eco-friendly water-based polyurethane dispersions for waterproof-breathable coating. The evaluation was done to study the effect of certain factors like the nature of dispersion, the number of coatings, quantity and quality of additives, and several processing conditions on the breathable properties of the fabric. The evaluated results showed that the water vapour permeability values increased with an increase in a hydrophilic component while the water penetration resistance increased with an increase in the hydrophobic component. By this, it was clear that a combination of certain concentrations can be changed and used as per the required specification and end-use of the material.[18]

2.9.4. The optimum combination of components in a coating material

Dilan Vethandamoorthy, Eranda Mandawala, Wasana Bandara have made research in which they determined the optimum combination of components in coating material to obtain high water resistance and moisture-absorbent properties. Initially, they made use of Silicone caulk and Mineral spirit in thirteen different combinations to coat the fabric along with one sample with one mixture for control but this method was not up to the mark as water penetrated through the fabric because of high pressure. Later they made use of Silicone caulk with Acrylic Matt Topcoat in thirteen different combinations to coat the material alongside one sample with one mixture for control. For the setting process, the material was given 5 -6 hrs. on which the Surface was coated using a flat-bottomed plastic rod. The direct Coating method was modified to design the proposed fabric. Some changes were made to the existing process of coating by adding some Rollers, beds and inlets for the betterment of the application condition. A Secondary Fabric Feed Roll was introduced for supplying the Air mesh fabric into the coating process. For supporting the fabric to move inside the

Combining Inlet to adjoin the fabrics together An Idler Roller was introduced. This fabric in a combined way moves inside a uniform steel bed to maintain uniformity in the Fabric. The fabric selected for this experimental purpose was a combination of a Polyester-cotton blend with a Chemical layer and Air mesh to its inner. The coating was done in two different ways in which one of the fabrics was produced as single coated fabric and the other as a double-coated fabric. After the experimentation, it was observed that Single coated fabric was able to withstand Bundesman Rainshower Test (ISO 9865:1991) and a Hydrostatic pressure (ISO 811:1981) of more than 1.9m and that to The Double coated fabric did not ignite in the Flammability Test. And later the testing with acid and base was also performed which did not show much effect on the coated material but somewhat showed a difference in the colour. The chemical layer that is present in the middle of the fabric acts as an insulator for heat. The fabric coated using the above combination provides lasting protection from different types of stains, chemicals, abrasion and rain, it is odourless and last but not least it is environmentally friendly.[9]

2.9.5. Suitability of polyacrylamide as a breathable coating material

Ninad S. Save, Manjeet Jassal and Ashwini K. Agrawal have investigated the suitability of polyacrylamide as a breathable coating material. Coatings of polyacrylamide on the cotton fabric were done by applying 4 wt. % polyacrylamide solution and a cross-linking agent like citric acid for this case of various concentrations in terms of density, sodium hypophosphite was used as a catalyst was used then followed by drying and curing. The coated and cured fabrics with polyacrylamide coatings were found to have good integrity. The degree of integrity decreased from higher to lower concentrations of crosslinkers. The integrity of polyacrylamide coating on the cotton surface is due to the reaction between citric acid and the hydroxyl group of cotton. The samples with 29% add-on and 50 mol% cross-linker concentration was observed to have higher resistance to water penetration and a high vapour transmission rate whereas the fabric with lower add-ons and cured with lower cross-linking densities showed lower resistance to water penetration. It was observed that vapour transmission rate will be good if lower cross link densities and less add on were used for coating purposes which would indirectly hamper the integrity and the wear resistance capacity of the fabric. After all the investigation it was suggested that to require an optimal balance of desirable properties like water vapour transmission rate, the integrity of coating on the fabric, air permeability durability and so on minimum add-on of 15% and cross-linker concentration of 20 mol% will be required. [13]

2.9.6. Development of ecological and water repellent wax particles for coating:

The researchers at Aalto University have developed ecological and water repellent wax particles for coating which is suitable for wood cellulose fibres along with other textile materials also. It, not only fives water repellency but also retains the breathability and natural feel of the textile. They made use of two layers of the starch mixed with two wax particles for making the fabric water repellent Testing was conducted for application techniques and it was observed that dipping, spraying and brushing techniques can be used depending on the quantity required. It was found that these coatings are not resistant to detergents. Finally, with the test results, it was concluded that the best water resistance result can be obtained when the drying temperature is lower than the melting temperature of the wax. [20]

2.10. Testing:

Aditya Kapoor, Arvind Kumar Baronia, Afzal Azim, Gaurav Agarwal, Narayan Prasad, Richa Mishra, Vivek Anand Saraswat have explained certain measuring standards for testing the breathability of personal protective equipment used in for medical care in their research papers. (21) They are as follows:

ASTM F1980 -Standard Guide for accelerated ageing of sterile barrier systems for medical devices

EN 14126:2003-Protective clothing. Performance requirements and test methods for protective clothing against infective agents

ISO 16604:2004 or ASTM F1670 Standard test method for resistance of materials used in protective clothing to penetration by synthetic blood

ASTM F1671- Standard test method for resistance of materials used in protective clothing to penetration by blood-borne pathogens using Phi-X174 bacteriophage penetration as a test system

EN 20811- Determination of resistance to water penetration—hydrostatic pressure test

ASTM D5034- Standard test method for breaking strength and elongation of textile fabrics (grab test)

ASTM D5733-Standard test method for tearing strength of non-woven fabrics by the trapezoid procedure 8 ASTM D6319 Specification for nitrile examination gloves for medical applications

ISO 11607-Packaging for terminally sterilized medical devices

ISO 811 - Hydrostatic pressure method for determining the fabric's resistance to penetration by water. The method applies to all types of fabrics that are intended to be water-resistant, whether or not they have been given a water-resistant or water-repellent finish. [21]

2.11. Applications of Waterproof Breathable fabric:

Waterproofs are breathable and have several applications. Depending on the activity the efficient material is used.

1. They are used in the clothing industry on a large scale, especially in sportswear, workwear leisurewear

2. They are used for making jackets, gloves, hats, rain pants, socks shoes and many more.

3. They are also used in extreme condition or cold places to make the weaver comfortable .at such places waterproof jackets are used which protects from both wind and water.

4. They are used in agrotech for making a ground cover for weed control, packaging material for goods, coverings etc

5. In medical textiles, they are used for making bed sheets, pillow protectors**,** stretchers, hygiene products, modern wound dressings, wheelchair cushions, and surgical drapes they provide comfort and repellency at the same time.[22]

Chapter 3
PLAN OF WORK

3.1. Materials

3.1.1. Fabric: -

Commercially scoured, bleached and heat-set ready to coat polyester fabric.

EPI	106
PPI	75
GSM	53
Denier	76

3.1.2. Chemicals:

a) Waterborne Polyurethane (WPU)
b) Silk Fibroin (SF)
c) Polyvinylpyrrolidone (PVP)
d) Cross-Linking Agent
e) Synthetic Thickener
f) Water

3.2. Methodology:

3.2.1. Details regarding experimentation to be carried out:

The following process is adopted for the coating of Polyester fabric. A specified quantity of Waterborne Polyurethane (WPU), Silk Fibroin (SF), Polyvinylpyrrolidone (PVP), Cross-linking agent and Synthetic Thickener is applied to polyester fabric. While coating polyester fabric, process parameters such as the concentration of Polyvinylpyrrolidone (PVP), and the Concentration of Fibroin (SF), are varied with 4 levels each.

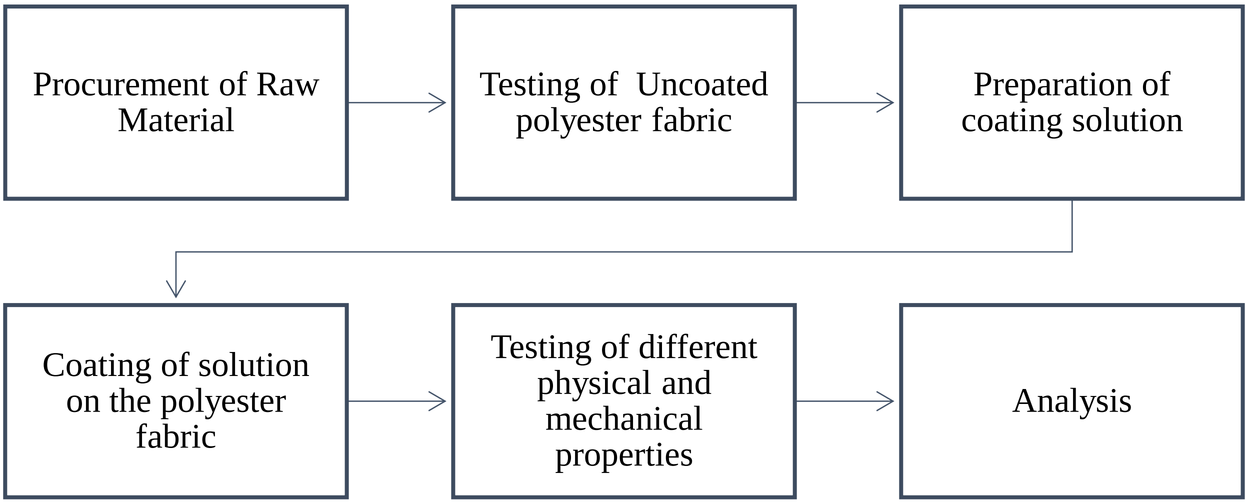

Fig 3.1 Process Flow

3.2.2. Coating Machine:

Coating machine available in the Institute research Laboratory, Mathis KTF-S-500 with following material flow diagram and specification:

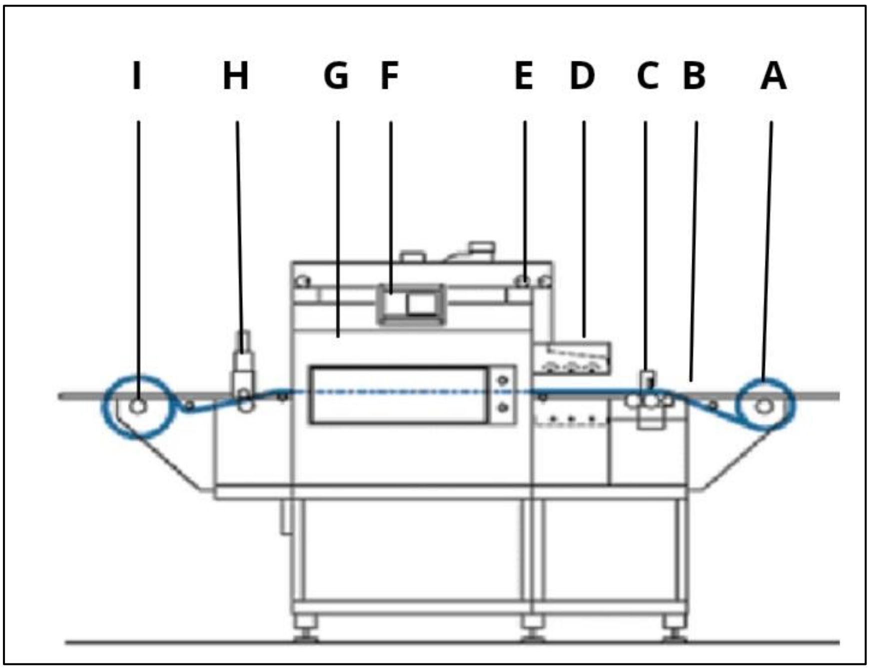

Fig 3.2 Coating Machine –Mathis KTF-S-500

A - Unwinding device

B - Draw out device

C - Coating device

D - Infrared Predryer

E - Exhaust system

F - Univision touch-process controller

G - Hot air drier

H - Laminating device

I - Unwinding device

Machine Specifications:

Working Width	450mm
Fabric Speed Range	0.1 to 2 m/min
Respective dwell time	20-420 sec
Circulating Air Speed	< 6m/Sec
Circulating Air	< 1000 m^3/hr
Exhaust	< 400 m^3/hr
Temperature Range	Ambient to 250^0 C
Coating Technique	Knife on – air, roller and belt

3.3. Design of Experiment:

Taguchi statistical technique has been applied for designing the experiment. The number of trials is reduced to 16 through the Taguchi technique. The table below depicts the design of the experiment.

Table 3.1 Recipe for Coating

Trial No.	WPU (gm)	PVP (%)	SF (%)	Cross-Linking Agent (gm)	Thickener (gm)
1.	50	0	0	2.5	2
2.	50	0	5	2.5	2
3.	50	0	10	2.5	2
4.	50	0	15	2.5	2
5.	50	5	0	2.5	2
6.	50	5	5	2.5	2
7.	50	5	10	2.5	2

8.	50	5	15	2.5	2
9.	50	10	0	2.5	2
10.	50	10	5	2.5	2
11.	50	10	10	2.5	2
12.	50	10	15	2.5	2
13.	50	15	0	2.5	2
14.	50	15	5	2.5	2
15.	50	15	10	2.5	2
16.	50	15	15	2.5	2

After coating by using the above formulations, samples will be cured at 140^{O}C for 2 mins.

3.4. Experimental Procedure:

3.4.1. Preparation of coating paste:

The required amount of chemicals was taken as per the required concentration in a container and a small amount of water was added to it. A calculated amount of cross-linking agent was added with constant stirring and the remaining amount of water was added. This is followed by the addition of synthetic thickener. Stirring was continued till desired viscosity was achieved.

3.4.2. Coating:

A length of polyester fabric having a width of 450 mm was used for coating. The coating technique employed was a knife on air. The fabric sample was mounted on a coating machine and a knife was set at the desired position. It was ensured that the knife was in a perfectly horizontal position. Both the side fabric inlet and outlet gripper rollers were pressurized and coating paste was added to the fabric before the knife. The coating was continued at 0.25m/min speed. Circulating air was set at 110°C for drying after coating by using the above formulations, samples will be cured at 140^{O}C for 2 mins.

3.5. Testing

Following tests are carried out for analysing the properties of waterproof breathable coated polyester.

3.5.1. GSM

Fabric GSM means gram square meter of the fabric. The GSM of the fabric changes after the application of the coating material on the fabric due to the % add-on to the fabric. It is essential to know the GSM before and after coating. A fabric of size 10 cm X 10 cm is cut and weighed. Later GSM is calculated using the following formula:

$$\frac{Wt.in\ grams * 10000}{Area\ of\ Fabric}$$

3.5.2. Thickness

After the application of coating solution on the fabric, the thickness varies. This thickness of the fabric controls different properties like drape, stiffness, thermal resistance etc. The thickness of the fabric is measured using a Shirley thickness tester.

3.5.3. Tensile Strength:

Tensile testing measures the force needed to elongate and break a sample. It is used to determine the strength and elasticity of fabric. The grab test method was used to measure the tensile strength. For a grab test, the grips of the testing machine clamp of fabric sample in the centre using jaws smaller than the sample width. The fabric sample is cut according to the template provided for the test. The tensile strength is measured in Kgf.

3.5.4. Tear Strength:

Tearing strength is defined as the force required to start or to continue to tear a fabric in either weft or warp direction, under specified conditions. It is tested on Elmendorf Apparatus. A fabric sample is cut with the help of a template provided for the apparatus. The force required to tear the sample is measured in gf.

3.5.5. Bending Length:

Bending length is defined as the falling length, when a fabric falls under its own weight to a specific length having specific angle.

3.5.6. Flexural Rigidity:

It is a ratio of a small change in bending moment per unit width of material to a correspondingly small change in curvature expressed in milligram centimetres. It is calculated using the formula:-

Flexural Rigidity (G) = WC^3 mg.cm

(W = weight per unit area of fabric in mg/sq. cm)

Overall flexural Rigidity = $\sqrt{Gw * Gf}$

Gw = Warp way Flexural Rigidity

Gf = Weft way Flexural Rigidity

3.5.7. Water Vapour Transmission

Water vapour transmission rate is a measure of the passage of water vapour through a substance. It is a measure of the permeability of the vapour barrier.

3.5.8. Hydrostatic Head Pressure:

A hydrostatic head pressure tester is used to measure the water penetration resistance of fabric under hydrostatic pressure while firmly clamped in the test rig of the standard area. It is used to measure how waterproof a fabric is. The pressure of water is monitored by a water-filled manometer which measures the pressure on the specimen in cm of water.

3.5.9. Air Permeability:

The air permeability of fabric is a measure of how well it allows the passage of air through it. The air permeability of the fabric is tested using Shirley Air Permeability Tester. The result was expressed as the unit of volume of air cm^3 passed per second through $1cm^2$ of the fabric at a pressure difference of 20 mm and 2 cm head of water.

Table 3.2 Testing of Untreated Sample

Sr. No	Content	Result
1	GSM	53 GSM
2	Thickness	0.09 mm
3	Tensile Strength Warp way Weft way	 44.6 kgf 45.4 kgf
4	Tear strength Warp way Weft way	 1394.2 gf 1749.4 gf
5	Bending Length Warp Weft	 2.762 cm 2.992 cm
6	Flexural Rigidity	128.955 mg.cm
7	Water vapour permeability	2024.09 $g/m^2/day$
8	Hydrostatic Head Pressure	0.5 cm
9	Air permeability	41.63 $cm^3/cm^2/s$

Chapter 4

RESULT AND DISCUSSION

4.1. Introduction

Application of formulated waterproof breathable coating paste on 100% polyester fabric is done as per methodology discussed in chapter 3. 100% polyester fabric is coated with the formulated paste, by using different finishing recipes as prescribed in previous chapter 3. The fabric samples are tested for GSM, Thickness, Tensile Strength, Tear Strength, Bending length, Water vapor Permeability, Hydrostatic head pressure, Air Permeability. The results of these tests are discussed in this chapter.

4.2. Physical properties

Table 4.1 represents the physical properties of treated samples.

Table 4.1 Physical properties of treated samples

Recipe	WPU	Thickener	Cross linking agent	PVP	SF	GSM	Thickness	Tensile Strength		Tear Strength		Bending Length		Flexural Rigidity	Water vapour Permeability	Hydrostatic Head Pressure	Air Permeability
								Warp	Weft	Warp	Weft	Warp	Weft				
1	50	2	2.5	0	0	64.7	0.1	49.8	47.4	824.2	906.8	3.452	2.98	211.15	1214	8.6	9.184
2	50	2	2.5	0	5	66	0.11	49.2	45.8	787.6	901.2	3.414	2.86	201.36	1156.6	9.6	9.442
3	50	2	2.5	0	10	66.2	0.11	56.8	43.8	830	890.2	3.398	2.91	204.15	983.13	12.4	9.964
4	50	2	2.5	0	15	64.7	0.11	49.2	41.8	826	867.6	3.482	3.058	221.49	1040.96	8.1	7.82
5	50	2	2.5	5	0	67.1	0.11	51.2	49.2	814.6	907	3.542	3.294	267	1387.9	10.2	8.584
6	50	2	2.5	5	5	64.1	0.11	54.2	42	862	927.2	3.604	3.24	255.36	1445.7	10.9	8.692
7	50	2	2.5	5	10	65.2	0.1	49.8	32.8	955	976.8	3.56	3.154	244.54	809.6	9.8	8.322
8	50	2	2.5	5	15	65.2	0.11	53.8	33.8	876	947.4	3.572	3.198	250.95	2024.09	11.5	8.144
9	50	2	2.5	10	0	64.4	0.1	56.2	48.6	892	891.8	3.672	3.348	275.86	1677.1	11.9	8.396
10	50	2	2.5	10	5	65.3	0.11	53.6	46.8	873.2	920	3.668	3.364	278.29	1561.4	11.3	8.97
11	50	2	2.5	10	10	64.3	0.11	50	47.6	927	949.4	3.644	3.3625	274.43	1619.2	10.8	9.112
12	50	2	2.5	10	15	64.5	0.11	49.2	47	927.4	969.4	3.612	3.374	272.27	1966.2	12.9	9.784
13	50	2	2.5	15	0	64.5	0.1	52.2	47.2	909	910.2	3.652	3.342	272.88	1734.9	13.4	8.644
14	50	2	2.5	15	5	64.9	0.11	52	51.4	805	878.6	3.722	3.468	296.79	1734.9	12.9	8.856
15	50	2	2.5	15	10	65.2	0.11	49.4	47.4	947.6	925.6	3.648	3.37	280.17	1619.2	13.2	8.67
16	50	2	2.5	15	15	66	0.11	50.6	50	895.6	895.6	3.556	3.278	262.65	1619.2	12.7	7.566

4.2.1 Effect of process parameters on GSM of fabric

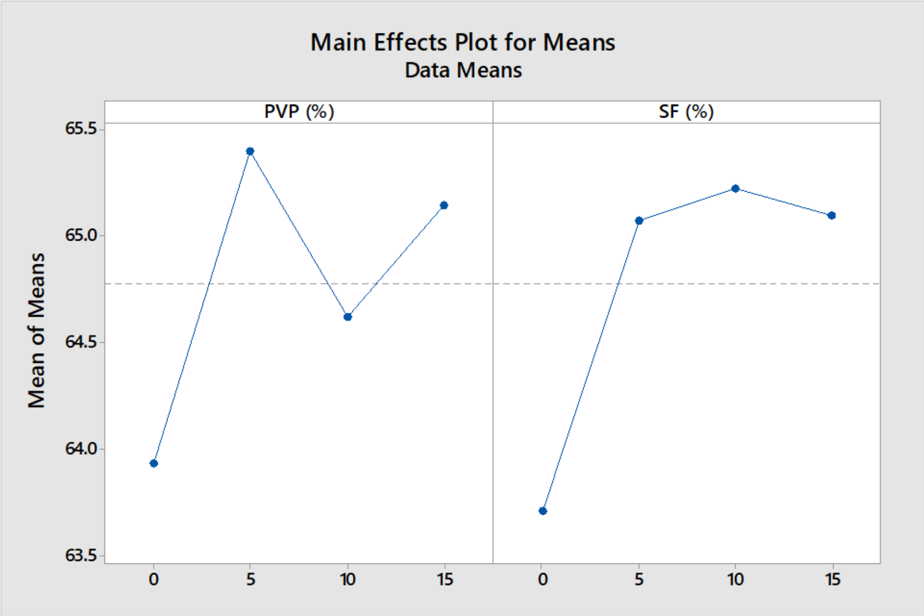

Fig 4.1 Main Effect Plot for GSM

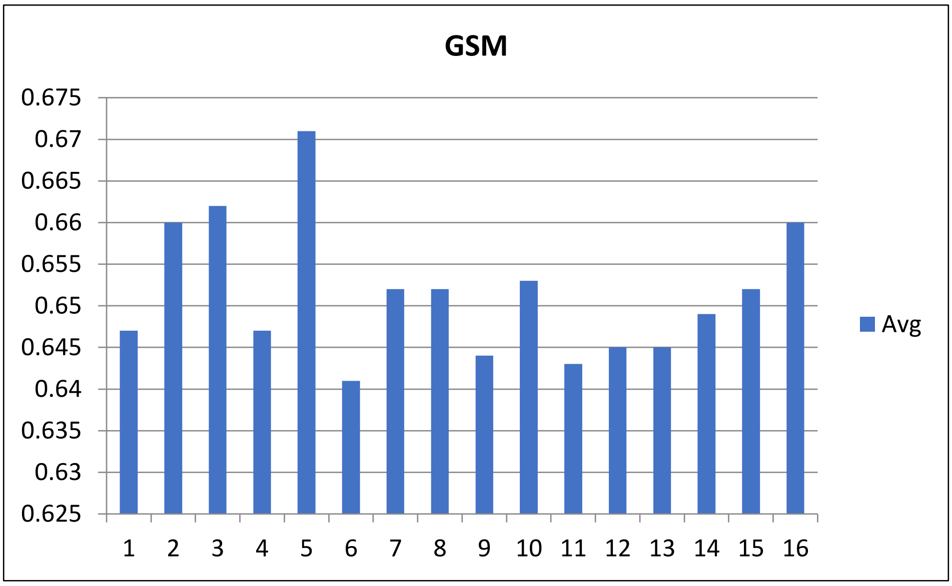

Fig 4.2 Change in GSM

From table 4.1 and fig. 4.1 and fig. 4.2, it is observed that there is no significant effect of the concentration of silk fibroin on the GSM of fabric. Also, it is observed that the rise in the GSM of the fabric is more in the case of varying concentrations of silk fibroin ($p=0.725$) as compared to the varied concentration of the PVP ($p=0.780$). In this set of experiments, the other parameters such as concentration of water-soluble PU, cross-linking agent and thickener are used for the coating kept constant.

4.2.2. Effect of process parameters on Thickness of fabric

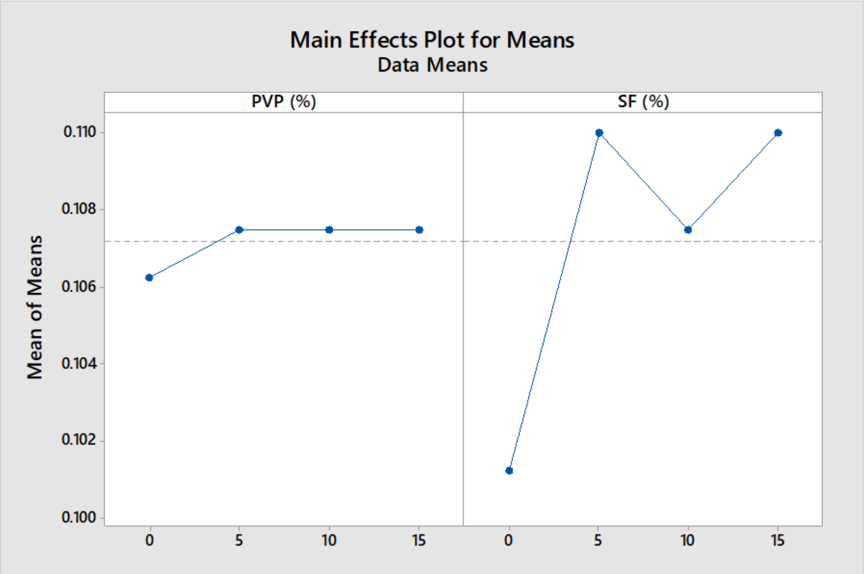

Fig 4.3 Main Effect Plot for Thickness

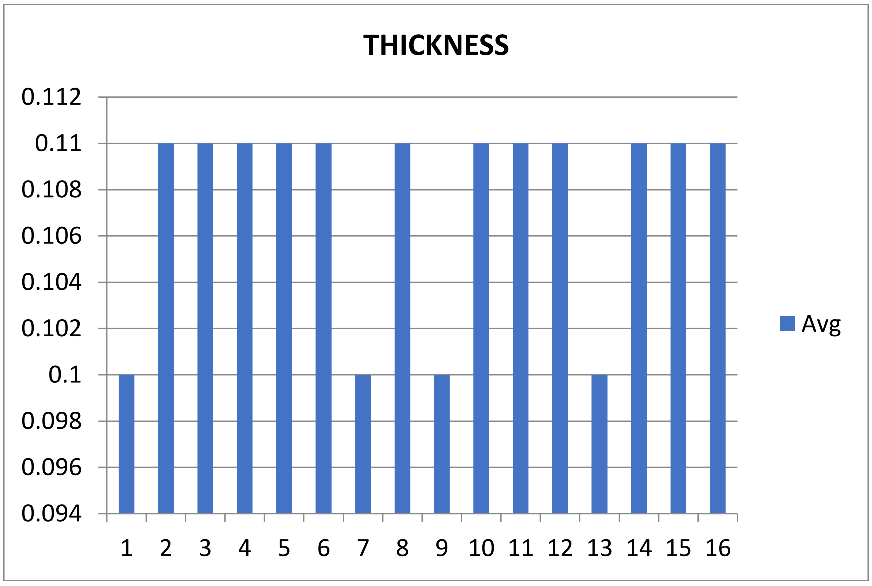

Fig 4.4 Change in Thickness

From table 4.1 and fig. 4.3 and fig. 4.4, it is observed that there is a significant effect of concentration of silk fibroin on the thickness of fabric ($p = 0.057$) at a 5% level of significance. This may be because, in presence of PVP and silk fibroin, the water-soluble PU gets modified and causes swelling of the coat deposited onto the surface of the polyester fabric. Also, it is observed that as the concentration of silk fibroin as well as the concentration of PVP increases, there is an increase in the thickness of the fabric is observed. In this set of experiments, the other parameters such as concentration of water-soluble PU, cross-linking agent and thickener are used for the coating kept constant.

4.2.3. Effect of process parameters on Tensile Strength of fabric (warp way)

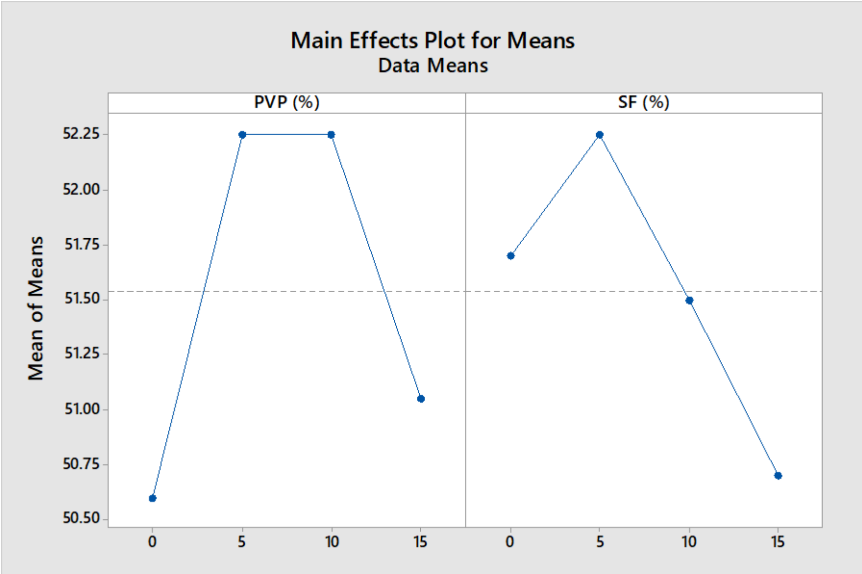

Fig 4.5 Main Effect Plot for Tensile Strength (Warp Way)

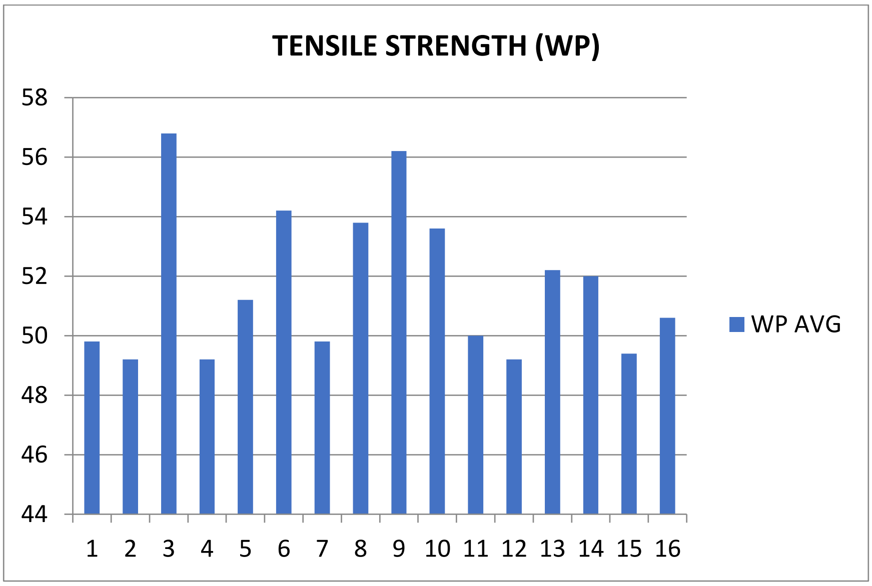

Fig 4.6 Change in Tensile Strength (Warp Way)

From table 4.1 and fig. 4.5 and fig. 4.6, it is observed that there is no significant effect of the concentration of silk fibroin and PVP on the tearing strength of the fabric. Also, it is observed that change in the tensile strength of the fabric in warp way is affected more in the case of varied concentration of PVP ($p=0.732$) as compared to the varied concentration of the silk fibroin ($p=0.929$). In this set of experiments, the other parameters such as concentration of water-soluble PU, cross-linking agent and thickener are used for the coating kept constant.

4.2.4. Effect of process parameters on Tensile Strength of fabric (weft way)

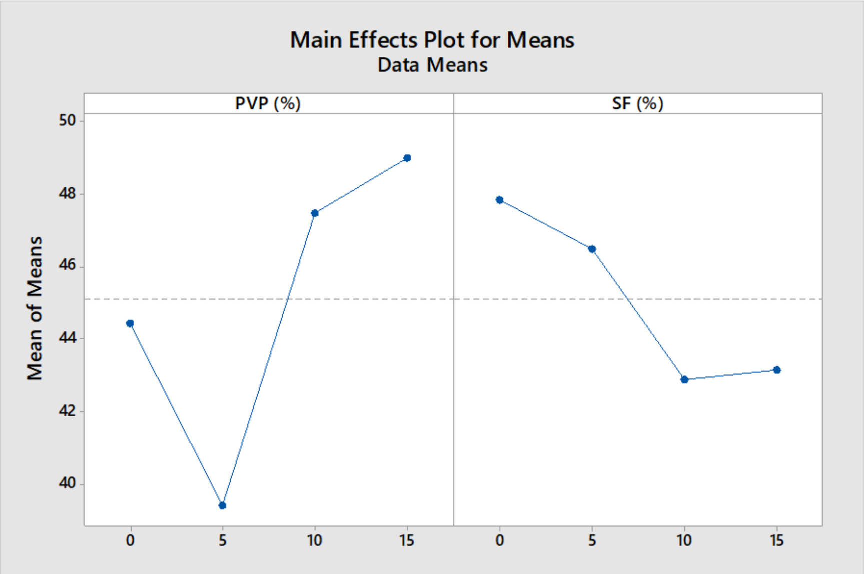

Fig 4.7 Main Effect Plot for Tensile Strength (Weft Way)

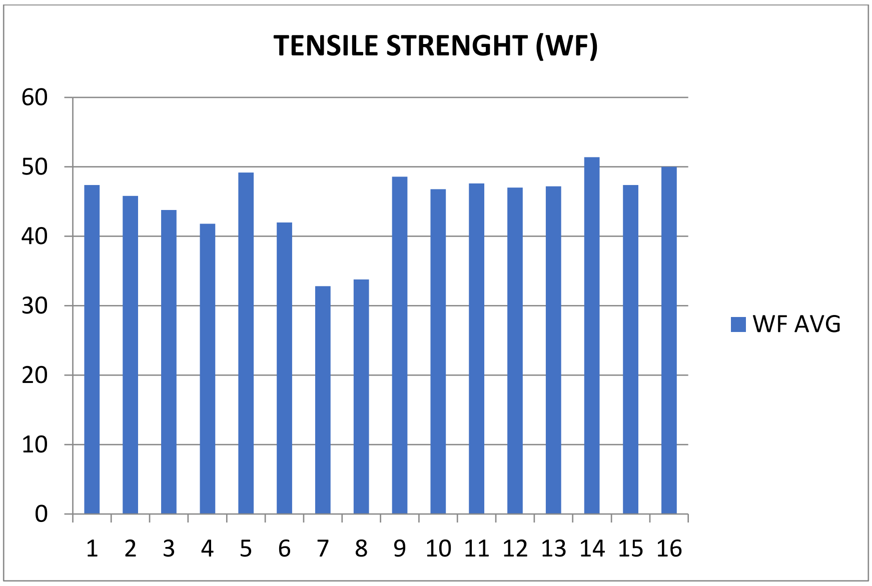

Fig 4.8 Change in Tensile Strength (Weft Way)

From table 4.1 and fig. 4.7 and fig. 4.8, it is observed that there is a significant effect of concentration of silk fibroin on the tensile strength of fabric in a weft way ($p = 0.019$) at a 5% level of significance. This may be because, in presence of PVP and silk fibroin, the water-soluble PU gets modified and improves the breaking force of the coated fabric in a weft way. Also, it is observed that as the concentration of silk fibroin as well as the concentration of PVP increases, there is an increase in the tensile strength of the fabric in the weft way is observed. In this set of experiments, the other parameters such as concentration of water-soluble PU, cross-linking agent and thickener are used for the coating kept constant.

4.2.5. Effect of process parameters on Tearing Strength of fabric (warp way)

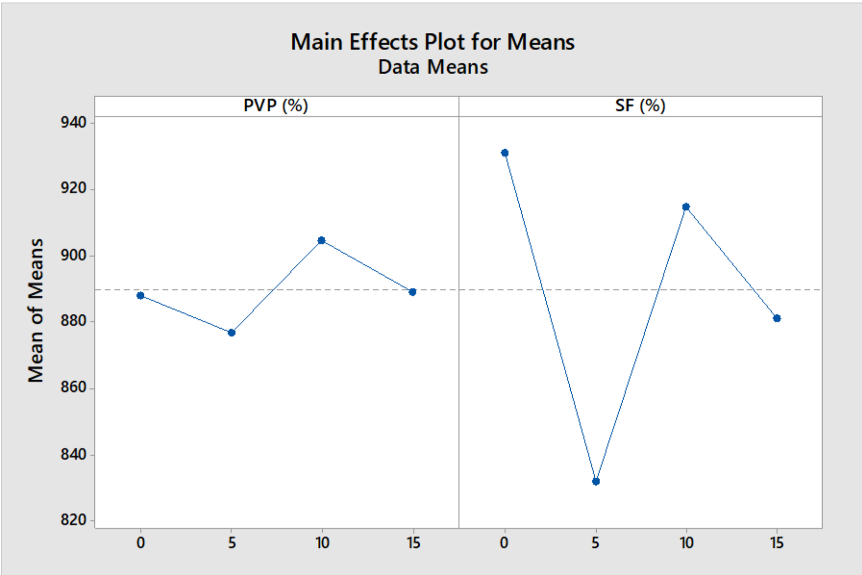

Fig 4.9 Main Effect Plot for Tearing Strength (Warp Way)

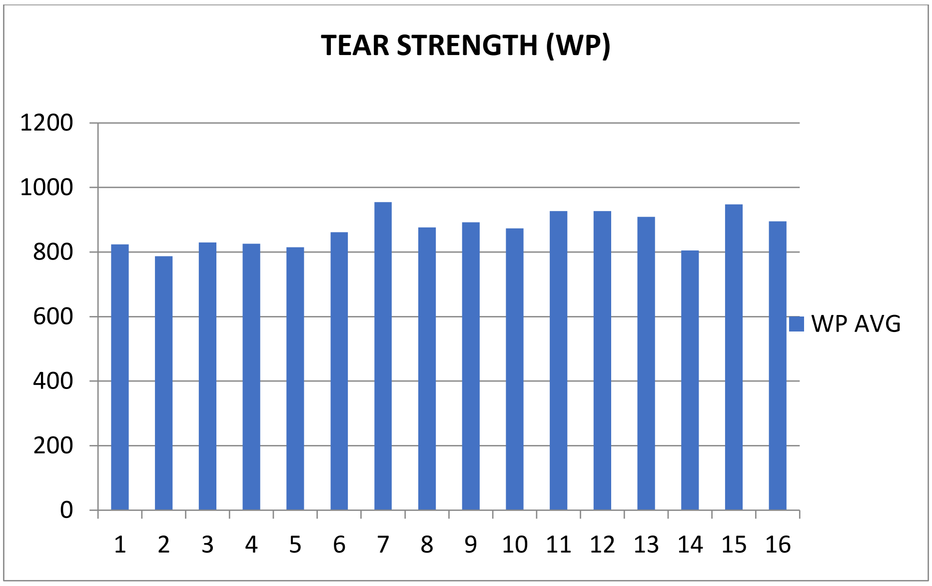

Fig 4.10 Change in Tearing Strength (Warp Way)

From table 4.1 and fig. 4.9 and fig. 4.10, it is observed that there is no significant effect of the concentration of silk fibroin and PVP on the tearing strength of the fabric. Also, it is observed that a decrease in the tearing strength of the fabric in warp way is affected more in the case of varied concentration of PVP (p=0.06) as compared to the varied concentration of the silk fibroin (p=0.53). In this set of experiments, the other parameters such as concentration of water-soluble PU, cross-linking agent and thickener are used for the coating kept constant. Also, PVP causes stiffing of fabric, resulting in decrease in tear strength of the fabric.

4.2.6. Effect of process parameters on Tearing Strength of fabric (weft way)

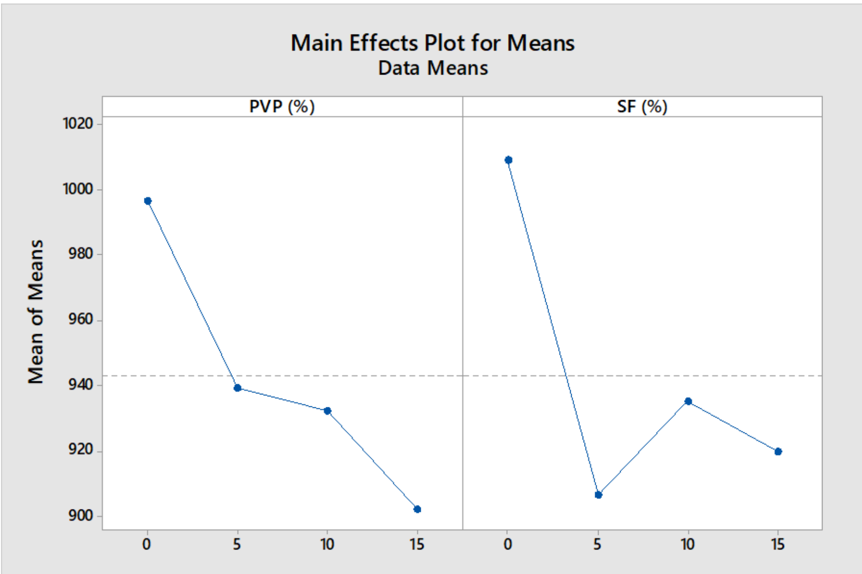

Fig 4.11 Main Effect Plot For Tearing Strength (Weft Way)

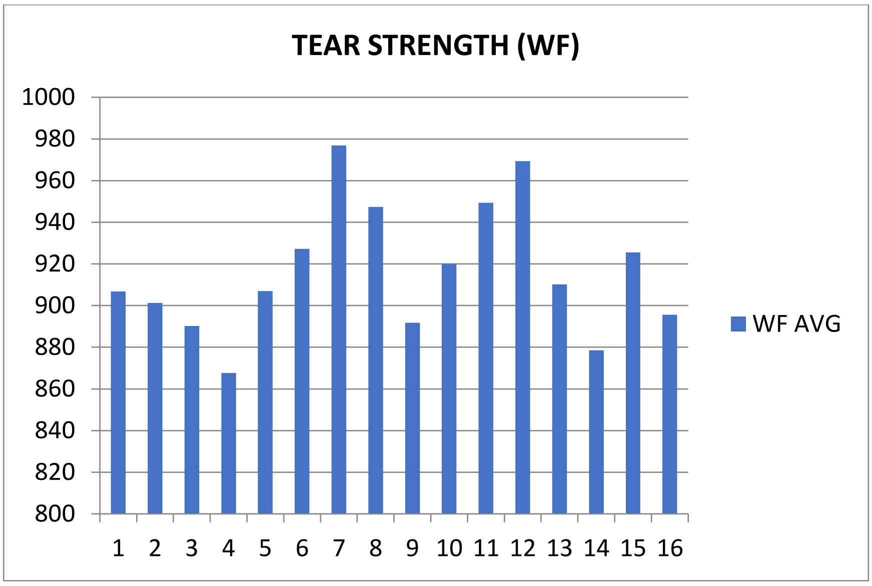

Fig 4.12 Change in Tearing Strength (Weft Way)

From table 4.1 and fig. 4.11 and fig. 4.12, it is observed that there is no significant effect of the concentration of silk fibroin and PVP on the tearing strength of the fabric. Also, it is observed that a decrease in the tearing strength of the fabric in the weft way is affected more in the case of varying concentrations of Silk fibroin ($p=0.755$) as compared to the varied concentration of the PVP ($p=0.811$). In this set of experiments, the other parameters such as concentration of water-soluble PU, cross-linking agent and thickener are used for the coating kept constant.

4.2.7. Effect of process parameters on Bending Length of fabric (warp way)

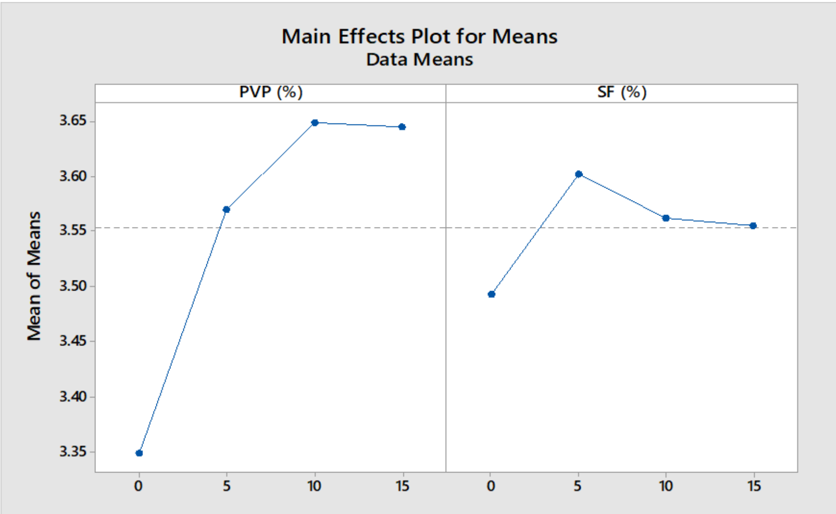

Fig 4.13 Main Effect Plot for Bending Length (Warp Way)

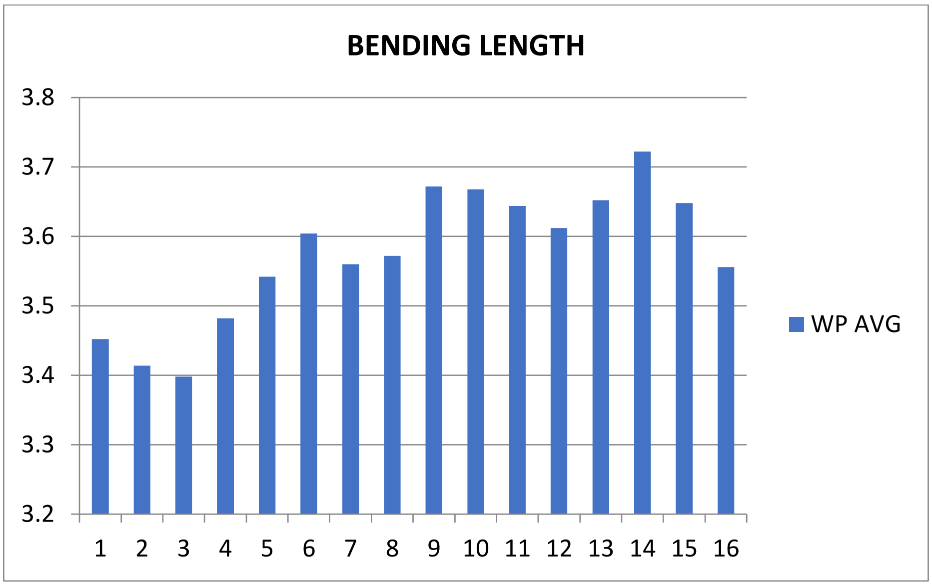

Fig 4.14 Change in Bending Length (Warp Way)

From table 4.1 and fig. 4.13 and fig. 4.14, it is observed that there is a significant effect of concentration of PVP on the bending length of fabric in warp way (p = 0.068) at a 5% level of significance. This may be because, in presence of PVP and silk fibroin, the water-soluble PU gets modified and provides more stiffness to the coated fabric in a warp way. Also, it is observed that as the concentration of silk fibroin as well as the concentration of PVP increases, there is an increase in the bending length of the fabric in warp way is observed. In this set of experiments, the other parameters such as concentration of water-soluble PU, cross-linking agent and thickener are used for the coating kept constant.

4.2.8. Effect of process parameters on Bending Length of fabric (weft way)

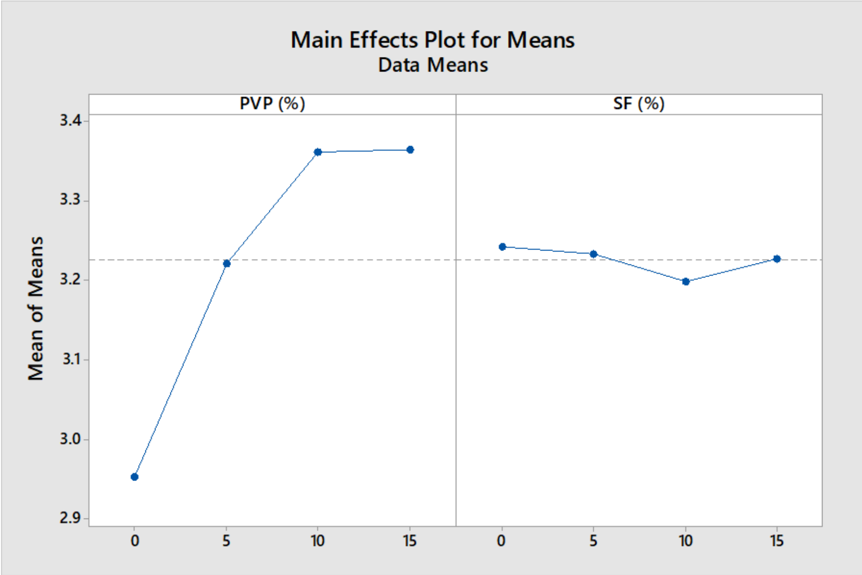

Fig 4.15 Main Effect Plot for Bending Length (Weft Way)

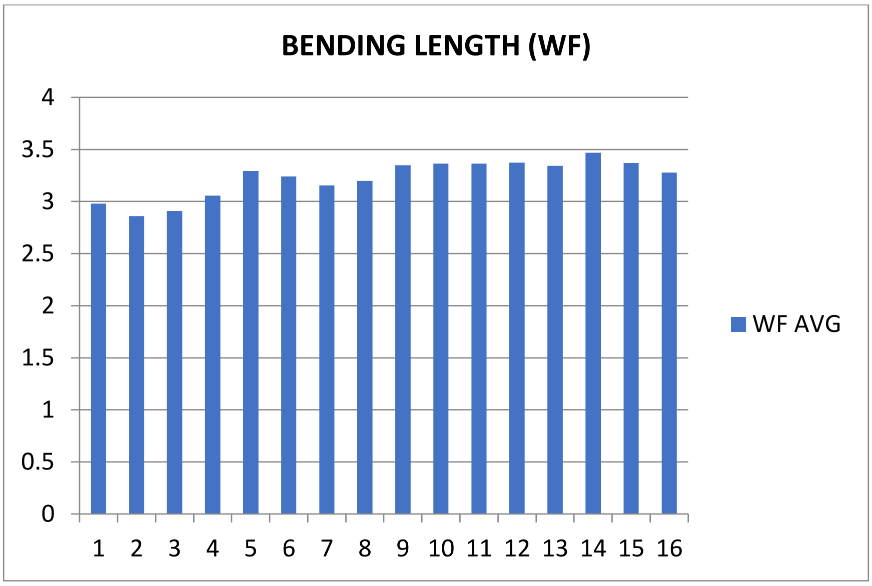

Fig 4.16 Change in Bending Length (Weft Way)

From table 4.1 and fig. 4.15 and fig. 4.16, it is observed that there is a significant effect of concentration of PVP on the bending length of fabric in the weft way (p = 0.000) at a 5% level of significance. This may be because, in presence of PVP and silk fibroin, the water-soluble PU gets modified and provides more stiffness to the coated fabric in a warp way. Also, it is observed that as the concentration of silk fibroin as well as the concentration of PVP increases, there is an increase in the bending length of the fabric in the weft way is observed. In this set of experiments, the other parameters such as concentration of water-soluble PU, cross-linking agent and thickener are used for the coating kept constant.

4.2.9. Effect of process parameters on Flexural Rigidity of fabric

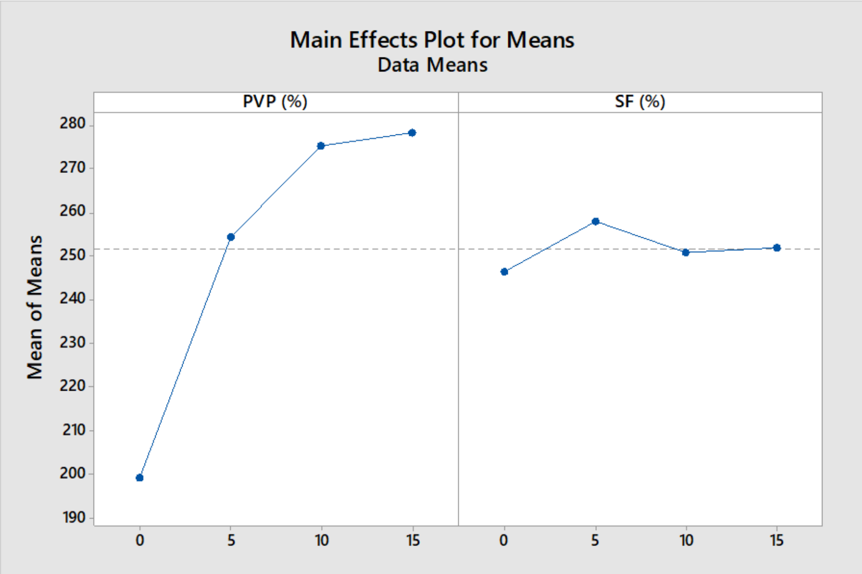

Fig 4.17 Main Effect Plot for Flexural Rigidity

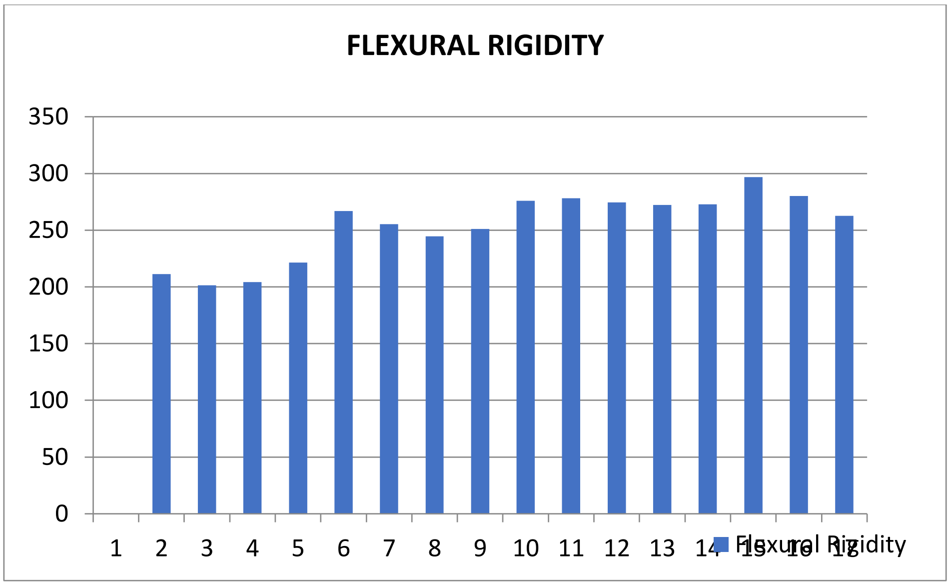

Fig 4.18 Change in Flexural Rigidity

From table 4.1 and fig. 4.17 and fig. 4.18, it is observed that there is a significant effect of concentration of PVP on the bending length of fabric in the weft way ($p = 0.001$) at a 5% level of significance. This may be because, in presence of PVP and silk fibroin, the water-soluble PU gets modified and enhances the bending length of coated fabric. Also, it is observed that as the concentration of silk fibroin as well as the concentration of PVP increases, there is an increase in the flexural rigidity of the fabric in the weft way is observed. In this set of experiments, the other parameters such as concentration of water-soluble PU, cross-linking agent and thickener are used for the coating kept constant.

4.2.10. Effect of process parameters on Water Vapour Permeability of fabric

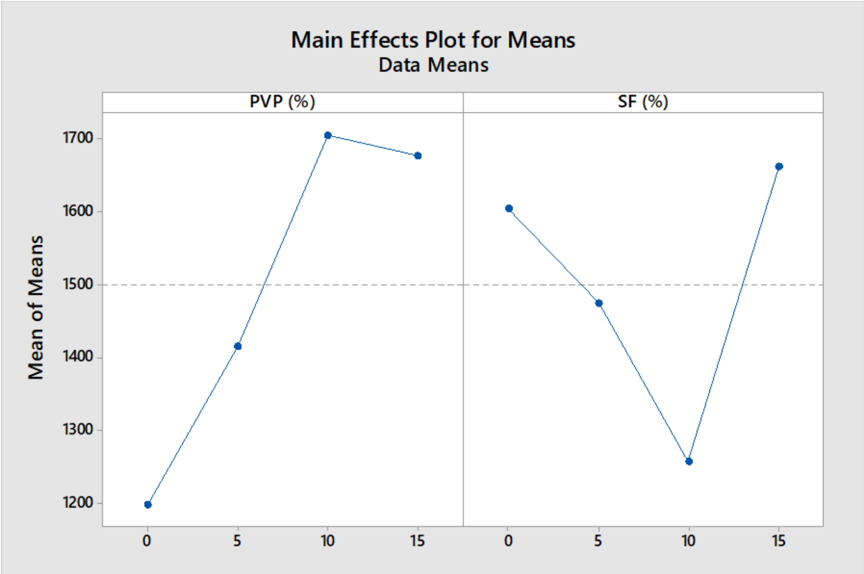

Fig 4.19 Main Effect Plot for Water Vapor Permeability

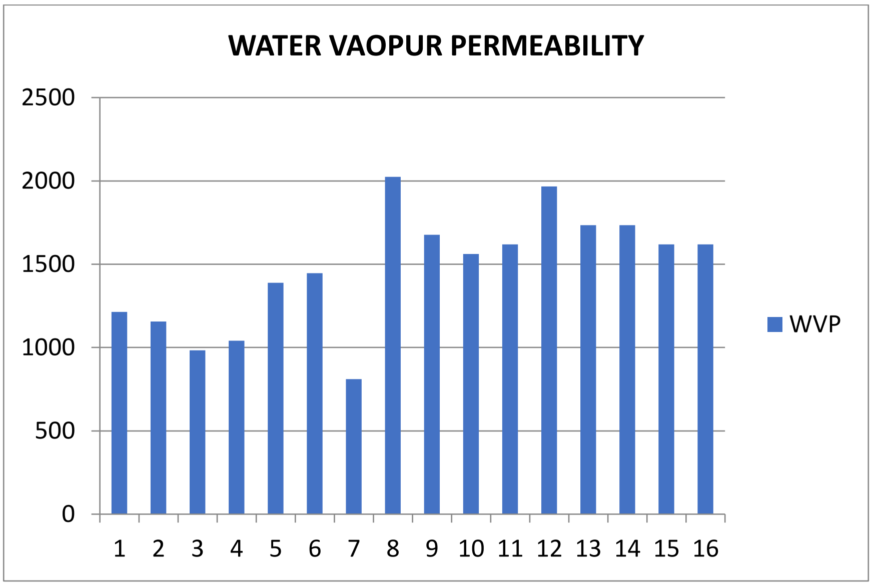

Fig 4.20 Change in Water Vapor Permeability

From table 4.1 and fig. 4.19 and fig. 4.20, it is observed that there is no significant effect of concentration of silk fibroin and PVP on water vapour permeability of the coated fabric. Also, it is observed that an increase in the water vapour permeability of the coated fabric is affected more in the case of varying concentrations of PVP (p=0.203) as compared to the varied concentration of the silk fibroin (p=0.305). In this set of experiments, the other parameters such as concentration of water-soluble PU, cross-linking agent and thickener are used for the coating kept constant.

4.2.11. Effect of process parameters on Hydrostatic Head Pressure of fabric

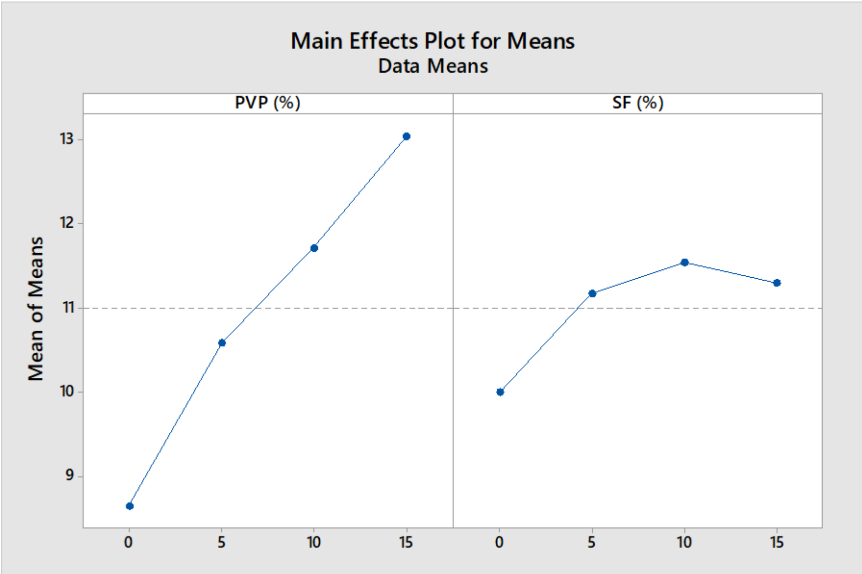

Fig 4.21 Main Effect Plot for Hydrostatic Head pressure

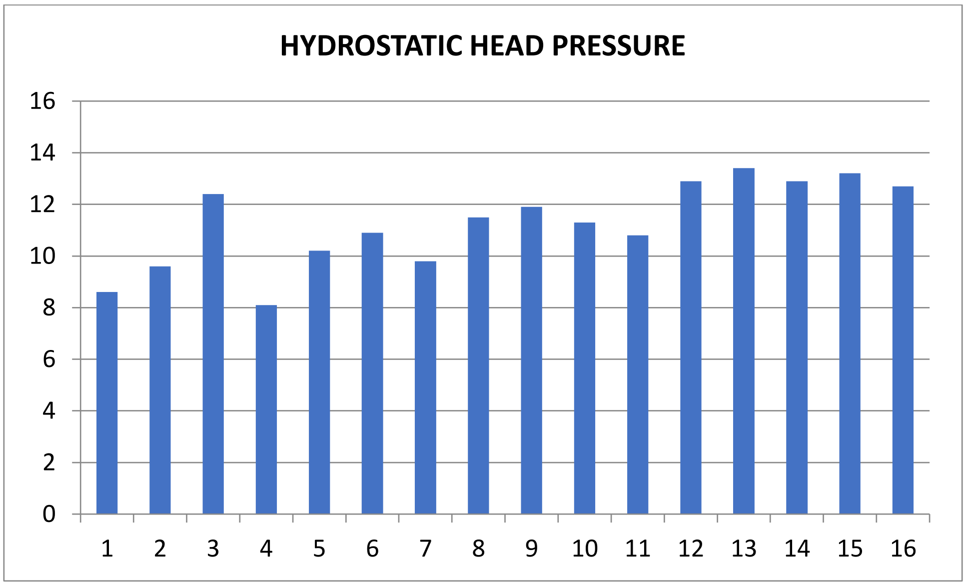

Fig 4.22 Change in Hydrostatic Head Pressure

From table 4.1 and fig. 4.21 and fig. 4.22, it is observed that there is no significant effect of concentration of silk fibroin and PVP on the hydrostatic head pressure of fabric. Also, it is observed that an increase in the hydrostatic head pressure of the coated fabric increases more in the case of varying concentrations of PVP (p=0.097) as compared to the varied concentration of the silk fibroin (p=0.638). In this set of experiments, the other parameters such as concentration of water-soluble PU, cross-linking agent and thickener are used for the coating kept constant.

4.2.12. Effect of process parameters on the air permeability of the fabric

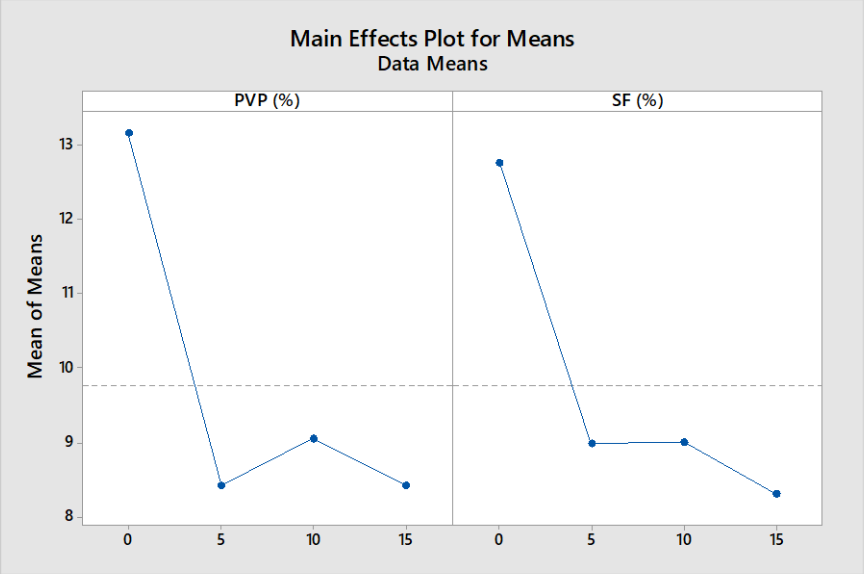

Fig 4.23 Main Effect Plot for Air Permeability

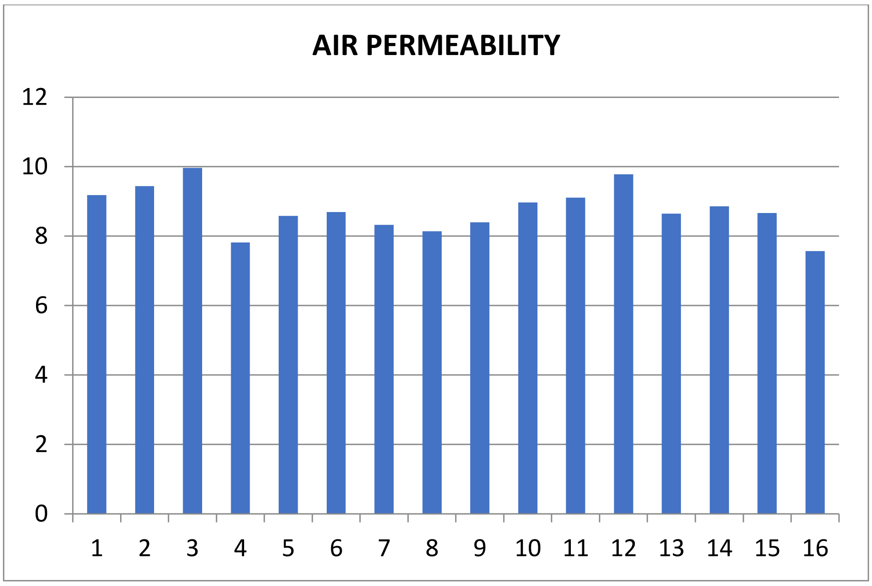

Fig 4.24 Change in Air Permeability

From table 4.1 and fig. 4.23 and fig. 4.24, it is observed that there is no significant effect of the concentration of silk fibroin and PVP on the air permeability of the fabric. Also, it is observed that an increase in the air permeability of the coated fabric increases more in the case of varying concentrations of PVP (p=0.638) as compared to the varied concentration of the silk fibroin (p=0.697). In this set of experiments, the other parameters such as concentration of water-soluble PU, cross-linking agent and thickener are used for the coating kept constant.

Chapter 5
CONCLUSIONS

In present study on waterproof breathable coating on polyester by incorporation of silk fibroin and PVP in coating formulations reveals change in the properties of coated fabric. From the above experimental results, following conclusions are drawn:

1. As varying concentration of silk fibroin and PVP is added to the recipe, there is no significant effect of the concentration of silk fibroin on the GSM of fabric.
2. As varying concentration of silk fibroin and PVP is added to the recipe, it is observed that there is no effect PVP on thickness of the fabric. But there is significant effect of silk fibroin on thickness of fabric.
3. It is observed that varying concentration of PVP has more effect than the silk fibroin on the tensile strength of the fabric. This may be because, in presence of PVP and silk fibroin, the water-soluble PU gets modified and improves the breaking force of the coated fabric in a weft way.
4. It is observed that varying concentration of PVP has more effect than the silk fibroin on the tear strength of the fabric both in warp and weft way.
5. As concentration of PVP increases there is increase in bending length of the fabric both in warp and weft, which results in increase in flexural rigidity of fabric.
6. There is no significant effect of concentration of silk fibroin and PVP on water vapour permeability of the coated fabric.
7. There is no significant effect of concentration of silk fibroin and PVP on the hydrostatic head pressure of fabric. In this PVP has more effect than silk fibroin on the hydrostatic head pressure of fabric.
8. There is no significant effect of concentration of silk fibroin and PVP on the air permeability of fabric. In this PVP has more effect than silk fibroin on the hydrostatic head pressure of fabric.

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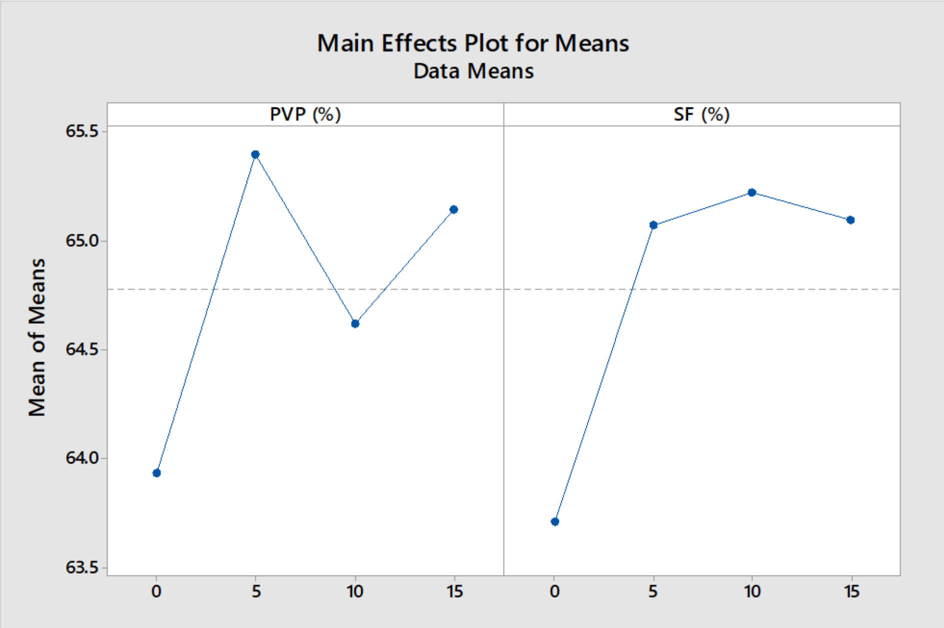
ANNEXURE

GSM

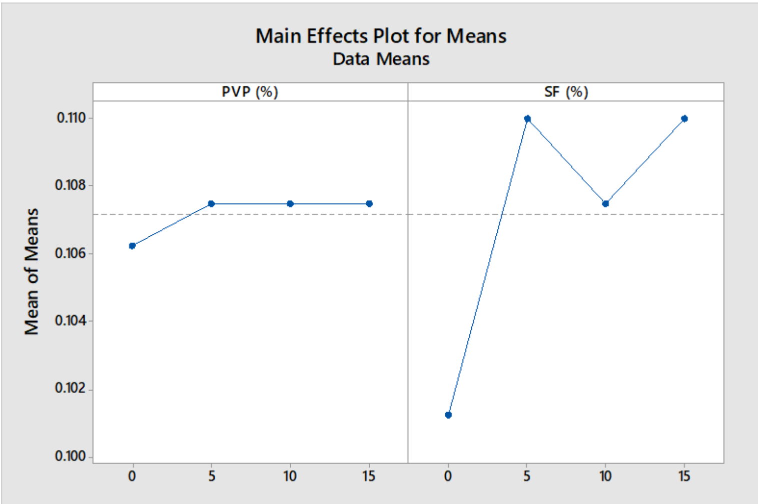


General Linear Model: GSM versus PVP (%), SF (%)

```
Method

Factor coding  (-1, 0, +1)


Factor Information

Factor    Type   Levels  Values
PVP (%)   Fixed       4  0, 5, 10, 15
SF (%)    Fixed       4  0, 5, 10, 15


Analysis of Variance

Source          DF  Adj SS  Adj MS  F-Value  P-Value
  PVP (%)        3   12.68   4.228     0.36    0.780
  SF (%)         3   15.56   5.187     0.45    0.725
Error           10  115.92  11.592
  Lack-of-Fit    9   47.48   5.275     0.08    0.994
  Pure Error     1   68.45  68.445
Total           16  148.88


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
3.40476  22.13%      0.00%       0.00%
```

```
Coefficients

Term          Coef  SE Coef  T-Value  P-Value   VIF
Constant    64.603    0.832    77.60    0.000
PVP (%)
  0          -1.37     1.37    -0.99    0.344  1.46
  5           0.80     1.46     0.54    0.598  1.48
  10          0.02     1.46     0.01    0.988  1.48
SF (%)
  0          -1.59     1.37    -1.16    0.274  1.46
  5           0.47     1.46     0.32    0.754  1.48
  10          0.62     1.46     0.42    0.680  1.48


Regression Equation

GSM = 64.603 - 1.37 PVP (%)_0 + 0.80 PVP (%)_5 + 0.02 PVP (%)_10 + 0.55 PVP (%)_15
      - 1.59 SF (%)_0 + 0.47 SF (%)_5 + 0.62 SF (%)_10 + 0.50 SF (%)_15


Fits and Diagnostics for Unusual Observations

Obs    GSM    Fit  Resid  Std Resid
  1  53.00  61.65  -8.65      -3.05  R

R  Large residual
```

Thickness



General Linear Model: Thickness versus PVP (%), SF (%)

```
Method

Factor coding  (-1, 0, +1)


Factor Information

Factor   Type   Levels  Values
PVP (%)  Fixed       4  0, 5, 10, 15
SF (%)   Fixed       4  0, 5, 10, 15
```

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
PVP (%)	3	0.000016	0.000005	0.21	0.887
SF (%)	3	0.000286	0.000095	3.69	0.051
Error	10	0.000259	0.000026		
Lack-of-Fit	9	0.000209	0.000023	0.46	0.824
Pure Error	1	0.000050	0.000050		
Total	16	0.000588			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0050862	56.02%	29.63%	0.00%

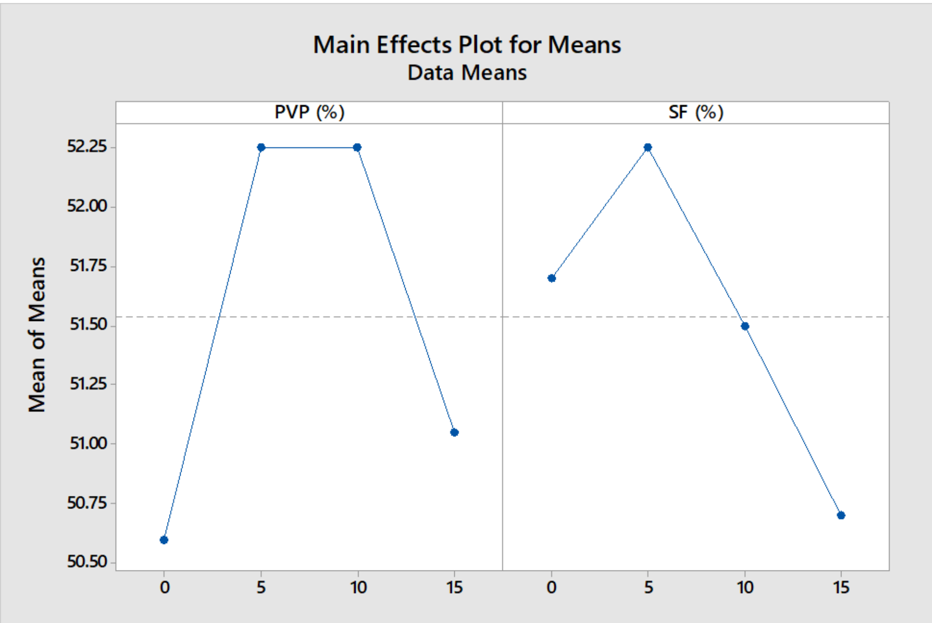
Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.10696	0.00124	86.01	0.000	
PVP (%)					
0	-0.00163	0.00205	-0.79	0.446	1.46
5	0.00054	0.00219	0.25	0.809	1.48
10	0.00054	0.00219	0.25	0.809	1.48
SF (%)					
0	-0.00663	0.00205	-3.23	0.009	1.46
5	0.00304	0.00219	1.39	0.194	1.48
10	0.00054	0.00219	0.25	0.809	1.48

Regression Equation

```
Thickness = 0.10696 - 0.00163 PVP (%)_0 + 0.00054 PVP (%)_5 + 0.00054 PVP (%)_10
            + 0.00054 PVP (%)_15 - 0.00663 SF (%)_0 + 0.00304 SF (%)_5
+ 0.00054 SF (%)_10
            + 0.00304 SF (%)_15
```

Tensile Strength (wp)



General Linear Model: Tensile Strength (wp) versus PVP (%), SF (%)

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
PVP (%)	Fixed	4	0, 5, 10, 15
SF (%)	Fixed	4	0, 5, 10, 15

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
PVP (%)	3	15.899	5.300	0.44	0.732
SF (%)	3	5.367	1.789	0.15	0.929
Error	10	121.571	12.157		
Lack-of-Fit	9	108.051	12.006	0.89	0.684
Pure Error	1	13.520	13.520		
Total	16	143.925			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
3.48671	15.53%	0.00%	0.00%

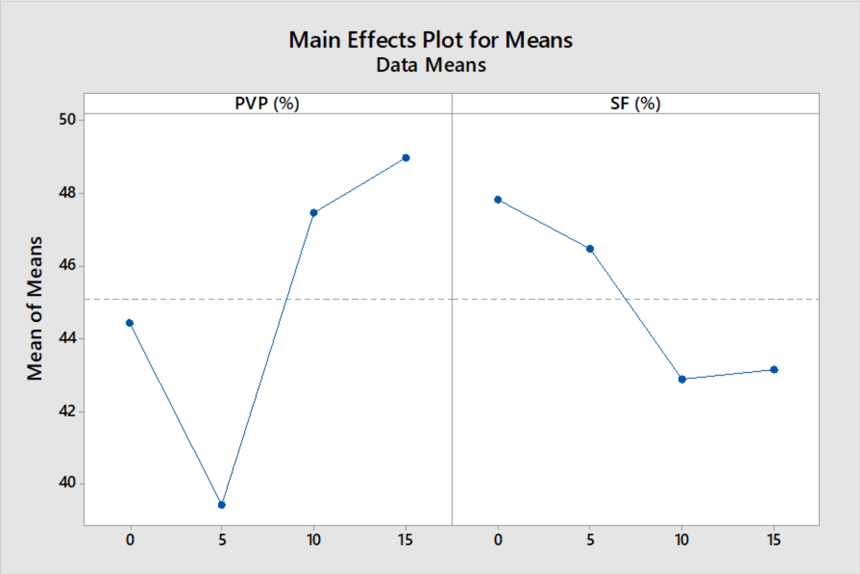
Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	51.383	0.853	60.27	0.000	
PVP (%)					
0	-1.40	1.41	-1.00	0.343	1.46
5	0.87	1.50	0.58	0.576	1.48
10	0.87	1.50	0.58	0.576	1.48
SF (%)					
0	-0.30	1.41	-0.21	0.834	1.46
5	0.87	1.50	0.58	0.576	1.48
10	0.12	1.50	0.08	0.939	1.48

Regression Equation

Tensile Strength (wp) = 51.383 - 1.40 PVP (%)_0 + 0.87 PVP (%)_5 + 0.87 PVP (%)_10 - 0.33 PVP (%)_15 - 0.30 SF (%)_0 + 0.87 SF (%)_5 + 0.12 SF (%)_10 - 0.68 SF (%)_15

Tensile Strength (wt)

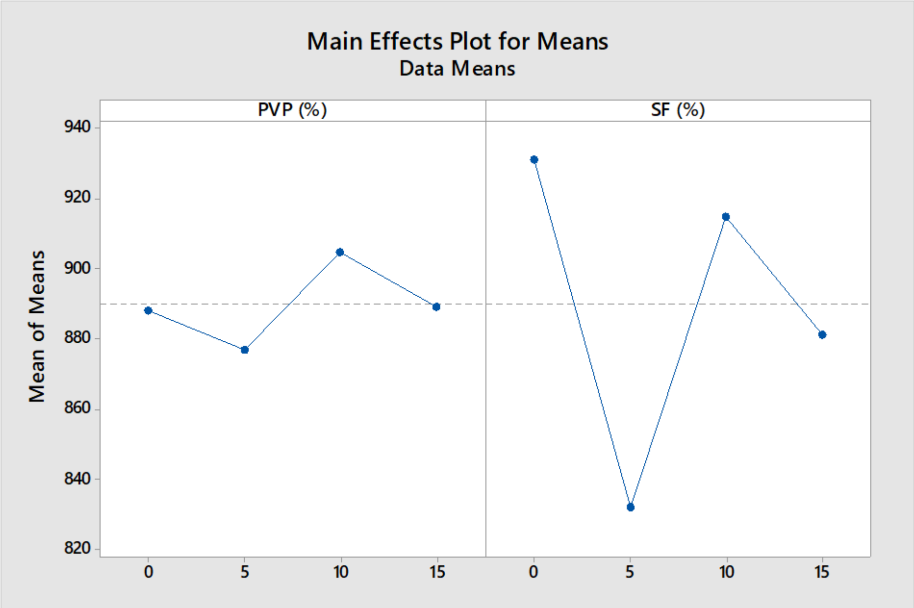


General Linear Model: Tensile Strength (wt) versus PVP (%), SF (%)

```
Method

Factor coding  (-1, 0, +1)


Factor Information

Factor   Type   Levels  Values
PVP (%)  Fixed       4  0, 5, 10, 15
SF (%)   Fixed       4  0, 5, 10, 15


Analysis of Variance

Source          DF   Adj SS  Adj MS  F-Value  P-Value
  PVP (%)        3  214.497  71.499     5.29    0.019
  SF (%)         3   75.257  25.086     1.86    0.201
Error           10  135.085  13.509
  Lack-of-Fit    9  133.085  14.787     7.39    0.278
  Pure Error     1    2.000   2.000
Total           16  422.151


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
3.67539  68.00%     48.80%       4.58%


Coefficients

Term         Coef  SE Coef  T-Value  P-Value   VIF
Constant   45.065    0.899    50.15    0.000
PVP (%)
  0         -0.75     1.48    -0.51    0.622  1.46
  5         -5.62     1.58    -3.55    0.005  1.48
  10         2.43     1.58     1.54    0.154  1.48
SF (%)
  0          2.65     1.48     1.78    0.105  1.46
  5          1.43     1.58     0.91    0.385  1.48
  10        -2.17     1.58    -1.37    0.201  1.48
```

```
Regression Equation

Tensile Strength ( wt) = 45.065 - 0.75 PVP (%)_0 - 5.62 PVP (%)_5
+ 2.43 PVP (%)_10
                         + 3.93 PVP (%)_15 + 2.65 SF (%)_0 + 1.43 SF (%)_5 -
 2.17 SF (%)_10
                         - 1.92 SF (%)_15


Fits and Diagnostics for Unusual Observations

      Tensile
     Strength                   Std
Obs     ( wt)    Fit  Resid  Resid
  6     49.20  42.10   7.10   2.52  R

R  Large residual
```

Tear Strength (wp)

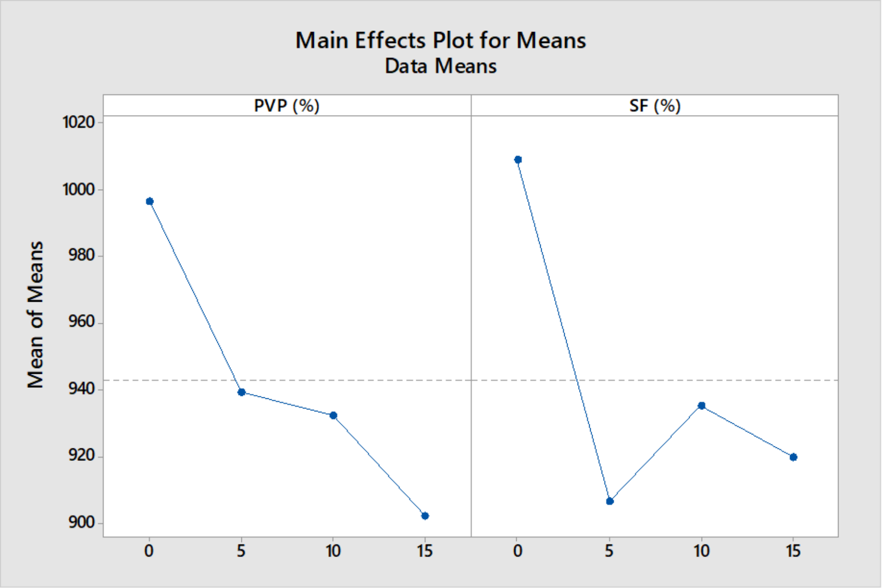


General Linear Model: Tear Strength (wp) versus PVP (%), SF (%)

```
Method

Factor coding  (-1, 0, +1)


Factor Information

Factor   Type   Levels  Values
PVP (%)  Fixed       4  0, 5, 10, 15
SF (%)   Fixed       4  0, 5, 10, 15


Analysis of Variance

Source         DF  Adj SS  Adj MS  F-Value  P-Value
  PVP (%)       3    4491    1497     0.06    0.980
  SF (%)        3   39682   13227     0.53    0.674
```

```
Error             10  251361   25136
  Lack-of-Fit      9   88911    9879      0.06     0.997
  Pure Error       1  162450  162450
Total             16  298854


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
158.544  15.89%      0.00%       0.00%


Coefficients

Term          Coef  SE Coef  T-Value  P-Value   VIF
Constant     897.6     38.8    23.16    0.000
PVP (%)
  0           21.8     64.0     0.34    0.740  1.46
  5          -20.7     68.2    -0.30    0.767  1.48
  10           7.3     68.2     0.11    0.917  1.48
SF (%)
  0           64.8     64.0     1.01    0.335  1.46
  5          -65.7     68.2    -0.96    0.358  1.48
  10          17.3     68.2     0.25    0.805  1.48


Regression Equation

Tear Strength ( wp)  = 897.6 + 21.8 PVP (%)_0 - 20.7 PVP (%)_5 + 7.3 PVP (%)_10
                      - 8.3 PVP (%)_15 + 64.8 SF (%)_0 - 65.7 SF (%)_5
+ 17.3 SF (%)_10
                      - 16.4 SF (%)_15
```

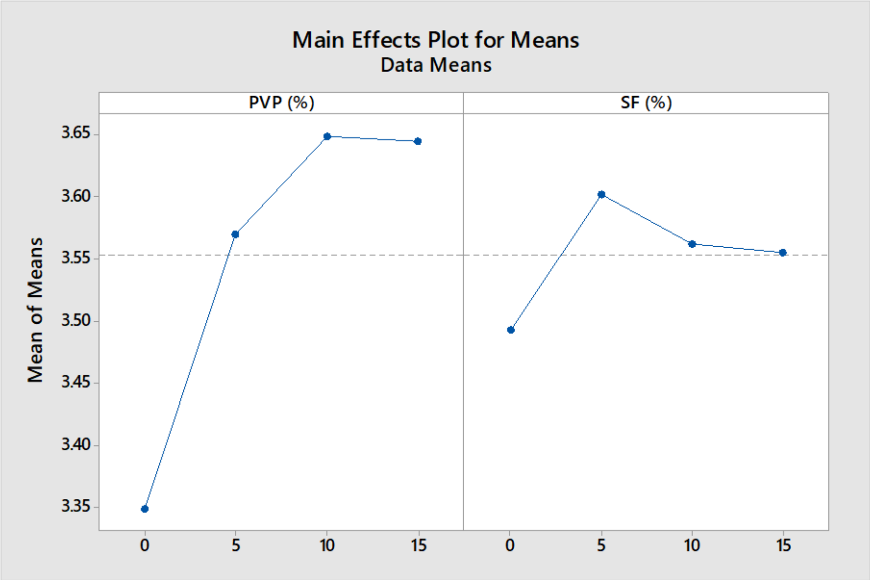
Tear Strength (wt)



General Linear Model: Tear Strength (wt) versus PVP (%), SF (%)

```
Method

Factor coding  (-1, 0, +1)


Factor Information

Factor    Type   Levels  Values
PVP (%)  Fixed       4  0, 5, 10, 15
SF (%)   Fixed       4  0, 5, 10, 15


Analysis of Variance

Source          DF  Adj SS  Adj MS  F-Value  P-Value
  PVP (%)        3   51095   17032     0.32    0.811
  SF (%)         3   64161   21387     0.40    0.755
Error           10  532936   53294
  Lack-of-Fit    9  177948   19772     0.06    0.998
  Pure Error     1  354987  354987
Total           16  667542


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
230.854  20.16%      0.00%       0.00%


Coefficients

Term       Coef  SE Coef  T-Value  P-Value   VIF
Constant  954.4     56.4    16.91    0.000
PVP (%)
  0        88.5     93.2     0.95    0.365  1.46
  5       -14.8     99.2    -0.15    0.884  1.48
  10      -21.8     99.2    -0.22    0.831  1.48
SF (%)
  0       101.0     93.2     1.08    0.304  1.46
  5       -47.6     99.2    -0.48    0.641  1.48
  10      -18.9     99.2    -0.19    0.853  1.48


Regression Equation

Tear Strength ( wt) = 954.4 + 88.5 PVP (%)_0 - 14.8 PVP (%)_5 - 21.8 PVP (%)_10
                      - 51.9 PVP (%)_15 + 101.0 SF (%)_0 - 47.6 SF (%)_5 -
 18.9 SF (%)_10
                      - 34.4 SF (%)_15


Fits and Diagnostics for Unusual Observations

         Tear
     Strength                 Std
Obs      ( wt)   Fit  Resid  Resid
  1       1749  1144    606   3.15  R

R  Large residual
```

Bending Length (wp)

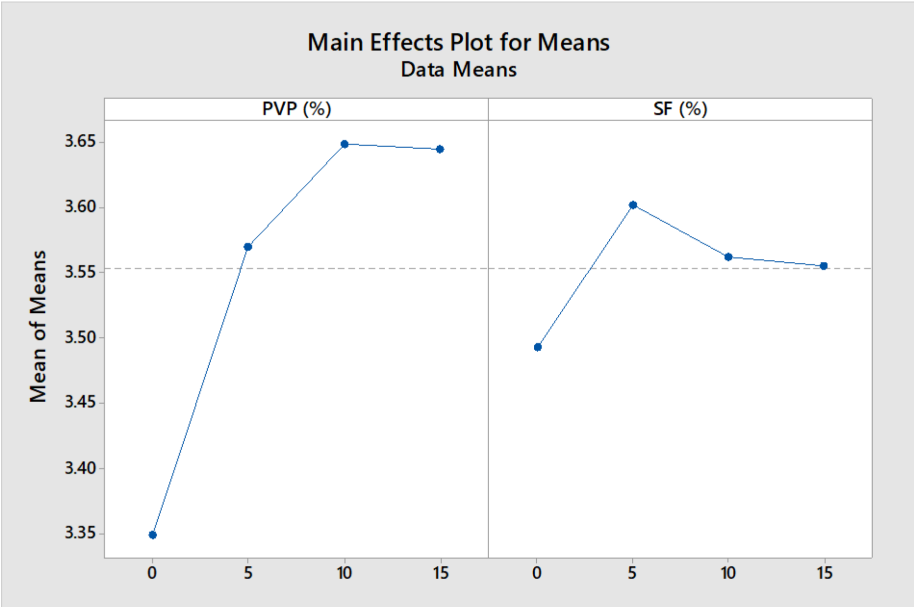


General Linear Model: Tear Strength (wt) versus PVP (%), SF (%)

```
Method

Factor coding  (-1, 0, +1)

Factor Information

Factor   Type   Levels  Values
PVP (%)  Fixed       4  0, 5, 10, 15
SF (%)   Fixed       4  0, 5, 10, 15

Analysis of Variance

Source          DF  Adj SS  Adj MS  F-Value  P-Value
  PVP (%)        3   51095   17032     0.32    0.811
  SF (%)         3   64161   21387     0.40    0.755
Error           10  532936   53294
  Lack-of-Fit    9  177948   19772     0.06    0.998
  Pure Error     1  354987  354987
Total           16  667542


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
230.854  20.16%      0.00%       0.00%


Coefficients

Term        Coef  SE Coef  T-Value  P-Value   VIF
Constant   954.4     56.4    16.91    0.000
PVP (%)
  0         88.5     93.2     0.95    0.365  1.46
  5        -14.8     99.2    -0.15    0.884  1.48
  10       -21.8     99.2    -0.22    0.831  1.48
SF (%)
  0        101.0     93.2     1.08    0.304  1.46
  5        -47.6     99.2    -0.48    0.641  1.48
  10       -18.9     99.2    -0.19    0.853  1.48
```

```
Regression Equation

Tear Strength ( wt) = 954.4 + 88.5 PVP (%)_0 - 14.8 PVP (%)_5 - 21.8 PVP (%)_10
                      - 51.9 PVP (%)_15 + 101.0 SF (%)_0 - 47.6 SF (%)_5 -
 18.9 SF (%)_10
                      - 34.4 SF (%)_15


Fits and Diagnostics for Unusual Observations

         Tear
     Strength                 Std
Obs     ( wt)   Fit  Resid  Resid
  1      1749  1144    606   3.15  R

R  Large residual
```

Bending Length (wp)

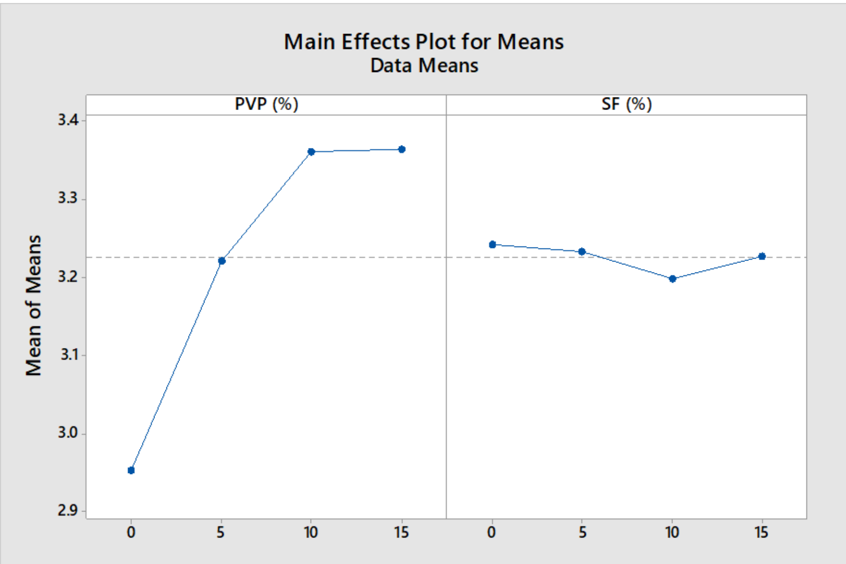


General Linear Model: Bending Length (wp) versus PVP (%), SF (%)

```
Method

Factor coding  (-1, 0, +1)


Factor Information

Factor   Type   Levels  Values
PVP (%)  Fixed       4  0, 5, 10, 15
SF (%)   Fixed       4  0, 5, 10, 15


Analysis of Variance

Source          DF   Adj SS   Adj MS  F-Value  P-Value
  PVP (%)        3  0.33260  0.11087     3.26    0.068
  SF (%)         3  0.04853  0.01618     0.48    0.706
Error           10  0.34013  0.03401
  Lack-of-Fit    9  0.10069  0.01119     0.05    0.999
```

```
  Pure Error     1  0.23943  0.23943
Total           16  0.76557


Model Summary

       S    R-sq  R-sq(adj)  R-sq(pred)
0.184425  55.57%     28.92%       0.30%


Coefficients

Term          Coef  SE Coef  T-Value  P-Value   VIF
Constant    3.5453   0.0451    78.62    0.000
PVP (%)
  0        -0.2272   0.0745    -3.05    0.012  1.46
  5         0.0242   0.0793     0.31    0.766  1.48
  10        0.1037   0.0793     1.31    0.220  1.48
SF (%)
  0        -0.0842   0.0745    -1.13    0.284  1.46
  5         0.0567   0.0793     0.72    0.491  1.48
  10        0.0172   0.0793     0.22    0.832  1.48


Regression Equation

Bending Length ( wp) = 3.5453 - 0.2272 PVP (%)_0 + 0.0242 PVP (%)_5
+ 0.1037 PVP (%)_10
                       + 0.0992 PVP (%)_15 - 0.0842 SF (%)_0 + 0.0567 SF (%)_5
                       + 0.0172 SF (%)_10 + 0.0102 SF (%)_15


Fits and Diagnostics for Unusual Observations

     Bending
      Length
Obs    ( wp)    Fit   Resid  Std Resid
  1    2.760  3.234  -0.474      -3.08  R

R  Large residual
```

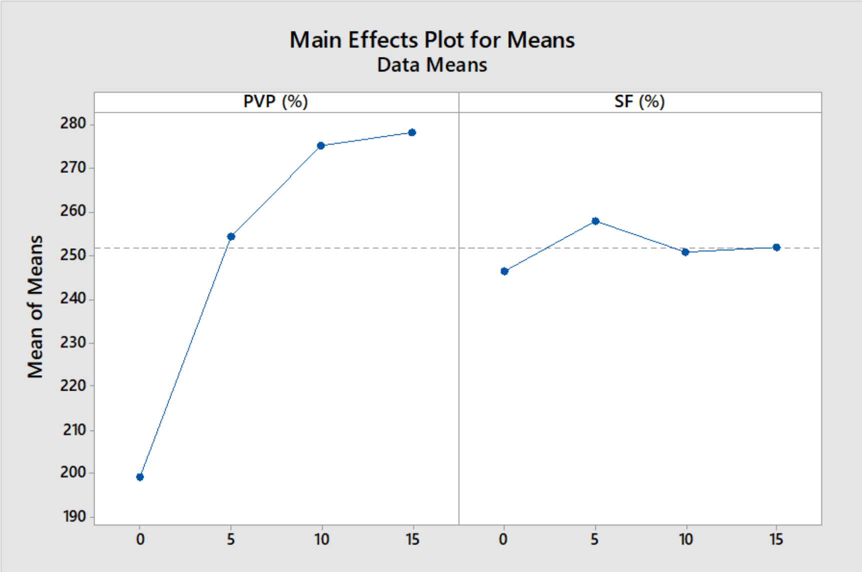
Bending Length (wt)



General Linear Model: Bending Length (wt) versus PVP (%), SF (%)

```
Method

Factor coding  (-1, 0, +1)


Factor Information

Factor    Type   Levels  Values
PVP (%)   Fixed       4  0, 5, 10, 15
SF (%)    Fixed       4  0, 5, 10, 15


Analysis of Variance

Source          DF    Adj SS    Adj MS  F-Value  P-Value
  PVP (%)        3  0.501282  0.167094    34.53    0.000
  SF (%)         3  0.004792  0.001597     0.33    0.804
Error           10  0.048394  0.004839
  Lack-of-Fit    9  0.048344  0.005372   107.43    0.075
  Pure Error     1  0.000050  0.000050
Total           16  0.555240


Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0695656  91.28%     86.05%      73.87%


Coefficients

Term          Coef  SE Coef  T-Value  P-Value   VIF
Constant    3.2260   0.0170   189.66    0.000
PVP (%)
  0        -0.2702   0.0281    -9.62    0.000  1.46
  5        -0.0045   0.0299    -0.15    0.884  1.48
  10        0.1361   0.0299     4.55    0.001  1.48
SF (%)
  0         0.0188   0.0281     0.67    0.518  1.46
  5         0.0070   0.0299     0.23    0.819  1.48
  10       -0.0269   0.0299    -0.90    0.390  1.48


Regression Equation

Bending Length ( wt) = 3.2260 - 0.2702 PVP (%)_0 - 0.0045 PVP (%)_5
+ 0.1361 PVP (%)_10
                       + 0.1385 PVP (%)_15 + 0.0188 SF (%)_0 + 0.0070 SF (%)_5
                       - 0.0269 SF (%)_10 + 0.0010 SF (%)_15
```

Flexural Rigidity

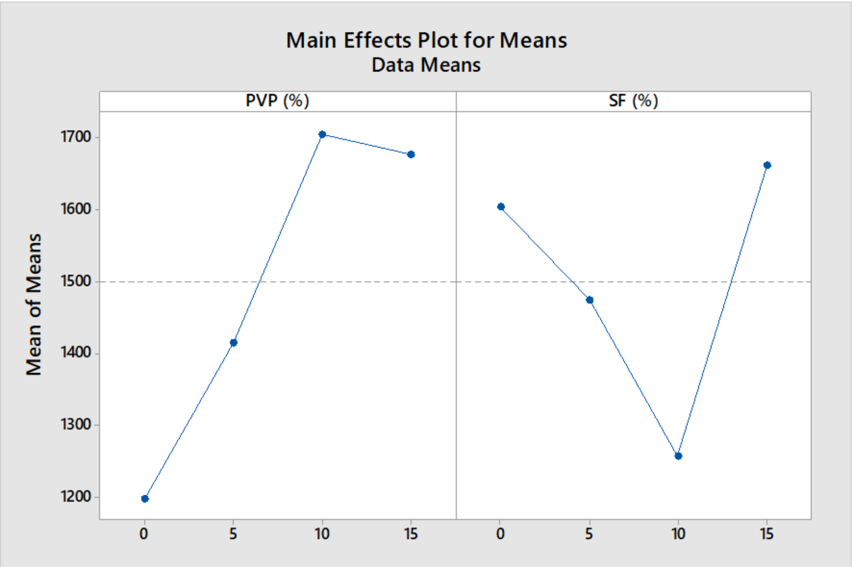


General Linear Model: Flexural Rigidity versus PVP (%), SF (%)

```
Method

Factor coding  (-1, 0, +1)

Factor Information

Factor   Type   Levels  Values
PVP (%)  Fixed       4  0, 5, 10, 15
SF (%)   Fixed       4  0, 5, 10, 15

Analysis of Variance

Source          DF   Adj SS  Adj MS  F-Value  P-Value
  PVP (%)        3  20304.8  6768.3    11.69    0.001
  SF (%)         3    555.1   185.0     0.32    0.811
Error           10   5788.6   578.9
  Lack-of-Fit    9   2410.6   267.8     0.08    0.994
  Pure Error     1   3378.0  3378.0
Total           16  27978.2

Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
24.0594  79.31%     66.90%      51.20%


Coefficients

Term        Coef  SE Coef  T-Value  P-Value   VIF
Constant  250.73     5.88    42.62    0.000
PVP (%)
  0       -55.62     9.71    -5.73    0.000  1.46
  5          3.7     10.3     0.36    0.725  1.48
  10        24.5     10.3     2.37    0.039  1.48
SF (%)
  0        -8.43     9.71    -0.87    0.406  1.46
  5          7.2     10.3     0.70    0.501  1.48
  10         0.1     10.3     0.01    0.993  1.48
```

```
Regression Equation

Flexural Rigidity = 250.73 - 55.62 PVP (%)_0 + 3.7 PVP (%)_5 + 24.5 PVP (%)_10
                    + 27.4 PVP (%)_15 - 8.43 SF (%)_0 + 7.2 SF (%)_5
+ 0.1 SF (%)_10
                    + 1.1 SF (%)_15


Fits and Diagnostics for Unusual Observations

     Flexural
Obs  Rigidity    Fit  Resid  Std Resid
  1     129.0  186.7  -57.7      -2.88  R

R  Large residual
```

Water vapour Permeability

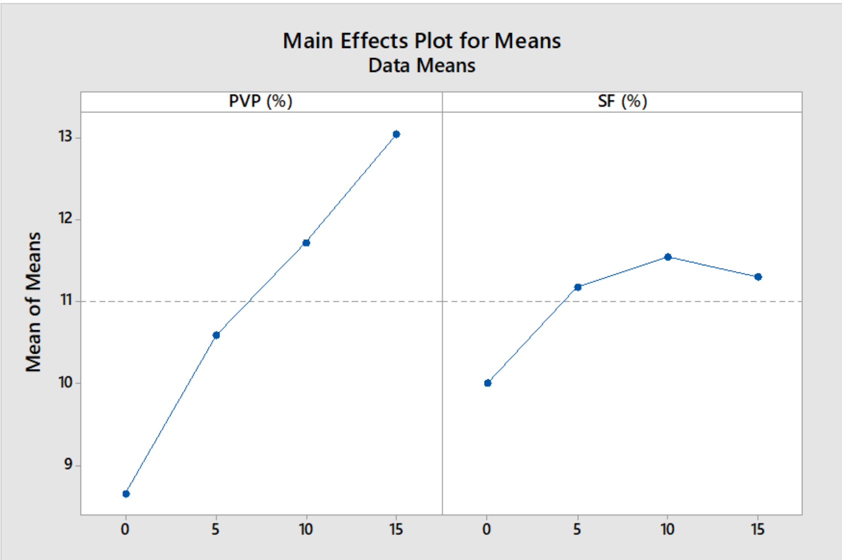


General Linear Model: Water vapour Permeability versus PVP (%), SF (%)

```
Method

Factor coding  (-1, 0, +1)

Factor Information

Factor   Type   Levels  Values
PVP (%)  Fixed       4  0, 5, 10, 15
SF (%)   Fixed       4  0, 5, 10, 15


Analysis of Variance

Source          DF   Adj SS  Adj MS  F-Value  P-Value
  PVP (%)        3   614358  204786     1.85    0.203
  SF (%)         3   458693  152898     1.38    0.305
Error           10  1109295  110929
  Lack-of-Fit    9   781172   86797     0.26    0.916
  Pure Error     1   328123  328123
Total           16  2123737
```

```
Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
333.061  47.77%     16.43%       0.00%


Coefficients

Term         Coef  SE Coef  T-Value  P-Value   VIF
Constant   1513.6     81.4    18.59    0.000
PVP (%)
  0          -259      134    -1.93    0.083  1.46
  5           -97      143    -0.68    0.514  1.48
  10          192      143     1.34    0.209  1.48
SF (%)
  0           146      134     1.08    0.304  1.46
  5           -39      143    -0.27    0.791  1.48
  10         -256      143    -1.79    0.104  1.48


Regression Equation

Water vapour Permeability = 1513.6 - 259 PVP (%)_0 - 97 PVP (%)_5 + 192 PVP (%)_10
                            + 163 PVP (%)_15 + 146 SF (%)_0 - 39 SF (%)_5 -
 256 SF (%)_10
                            + 149 SF (%)_15


Fits and Diagnostics for Unusual Observations

     Water vapour                   Std
Obs  Permeability   Fit  Resid  Resid
  1          2024  1400    624   2.25  R

R  Large residual
```

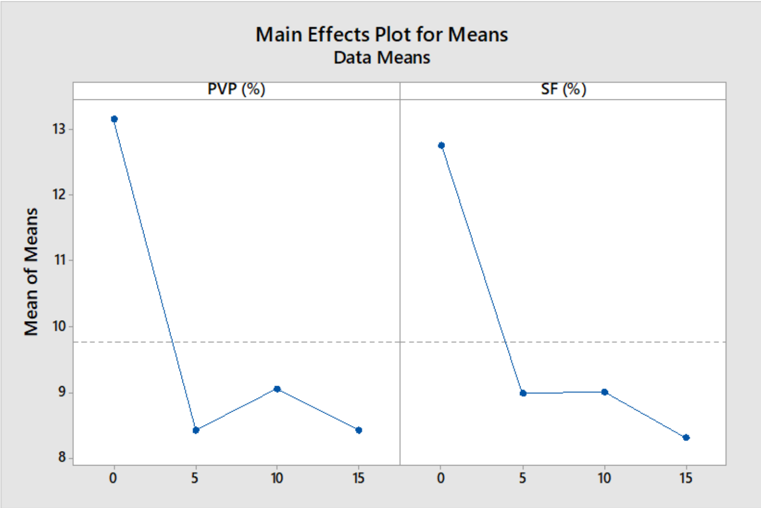
Hydrostatic Head Pressure



General Linear Model: Hydrostatic Head Pressure versus PVP (%), SF (%)

```
Method

Factor coding  (-1, 0, +1)


Factor Information

Factor    Type   Levels  Values
PVP (%)  Fixed        4  0, 5, 10, 15
SF (%)   Fixed        4  0, 5, 10, 15


Analysis of Variance

Source          DF  Adj SS  Adj MS  F-Value  P-Value
  PVP (%)        3   58.53  19.508     2.77    0.097
  SF (%)         3   12.37   4.123     0.58    0.638
Error           10   70.48   7.048
  Lack-of-Fit    9   37.68   4.186     0.13    0.979
  Pure Error     1   32.81  32.805
Total           16  150.00


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
2.65482  53.01%     24.82%       0.00%


Coefficients

Term        Coef  SE Coef  T-Value  P-Value   VIF
Constant  10.874    0.649    16.75    0.000
PVP (%)
  0        -2.75     1.07    -2.57    0.028  1.46
  5        -0.27     1.14    -0.24    0.815  1.48
  10        0.85     1.14     0.75    0.473  1.48
SF (%)
  0        -1.40     1.07    -1.31    0.220  1.46
  5         0.30     1.14     0.26    0.797  1.48
  10        0.68     1.14     0.59    0.567  1.48


Regression Equation

Hydrostatic Head Pressure = 10.874 - 2.75 PVP (%)_0 - 0.27 PVP (%)_5
+ 0.85 PVP (%)_10
                            + 2.18 PVP (%)_15 - 1.40 SF (%)_0 + 0.30 SF (%)_5
                            + 0.68 SF (%)_10 + 0.43 SF (%)_15


Fits and Diagnostics for Unusual Observations

       Hydrostatic
Obs  Head Pressure   Fit  Resid  Std Resid
  1           0.50  6.72  -6.22      -2.81  R

R  Large residual
```

Air Permeability



General Linear Model: Air Permeability versus PVP (%), SF (%)

```
Method

Factor coding  (-1, 0, +1)


Factor Information

Factor   Type   Levels  Values
PVP (%)  Fixed       4  0, 5, 10, 15
SF (%)   Fixed       4  0, 5, 10, 15

Analysis of Variance

Source          DF  Adj SS   Adj MS  F-Value  P-Value
  PVP (%)        3   130.5    43.49     0.59    0.638
  SF (%)         3   109.0    36.35     0.49    0.697
Error           10   742.1    74.21
  Lack-of-Fit    9   215.7    23.97     0.05    0.999
  Pure Error     1   526.4   526.37
Total           16  1023.3


Model Summary

      S    R-sq  R-sq(adj)  R-sq(pred)
8.61448  27.48%      0.00%       0.00%


Coefficients

Term       Coef  SE Coef  T-Value  P-Value   VIF
Constant  10.18     2.11     4.83    0.001
PVP (%)
  0        4.59     3.48     1.32    0.216  1.46
  5       -1.74     3.70    -0.47    0.648  1.48
  10      -1.11     3.70    -0.30    0.770  1.48
SF (%)
  0        4.19     3.48     1.21    0.256  1.46
  5       -1.19     3.70    -0.32    0.755  1.48
  10      -1.16     3.70    -0.31    0.761  1.48
```

```
Regression Equation

Air Permeability = 10.18 + 4.59 PVP (%)_0 - 1.74 PVP (%)_5 - 1.11 PVP (%)_10
                   - 1.74 PVP (%)_15 + 4.19 SF (%)_0 - 1.19 SF (%)_5 -
 1.16 SF (%)_10
                   - 1.85 SF (%)_15


Fits and Diagnostics for Unusual Observations

              Air                  Std
Obs  Permeability    Fit  Resid  Resid
  1         41.63  18.96  22.67   3.15  R

R  Large residual
```