Cape Peninsula
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THE EFFECT OF PROCESS PARAMETERS ON THE QUALITY OF NEEDLE-PUNCHED NONWOVEN COMPONENTS USED IN THE AUTOMOTIVE INDUSTRY

by

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Thesis submitted in fulfilment of the requirements for the Master of Engineering degree

Master of Engineering: Quality

in the Faculty of Engineering and the Built Environment

at the Cape Peninsula University of Technology

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Bellville
February 2025

DECLARATION

I, Nontsikelelo Yvonne Dumakude, declare that the contents of this thesis represent my unaided work and that the thesis/dissertation has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

02 February 2025

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ABSTRACT

This study investigated the effect of process parameters on the quality of needled nonwoven (NW) components used in the automotive industry and addressed observed non-conformance. The 6.7dtex and 11dtex Polyester fibres were blended, carded, and needled using various process parameters. The effect of the depth of needle penetration, and stroke frequency on the nonwoven properties such as weight, thickness, tensile strength, dimensional stability, flammability, and wear resistance were investigated by running a series of controlled experiments that employed a 2x2 factorial design. The adhesive and binder were applied on the NW fabric and then tested using International Organisation for Standardization (ISO) test methods. Samples were randomly selected to minimise bias and improve generalisability.

Statistical techniques were employed to analyse the collected data. Suitable methods included ANOVA, which determined the significance of the relationship between process parameters and quality attributes. Controlled testing conditions (laboratory and samples), equipment, materials, and testing methods throughout the experiments were used to ensure the reliability and validity of the results. Compliance with ethical guidelines was ensured when working with sensitive information or proprietary data.

The findings of this study demonstrated that the fabrics manufactured from a blend of 6,7dtex and 11dtex PET fibres, finished with PE adhesive and latex binder achieved better performance because of their compact structure. The process parameters used achieved better mechanical properties of the structures needed for moulding and wear resistance properties needed for the service life and durability of the NW fabric for automotive applications.

This study contributes significant results for application by automotive trim manufacturers in understanding the impact of the process parameters on the quality of nonwoven components and providing guidance to improve product quality. The significance of this study’s findings lies in their potential to offer a solution to the ongoing problems of NW component failures and contribute to knowledge preservation.

Keywords: Quality, nonwoven component, needle punched, process parameters, automotive interior trims, automotive textiles

ACKNOWLEDGEMENTS

I wish to thank:

- My supervisors for their dedication and time taken to guide me through this research.
- The companies that assisted with samples that made this research possible: fibres, LDPE, and latex.
- Former colleagues who would answer my calls and emails and help with my many requests.
- I appreciate the support given by CPUT staff – Clothing & Textile department.

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ABBREVIATIONS AND ACRONYMS

Abbreviation/Acronym	
AIAG	Automotive Industry Action Group
ANOVA	Analysis of Variance
APQP	Advanced Product and Quality Planning
ASTM	American Society for Testing and Materials
BR	Burning rate
CAGR	Compound Annual Growth Rate
CD	Cross Direction
CO_2	Carbon Dioxide
COA	Certificate of Analysis
CSR	Customer Specific Requirements
DS	De Saedeleir
Dtex	Decitex
EDANA	European Disposables and Nonwovens Association
FMEA	Failure Mode and Effect Analysis
FTIR	Fourier-transform infrared spectrophotometer
IATF	International Automotive Task Force
INDA	Association of the Nonwovens Fabric Industry
IR	Infrared
ISO	International Organisation for Standardisation
LDPE	Low density polyethylene
MD	Machine Direction
MSA	Measurement System Analysis
NP	Needle penetration
NVH	Noise, Vibration, and Harshness
NW	Nonwoven

OEM	Original Equipment Manufacturer
PA	Polyamide
PE	Polyethylene
PET	Polyethylene terephthalate (Polyester)
PP	Polypropylene
PPAP	Production Part Approval Process
PPSI	Penetration per square inch
QMS	Quality Management System
RH	Relative Humidity
r-PET	Recycled Polyester
SF	Stroke Frequency
SPC	Statistical Process Control
TGA	Thermogravimetric Analyser
UV	Ultraviolet

CHAPTER 1: INTRODUCTION

1.1 Introduction

Nonwovens are engineered fabrics made from fibres bonded together by mechanical, thermal, or chemical treatment (Parrish and Erin, 2016). Official definitions from professional organizations like EDANA (European Disposables and Nonwovens Association) and INDA (International Nonwovens and Disposables Association) vary in certain aspects, showcasing the diversity of nonwoven fabrics. According to ISO 9092:1988, a nonwoven fabric is ‘a manufactured sheet, web or batt of directionally or randomly orientated fibres, bonded by friction, and/or cohesion and/or adhesion, excluding paper and products which are woven, knitted, tufted, stitch-bonded incorporating binding yarns or filaments, or felted by wet-milling, whether or not additionally needled’ (Karthik & Rathinamoorthy, 2017). They can be made from staple fibres or continuous filaments (Sadeghi *et al*., 2021).

Different manufacturing processes and raw materials create nonwoven materials, resulting in distinct properties and diverse economic applications. The five primary types of nonwoven production are meltblown, spunbond/spunlace, drylaid, wetlaid, and air-laid. To achieve the desired mechanical properties in nonwovens, they must be bonded using mechanical, chemical/adhesive, or thermal methods (Wysokińska *et al*., 2020). According to Atakan (2014), these are the common technologies that are employed to manufacture nonwovens for automotive applications (sqm): spunbond (66%), Needle punching (27%), hydroentangled / resin (6%), others (1%).

These adaptable materials can be implemented in various products, such. as hygiene-related items, filters, clothing, construction, automobiles, agriculture, textiles, and composites (Wysokińska *et al*., 2020; Chaka, 2021). Nonwovens offer an advantage due to their eco-friendliness. Being lightweight, made from sustainable materials, using recycled polymers, efficient, flexible, and mouldable, they contribute positively to the environment and promote sustainability—which is why automotive is 35% of the main market for technical textiles and continues to grow significantly (Atakan *et al*., 2020).

Paul (2019) stated that technical textiles designed for the automotive industry are commonly referred to as automotive textiles. These textiles are used in various modes of transport, such as cars, buses, trains, ships, and airplanes. Automotive textiles have a wide variety of uses, ranging from seats, carpets, and belts, to airbags, reinforced composites for vehicle bodies, filters, battery separators, and even engine components. Seat upholstery and roof coverings are the most popular applications of these textiles, providing insulation, safety, comfort, style, and functionality. Additionally, automotive textiles have a range of other uses, including composites, tyre reinforcement, sound insulation, and vibration control.

Figure 1.1 shows the key nonwoven applications as depicted by Seile and Belakova (2015). These include areas such as carpet (43%), headliner (6%), hood liner (10%), trunk (13%), insulation (17%), door panels (1%), seating (6%), package trays (3%) and other areas (+1%). Nonwovens are often utilised in the carpet manufacturing industry to serve as primary and secondary backing due to their exceptional mouldability, durability, and noise-reducing properties, which are highly valued by drivers (Ferdousi *et al*., 2023).

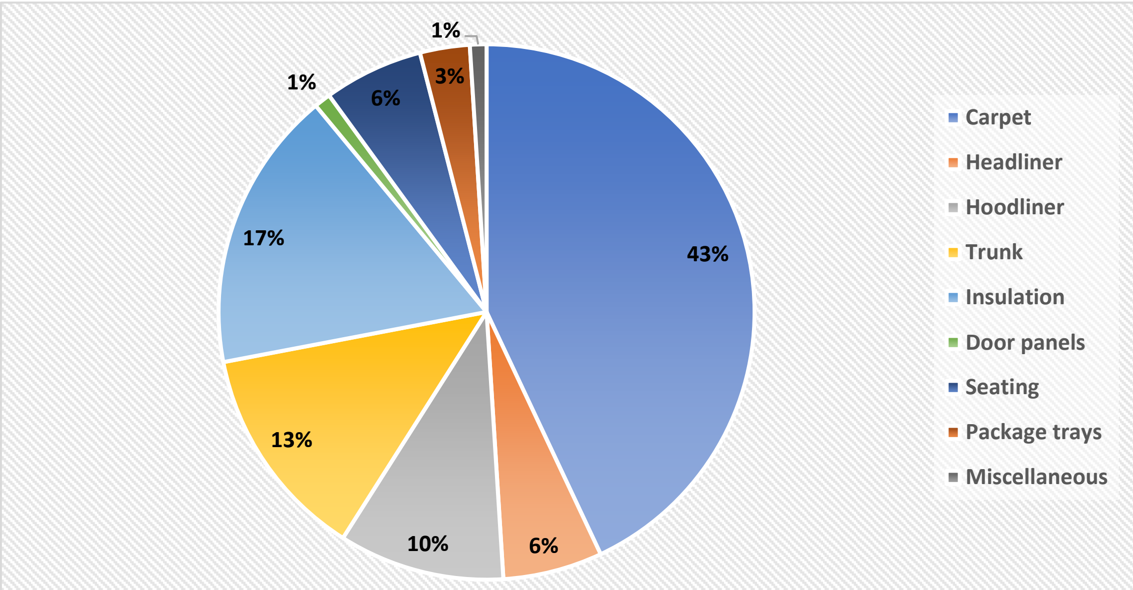


Figure 1.1 Nonwoven applications in a car

Vehicle manufacturers are referred to as original equipment manufacturers (OEMs) in the global automotive industry, and they manage the initial overall design, assembly, and marketing of the vehicle and brand from the dealership to the consumer. Tier 1 is the principal supplier to OEM; they handle the manufacture of complete system components such as an interior compartment. Tier 2 supplies sub-assemblies (i.e. nonwoven carpet) to Tier 1, individual parts of these would be sourced to Tier 3 (Fibres and binders' supplier) supplies individual parts used by sub-assemblies, and materials (Granules for fibre manufacturing and or binder) would be provided by a Tier 4 supply material (Sinha *et al.*, 2015).

This study aims to investigate the impact of process parameters on the performance of interior carpets. Figure 1.2 illustrates the nonwovens used in cars.

Figure 1.2 Nonwovens in a car

(Source: EDANA, 2022)

1.2 Background to the research problem

Every car features a metallic or reinforced-fibre shell, textile-based interior upholstery and covering components. Using nonwoven materials, floor coverings can be produced either flat or in structured forms, such as random velour, through carding, cross-lapping, and needle punching. The desired velour surface structure is achieved by pre-needling the batt, followed by additional structuring on a second loom to create the surface pile. This velour floorcovering is further processed by back coating with a latex and a thermoplastic polyethylene (PE) powder backing depending on the vehicle segment (Atakan *et al.*, 2020). In the automotive industry, vehicle manufacturers are supplied with finished preformed velour structured floor coverings and trims. There has been a challenge in the quality of these floor coverings from tearing or delamination during moulding.

According to Yilmaz (2020), the quality of needle-punched nonwoven components is influenced by several process parameters, including needle density, needle penetration depth, needle punching frequency, and feed rate. These parameters can affect the mechanical properties, thickness, density, and uniformity of the nonwoven material that, in turn, impact its performance and durability in automotive applications.

The properties and applications of automotive components are primarily determined by the fibres used to manufacture them. The physical and mechanical characteristics of these components are heavily influenced by the type of fibres used. Textile fibres serve as the fundamental building blocks of any textile structure, making the selection of appropriate fibres crucial in achieving the desired properties in conventional or technical textiles, such as automotive textiles (Ahmad, 2020).

Nonwovens used for trims should have sufficient strength to withstand the stresses and strains encountered during use. Inadequate strength can lead to tearing, delamination, or premature wear of the trim. Insufficient strength can be attributed to factors such as low fibre strength, inadequate bonding, or improper manufacturing techniques. Researchers have conducted studies to assess the mechanical strength and durability of nonwoven fabrics composed of blends of original and recycled fibres for various applications. The tensile properties of the final product are considered a significant parameter for fabric durability, regardless of the specific application area (Sharma & Goel, 2017; Lin *et al.*, 2015).

Çinçik and Koç (2013) investigated the tensile strength and elongation of needle-punched nonwovens composed of a polyester and viscose blend. The results revealed that increased polyester content correlates with increased tensile elongation in both the machine and cross directions. This enhancement is attributed to polyester fibres' loose entanglement and spin finish materials on the polyester. Moreover, it was noted that fabrics with greater weight, particularly those with more polyester fibres, demonstrate increased tensile elongation. Conversely, fabrics with a higher needling density tend to display reduced tensile elongation in both directions.

The scientific community has increasingly focused on and invested in using recycled fibres in the automotive industry due to the demand for environmentally friendly, lightweight, and renewable materials with enhanced properties. This has also been driven by the goal of achieving fuel savings using lightweight materials, ultimately significantly reducing CO_2 emissions. In addition to lightweight multi-material design options and metallic alloys, the emergence of textile fibre-reinforced composite structures presents a viable solution for developing lightweight vehicles (Azwa *et al.*, 2013).

Nonwovens should have good dimensional stability to maintain their shape and fit over time. However, certain factors such as exposure to heat, moisture, or mechanical stress can cause nonwovens to shrink or stretch, leading to poor dimensional stability. This can result in ill-fitting trims and compromised functionality. The coating binder (latex) on the back stabilises the floor covering and locks the fibres, whereas the PE powder is applied to give a good thermomouldable process, which ensures that the process runs efficiently, and parts produced fit together, thus reducing noise (Behera, 2019). The coated floorcovering is then moved into moulding, where it will be preheated for a given time and that will soften the PE powder thus allowing the floorcovering to be moulded easily.

Some of the general properties of the automotive carpet are light fastness, mouldability, and soil and abrasion resistance. Meeting customer-specific requirements (CSR) guarantees business revenue and keeps customers happy. The Automotive Industry Action Group (AIAG), in collaboration with Deloitte (2020), highlighted that retirement negatively impacts the quality of automotive components due to the loss of experienced professionals that results in a decline in knowledge, mentorship, and guidance. This may result in a widespread loss of expertise within the industry, impeding its capacity to learn from previous errors, enhance operational efficiency, and nurture the growth of new talent.

The three strategies that can contribute to avoiding the loss of knowledge are Failure Mode and Effect Analysis (FMEA), electronic storage and retrieval of documents, and databases. A survey conducted by AIAG and Deloitte shows that most organizations cannot preserve and transfer knowledge, increasing the manufacturing of parts that do not meet the CSR. There are many examples of product recalls resulting from poorly designed or manufactured products and/ or processes.

1.3 Research Problems and Aims

Automotive manufacturers are very quality-conscious. In the local automotive manufacturing sector, the trims manufactured by the third tier are non-conforming to stringent performance and quality standards. These challenges lead to delayed lead times to supply customers. There has been an increased use of recycled fibres, a need for higher nonwoven homogeneity, and higher reproducibility according to specifications. Consequently, automotive manufacturers must enhance their quality monitoring systems and processes to build and sustain customer trust, expand market share, and minimise product returns. Factors contributing to nonconformities in nonwoven moulded carpets include selecting raw materials, process parameters at different manufacturing stages, and adherence to regulatory standards.(Palak and Kayaoğlu, 2021).

Efficient production and continuous improvements that boost profit margins are vital to the automotive industry. Failure to deliver components can halt vehicle assembly. (Sinha *et al.*, 2015).

This study examines how different process parameters affect the quality of needle-punched nonwoven components used in the automotive sector. Specifically, it will determine the optimal process parameters that result in the highest-quality nonwoven components, taking into consideration factors such as strength, durability, dimensional stability, and overall performance. The objective of this research is to offer valuable insights for automotive manufacturers by exploring the correlation between process parameters and the quality of needle-punched nonwovens, ultimately helping to enhance production processes and improve product quality.

1.4 Primary Research question

How are the quality characteristics of needle-punched nonwoven components intended for use in the automotive industry affected by different process parameters?

1.4.1 Sub-Research Questions

- How do variations in process parameters impact the physical properties of laminated needle-punched nonwoven components used in the automotive industry?
- What is the relationship between different process parameters and the thermal properties of laminated needle-punched nonwoven components?
- How do the thermal properties of the constituents of the laminate and the thermal process parameters influence the quality and performance attributes of the laminated needle-punched nonwoven components?
- To what extent do alterations in process parameters affect the overall durability and lifespan of laminated needle-punched nonwoven components?
- What optimal process parameter settings lead to quality and performance improvement of laminated needle-punched nonwoven components for automotive applications?

1.5 Research objectives

- Investigate the effect of variations in different process parameters on the physical properties of laminated needle-punched nonwoven components used in the automotive industry.
- Examine the relationship between various process parameters and the dimensional stability characteristics of laminated needle-punched nonwoven components for automotive applications.
- Assess how alterations in process parameters influence the thermal resistance (heat retention, thermal conductivity) of laminated needle-punched nonwoven components intended for use in the automotive industry.
- Quantify the extent to which alterations in process parameters affect the overall durability and lifespan of laminated needle-punched nonwoven components.
- Determine the optimal process parameter settings leading to the quality and performance improvement of laminated needle-punched nonwoven components for automotive applications.

1.6 Research design and methodology

The research design for this study involved a controlled experimental approach. The research method used was quantitative since the objective of the study was to measure the relationship between the process parameters and the quality of nonwoven materials.

According to Bryman (2012), quantitative research involves collecting and analysing data focusing on quantification. The quantitative experimental approach offers substantial advantages in objectivity, replicability, and statistical rigor, it also carries inherent limitations regarding context, flexibility, and the potential for oversimplification. The quantitative research paradigm, often called the scientific research paradigm, is based on empirical data. The paradigm assures validity through careful clarification, definition, and pilot tests. That is testing out the instruments beforehand. Statistical tests are used to establish dependability (Seppelt *et al.*, 2011).

An experimental research design was employed to systematically investigate the impact of different process parameters on the quality of needle-punched nonwoven components under controlled conditions. Experimental research allows for the manipulation of variables to establish cause-and-effect relationships. Rahi's (2017), work justified the choice of experimental design, as this design allows a researcher to test the relationship between and among variables.

Multiple independent variables (stroke frequency and needle penetration depth) were systematically varied to observe their effects on the dependent variable of the quality attributes (weight, thickness, tensile strength, flammability, Taber abrasion, and dimensional changes to heat).

1.7 Data Collection method

The method that was used to collect data for this study was experiments. The data collection tools used are reliable and accurate, such as digital imaging or mechanical testing equipment. The equipments used were calibrated to ensure consistency and accuracy.

Experiments were run where nonwoven samples were processed in the Nonwoven plant using polyester fibre of different fineness because the fibres were readily available and then tested in the laboratory using International Organisation for Standardisation (ISO) test standards to ensure the quality of the research. FTIR, TGA characterised fibres and low-density polyethylene (LDPE) for thermal behaviour, and Microtrac laser diffraction for particle size analysis before the experiment. The dependent variables for the experiment included fibre properties and nonwoven component properties. The independent variables included needle penetration and stroke frequency. The factorial design employed was 2x2, where a series of controlled experiments were run, each focusing on one specific process parameter.

Once the needle-punched nonwovens were manufactured, the LDPE was scattered onto the backside of the nonwoven for the lamination process. The material was then heated at a specified temperature - 150°C, for the specified time (9 minutes) and then compressed by the Fast Press for 30 seconds to enhance lamination. Experiments are the most employed data collection method in the nonwoven process parameters research (Ishikawa *et al.*, 2019, Maity *et al.*, 2021) and are evident from the researchers referenced in Chapter 2. According to Lin *et al.* (2017), experiments provide the opportunity of determining the cause and effect and allow the hypothesis to be tested.

1.8 Sampling strategy

A representative sample of needle-punched nonwoven components for each experimental run was selected for testing. The samples were chosen randomly to minimise bias and improve the generalisability of the results. The samples were prepared for the following tests: weight, thickness, tensile strength, dimensional stability, abrasion resistance, and flammability. These tests were conducted using the ASTM or ISO test methods in the Cape Peninsula University of Technology (CPUT) testing laboratory. These test methods include sampling, specimen size, specimen preparation, testing conditions, design, testing device, and interpretation and statement of the results as stated by Cherif (2016). This approach is also supported by Rahi (2017), who argues that random (Probability) sampling is appropriate for studies aiming to minimise bias.

1.9 Data analysis

The gathered data was analysed using statistical methods. Suitable methods included ANOVA, regression analysis, and correlation analysis to determine the significance of the relationship between process parameters and quality attributes. The data's trends, patterns, and outliers were identified to derive meaningful conclusions. The choice of these statistical methods is consistent with the approach taken by Chauhan *et al.* (2020) in a similar scientific research context.

1.10 Ethical considerations

Compliance with ethical guidelines was ensured when working with human subjects, sensitive information, or proprietary data. The research adhered to ethical guidelines outlined by the CPUT ethics committee. The ethical framework aligns with the principles outlined by Gajjar (2013).

This includes following data policies in terms of data sharing and preservation. Using Fighshare, a private link or reserved Digital Object Identifier (DOI) will be generated for each dataset. The data for the project will be managed and stored in one of the data repositories (Figshare https://cput.figshare.com/, Media Tum http://rdm.cput.ac.za/, and the Institutional repository http://digitalknowledge.cput.ac.za/).

1.10.1 Anonymity and Confidentiality

The material used to run the experiments states the manufacturer or the source but not the supplier; the process settings used were chosen as guidelines and not obtained from any company; however, that will not prohibit any significant information. The industry's data is anonymised and confidential to protect the intellectual property of the companies involved.

1.10.2 Safety

Since experiments were carried out, there was no harm to participants as the standard operating procedure (SOP) of the machinery and laboratory equipment will be followed for experiments and testing. The experienced personnel assisted, and personal protective equipment (PPE) was worn to reduce the risk associated with processing fibres. From the production material, the remaining raw materials (pellets, latex, powder, and fibres) were collected for recycling and stored for future projects by other students, preventing any potential harm to the environment.

1.10.3 Honesty

The findings of this research will be reported honestly, without misrepresenting or manipulating the outcome or intentionally misleading others.

1.11 Significance of the study

This study will provide empirical evidence to address the primary research question and sub-questions leading to actionable insights for enhancing the quality and performance of these materials in the automotive sector. It will assist automotive trim manufacturers in understanding the influence of the process parameters on the quality of nonwoven components and provide guidance to improve product quality. The results are expected to solve the ongoing problems of high internal failures and contribute to vital knowledge preservation for automobiles.

1.12 Limitation of the study

This research only used polyester fibres because of their low cost and ease of availability for manufacturing the main floor carpet. The samples were only needled and then laminated; due to infrastructure unavailability, there was no structure loom to brush the surface of the nonwoven. Due to equipment unavailability, thermal conductivity was not conducted; however, it will be mentioned as a recommendation for future studies.

The focus was only on needle-punched nonwoven components that can be used for the local automotive industry, whereas nonwoven can be used for many applications worldwide. This research was conducted for academic purposes, with experiments carried out in the laboratory. However, if feasible, field tests should be performed to compare and validate the laboratory results.

1.13 Thesis overview

Figure 1.3 provides an overview of this thesis, illustrating the key components and structure of the research.

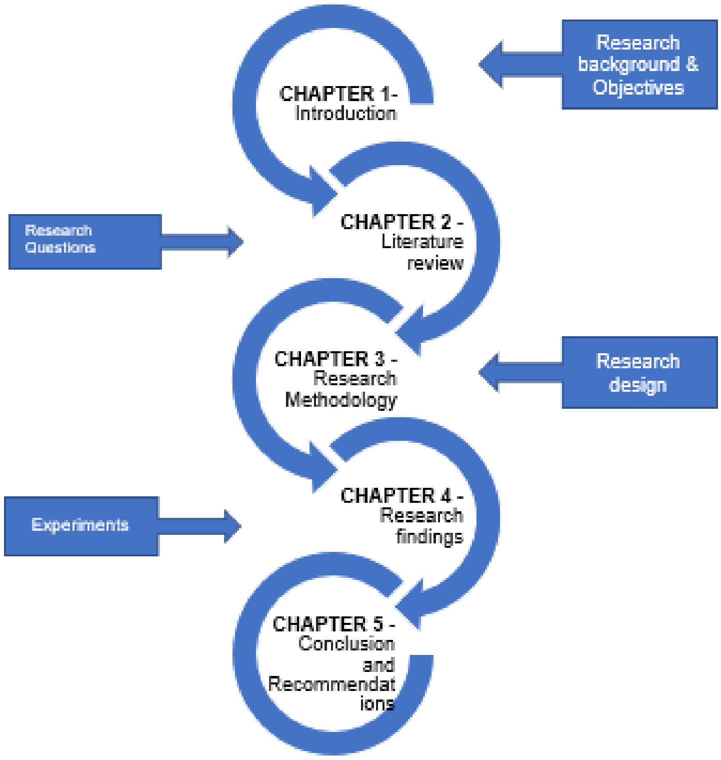


Figure 1.3 Thesis Overview

Chapter 1 – Introduction

This Chapter provides an overview of the research topic, its significance, and research questions. It also discusses this research's objectives and outlines the thesis's structure.

Chapter 2 – Literature Review

In this chapter, the existing literature on the research topic is reviewed and analysed to provide context for the study. Key theories, concepts, and findings from previous research are discussed to inform the current study.

Trim manufacturing in the automotive industry mostly encounters nonconformances, mainly failure in tensile strength due to processing parameters and finishing. This study aims to explore the process parameters that would improve the quality of the nonwoven (NW) components produced to reduce customer returns, thus increasing business revenue. The process parameters studied are the stroke frequency and needle penetration depth.

Chapter 3 – Research Methodology

This chapter details the research design, data collection methods, and data analysis techniques used in the study. It explains how the research questions were addressed and outlines the steps taken to ensure the validity and reliability of the findings.

Chapter 4 – Research findings

The results of the study, encompassing both statistical analysis and the interpretation of qualitative data, are detailed and examined in this chapter. The key results concerning the research questions and existing literature are also discussed.

Chapter 5 – Conclusion and Recommendations

This final chapter summarises the study's key findings. It highlights the conclusions drawn from the research and provides recommendations for practical application or further research.

CHAPTER 2: NONWOVENS IN AUTOMOTIVES

2.1 Introduction

The average car uses over 33m² of textile fabric of all types and applications for interiors alone – nonwovens represent more than 10% of that. Nonwovens are used in automotive carpets for both primary and secondary backings, providing superior mouldability and the necessary durability for modern drivers. (Russel, 2022). Association of the Nonwovens Fabric Industry (INDA), 2004 reported that almost 350 million square metres of nonwoven fabrics are used, valued at nearly US$275 million. The usage is much greater when the unseen fabrics under the hood, filtration, sound absorption, and the like are added (Jerkovic *et al.*, 2013).

Table 2.1 outlines typical nonwoven applications in auto interior manufacturing. Most nonwoven textiles used in a vehicle consist of carpet (found in both passenger and trunk areas) and insulation, making up 73% of overall nonwoven usage. Engineered nonwovens are currently incorporated into more than 40 automotive parts, with the number of applications expanding (Paul, 2019).

Table 2.1 Nonwoven as an auto interior material

Interior part	Component	Nonwoven area usage (%)	Nonwoven technology
Passenger carpet	Decor fabric, first and second layer of underlayment	43	Needle-punch, spunbond
Insulation	Acoustic and thermal insulators wherever needed	17	Needle-punch, spunbond
Trunk trim	Floor cover, insulating layer, side liners	13	Needle-punch, spunbond
Rear shelf/ package tray	Facing and backing fabrics	3	Needle-punch
Hoodliner	Absorbing layer	10	Needle-punch
Headliner	Decor fabric. Insulator, substrate	6	Needle-punch, spunbond
Seat	Decor fabric, back fabric, bolster fabric, construction reinforcement	6	Needle-punch, spunbond, spunlacing
Door trim	Lower facing. Panel trim (door insert/bolster)	1	Needle-punch, spunbond, spunlacing

Miscellaneous	1	Needle-punch, spunbond, spunlacing

(Source: Atakan, 2014)

As reported by Precedence Research in 2022, the global automotive interiors market was valued at approximately US$120.26 billion in 2021 and is projected to exceed US$174.2 billion by 2030, with a compound annual growth rate (CAGR) of 4.2% from 2021 to 2030, as illustrated in Figure 2.1. The report also highlighted several key factors driving growth in the global automotive interiors market, including the increasing demand for lightweight vehicles, the rising popularity of autonomous vehicles, a greater emphasis on comfortable interiors, and the growing adoption of electric vehicles.

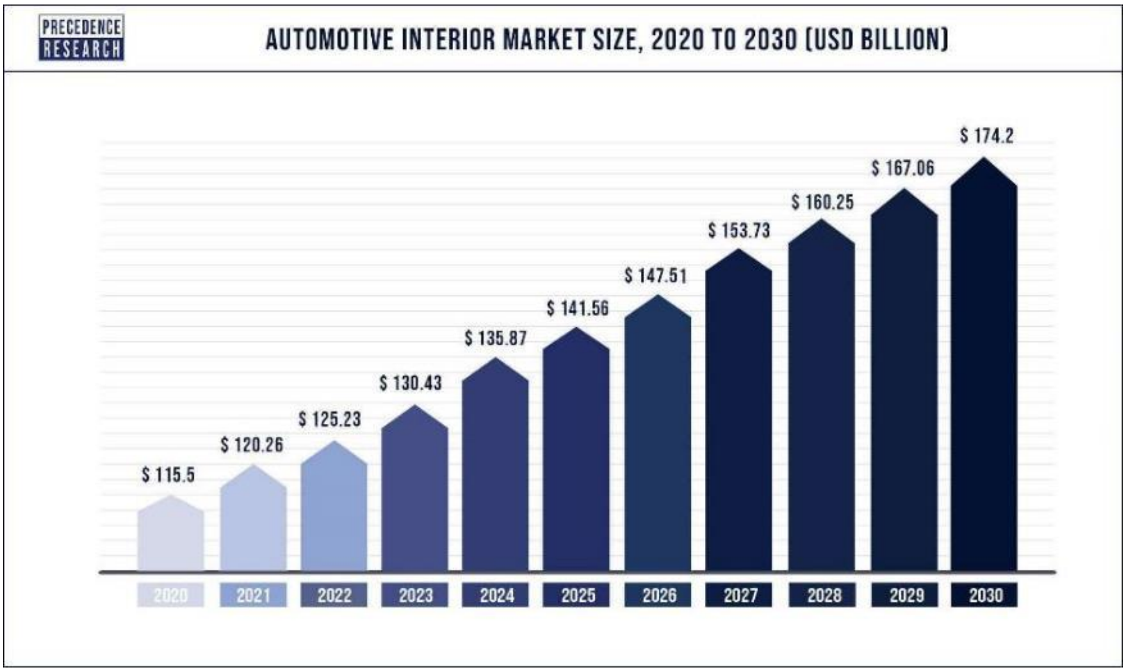


Figure 2.1 Automotive interior market size

(Source: Precedence research, 2022)

According to Maximize Market Research (2023), the rising emphasis on safety and technological innovations is boosting the demand for advanced automotive interiors. Moreover, the growing need for lightweight commercial vehicles for transport is also propelling market growth. The global automotive interior market is witnessing substantial expansion, driven by the adoption of intelligent lighting systems, advanced seating solutions, and increased investments to create more comfortable and convenient interiors.

The use of lightweight materials to provide innovative aesthetics and finishes for automotive interiors is a key driving factor. Furthermore, government regulations related to carbon emissions, safety, and energy efficiency are leading to greater investments in lightweight and innovative materials to reduce vehicle weight and improve energy efficiency, thus playing a critical role in market expansion. Around 5-7% of fuel can be saved by implementing a weight reduction of 10% per vehicle (Precedence Research, 2022).

The use of lightweight materials improves fuel efficiency, reduces emissions, and enhances vehicle performance, making sustainability a key priority in the automotive sector. There is a significant increase in the use of recycled materials in the production of nonwovens. Government regulations are being imposed to limit both carbon dioxide emissions and noise, vibration, and harshness (NVH) from vehicles. Electric vehicles are becoming more popular due to their environmentally friendly nature and quieter operation (Kellie, 2016). Figure 2.2 shows why nonwovens are succeeding in the automotive market.

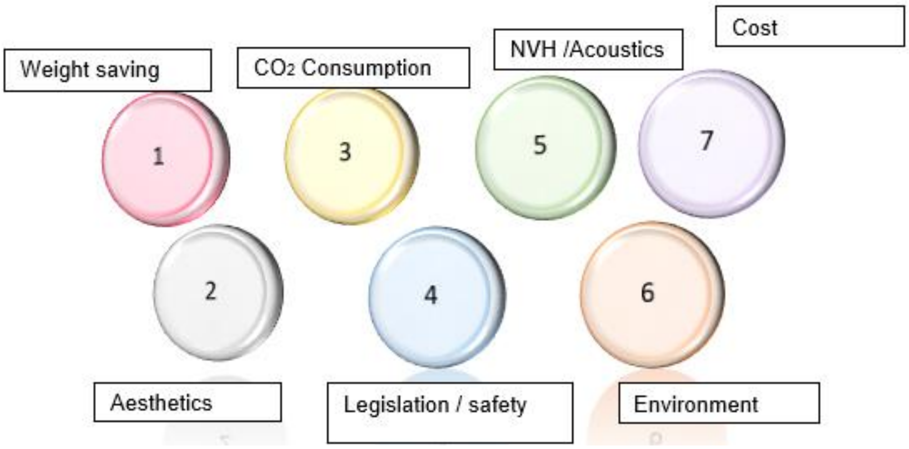


Figure 2.2 Automotive technology drivers

(Source: Kellie, 2016)

2.2 Raw materials

2.2.1 Fibres

Arenas (2016), states that around 25kg of fibres are used in a standard passenger car, and this amount can be increased for safety and comfort requirements. Fibre usage in automotive is in different textile forms such as knits, woven, and nonwoven structures.

Each application area has performance requirements that are to be fulfilled by the textile products used (Saricam & Okur, 2018). Manmade fibres are generally used to fulfil these requirements, see Table 2.2.

Table 2.2: Performance requirements of automotive applications and fibres used

Application	Requirement	Fibres used
Seat covers	Abrasion & UV resistance, attractive design	Polyester (PET), Wool, Polyamide (PA), Acrylic
Carpets	Light fastness, moldability, compression recovery, tensile strength	PA, PET, Polypropylene (PP)
Seatbelts	Tensile strength, abrasion & UV resistance	PET
Airbags	Ability to withstand high temperatures inflation gases, durability to storage in compact state for years	PA
Composites (Headliner & Boot liner)	Stiffness, strength, lightweight, energy absorbing, and thermal stability	Glass, carbon, PET

(Source: Saricam & Okur, 2018)

Products made from these fibres offer processing stability, higher strength, consistent elongation, and exceptional thermal and dimensional stability. Table 2.3 summarises textile fibres' advantages and disadvantages in automotive applications. It can be seen from Table 2.2, that PET & PA are the prominent fibres in automotive applications; however, PP is also included in the table, due to its very low cost (Albini *et al.*, 2019).

Table 2.3: Advantages & disadvantages of different textile fibres used for automotive applications

Fibre type	Advantages	Disadvantages
PET	• High abrasion resistance • High UV resistance • High Stiffness • Low cost	• Low moisture absorbency • Low compression resilience • A little less in wearing resistance
PA6 &6.6	• High strain recovery • High elongation • Good thermal absorptivity • High toughness & wearing resistance	• Moderate UV resistance • High energy consumption for fibre production
PP	• Low density • Very low cost • Low energy for fibres production • Excellent resistance to chemicals	• Low melting point • Moderate abrasion resistance • Low moisture absorbance • Low heat resistance

(Source: Saricam & Okur, 2018)

Moreover, with the increasing emphasis on environmental awareness and the need to conserve resources, product reuse and recycling have become essential in the production of automotive components. Recycled polyester fibre can be used for automotive upholstery, particularly in carpets and seat covers. Additionally, polyester nonwovens can be recycled into new materials. Polyester resin can also function as a matrix material, particularly for natural fibre composites, which allows waste materials from pre-assembled automotive components like headliners, boot liners, and parcel trays. Thus, polyester is therefore a fibre of choice for recycling and promoting sustainability (Saricam & Okur, 2018).

There has been a significant rise in research focused on natural fibres and products derived from them. Natural fibre composites, and natural fibres in general, are playing a crucial role in shaping a sustainable and environmentally friendly future. The automotive industry is taking significant strides toward adopting an eco-friendlier production chain by incorporating natural fibres as the foundation for manufacturing various components. These components include seat backs, door panels, spare tire covers, and boot linings (Dunne *et al.*, 2016).

The research conducted by Jaouadi *et al.* in 2015 demonstrated the many advantages of Kenaf fibre for reinforcing composites in the automotive industry, particularly by textile nonwovens. Kenaf-based nonwovens have been shown to possess superior properties compared to the currently used glass mats for composite reinforcement. These advantages include a lighter structure, improved mechanical specific properties, and notably better thermal properties. However, certain disadvantages may hinder industrial development. These disadvantages primarily stem from the intrinsic properties of the fibre, such as difficulties in reproducing the implementation method on an industrial scale, irregularity in physical properties, and the dependence of fibre quantity and quality on environmental conditions and humidity.

2.2.2 Polyolefins

Propylene, ethylene, isoprene, butines, and other olefins that are usually obtained from natural carbon sources such as crude oil and natural gas are polymerized to produce polyolefins, a form of thermoplastic polymer. Atoms of hydrogen and carbon, having or without side branches, make up these polymers (AlMa'adeed & Krupa, 2016). E.W. Fawcett and R.O. Gibson of the Imperial Chemical Company created polyethylene, the first polyolefin, in 1933 by combining pure ethylene with high pressure and temperature. Figure 2.3 shows pellets of polyethylene (Bibi *et al.*, 2023).

Figure 2.3 Polyethylene pellets

(Source: AlMa'adeed and Krupa, 2016)

Polyethylene is one of the polyolefins highly regarded for its lightweight nature, low density, ease of processing, superior chemical resistance, water repellence, and strength. In addition, polyolefins are commonly used in automotive components due to their durability and resistance to harsh environmental conditions. Overall, polyolefins remain an economical and adaptable substance for a range of uses in the textile and nonwoven industries (Trossarelli & Brunella, 2003).

Ouederni (2016) stated that nonwoven fabrics require bonding to enhance the strength and integrity of the loose fibrous structure. This bonding can be achieved through mechanical methods such as needle-punching or water jets in hydro-entangled wet-laid nonwovens. Chemical bonding is another widely employed technique, which involves applying latex or other adhesive chemicals to the fabric and then curing the adhesive in an oven to secure the structure.

Thermal bonding, using polyolefin fibres, offers a practical alternative for bonding nonwoven fabrics. This technique involves integrating low melting fibres into the fabric, which liquefy and combine as the fabric moves through heated rollers. The temperature of these rollers is intentionally set above the polyolefin fibre's melting point, with a specific level of pressure applied to the web. Through a combination of heat and pressure, the polyolefin fibres are fused and strengthened, enhancing the overall structure of the nonwoven material. Polyethylene (PE) and polypropylene (PP) are commonly chosen as thermal binding agents in producing nonwoven fabrics. (Dharmathikary *et al.*, 2009).

Karthik and Rathinamoorthy (2017) consider thermal bonding to be eco-friendly as it eliminates the need for chemicals and solvents in the production of nonwovens. Additionally, it provides a more open structure and a softer feel in hygiene and other applications than chemical bonding.

2.3 Manufacturing process of nonwovens

The nonwoven fabrics manufacturing process (Fig. 2.4) consists of four stages (Wirth,1988):

- Fibre opening
- Web formation
- Web bonding
- Finishing

This research employed the dry-laid method for web formation, a mechanical process for web bonding, and a coating process for finishing the samples.

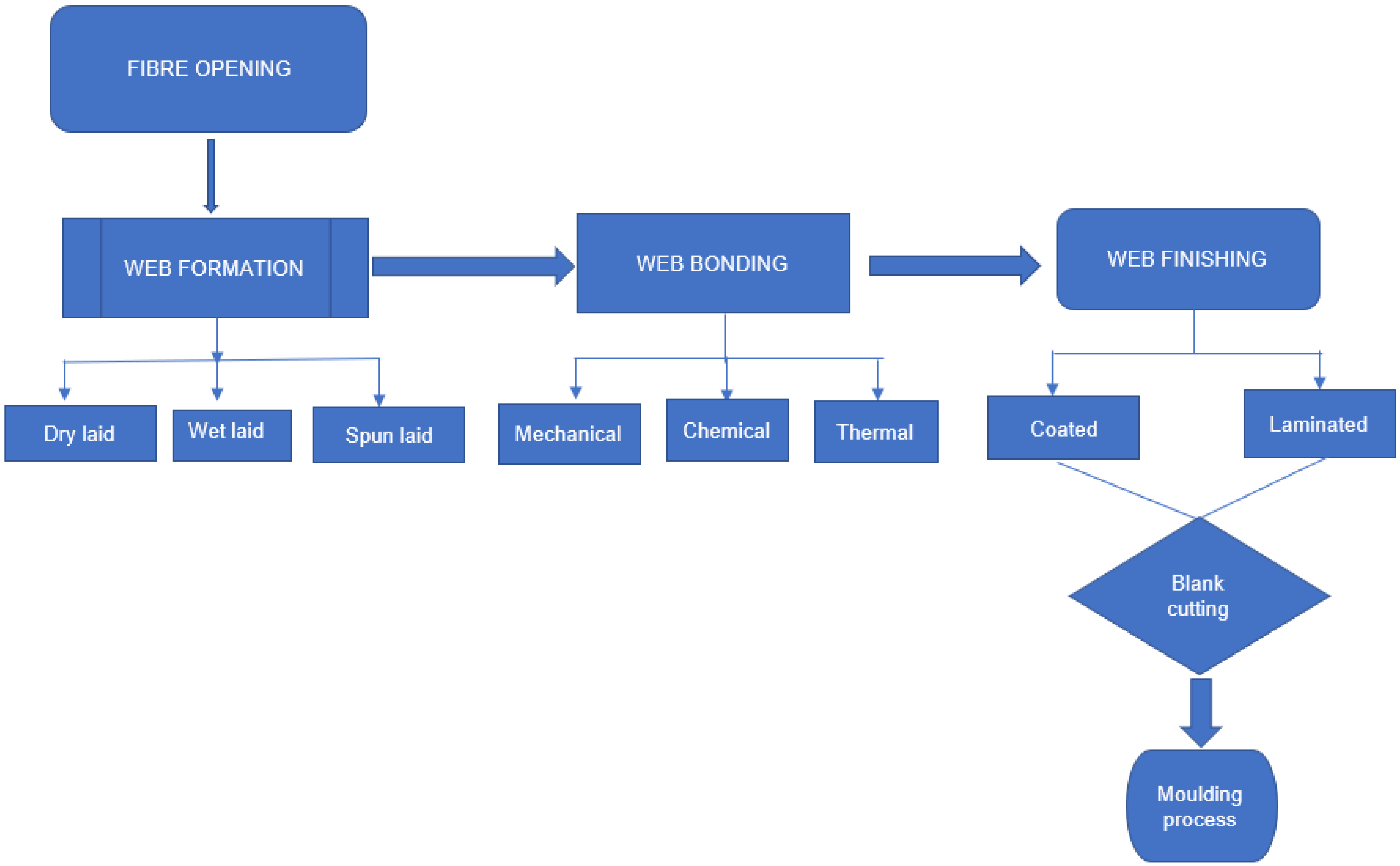


Figure 2.4 – Flowchart for nonwoven manufacturing

2.3.1 Web formation

The fabric manufacturing process begins with arranging the opened fibres in a sheet or web. These fibres can be stapled fibres compressed in bales or filaments extruded from the molten granules (Midha & Sikka, 2019).

2.3.1.1 Dry laid

Dry-laid web formation produces about 60% of the nonwoven fabric using traditional opening machines also utilised in the spinning process. The opened fibres are pushed through the rotating roller and more apparent card for individualisation of fibres and web formation. The carded fibrous web is cross-laid or parallel-laid, and the latter is mainly used for manufacturing fleece and cleaning cloth fabrics (Brydon *et al.*, 2022). Parallel-laid webs exhibit higher tensile strength, a lower elongation, and low tear strength in the machine direction due to the fibre being oriented in the longitudinal direction (Mao *et al.*, 2022; Russel, 2022).

Cross-lapper machines produce transverse laying of carded webs; see Figure 2.5. A cross lapper is made up of carriage pieces powered by a servo motor to adjust width and thickness. The carriages transport the fibrous web towards one end of the belt and reverse the direction of motion at the other (Vinay & Monica, 2019). Transverse-laid webs produce nonwoven fabrics with increased tensile strength in the cross machine direction, and this is because the majority of the fibres are oriented transversely due to the cross-lapping process (Russel, 2022).

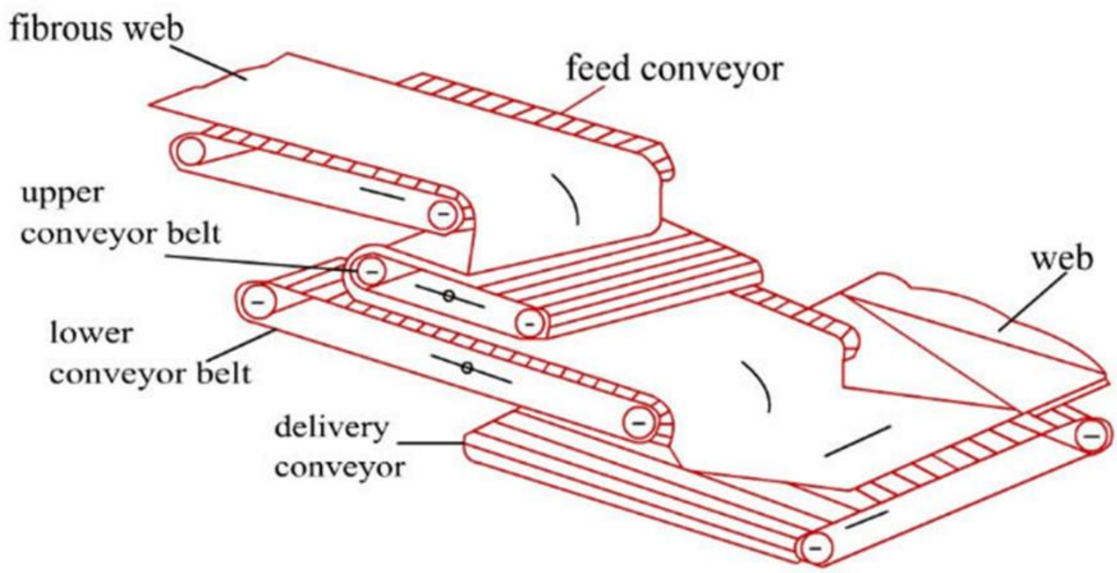


Figure 2.5 Cross lapper

(Source: Pietsch and Fuchs, 2016)

The tensile strength varies based on its layering and drafting procedure. Fabrics produced by transverse-laid webs achieve increased compressibility and lower recovery compared to the parallel-laid carded web. The downside of using a cross-laid web is the difficulty experienced when matching the input speed to the cross-lapper with the speed of the carded web, which goes into needling. However, reducing the carded web speed accommodates the downside (Brydon *et al.*, 2022).

2.3.2 Web bonding

2.3.2.1 Needle punching

Needle punching is a nonwoven technique that involves repeatedly inserting barbed needles into a premade, dried fibrous web to mechanically entangle the fibres and create a nonwoven fabric. The fibres are re-oriented into a vertical plane to form tufts or stitching channels (Anand *et al.*, 2022). According to Kamath et al (2005), fibre webs are characterised by the following:

- Improved needle design
- Increased needle density per working width
- Increased stroke frequencies
- Working widths

The needle board (Figure 2.6) is mounted on a beam given in up-and-down reciprocating motion using an eccentric crank mechanism (Shaik *et al.*, 2021). Zidi *et al.*, (2020) stated that this results in fibres being mechanically interlocked, thereby providing mechanical strength.

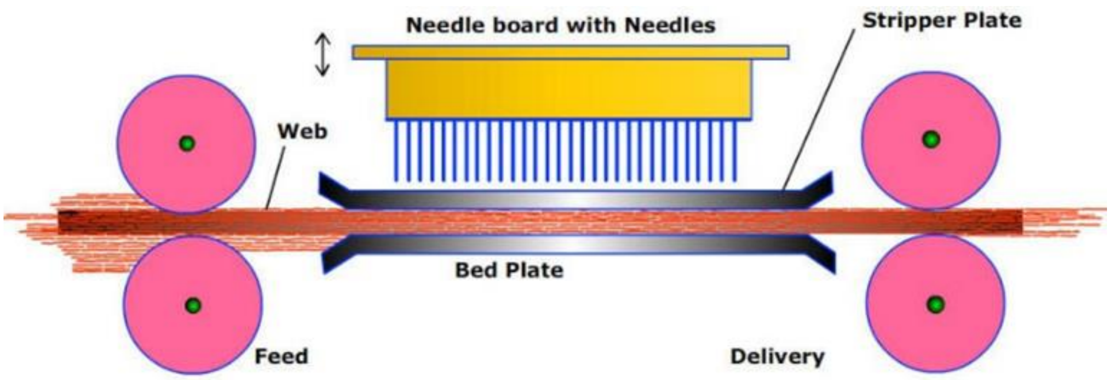


Figure 2.6 Needle punching process

(Source: Shaik *et al.*, 2021)

Modern needle looms function with continuous felt transport to achieve optimal needling efficiency, these are the important process solutions:

- Batt feeding
- needling zone
- felt delivery

Batt feeding - an uncontrolled draft while feeding into the needle loom can cause intra-fiber migration, resulting in changes in length dimensions during needling (Albrecht *et al.*, 2006). This can lead to irregular surface mass or variations in felt thickness. Therefore, maintaining a consistent batt feed is crucial during pre-needling (Kumar, 2015).

Needling zone - in the needling process, web fibres are intertwined using specially designed needles (Fig 2.7). The barbed needles penetrate the fibrous web, condensing it in the process. During the downward movement, the fibres captured by the barbs are aligned within the needle hole channel. A unique barb design ensures that a portion of the web fibres maintains their orthogonal orientation within the needle hole channel as the needle moves upward (Pietsch and Fuchs, 2016).

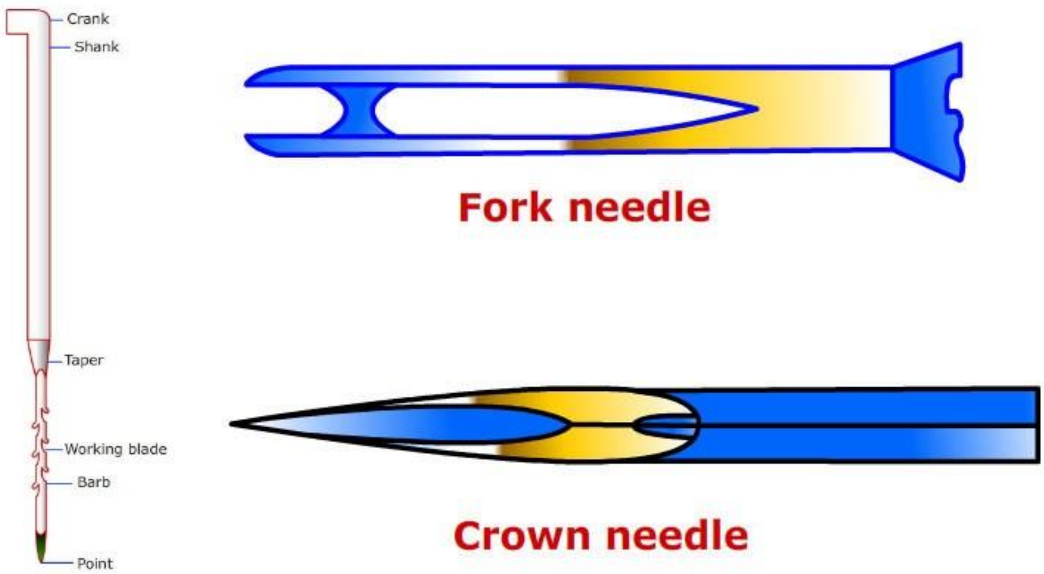


Figure 2.7 The needles

(Source: Farag, 2019)

As the barbs move up and down, they interlock and mix the fibres, forming a three-dimensional interlocked structure in the nonwoven fabric. Key factors influencing the needle-punching process include the number of barbs on the needle, punch density, depth of needle penetration, needling speed, and types of fibres used (Sun, 2014; Atakan *et al.*, 2020).

The needle punching may be done in two stages: pre-needling and finish needling and this gives the advantage of increasing weight after pre-needling by adding felt.

Pre-needling – The feeding system of the machine allows dimensionally stable feeding of the web to the actual needling zone. The gap between the stripper plate and bed plate has to be selected by the material thickness of the nonwoven . Furthermore, the gap minimises distortion of the voluminous batt as it enters the needling(Atakan *et al.*, 2020).

Finish needling – The needle with close barb spacing is preferred as it permits all the barbs to penetrate the fleece at a relatively shallow depth, this allows maximum consolidation and compaction of the pre-needled web (Sun, 2014).

Structure needling – some felts are taken straight to finishing after the bonding, and others go for further processing on a needle loom to produce a velour surface. A fork needle is used. The fibre is forced into a moving brush bedplate by the needles. With zero draft, the fibres are transported by the brush from entry to the exit of the loom. This allows for a non-linear look, perfect for moulded products (Gopalakrishnan, 2021). The crown needles are designed to be used in conjunction with random velour needle loom to introduce fibre loops that protrude from the surface of the fabric (Anand *et al.*, 2022).

2.3.2.2 Needling process parameters

Process parameters such as depth of needle penetration, feed rate, punch density, and stroke frequency influence performance characteristics and structural arrangements of needle-punched nonwoven fabrics (Ventura *et al.*, 2014; Tshifularo *et al.*, 2020).

Debnath *et al.* (2020) refer to the depth of needle penetration as the longest distance that the first barb reaches below the lower surface of the web or bedplate. Moyo *et al.* (2013) describe that the movement of the bedplate is used to either increase or decrease the penetration. Ventura *et al.* (2014) studied the effects of the processing parameters and their analysis significantly found that an increase in needle penetration results in an increase of longitudinal deformation of the batt and fibre entanglement, thus reducing the fabric weight, thickness, and air permeability but increasing the mechanical resistance.

When the needles descend, the barbs of the needle move with the fibres. However, as the needle ascends, the barb releases the fibres. Multiple studies (Tshifularo *et al.*, 2020; Moyo *et al.*, 2013; Ozen *et al.*, 2015) have been conducted on the depth of needle penetration, and they all agree that, as the depth of needle penetration increases, tensile strength increases, owing to the linkages of fibre tufts, but elongation decreases.

Punch density is defined by Wang *et al.* (2013) as the quantity of needles per unit area that penetrate the fibrous web. Punch density is also referred to as the amount of needling that, in turn, determines the degree of fibre entanglement and that degree influences properties such as tensile strength and fabric density (Atakan *et al.*, 2020).

According to Moyo *et al.* (2013), increasing punching density increases the breaking strength to an extent and then decreases. Furthermore, they point out that the punching density also affects the packing factor directly, an increase in punch density results in an increase in the packing factor due to more fibres entangled, increasing structural consolidation. Moreover, it produces a stiffer fabric with high tensile strength but low extension. The increased needling also increases abrasion resistance and reduces softness due to better fabric consolidation (Debnath *et al.*, 2020).

Tay and Nasir (2021) found that punch density influences fabric pore size. Pore size is somewhat reduced by increasing punch density but, because of greater fibre breakage, pore size increases when punch density rises over the ideal level.

Kuo *et al.* (2007) define feed rate as the rate at which the web is fed to the machine. The feed rate influences the web density; a higher feed rate forms thicker and denser nonwoven material. According to Atakan *et al.* (2020), adjustments to the cross-lapper machine's feed rate and conveyor speed can impact the fibrous web's thickness. They observed that needle-punched nonwoven fabric with a lower feed rate and stroke frequency demonstrated more excellent permeability characteristics. A lower feed rate reduces the number of fibres available, leading to a more open fabric structure with larger pores. In contrast, fabric produced at a higher feed rate and stroke frequency had smaller pores. As a result, fabrics with a more open structure were achieved with lower feed rates, especially at lower stroke frequencies.

Stroke frequency refers to the rate at which the needle board moves per second, pushing needles through the bedplate and into the web (Moyo *et al.*, 2013). According to Tshifularo (2020), an increase in stroke frequency results in an increasing number of fibres reoriented from cross direction to machine direction, thus decreasing the larger pores of the structure significantly. There is an improved web consolidation if the stroke frequency is increased and balanced with the linear speed. The critical parameter affecting fibre entanglement is penetration per square inch (PPSI). This measure is inversely related to the web's speed and directly relates to the number of needles on the needle board and the frequency of strokes.

2.3.3 Finishing

Nonwoven fabrics can be finished using mechanical, thermal, and chemical methods to apply specific functionalities such as hydrophobicity and hydrophilicity (Cherif, 2016).

2.3.3.1 Coating

The goal of coating is to change the substrate or the entire composite visually, physically, or technically -see the process flowchart in Figure 2.8. The characteristics of the substrate influence the process, the available coating equipment, the coating material, and the intended outcome. According to Brentin (1982), the four main objectives of coating are as follows:

- To penetrate and secure the tufts, bind the fibres to prevent pilling and fuzzing, and coat the entire structure to prevent fraying during cutting and installation.
- To bond with the secondary backing.
- To achieve the desired overall physical properties, including enhanced dimensional stability, added weight, preferred texture, and improved resilience.
- To enhance the flame resistance of the carpet.

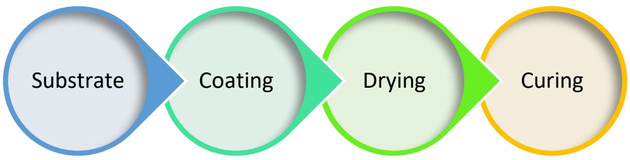


Figure 2.8 Coating process flow chart

The following are some of the coating methods:

The lick-roll (kiss roll) method - A roller with variable speed is used to feed the carpet through the assembly. A lick roll (Figure 2.9) is applied to the back of the carpet and rotates within a latex compound wash. The ultimate coating thickness is controlled by a doctor blade. Using low-viscosity dispersions, the backing is dried and vulcanised by going through a hot air oven (Blackley, 2012).

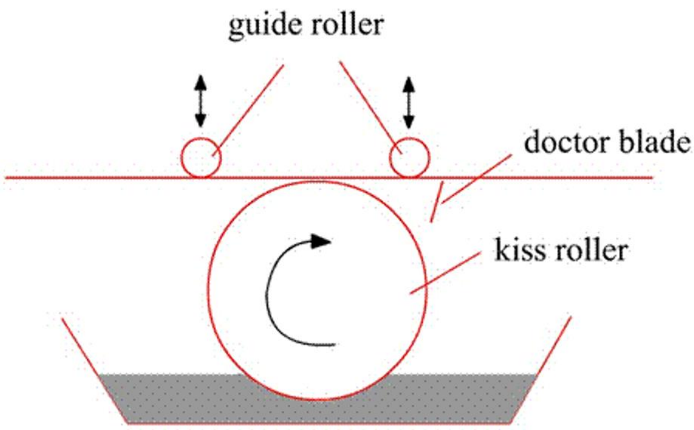


Figure 2.9 Kiss roll coating

(Source: Vishal, 2019)

Knife or Doctor coating - Vade (2020) noted that the conventional coating method employs a doctor blade mechanism for spreading. The various techniques include knife-over-roll, blanket, and air knife coating. Nonwovens can also be coated with foam using natural or synthetic latex dispersions and foaming agents such as ammonium stearate, potassium oleate, or sulphosuccinamate (Stukenbrock, 2002). Furthermore, these agents allow the dispersion to be aerated to a desired density, ranging from 1.2 to 5 times its original volume (Albrecht, 2006).

Rotogravure coating can produce patterned coatings. Heated rotogravure rollers are used to apply hot melts fused with thermoplastics. The hot melt can be used as an adhesive that forms a bond immediately with the second fabric or can be left as a coating and, after it has cooled down, laminated with a second fabric layer after reactivating the adhesive (Ferdousi *et al.*, 2023).

Rotary screen coating - This technique is employed to apply a hot-sealing coating to fusible nonwoven interlinings. The paste dot method is preferred because it enables wider working widths and higher production rates than the powder dot method (Vade, 2020). The study further demonstrates that the process utilises doctor and magnetic roller squeegee systems. Rotary screen coating can apply both aqueous and non-aqueous pastes (Stukenbrock, 2002). Additionally, powder application is feasible under certain conditions, provided that the powder is sufficiently free-flowing and the particle size is appropriately sized relative to the diameter of the holes in the perforated screen (Stukenbrock, 2002).

Dry powder coating - Sen (2007) outlines two processes for this coating technique:

a) Scatter coating- A layer of polymer powder, ranging from 20-300μm, is evenly distributed onto a moving textile substrate. This substrate is then passed through a fusion oven and calendared. The feed rate and the web's speed influence the coating's weight.
b) Dot coating—A heated substrate with a surface temperature just below the melting point of the polymer comes into contact with an engraved roll containing dry powder. The engraving dictates the pattern of the application of polymer powder onto the web. The engraving roller is kept cool to prevent the polymer from adhering to it.

Fusible polymer powders including polyethylene, polyester, and polyamide are coated using these techniques. Fusible interlinings, carpet back coating (especially for contoured automobile carpets in the automotive industry), and lamination are some of the uses.

2.3.3.2 Coating summary

Applying a binder in foam form, followed by curing in a stenter, imparts dimensional stability and strength to the carpet. An auto-forming unit is beneficial as it facilitates automatic adjustment of the foam ratio to achieve uniform pick-up. An acrylic binder is typically used due to its ability to provide the necessary strength. The binder pick-up is kept low since the material will be laminated with LDPE later. For carpets that will undergo subsequent lamination, the binder pick-up generally ranges from 10-20% (Sen, 2007). It is essential to monitor and control the foam ratio during the process to minimise variations in binder pick-up, which can ultimately affect carpet weight (Atakan, 2014).

Curing of the binder occurs in a stenter where heat is applied using electrical heaters positioned on both sides of the material. According to Atakan (2014), the temperature on the binder side is maintained at 140°C, while the fibre side is kept at 110°C. The speed of the material is adjusted based on the type of material and binder pick-up, typically ranging from 2-3 m/min. To reduce processing time and costs, a thermobondable binder may be employed, eliminating the need for lamination with LDPE powder (Alam & Kibria, 2022).

The thermobondable binder is a specialised styrene-butadiene latex, which binds the fibres and enhances the mouldability of the material. Santos *et al.* (2021) noted that the binder film is a thermoplastic that begins to soften in the range of 35-90°C. The softening effect intensifies as temperatures increase, particularly around 120°C, facilitating moulding. The ratio of styrene to butadiene in the binder influences its stiffness and thermoplastic properties (Santos *et al.*, 2021).

The coating process is followed by drying and curing, as depicted in Fig. 2.7. Drying refers to removing applied solvents and forming the film (Karthik & Rathinamoorthy, 2017). The subsequent curing process creates a functional layer through various polymerisation reactions. Heat can be transferred or applied through contact or convection methods. The materials are passed over heated cylinders in contact methods, while convection processes depend on hot air circulation. For infrared (IR) dryers, the energy required for drying is supplied through the absorption of IR radiation. In coil coating, short-wavelength UV radiation-induced high-frequency eddy currents (Giessmann, 2010).

2.3.3.3 Lamination

Lamination refers to the permanent bonding of two or more prefabricated sheet materials. Carpets are backcoated with a standard binder (acrylic) and must be laminated with LDPE powder, film, or both to facilitate moulding. The characteristics of LDPE powder significantly affect the moulding process (Vade, 2015).

The average particle size of the powder is around 300 microns. For practical moulding, the granule size should not be uniform; instead, a mix of coarser and finer particles surrounding the average size enhances mouldability. An applicator dusts the powder onto the moving carpet, with automatic controls ensuring the appropriate application. The material is then preheated in stages using electrical heaters to reach a softening temperature before being calendered between pairs of high-pressure rollers. Finally, the laminated carpet is cut into blanks for further processing (Atakan, 2014).

2.3.3.4 Moulding

Now cut into blanks, the laminated carpets are secured by grippers on both sides and transported to a pre-heating zone, where the LDPE lamination is softened. After a designated preheating duration, the material is moved to a moulding press, including a male and female mould. These moulds are precisely crafted according to the car body design. Since the car body design is proprietary to the manufacturer, the moulds must be created after obtaining a formal agreement to maintain confidentiality. The moulds can be made from either aluminum or resin-bonded fiberglass. Although aluminum moulds are more expensive, they have a longer lifespan and include a cooling system that reduces moulding time and enhances productivity (Russel, 2022).

As Atakan *et al.* (2020) noted, preheating duration in the moulding process is a crucial factor impacting the moulding quality. Excessive preheating and tensioning can lead to holes in the carpet, which are influenced by the type of fibre, carpet GSM, binder, and lamination used. Moreover, wrinkling may occur if preheating is excessive or if material tensioning is insufficient during moulding. The preheating time must be optimized for fibre types and carpet density (Balasubramanian, 2003). Carpets with a higher polyester content generally require more preheating than those made primarily of polypropylene. Additionally, heavier carpets demand longer pressing times.

2.4 Quality

Quality gurus define quality differently. Crosby (1979) defines quality as conformance to requirements. Juran (1988) sees quality as fitness for purpose, manufacturing a product that satisfies customers' needs. Deming’s (1982) philosophy says only a customer can define quality (Kumar *et al.*, 2016).

Customers demand that the vehicles and the textile products used in them last longer, be aesthetically pleasing throughout ownership, and maintain resale value. Only products that meet the OEM standards should be submitted for vehicle production. Meeting those requirements for every batch and shipment is non-negotiable, especially if continued supplier relations are expected (Sinha *et al.*, 2015). The industry requires International Automotive Task Force (IATF) 16949 certification to meet the industry’s standards consistently (Laskurain *et al.*, 2018).

According to Bozola *et al.* (2023), IATF 16949 is a standard that outlines the requirements for a Quality Management System (QMS) specifically tailored for the automotive industry. The main emphasis of IATF 16949 is the establishment of a QMS that fosters continual improvement, prioritizing defect prevention and minimising variation and waste within the supply chain. This standard, along with relevant customer-specific requirements, delineates the QMS criteria for automotive production, service, and accessory parts, incorporating specific requirements and essential tools from the automotive sector, including:

- Advanced Product and Quality Planning (APQP)
- Failure mode and effect analysis (FMEA)
- Statistical Process Control (SPC)
- Measurement System Analysis (MSA)
- Production Part Approval Process (PPAP) (Bozola *et al.,* 2023)

Quality standards, efficiency, productivity, and flexibility for the automotive sector are increasing. This means the implementation of the QMS and the use of quality tools and techniques (Ionescu *et al.*, 2022). The objective is to fulfil customer needs both efficiently and effectively. IATF 16949 is an additional standard that works alongside the International Organization for Standardization (ISO) standards, including:

- ISO 9001 – establishes the fundamental requirements for a Quality Management System (QMS).
- ISO 9000 – addresses the essential concepts and terminology.
- ISO 9004 – concentrates on enhancing the efficiency and effectiveness of a QMS.
- ISO 19011 – provides guidelines for auditing management systems.
- ISO 31000 – details principles and guidelines for risk management.

Figure 2.10 shows the evolution of the IATF 16949 from 1994 until 2016.

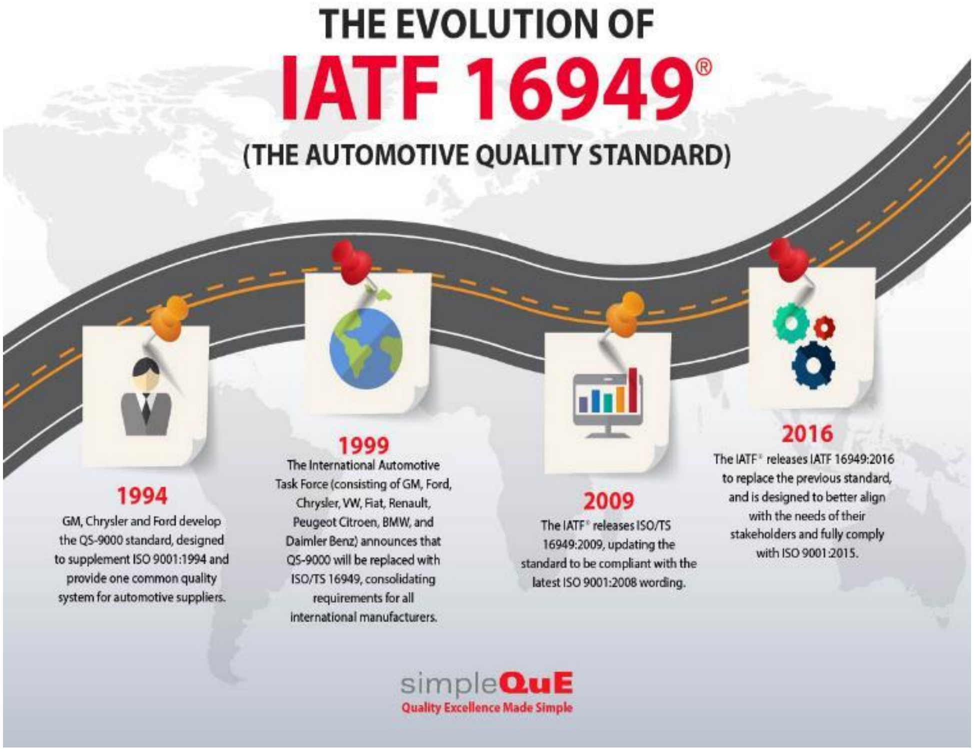


Figure 2.10 Evolution of IATF 16949

(The Evolution of IATF 16949® - simpleQuE, 2022)

IATF 16949 was developed in 1994 as QS-9000. The latest standard, IATF 16949:2016, was published in October 2016, replacing ISO/TS 16949. It incorporates the structure and requirements of the QMS standard ISO 9001:2015. Furthermore, it includes additional automotive customer-specific requirements, such as product safety (Reid, 2017).

2.5 Major Quality Problems in Automotive carpets

The carpets' quality does not always conform to the customer's requirements, which leads to rejection. Below are some issues encountered and the precautionary measures taken to address them.

2.5.1 Colour variation

Nonwovens are also used for aesthetics (Pourmohammadi, 2013), which makes colour uniformity of paramount importance. The colour variation of the carpet not matching the approved Master sample results in rejection. Two measures can assist in preventing the problem:

- Fibre colour matching (ASTM D1729-2016) against the master sample under the colour cabinet in a dark room to eliminate interference with the light. The master sample is to be kept away from light during storage, and when the fibre does not match the master sample, match the current run sample against the three previous runs to see if it is still not a match. Moreover, the sampling should be increased if it is not a match.
- Blending thoroughly by increasing the transfers to blow rooms before carding.

2.5.2 Contamination

Cross-contamination from the previous run occurs due to insufficient cleaning of card wires, stitching plates, and blow rooms. Wire hooks should be used to remove fibres in between barbs, and proper production planning should ensure that like colours are manufactured first and allowed enough time to clean before running the next colour (Atakan, 2014).

2.5.3 Weight variations

Amir Nasr *et al.* (2014) stated that periodic variations of nonwoven basis weight at a large scale are often considered an indication of process inconsistency and a cause of premature failure. Weight variations can occur at a needling stage due to the loading of the material on the cylinder, workers, strippers, and transfer roller after the stoppage, however, the issue is common with fine deniers. To minimise loading, the optimum use of an antistatic spray on the fibres and controlling the temperature and humidity. Reducing the doffer speed with higher web density assists in minimising weight variation. Weight variation can occur in the finishing- coating, however, controlling the foam ratio of the binder reduces the variations in binder pick-up (Brydon *et al.*, 2022).

2.5.4 Lines on the fabric

Lines on the fabric can either form along the machine direction or cross direction, but the lines are caused by the needles. Broken or worn-out needles cause longitudinal lines, so a proper needle replacement schedule shall be drawn up. Horizontal lines are due to needles penetrating in the same hole and can be prevented by reducing the stroke frequency but keeping the fabric delivery speed constant (Atakan, 2014).

2.5.5 Holes on the carpet (Tearing)

As the punch density increases, the elongation at break decreases in both the machine and cross-machine directions. When the punch density is higher, there is more entanglement of the fibres and a tighter construction, even for the same mass per unit area groups. This tighter construction reduces the mobility of the fibres and their ability to slide over each other. Consequently, the elongation at break values decreases (Gonca & Torcan, 2020).

During the moulding process, tearing of the carpet occurs mostly from excessive preheating. Increased mechanical strength also contributes to nonwoven structures being stiff, thus tearing when excessive tension is applied. Moulds should be free from burrs and should have proper maintenance schedules also reduce the punch density and add a binder to improve extension. (Vaidya & Chawla, 2008).

2.5.6 Wrinkling

Inadequate or excessive heating of the material during moulding, increase PE powder application as it has thermomouldable properties.

2.5.7 Abrasion resistance

High abrasion resistance is a crucial performance requirement for automobile carpets. The durability and service life of a needle-punched product is significantly influenced by its abrasion resistance, which is typically measured by the number of cycles required for disintegration or weight loss. Abrasion not only diminishes the strength of the fabric but also negatively impacts its appearance. Therefore, maintaining the original appearance of the carpet is another important evaluation criterion to ensure its acceptability for use (Atakan *et al.*, 2020).

Textile finishing or surface modification techniques can be utilised to enhance the abrasion resistance of a fabric. This can be achieved by increasing punch density, which in turn increases fibre entanglement resulting in wear resistance, applying the binder which will hold fibres in place. Various testing methods have been developed to assess and predict the durability of textiles and their finishes, as well as to evaluate modifications aimed at improving durability. These testing methods simulate long-term mechanical and/or abrasive stresses that fabrics may encounter (Textor, 2019).

2.6 Product test criteria

Russell (2022) states that the physical, chemical, and mechanical properties of nonwoven fabrics govern the suitability of the parts being produced and simulate actual conditions throughout the automobile's lifespan. Each Original Equipment Manufacturer (OEM) employs techniques to simulate actual usage conditions over time through accelerated laboratory testing. The test method uses standard conditions, and the part is tested taking into consideration what it must withstand when in use and where it will be situated in a car.

With intense competition among OEMs, the test standards are gradually raised so that cars produced nowadays have increased life expectancy and improved interiors (Zhang & Xu, 2022). Abrasion resistance, anti-soiling properties, cleanability, and light fastness at high temperatures are critical.

The engineering standard (TSL3600G) provides the scope of the test methods and performance for carpet materials. Table 2.4 below shows the classification of carpets and their composition, including materials for structure, fibres to be used on the base fabric, and the type of backing.

Table 2.4- Classification of carpets

Class		Material code	Applicable portion	Composition				
				Structure(1)	Base fabric(2)	Latex	Backing(3)	High abrasion resistance(4)
1	A	TSL3600G-1A	Floor	Tufted carpet	Woven or non-woven fabric	SBR(5), polyacrylate resin, etc.	Resin coating	---
	B-1	TSL3600G-1B		Needle punched carpet				Required
	B-2	TSL3600G-1B2						Not required
2	A	TSL3600G-2A	Interior trim surface	Tufted carpet	Woven or non-woven fabric	SBR, polyacrylate resin, etc.		---
	B	TSL3600G-2B		Needle punched carpet	---			
3	A	TSL3600G-3A	Deck surface, Rr seat back surface	Tufted carpet	Woven or non-woven fabric	---		
	B-1	TSL3600G-3B		Needle punched carpet				Required
	B-2	TSL3600G-3B2						Not required

(Source: Toyota Engineering Standard, TSL3600G)

Tables 2.5a & b below show the requirements set by the OEM that the carpet shall satisfy. The tests listed are done during the prequalification stage and annually depending on the customer's requirements for the requalification. However, every batch that is manufactured conducts these tests: colour matching, mass, thickness, tensile strength, Taber abrasion, and flammability. IATF 16949 (2016) has a clause 4.4.1.2 about product safety that states that the organisation shall ensure that the parts it manufactures meet the customer's requirements and will not cause any harm to the end user. One of the tests that the organisation performs to ensure product safety is the flammability test.

Table 2.5a Requirements

Test item			Class 1 A	Class 1 B-1	Class 1 B-2	Class 2 A	Class 2 B	Class 3 A	Class 3 B-1	Class 3 B-2
Mass (g/m²)			As specified in drawing							
Thickness (mm)			As specified in drawing							
Tensile strength (N/25.4 mm)			250 min.					480 min.		
Tear strength (N) (Reference)			20 min.							
Taber abrasion	Stringiness (Grade)		Grade 3 or above.							
	Abrasion tear (Grade)	20 times	---		Grade 3 or above					Grade 3 or above
		100 times	---	Grade 3 or above	---				Grade 3 or above	---
		300 times	Grade 3 or above	Grade 2 or above	---			Grade 3 or above	Grade 2 or above	---
	Fiber-loss(6) (g) (Reference)		0.200 max.					0.200 max.	---	
Heat shrinkage (%)			---			1.0 max.	2.0 max.	1.0 max.	2.0 max.	
Rigidity (N) (Reference)			3 to 12			---				
Tensile strength after heating (Reference)	Breaking strength (N/25.4 mm)		250 min.			---				
	Elongation at break (%)		70 min.			---				
	Strength at 30 % elongation (N)		100 min.			---				
Change in length between gages after heating (%) (Reference)			50 min.	---						
Flammability (mm/min)	Original state		Under 100							
	After heat aging		Under 100							
Glass fogging(7) (%)	Method A		10 max.							
	Method B and composite method		90 min.							

(Source: Toyota Engineering Standard, TSL3600G)

Table 2.5b Requirements

Test item			Class 1 A	1 B-1	1 B-2	2 A	2 B	3 A	3 B-1	3 B-2
Smell	DRY (initial, over time)	Intensity	3 max.							
		Degree of pleasantness/ unpleasantness	-1.5 min.							
		Nature	"Irritating", "fishy": 1.0 max.							
	WET (initial, over time)	Intensity	3.5 max.							
		Degree of pleasantness/ unpleasantness	-2 min.							
		Nature	"Irritating", "fishy": 1.0 max.							
	Water extraction (type 1 A)	Intensity	—							
		Degree of pleasantness/ unpleasantness	—							
		Nature								
	Water extraction (type 2 A)	Intensity	3 max.							
		Degree of pleasantness/ unpleasantness	-1.5 min.							
		Nature	"Irritating", "fishy": 1.0 max.							
	Water extraction (type 2 B)	Intensity	2 max.							
		Degree of pleasantness/ unpleasantness	-1.0 min.							
		Nature	"Irritating", "fishy": 1.0 max.							
Color fastness (Grade)		Color fastness to dry crocking	Grade 3 or above							
		Outdoor exposure	Change in color, fading: Grade 4 or above							
		Color fastness to light	Discoloration: Grade 4 or above Fading: Grade 3 or above							
		Light aging resistance	Deterioration: Grade 3 or above							

(Source: Toyota Engineering Standard, TSL3600G)

2.7 Summary

The chapter focuses on the effect of process parameters on the quality of needle-punched nonwoven components used in the automotive industry. The chapter begins by highlighting the importance of understanding the relationship between process parameters and the quality of nonwoven components.

The chapter discusses numerous studies conducted to investigate the effect of process parameters on the properties of needle-punched nonwoven fabrics. These studies examine parameters such as needle density, needle penetration depth, needle punching frequency, and feed rate. The research findings indicate that these parameters have a significant impact on the mechanical properties, thickness uniformity, and dimensional stability of the nonwoven materials.

Furthermore, the chapter explores the problems experienced with nonwovens used to manufacture trims in the automotive industry. These problems include delamination, weight variation, poor dimensional stability, and insufficient strength. The chapter emphasises the need for careful material selection, optimisation of manufacturing processes, and quality control measures to address these issues.

Additionally, the chapter highlights the importance of fibre selection in achieving desired properties in automotive textiles. It emphasizes that the properties and applications of automotive components depend on the type of fibres used. The chapter concludes by discussing the significance of tensile properties and abrasion resistance in determining the durability and performance of nonwoven fabrics. It also mentions the use of textile finishing techniques to improve abrasion resistance.

Overall, Chapter 2 provides a comprehensive overview of the research problem, the effect of process parameters on nonwoven components, problems experienced with nonwovens used for trims, the importance of fibre selection, and the significance of tensile properties and abrasion resistance in automotive textiles.

From the above review of the literature, it is apparent that the authors agree on the influence of the needling parameters on the performance of the nonwovens. Most literature is on the other nonwoven end uses, i.e., filtration and geotextiles. Moyo *et al.* (2013) recommended that a database for the storage of process parameters would contribute to a better understanding of the products and ensure process efficiency.

CHAPTER 3: MATERIALS AND METHODS

3.1 Introduction

The main purpose of this study was to determine the effect of the process parameters on the quality of the needle-punched nonwoven components that are used in the automotive industry. This chapter offers a comprehensive overview of the materials and methods employed in the research study. That is, information on the materials, equipment, procedures, and data analysis techniques employed in this the study. This chapter details the methodology to ensure the study's reproducibility and provide a clear understanding of how the data was collected and analysed.

3.2 Steps followed in methodology

The following are the descriptions of the steps followed in the methodology:

Literature review

- A comprehensive review of the existing literature related to needle punching nonwoven was conducted.
- Identified various applications, types of fibres used, manufacturing processes, and performance characteristics relevant to this study.

Setting the objectives

- Defined the research objectives that will be investigated in this research.

Material selection and characterisation

- The appropriate fibres to be used were chosen and the additive and bonding agents suitable for automotive components were selected.
- Performed microscopic analysis (FTIR, TGA), powder particle size

Experimental design

- Outlined the experimental set-up that included:
- − NW web bonding technique to be used: needle punching
- − Variables selection: process parameters – stroke frequency and needle penetration
- − Established the quantity of PE powder and latex as well as temperatures and holding times to be used in the finishing process
- Created a factorial design to test various combinations of parameters.

Sample preparation

- Blended fibres that were subjected to opening before processing.
- Pulverised PE granules into powder for ease of application during the coating process,
- And mixed thickening agent and stabiliser with latex before application onto nonwoven fabric.

Needle-punching & Finishing process

- Carried out the processing as per the experimental design and recorded the parameters used during the process for reproducibility.

Characterisation of NW fabric

- Measured physical and mechanical properties of the needled and coated NW fabric, including weight, thickness, and tensile strength
- Conducted tests performance testing specifically for floor covering used in automotive, such as dimensional changes to heat, abrasion resistance, and flammability.

Data analysis

- Used statistical methods, including ANOVA, to analyse the results of the experiments
- Compared findings against the existing literature
- Results were interpreted in the context of the research objective

3.3 Materials

3.3.1 Fibres

Four different Polyester recycled fibres from different suppliers were used in this study. The following are the suppliers with additional information in Table 3.1:

- De Saedeleir (DS) Fibres from Belgium
- Propet fibres from Cape Town, South Africa

Table 3.1 Characteristics of the Fibre sample

Fibre samples	Colour	Fibre fineness
Sample A	Black	6.7Dtex x 60mm
Sample B	Black	6.7Dtex x 60mm
Sample C	Blue Grey	11Dtex x 60mm
Sample D	White	6.7Dtex x 60mm

The polyester fibres (Table 3.1) were initially tested in the laboratory using ISO test methods to ensure the quality of the research. These fibres were then needle punched to make nonwoven samples for component products at the CPUT Nonwoven plant machine.

There have been numerous studies (Atakan *et al.* 2020; Çinçik and Gunaydin 2017; Gurudatt *et al.* 2005) comparing the use of recycled polyester and virgin polyester. The key issue is whether recycled polyester possesses properties comparable to virgin PET. It is essential to investigate the properties of recycled polyester that are pertinent to its processing. Furthermore, examining the mechanical behaviour of recycled polyester is necessary to determine its suitability for automotive carpet applications confidently and to assert that its properties are like or, in some cases, even superior to those of virgin PET. These studies concluded that the difference between virgin and recycled polyester is minimal, such as virgin has slightly higher tenacity than recycled PET, crystallinity is similar, and that the use of recycled PET in the manufacturing of needle-punched car carpets is feasible and may represent a cost-effective solution.

3.3.2 PE Coating powder

The nonwoven fabric was coated with polyethylene (PE) powder, which was milled from low-density polyethylene (LDPE) granules obtained from Sasol based in Sasolburg, South Africa. Below in Table 3.2, is the description of the granules:

Table 3.2 Characteristics of LDPE granules

Characteristics	Value
Density	0.9200 g/cm³
Melt flow index	21.16 g/10m

3.3.3 Latex

Latex used as a binder on the nonwoven fabric was sourced locally. Latex was mixed with 1% of Zen D55 thickening agent to form foam and 3% Witex stabiliser so that the foam didn’t collapse right away. The following are the properties of the latex:

Table 3.3 Properties of Latex

Properties	Value
Viscosity at 25°C (Brookfield RVT, Spindle 2, 100rpm)	40 – 160 mPa s
Solids Content	45%
pH	4.0 – 5.5

3.3.4 Needlepunching equipment

The fibres were needled using a Aolong needle punching of nonwoven, below are the machine components which are the pre-opener and the cabinet blender that were responsible for opening and blending multiple fibres used for this study shown in Figure 3.1 a

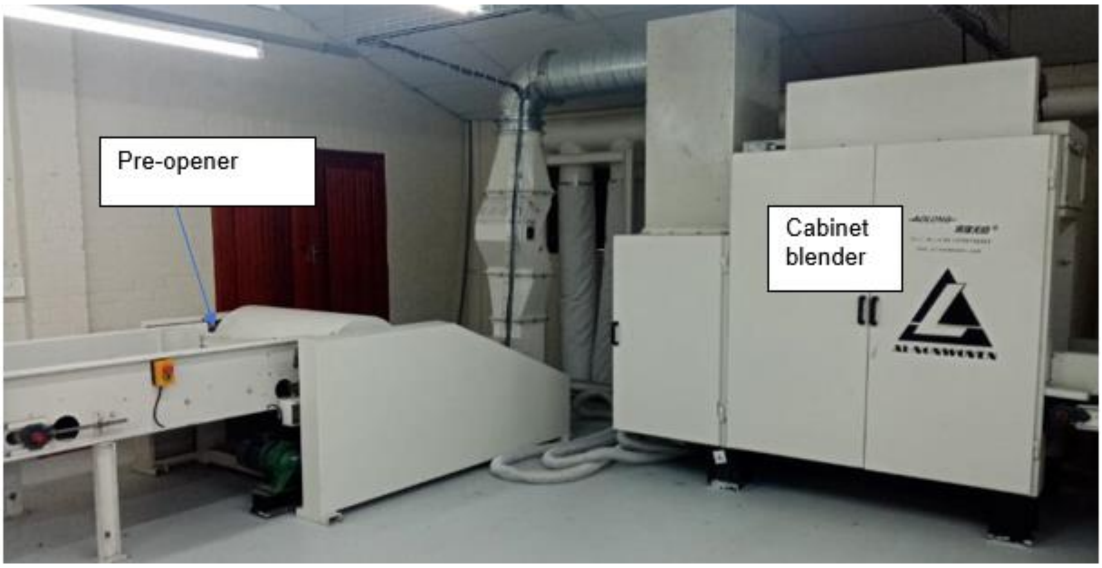


Figure 3.1 a : Aolong nonwoven pre-opener and cabinet blender

A web was formed by the carding action (Figure 3.1 b), and the web laid into multiple layers on the cross-lapper to attain the desired weight and thickness.

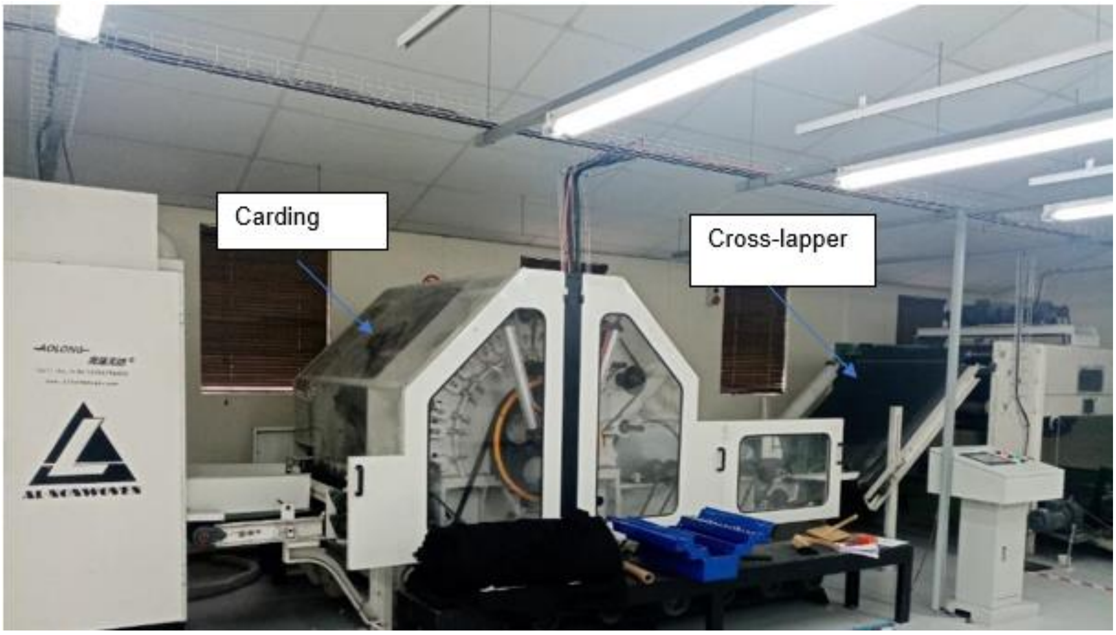


Figure 3.1 b: Carding and cross lapper

The batt was fed into the pre-needler which reduced the voluminous batt, and then it was passed onto finish needling which interlocked the fibres due to the repeated movement of the barbed needles, see Figure 3.1 c.

Figure 3.1 c: Needling process

3.4 Methodology

3.4.1 Raw materials

To study the effects of stroke frequency and needle penetration on the properties of needle-punched nonwovens, four different types of recycled polyester fibres.

Additionally, the polyethylene powder and latex were used as binders and their impact on the production process was explored. Gurudatt *et al.* (2005) conducted a similar study comparing fibres sourced from recycled PET bottles with those derived from recycled polyester fibre wastes and virgin polyester fibres, all processed under the same condition for the development of moulded automotive carpets.

3.4.2 Nonwoven production

The independent variables selected to produce the nonwoven samples were fibre properties, needle penetration, and stroke frequency. These independent variables are the important determinants of nonwoven component properties responsible for non-conformance. A 2x2 factorial design was employed to investigate the effect of different parameters as shown in Table 3.4. These samples were tested for weight, thickness, tensile strength, dimensional stability to heat, and flammability.

Table 3.4 Needle-punching process parameters

Sample No.	Stroke frequency (strokes/min)	Needle penetration (mm)
1A	1 (30 strokes/min)	1 (30mm)
1B	1 (30 strokes/min)	2 (15mm)
2A	2 (40 strokes/min)	1 (30mm)
2B	2 (40 strokes/min)	2 (15mm)

3.4.3 Coating

The nonwoven samples, after needling, were then coated with a binder and an adhesive - the polyethylene powder and latex. Polyethylene powder was used as a binder to improve the cohesion and strength of the nonwoven fabric. Additionally, latex was used as an adhesive to adhere the secondary backing to the nonwoven fabric.

The nonwoven fabric was sprayed with 15 ml of the adhesive and heated at 150°C for 2 minutes and then weighed. 15 grams (g) of PE powder was evenly applied on the coated NW fabric and then heated at 150°C for 9 minutes to dissolve the binder. Once heated, the binder was pressed on the fast press for 30 seconds to flatten the surface and aid in the curing of the binder, see Figure 3.2 (a) showing application of the binder and adhesive and Figure 3.2 (b) curing of the coating.

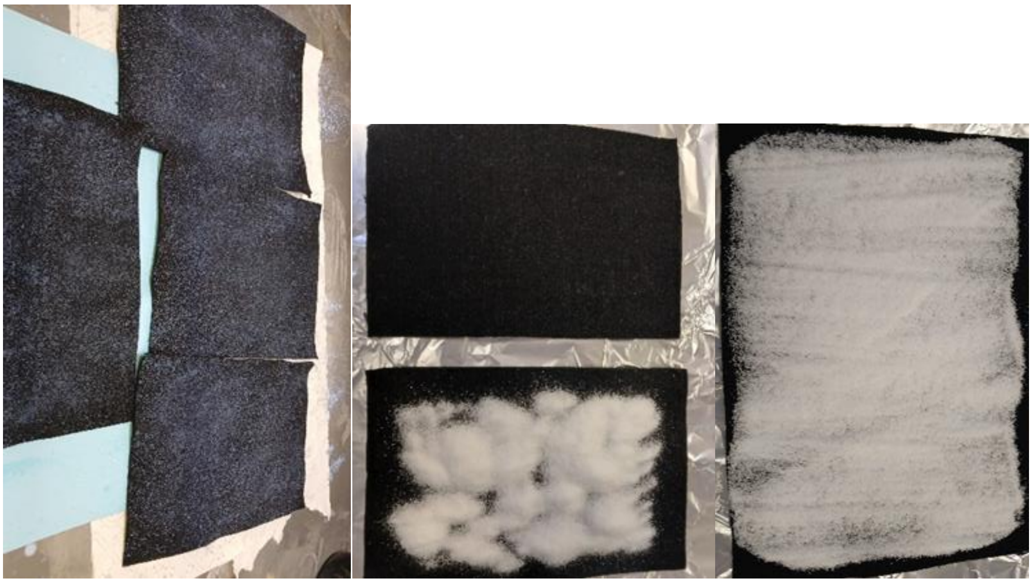


Figure 3.2 (a) Latex and PE powder application

The latex-coated fabric was heated for 2 minutes before the binder application. After that, the binder was cured by heating it at 150°C for 9 minutes in an oven. Soon after the cured samples were placed on the Fast press for 30 seconds- applying heat and pressure on the crystallised PE to aid curing. Non-sticking paper was used to cover the surface of the NW fabric.

Figure 3.2 (b) Heating and curing process

Granular PE received from Sasol needed to be milled into powder to increase its surface area and improve its distribution on the surface of the NW and in the application. Figure 3.3 is the grinder that was used to mill the LDPE from granules to finer powder particles.

Figure 3.3: FZ 102 Micro Plant Grinder

The FZ 102 Micro Plant Grinder is a laboratory mill designed for grinding and homogenizing soft to medium-hard materials. The PE granule samples were loaded into the grinding chamber gradually so as to not overload it. The equipment combines a high-speed rotating knife and a stationary knife to create a cutting surface for crushing granules into powder particles – see Figure 3.4.

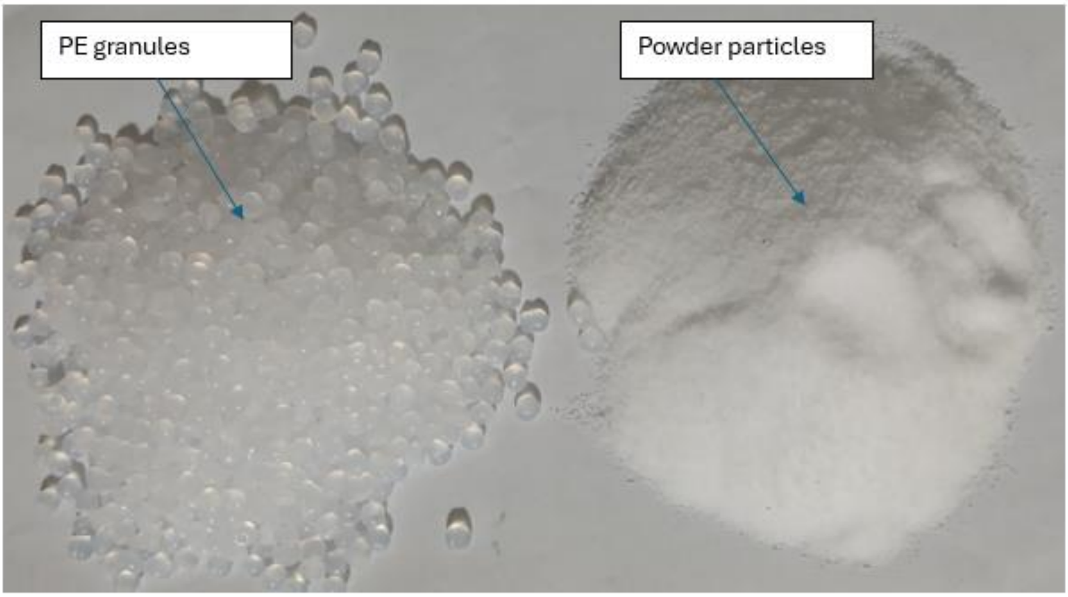


Figure 3.4 Granules vs powder particles

3.5 Characterisation of raw materials

The fibre samples were tested to assess their physical, mechanical, and morphological characteristics. This was to compare their properties as the variables used to manufacture them differed. Midha and Mukhopadyay (2005) conducted a study to gain insight into the bulk and physical properties of the raw materials, machine parameters, and process variables. The properties of the nonwoven fabric are influenced by the type of fibres used, the arrangement of those fibres within the structure, and the level of consolidation achieved. Understanding how various parameters affect the fabric's properties is crucial for designing a fabric that is suitable for its intended application.

Some of the characteristics of the recycled fibres were taken from the supplier's certificate of analysis (COA) such as:

- Fibre fineness
- Fibre Tenacity and elongation at break
- Fibre Shrinkage
- Crimps
- Staple length
- Latex Viscosity
- Latex solid content

The following equipment was used for characterisation and the tests conducted:

- Thermogravimetric analyser (TGA)

- Fourier-transform infrared spectrophotometer (FTIR)
- PE powder particle size analyser

3.5.1 Thermogravimetric Analysis (TGA)

TGA analysis of the samples was carried out using a TGA 4000 instrument supplied by Perkin Elmer (Figure 3.5) at Cape Peninsula University of Technology (CPUT), Clothing and Textiles Laboratory department.

Figure 3.5 TGA 4000

This technique was used to determine the thermal stability and decomposition behaviour of fibres and PE powder, which involved measuring the weight change of a sample as it was heated in a controlled atmosphere. The analysis of the raw materials was conducted by heating from 25°C to 700°C at a heating rate of 10°C / minute in a nitrogen gas environment. To remove any residual thermal effects, the samples were equilibrated for 1 minute at 25°C before the analysis.

3.5.2 Fourier-Transform Infrared spectroscopy (FTIR)

This technique was used for the analysis and characterisation of materials based on their interactions with infrared radiation. FTIR operates by exposing a sample to infrared light and analysing the absorption or transmission of that light across various wavelengths. Different chemical bonds in a material will absorb infrared radiation at certain frequencies and produce distinct absorption bands in the FTIR spectrum (Karbownik *et al.*, 2019). By analysing these absorption bands, types of chemical bonds present in the material can be identified and provide information regarding its structure and composition. FTIR spectra of the samples were compared to the reference spectra of known materials to accurately identify and characterise fibres and PE powder used in this study.

IR spectra were acquired using a Perkin Elmer Spectrum Two (ATR) in the 4000 – 450cm^{-1} range, shown in Figure 3.6 below.

Figure 3.6 Perkin Elmer Spectrum Two

Two PET fibres and PE powder samples were analysed using this technique. One benefit of using this technique is that it doesn't require any specific sample preparation. Samples were simply placed in the sample compartment of the spectrometer against the ATR crystal window. This study utilised a spectral resolution of 4cm^{-1}.

3.5.3 PE powder particle size

This study employed the Microtrac laser diffraction technique to analyse the particle size distribution. This technique utilises a laser beam (Figure 3.7) that interacts with a group of particles, the particle size has a direct correlation with the angle of light scattering. The observed light scattering angle increases with decreasing particle size. Because it greatly affects the bulk and flow properties of the particles, the particle size distribution of a mix of particles is essential in defining the material's overall quality (Nsugbe, 2017).

Figure 3.7 Microtrac laser diffraction

3.6 Characterisation and Testing of Nonwovens

The characterisation and testing of nonwoven materials are crucial, as the results obtained from different testing methods and techniques offer valuable information. This information is instrumental in enhancing quality, developing new products, and predicting the overall performance of the products (Mao, 2016).

Prior to testing, the textiles were conditioned for 24 hours at 21 ± 1 ℃ and 65 ± 2% relative humidity (RH) in a conventional testing environment. Random samples were then taken from both the length and width directions of the fabric. The following paragraphs briefly outline the test methods employed for fabric analysis.

3.6.1 Weight (grammage)

Four samples of 20cm x 20cm were randomly cut and weighed on the ADAM PGL 3002 scale The weight per unit area per sample was calculated following the ASTM D3776-96 standards. Four square samples measuring 20cm by 20cm were selected randomly from each fabric and individually weighed in grams using the ADAM PGL 3002 scale. The average weight in g/m^2 was then recorded.

3.6.2 Thickness

The thickness of nonwoven fabrics was calculated by measuring the linear distance that a movable plane (Figure 3.8) was displaced from a parallel surface by the specimen under a set pressure as per ASTM D5729-97 (Kamath, 2005). The same samples that were used for weight measurement were used for thickness measurement, and the mean in mm was noted.

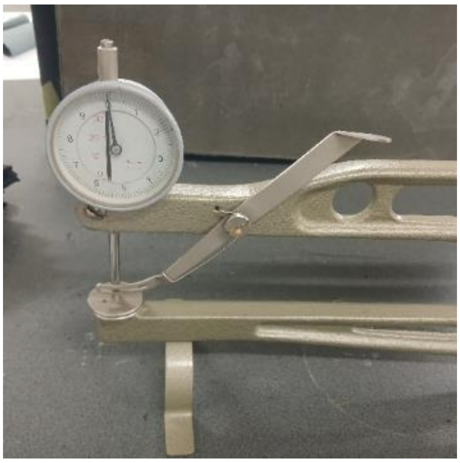


Figure 3.8 Thickness gauge

3.6.3 Tensile Strength and Elongation

Four samples from both length and width directions were cut in sizes of 300mm long x 50±0.5mm wide and were tested using the Titan machine (Figure 3.9). The gauge length was set to 200±1mm and the test speed was 100mm/min as per ISO 9073-3.

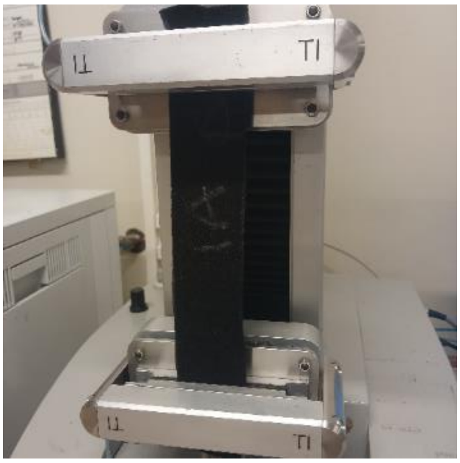


Figure 3.9 Titan tensile testing machine

3.6.4 Dimensional changes to heat

Coated nonwoven (Figure 3.10) samples were measured in both warp and weft directions before exposing them to heat. All four samples were heated at 150°C for 5 minutes and then cooled before re-measuring.

Figure 3.10: Coated NW samples marked for heat shrinkage

3.6.5 Burn rate

A horizontal flammability test was conducted on the samples using the ISO 3795:1989 test method. The Deatak flammability tester, model HC-1-X (Figure 3.11) was used to check the burning rate (BR). The test is normally performed on five samples per direction, however, due to a shortage of samples- only two samples per direction were tested.

Sample size of the horizontal burning rate test involved placing a sample material in a U-shaped holder and exposing it to a low-energy flame for 15 seconds in a controlled combustion chamber. The flame was directed at the free end of the sample, and the test determined whether the flame extinguished or how long it took to travel a specified distance (Nie, 2013).

The horizontal burning rate is expressed in mm/min (millimetres per minute) and is typically denoted by the symbol "BR". The BR value was calculated by dividing the distance between the ignition point and the point where the flame reached the opposite end by the time taken to spread.

The BR value is used to evaluate the flammability of materials, particularly in automotive applications. Materials with higher BR values are considered more flammable and may require additional safety measures to prevent fires such as using additives with flame retardant.

In summary, the horizontal burning rate measures how quickly a flame spreads horizontally along a material surface, and it is an important parameter in assessing the flammability of materials.

Figure 3.11: Deatak flammability tester

(Source: Deatak)

3.6.6 Wear resistance (Taber)

The wear resistance for the coated samples was conducted on the Taber, model 5135 abraser (Figure 3.12), using American Society for Testing and Materials (ASTM) D3884:09. Samples were tested using CS-10 abrasive wheels and a 500g load for 400 cycles. One sample from each subset was tested, to assess the durability and fibre loss.

Figure 3.12 Taber Abraser, Model 5135

CHAPTER 4 – RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the results of the series of experiments conducted to investigate the impact of each of the following factors on the properties of the needled fabric:

- The effect of raw materials
- The effect of Needle Penetration
- The effect of Stroke frequency
- Binder levels

4.2 The effect of Raw materials

4.2.1 Fibre Composition

The raw materials utilised in this study were recycled Polyester fibres, Sasol LDPE, and latex as a binder. These are the results (Table 4.1) extracted from the supplier's COAs for fibres:

Table 4.1 Fibre properties

Properties	Test method	Sample A	Sample B	Sample C	Sample D
Fineness (dtex)	ISO 1973	6.7	6.7	11	6.7
Tenacity (cN/dtex)	ISO 5079	2.53	3.41	2.66	4.40
Elongation %	ISO 5079	96.78	66.9	78.47	54.1
Crimp (n/cm)		3.0	2.8	2.9	3.1
Shrinkage (%)		0.11	4.8	0.65	5.0
Staple length (mm)		60	60	60	60

The fibre fineness of the individual fibres used in the blend is not uniform, which is reflected in the varying tenacity of the blend. The combination of 6 dtex and 11 dtex recycled PET fibres in a blend offers a unique balance of benefits. The 6 dtex fibres enhance the carpet's entanglement, creating a more robust structure, while the 11 dtex fibres contribute to the carpet's overall physical performance, specifically in needle-punched car carpets. Despite the differences in properties among the fibres, the fibres were intentionally blended to achieve uniformity of the properties.

Crimp and crimp retention play a crucial role in nonwoven processing, as they significantly impact processing efficiency, fabric cohesion, and bulk properties, including bulk stability. The fabric's performance and serviceability in a manufacturing are influenced by its bulk and physical characteristics. Bulk characteristics directly affect the fabric's thermal and compressional behavior, while physical properties are influenced by the material's bulk, either directly or indirectly (Midha & Mukhopadyay, 2005). From the Table above, crimp can be seen that it is similar for all fibres. Variation in the shrinkage (%) is due to different test methods used to test it, but it is still within tolerance. Virgin PES fibres have elongation % ranging from 35 - 60%, and from Table 4.1 it is evident that r-PET has a higher elongation %. Fibre selection is crucial as it influences the processing and quality attributes of the nonwoven fabric.

The thermal stability and decomposition behaviour of fibres and PE powder were characterised using FTIR and TGA used for determining the structure and composition as previously mentioned in Chapter 3, and Microtrac particle size distribution for PE.

4.2.2 FTIR

A comparison of the Sasol LDPE with pure polyethylene (Figure 4.1) revealed similar absorbance bands, indicating that the LDPE used in this study is also pure polyethylene. The characteristic absorbance bands for polyethylene, which are located at 720 cm^{-1}, 1472 cm^{-1}, 1472 cm^{-1}, 2850 cm^{-1}, and 2917 cm^{-1}, were identified. The peaks at 720 cm^{-1} and 1470 cm^{-1} were specifically used to detect and quantify the presence of polyethylene (D'Amelia *et al.*, 2016).

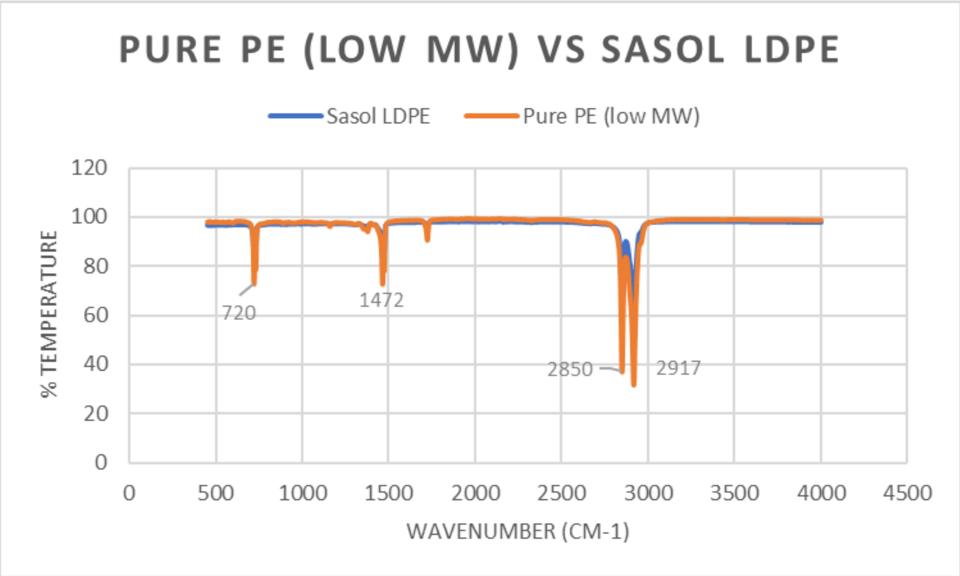


Figure 4.1 FTIR spectra for Pure PE and Sasol LDPE

The infrared (IR) spectrum of the fibres, depicted in Figure 4.2, exhibited distinct peaks that are characteristic of esters. The peak at 1716 cm^{-1} was attributed to the C=O stretching vibration, while the band at 1247 cm^{-1} corresponded to the C-C(O)-C stretching vibration in esters. Additionally, the peak near 872 cm^{-1} was identified as the Para-disubstituted benzene stretching mode (Lubna *et al.*, 2018). The three main peaks in the infrared (IR) spectrum of polyester are responsible for the functional group of the polymer, which is characterized by distinct absorption frequencies (Holland & Hay, 2002).

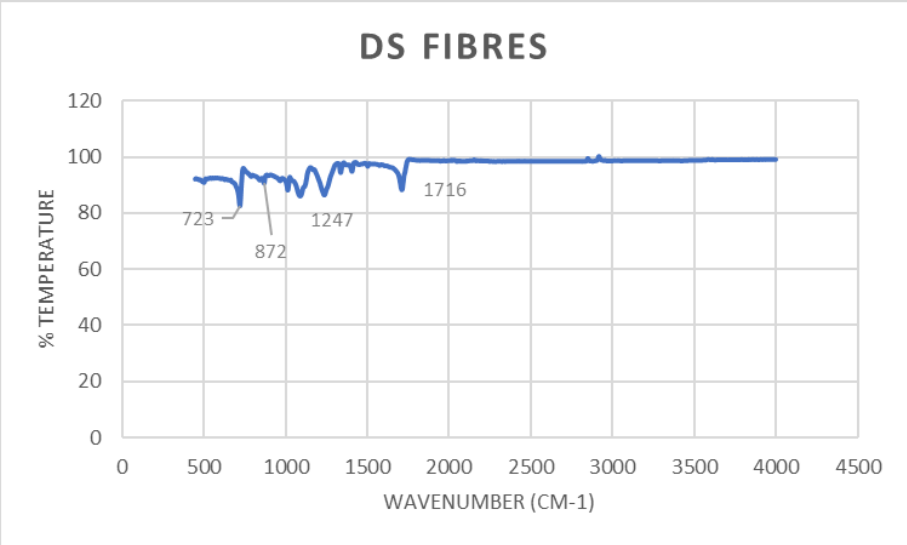


Figure 4.2 FTIR spectra for DS fibres

4.2.3 TGA

From the thermograms (Figure 4.3), it can be observed that the thermal degradation of r-PET and PE granules occurs between 379 - 451°C, and 400 - 490°C, respectively. This is attributed to partial bond scission and decomposition, ultimately leaving a residue at the end of the analysis (Lubna *et al.*, 2018).

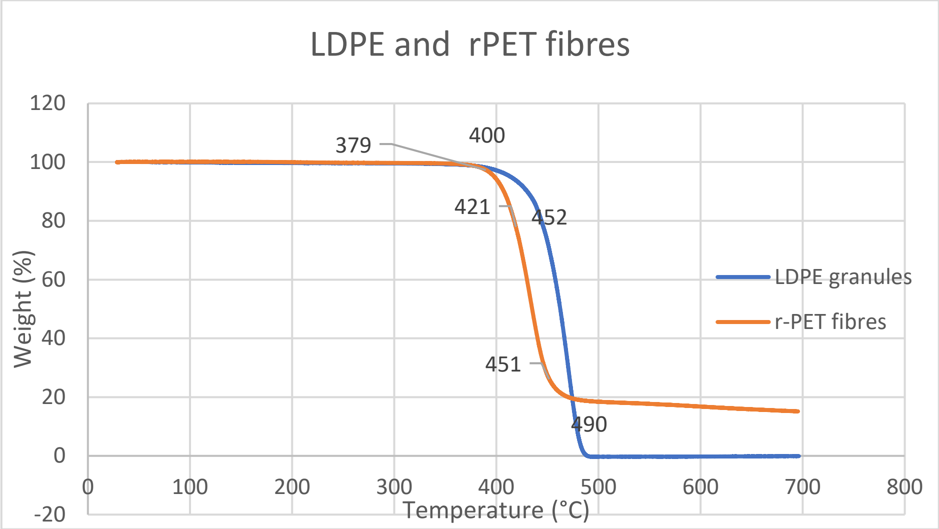


Figure 4.3 LDPE and r-PET thermograms

4.2.4 Particle size distribution

Microtrac laser analysed the particle size distribution (Figure 4.4) and the analysis showed that the average particle size is 339.7µm. The size of particles in particulate materials has a significant impact on various properties, making it a crucial indicator of quality and performance. The size and shape of particles in powders can affect their flow and compaction properties, with larger, more spherical particles typically flowing more easily than smaller or irregularly shaped particles (Amidon *et al.*, 2009). Furthermore, smaller particles tend to melt more rapidly and that was evident during this study.

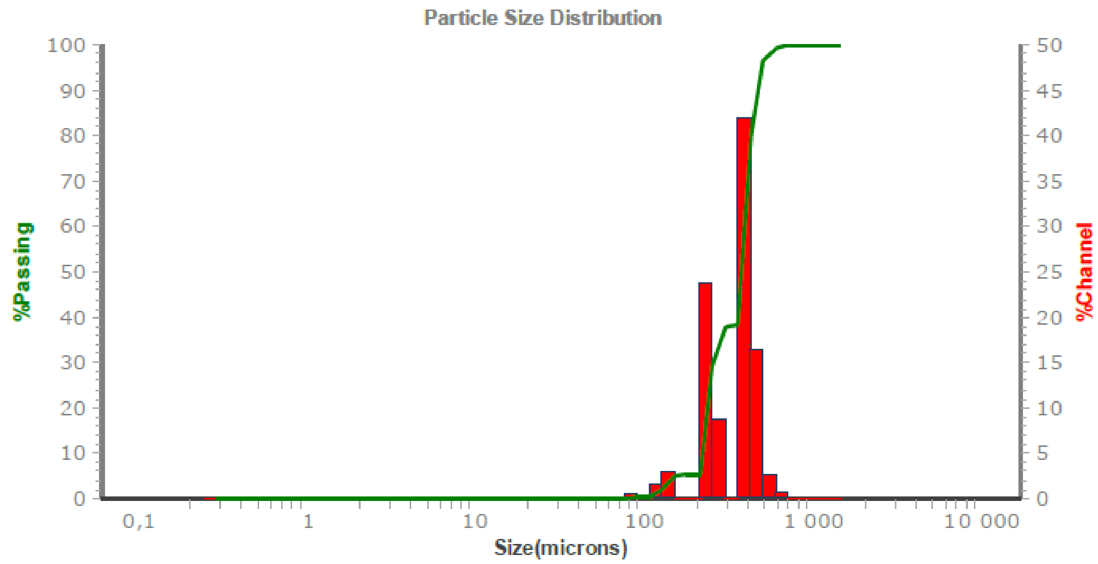


Figure 4.4 Particle size distribution

4.3 Areal weight

The results, including F-statistics, p-values, and conclusions on the significance of each variable, are presented in Table 4.2. The analysis of basis weight data was conducted using statistical methods, specifically with Microsoft Excel. The ANOVA procedure was employed to identify which variables significantly contributed to the differences in the distribution of basis weight.

Table 4.2 Summary of Statistics

Variable	F-statistic	p-value	F-critical	Interpretation
Needle Penetration (NP)	10.626	0.0311	7.70865	Significant
Stroke Frequency (SF)	5.076	0.087	7.70865	Insignificant
NP * SF	6.7002	0.0142	4.0662	Significant

For each variable, a statistical test is performed to determine whether it has a significant impact on the differences in aerial weight, with two possible outcomes: the null hypothesis, which assumes that the variable does not affect the differences in areal weight, or the alternative hypothesis, which suggests that the variable does contribute to these differences.

The p-value was used for this analysis to reject the null hypothesis for the NP variable since $p<0.05$ and accept the null hypothesis for the SF variable as the p-value >0.05- meaning this variable does not affect the differences in areal weight. However, the alternate hypothesis is acceptable when acknowledging that both variables did not individually contribute to the difference in weights, as there is a slight difference between the two variables. This was done at a 95% confidence interval.

The significant effects of the variables on the differences in areal weight measurements were studied further in Table 4.2. As can be observed from the graph below Figure 4.5, sample 1B has the heavier weight, followed by 1A and 2B and the lightest in weight is 2A where both the stroke frequency and needle penetration were the highest. In parallel to the literature by Moyo *et al.* (2013), an increase in both stroke frequency and needle penetration reduces the areal weight due to drafting.

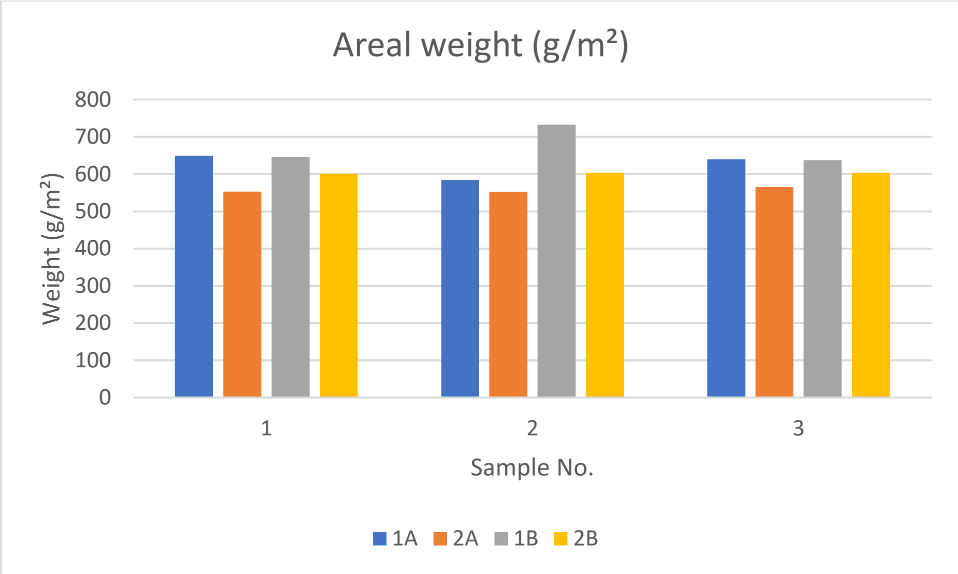


Figure 4.5 Areal weights

4.4 The effect of process parameters

The results showing the influence of stroke frequency and needle penetration depth on the quality of needle punched nonwoven components produced are summarised in Table 4.3. graphs are shown as the following: Tensile strength for 1A and 2A in Figure 4.6 (a) to 4.6 (c), Tensile strength for 1B and 2B in Figure 4.7 (a) to 4.7 (c), Flammability in Figure 4.8 and Abrasion in Figure 4.9.

Table 4.3 Summary of the effect of stroke frequency and needle penetration depth on the quality of needle punched NW.

					Machine Direction (MD)		Cross direction (CD)		MD	CD	Taber
Sample ID	SF (strokes/min)	NP (mm)	Weight (g/m²)	Thickness (mm)	Tensile Strength (N)	Elongation (%)	Tensile Strength (N)	Elongation (%)	Flammability (mm/min)	Flammability (mm/min)	Fibre loss (g)
1A	30	30	624	2.9	662,93	52,36	446,08	89,06		84.3	0.003
2A	40	30	557	2.9	471.80	48.03	286,56	62,34	104	100.5	0.032
1B	30	15	672	3.3	574.60	65.55	357.55	110.18	79.6	76.1	0.073
2B	40	15	603	3.1	586.92	62.39	395.92	70.12	95.5	98.8	0.045

4.5 Tensile Strength

The material's tensile strength was tested in both machine and cross directions, revealing a significant difference between the two. The results in Figure 4.6b showed that the material exhibited higher tensile strength in the machine direction than in the cross direction, indicating anisotropy. Furthermore, sample 2A was found to have the lowest weight and thickness, which was attributed to drafting caused by the increased stroke frequency and needle penetration during the manufacturing process. According to the literature (Tshifularo *et al.* 2020 and Anandjiwala and Boguslavsky, 2008), tensile strength is directly proportional to increased stroke frequency and needle penetration depth.

Sample 1A was manufactured using a similar needle penetration to Sample 2A but with a reduced stroke frequency of 30 strokes per minute. This resulted in a slight increase in weight, which was greater than that of Sample 2A. The increased weight, in turn, affected the tensile properties, leading to a higher tensile strength in Sample 1A (Figure 4.6a) compared to Sample 2A.

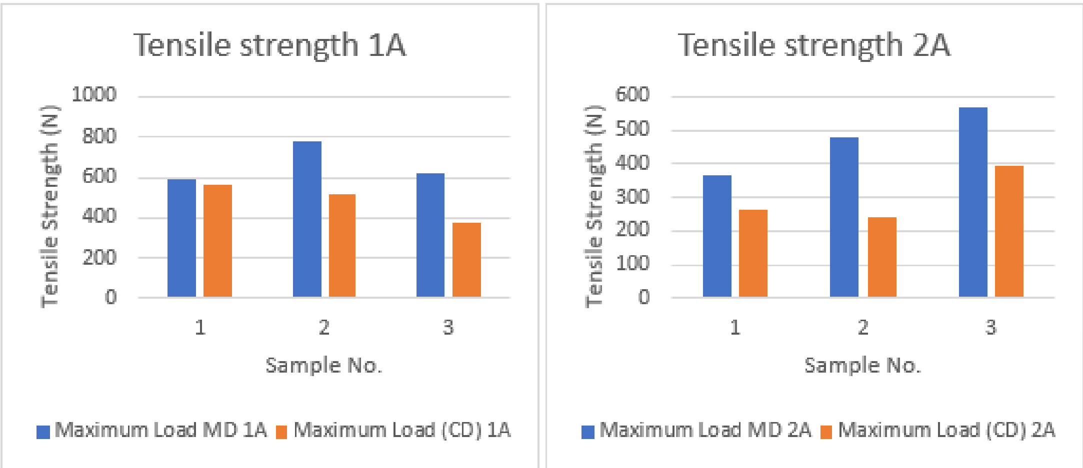


Figure 4.6 (a & b) Tensile strength for samples 1A & 2A

Contrary to the trend in tensile strength, the elongation percentage exhibits the opposite behavior. As the tensile strength increases, the elongation percentage decreases, as evident in Figure 4.6c. Specifically, the figure shows that the elongation percentage is higher in the cross direction, which is attributed to increased stroke frequency producing a stiffer structure, resulting in a reduced elongation percentage.

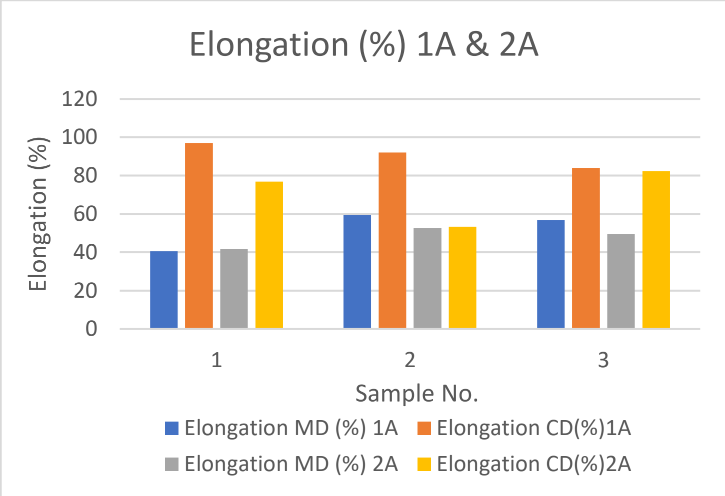
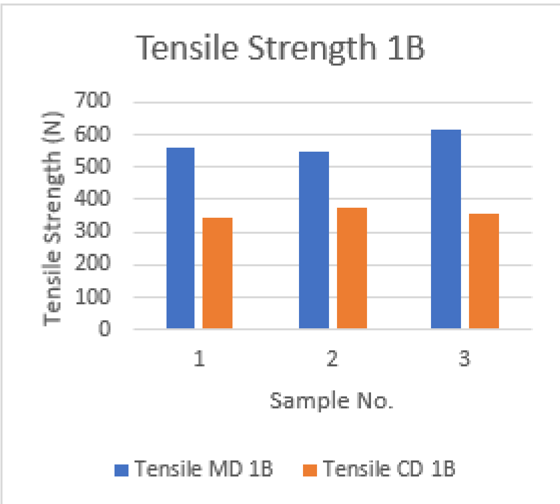


Figure 4.6c Elongation (%) for samples 1A & 2A

Sample 1B's (Figure 4.7a & b) tensile strength results are unusual for a nonwoven, as they exhibit minimal variation between samples. A notable difference is observed in the elongation percentage between Sample 1B and 2B (Figure 4.7c), with Sample 1B showing the highest elongation percentage. This is attributed to the use of lower needle penetration and stroke frequency, which led to poor interlocking and entanglement of fibres, leading to increased elongation. According to literature by Midha and Mukhopadyay (2005), when needle penetration increases, the fabric is stretched.



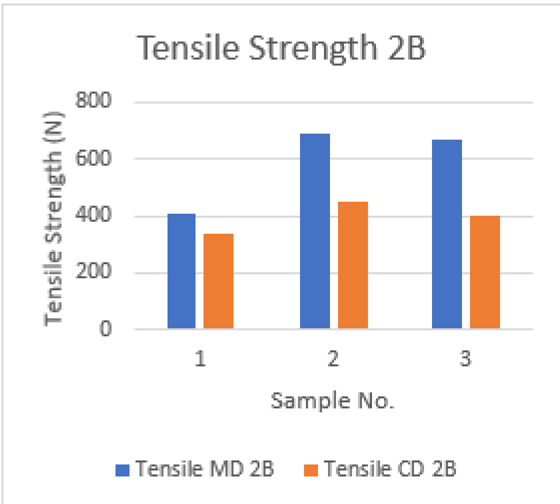


Figure 4.7(a & b) Tensile strength for sample 1B & 2B

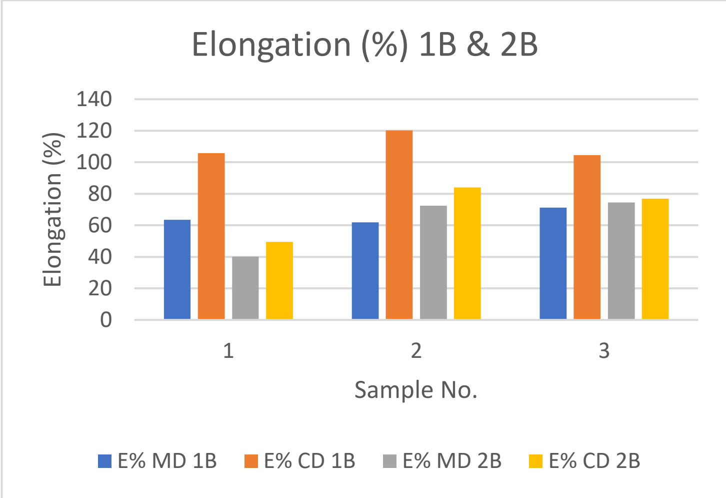


Figure 4.7c Elongation % for sample 1B & 2B

4.5.1 Statistical analysis

The statistical analysis in Table 4.4 shows a significant relationship between the variables and the nonwoven's tensile strength. This suggests that changes in needle penetration and stroke frequency have a measurable impact on the material's tensile strength, highlighting the importance of considering these factors in manufacturing.

Table 4.4 Statistical analysis

Variables	F-statistic	p-value	F-critical	Interpretation
Needle Penetration (NP) 1A & 2A	5.0468	0.0485	4.965	Significant
Stroke Frequency (SF)1B & 2B	19.9692	0.0012	4.965	Significant

Since the variables and the tensile strength are related, correlation analysis was conducted to determine the strength of the relationship (see Tables 4.5 and 4.6).

Table 4.5 Correlation between SF and the Maximum Load

	MD 2B	*MD 1B*	*CD 2B*	*CD 1B*
MD 2B	1			
MD 1B	0,207440102	1		
CD 2B	0,940023989	-0,138689785	1	

CD 1B	0,853360967	-0,332959302	0,98000655	1

A positive but weak relationship exists between 1B and 2B machine direction (MD) and 1B and 2B cross direction (CD), with a correlation value of 0.988. This indicates a positive, strong relationship that can be seen in the actual tensile results, which show that they are close to one another: 357,55 and 395,92N.

Table 4.6 Correlation between NP and the Maximum load

	MD 1A	*MD 2A*	*CD 1A*	*CD 2A*
MD 1A	1			
MD 2A	0,233797386	1		
CD 1A	0,103918818	-0,942725228	1	
CD 2A	-0,473941405	0,745345801	-0,92504029	1

1A and 2A MD showed a weak but positive relationship due to the similar needle penetration settings. A correlation value of -0.93 was found between 1A and 2A CD, which shows a weak inverse relationship; there is over 60% difference between the two variables.

One notable pattern observed throughout the tensile strength results is a consistent inverse relationship between the material's properties in the machine and cross directions. Specifically, the tensile strength results indicate that as the material's properties improve in the machine direction, they tend to deteriorate in the cross direction and vice versa. This inverse relationship is a consistent feature across the entire dataset, highlighting the anisotropic nature of the material's mechanical properties. Similar findings were reported in the Gaur *et al.* (2020) study.

4.6 Dimensional changes to heat

The samples were assessed, and there were no noticeable changes (Table 4.7) in dimensions after the heat exposure, which could be due to the multiple heat exposures experienced by the sample during the coating and pressing processes. Moreover, that acted like a heat-setting process since polyester fibres are thermoplastic and can be heat-set thus improving stability and reducing shrinkage. Midha and Mikhopadyay (2005) stated that the dimensional stability of a fabric improves by heat settings, but it is essential to determine the optimal heat setting time.

Table 4.7 Dimensional changes to heat

Sample ID	Dimensions (mm)				Dimensional Changes (%)
	Before heat		After heat		
	MD	CD	MD	CD	
1A	147	150	147	150	0
2A	145	147	145	147	0
1B	150	200	150	200	0
2B	150	200	150	200	0

4.7 Burn rate

Various factors also influenced the flammability of the samples used in this study. Specifically, flammability can be affected by fibre content, fabric construction, fabric weight, and finishes. Notably, the polyester fibre used in this study has a moderate level of flammability (Petkova *et al.*, 2022). However, since the fibre content and finishes were similar across all samples, these factors can be eliminated as likely contributors to flammability. Instead, the analysis suggests that fabric weight played an important part in determining the flammability of the samples. This is evident from the data in Table 4.3, which shows that sample 2A had the highest burn rate of 104mm/min in machine direction and 100.5mm/min in cross direction, corresponding to a fabric weight of 557g/m^2. The fabric weight contributed to the high burn rate observed in this sample because the machine parameters were suitable for a non-porous structure.

The analysis of the flammability results revealed a consistent trend across the samples, except for sample 2B. Specifically, the burn rate in MD was consistently higher than the burn rate in CD, indicating an anisotropic behaviour. However, this trend was not observed in sample 2B, which used 15mm of needle penetration. This deviation from the general trend may be attributed to the unique fabric construction characteristics introduced by the increased needle penetration, which could have altered the fabric's response to flame. On the other hand, most of the samples exhibited a consistent pattern of higher burn rates in the machine direction, suggesting that fabric weight and other factors (coating) may contribute to this trend.

4.8 Wear resistance

The abrasion resistance of the carpets was also evaluated. The assessment of abrasion resistance was based on two critical criteria: fibre loss and carpet appearance after 400 cycles – see Table 4.8. This comprehensive evaluation enabled a thorough understanding of the carpets' performance under repeated wear and tear. The results of this testing provided valuable insights into the durability and maintenance requirements of the carpets, as well as their ability to withstand the demands of everyday use.

Table 4.8 Abrasion results

Sample ID	Fibre loss (g)	Appearance results
1A	0.003	Pass
2A	0.032	Pass
1B	0.073	Pass
2B	0.045	Pass

The abrasion standards for automotive vary with the manufacturers, but the lowest is a maximum of 0.25g. All the samples (Figure 4.10) were within the acceptable standard, and the appearance was assessed using Figure 4.11.

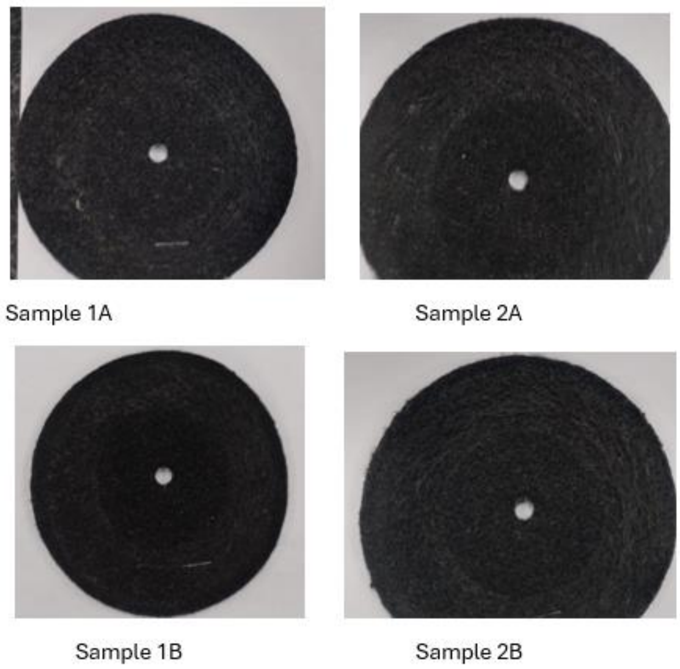


Figure 4.10 Taber abrasion tested samples.

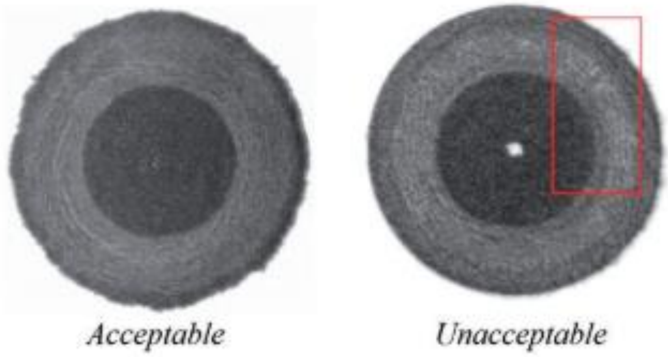


Figure 4.11 Example of an acceptable standard of Taber abrasion

The abrasion resistance testing revealed that Sample 1A exhibited exceptional performance, with a fibre loss of only 0.003g. This outstanding result is attributed to the superior fabric consolidation achieved through the optimised needle penetration and stroke frequency used in its production. The balanced combination of these parameters allowed for a more uniform and dense fabric structure which, in turn, enhanced the carpet's ability to resist fibre loss and maintain its appearance under repeated abrasion cycles. According to Midha (2011), needling machine parameters influence abrasion. Results of the study showed that lower needle penetration led to reduced fabric consolidation, affecting fibre loss during abrasion.

CHAPTER 5 – CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter summarises the key findings of the research, and recommendations based on these insights are provided. The aim was to determine the nonwoven optimal process parameter settings that influence the tensile strength, and dimensional changes experienced but not desired due to heat, wear resistance, and burn rate. This was achieved by employing an experimental research design that involved systematically varying process parameters. The selected process parameters were the stroke frequency and the depth of the needle penetration and their effect on the dependent variables was observed.

The needled nonwovens for automotive NW components are unique and require further enhancement to achieve the desired performance employing binders and adhesives. Therefore, this study further explored the effect of the binder and adhesive on the fabric, providing valuable insights for developing NW components used in the automotive industry. The NW fabrics were manufactured using recycled polyester sourced from different suppliers, and binder and adhesive were applied to finish the fabric. A one-way analysis of variance was performed to investigate the independent and combined effects of stroke frequency and depth of needle penetration on the fabric properties. This statistical analysis aimed to identify significant differences in the fabric properties resulting from the variations in these two process parameters.

5.2 Conclusion

The results of this study demonstrated ideal process parameters that can be used to achieve better mechanical properties needed for moulding and achieving higher wear resistance properties required for the service life and durability of the NW fabric for automotive applications. The influence of process parameters on the quality of needle-punched nonwoven components used in automotive applications was found to be significant. The systematic analysis of the relationships between these parameters and the resultant material properties has made it possible to draw guidelines for optimising the manufacturing process.

The findings of this study can be used by automotive trim manufacturers to select process parameters for high-quality nonwoven components and provide guidance to improve product quality. Furthermore, these findings offer a possible solution to the ongoing problems of NW component failures. As the automotive industry continues to evolve, further research in this area will be vital to develop innovative solutions that meet sustainability, lightweight, and performance demands. The insights gained from this study pave the way for future advancements in nonwoven technology that could greatly benefit automotive engineering and allied fields.

These findings provide the much-sought answers the automotive industry players need to reduce non-conformances. The information adds to the existing body of literature and underscores the importance of precision in parameter selection to enhance the performance and durability of nonwoven materials to produce more efficient and reliable automotive components.

5.2.1 Research problem revised

The research problem for this study was: In the local automotive manufacturing sector, the trims manufactured by the third tier are non-conforming to stringent performance and quality standards. These challenges lead to delayed lead times to supply customers, and in some extreme cases, product recalls happen when malfunctions are discovered when the automobiles are already on the market.

5.2.2 Research question revised

The primary research question that prompted this study was: How are the quality characteristics of needle-punched nonwoven components intended for use in the automotive industry affected by different process parameters?

This was answered by employing an experimental research design in Chapter 3 that involved systematically varying process parameters. The selected process parameters were the stroke frequency and the depth of the needle penetration and their effect on the dependent variables was observed.

5.2.3 Research objectives revised

Statements were grouped to give answers to these objectives:

Objective 1: The effect of raw materials on the physical properties of the laminated needle-punched nonwoven components used in the automotive industry.

In Chapter 3, the raw materials studied in the manufacture of the nonwoven components for this study were fibres and binders, which are polyethylene powder and latex.

a) Fibres

The fibre raw material used was similar, even though the suppliers were different as seen in Chapter 3. This was important to establish because fibre selection determines process efficiency, the loftiness of the web produced and ultimately the NW fabric quality attributes. The fibre characterisation results indicated that the LDPE and recycled PET fibres were chemically pure LDPE and virgin PET, respectively, based on their thermal stability and decomposition and band assignments. There were no new band assignments, that is, every absorption band present in r-PET was also present in PET. TGA and FTIR are suitable techniques for differentiating between virgin and r-PET.

In a study conducted by Kayakan and Dogan (2008), it was concluded that the TGA experiment demonstrated that the heating rate significantly influences the decomposition response. The breakdown temperature of the plastic samples rises in tandem with the heating rate, which was also evident in this study.

b) Binder Polymer Particle size

Larger granules were not melting completely resulting in a poor film that delaminated easily as observed in Chapter 4. The average particle size also affects the flow rate of the powder as it is scattered onto the back of the NW fabric, which poses a quality challenge in the industry and thus this research. When the flow rate is not consistent, it could lead to some areas with less or more powder, thus creating weaker areas on the NW fabric which will be prone to tear. For this study, the average size distribution of the powder was 339.7µm, which was suitable for the application. The powder melted completely bonding with the adjacent fibres, reinforcing the fabric's structure which aided the tensile elongation. Understanding the particle size distribution of PE powder is crucial for controlling product quality and predicting material behaviour in various applications. Multiple methods can be employed to determine size distribution, manufacturers can effectively characterise the particle size of PE powder and make informed decisions about its use in different processes and products.

c) Latex Binders

Binders played a crucial role in enhancing the performance and quality of nonwoven fabrics. They also enhance the strength and durability of the fabric as seen in Chapter 4. Applying the binders should be sufficient to allow some flexibility of the NW fabric required for the moulding process. A study by Wiltzius (1997) stated that the “solids concentration of latex dispersions is a crucial consideration from an economic standpoint. Because it improves characteristics, increases production rates, and reduces energy costs, a higher solids content is preferred. To provide good flow characteristics on the coater, the solids concentration must not above the maximum viscosity. As a result, runnability and solids content are traded off. The aim is to achieve the maximum solids level without impairing the coater's runnability." For this study, it was evident that the strength of the nonwoven increased due to the binding properties of the latex that was used and aided with the dimensional stability of the structure not being affected much by heat.

Objective 2: The relationship between various process parameters and the dimensional stability characteristics of laminated needle-punched nonwoven components for automotive applications

The dimensional stability of laminated needle-punched nonwoven components in automotive applications is influenced by various process parameters according to Chapter 4. Understanding the relationship between these parameters and the dimensional stability characteristics is crucial for enhancing the performance of these materials. By optimising these parameters, manufacturers can improve the performance, durability, and reliability of nonwoven components in automotive environments.

a) Dimensional Changes to Heat

The laminated nonwoven sample was exposed to heat and the shrinkage was calculated as seen in Chapter 4. No noticeable change was observed in the dimensions after exposure to heat, and that is due to the ability of PES fibre to withstand heat up to a certain temperature and the binders applied that filled the pores within the NW fabric structure; thus, enhancing dimensional stability. This means that the NW fabric can be flexible to be moulded into any shape without worrying about tearing or delamination during moulding.

Objective 3: The alterations in process parameters influence the thermal resistance (heat retention, thermal conductivity) of laminated needle-punched nonwoven components intended for use in the automotive industry.

While the specific thermal resistance of laminated needle-punched nonwoven components was not evaluated due to testing limitations, it is evident that alterations in process parameters can influence both heat retention and thermal conductivity. A study by Cai *et al.*, (2021) indicated that the parameters that influence thermal resistance are weight, thickness, the surface of NW, and fibre type. The literature by Wazna *et al*., 2019 concluded that nonwovens are excellent options for affordable and eco-friendly insulation materials, suitable for use not only in buildings but also in the automotive, furniture, and clothing industries.

Objective 4: The extent to which alterations in process parameters affect the overall durability and lifespan of laminated needle-punched nonwoven components.

The key conclusion from the study of the process parameters, namely stroke frequency and depth of needle penetration is discussed below:

a) Needle punching parameters

- The investigation revealed in Chapter 4 a significant relationship influence of the needle penetration depth and stroke frequency on the weight and thickness of the needle-punched non-woven (NW) fabric. There is a proportional relationship between weight and stroke frequency; an increase in stroke frequency results in a higher weight. The fabric's thickness decreased as the needle penetration depth increased, due to the greater interlocking and entanglement of fibres. This is attributed to the fact that the needle's barbs carried many fibres with increased depth of penetration, leading to a more compact fabric.

- The tensile strength in the machine direction surpassed that in the cross-machine direction (Das, Pradhan, Chattopadhyay, & Singh, 2012). Additionally, the tensile strength was found to increase with rising stroke frequency, needle penetration, and weight. Interestingly, an increase in needle penetration was found to decrease elongation percentages in the machine direction. Higher consolidation decreases elongation, the desire is that the elongation be enough to allow the NW to be moulded into a desirable end-use.

In parallel to the literature in Chapter 2, Kothari *et al.* (2007) conducted a similar study. However, they used 6 denier and 15 denier fibres and the following were the results of their study, which are in line with the current study:

- As the proportion of finer fibres increases, the recovery of fabrics with corresponding punch density rises. Conversely, the compressibility of the fabrics decreases with higher punch density.
- The breaking load measured in the machine direction exceeds that measured in the cross direction. Fabrics made from 15 denier fibres demonstrate an increase in

average load-bearing capacity in the machine direction as punch density rises, while those made from 6 denier fibres exhibit a decreasing trend in average peak load. In terms of machine direction strength, the fabrics crafted from both 6 and 15 denier fibres show a relatively stable response in peak load with changes in punch density, with values falling between those of the other two fabric types.

- Additionally, 6 denier fibre fabrics exhibit more crimping compared to 15 denier fibre fabrics.
- Dimensional changes in 15 denier fibre fabrics are nearly negligible and uniform, showing no impact from punch density, whereas shrinkage is greatest in 6 denier fabrics. For fabrics made from finer fibres, shrinkage initially increases with punch density before decreasing. Furthermore, the dimensional stability of fabrics composed of a 50:50 blend of 6 and 15 denier fibres is found to be higher compared to fabrics with other fibre combinations.

b) Burn rate

Burn rate is a critical legal requirement for the automotive industry as seen in Chapter 3. The NW fabric mustn't burn or have a burning rate of over 100mm/min, which will give a passenger enough time to escape the vehicle should it catch fire. This study found that the burn rate of NW fabric is heavily influenced by its weight and the finishes applied. While fibre selection and finishes play a role in determining burn rate, it was discovered that PET fibres are capable of self-extinguishing when a flame is applied. However, when adhesives lacking flame retardant properties are applied, the burning rate could exceed 100mm/min. Nazare and Horrocks (2008) agree that the lighter the fabric, the quicker it ignites and the faster it burns compared with a heavier fabric made of the same material.

c) Taber abrasion

- Samples produced from this study will be able to withstand the demands of everyday use, because of the less fibre loss observed as seen in Chapter 4. The use of a binder reduces the bearding of NW fabric, this inter-fibre bonding was the reason for enhanced durability and excellent abrasion resistance. In the research conducted by Atakan *et al.* (2018), automotive floor carpets with a velour design were created using needle-punched and moulded techniques, incorporating a mixture of 6 and 11 denier recycled polyethylene terephthalate fibres. The study found that the 6 denier rPET fibres offered improved cohesion, while the 11 denier fibres enhanced the physical performance. The combination of both fibres yielded commendable Taber abrasion resistance, which can also be observed from the results of this study.

Objective 5: The optimal process parameter settings leading to the quality and performance improvement of laminated needle-punched nonwoven components for automotive applications

- The optimal process parameter settings play a crucial role in enhancing the quality and performance of laminated needle-punched nonwoven components for automotive applications as seen in Chapter 4. Here are key parameters and their optimal settings aimed at achieving desirable outcomes:

a) Needle Parameters

- **Optimal Setting**: A balanced stroke frequency and needle penetration depth (e.g., 30 strokes/min and 30mm needle penetration depth) is recommended. This enhances fabric structure and tensile strength without compromising flexibility.
- **Impact**: Increased density can improve dimensional stability and strength while minimising air gaps that can reduce thermal resistance.

b) Lamination Method

- **Optimal Setting**: Adhesive type as well as particle size around 300 µm and controlled temperature of 150-180°C. These methods enhance adhesion and create a seamless bond between layers.
- **Impact**: These have great influence on moulding by reducing the likelihood of delamination and ensuring effective heat retention.

c) Fibre Composition

- **Optimal Setting**: Use a blend of synthetic fibres (e.g., recycled polyester or polypropylene) with specific percentages tailored to the application—typically 6 Denier and 11 Denier
- **Impact**: Synthetic fibers frequently improve physical performance and have better structural entanglement.

Meticulous attention to these optimal process parameters will significantly improve the quality and performance of laminated needle-punched nonwoven components in automotive applications. By fine-tuning these settings, manufacturers can achieve enhanced thermal resistance, durability, and overall effectiveness of their nonwoven materials, ultimately leading to more reliable and efficient automotive components.

5.3 Recommendations for future work

Based on the limitations of this study mentioned in Chapter 1, several areas for future work can be identified. These recommendations aim to enhance the understanding of material behaviour, refine manufacturing processes, and explore new applications as supported by Yilmaz *et al*.,2020; Chauhan *et al*., 2020. Here are some specific recommendations:

5.3.1 Material Development

- **Explore New Fibres**

a) Investigate alternative fibres, such as biopolymers or recycled materials, to enhance sustainability while maintaining performance.

- **Adhesive Innovations**

b) Develop and test new adhesive formulations that operate effectively at lower temperatures, improving energy efficiency and reducing the risk of thermal degradation of the nonwovens.

5.3.2 Process Optimisation

- **Advanced Process Monitoring**

a) Implement real-time monitoring systems for temperature, pressure, and moisture during production to ensure optimal process control and consistency.

- **Automated Adjustment Systems**

b) Develop automated systems that can dynamically adjust parameters during production based on ongoing feedback to maintain optimal conditions.

5.3.3 Performance Testing

- **Expanded Testing Regimens**

a) Conduct a broader range of performance tests, including substances of concern, thermal insulation, sound absorption, and durability under various environmental conditions.

- **Long-Term Studies**

b) Initiate long-term performance evaluations under automotive conditions to assess aging, wear, and material property changes over time.

5.3.4 Thermal and Fire Resistance Studies

- **Thermal Properties Analysis**

a) Investigate the thermal conductivity and fire resistance properties of laminated nonwovens, which are critical in automotive applications. Studies on flame retardant treatments and their effectiveness should also be explored.

- **Impact of Environmental Factors**

b) Assess the impact of environmental factors such as temperature variations, humidity, and UV exposure on the performance and lifespan of the laminated components.

5.3.5 End-Use Applications

- **Broaden Application Scope**

a) Investigate the use of laminated needle-punched nonwovens in other sectors such as building materials, insulation for HVAC systems, or soundproofing in residential and commercial construction.

- **Footwear and Personal Protective Equipment**

b) Explore innovative footwear and personal protective equipment applications, focusing on comfort and performance features.

5.3.6 Sustainability Assessment

- **Life Cycle Analysis**

a) Conduct detailed life cycle assessments to quantify the environmental impact of different raw materials and processes, guiding future development toward more sustainable practices.

- **Recycling Studies**

b) Investigate methods for recycling or repurposing used nonwoven materials to reduce waste and enhance circular economy principles in manufacturing.

Future work in the field of laminated needle-punched nonwoven components for automotive applications should focus on material innovation, process optimisation, comprehensive testing, and sustainability. By pursuing these recommendations, researchers and manufacturers can significantly improve the performance, reliability, and environmental impact of these materials, ultimately benefiting the automotive industry and beyond.

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