COMPARATIVE PERFORMANCE OF NATURAL AND SYNTHETIC FIBRE NONWOVEN GEOTEXTILES

C.A. TSHIFULARO

(Student Number: 213520524)

2016

COMPARATIVE PERFORMANCE OF NATURAL AND SYNTHETIC FIBRE NONWOVEN GEOTEXTILES

By

Cyrus Alushavhiwi Tshifularo

Submitted in partial fulfilment of the requirements for the degree of Philosophiae Doctor in the Faculty of Science at the Nelson Mandela Metropolitan University

December, 2016

Promoter: **Prof. Rajesh Anandjiwala**

Co-Promoter **Dr. Asis Patnaik**

DECLARATION

I, Cyrus Alushavhiwi Tshifularo (student number: 213520524) hereby declare that the thesis for Philosophiae Doctor (PhD) in Textile Science is my own work and that it has not been previously submitted for assessment or completion of any postgraduate qualification to another University or for another qualification.

Cyrus Alushavhiwi Tshifularo

……………………………………..

Signature

ACKNOWLEDGEMENTS

I Cyrus Alushavhiwi Tshifularo, would like to express my profound gratitude to the promoter, Professor Rajesh Anandjiwala and my co-promoter, Dr Asis Patnaik for their endless support and guidance during my studies.

I would like to thank Dr Jacques Pietersen, Department of statistics of the Nelson Mandela Metropolitan University, for his support in statistical data analysis.

I also appreciate the support given by CSIR and administrative staff during this study, not forgetting the financial support from CSIR and Nelson Mandela Metropolitan University.

My intense gratitude to my colleagues Teboho Mokhena, Lebo Maduna, Mlando Mvubu, Haydon Whitebooi, Ntsiki Dumakude, Asanda Mtibe, Steve Chapple, Osei Ofosu, Dr Thabang Mokhothu, Dr Paula Melariri and Dr Sudhakar Muniyasamy.

Special thanks to my parents Samuel and Violet Tshifularo, my siblings Ntambudzeni, Avhaluvhei, Tshifhiwa, Tendani, Vhulungani, my nephews Teboho and Bokang and my friend Gundo Muthige.

ABSTRACT

The aim of this work was to establish a range of suitable process parameters which can be utilized to produce needlepunched nonwoven fabrics for geotextile applications.

Nonwoven fabrics were produced from 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres. The depths of needle penetration of 4, 7 and 10 mm, stroke frequencies of 250, 350 and 450 strokes/min and mass per unit area of 300, 600 and 900 g/m^2 were utilized for producing the fabrics, on a Dilo loom.

The effect of depth of needle penetration, stroke frequency and mass per unit area on the fabric properties, namely, tensile strength, puncture resistance, pore size, water permeability and transmissivity were analysed. In addition, the effect of chemicals, namely, 10% ammonium hydroxide (NH_4OH), 10% sodium chloride (NaCl) and 3% sulphuric acid (H_2SO_4) solutions on degradation of the fabric was also studied.

The results have shown that density, thickness and nominal weight of the needlepunched nonwoven fabrics were related to each other and they were influenced by stroke frequency, depth of needle penetration and feed rate of the needlepunching process. The increase in nominal weight of the fabrics also increases thickness and density of the fabrics.

The tensile strength and puncture resistance of the fabrics increased with the increases in stroke frequency, depth of needle penetration and fabric mass per unit area. However, lower tensile strength and puncture resistance were achieved in the fabrics produced at lower stroke frequency, lower depth of needle penetration and lower mass per unit area. Bigger pores were resulted in the fabrics produced at lower stroke frequency, lower depth of needle penetration and lower mass per unit area, however, pore size decreased with increases in stroke frequency, depth of needle penetration and mass per unit area. Water permeability depends on the pore size, properties of the fibres, stroke frequency, depth of needle penetration and mass per unit area.

Higher tensile strength and higher puncture resistance were achieved in the needlepunched nonwoven fabrics produced from 100% PP fibres, therefore, they are suitable for some load-bearing geotextile applications, such as reinforcement and separation. However, higher water permeability was achieved in the fabrics produced from 100% kenaf fibres, therefore, they are ideal for geotextile applications where good water permeability is required. Higher values for transmissivity were obtained in the fabrics produced from a blend of 50/50% PP/kenaf fibres, therefore they are suitable for drainage applications.

The fabrics produced from a blend of 50/50% PP/kenaf fibres achieved better values of tensile strength, puncture resistance, pore size and water permeability in comparison to that produced from 100% PP and 100% kenaf fibres. However, better tensile strength and puncture resistance were achieved in the fabrics produced from 100% PP fibres and bigger pore size and higher water permeability were achieved in the fabrics produced from 100% kenaf fibres. Therefore, it can be suggested that the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres can fulfil almost all requirements of geotextile applications, such as, filtration, separation, reinforcement and drainage.

The fabrics produced from 100% PP fibres were not damaged or deteriorated when treated with all the three chemicals due to chemical inertness of polypropylene. However, the fabrics produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres were damaged and deteriorated when treated with H_2SO_4.

CONTENTS

List of Figures

List of Tables

List of abbreviations and symbols

A	Area of the specimen
AASHTO	American Association of State Highway and Transportation Officials
ANOVA	Statistical analysis
AOS	Apparent opening size
ASTM	American society for testing and materials
CAGR	Compounded annual growth rate
CBR test	Static puncture test
CCL	Compact clay liners
CD	Cross-machine direction
cm	Centimetres
CO_2	Carbon dioxide
CRE	Constant rate of extension
CRL	Constant rate of loading
CRT	Constant rate of traverse
$C_2H_4O_2$	Acetic acid
D_i	Indicative diameter based on soil particles
F	Frequency of punching
g/m^2	Grams per square metre
GCL	Geosynthetics clay liners
HALS	Hindered Amine Light Stabilizers
HDPE	High density polyethylene
H_2O_2	Hydrogen peroxide
H_2SO_4	Sulphuric acid
ISO/EN	International Organization for Standardization
kg/m^3	Kilogram per cubic metre
kN	Kilonewton
kN/m	Kilonewton per metre
kPa	Kilopascal
LDPE	Low density polyethylene
L^2/s	Litre squared per second
MD	Machine direction

mm	Millimetres
mN/m	Millinewton per meter
m/s	Metres per second
n	Number of needles in the needle board
N	Newton
N	Limiting value
$NaC_7H_5O_2$	Sodium benzoate
NaCl	Sodium chloride
NaOH	Sodium hydroxide
WSP/NWSP	Non-Woven Standard Procedures
OFDA	Optical fibre diameter analyser
O_n	Measure of geotextile pore opening
O_{95}	Pore size
P_R	Porosity
PA	Polyamide
PE	Polyethylene
PET	Polyethylene terephthalate
pH	Quantitative measure of the acidity
POA	Porosity or per cent open area
PP	Polypropylene
PVC	Polyvinylchloride
Q	Flow rate
q_w	Drainage discharge capacity
$R_{(e)}$	Reynolds number
RH	Relative humidity
SEM	Scanning electron microscope
SPSS	Software package used for statistical analysis
µm	Micrometer
UV	Ultraviolet
V	Feed rate of the material
V	Velocity
V_1	Total volume of the system
V_s	Volume of the solids
W	Effective width of the needle board

Chapter 1

Introduction

1.1 Family of Geosynthetics

Geotextiles are classified within a family of geosynthetics and they are mainly produced from synthetic fibres (Austin and Gilchrist, 1996). The major functions of the geosynthetic materials are separation, reinforcement, drainage and filtration. Geosynthetics are used in civil engineering applications, namely, road construction, prevention of soil erosion, river and pond liners, etc. Advantages of using geosynthetics are that they are easy to install, readily available and relatively inexpensive. The following materials constitute a family of geosynthetics (Austin and Gilchrist, 1996; Basu et al., 2009; Bathurst, 2015; Bhatia and Smith, 1996):

- Geotextiles
- Geogrids
- Geonets
- Geomembranes
- Geosynthetic clay liners
- Geofoams
- Geocomposites

1.1.1 Geotextiles

The word geotextile is composed of two terms, geo and textile, which implies a combination of textile and earth (Bouazza et al., 2002a). Geotextile is defined as a linear permeable material, which can be in the form of woven, knitted and nonwoven fabrics. It is applied in association with soil and rocks for a number of civil engineering and other geotechnical applications (Bouazza, 2002b). Geotextiles have replaced graded soil filters and gravel blankets being used in the past for filtration and reinforcement applications. They are categorized into three main groups, namely knitted, woven and nonwoven geotextiles. Nonwoven geotextiles are produced either from staple fibres or continuous filaments. A fibrous web produced from fibres and filaments is subsequently bonded individually or by a combination of needlepunching, hydroentanglement, chemical and thermal bonding processes depending upon the end-use requirement. Geotextiles are utilized in both short and long term applications. Both natural and synthetic fibres are utilized in the production of nonwoven geotextiles. Natural fibres are suitable for short term applications, such as soil erosion, slope stabilisation, vertical drains and river bank protection. Increased usage of natural fibres in such applications is attributed to their biodegradability, environmental friendliness and ease of availability. Synthetic fibres are suitable for long term durable applications such as, drainage, reinforcement, separation and filtration. The rationale of using synthetic fibres in such applications is attributed to their higher strength and chemical inertness **(**Bouazza et al., 2002a; Bouazza, 2002b; Daniel and Koerner, 1991; English, 1994).

1.1.2 Geogrids

Geogrids are defined as interconnecting structures with openings varying between 10 to 100 mm (Geosynthetics knowledge centre, accessed on 04 June 2015, http://geosintetik.blogspot.co.za/2007/02/geosynthetics-terminolgy.html). In addition, geogrid is defined as an open structure which resembles a grid and it is generally produced from a synthetic polymer, such as polypropylene (PP) (Bouazza, 2002b). The openings in the interconnected structure must be sufficient to allow the passage of soil particles through it. There are two types of geogrid, namely, sheet and fabric. The sheet type geogrid is produced from high density polyethylene (HDPE) geomembrane sheet. Punching and drawing processes are employed in manufacturing a sheet type geogrid. Fabric type geogrids are produced using high tenacity polyester filaments and more often they are coated with polyvinylchloride (PVC) and bitumen stabilizers to minimise the rate of degradation. The inner yarns and the covering material are important in the production of fabric geogrids. The major characteristics of the inner yarns are better tensile strength, elongation and Young’s modulus. Geogrids are mostly used as reinforcement because of their better strength and they are widely employed in civil, geotechnical and structural engineering applications (Austin and Gilchrist, 1996; Giroud and Bonaparte, 1989; Geosynthetics knowledge centre, accessed on 04 June 2015, http://geosintetik.blogspot.co.za/2007/02/geosynthetics-terminolgy.html).

1.1.3 Geonets

Geonet is defined as a lightweight interconnected structure with openings (Basu et al., 2009). Furthermore, geonet is defined as sets of parallel ribs of different sizes and shapes with open pores which allow fluid to flow along in-plane direction (Horvath, 1994). The ribs differ in terms of its size and shape. Geonets are produced using polymer extrusion process where filaments intersect each other at an acute angle. The intersecting filaments results in a sheet with open pores through which either fluid or gas flows. Geonets are divided into bi-planar and triplanar geonets, the former are most widely used. The bi-planar geonets are composed of interconnected ribs at various angles. However, triplanar geonets are composed of central ribs that are parallel to each other. Generally, geonets are produced from polyethylene (PE) of specific gravity ranging between 0.94 and 0.95 g/cm^3. The additives, such as carbon black are coated on the geonets to increase their resistance to acid and alkali. The primary application of geonets is for in-plane drainage. However, geonet also act as leachate collection medium in landfills and waste piles. In addition, geonets are used with either geotextiles or geomembranes. In situation where soil is placed above geonets, geotextile is used as a separator to prevent soil particles from entering in the geonet through pores (Austin and Gilchrist, 1996; Bouazza, 2002b; Horvath, 1994; Hwu et al., 1990).

1.1.4 Geomembranes

Geomembranes are defined as impermeable membranes or barriers which control fluid and gas migration (Jeon et al., 2002). They are soft and easily shaped materials with properties remaining unaffected even at higher temperatures (Koerner, 2012). Geomembranes were previously produced from thermoset polymers, however, they are currently produced from thermoplastic polymers. Geomembrane sheets are produced from butyl rubber, PE and PP. Extrusion, calendaring and spread coating are widely utilized processes in the production of geomembranes. The low density polyethylene (LDPE), HDPE and PP are used to produce geomembranes by extrusion process. Geomembranes were used in the past as canal and pond liners, however, they are currently being used in municipal solid waste landfills, waste piles and leachate collection tanks. Geomembranes produced from HDPE are utilized in landfills for hazardous waste because of their resistance to chemicals and better tensile strength (Jeon et al., 2002; Koerner, 2012; Lin and Lin, 2005).

1.1.5 Geosynthetic clay liners

Geosynthetic clay liners (GCL) are defined as geocomposite material produced using either geotextiles or geomembranes containing a layer of sodium or calcium bentonite clay (Markets-and-Markets, accessed on 21 May 2015, http://www.marketsandmarkets.com/PressReleases/geosynthetics.asp). GCL produced using geotextiles are bonded together by adhesive, stich-bonding or needle punching methods. The stronger bonds are achieved by heating both geotextiles and bentonite together. Furthermore, GCL produced using geotextiles are reinforced by sewing both geotextiles and bentonite with parallel rows of stitch bonded yarns. However, adhesives are used to bond GCL produced from geomembrane and bentonite. GCL differs depending on the form of bentonite, minerals used, type of geotextile and bonding method employed. Compacted clay liners (CCL) have replaced GCL and composite liners in cover system because of their lower hydraulic conductivity of about $\pm K_w < 10^{-10}$ m/s, easy to construct, smaller thickness, better freeze thaw and cost effectiveness. Disadvantages of GCL include decrease in post-peak shear strength, loss of bentonite during construction and GCL is also affected by ion exchange process. GCL is used in waste containment, environmental barriers and fuel storage applications (Bouazza, 2002b; Park and Nibras, 1993; Markets and Markets, http://www.marketsandmarkets.com/PressReleases/geosynthetics.asp, accessed on 21 May 2015).

1.1.6 Geofoam

Geofoam is defined as either block or slab formed by enlarging polystyrene foam (Bathurst, 2015). This results in a compact low density structure which allows only gas to flow through it. Production of geofoam is based on polymer extrusion process, where polystyrene foam is extruded to produce either block or slab structure. This results in a closed cell lightweight structure which allows gas to flow through it. Advantages of using geofoam are their lightweight, not prone to settlement and insulating properties. Disadvantages of geofoam are that they are affected by petroleum solvents, damaged by insects and susceptible to fire hazard. The effect of petroleum solvents is minimised by covering geofoam with hydrocarbon resistant materials, such as HDPE and PP. In addition, geofoam is treated with fire retardants to improve its fire properties. Geofoam fill is about 1 to 3% heavier than conventional soil fills. Therefore, geofoam is suitable in load carrying applications which include frost sensitive soils and highways over compressible soils (Austin and Gilchrist, 1996; Bathurst, 2015; Bhatia and Smith, 1996; Pilarczyk, 2000).

1.1.7 Geocomposites

Geocomposites are defined as geosynthetic material composed of two or more different materials from a family of geosynthetics (Pilarczyk, 2000). The production of geocomposites results in a product with separation, reinforcement, filtration and drainage properties. Geotextile-geonet, geotextile-geogrid and geonet-geomembrane are examples of geocomposites. Both geotextile and geonet are combined together to carry leachate in landfill liner and cover systems. Geotextile increases puncture resistance, tearing resistance and friction when bonded to geonet (Austin and Gilchrist, 1996; Pilarczyk, 2000; Rawal et al., 2010a).

1.1.8 Materials used in the production of geosynthetics

Geosynthetics are mainly produced from synthetic polymers, such as PVC, LDPE, PP and polyethylene terephthalate (PET). Recently, natural fibres such as, kenaf, hemp, jute, agave, sisal and flax are also being utilized for producing geotextiles because of their comparable tensile strength, availability and environmental friendliness (Basu et al., 2009, Bouazza et al., 2002a, Rowe and Skinner, 2001).

1.1.9 Market

The market for the geosynthetic products is increasing depending upon their applications and regions. The demand for the geosynthetics is influenced by government policies, environmental concerns and cost. Both developing and developed countries are constructing roadways, railroads and river banks to sustain economic growth. The market statistics show that the applications of geotextiles are more widespread in comparison to those of geomembranes and geogrids. The share of geotextiles was accounting closer to 58% of the total market for geosynthetics in 2013. The forecast shows that the market share of geotextiles will continue to lead until 2019.

Geosynthetic materials are mostly produced in USA followed by Asia-Pacific and Europe. While USA dominated the market share in 2013, it is expected that the Asia-Pacific countries will surpass the USA market share by 2019. The market for geosynthetics is expected to grow to US$ 15.4 billion by 2019 with a compounded annual growth rate (CAGR) of about 11%. This growth is mainly attributed to increasing demand and growing awareness about environmental protection (Markets and Markets, accessed on 21 May 2015, http://www.marketsandmarkets.com/PressReleases/geosynthetics.asp).

Chapter 2

Literature review

2.1 Classes of geotextiles

Geotextile belongs to the geosynthetics family where in the word geotextile, prefix, geo means earth and suffix, textile means fabric (Bhatia and Smith, 1996). Furthermore, geotextile is defined as a porous fabric which is used in various civil engineering applications, such as construction of roads and railway tracks (Rawal et al., 2008). Geotextile constitutes the largest group by volume in the family of geosynthetics (Koerner and Koerner, 2011). It was expected to perform more than one function which includes filtration, separation, drainage and reinforcement (Bhatia and Smith, 1996). Geotextiles are differentiated by polymer type, fibre type and manufacturing process. Geotextiles are categorised into three main classes, namely, woven, knitted and nonwoven (Rawal et al., 2008; Koerner and Koerner, 2011; Narejo et al., 2003; Bhatia and Smith, 1996).

2.1.1 Woven geotextiles

The fabrics produced by a weaving process are termed as woven geotextiles (Wang, 2001). The main advantage of using woven geotextiles in reinforcement application is their better tensile strength. The mass per unit area, thickness, water permeability and apparent opening size of woven fabrics utilized in geotextile applications range between 80 – 400 g/m^2, 0.3 – 3 mm, 0.0008 - 0.01 cm/s and 0.15 – 0.85 mm, respectively (Bhatia and Smith, 1996). Woven geotextiles are used in road reinforcement and for preventing soil erosion (Basudhar, 2010; Wang, 2001).

2.1.2 Knitted geotextiles

Knitted geotextiles are defined as fabrics produced by inter-looping yarns to form warp or weft knitted structures. Knitted geotextiles are relatively lighter in comparison to their woven counterparts and they are mainly applied as filters in pipe. Therefore, knitted geotextiles are easy to handle as well as transportation cost is relatively lower (Lawler and Wilson, 2002; Rawal et al., 2010a).

2.1.3 Nonwoven geotextiles

Nonwoven geotextiles are defined as fibrous sheets, webs or batts where fibres or filaments are oriented in different directions (Russell, 2006). They are permeable materials designed for various civil engineering applications, such as filtration, drainage, separation and reinforcement. Nonwovens are "engineered fabrics" and they are known for their versatility and favourable properties. They are versatile, because different production techniques can be combined to achieve desirable properties for specific performance requirements. Nonwoven fabrics are produced by employing different bonding techniques, such as needlepunching, hydroentanglement, thermal, spunbonding and chemical bonding. The needlepunching method is widely used to produce nonwoven fabrics for geotextile applications. Nonwoven geotextiles are widely used in landfills, slope stabilization, road and railway track construction where they are required to fulfil several functions. Nonwoven fabrics are suitable for such applications because of their dimensional stability, good permeability and high tensile strength (Rawal and Anandjiwala, 2007; Rawal et al., 2008; Albretch et al., 2006; Russell, 2006).

The mass per unit area, thickness, water permeability and apparent opening size of the nonwoven fabrics for geotextile applications range between 80 – 1700 g/m^2, 0.25 – 150 mm, 0.003 – 0.3 cm/s and 0.075 – 0.85 mm, respectively. The achievement of the above properties depends upon the manufacturing processes (Bhatia and Smith, 1996; Maitre et al., 2001).

2.1.3.1 Needlepunched nonwovens

The needlepunched nonwoven fabrics for geotextile applications are produced from both short and long staple fibres of natural and synthetic origins. Figure 2.1 shows a photograph of the needlepunched nonwoven fabric (Wang, 2001). The needle barbs penetrate the fibrous web to re-orient and interlock the fibres. This results in a three-dimensional nonwoven fabric meeting requirements as geotextile. The fibres in the needlepunched nonwoven fabrics are held together by interfibre friction due to fibre entanglement. Fineness of the fibres used in the manufacturing process ranges between 1 to 100 decitex while mass per unit area of the fabric ranges between 100 to 2000 g/m^2 (Wang, 2001; Bhatia and Smith, 1996; Russell, 2006; Midha and Mukhopadyay, 2005).

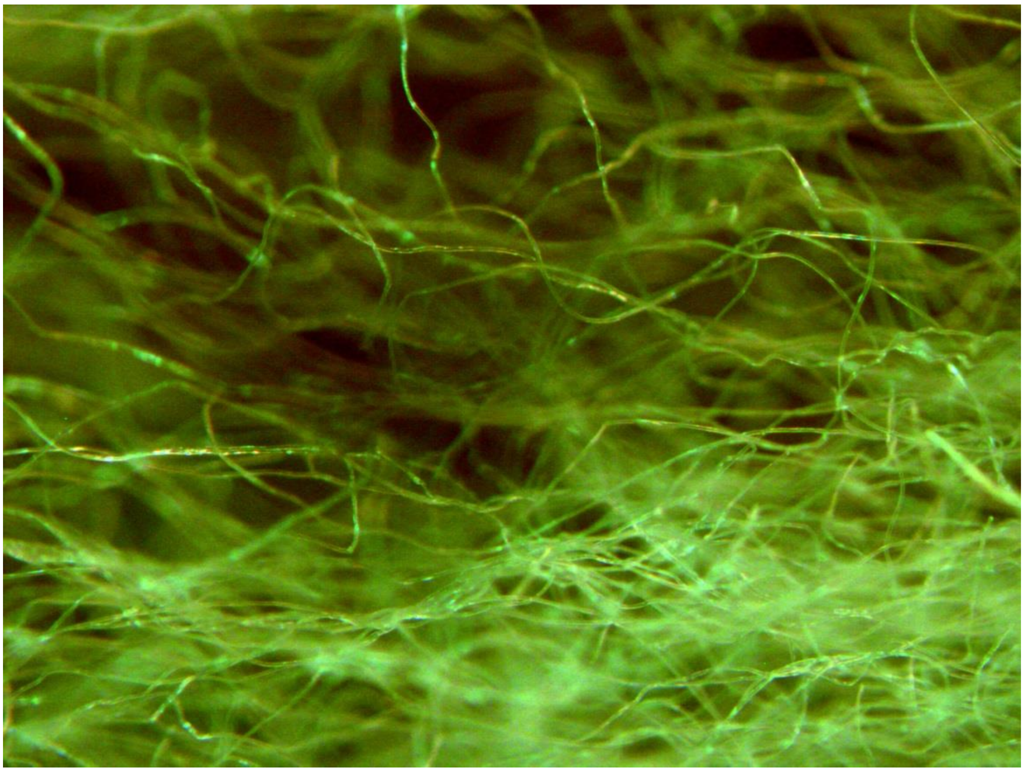

Figure 2.1 Needlepunched nonwoven fabric (Source: Wang, 2001)

The structure of the needlepunched nonwoven fabric is complex and it is made up of several layers of randomly oriented fibres. Needlepunched nonwoven fabrics are bulkier in comparison to woven and knitted fabrics of the same weight per unit area (Hwang et al., 1998). Furthermore, needlepunched nonwoven fabrics are anisotropic porous media with solid and void phases (Gautier et al., 2007; Liu and Chu, 2006; Rawal and Saraswat, 2011a). The porous structure of the nonwoven fabric is suitable for separation and filtration applications. Needlepunched nonwoven fabrics are employed in filtration applications in dams and drainage pipes. The needlepunched nonwoven fabrics provide lower tensile strength, lesser stiffness and better drainage capacity in comparison to those of woven fabrics of the same mass per unit area (Ariadurai et al., 1999; Patanaik and Anandjiwala, 2008; Wang, 2001). The ever-increasing uses of needlepunched nonwoven fabrics were influenced by lower production cost and shorter time required to produce the fabric. Furthermore, the use of needlepunched nonwoven fabric is influenced by their higher permeability and porosity (Anandjiwala and Boguslavsky, 2008; Russell, 2006; Rawal and Anandjiwala, 2006).

2.2 Fibres

Both synthetic and natural fibres are used in the production of needlepunched nonwoven fabrics, however, synthetic fibres such as (PP) and (PET) are more prevalent because they are relatively inexpensive and they do not degrade under biological and chemical processes. However, as synthetic fibres are produced from non-renewable fossil-fuel based resources, they cause environmental pollution and pose associated health risks (Rawal et al., 2010a). The selection of fibres for the fabric production depends on the required fabric characteristics, processing conditions and cost effectiveness (Koerner, 2012).

2.2.1 Natural fibres

Natural fibres originate from naturally renewable sources, such as plants and animals (Steve, 2010). Jute, hemp, kenaf, sisal and flax fibres are some of the examples of natural fibres extracted from plants. Plant fibres are categorized according to the part of the plant from which they are obtained, such as leaf (sisal), seed (cotton), fruit (coir) and bast (kenaf). Bast fibres are found in the outer layer of the stem with pectin. They are extracted by subjecting to a retting process in which non-cellulosic materials attached to the fibres are removed. Dew, water, enzymatic, mechanical and chemical are different types of retting processes. In dew retting process, plant stems are cut and left on the field to rot for 2 to 3 weeks. The efficiency of dew retting process depends on the ability of soil fungi to degrade pectin and hemicellulose by releasing polygalacturunase and xylanase. In water retting process, plant stems are placed in water for 14 to 28 days so that pectin, lignin and hemicellulose degrade and cellulosic fibres are loosened. Disadvantages of water retting process include water pollution and longer retting time. Enzymatic retting, also known as microbial retting is a process performed using pectic enzymes produced by bacterial action. The pectinases are used to separate bast fibres from the cortex. The amount of pectinases produced by the bacteria depends on the quantity of the bacteria. The time required in enzymatic retting process is much shorter and it ranges between 12 to 24 hours. Enzymatic retting process produces long fibres which are attributed to advanced biotechnological tools used in the retting process. In the chemical retting process, solutions of sodium hydroxide (NaOH), sodium benzoate ($NaC_7H_5O_2$) and hydrogen peroxide (H_2O_2) are heated to boiling temperature and applied to the stems to separate fibres. The disadvantages of chemical retting process include degradation of fibres with resultant loss in tensile strength and change in colour of the fibres due to high concentration of chemicals (Paridah et al., 2011). Natural fibres are suitable for short-term geotextile applications, such as vertical drains, road bases, river bank protection and erosion control, etc. The advantages of using natural fibres for producing geotextiles include comparable tensile strength, biodegradability and robustness (Rawal et al., 2010a).

The drawbacks of natural fibres include their lower extensibility, lower stiffness and higher moisture absorption. In addition, their properties such as, fibre length and fineness are inherently variable depending upon cultivation conditions and origin. The variation in fibre length and fineness of natural fibres may influence alignment of shorter fibres. Furthermore, the variations in fibre length and fineness also influence some properties of the nonwoven fabrics, such as pore size and tensile strength. Natural fibres are hydrophilic which influences flow of liquid in nonwoven fabrics. This is attributed to lignocellulose which absorbs water by creating hydrogen bonds between water and hydroxyl groups of the fibres (Basu et al., 2009; Edeerozey et al., 2007; Rawal and Anandjiwala, 2007; Rawal and Sayeed, 2013b). The properties of natural fibres are influenced by environmental and climatic conditions in the various regions of the world. Furthermore, retting, harvesting date and cultivation are some of the important factors which affect quality of natural fibres. Basu et al. (2009) have found that the fabric produced from natural fibres can compete with that produced from synthetic fibres if they are correctly "engineered". The use of natural fibres results in conservation of fossil resources, their natural renewability and neutralisation of Carbon dioxide (CO_2) (Müssig and Martens, 2003; Basu et al., 2009; Steve, 2010).

2.2.2 Synthetic fibres

Synthetic fibres, also known as man-made fibres, such as polyamide (PA), PP and PET are widely utilized in manufacturing needlepunched nonwoven fabrics (Koerner, 2012; Rawal and Sayeed, 2013b; Rawal et al., 2010a). Production of synthetic fibres includes extrusion of melted polymer pellets through spinneret containing small holes with diameter ranging from 100 to 3000 µm. In the spinning process, polymers are extruded through the holes of the spinneret and solidified to produce continuous filaments. Three main polymer spinning processes are wet spinning, dry spinning and melt spinning. In the wet spinning process the polymers are dissolved in a solvent and extruded through the holes of the spinneret to spin filaments. Dry spinning differs from the wet spinning only in solidifying filaments by evaporating the solvent either by air stream or inert gas. Acetate and spandex fibres are produced by dry spinning process. In melt spinning process, the continuous filaments are produced by melting polymers and then extruding the molt through the spinneret and quenching by cool air. Nylon, PET and olefin fibres are produced by melt spinning process. The diameter and cross-section of the filaments depend on the size and shape of the holes in the spinneret and the spinning conditions. Bhatia and Smith (1996) have found that synthetic fibres produced from the same polymer differ depending on the manufacturing process as well as spin finish on the fibres. Needlepunched nonwoven fabrics produced from synthetic fibres are utilized in long-term geotextile applications, such as drainage, reinforcement and separation, due to their lower cost, higher strength and chemical inertness (Bhatia and Smith, 1996; Müssig and Martens, 2003; Rawal and Sayeed, 2013b).

2.2.3 Fibre properties

Fibre properties influence fabric properties and its end-use performance. The changes in fibre properties influence the mechanical properties and failure mechanism of the fabric. Fibre properties, namely, crimp, fineness, length, diameter and cross-section are important for assessing their suitability (Çinçik and Koç, 2013; Midha and Mukhopadyay, 2005).

2.2.3.1 Fibre crimp

The crimp is defined as the waviness of a fibre per unit length. Fibre crimp influences the uniformity of the fibrous web and stress-strain properties of the needlepunched nonwoven fabrics (Debnath and Madhusoothanan, 2009). Adanur et al. (1999) have reported that fibre crimp distribution influences the shape of the stress-strain curve of the fabric (Adanur et al., 1999). Furthermore, fibre crimp influences initial modulus and failure mode at maximum load. It is difficult to process straight fibres on a needlepunching machine. Therefore, it is easy to control or manage the fibrous web when needlepunched nonwoven fabrics are produced from crimped fibres. Fibre crimp influences fabric bulk, however, the fabrics produced from high crimp fibres may have lower fabric strength because of poor fibre entanglement (Mrština and Fejgl, 1990; Debnath and Madhusoothanan, 2009).

2.2.3.2 Fibre fineness

The fineness of a fibre is defined as mass per unit length and it is measured using gravimetric method, microscope and optical fibre diameter analyzer (OFDA) (Debnath and Madhusoothanan, 2009). The increase in fibre fineness increases the surface area of the fibre. Fibre fineness influences evenness of the web and it promotes improved fibre entanglement in needlepunching process (Hearle and Morton, 2008). However, it is difficult to produce a uniform web when feeding fine fibres at higher roller speeds as compared to coarser fibres, due to fact that finer fibres are not easy to open. Kothari et al. (2008) have reported that fibre fineness influences fabric thickness. Fibre fineness of around 3.3 dtex provides the fabric with improved abrasion resistance and bursting strength (Kothari et al., 2008; Debnath and Madhusoothanan, 2009). The fabrics produced from coarser fibres have higher compressibility and lower recovery properties in comparison to that from finer fibres. This is attributed to easy bending of finer fibres and relatively compact fabric structure (Ganguly et al., 1999; Debnath and Madhusoothanan, 2009).

2.2.3.3 Fibre length

Fibre length differs depending on the type of fibre. In addition, length of natural fibres varies depending on the environmental conditions, region of origin and harvesting time. The fibre length of cotton ranges between 28 to 60 mm and that of kenaf fibre ranges between 50 to 120 mm (Mrština and Fejgl, 1990; Mwaikambo, 2006). The length of the fibre influences fibre breakage during processing, pore size and pore size distribution in the needlepunched nonwoven fabrics. The recommended fibre length for needlepunching nonwoven geotextiles should be between 38 to 90 mm (Hearle and Morton, 2008; Mrština and Fejgl, 1990). The fabrics produced from longer and finer fibres achieve higher tensile strength, which is attributed to improved fibre orientation in load direction (Midha and Mukhopadyay, 2005). Shorter fibres influence deformation of the fibrous web during needlepunching process. In addition, shorter fibres may highly contribute to the deformation of the fibrous web in comparison to longer fibres when producing needlepunched nonwoven fabrics (Mrština and Fejgl, 1990). This is attributed to uncontrolled drafting of the fibrous web when fed to the needle loom which results in intra-fibre migration. The change in the dimensions of fibrous web influences fabric thickness and mass per unit area (Ghosh and Chapman, 2002; Adanur and Liao, 1999; Ganguly et al., 1999; Albrecht et al., 2006).

2.2.3.4 Fibre diameter

Fibre diameter affects many performance properties, such as puncture resistance, reinforcement capacity and abrasion resistance of the needlepunched nonwoven fabrics. As mentioned earlier, both synthetic and natural fibres are utilized in the production of needlepunched nonwoven fabrics. The diameter of synthetic fibres depends on the fibre spinning processes, however, that of natural fibres vary depending on the part of the plant and the retting process. Irregularity in fibre diameter results in the fabrics with different areal densities, mean pore diameters and pore size distributions. Li et al. (2006) have analysed fibre diameters using distance transform method from captured images of fibre segments and reported mean values of the fibre diameter (Li et al., 2006).

2.2.3.5 Fibre orientation

Orientation of fibres in the needlepunched nonwoven fabric is an important parameter. The fibres in the web are oriented randomly or predominantly in machine and cross-machine directions (Mrština and Fejgl, 1990). The orientation of the fibres in the fabric depends on the needlepunching process parameters, such as depth of needle penetration and stroke frequency. Fibre orientation influences tensile strength, compression and pore size of the needlepunched nonwoven fabrics (Russell, 2006). Fibre orientation also influences the flow of liquid in the needlepunched nonwoven fabrics due to the fact that fibre orientation differs from region to region in the fabric. Amiot et al. (2014) have found that fibre orientation is important in determining permeability, compression resistance and tensile characteristics of the needlepunched nonwoven fabrics. Fibre orientation is analysed from fibre orientation angle with respect to machine or cross-machine direction. Fibre orientation angle is defined as the directional position of individual fibres in the fabric structure relative to either machine or cross-machine direction (Adanur and Liao, 1999; Lin et al., 2006; Jaganathan et al., 2008; Amiot et al., 2014; Patanaik and Anandjiwala, 2008).

2.2.3.6 Fibre cross-section

The cross-section of the fibres can be round, hollow, trilobal or multilobal depending upon the requirement of the end-use applications (Midha and Mukhopadyay, 2005). Fibre cross-section influences fibre properties and characteristics of the resultant fabrics. Bueno et al. (2004) have found that the cross-section of the fibres affects bulk, flexural rigidity and abrasion resistance of the fabrics (Bueno et al., 2004). The bulkiness of the fabric is high when it is produced from hollow cross-section fibres in comparison to that produced from trilobal and round cross-section fibres. Debnath et al. (1994) have found that the fabric produced from hollow cross-section fibres have lower thickness as compared to that produced from fibres with trilobal cross-section (Debnath et al., 1994). This is attributed to lower fibre crimp in the case of hollow cross-section fibres. In addition, the fabrics produced from hollow cross-section fibres achieve higher breaking elongation and bursting strength in comparison to that produced from trilobal and round cross-section fibres. However, the fabric produced from fibres with trilobal cross-section achieved higher abrasion resistance in comparison to that produced from round and hollow cross-section fibres (Çinçik and Koç, 2013; Midha and Mukhopadyay, 2005; Debnath and Madhusoothanan, 2009; Bueno et al., 2004).

2.3 Stages in the production of nonwoven fabrics

2.3.1 Web formation

Web formation is classified into dry-laid, air-laid, wet-laid and polymer-laid processes (Russell, 2006).

2.3.1.1 Dry-laid

Both natural and manmade fibres are suitable for dry-laid web formation process. The staple fibres of about 1.2 to 20 cm in length can be processed in dry-laid web formation process, however, continuous fibres are not utilized (Dahiya et al., 2004). The continuous manmade fibres in filament form are cut into staple fibres for dry-laid web formation process. The selection of fibres for dry-laid web formation process depends on desirable fabric properties, such as abrasion resistance, permeability and bursting strength. The fibres are processed to form a fibrous web and subsequently bonded together by mechanical, thermal or chemical bonding technique. Dry-laid web formation is divided into air-laid and carded. The carding process produces a fibrous web by opening the fibre bundles into individual fibres and transferring them as continuous fibrous web (Russell, 2006; Rawal et al., 2010; Albretech et al., 2006; Dahiya et al., 2004).

The carded fibrous web is either cross-laid or parallel-laid and the latter is mostly used in the production of fleeces as well as cleaning cloth fabrics (Ganguly et al., 1999). Majority of the fibres in the parallel-laid carded web are oriented in the direction of a moving web.

Selection of speeds and number of layers in the parallel-laid carded web depend on the required end-use properties of the fabric. The fabrics produced from parallel-laid carded web achieve higher tensile strength, lower elongation and higher tear strength in the machine direction in comparison to that in the cross-machine direction (Canbolat, 2011; Russell, 2006; Maitre et al., 2001).

In the cross-laid carded web, the fibrous web is cross-lapped in the right angle direction with respect to machine direction before bonding (Midha and Mukhopadyay, 2005). The nonwoven fabrics produced from cross-laid carded webs achieve better tensile strength in the cross-machine direction in comparison to that in the machine direction. This is attributed to the fact that majority of fibres are oriented in the cross-machine direction as a result of cross-lapping process (Russell, 2006). The fabric tensile strength can differ depending on how the fibrous web has been laid and drafting process. However, the fabric tensile strength in the cross-machine direction and machine direction can be adjusted to meet required end-use properties. Debnath et al. (2009) have found that the fabric produced using cross-laid carded webs achieve higher compressibility and lower recovery in comparison to that produced from parallel-laid carded webs. The major disadvantage of the cross-laid carded web is that it is difficult to match the input speed to the cross lapper with the speed of carded web being fed to the needlepunching machine owing to limitations in cross-lapping process. Therefore, the speed of the carded web has to be lowered to accommodate this limitation (Russell, 2006; Debnath et al., 2009).

2.3.1.2 Air-laid

Air-laid web formation is a dry-laid process and it is also called aerodynamic or random-laid web formation. Both short and long staple fibres are utilized in air-laid web formation process. Fibres are transported by air, placed inside a condenser cage, drawn and deposited on a moving belt to form a fibrous web. Air-laid web is versatile because different types of fibres can be processed to achieve desired fabric specifications. The versatility of the process is influenced by fibre transportation, machine design and air laying process (Russell, 2006). The fabrics produced by air-laid web achieve better tensile strength. Advantage of air-laid web includes isotropic structure due to random orientation of fibres. The ratio of tensile strength of fabric in cross-machine direction to machine direction approaches close to unity depending upon fibre specifications and process parameters. The disadvantage of air-laid web is that the fabric uniformity depends on the degree of fibre opening by the air stream (Horrocks and Anand, 2000). The opening of fibres in the air-laid web formation differs depending on the type of machine used. However, the degree of fibre opening in the air-laid web is lower in comparison to that in the carded web (Lin and Tsai, 2001). Furthermore, non-uniformity of air flowing next to the walls of the conduit may also influence web uniformity. Better fibre opening is required in air-laid web because poor fibre opening will result in the web containing cluster of unopened fibres. Disposable fabrics are abundantly produced using air-laid web (Rusell, 2006).

2.3.1.3 Wet-laid

The wet-laid web formation process is similar to that used in the paper making process. Figure 2.2 shows schematics of the wet-laid web formation process (Textile innovation knowledge platform, accessed on 02 May 2016, http://www.tikp.co.uk/knowledge/technology/nonwovens/under-construction). The wet-laid process was adopted in nonwoven manufacturing to achieve higher production speeds prevalent in paper making process in comparison to that in textile production (Horrocks and Anand, 2000). Wet-laid nonwoven fabrics are those in which at least 50% of the fibres are man-made fibres with a length to diameter ratio exceeding 300. The nonwoven fabric is produced by suspending short fibres in the fluid and then separated from the fluid by placing them on a porous surface. Subsequently, the fibres are bonded together by mechanical, chemical and thermal bonding process (Russell, 2006). The wet-laid nonwoven fabrics account for about 10% of the total market and major applications include drapes, gowns and sheets in hospitals and as cover stocks in disposable diapers (Horrocks and Anand, 2000).

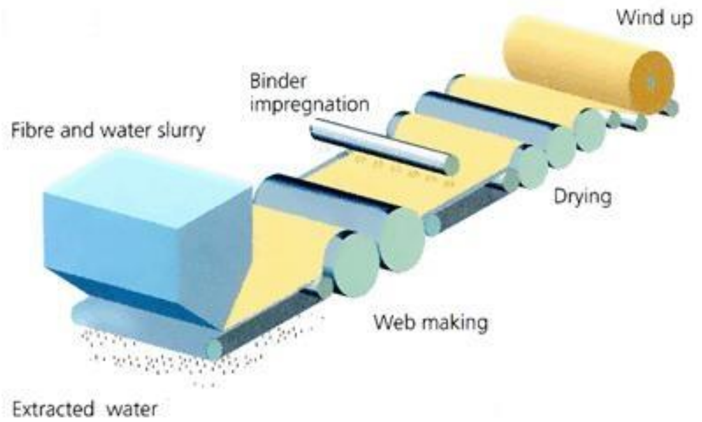

Figure 2.2 Wet-laid web formation process (Textile innovation knowledge platform, http://www.tikp.co.uk/knowledge/technology/nonwovens/under-construction)

2.3.1.4 Polymer-laid

Polymer-laid web formation is classified into spunbond, meltblown, flash-spun and aperture films (Russell, 2006). Continuous filaments of PET and PP are widely used in the spun-laid process. However, PE and PA are also used in some applications. Polymers are melted and then extruded through the spinnerets. This results in continuous filaments emerging from the spinneret which are quenched to solidify and subsequently placed on a conveyor belt to form a fibrous web. Spun-laid process is the shortest method producing a nonwoven fabric from polymer in one step. This is attributed to simultaneous process of continuous laying and bonding of fibres. The micro fibres produced in the spun-laid process results in better filament distribution and thereby provide smaller pores between the fibres in the fabric which increases its filtration efficiency. Due to these reasons, the fabrics produced by a spun-laid process are in demand in comparison to other web formation methods for automobile (trim parts, interior door panel and seat covers) and sanitary (diapers) applications (Russel, 2006; Horrocks and Anand, 2000).

2.3.2 Web bonding

Mechanical, chemical, thermal and spunbonding processes are widely utilized to bond fibrous web to produce nonwoven fabrics. Mechanical bonding process is classified into needlepunching, hydroentanglement and stitch bonding (Russell, 2006). Bonding of fibres is achieved separately and in distinct operation which depends on the web formation method and desired end-use properties of the fabric. Bonding a fibrous web with foam and powders are examples of chemical bonding process. Calendar bonding, through air bonding, print bonding and ultrasonic bonding are examples of thermal bonding process. Two or more bonding processes are also employed in tandem to achieve specified fabric properties. The major attributes of bonding process are bond type, bond density, bond strength and bonding point distributions. The bonding method employed influences the fabric properties, such as tensile strength, porosity, filtration and other functional properties (Rawal et al., 2010a; Rawal and Anandjiwala, 2006; Canbolat, 2011).

2.3.2.1 Needlepunching

Needlepunching is a mechanical bonding process in which barb needles interlock the fibrous web to produce nonwoven fabrics (Mrština and Fejgl, 1990). Figure 2.3 shows a schematic diagram of needlepunching process (Kamath et al., 2004). The needles are mounted on a needle board which is held by the needle beam as shown in Figure 2.3. The movement of the fibrous web through the needle loom depends on the speeds of the feed roller and the exit roller. The barb needles carry fibres from the top surface of the fibrous web to interlock them when moving in the downward direction and the fibres are released from the barb when moving in the upward direction. This interlocking of the fibres in the web produces nonwoven fabric (Kamath et al., 2004). Needlepunching process is a traditional method known for its flexibility, quality and product diversity. It is classified into vertical-needle punching with plane plates, oblique needlepunching, combined needlepunching with cylindrical strippers and beds.

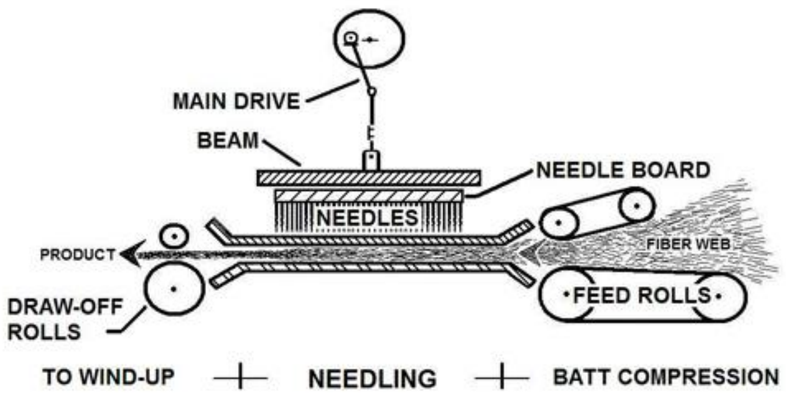

Figure 2.3 Schematic diagram of needlepunching process (Kamath et al., 2004)

Vertical needlepunching method is the oldest method where fibres are carried by the barb or groove of the needles. The fibrous web is needlepunched either on one or both sides. In the oblique needlepunching method, the needles penetrate the fibrous web between 45^{o} to 75^{o} angles (Mrština and Fejgl, 1990). Fabrics produced by oblique needlepunching method achieve better tensile strength in comparison to that produced by vertical needlepunching method (Patel and Bhramhatt, 2010). In the production of needlepunched nonwoven fabric, the fibres are opened, mixed and cleaned before subjecting to a carding process. After carding, the fibres are converted into fibrous web of loosely held fibres. The web is either cross-laid or parallel-laid. Fibres in the web are interlocked and intermingled by the barbs of the needles during their movements in upward and downward directions. This results in a three-dimensional interlocked structure of the nonwoven fabric. The parameters, such as number of needle barbs, punch density, depth of needle penetration, needling speed and fibre types are important in needlepunching process. Needlepunched nonwoven fabrics are utilized in medical, filters, geotextiles, heat insulation and sound absorption applications (Patel and Bhramhatt, 2010; Rawal et al., 2010a; Rawal and Anandjiwala, 2006; Russell, 2006).

2.3.2.2 Hydroentanglement

Hydroentanglement is a mechanical bonding process which utilizes high pressure collimated water jets instead of conventional barbed needles to interlock and bond fibres to produce nonwoven fabrics (Xiang, 2007). Fine, pressurised multiple rows of water jets strike the fibrous web to re-orientate and entangle the fibres. The fibres are entangled with each other as a result of the waterjet force. The fabric is held together by the fibre-to-fibre friction, cohesion and adhesion. Different hydraulic systems are available in hydroentanglement process. However, the same general elements of entangling fibres which includes, web supporting substrate, water jet nozzles, filtration, water extraction and water circulation are common to all different systems. Nonwoven fabrics produced by hydroentanglement processes are utilized in medical, personal care and hygiene products. The fabrics produced by hydroentanglement process provide better tensile strength in comparison to that produced by needlepunching process (Kothari and Agarwal, 2008). About 12% of nonwoven fabrics available on the market are produced by the hydroentanglement process. Hydroentanglement method can be combined with either meltblown or spunbond method to improve fabric properties (Ghassemieh et al., 2001; Xiang, 2007).

2.3.2.3 Spunbonding

Spunbonding, also known as spunlaid, is a bonding method where polymer resins are extruded to form uniform filaments (Huang and Gao, 1999). Filaments are laid on a collecting belt to form a fibrous web which is subsequently transported to bonding process. Small holes on the surface of the collecting belt minimises the air stream which may cause non-uniformity of the fibres in a fibrous web if not monitored (Huang and Gao, 1999). The fibrous web is bonded together by either heated rollers or hot needles (Rawal et al., 2010a). Advantage of utilizing spunbonding includes better orientation of fibres and high tensile and tearing strengths of the fabrics. Furthermore, the spunbonding is cost effective because production of fibres and fabric are combined together. Fabrics produced by spunbonding method are utilized in carpet backing, medical and geotextile applications (Russel, 2006).

2.3.2.4 Thermal bonding

In thermal bonding method a fibrous web is bonded together by passing it through heated chambers or through the nip of a pair of heated rollers to produce nonwoven fabrics (Rawal et al., 2010a). Thermal bonding is divided into two types, namely, through air and calendar bonding (Koerner, 2013). In through air-bonding process, the fibrous web passes through hot air in a chamber to form bonds at the fibre-to-fibre crossing points. However, in calendar bonding process the fibrous web passes through a nip of a pair of heated rollers under high pressure and high temperature to produce nonwoven fabrics. Advantages of using calendar bonding process include better fabric smoothness, easy dust release, compact structure, smaller pores and high filtration efficiency (Rawal et al., 2010a; Anandjiwala and Boguslavsky, 2008).

2.3.2.5 Chemical bonding

In chemical bonding method, binder, adhesive and latex are applied to bond fibres to produce nonwoven fabrics (Russel, 2006). In the past, natural binders, such as starch and rubber, were utilized. However, synthetic polymers such as vinyl acrylic ester and synthetic rubber are also used as binders. Synthetic polymers are applied to the fibrous web as aqueous dispersion and they are supplied as polymer solutions of lower viscosity to allow penetration into the fibrous web (Russel, 2006; Rawal et al., 2010b). Binders are applied on the fibrous web by impregnating, coating and print bonding. Print bonding is widely utilized in fabric patterning. The type of binder influences the properties of the chemical bonded nonwoven fabric, such as tensile strength, stiffness and softness. In addition, the type of binder used determines if the fabric can be either recycled or biochemically degraded. Chemical binders are also applied to nonwoven fabrics produced by other bonding method in order to improve their functional properties. For example, needlepunched nonwoven fabrics are finished with chemical bonding process to improve fabric properties, such as tensile strength and modify surface pore characteristics (Adanur, 1995; Russel, 2006).

2.3.3 Finishing process

Finishing process of the nonwoven fabrics is aimed at improving their properties. It is divided into wet and dry finishing processes. Wet finishing is categorised into washing, chemical impregnation and dyeing processes (Russell, 2006). Some special chemical finishing also includes antimicrobial, flameproof and ultraviolet (UV) stabilisers. UV stabilisers protect the polymers from ageing and thermal degradation (Rawal et al., 2010a). Benzophenone, benzotriazone and hindered-amine (HALS) are examples of such UV stabilisers applied to protect polymers from ultraviolet radiation. Untreated polymers are susceptible to chemical breakdown due to photo degradation (ultraviolet radiation). Slater (2003) have found that additives used to protect the polymers increase their lifespan. Dry finishing processes include calendaring, embossing, wrenching and micro-creping (Slater, 2003). In calendar finishing process, the fabric passes through a nip of rollers under high pressure and high temperature. Process variables, such as pressure on the calendar roller, temperature and time are important in finishing fabrics by calendaring. Calendaring improves fabric surface characteristics, smoothing and water permeability (Slater, 2003; Midha and Mukhopadyay, 2005).

In the emboss finishing process the rollers are engraved with patterns. The patterns are visible after the fabric passes through the rollers. Emboss finishing process is widely utilized in paper design and soft fabrics (Adanur, 1995; Russell, 2006; Slater, 2003).

The Clupak process is the same as sanforising and it was firstly utilized in the paper industry. However, wet-laid nonwoven bonded fabrics later utilized the Clupak process. Figure 2.4 shows the Clupak process (Finishing process of nonwoven fabrics, printing process of nonwoven fabrics, accessed on 02 May 2016, http://textilelearner.blogspot.co.za/2012/01/finishing-process-of-nonwoven-fabrics.html).

Fabrics produced from hydrophilic fibres are appropriate or preferable in the Clupak process in comparison to that produced from hydrophobic fibres. Due to lower moisture absorption and sensitivity to heat, the fabrics produced from polyolefin fibres are not suitable for the Clupak process. The Clupak process improves fabric handle which results in softer fabrics.

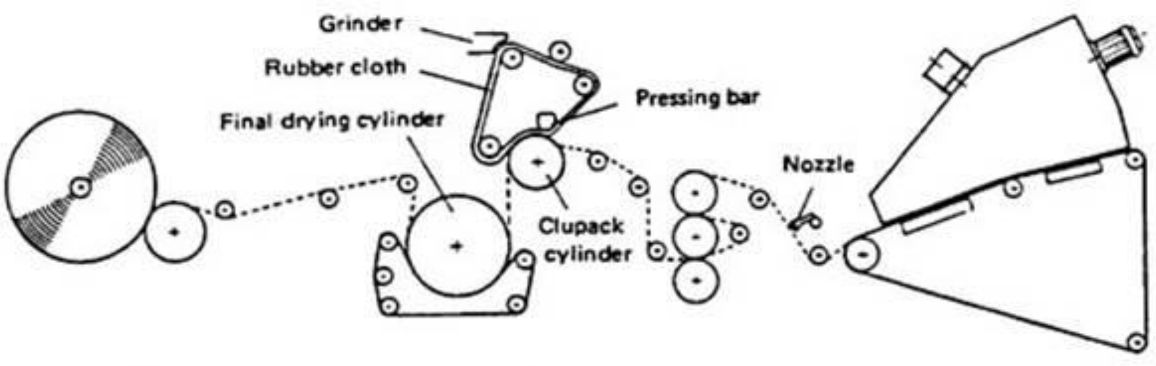

Figure 2.4 Clupak process (Finishing process of nonwoven fabrics, printing process of nonwoven fabrics, accessed on 02 May 2016, http://textilelearner.blogspot.co.za/2012/01/finishing-process-of-nonwoven-fabrics.html).

In the Micrex process the creeping effect is visible due to compaction of the fibrous web. The large surface area as well as the flexibility in the Micrex process is improved in comparison to Clupak process. Rotating conveyor roller, surface with strew-shaped grooves and two guide plates forming a knee lying against the cylinder are basic elements of the Micrex process. One of the guide plates is fixed while the other is elastic. Figure 2.5 shows the Micrex creeping process. The fibrous web is fed between the two guide plates using a scraper-like compressing device which is inclined at an acute angle to the surface roller.

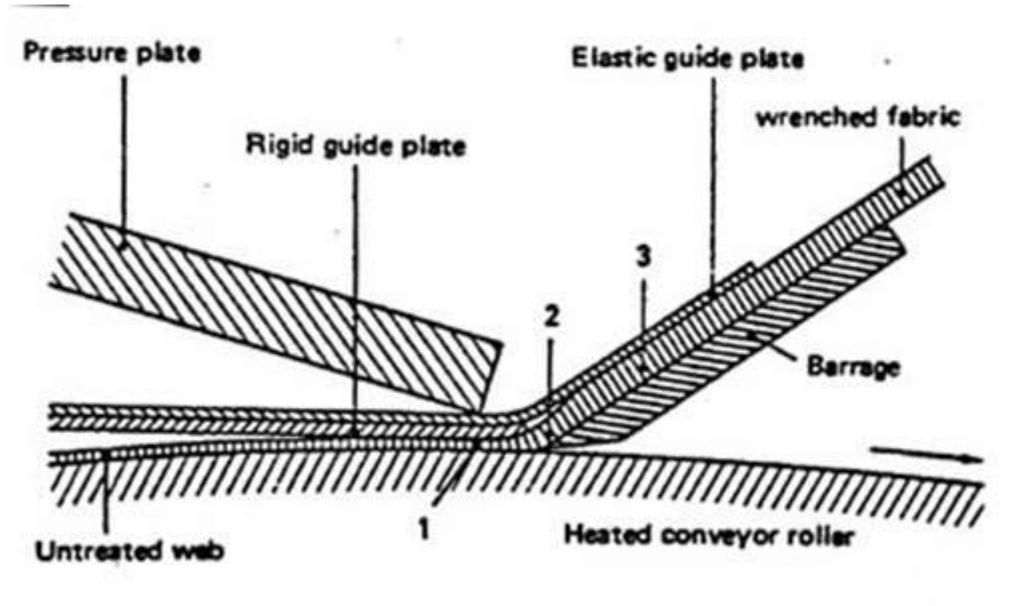

Figure 2.5 Micrex creeping process (Finishing process of nonwoven fabrics, printing process of nonwoven fabrics, accessed on 02 May 2016, http://textilelearner.blogspot.co.za/2012/01/finishing-process-of-nonwoven-fabrics.html,).

2.4 Process parameters in needlepunching

The process parameters, such as depth of needle penetration, feed rate, punch density and stroke frequency influence performance and structural arrangement of the needlepunched nonwoven fabrics (Kothari and Das, 1992; Mrština and Fejgl, 1990). Rawal et al. (2008) have found that the process parameters influence geometrical, mechanical and hydraulic properties of the needlepunched nonwoven fabrics.

2.4.1 Depth of needle penetration

Depth of needle penetration is defined as the distance by which a needle point penetrates from the top surface of the fibrous web towards the bottom surface. Movement of the fibres in the fibrous web depends on the depth of needle penetration. During the downward movement of the needles, the barbs of the needle carry the fibres on the top surface of the fibrous web with them. However, the fibres are released by the barb in entangled position during the upward movement of the needles. The action of the needles in the fibrous web is shown schematically in Figure 2.6 (Kamath et al., 2004). The number of fibres carried by the needle depends on the depth and shape of the barb. The increase in the depth of needle penetration increases the number of fibres carried by the barbs and thus, it increases fabric tensile strength to an optimal level (Rawal et al., 2010a). This is attributed to reorientation and improved entanglement of fibres in the fibrous web. In addition, an increase in depth of needle penetration increases relative frequency of fibres oriented in the machine direction (Rawal and Anandjiwala, 2006). Fibres may be released and recovered from the stress as well as strain. However, during the recovery process, fibres that were preferably oriented in the cross machine direction during web laying process are re-oriented in the machine direction (Moyo et al., 2012).

Depth of needle penetration influences thickness, tensile strength and mass per unit area of the fabric. The thickness of the fibrous web decreases with an increase in depth of needle penetration (Majumdar at al., 2013). Moyo et al. (2012) have reported that the depth of needle penetration is the main process parameter which influences mechanical properties, dimensional stability and fabric density. Increase in the depth of needle penetration also minimises slippage of fibres in the fabric and thereby decreases fabric elongation (Midha and Mukhopadyay, 2005; Moyo et al., 2012; Cincik and Koc, 2013).

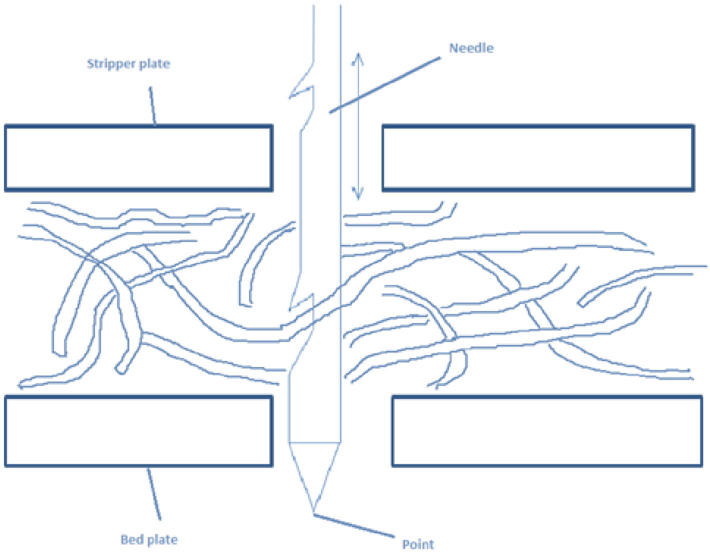

Figure 2.6 A schematic diagram showing action of needles in the fibrous web (Source: Kamath et al., 2004).

Higher depth of needle penetration is needed to process fibrous web with higher mass per unit area. Anandjiwala and Boguslavsky (2008) have reported that higher needling force is required to entangle and interlock heavier fibrous web. However, an increase in depth of needle penetration above the optimal level decreases fabric tensile strength because of higher fibre breakages (Anandjiwala and Boguslavsky, 2008). Breakages of fibres are also influenced by the distance travelled by the fibres when the barbs of the needles carry them along. The distance travelled by fibres depends on the thickness of the fibrous web, fibre position on the fibrous web and barbs position on the needle. Roy et al. (2009) have found that higher depth of needle penetration as well as high punch density decrease the fabric tensile strength due to higher fibre breakages. Breakage of fibres results in an open fabric structure and decreases bursting strength. Higher depth of needle penetration also may result in excessive needle breakages (Midha and Mukhopadyay, 2005; Foster, 2015; Roy and Ray, 2009).

2.4.2 Punch density

Punch density, given as punches/cm^2, is defined as a number of needles per unit area penetrating the fibrous web (Wang et al., 2013). Punch density is a function of output speed, number of needles per unit area and the stroke frequency. In addition, punch density depends on the feed rate of web, punching frequency and density of the needles (Kamath et al., 2004). Mathematically, punch density is expressed as follows:

$$Punch\ density = \frac{[n * F]}{[V * W]}$$

Where, n = number of needles in the needle board

F = frequency of punching (number of punches/minute)

V = feed rate of the material (meters/minute)

W = effective width of the needle board (cm)

The needlepunching process is more effective when more fibres are available in the fibrous web (Yüksekkaya et al., 2010; Dedov, 2005). Increase in the punch density increases fabric tensile strength up to an optimal level. However, the tensile strength of the fabric decreases with an increase in punching density above the optimal level (Majumdar at al., 2013). The increase in punch density decreases thickness, area density and compression properties of the fabric (Kothari et al., 2008). This is attributed to higher breakages and reorientation of fibres in relatively open fabric structure. Wang et al. (2013) have found that punch density influences puncture resistance of the needlepunched nonwoven fabrics (Wang et al., 2013). In addition, higher punch density may produce isotropic nonwoven fabrics in selected web area density. Midha et al. (2005) have found that depth of needle penetration is responsible for fibre movement while punch density influences fibre entanglement. Furthermore, punch density influences pore size in the fabric. In the beginning, the increase in punch density decreases pore size to an optimal level, however, pore size increases with an increase in punch density above the optimal level due to higher fibre breakages (Rawal et al., 2008; Li et al., 2013; Midha and Mukhopadyay, 2005).

2.4.3 Feed rate

Feed rate is defined as the rate of feeding the web to the machine and is measured in meters/min (Kuo et al., 2007). The increase in the feed rate increases number of fibres in the machine direction. In addition, the increase in feed rate influences web per unit area and resultant fabric mass per unit area. Kuo et al. (2007) have reported that the increase in the feed rate and conveyor speed of the cross-lapper machine influence thickness of the fibrous web. Needlepunched nonwoven fabric produced at lower feed rate and lower stroke frequency achieves higher water permeability. This is attributed to the fact that at lower feed rate, fewer fibres are available which results in relatively open fabric structure with bigger pores. However, fabric produced at higher feed rate and higher stroke frequency achieves relatively smaller pores. Fabric with an open structure is produced at lower feed rate when using natural fibres (Kuo et al., 2007; Rawal and Anandjiwala, 2006; Rawal et al., 2008).

2.4.4 Stroke frequency

Stroke frequency, measured in strokes/min, is defined as the rate or speed of punching which determines the production of the needlepunching machine (Midha and Mukhopadyay, 2005; Russel, 2006). The increase in the stroke frequency increases fabric compactness to an optimum level. However, further increase in the stoke frequency above the optimum level results in fibre breakages (Midha and Mukhopadyay, 2005). Stroke frequency influences tensile strength, density and pore size of the fabrics (Rawal et al., 2010a). Better fabric consolidation is obtained at balanced linear speed and stroke frequency. The main parameter influencing fibre entanglement is called penetration/square inch (PPSI), which is directly proportional to number of needles on the needle board and stroke frequency but inversely proportional to the speed of the web (Moyo et al., 2012).

Rawal et al. (2010a) have reported that the increase in stroke frequency decreases fabric permeability and transmissivity which is attributed to increased fibre entanglement and interlocking in the fabric, therefore, resulting in compact fabric with smaller pores. Rawal et al. (2006) have also found that increases in both stroke frequency and depth of needle penetration cause decrease in pore size. The fabric produced at lower stroke frequency and lower depth of needle penetration achieves higher water permeability. This is attributed to lower entanglement of fibres in the fabric which results in less compact fabric with bigger pores. Needlepunched nonwoven fabrics produced at higher stroke frequency will have more fibres protruded from the fabric structure which is attributed to higher fibre breakages. In addition, higher stroke frequency decreases amount of fibres in the machine direction.

2.4.5 Machine parameters

Machine parameters also influence the production and quality of the needlepunched nonwoven fabrics. Machine parameters are classified into needle type, needle density and their arrangement on the board and movement of the needleboard, i.e vertical straight or elliptical (Rawal et al., 2010a; Rawal and Anandjiwala, 2006).

2.5 Fabric properties

The properties of the needlepunched nonwoven fabrics depend on fibre type, fibre arrangement in the structure and degree of consolidation. In addition, fabric properties are influenced by the method used to intermingle and bond the fibres together (Bueno et al., 2004). Fabric properties are classified into physical, mechanical and performance properties. However, tensile strength, elongation and compression properties are examples of some of the important mechanical properties of the nonwoven fabrics (Midha and Mukhopadyay, 2005)

2.5.1 Physical properties

Physical properties include fabric thickness and mass per unit area, which influence bulkiness of the nonwoven fabrics (Midha and Mukhopadyay, 2005).

2.5.1.1 Fabric thickness

The thickness of the fabric is defined as the distance between top and bottom surfaces of the fabric measured under applied pressure (Russell, 2006). The thickness of the fabric is influenced by mass per unit area and compressibility of the fabric as well as depth of needle penetration. It increases with an increase in fabric mass per unit area and decreases with an increase in the depth of needle penetration to an optimum level beyond which it increases (Wojtasik, 2008). The decrease in the fabric thickness is influenced by fabric compactness while the increase is influenced by fibre breakages (Carvalho et al., 2011; Kothari et al., 2008). Higher fabric thickness is obtained when a fabric is produced from longer fibres. The thickness of the fabric influences pore size, fabric density and puncture resistance of the fabric (Rawal et al., 2008; Midha and Mukhopadyay, 2005).

2.5.1.2 Mass per unit area

The fabric weight, expressed in g/m^2, is defined as the mass per unit area of the fabric (Russell, 2006). Both mass per unit area and thickness of the fabric are required to determine packing density and porosity of the fabric (Li et al., 2006). The packing density influences movement of fibres in the fabric and fabric porosity. Fabric density (bulk density) is defined as the mass per unit volume and it is expressed in kg/m^3. The bulk density as well as porosity influence flow of fluids, heat and sound transmission through the fabric (Dierickx and Van der Sluys, 1990). Higher bulk density influences soil stability and restricts movement of soil particles through smaller pores of the fabrics whereas lower bulk density influences clogging of the fabrics (Russell, 2006). The fabric density depends on the areal density of the web and punch density. Increase in the mass per unit area of the fabric decreases pore size and pore size distribution of the fabric (Li et al, 2006; Russell, 2006; Rawal et al., 2008).

Generally, mass per unit area and thickness of the nonwoven fabrics are non-uniform. This non-uniformity is influenced by web formation technique, type of bonding, type of fibres and their properties. Non-uniformities in the mass per unit area and thickness of the nonwoven fabric influence packing density, permeability and tensile strength of the fabric. The increase in mass per unit area of the fabric increases the tensile strength of the fabric (Rawal and Anandjiwala, 2007). The thickness and mass per unit area of the fabric decrease with the increase in either stroke frequency or depth of needle penetration. Rawal et al. (2007) have found that the increase in stroke frequency or depth of needle penetration decreases fabric thickness as well as mass per unit area (Rawal and Anandjiwala, 2007; Carvalho et al., 2011).

2.5.2 Mechanical properties

Mechanical properties of the nonwoven fabrics are influenced by the change in fibre orientation and fibre curl (Adanur and Liao, 1999). Tensile strength and elongation are examples of major mechanical properties (Dedov, 2004).

2.5.2.1 Tensile strength

Fabric tensile strength is an important parameter in geotextile applications, such as landfill and road construction (Rawal et al., 2010a). The tensile strength of the fabric is influenced by fibre properties and fabric structure. In addition, the tensile strength of the fabric is influenced by its mass per unit area and process parameters, such as depth of needle penetration and stroke frequency. Ghosh et al. (2002) have found that the tensile strength of the fabric increases with increases in punch density and depth of needle penetration.

Furthermore, the tensile strength of the nonwoven fabrics is influenced by fibre slippage, fibre curling and fibre orientation. The tensile strength of the fabric increases with an increase in fibre length. This is attributed to better interlocking and cohesion of longer fibres during fabric production (Ghosh et al., 1994; Ghosh and Chapman, 2002). The machine direction tensile strength of the fabrics produced from a parallel-laid carded web depends on the fibre strength. However, the tensile strength of the fabric in the cross-machine direction depends on the bond strength (Horrocks and Anand, 2000). The tensile strength of the nonwoven fabrics is higher in the cross-machine direction in comparison to that in the machine-direction in the case of cross-lapped fibrous web. This is attributed to orientation of majority of fibres in the cross-machine direction due to cross-lapping process (Rawal et al., 2010a). The tensile strength of the nonwoven fabrics produced from natural fibres may decrease due to biodegradation and damage during production (Collins et al., 2005). Biodegradation is influenced by mechanical, chemical, environmental and bacterial actions (Rollin and Lombard, 1988).

2.5.2.2 Elongation

Fabric elongation is defined as an extension in the load direction caused by a pulling force. Fabric elongation is influenced by manufacturing parameters, such as depth of needle penetration, punch density and mass per unit area. However, fabric elongation decreases with an increase in fabric density (Midha and Mukhopadyay, 2005). Higher elongation is obtained in the fabric produced from hollow cross-section fibres in comparison to that produced from trilobal and round cross-section fibres (Midha and Mukhopadyay, 2005; Çinçik and Koç, 2013).

2.5.3 Compression and recovery (compressive properties)

Compression is defined as the decrease in fabric thickness with an increase in pressure. The compression loading is divided into static and dynamic (Rawal, 2008). Movement of vehicle on the road and people walking on the floor are examples of dynamic loading (Ajayi and Elder, 1997). Increase in the amount of loading decreases compression and recovery parameters to an optimum level (Palmeira and Gardoni, 2002). However, compression and recovery parameters of the fabric remain the same above an optimum level (Elsharief and Lovell, 1996). Recovery in the fabric under compressive loads depends on the fibre entanglement and consolidation of the fibrous web (Kothari and Das, 1992). Better recovery properties are obtained in the fabrics produced with higher mass per unit area. In the beginning, the increase in fabric mass per unit area lowers compression parameters, percentage energy loss and percentage thickness loss. However, further increase in fabric mass per unit area increases compression parameters, such as percentage energy loss and percentage thickness loss (Midha and Mukhopadyay, 2005). Kothari et al.

(2008) have found that the nonwoven fabric produced from finer fibres provide better compression recovery in comparison to that produced from coarser fibres. Compression of the fabric depends on the manufacturing process and amount of pressure exerted on the fabric (Kothari et al., 2008).

Fabric compressibility decreases with increases in stroke frequency and depth of needle penetration. Roy et al. (2009) have found that fabric compression decreases with increases in fabric weight, punch density and depth of needle penetration (Roy et al., 2009). Compression properties of the needlepunched nonwoven fabrics are improved with the addition of bi-component fibres and by heat-setting process (Dedov, 2007). Reinforced nonwoven fabrics achieve better compression resilience in comparison to unreinforced nonwoven fabrics (Midha and Mukhopadyay, 2005). The fabrics produced from hollow cross-section fibres provide higher compression resilience in comparison to those produced from round and trilobal cross-section fibres. Compressibility and percentage energy loss increase with the increase in amount of finer fibres to optimum levels. However, compressibility and percentage energy loss decrease with the increase in the amount of finer fibres above the optimum level. Debnath et al. (2009) have found that nonwoven fabric produced from coarser fibres achieve higher compressibility and lower recovery in comparison to that produced from finer fibres. Bulk density under cyclic compression is either recovered or not recovered. Irreversible bulk density is influenced by fibre types, structure of the fabric and type of loading (Wei et al., 1985; Debnath et al., 2009).

2.5.4 Performance properties

The following performance properties of the nonwoven fabrics are important for geotextile applications:

- Abrasion resistance
- Puncture resistance
- Dimension stability
- UV resistance
- Creep
- Reinforcement
- Separation

2.5.4.1 Abrasion resistance

Abrasion resistance in geotextile is defined as an ability of the fabric to withstand abrasion resulting from continuous rubbing with particles (Saathoff et al., 2007). Abrasion results from sand or soil particles in contact with nonwoven fabrics, thereby, removal of fibres from the fabric. Saathoff et al. (2007) have found that abrasion is very high when nonwoven fabrics are closer to particles of coral and shell fragments. Abrasion resistance increases with the increases in mass per unit area and thickness of the fabric (Lin et al., 2006; Saathoff et al., 2007). In addition, abrasion resistance increases with the increases in both depth of needle penetration and stroke frequency. Furthermore, abrasion resistance of the fabric is improved by reinforcing it with a scrim (Midha and Mukhopadyay, 2005). Abrasion resistance depends on fibre fineness, fibre length and type of fibre used (Lin et al., 2006).

2.5.4.2 Puncture resistance

Puncture resistance is related to in-plane load-deformation properties of the geotextiles and it is important in separation applications (Ghosh, 1988). The geotextiles face compacting forces, particularly normal to plane, as they are already under in-plane tension due to non-uniform surface of the subgrade soil. The compacting forces on the geotextile may result in puncture failure. Lhote and Rigo (1988) have found that the puncture resistance of the geotextiles decreases with the decrease in shear strength of the subgrade soil (Lhote and Rigo, 1988). Puncture resistance of the nonwoven fabric depends on the process parameters, such as depth of needle penetration, stroke frequency and punch density. Furthermore, puncture resistance is influenced by web areal density and types of fibre used. Koerner and Koerner (2011) have found that the fabric produced from PP fibres achieve better puncture resistance in comparison to that produced from PET fibres (Ghosh, 1988; Koerner and Koerner, 2011). Puncture resistance shows linear relationships with areal density and thickness of the fabric. The puncture resistance is influenced mainly by the web areal density in comparison to depth of needle penetration. Puncture resistance decreases with an increase in punch density (Rawal et al., 2008).

Puncture resistance is also influenced by long term creep, chemical resistance and degradation of the geotextiles. In addition, particles closer to geotextiles influence puncture failure because of their angularity, bluntness and packing density (Koerner et al., 1996). Narejo et al. (1996) have found that puncture resistance of the geotextiles in a bed of stones is higher in comparison to that in isolated stones with same protrusion height

(Narejo et al., 1996). The geotextile with better elongation properties can minimise puncture failure as it is able to follow unevenness and irregularities of the particles without being damaged (Ghosh, 1988; Rawal et al., 2008).

2.5.4.3 Dimensional stability

Dimensional stability is defined as the ability of the fabric to retain its original shape or dimensions while being utilized in geotextile applications (Bhat, 1995). The fabric dimensions are fabric length, width and thickness for a three-dimensional fabric. Needlepunched nonwoven fabrics are the major constituents in reinforcement applications. Dimensional stability of the fabric is influenced by manufacturing process, such as punch density, web areal density and depth of needle penetration. Rawal et al. (2008) have shown that depth of needle penetration, web area density and punch density influence the dimension stability of the fabric. The dimensional stability of the fabrics differs depending on the type of fibres in the fabric (Kothari et al., 2008; Rawal et al., 2008). The dimensional stability of the fabric influences its performance and it can be improved by heat setting thermoplastic fibres. Heat setting increases fabric thickness while decreasing thermal shrinkage (Midha and Mukhopadyay, 2005).

2.5.4.4 Ultraviolet (UV) resistance

Nonwoven fabrics may degrade due to chemicals, high temperature, oxidation and UV radiation. UV radiation decreases tensile strength and increases brittleness of the fabric with poor creep properties (Szostak-Kotowa, 2004). In addition, UV radiation can change fabric appearance, molecular structure of the fibres and colour of the fabric. Nonwoven fabrics are protected from UV radiation by special finishing which increases their lifespan. Unprotected fabrics may degrade very quickly. Nonwoven fabrics produced from PP and LDPE fibres are mostly affected by UV radiation. Wojtasik et al. (2008) have found that PP fibres are susceptible to oxidation (Wojtasik et al., 2008). Additives, such as titanium dioxide, carbon black and phosphatic compounds are utilized to protect nonwoven fabrics against UV radiation. However, carbon black is widely utilized to protect the fabric against UV radiation. Additives may either increase or decrease the rate of degradation (Rawal et al., 2010a; Szostak-Kotowa, 2004; Karademir and Frost, 2014).

2.5.4.5 Creep

Creep is defined as fabric extension with time under stress (Rawal et al., 2010a, Koerner et al., 2014). The creep of the needlepunched nonwoven fabric shows a logarithmic relationship with time (Rawal et al., 2010a). Creep is important for the fabrics utilized in reinforcement applications as they are affected by tensile loads. Creep is influenced by fabric properties, manufacturing process, temperature and time (Das et al., 2005). In addition, creep is influenced by fabric structural arrangements, amount of loading and relative humidity. Creep limit is defined as a load in terms of unit width and it is important when determining fabric creep because it bursts above the creep limit (Koerner et al., 2014). Creep limits ranging between 20 to 60 % of fabric tensile strength are normally acceptable (Bueno et al., 2005). The creep of the nonwoven fabrics increases with an increase in the amount of loading due to increases in fibre-to-fibre slippage and forces exerted on individual fibres. Creep is lower in the direction where majority of fibres are oriented and vice-a-versa.

Creep recovery is categorized into instantaneous elastic, instantaneous plastic and viscoelastic. Ajayi and Elder (1997) have found that nonwoven fabrics are viscoelastic and their frictional properties depend on time (Ajayi and Elder, 1997). Creep deformation and failure are analysed by accelerated time-temperature methods. Bueno et al. (2005) have found that studies on time-temperature relationships are necessary to analyse the long term creep behaviour of geotextiles. This is attributed to degradation of polymers at higher temperature. Advantage of utilizing accelerated time-temperature method includes minimising testing time (Bueno et al., 2005; Rawal et al., 2010a; Guicheret-Retel et al., 2015).

2.5.4.6 Reinforcement

In the past, mainly galvanized steel was utilized in reinforcement applications. However, steel is inextensible and it shows linear stress distribution (Bais-Singh et al., 1996). Nonwoven fabrics have gradually replaced steel in reinforcement applications, which is attributed to relatively much lower stiffness of nonwoven fabrics in comparison to that of steel (El Mogahzy et al., 1994). Higher tensile modulus and higher mass per unit area are important for nonwoven fabrics utilized in reinforcement applications (Zhai et al., 1996; Narejo, 2003). In addition, number of soil layers and anchor length are important in reinforcement applications (Adanur and Liao, 1998).

Nonwoven fabrics are utilized in reinforcement applications, such as civil engineering and geotechnical applications (Hong and Wu, 2011; Subaida et al., 2008). Reinforcement requirement depends on type of loading, place or area being reinforced, type and extent of deformation, subgrade and granular fill (Huang and Wang, 2009). In addition, reinforcement depends on the manufacturing process, fabric mass per unit area, fabric thickness and interface friction (Rowe and Li, 1999; Hosseinpour et al., 2010). Nonwoven fabrics are utilized in reinforcement applications to increase cohesion and for lowering lateral deformations. Furthermore, nonwoven fabrics are also utilized in reinforcement applications to lower dilation and loss of post peak strength (Adanur and Liao, 1998). The peak strength is influenced by coefficient of friction between the nonwoven fabric and soil. Nonwoven fabrics transfer stress from the soil by friction and interlocking, it absorbs stress and spreads it throughout the fabric (Zhai et al., 1996; Haeri et al., 2000; Ochiai et al., 1996).

The ability of the fabric to withstand stress depends on the interaction between soil and the fabric which is divided into shearing and pull-out interactions. Shearing interaction is responsible for sliding of soil over the fabric. However, pull-out interaction is responsible for slippage of fabric on the reinforced soil (Rawal et al., 2010a). Soil-fabric interaction is influenced by the properties of the geotextile and soil, interface friction and extensibility (Rawal, 2006a; Rawal et al., 2008).

The stress-strain behaviour is an important parameter for nonwoven fabrics utilized in reinforcement applications when subjected to direct shear or pull-out load. The stability of the slope reinforced with geotextile is influenced by the ability of the geotextile to sustain the stress and displacement (Zhai et al., 1996). The stress exerted at the soil-geotextile interface influences soil density, geotextile stretching and fluid flow. Nonwoven fabric utilized in reinforcement application may either be pulled out or ruptured depending on the vertical pressure and fabric length (Ochiai et al., 1996). Pull-out resistance decreases with increases in mass per unit area and thickness of the fabric. Pull-out resistance is directly related to structural composition and fabric characteristics. It is a function of the relative density and soil particle size (Barbier et al., 2009; Hearle et al., 2008).

2.5.4.7 Separation

Separation is a process where subgrade fine soil materials are separated from subbase aggregates from mixing with each other (Hong and Wu, 2011). Geotextile has replaced sand being utilized as a filter and separator in the past. Geotextile increases the bearing capacity of the soft subgrade soil (Bergado et al., 2001). Separation is categorized into separation of solid-gas, solid-liquid, liquid-liquid and solid-solid (Palmeira, 2009). Nonwoven fabrics are utilized in separation applications, which include road construction and airfield (Butler et al., 2000). They are subjected to earth pressure and dynamic loading. Vehicle movement and landing of aircraft are examples of dynamic loading. The dynamic loading results in fine particles getting pushed into the subbase which results in its contamination. Nonwoven fabrics for separation applications must have better tensile strength (Ghosh, 1988; Hong et al., 2011). Narejo et al. (2003) have found that retention is important in separation applications. Nonwoven fabrics with smaller pores are widely utilized in separation applications because of its better retention properties (El Mogahzy et al., 1994; Wu et al., 2006; Hong and Wu, 2011).

2.5.5 Fluid management properties

Cross-plane and in-plane permeability as well as retention are examples of some important fluid management properties of geotextiles.

2.5.5.1 Cross-plane water permeability

Cross-plane permeability is the same as filtration process because the fluid is flowing through the fabric in a cross-plane direction. Fluid flow is classified into laminar, turbulent and streamline (Jaganathan et al., 2008). Laminar flow is defined as smooth flowing of fluid combined with particles in two or more separate paths which do not interfere with each other. The example of laminar flow is slowly flowing fluid inside a pipe. However, turbulent flow is defined as irregular flow. Laminar and turbulent flows are characterized and quantified using the Reynolds number ($R_{(e)}$). The values of Reynold number ($R_{(e)}$) are lesser than 2000 in laminar flow but greater than 4000 in turbulent flow. The streamline flow is defined as fluid flowing at a constant velocity and it is occurring in cross-plane permeability (White and Corfield, 2006).

Water permeability is a property which characterizes amount of fluid flowing through the fabric under pressure gradient. In addition, water permeability is defined as the flow of liquid through the pores of nonwoven fabric without pressure build-up (Rawal, 2006a; Patanaik and Anandjiwala, 2009). However, pressure build-up can be prevented by pores greater than 300µm. Permeability determines the performance characteristics of needlepunched nonwoven fabrics (Patanaik and Anandjiwala, 2009; Rawal, 2006a).

The permeability of the fabric depends on the pore size characterized by width and depth. The width of the pores determines the amount of fluid flow through the pores. However, pore depth determines the passage of fluid flow (Rawal et al., 2010a). Patnaik and Anandjiwala (2009) have found that permeability of the nonwoven fabric is influenced by pore size and pore size distribution. In addition, permeability of the fabric depends on liquid viscosity, surface tension, packing density and process parameters. Furthermore, permeability of the fabric depends on the porosity, fibre type, fibre properties and anisotropy. Mao and Russel (2003) have found that permeability of the fabric depends on fibre orientation. The permeability of the anisotropic fabric depends on the direction of fluid flow and it varies from region to region due to differences in fibre orientation. However, permeability is uniform throughout in the case of isotropic fabrics (Patanaik and Anandjiwala, 2009; Mao and Russell, 2003).

Permeability of a thin fabric of lower mass per unit area is relatively higher in comparison to that for the thicker fabric of higher mass per unit area (Kopitar et al., 2013; Debnath and Madhussothanan, 2010). Permeability of the nonwoven fabric decreases with time because of clogging of pores as well as stress or pressure exerted on the fabric (Palmeira and Gardoni, 2002; Muthukumaran and Ilamparuthi, 2006).

The permeability of the nonwoven fabric is higher in comparison to that of the soil. This minimises pressure build-up in the composite of soil-nonwoven fabric (Palmeira and Gardoni, 2002; Wei et al., 1985). Giroud (1981) have found that water flows freely in the composite of soil-nonwoven fabric when the permeability of the nonwoven fabric is higher than that of soil. This is attributed to the difference in the properties of soil and nonwoven fabric. Permeability of the soil-nonwoven fabric composite is influenced by flow conditions, boundary conditions, compression and soil type (Giroud, 1981; Dierickx and Van der Sluys, 1990; Hufenus and Schrade, 2004). Higher density soil particles are impermeable, so they lower permeability of the soil-nonwoven fabric composite. However, fine soil particles influence cake formation. Increase in the thickness of a cake decreases pore size as well as permeability. Cake formation is a function of time and it influences fabric permeability (Wu et al., 2006; Johnston, 1998).

2.5.5.2 In-plane permeability (transmissivity)

In-plane permeability is defined as the flow of liquid in the horizontal direction of the geotextiles without losing soil particles (Rawal and Anandjiwala, 2006). The flow of water in the horizontal direction of the geotextile is controlled by Darcy's law. It is applicable only if the flow is laminar. In addition, Darcy's law is applicable when the Reynold number is lower and fluid flow is Newtonian (Hufenus and Schrade, 2004; Chai et al., 2004). The in-plane permeability is important in drainage applications. Nonwoven geotextiles are mostly used in drainage applications in comparison to woven geotextiles. This is attributed to the distinctive pores in nonwoven fabrics (Patanaik and Anandjiwala, 2008). Giroud (1981) have found that woven and thermal bonded nonwoven fabrics are generally not suitable for drainage applications. This is attributed to inadequate transmissivity properties of woven and heat bonded nonwoven fabrics (Giroud, 1981). Transmissivity of the nonwoven fabrics depends on fabric thickness, raw materials, structural arrangement of fibres and process parameters (Rawal and Anandjiwala, 2006). The increases in both stroke frequency and depth of needle penetration decrease transmissivity of the fabric. Hwang et al. (1999) have reported that an increase in stroke frequency decreases transmissivity of the fabric. However, transmissivity of the nonwoven fabrics increases with an increase in feed rate. The transmissivity of the needlepunched nonwoven fabric also decreases with time due to creep, increase in the stress level and clogging. Transmissivity of the nonwoven fabrics decreases with an increase in stress level to an optimum level, after which it remains the same above the optimum level. Chai et al. (2004) have reported that transmissivity of the fabric decreases to constant value but not zero. This is attributed to an increase in the stress level which decreases pore size of the fabric. The decrease in the transmissivity of the nonwoven fabrics is influenced by surrounding soil, settlement, hydraulic gradient and trapped soil particles. The decrease in fabric transmissivity has an effect on drainage discharge capacity (q_w) which is defined as the rate of fluid flow through the drain in a unit hydraulic gradient (Hufenus and Schrade, 2004; Palmeira and Gardoni, 2002).

In-plane permeability of homogenous multilayer fabrics is different in comparison to that of heterogeneous multilayer fabrics (Adams and Rebenfeld, 1987). This is attributed to the homogeneity of the multi-layered fabrics which have same fabric orientation and directional permeability. However, heterogeneous multilayer fabrics differ in terms of fabric anisotropy, orientation of fibre and directional permeability (Adams and Rebenfeld, 1991). The in-plane permeability of the heterogeneous multilayer fabrics is influenced by permeability and structural arrangement of each layer. The in-plane permeability of the multiple layers can be improved by replacing low permeability layers by high permeability layers (Adams and Rebenfeld, 1987; 1991). The in-plane permeability minimises problems caused by fluid in cohesive soil since it is difficult for the fluid to flow through cohesive soil (Kopitar et al., 2013; Palmeira and Gardoni, 2002; Giroud, 1981).

2.5.5.3 Retention

Retention is defined as the ability of the pores of the fabrics to retain soil particles while allowing fluid flow through them. Retention is a function of porosity or per cent open area (POA). Retention of the particles is influenced by stress level, hydraulic gradient, soil particles and type of flow (steady state or dynamic flow). Examples of steady state flow are standard dewatering drains, wall drains and leachate collection drains. However, dynamic flows are pavement edge drains, shoreline and coastal embankment (Palmeira and Gardoni, 2002; Cazzuffi et al., 1999; Liu and Chu, 2006). In addition, particle retention is influenced by fibre diameter, packing density and pore size of the nonwoven fabrics (Corcoran and Bhatia, 1996). The relationship between soil particle size and pore size is important in retention process. This is attributed to retention of the particles by the needlepunched nonwoven fabrics which depend on the apparent pore opening size (AOS). Nonwoven fabrics with pores smaller than pore size of O_{95} influence their particle retention capability. John et al. (1987) have found that nonwoven fabrics used in filtration application must have smaller pores for better particle retention properties. Retention is mathematically expressed as follows:

$$\frac{O_n}{D_i} \leq N$$

O_n = Measure of geotextile pore opening,

D_i = Indicative diameter based on soil particles and

N = Limiting value.

Graded soil particles that are closer to the filter may result in piping, bridging and blinding. Blinding is influenced by interlocking of fibres in the nonwoven fabrics and arrangement of soil particles. Possibility of piping is higher when the filter is under long term cyclic load. This may adversely affect the filters not designed for long term cyclic loading (Watson and John, 1999; Chew et al., 2003; Giroud, 1981).

2.5.6 Structural properties

Pore size and pore size distribution as well as porosity are some important structural properties of the geotextiles.

2.5.6.1 Pore size and its distribution

Pores are defined as voids or open space in nonwoven fabrics which are characterized in terms of surface area, highest pore diameter and pore volume (Bhatia and Smith, 1996). The pore volume determines the amount of fluid flow through pores in the nonwoven fabrics. Real pore volume is directly proportional to the surface density. In addition, pores are defined in terms of equivalent diameter, average diameter and lower diameter. Jena and Gupta (2002) have found that the diameter of pores changes along the pore path. The pores in needlepunched nonwoven fabrics are classified as blind, closed and through pores (Jena and Gupta, 2002; Patanaik and Anandjiwala, 2009). Figure 2.7 shows different types of pores (Jena and Gupta, 2002). Closed pores are not accessible, whereas blind pores terminate in the middle of the fabric and therefore, it is impossible for the fluid to flow through. The through pores are useful in geotextile applications because they allow fluid to flow through.

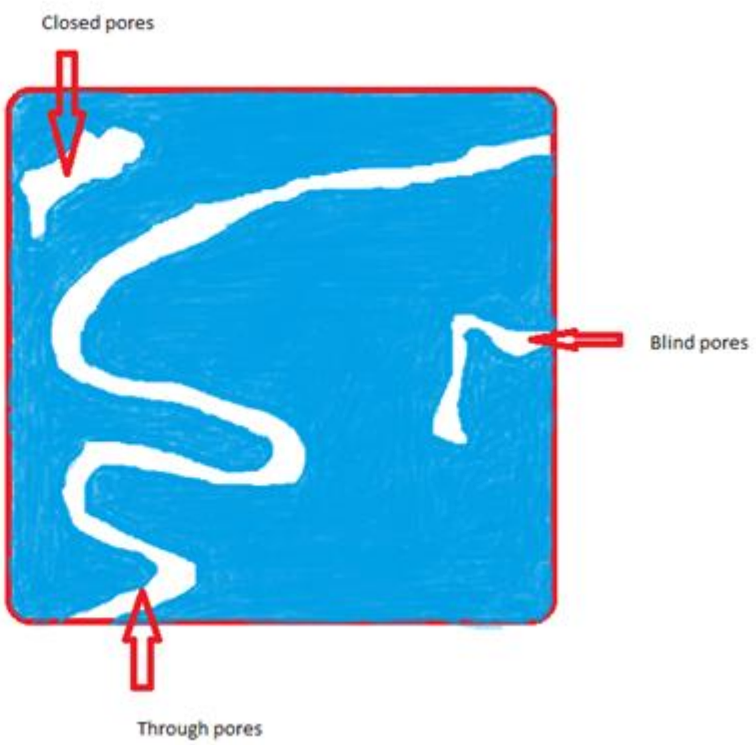

Figure 2.7 Different types of pores (Source: Jena and Gupta, 2002).

The characteristics of through pores include constricted pore diameter, pore shape and pore size distribution. Constricted pore size is also called smaller pores (Jena and Gupta, 2003). Pores are complex in size, shape and capillary geometry which is attributed to manufacturing process and type of fibres used. Fluid is able to flow through the pores because of interconnectivity of pores within the fabric. The connectivity of pores is influenced by fabric thickness, solid volume fraction and fibre diameter (Jaganathan et al., 2008). Komori and Makashima (1979) have found that the width and depth of pores influence fluid flow. The increases in both fabric thickness and solid volume fraction decrease pore connectivity. However, pore connectivity increases with an increase in fibre diameter while thickness of the fabric and solid volume fraction remain unchanged (Rawal, 2010a; Neckar and Ibrahim, 2003; Jena and Gupta, 2002).

Pores of needlepunched nonwoven fabrics are important for geotextile applications, such as filtration and drainage, because fluid can flow through the fabric freely and they meet the clogging requirements (Rawal, 2010a). Pores of needlepunched nonwoven fabrics are influenced by process parameters, such as stroke frequency and depth of needle penetration. The increases in both stroke frequency and depth of needle penetration tend to decrease the pore size. In addition, the pores in needlepunched nonwoven fabrics are also influenced by compression, pressure and fibre properties. Anandjiwala and Boguslavsky (2008) have found that the inherent variations in properties of natural fibres influence pore size. The pore size decreases when the nonwoven fabric is under compression (Midha and Mukhopadyay, 2005; Anandjiwala and Boguslavsky, 2008; Palmeira and Gardoni, 2002). Smaller pores are mostly affected due to compression in comparison to bigger pores such as, pores O_{98}, O_{96} and O_{90}. The decrease in pore size will reduce fluid flow through the pores. Furthermore, the pores of needlepunched nonwoven fabric are influenced by chemicals, fibre orientation and inhomogeneity. Inhomogeneity in pores depends on the manufacturing process. The inhomogeneity of pores is higher when the fabric is produced from fibres with smaller diameters in comparison to that produced from fibres with higher diameters (Dhaniyala and Liu, 2001; Rawal and Saraswat, 2011a; Havlová, 2013).

Pore size distribution is important for the retention of soil particles and it is represented by gamma distribution. Pore size distribution in nonwoven geotextiles is influenced by the elementary plane thickness (Lombard et al., 1989; Jena and Gupta, 2002; 2003; Jaganathan et al., 2008).

Porosity

Porosity is defined as the ratio of nonsolid volume to total volume of the fabric (Wei et al., 1985). It determines the number of air gaps present in the needlepunched nonwoven fabrics. Porosity is mathematically expressed as follows:

$$P_R = \frac{V_1 - V_s}{V_1} * 100$$

where P_R = porosity in (%),

V_1= total volume of the system (m^3) and

V_s = volume of the solids (m^3).

The porosity of the needlepunched nonwoven fabric is influenced by mass per unit area and thickness of the fabric as well as manufacturing process (Kopitar et al., 2013). The increases in mass per unit area, depth of needle penetration and stroke frequency decrease porosity of the fabric. Militký et al. (2004) have found that porosity of the fabric depends on the method used during manufacturing (Militký et al., 2004). The porosity of the nonwoven fabric decreases when the fabric is under compression. In addition, porosity of the needlepunched nonwoven fabric decreases with time due to clogging (Palmeira and Gardoni, 2002). Porosity shows a linear relationship with liquid flow and relative open area, which is important in analysing porosity. The porosity and bulk density influence fabric permeability. Koerner et al. (2013) have found that porosity of nonwoven fabric ranges between 50 to 90%.

2.5.7 Interaction between soil and geotextile

The interaction between soil and geotextile is important in reinforcement and separation applications which are influenced by earth pressure and dynamic loading. Loading influences soil density, fluid flow at the soil-geotextile interface, compression and stretching of the fabric. Chemical resistance, bio-degradation and clogging are important in understanding the interaction between soil and geotextile (Palmeira, 2009).

2.5.7.1 Chemical resistance

Chemicals may increase the rate of degradation of geotextiles which results in the reduction in their tensile strength and resultant performance failure. Chemicals are caused or influenced by waste in landfills, acidic and alkaline soils (Hong et al., 2011). Higher temperature may also influence chemical degradation. Chemicals change the fabric structure due to oxidation, chain scission, cross linking and swelling (Tholkappiyan, 2010). Absorption of chemicals causes fibre swelling which results in removal of fillers from the fabric. However, the fabrics produced from PP fibres are not affected by chemicals (Rawal et al., 2010a). In addition, chemicals influence puncture resistance and drainage performance of the fabric. Drainage system may be blocked by fluid containing chemicals. Additives, such as 2.5% carbon black and phosphatic compounds improve chemical resistance of geotextiles (Palmeira, 2009).

2.5.7.2 Biodegradation

Biodegradation decreases tensile strength, induces change in colour and appearance of the geotextiles. It is influenced by chemicals, hydrolysis, bacteria and UV radiation (Slater, 2003). In addition, biodegradation is also influenced by oxidation, chemical reaction, pH and relative humidity (Keun et al., 2005). Furthermore, biodegradation is influenced by water hardness and biological as well as enzymatic actions of micro-organisms with CO_2 (Rawal et al., 2010a; Keun et al., 2005). The fabrics produced from natural fibres are more susceptible to biodegradation in comparison to that produced from synthetic fibres. This is attributed to micro-organisms, such as fungi, attacking natural fibres. Micro-organisms are influenced by starch, fats and oils. The rate of biodegradation in the fabric produced from synthetic fibres is either very slow or nil in comparison to that produced from natural fibres (Rawal et al., 2010a). This is attributed to lack of hydrolysis of the crystalline region in synthetic fibres. Additives, such as 2.5% carbon black and titanium dioxide are utilized to lower the rate of biodegradation (Slater, 2003).

2.5.7.3 Clogging

Clogging is defined as the decrease in fluid flow through pores of the fabric (Guyer, 2009). Fabric pores clog as a result of soil particles trapped inside pores, bacteria growth and organic materials. Furthermore, fabric pores clog because of blocking, blinding and piping. Clogging occurs when the composite of soil and geotextile is not reaching a state of equilibrium (Maheshwari and Gunjagi, 2008; Rawal et al., 2010a). Clogging is influenced by hydraulic gradient, porosity of the fabric, particle distribution and grain size of the soil (Dürst et al., 1981). The relationship between pore size and grain size of the soil is used to determine clogging of the nonwoven fabrics. Clogging is higher in cohesive and finer soil particles (Dierickx and Van der Sluys, 1990) and when dredged sediments are being filtered through a thin fabric produced from finer fibres (Luettich et al., 1992). Wei et al. (1985) have found that the possibility of clogging is higher in the case of thin fabrics. Clogging is minimised by utilizing either fabric with a porosity value above 30 % or fabric containing larger pores, such as (O_{95}) (Palmeira and Gardoni, 2000). In addition, a fabric with many openings minimise clogging in comparison to that with fewer openings because when some pores are clogged, others are still open (Bhatia and Smith, 1996; Rawal et al., 2010a).

2.5.8 Geotextile applications

Geotextile is utilized in filtration, drainage, reinforcement and separation applications.

2.5.8.1 Filtration

Filtration is a primary function of the geotextile and it is a process where particles in water are retained and water is allowed to flow through the pores of the nonwoven fabric. Therefore, the pore size of the nonwoven geotextile must be smaller in comparison to particle sizes being filtered and big enough to allow fluid flow without pressure build-up. The filter requirements include permeability, retention, anti-clogging, durability and survivability (Gabr et al., 1998; Anandjiwala and Boguslavsky, 2008; Faure et al., 2006; Geotextile filter design, application and product selection guide, accessed on 03 May 2016, http://www.tencate.com/pt/lam/Images/tn_geofilter_tcm31-11025.pdf).

The rate of filtration is defined as the volume of filtrate collected per unit time. Continuous filtering of filtrate combined with particles may result in some particles being trapped inside pores and it is called a filter cake. The rate of filtration decreases with an increase in the thickness of the filter cake. Pressure drop increases when the rate of filtration is constant, however, the rate of filtration decreases when pressure drop is constant. The rate of filtration is influenced by pressure drop, surface area of the filter and viscosity of the filtrate.

The fibrous filter is composed of randomly orientated fibres which are utilized to retain or capture particles. Particles are captured by different physical mechanisms which include direct interception, inertial impaction and diffusion. In the direct interception mechanism the particles are intercepted and captured by the fibres when they are within a small distance from them. This distance is either equal or less than the diameter of the particles. Direct interception captures particles greater than 0.2 µm in size.

In the inertial impaction mechanism the particles are captured by the fibres when they are unable to negotiate the path formed by a complex network of random fibres due to higher inertia of the particles.

In the diffusion mechanism, the particles move in a Brownian motion (randomly) in the flow and they are either collided to each other or with the fibres. Diffusion mechanism captures particles smaller than 0.2 µm in size (Dickson, 1997; Camfil, accessed on 23 May 2016, http://www.camfil.com/Filter technology/Principles of Filtration/Interception/).

2.5.8.2 Drainage

Nonwoven geotextiles are utilized in drainage applications to transport either water or waste in a vertical direction while retaining soil particles. Drainage systems are normally installed less than 1 metre deep. However, the drainage systems may also be installed deeper than 1 metre depending on the groundwater table and drain leachate (Geotextile filter design, application and product selection guide, accessed on 03 May 2016, http://www.tencate.com/pt/lam/Images/tn_geofilter_tcm31-11025.pdf). Drainage systems are installed either on the surface or subsurface where the latter system has some advantages, such as longer lifetime, preservation of land and lower maintenance cost in comparison to the surface drainage system (Dierickx and Van der Sluys, 1990).

Nonwoven geotextiles are also utilized for drainage and as a filter for preventing soil erosion. Fine soil particles that are closer to the drainage system may result in clogging. The clogging of the drainage system causes instability around it and decrease in hydraulic conductivity. In addition, clogging of the drainage system also decreases its discharge capacity which decreases non-linearly with hydraulic gradient and it depends on the lateral earth pressure, folding and bending of the drainage system caused by large settlements (Dierickx and Van der Sluys, 1990; Bergado et al., 1996). Nonwoven geotextiles are utilized in drainage applications which include subsoil improvements, airfields, leachate collections and dams (Chai et al., 2004; Palmeira et al., 2000; Wu et al., 2006).

2.5.8.3 Reinforcement

Nonwoven geotextiles are utilized to reinforce weak soil to increase its stiffness and ductility. The weak soil can be either natural soil deposit or sludge landfill. Nonwoven geotextiles transfer stress from soil to the reinforcement by friction, interlocking and bearing resistance as discussed earlier. The major benefit of using nonwoven geotextiles in reinforcement applications is their better cohesion properties. However, cohesion between soil and the fabric depends on the number of layers of the nonwoven fabrics (Haeri et al., 2000; Jeon, 2011; Wang et al., 1996).

Reinforcement capability of the nonwoven fabrics in geotextile application depends on the pore dimensions, mass per unit area and thickness of the nonwoven fabric. The interaction between soil and nonwoven fabric is responsible for the interlocking of soil particles and the nonwoven fabric in reinforcement applications. Nonwoven geotextiles are utilized in reinforcement applications such as earth retaining structure and railway and roadway foundations (Abramento and Whittle, 1995; Giroud et al., 1984; Haeri et al., 2000).

2.5.8.4 Separation

Nonwoven geotextiles in separation applications are employed to separate subgrade fine soil materials and subbase aggregates from mixing with each other under different types of loads. Nonwoven fabrics for separation application must possess better tensile strength and smaller pores for retention of particles. According to American Association of State Highway and Transportation Officials (AASHTO), the size of the pores in nonwoven fabric for separation application must be lesser than or equal to 0.6 mm (Hong and Wu, 2011a; Narejo, 2003; AASHTO NTPEP, 2002).

Nonwoven geotextiles are utilized in separation applications, such as soil separation, railway and roadway applications. Nonwoven geotextiles utilized as a separator in roadway applications may get clogged due to in-plane stress, strain and dynamic load (Narejo, 2003; Bhatia et al., 1990; Bhatia and Smith, 1996; Hong and Wu, 2011a).

2.6 Principles of the testing method

Several physical, mechanical and specialized tests are performed to analyse the performance properties of the nonwoven fabrics. The following methods are utilized to analyse nonwoven fabrics particularly for geotextile applications:

- Fabric tensile strength according to ASTM D 5034 – 13 standards.
- Pull out test to analyse fabric used in reinforcement applications according to ASTM C 900 – 15 standards.
- Direct shear test to analyse the relationship between stress-strain of nonwoven fabrics according to ASTM D 3080 – 11 standards.

- Cone drop test to analyse the damage to nonwoven fabrics used in filtration and separation applications when closer to sharp or angular objects according to EN ISO-13433 standards.
- Puncture resistance of the fabric according to PN-EN ISO 12236 standards.
- Gradient ratio test to analyse fabrics used for long term filtration according to ASTM D 5101 – 12 standards.
- Transmissivity of the fabric according to ASTM D 4716 – 14 standards.
- Pores in nonwoven fabrics by capillary flow porometer according to ASTM F 316 - 11 standards.
- Chemical resistance of the fabric according to ASTM D 543- 06 standards.

2.6.1 Fabric tensile strength (Grab test)

Grab test is used to analyse elongation and breaking strength of woven, nonwoven and felted fabrics. However, it is not suitable to test glass and knitted fabrics as well as any other textile fabrics which can stretch more than 11%. The tensile strength of the fabric is analysed according to constant rate of extension (CRE), constant rate of loading (CRL) and constant rate of traverse (CRT) principles. CRE principle implies that the rate of increase of specimen length is kept uniform with time. In CRL principle, the rate of increase of load is kept uniform with time. The extension rate is dependent on the load-elongation of the specimen. However, in CRT principle, one clamp is being pulled at uniform rate while load exerted on the other clamp is recorded.

Wide-width tensile test can also be used to analyse tensile strength of the nonwoven fabrics according to EN 10319:2008 standards. However, the width of the sample in wide-width tensile test is much greater in comparison to length, which minimises contraction of the fabric during test (NPTEL, tensile testing, accessed on 21 January 2016, http://nptel.ac.in/courses/116102029/42; ASTM D5034 - 2013; Bolt and Duszynska, 2010).

2.6.2 Pull out test

In pull out test the force required to pull out the fabric from either soil or concrete is measured (ASTM C900 2015). The pull out test analyses strength and deformation of the geotextiles. The results obtained using pull out test are useful in assessing soil-reinforcement interaction. However, the results obtained using pull out test method are influenced by the boundary conditions at the upper surface of the soil specimen, friction between side walls and soil, pull out box dimensions and clamping device. Usually, a large scale test is performed to minimise the problem caused by boundary conditions. Problems caused by friction between side walls and soil are minimised by using plastic film layers, oil or grease (Palmeira, 2009).

2.6.3 Direct shear

Direct shear test analyses shear strength parameters of either sandy or silty soil. Soil structures such as earth dams, retaining walls, slopes and foundations are analysed according to the theory of soil mechanics. The soil sample being tested is placed in a cubic shear box composed of upper and lower boxes. The stress is applied on the sample while the top part of the sample is being pulled until the sample fails. Results of the applied stress as well as strain are recorded at various intervals and a graph of stress vs strain is plotted. Advantages of using direct shear test include simplicity of the test and possibility to analyse friction between two materials (Direct shear test, accessed on 11 July 2016, http://home.iitk.ac.in/~madhav/expt10.html).

2.6.4 Cone drop

Cone drop method analyses the effect of sharp and angular particles dropped on the surface of the geotextile. It analyses whether the geotextile used in filtration and separation applications will be able to withstand the damage caused by sharp and angular particles (ISO 13433: 2006). The specimen is clamped between two steel rings. A steel cone with 45^o tip angle and weight of 1000g is released from a fixed height of 500 mm into the centre of a specimen with diameter of 150 mm. The cone is removed after it penetrates the tested specimen and the degree of penetration is measured by inserting a graduated narrow angle cone into the hole. The major disadvantage of the cone drop method is that it produces incorrect tensile strength results (ISO 13433: 2006; Bolt and Duszynska, 2010).

2.6.5 Static puncture test (CBR test)

Puncture test is also known as compressive test in which a sample is compressed by a probe at the centre until it is punctured or ruptured (EN ISO 12236). Puncture tests are performed to analyse elongation and puncture resistance of nonwoven fabrics utilized to separate big stones and soil from each other. The test is normally performed on dry specimens conditioned under specified atmosphere and it is not applicable for materials with apertures greater than 10 mm. If the specimen being tested has two sides with different characteristics, then the tests should be performed on both the sides. The results of static puncture test are expressed in terms of mean push-through force (kN), mean push-through displacement (mm) and coefficient variations in their measurements (EN ISO 12236, Bolt and Duszynska, 2010).

2.6.6 Gradient ratio

In this test the hydraulic gradient of fluid flowing downward through soil-geotextile under constant pressure head is measured and it analyses clogging of the soil-geotextile (ASTM D 5101 - 2012). The soil-geotextile specimen is supported by the wire mesh screen that is placed under the geotextile. The hydraulic head is analysed in different parts of the soil-geotextile specimen after 24 hours and the test results provide the values of the gradient ratio and the discharge flow. The discharge flow indicates permeability capability of the whole system. However, the gradient ratio shows the relative seepage capability of two layers (soil and geotextiles). The results of this test are influenced by entrapment of particles and non-uniformity of the specimen. Disadvantages of the gradient ratio tests are preferential flow of fluid. In addition, gradient ratio test method is unable to analyse slit, clay and gap-graded soil as well as fine grained materials such as dredge sediments (Wu et al., 2006; Wu et al., 2008; Rollin and Lombard, 1988).

2.6.7 Capillary flow porometry

The principle of capillary flow porometry is to displace a wetting liquid from pores of the nonwoven fabric by applying gas at increasing pressure (Capillary flow porometry, accessed on 29 February 2016, https://en.wikipedia.org/wiki/Capillary_flow_porometry; ASTM F 316 - 2011). Capillary flow porometer method is versatile, not harmful to environment, analyse pore size and pore size distribution without damaging pores and the results are reproducible with small errors.

Mercury intrusion porometer is also used to analyse pores of nonwoven fabrics. It analyses pores using mercury which is a non-wetting liquid with a surface tension of around 460 mN/m. Mercury intrusion porometer analyses pores differently in comparison to other techniques. It analyses pores individually while other techniques analyse pores as continuous channel. Mercury intrusion porometer is able to analyse pore volume, diameters of through and blind pores. Disadvantages of utilizing mercury intrusion porometer include damaging pores of nonwoven fabric, harmful to human health and environmental pollution. Damage to pores is caused by high pressure needed to force mercury out of pores (Jena and Gupta, 2002; 2003; Porometer, the principle of capillary flow porometry (CFP), accessed on 29 February 2016, http://www.porometer.com/porometers/technology/).

In hydrodynamic sieving, water combined with finer and coarser glass beads is sieved through the pores of nonwoven fabric. Disadvantages of hydrodynamic sieving are that it analyses bigger pores and a possibility of particles being blocked and bridge formation exists. Blocking of particles is attributed to bigger glass bead particles which settle first when water is being drained. Therefore, smaller glass bead particles in comparison to the pores of nonwoven fabric being tested are unable to pass through pores due to the blockage created by bigger glass beads (Bhatia and Smith, 1996).

2.6.8 Transmissivity

The transmissivity of the fabric is analysed using the principle of hydraulic methods based on Darcy's law (ASTM D 4716 – 2014). Darcy's law can be applied when analysing field measurements and laboratory results. Laboratory results may be obtained using either constant or falling pressure heads. Transmissivity is related to hydraulic conductivity. The transmissivity test method was designed as an index test method, however, it can be also used as performance test method if the hydraulic gradients and specimen contact surface are modelled as field conditions. The test can be performed at different stresses depending on the user or type of the test. Results obtained using the transmissivity test methods are influenced by the stress caused by the pressure exerted on the plate where the sample being tested is placed. The stress may damage the specimen being tested and may lead to wrong results. Disadvantage of the method used to analyse transmissivity of the fabric is formation of air bubbles (Hufenus and Schrade, 2004; Palmeira and Gardoni, 2002).

Permeability

Water permeability (hydraulic conductivity) is analysed by methods based on the principle of hydraulic pressure head and falling hydraulic pressure head. In addition, air flow method can be also used to analyse water permeability using air flow apparatus. Constant head method is used to analyse permeable soils ($k > 10^{-4}$ cm/s). Falling head method based on Darcy's law is used to analyse less permeable soils (k < 10^{-4} cm/s) (ASTM D 4491 - 2015, standard test methods for water permeability of geotextiles by permittivity, ASTM International, West Conshohocken, PA, 2015, www.astm.org).

2.6.9 Chemical resistance

Chemical resistance of the nonwoven fabrics were analysed by exposing them into chemicals for a defined period. The period can be categorized into prescribed minutes, hours, days as well as months at various pH and temperatures. Chemicals, such as sodium chloride (NaCl), sodium hydroxide (NaOH), sulphuric acid (H_2SO_4) and acetic acid ($C_2H_4O_2$) solutions were utilized to analyse their effects on the nonwoven fabrics (Gassan and Bledzki, 1999; Johar et al., 2012). The scanning electron microscope (SEM) was used to capture images of the untested and tested samples at various magnifications after the removal of chemicals. Change in the mass per unit area, dimensions, appearance and tensile strength of the tested samples were analysed and compared to those of the untested samples. Gassan and Bledzki (1999) have reported that NaOH removes portion of wax, lignin and hemicellulose of jute fibres while increasing their tensile strength and modulus. However, the tensile strength of the fibres decreases with an increase in concentration of NaOH above 6% due to fibre damage (Edeerozey et al., 2007; Gassan and Bledzki, 1999).

2.7 Problem statement

Many studies conducted on geotextile applications were based on the utilization of synthetic fibres, such as PP, PET and PE as raw materials for producing nonwoven fabrics due to their better mechanical properties, chemical inertness, lower cost and most importantly ease of processing. The major drawbacks of synthetic fibres are their non-renewable nature, petroleum base and resultant greenhouse gas emissions. However, both incineration and dumping in landfills are expensive besides contributing to environmental pollution.

There is a worldwide concern about non-renewable materials produced from petroleum resources and the new environmental regulations are given much attention on reducing carbon footprint and replacement of petroleum products with eco-friendly materials. In addition, most of the research work carried out previously on the needlepunched nonwoven geotextile reported the drawbacks of synthetic fibres, however, little has been mentioned or discussed on how the drawbacks can be minimised. In this regard, natural fibres received little attention despite their favourable properties which include availability, renewability, robustness and biodegradability. The commonly available natural fibres, namely, kenaf, hemp, jute, agave, sisal, coir and flax are utilized in the production of nonwoven fabrics. Kenaf fibres were utilized in this study due to their better mechanical properties, abrasion resistance, resistance to insects, environmental friendliness and biodegradability. In addition, kenaf plant has a shorter plantation cycle and it is flexible to various environmental conditions. It can be planted in subtropical and tropical parts of Africa as well as Asian countries. However, natural fibres have their own drawbacks, such as inherent variations in fibre properties, such as fineness and length depending upon the cultivations as well as climatic conditions in the region of origin. In addition, needlepunched nonwoven fabrics produced from natural fibres pose the following problems during processing:

- Fibre breakages at highest values of depth of needle penetration and punch density.
- Insufficient or lower entanglement of coarser fibres at lowest values of mass per unit area, depth of needle penetration and punch density.
- Fibres escaping a grip of needle grooves during needle penetration in fibrous web particularly when producing heavier fabric.
- Lower depth of needle penetration and lower stroke frequency in fibrous web with higher mass per unit area which results in an insufficient interlocking and entanglement of the fibres

Majority of research studies on nonwoven geotextile produced from natural fibres (sisal, coir, jute) were mostly focussed on prevention of soil erosion and reinforcement but not well addressing the above problems during processing, therefore, the present objective of this study is to produce needlepunched nonwoven fabrics from natural fibres (kenaf fibres) and to evaluate their suitability for geotextile applications. In addition, the objective of this study is to explore the possibility of natural fibres as an alternative to the synthetic fibres in developing geotextile products.

An attempt will be made to produce needlepunched nonwoven fabrics from different fibres and their blends, namely, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf with better performance properties, as required in geotextile applications. PP fibres will be used to produce “control sample” due to their dominance in the needlepunched nonwoven geotextile as well as better mechanical properties in comparison to kenaf fibres. Problems occurring during the production of nonwoven fabrics produced from kenaf fibres will be minimised by blending PP and kenaf fibres together. In addition, synergistic effect of a blend of 50/50% PP/kenaf fibres will be achieved as both of them have their own advantages and disadvantages. The depth of needle penetration, stroke frequency and mass per unit area will be varied in order to analyse common problems of producing needlepunched nonwoven fabrics from natural fibres. The information generated will be utilized to propose possible solution to overcome these problems.

2.8 Research methodology

In order to accomplish the objectives mentioned above, needlepunched nonwoven fabrics will be produced from 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres. The mass per unit area 300, 600 and 900 g/m^2, depth of needle penetration 4, 7 and 10 mm and stroke frequency 250, 350 and 450 strokes/min will be varied to study their effects on processing conditions and resulting properties of the needlepunched nonwoven fabrics. The fabrics produced from 100% kenaf fibres are expected to pose processing problems, such as fibre breakages, lower entanglement of coarser fibres particularly at lower depth of needle penetration and punch density as discussed earlier, therefore, kenaf and PP fibres were blended to minimise the processing problems.

The three way statistical analysis (ANOVA) was utilized to determine the interaction effects of the stroke frequency, depth of needle penetration and mass per unit area on the properties of nonwoven fabrics produced from 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres. A full factorial design will be used and the analyses at 5% significance level using SPSS 23 and Statistica 12 programs will be computed. The full factorial design is ideal to analyse the effects of three independent variables, namely, depth of needle penetration, stroke frequency and mass per unit area on the properties of the needlepunched nonwoven fabrics. The Tukey test will be applied at 95% confidence level to compare group means.

The produced fabrics will be conditioned for 24 hours in the laboratory and the following fabric properties: mass per unit area, thickness of the fabric, tensile strength, puncture resistance, water permeability, transmissivity, pore size and pore size distribution will be analysed according to their standard test methods (ASTM D3776 – 96; WSP120.6 – 05; ASTM D5034 -13; PN-EN ISO 12236; ASTM D4491 – 15; ASTM D4716 – 14 and ASTM F316 – 11). The statistical analysis (ANOVA) will be conducted to establish the most suitable process variables to produce needlepunched nonwoven fabrics from 100%

kenaf fibres, a blend of 50/50% PP/kenaf and 100% PP fibres. The analysis will be used to understand the fabric structure and applicability of the resulting nonwoven fabric in geotextile applications.

2.9 Expected outcome

Needlepunched nonwoven fabrics produced from 100% kenaf, a blend of 50/50% PP/kenaf and 100% PP fibres with suitable properties for geotextile applications, namely, better tensile strength, filtration, separation, permeability and drainage will be produced. Both natural and synthetic fibres have their own advantages and disadvantages in terms of physical, chemical and environmental performance, therefore, blending natural and synthetic fibres together will improve fabric properties, so that synergistic effect can be achieved. In addition, blending natural and synthetic fibres will lower the amount of synthetic fibres used. Furthermore, production of synthetic fibres, air and water pollutions will be minimised if lower amount of synthetic fibres are utilized. Due to the fact that kenaf fibres are biodegradable, it is also expected that nonwoven fabrics produced from kenaf fibres will minimise environmental pollution. Fabrics produced from 100% PP fibres were expected to achieve better tensile strength and puncture resistance due to properties of PP fibres, such as flexibility, high extensibility, better tensile strength, elastic recovery and lesser fibre deformation during needlepunching process. However, it was expected that bigger pore sizes and higher water permeability will be achieved in the fabrics produced from 100% kenaf fibres due to higher bending rigidity, breakage of fibres during needlepunching process, variations in fineness and length of kenaf fibres. It was expected also that fabrics produced from a blend of 50/50% PP/kenaf fibres will achieved better values of tensile strength and puncture resistance in comparison to that produced from 100 % kenaf fibres, however, lower than those for the fabrics produced from 100% PP fibres. In addition, it was expected that fabrics produced from a blend of 50/50% PP/kenaf fibres will achieved bigger pore sizes and higher water permeability in comparison to those produced from 100% PP fibres, however, lower than those for the fabrics produced from 100% kenaf fibres.

Chapter 3

Experimental

Experimental work has been divided into two sections, namely preliminary and main trials. Both synthetic and natural fibres were utilized to produce needlepunched nonwoven fabrics in all the trials. The effect of depth of needle penetration, stroke frequency and mass per unit area on the properties of needlepunched nonwoven fabrics produced from different fibres and their blends, namely, 100% PET, a blend of 50/50% PET/PP, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf were analysed. The fabric properties, namely, tensile strength, puncture resistance, pore size, water permeability and transmissivity were analysed.

The results obtained from the preliminary trial were required to design the main trial according to full factorial experimental design. The effect of depth of needle penetration, stroke frequency and mass per unit area on the properties of needlepunched nonwoven fabrics produced from different fibres and their blends, namely, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf were analysed. The fabric properties studied in the preliminary trials were also analysed and compared. The statistical analysis (ANOVA) was conducted to establish the most suitable process variables to produce needlepunched nonwoven fabrics from 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres.

3.1. Preliminary trial

The aim of this elementary trial was to obtain a range of suitable process parameters which can be utilized to produce needlepunched nonwoven fabrics for geotextile applications. Both PET and PP fibres were utilized in this preliminary trial due to their unique properties, availability and most importantly ease of processability. Chemical inertness, better tensile strength, quick drying capacity and higher creep are advantages of PP fibres. Higher tenacity, abrasion resistance and resistant to light are advantages of PET fibres. The length and fineness of PP fibres were 40 mm and 2.2 decitex, respectively. The length and fineness of PET fibres were 60 mm and 6.7 decitex, respectively. However, natural fibres, such as kenaf, also show some advantages, namely comparable tensile strength, environmental friendliness and biodegradability. The length and fineness of kenaf fibres before cottonization were 120 mm and 5.1 decitex, respectively. The kenaf fibres were opened and cleaned using Temafa Cottonizer machine before subjecting to carding process. Opening was performed to shorten fibre length and removing dirt such as plant debris, dust and wax. After fibres were cottonised, they were transported to Linstar (fine opener). The Linstar was composed of a main cylinder, intake on top and intake down were adjusted to control fibre length. A single pass in Lomy at a processing speed of 684 revolutions/min was employed. The processing speed of the main cylinder, intake on top and intake down are shown in Table 3.1 below.

Table 3.1 Processing speeds of the main cylinder, intake on top and intake down for kenaf fibres

Linster machine components	Processing speed (m/min)
Main cylinder	6.5
Intake on top	5.9
Intake down	5

The advantages of PET, PP and kenaf fibres make them suitable for filtration, water permeability and drainage (transmissivity) applications. Needlepunched nonwoven fabrics were produced from different fibres and their blends, namely, 100% PET, a blend of 50/50% PET/PP, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf. The feed rate, output speed as well as process parameters utilized while producing the fabrics are shown in Tables 3.2 and 3.3, respectively. The depth of needle penetration, stroke frequency and mass per unit area were varied in order to produce needlepunched nonwoven fabrics with better tensile strength and suitability as geotextiles in filtration, separation, permeability and drainage (transmissivity) applications. In addition, the depth of needle penetration, stroke frequency and mass per unit area were varied to obtain maximum and minimum values of the fabric properties.

Table 3.2 Feed rate and output speed utilized during carding process for 100 % PET, a blend of 50/50% PET/PP, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres

Fibre types	Feed rate (m/min)	Output speed (m/min)
100 % PET	0.6	0.9
50/50 % PET/PP blend	0.7	1.0
100 % PP	0.6	0.9
50/50 % PP/kenaf blend	0.7	1.3
100 % kenaf	0.6	1.2

Table 3.3 Process parameters used to produce needlepunched nonwoven fabrics from different fibres and their blends, namely, 100% PET, a blend of 50/50% PET/PP, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf

Fibre types	Depth of needle penetration (mm)	Stoke frequency (strokes/min)	Mass per unit area (g/m^2)
100% PET	3	250	300 (260)
100% PET	5	250	600 (500)
100% PET	8	250	600 (530)
100% PET	12	350	900 (1010)
50/50% PP/PET	8	350	900 (1000)
100% PP	3	250	300 (332)
100% PP	5	250	500 (480)
100% PP	8	350	100 (925)
50/50% PP/kenaf blend	3	250	300 (295)
50/50% PP/kenaf blend	5	250	500 (540)
50/50% PP/kenaf blend	8	350	1000 (990)
100% kenaf	3	250	300 (315)
100% kenaf	5	250	500 (462)
100% kenaf	8	350	1000 (1020)

Note: Value in the parenthesis shows the actual mass per unit area.

3.1.1 Production of needlepunched nonwoven fabrics

Production of nonwoven fabric includes fibre preparation (opening and blending), carding, web laying and needlepunching.

Fibre opening and blending

Fibre opening was carried out to open fibre bundles into individual fibres. Each type of fibre has its own advantages and disadvantages, therefore, fibres were blended to improve the properties of the fabrics due to synergistic attributes of individual fibre properties. A blending ratio of (50/50%) was used in this study and fibres were mixed manually due to small quantity required in our trials. The opening and blending of the fibres are important as they influence fabric properties required for final applications.

Carding

The fibres were transported to carding machine by a chute feeding system. They were carded to separate fibre tufts into individual fibres, obtain better fibre orientation and formation of the fibrous web. The carding machine utilized is equipped with a master cylinder of 2.5 m in diameter and covered with universal card clothing. The large rotating cylinder is also known as the heart of the carding machine and it is responsible for distributing fibres during production. The fibres are removed from the rotating cylinder in a continuous fibrous web by the doffer-stripper rollers surrounding the upper part of a master cylinder.

Web formation

The web formation by cross-lapping technique was used in this study. The conveyors transport the web from the carding machine to the cross-lapping process. The web leaving the carding machine was deposited on an inclined lattice and laid in the cross-wise manner on a horizontal lattice to produce multiple layers of fibrous web of desired weight. The web moves in a right angle direction with respect to the direction of carding.

Needlepunching

The Groz-Beckert felting needles with technical specifications of 15x18x32x3 R333 G3027 and Dilo needlepunching machine composed of 6000 needles per running meter was utilized to produce needlepunched nonwoven fabrics. The cross-lapped web was transported on a conveyor through the needle loom for pre-needling. The nominal mass per unit area of the web was 300 g/m^2, therefore, two layers of the web were combined together to achieve the nominal mass per unit area of 600 g/m^2. Three layers of the web were combined together to achieve the nominal mass per unit area of 900 g/m^2. The web composed of one, two and three layers were needlepunched at different stroke frequencies and depth of needle penetrations to achieve desired consolidation and density of the fabric.

3.2 Characterization of the nonwoven fabrics

The fabrics were conditioned for 24 hours in a standard testing atmosphere maintained at 21 ± 1 °C and 65 ± 2% relative humidity (RH) before any test was performed. Samples were cut randomly along fabric length and width directions. The test methods used to analyse fabrics are briefly discussed below:

3.2.1 Mass per unit area

The mass per unit area of each sample was determined according to the ASTM D3776 – 96 standards (American Society for Testing and Materials, ASTM D 3776 -96, ATM D 5034 -96, 1997 Annual Book of ASTM Standards, Vol. 7.01, ASTM, West Conshohocken, PA, U.S.A. (1997)). Five square samples of 20cm x 20cm were cut randomly from each fabric and weighed individually on a Mettler balance in grams. The average weight was recorded in g/m^2.

3.2.2 Thickness of the fabric

Thickness of each sample was analysed according to the WSP120.6 – 05 standards (EDANA WSP 120.6, Standard test methods for the nonwovens and related industries – thickness, European Disposables and Nonwoven Association (EDANA), Brussels, 2005). A constant pressure of 1 kPa was applied with the help of a round metal disc of 50 mm in diameter and weighing 170 grams. Five round samples of 50 mm in diameter were cut randomly from each fabric for testing and the average value of thickness was recorded in mm.

3.2.3 Tensile strength (Grab test)

The tensile strength of each sample was tested on an Instron 3369 universal tester according to the ASTM D5034 - 96 standards (American Society for Testing and Materials, ASTM D 3776 -96, ATM D 5034 -96, 1997 Annual Book of ASTM Standards, Vol. 7.01, ASTM, West Conshohocken, PA, U.S.A. (1997)). A gauge length of 75 mm, load cell of 5000 N and constant rate of extension of 300 mm/min were used during the test. Five random samples, 50 mm wide and 200 mm in length, were cut in both cross-machine and machine directions and tested. The average value for each sample was recorded in kN/m.

3.2.4 Puncture resistance

Puncture resistance of each sample was tested according to the EN ISO 12236 standards (EN ISO 12236, Geotextiles and geotextiles related products – Static puncture test. Brussels, 2006. 14 p). Rectangular samples, 230 mm x 250 mm, were cut for each test. Each tested sample was clamped between two steel rings. A plunger with a diameter of 50 mm and 2500g in weight was used to puncture the sample in the perpendicular direction at a constant rate of 50 ± 5 mm/min and force of 5 kN. Five random samples from each fabric were tested and an average value was recorded in N.

3.2.5 Pore size and pore size distribution

Fabric pore size was analysed on a capillary flow porometer (CFP-1100-AEXCC) according to the ASTM F316 - 11 standards (ASTM F 316 - 2011, Standard Test Methods for Pore Size Characteristics of Membrane Filters by Bubble Point and Mean Flow Pore Test, ASTM International, West Conshohocken, PA, 2011, www.astm.org). The capillary flow porometer (CFP-1100-AEXCC) is shown in Figure 3.1. The capillary flow porometer is a liquid extrusion technique which measures differential gas pressure and flow rate through wet and dry samples. Galwick liquid with a surface tension of 15.9 dynes/cm was used to wet the sample. After the sample was dipped in Galwick liquid and fully saturated, it was placed inside a sample holder with diameter ranges between 55 to 60 mm. The liquid inside pores was emptied using pressurized non-reacting gas. Bigger pores were emptied first as they require lower pressure in comparison to smaller pores which require higher pressure. Pores that were emptied first or at lower pressure were taken as largest pore diameters (bubble point). In addition, the variations in pressure and gas flow rate through dry and wet samples were measured and utilized to determine pore size distribution. The flow rate increases with an increase in gas pressure in a dry sample. However, in a wet sample no gas flow was apparent in the beginning as pores were completely filled with liquid. The increase in gas pressure emptied the pores filled with liquid until all pores were empty and the flow rate through both wet and dry samples were the same. Five random samples from each fabric were tested and the minimum, the largest and the mean flow pore diameters were calculated automatically by the capillary flow porometry instrument. The average value of pore size were calculated manually and recorded in µm (Jena and Gupta, 2002; 2003).

Figure 3.1 The capillary flow porometer (CFP-1100-AEXCC)

3.2.6 Water permeability

Water permeability of the fabric was analysed using GE-TE-FLOW-K permeameter according to the EN ISO11058-10 standards (ISO 11058:2010, Geotextiles and geotextile-related products - Determination of water permeability characteristics normal to the plane, without-load, accessed on 03 March 2016, http://www.iso.org/iso/catalogue_detail.htm?csnumber=54545). The GE-TE-FLOW-K permeameter measures water permeability based on the principle of falling hydraulic head with a hydraulic difference height of 0 < H < 540 mm. In the falling head method, water was transported to the fabric plane that results in a laminar flow through the fabric. Distilled water was used to analyse water permeability and the temperature of water during the test was kept at 20 ^{o}C. Sample with a diameter of 75 mm was placed in the sample holder, fastened and inserted in the testing instrument. The change in pressure and the flow rate of water against time were used to measure fabric permeability. Five random samples from each fabric were tested and the average value was recorded in m/s.

3.2.7 Transmissivity

The transmissivity of the fabric was analysed using hydraulic transmissivity device and CEN/ISO drain tester, according to the ASTM D4716 - 14 standards (ASTM D 4716, Standard Test Method for Determining the (In-plane) Flow Rate per Unit Width and Hydraulic Transmissivity of a Geosynthetic Using a Constant Head, ASTM International, West Conshohocken, PA, 2013, www.astm.org). The hydraulic transmissivity device and

CEN/ISO drain tester is shown in Figure 3.2. The rectangular tank was filled with test water closer to 305 mm height. The square samples in of 305 mm x 305 mm were cut and placed in the sample holder to measure the flow rate under normal stress of 5 000 kPa. Water from the rectangular tank flows through the tested sample and fill a smaller tank. A container was used to collect the water flowing from the smaller tank. The duration it takes for the water to reach the quantity of 4 litres was recorded using a stop watch. Three random samples from each fabric were analysed and the average value was recorded in L^2/s.

Figure 3.2 The hydraulic transmissivity device and CEN/ISO drain tester

In fluid dynamics, the volumetric flow rate, also known as the rate of fluid flow is defined as the volume or quantity of fluid per unit time. Mathematically, volumetric flow rate is expressed as follows:

$$Q = VA$$

Where, Q = flow rate (cm^3/s),

V = velocity (cm/s), and

A = area of the specimen (cm^2).

In addition, the effect of chemicals on the nonwoven fabric properties produced from 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres were analysed according to ASTM D543 - 14 standards (ASTM D 543 - 14, Standard practices for evaluating the resistance of plastics to chemical reagents, ASTM International, West Conshohocken, PA, 2006, www.astm.org). Chemicals such as, 10 % ammonium hydroxide (NH_4OH), 10% sodium chloride (NaCl) and 3% sulphuric acid (H_2SO_4) solutions were utilized to analyse their effects on the nonwoven fabrics. Three random samples from each fabric were placed inside three bottles containing chemicals for 7, 14 and 31 days, respectively. The samples were dried after the end of each test using an oven at a temperature of 100 ^oC. Fabric properties, such as tensile strength, mass per unit area and thickness were analysed to assess the detrimental effect of the chemicals. The scanning electron microscope (SEM) was used to scan both untested and tested samples so that they can be visually compared.

3.3 Main trial

The results obtained in preliminary trial were utilized to design the main trial. The results from preliminary trial showed that needlepunched nonwoven fabrics with better performance properties as required in geotextile application can be produced if proper process parameters are selected. Needlepunched nonwoven fabrics were produced from different fibres and their blends, namely, 100% PET, a blend of 50/50% PET/PP, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf in the preliminary trial. However, in the main trial only PP and kenaf fibres were utilized to produce needlepunched nonwoven fabrics. Similar feed rates and output speeds utilized in the production of nonwoven fabrics in the preliminary trial were used in the main trial according to full factorial design. This results in a total of 81 fabrics to be produced in this trial. The process parameters, namely, depth of needle penetration and stroke frequency and mass per unit area, in the main trial were different in comparison to those in the preliminary trial. The depths of needle penetration were 4, 7 and 10 mm, stroke frequencies were 250, 350 and 450 strokes/min and mass per unit area were 300, 600 and 900 g/m^2 in the main trial. The process parameters for producing all samples are shown in Tables 3.6. In addition, sample were marked or labelled as sample 1, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres. This was repeated in all the 27 fabrics analysed. The fabric properties, such as, tensile strength, puncture resistance, pore size, water permeability and transmissivity were analysed in a similar way as discussed in the preliminary trial.

The statistical analysis (ANOVA) was conducted to establish suitable process parameters to produce needlepunched nonwoven fabrics from 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres. ANOVA was used to analyse the hypothesis that the means of two or more populations are equal or different. It analyses the importance of one or more factors by comparing the variable means at different factor levels. The null hypothesis says that all factor means are equal, however, the alternative hypothesis says that at least one factor is different. ANOVA uses F-ratio to determine the statistical significance (variance of the factor) (Pagano and Gauvreau, 2000).

The three way ANOVA was conducted to determine the interaction effects of the independent variables on the dependent variables. It was assumed that the dependent variables were measured at continuous level, each of the three independent variables should consist of two or more categorical independent groups and there was no significant outlier. Advantages of using three way ANOVA were that it was able to analyse the simultaneous effect of three independent variables on a dependent variable and it minimises type one error (Landau and Everitt, 2004). Disadvantages of using three way ANOVA were that it was difficult to identify independent variables that are affecting dependent variables, possibility of losing degree of freedom when adding each new variable and the dependent variable must be uncorrelated (Tabachnick and Fidell, 1999; Cooley and Lohnes, 1971).

Table 3.4 Process parameters used to produce fabrics from 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres

Sample ID	Depth of needle penetration (mm)	Stroke frequency (strokes/min)	Fabric weight (g/m^2)		
1	4	250	300 (355)	300 (320)	300 (310)
2	7	250	300 (343)	300 (270)	300 (290)
3	10	250	300 (290)	300 (310)	300 (352)
4	4	350	300 (318)	300 (290)	300 (340)
5	7	350	300 (310)	300 (340)	300 (320)
6	10	350	300 (280)	300 (320)	300 (330)
7	4	450	300 (320)	300 (288)	300 (295)
8	7	450	300 (325)	300 (260)	300 (333)
9	10	450	300 (315)	300 (342)	300 (255)
10	4	250	600 (590)	600 (590)	600 (590)
11	7	250	600 (573)	600 (653)	600 (650)
12	10	250	600 (620)	600 (610)	600 (580)
13	4	350	600 (630)	600 (573)	600 (595)
14	7	350	600 (660)	600 (660)	600 (610)
15	10	350	600 (650)	600 (620)	600 (630)
16	4	450	600 (605)	600 (550)	600 (520)
17	7	450	600 (592)	600 (492)	600 (570)
18	10	450	600 (610)	600 (580)	600 (565)
19	4	250	900 (920)	900 (930)	900 (890)
20	7	250	900 (895)	900 (890)	900 (910)
21	10	250	900 (950)	900 (920)	900 (930)
22	4	350	900 (918)	900 (850)	900 (800)
23	7	350	900 (910)	900 (880)	900 (918)
24	10	350	900 (930)	900 (950)	900 (780)
25	4	450	900 (870)	900 (912)	900 (790)
26	7	450	900 (857)	900 (787)	900 (740)
27	10	450	900 (905)	900 (833)	900 (840)

Note**:** Value in the parenthesis shows the actual mass per unit area.

The three way ANOVA was utilized to determine the interaction effect of the stroke frequency, depth of needle penetration and mass per unit area on the properties of nonwoven fabrics, such as, tensile strength, puncture resistance, pore size, permeability and transmissivity, respectively. A full factorial design was used and the analyses at 5% significant level using SPSS 23 and Statistica 12 programs were computed. The full factorial design was used in order to analyse the effect of three independent variables, namely, depth of needle penetration, stroke frequency and mass per unit area on the properties of needlepunched nonwoven fabrics. The Tukey test was applied at 95% confidence level to compare group means.

Chapter 4

RESULTS AND DISCUSSION

This chapter is divided into two sections, namely preliminary and main trials.

4.1 Preliminary trial

The depth of needle penetration, stroke frequency and mass per unit area influence the properties of the needlepunched nonwoven fabrics which include tensile strength, puncture resistance, pore size, water permeability and transmissivity (Rawal et al., 2010; Rawal and Anandjiwala, 2007). Needlepunched nonwoven fabrics were produced from different fibres and their blends, namely, 100% PET, a blend of 50/50% PET/PP, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf. Both PET and PP fibres were utilized in this preliminary trial due to their unique properties, availability and most importantly ease of processability. Chemical inertness, better tensile strength, quick drying capacity, higher creep, higher tenacity, higher abrasion resistance and resistance to light are major advantages of synthetic fibres, such as PP and PET. However, the natural fibres, such as kenaf, also offer some advantages, such as comparable tensile strength, environmental friendliness and biodegradability. These advantages of PET, PP and kenaf fibres make them suitable for geotextile applications in filtration, water permeability, separation, reinforcement and drainage. The influence of depth of needle penetration, stroke frequency and mass per unit area on the properties of the needlepunched nonwoven fabrics produced are shown in Table 4.1.

Table 4.1 Influence of depth of needle penetration, stroke frequency and mass per unit area on the properties of needlepunched nonwoven fabrics produced from different fibres and their blends, namely, 100% PET, a blend of 50/50% PET/PP, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf.

Fibre types	Depth of needle penetration (mm)	Stroke frequency (strokes/min)	Nominal mass per unit area (g/m^2)	Tensile strength (MD) (KN/m)	Tensile strength (CD) (KN/m)	Ratio of MD/CD	Puncture resistance (N)	Pore size (μm)	Permeability (m/s)	Transmissivity (L^2/s)
100% PET	3	250	300 (260)	60.9	155.7	0.4	365.2	87.9	4.5	1.2
100% PET	5	250	600 (500)	216.9	315.3	0.7	462.4	71.6	2.2	0.9
100% PET	8	250	600 (530)	549.7	1035.2	0.5	675.2	53.2	1.9	0.5
100% PET	12	350	900 (1010)	668.5	1198.8	0.6	2107.4	62.3	3.1	1.3
50/50% PET/PP	8	350	900 (1000)	615.8	1164.1	0.5	1456.5	40.4	1.4	0.8
100% PP	3	250	300 (332)	37.9	111.4	0.3	53	81.2	4.6	0.5
100% PP	5	250	500 (480)	139.5	327.6	0.4	143	66.1	3.1	0.3
100% PP	8	350	1000 (925)	324.6	944.5	0.3	788	39.3	3.8	0.1
50/50% PP/kenaf blend	3	250	300 (295)	27.5	62.4	0.4	16	90.8	7.7	1.3
50/50% PP/kenaf blend	5	250	500 (540)	90.7	114.1	0.5	119	77.5	6.8	0.7
50/50% PP/kenaf blend	8	350	1000 (990)	183.3	344.7	0.5	420	82.2	7.2	0.4
100% kenaf	3	250	300 (315)	15.4	29.6	0.5	13	112.7	11.3	0.9
100% kenaf	5	250	500 (462)	56.3	105.2	0.7	53	88.1	7.8	0.5
100% kenaf	8	350	1000 (1020)	138.8	259.3	0.5	290	71.4	12.1	1.1

Note: Value in the parenthesis shows the actual mass per unit area.

The depths of needle penetration of 3, 5, 8 and 12 mm, stroke frequencies of 250 and 350 strokes/min and mass per unit area of 300, 500, 600, 900 and 1000 g/m^2 were utilized for producing needlepunched nonwoven fabrics in the preliminary trial. The results showed that the tensile strength and puncture resistance of the fabrics, in general, increased with increases in depth of needle penetration, stroke frequency and mass per unit area. The tensile strengths in cross-machine direction (CD) for all the fabrics were generally higher in comparison to those in machine direction (MD). The ratio of tensile strengths in MD to CD was less than 1, which implied anisotropy in the nonwoven fabrics. The pore sizes and values of water permeability of the nonwoven fabrics produced from 100% PET, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres decreased with increases in depth of needle penetration, stroke frequency and mass per unit area.

4.1.1 Tensile strength

As shown in Table 4.1, lowest tensile strengths were achieved for the fabrics produced from 100% PET, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres at the lowest values of depth of needle penetration, stroke frequency and mass per unit area in comparison to those produced at the highest values of depth of needle penetration, stroke frequency and mass per unit area. This was attributed to poor interlocking and entanglement of the fibres which provided less compact fabrics. The tensile strength of the nonwoven fabrics was also influenced by barbs of the needles which carried a fewer number of fibres at lower depth of needle penetration. In addition, the lower tensile strength was attributed to a fewer number of fibres in the fabric of lower mass per unit area. The higher tensile strengths of all the nonwoven fabrics produced were attributed to increases in depth of needle penetration, stroke frequency and mass per unit area. Higher fabric tensile strengths were achieved in the fabrics produced at higher values of depth of needle penetration, stroke frequency and mass per unit area. However, a possibility of needle breakages when producing the fabric at higher values of depth of needle penetration, stroke frequency and mass per unit area was higher in comparison to that produced at lower values of depth of needle penetration, stroke frequency and mass per unit area. The tensile strengths of the nonwoven fabrics produced from a blend of 50/50% PET/PP fibres and a blend of 50/50% PP/kenaf fibres were influenced by differences in the properties of PET, PP and kenaf fibres, such as fineness, length, diameter, cross-section and crimp of the fibres. The tensile strengths in CD for all the fabrics were higher in comparison to those in the machine direction (MD). This was attributed to pre-dominance of fibre orientation in the cross-machine direction due to cross-lapping process.

4.1.2 Puncture resistance

As shown in Table 4.1, the values of puncture resistance for all the fabrics produced increased with the increases in depth of needle penetration, stroke frequency and mass per unit area. This was attributed to higher values of depth of needle penetration and stroke frequency which provided a more compact fabric due to increased interlocking and entanglement of the fibres. In addition, the increase in puncture resistance was also influenced by a higher number of fibres at higher mass per unit area of the fabric which improved uniformity and compactness of the web. The barbs of the needles were able to carry more fibres, therefore, resulted in better interlocking and entanglement of the fibres. However, the lowest values of the puncture resistance were obtained in needlepunched nonwoven fabrics produced from 100% PET, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres at lower values of depth of needle penetration, stroke frequency and mass per unit area. This was attributed to poor interlocking and entanglement of the fibres, therefore, a less compact fabric. Lower interlocking and entanglement of the fibres influence compactness of the web and fabric areal density, therefore, influence the puncture resistance (Rawal et al., 2008). In addition, the lower value of the puncture resistance was also influenced by a fewer number of fibres at lower mass per unit area of the fabric and poor interlocking and entanglement of the fibres. The values of the puncture resistance of the needlepunched nonwoven fabrics produced from blends of 50/50% PET/PP and 50/50% PP/kenaf fibres were influenced by variations in the properties of PET, PP and kenaf fibres as mentioned in Section 4.1.1 above. Koerner and Koerner (2011) have also reported that the puncture resistance of the needlepunched nonwoven fabrics produced from 100% PP fibres was higher in comparison to that produced from 100% PET fibres due to lower specific gravity of PP fibres.

4.1.3 Pore size

As shown in Table 4.1, the pore sizes of the needlepunched nonwoven fabrics produced from 100% PET, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres decreased with the increases in depth of needle penetration, stroke frequency and mass per unit area. This was attributed to increases in depth of needle penetration and stroke frequency which improved interlocking and entanglement of the fibres, therefore, a more consolidated fabric. In addition, the decrease in mean pore size was also attributed to the increase in number of fibres in the fabric at higher mass per unit area with improved web uniformity and interlocking of the fibres.

Bigger pores were obtained in the fabrics produced from 100% PET, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres at lower values of depth of needle penetration, stroke frequency and mass per unit area. The bigger pores were attributed to lower interlocking and entanglement of the fibres which resulted in less compact fabric. In addition, bigger pores were due to fewer number of fibres in the nonwoven fabrics of lower mass per unit area. The pore size of the nonwoven fabric produced from 100% kenaf fibres was bigger in comparison to that produced from a blend of 50/50% PP/kenaf, 100% PP and 100% PET fibres. Bigger pores were attributed to higher bending rigidity of the kenaf fibres which influenced their interlocking and entanglement.

4.1.4 Water permeability

As shown in Table 4.1, higher values of water permeability were obtained in needlepunched nonwoven fabrics produced from 100% PET, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres at lower values of depth of needle penetration, stroke frequency and mass per unit area. This higher water permeability was attributed to a fewer number of fibres in the fabric produced with lower mass per unit area, therefore, results in less compact fabric with bigger pores. The water permeability of the needlepunched nonwoven fabrics produced from 100% PET, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres decreased with the increases in depth of needle penetration, stroke frequency and mass per unit area. The decrease in water permeability was attributed to higher values of depth of needle penetration and stroke frequency which increased interlocking and entanglement of the fibres, therefore, resulted in more compact fabrics with smaller pores and lower water permeability.

The values of water permeability of the needlepunched nonwoven fabrics produced from 100% PET and 100% PP fibres were also influenced by fibre-to-fibre friction and bending resistance of both the fibres which might influence web uniformity and fibre interlocking. However, water permeability values of the needlepunched nonwoven fabrics produced from blends of 50/50% PET/PP and 50/50% PP/kenaf fibres were affected by variations in the properties of PP and kenaf fibres which might have influenced fibre orientation and fibre orientation distribution in the fabrics. This may result in fabric with non-uniform mass per unit area and thickness which influence the water permeability. The water permeability of the nonwoven fabrics produced from 100% kenaf fibres was attributed to variations in fibre volume fraction and areal density resulting from variations in fineness and length of kenaf fibres. The water permeability of the needlepunched nonwoven fabrics produced from 100% kenaf fibres was higher in comparison to that produced from a blend of 50/50% PP/kenaf, 100% PP and 100% PET fibres. The higher value of water permeability was attributed to the hydrophilic properties of kenaf fibres as well as bigger pores resulted from inadequate interlocking of the kenaf fibres due to higher bending rigidity.

4.1.5 Transmissivity

As shown in Table 4.1, the values of transmissivity of the needlepunched nonwoven fabrics produced from 100% PET, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres decreased with the increases in depth of needle penetration and stroke frequency. This decrease was attributed to higher values of depth of needle penetration and stroke frequency which reorient majority of the fibres from horizontal to vertical (thickness) direction (Rawal and Anandjiwala, 2006). In addition, the decrease was attributed to preferential flow of water due to structural heterogeneities as well as fabric anisotropies. Higher values of transmissivity were achieved in the fabric produced at lower values of depth of needle penetration, stroke frequency and mass per unit area in comparison to that produced at higher values of depth of needle penetration, stroke frequency and mass per unit area. This was attributed to fewer number of fibres at lower mass per unit area.

The transmissivity of the needlepunched nonwoven fabrics produced from 100% PP fibres was influenced by the lower values of fibre-to-fibre friction co-efficient and bending rigidity of PP fibres which influence areal density and thickness of the nonwoven fabrics. The transmissivity of the needlepunched nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres was influenced by variations in fineness of PP and kenaf fibres. Hwang et al. (1999) have reported that transmissivity of nonwoven fabrics increased with the increase in fibre fineness.

Justification for conducting preliminary trial

The depth of needle penetration, stroke frequency and mass per unit area were varied in this preliminary trial to obtain maximum and minimum values of the fabric properties, namely, tensile strength, puncture resistance, pore size, water permeability and transmissivity. The results from the preliminary trials have shown that needlepunched nonwoven fabrics with lower tensile strength and lower puncture resistance were produced at lower values of depth of needle penetration, stroke frequency and mass per unit area. However, higher values of pore size, water permeability and transmissivity were achieved in the fabrics produced at lower values of depth of needle penetration, stroke frequency and mass per unit area. Better values of tensile strength and puncture resistance were obtained in the fabrics produced at higher values of depth of needle penetration, stroke frequency and mass per unit area while the pore size, water permeability and transmissivity decreased with the increases in depth of the needle penetration, stroke frequency and mass per unit area.

These preliminary trials have shown that needlepunched nonwoven fabrics with better performance properties, as required in geotextile application, can be produced if proper process parameters are selected. In addition, the results from these preliminary trials have shown that needlepunched nonwoven fabrics for geotextile application can be produced from 100 % kenaf fibres by suitably adjusting process parameters. This exploratory trial helped in designing needlepunched nonwoven fabrics for the main trial reported in the following section.

4.2 Main trial

The results obtained from the preliminary trial showed that the needlepunched nonwoven fabrics for geotextile applications with better performance properties can be produced if proper process parameters are selected. In addition, the results obtained from the preliminary trial showed that the fabrics produced from 100% kenaf fibres achieved better tensile strength and puncture resistance at higher values of depth of needle penetration, stroke frequency and mass per unit area. The needlepunched nonwoven fabrics were produced from different fibres and their blends, namely, 100% PET, a blend of 50/50% PET/PP, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres in the preliminary trial. However, in the main trial only PP and kenaf fibres were utilized to produce needlepunched nonwoven fabrics. The process parameters, namely, depth of needle penetration and stroke frequency and mass per unit area, in the main trial were different in comparison to those in the preliminary trial. The depths of needle penetration were 4, 7 and 10 mm, stroke frequencies were 250, 350 and 450 strokes/min and mass per unit area were 300, 600 and 900 g/m^2 in this main trial. The depth of needle penetration, stroke frequency and mass per unit area were suitably adjusted to produce geotextiles with maximum and minimum values of different properties suitable for filtration, separation, water permeability and transmissivity applications. The influence of the selected parameters on the properties of the needlepunched nonwoven fabrics are analysed and discussed in this section. The comparison between different properties of the fabrics produced from different fibres and their blends, namely, 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf at different values of depth of needle penetration, stroke frequencies and area weight are shown in Tables 4.2(a) to 4.2(c).

Table 4.2 (a) Area weight, fabric thickness and density of needlepunched nonwoven fabrics produced from different fibres and their blends, namely 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf at different depths of needle penetration and stroke frequencies.

Sample ID	Depth of needle penetration (mm)	Stroke frequency (strokes/min)	Actual fabric weight (g/m^2)			Fabric thickness (mm)			Fabric density (kg/m^3)		
			100% PP	50/50% PP/kenaf	100% kenaf	100% PP	50/50% PP/kenaf	100% kenaf	100% PP	50/50% PP/kenaf	100% kenaf
1	4	250	300 (355)	300 (320)	300 (310)	5.9	6.7	9.1	1504.2	1194.0	851.6
2	7	250	300 (343)	300 (270)	300 (290)	5.1	4.4	9.8	1681.3	1534.1	739.7
3	10	250	300 (290)	300 (310)	300 (352)	4.4	5.6	6.7	1647.7	1383.9	1313.4
4	4	350	300 (318)	300 (290)	300 (340)	3.9	6.5	4.8	2038.4	1115.3	1770.8
5	7	350	300 (310)	300 (340)	300 (320)	3.2	5.2	5.6	2421.9	1634.6	1428.5
6	10	350	300(280)	300 (320)	300 (330)	3.5	4.9	6.0	2000.0	1632.6	1375.0
7	4	450	300 (320)	300 (288)	300 (295)	4.2	6.1	4.9	1904.7	1180.3	1505.1
8	7	450	300 (325)	300 (260)	300 (333)	3.5	4.4	3.7	2321.4	1477.2	2250
9	10	450	300 (315)	300 (342)	300 (255)	3.9	5.3	4.4	2019.2	1613.2	1448.8
10	4	250	600 (590)	600 (590)	600 (590)	6.8	8.0	9.1	2169.1	1843.7	1620.8
11	7	250	600 (573)	600 (653)	600 (650)	7.1	9.3	8.0	2017.6	1755.3	2031.2
12	10	250	600 (620)	600 (610)	600 (580)	7.8	7.9	6.2	1987.2	1930.3	2338.7
13	4	350	600 (630)	600(573)	600 (595)	8.4	8.5	7.4	1875.0	1685.2	2010.1
14	7	350	600 (660)	600 (660)	600 (610)	7.2	5.9	6.7	2291.6	2796.6	2276.1
15	10	350	600 (650)	600 (620)	600 (630)	9.6	6.9	8.1	1692.7	2246.3	1944.4
16	4	450	600 (605)	600 (550)	600 (520)	8.4	7.2	5.3	1800.6	1909.7	2452.8
17	7	450	600 (592)	600 (492)	600 (570)	6.9	5.5	4.8	2144.9	2236.3	2968.7
18	10	450	600 (610)	600 (580)	600 (565)	7.6	6.4	6.6	2006.5	2265.6	2140.2
19	4	250	900 (920)	900 (930)	900 (890)	11.7	8.5	9.6	1965.8	2735.2	2317.7
20	7	250	900 (895)	900 (890)	900 (910)	10.8	10.6	11.1	2071.7	2099.1	2049.5
21	10	250	900 (950)	900 (920)	900 (930)	12.5	8.1	12.7	1900.0	2839.5	1830.7
22	4	350	900 (918)	900 (850)	900 (800)	11.2	9.6	10.2	2049.1	2213.5	1960.7
23	7	350	900 (910)	900 (880)	900 (918)	10.1	10.3	10.4	2252.4	2135.9	2206.7
24	10	350	900 (930)	900 (950)	900 (780)	11.3	13.1	7.3	2057.5	1812.9	2671.2
25	4	450	900 (870)	900 (912)	900 (790)	12.1	11.8	9.1	1797.5	1932.2	2170.3
26	7	450	900 (857)	900 (787)	900 (740)	10.5	9.1	7.8	2040.4	2162.1	2371.7
27	10	450	900 (905)	900 (833)	900 (840)	11.3	10.7	8.2	2002.2	1946.2	2560.9

Note: Value in the parenthesis shows the actual mass per unit area

Table 4.2 (b) Tensile strength and puncture resistance of needlepunched nonwoven fa
brics produced from different fibres and their blends, namely 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf at different depths of needle penetrations and stroke frequencies.

Sample ID	Tensile strength (MD) (kN/m)			Tensile strength (CD) (kN/m)			Ratio of MD/CD			Puncture resistance		
	100% PP	50/50% PP/kenaf	100% kenaf	100% PP	50/50% PP/kenaf	100% kenaf	100% PP	50/50% PP/kenaf	100% kenaf	100% PP	50/50% PP/kenaf	100% kenaf
1	39.1	32.0	27.3	106.1	62.0	35.0	0.4	0.5	0.8	66.0	20.4	11.4
2	105.8	71.9	70.6	128.6	85.1	55.9	0.8	0.8	1.3	137.1	37.5	21.1
3	146.7	99.1	79.1	308.3	116.3	88.8	0.5	0.9	0.9	158.8	49.5	39.3
4	51.9	43.2	39.2	58.0	49.0	43.3	0.9	0.9	0.9	111.7	22.6	13.2
5	228.0	69.4	68.3	226.2	129.7	76.6	1.0	0.5	0.9	195.2	40.1	59.3
6	188.7	114.9	51.5	483.5	242.3	147.9	0.4	0.5	0.3	294.9	70.1	94.3
7	66.4	51.9	71.6	93.9	76.5	29.9	0.7	0.7	2.4	135.6	61.1	14.9
8	270.9	95.9	44.1	398.7	187.7	131.4	0.7	0.5	0.3	369.6	158.9	53.3
9	254.5	63.6	90.1	384.7	157.3	98.0	0.7	0.4	0.9	416.2	144.9	84.2
10	180.1	59.1	54.0	171.2	106.4	87.1	1.1	0.6	0.6	299.0	33.3	15.0
11	200.6	119.9	90.7	437.9	231.5	130.2	0.5	0.5	0.7	650.1	58.7	21.1
12	311.0	129.0	100.3	600.0	318.3	146.6	0.5	0.4	0.7	540.0	94.0	47.2
13	134.4	66.1	70.7	377.2	136.5	134.4	0.4	0.5	0.5	436.6	139.2	24.9
14	460.2	105.8	84.8	632.6	268.7	150.2	0.7	0.4	0.6	501.1	179.6	44.4
15	626.6	144.6	120.7	811.3	326.6	166.7	0.8	0.4	0.7	620.9	201.9	86.6
16	123.1	66.5	81.7	392.4	136.4	125.3	0.3	0.5	0.7	442.9	154.7	33.2
17	500.9	126.7	111.1	701.4	340.6	148.6	0.7	0.4	0.7	573.7	311.7	143.9
18	551.6	195.3	111.1	805.4	252.9	141.5	0.7	0.8	0.8	700.6	293.7	128.8
19	564.4	139.1	70.6	636.7	316.5	133.6	0.9	0.4	0.5	431.5	154.6	132.4
20	795.9	170.7	121.9	926.8	295.8	154.3	0.9	0.6	0.8	452.2	287.6	175.2
21	682.8	190.6	110.4	873.8	337.8	141.1	0.8	0.6	0.8	553.4	142.1	162.5
22	225.6	107.3	64.8	560.5	250.4	119.7	0.4	0.4	0.5	553.1	316.2	40.6
23	310.5	214.1	147.9	912.5	519.7	210.4	0.3	0.4	0.7	778.4	327.4	266.2
24	471.3	185.2	133.9	1205.8	505.3	195.2	0.4	0.4	0.7	754.8	405.6	333.9
25	283.5	120.1	115.4	605.3	230.9	148.1	0.5	0.5	0.8`	466.5	294.8	122.3
26	253.6	158.0	97.7	892.0	308.5	135.9	0.3	0.5	0.7	597.4	424.7	245.8
27	322.9	206.1	74.3	1131.7	476.6	163.7	0.3	0.4	0.5	793.3	367.5	335.3

Table 4.2 (c) Pore size, water permeability and transmissivity of needlepunched nonwoven fabrics produced from different fibres and their blends, namely 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf at different depths of needle penetration and stroke frequencies.

Sample ID	Pore size (µm)			Permeability (m/s)			Transmissivity (L^2/s)		
	100% PP	50/50% PP/kenaf	100% kenaf	100% PP	50/50% PP/kenaf	100% Kenaf	100% PP	50/50% PP/kenaf	100% kenaf
1	73.0	96.8	110	3.7	10.5	9.8	0.4	0.8	0.4
2	62.8	88.7	101.7	3.6	6.5	8.7	0.3	1.0	0.5
3	49.5	70.1	118.4	3.4	5.3	7.7	0.3	1.6	0.6
4	82.0	80.5	103.2	3.5	9.3	9.4	0.3	1.2	0.9
5	72.9	73.2	92.0	3.3	7.5	8.1	0.8	1.5	1.1
6	89.6	69.1	109.1	2.2	5.1	7.5	1.2	1.1	1.1
7	63.6	98.0	98.2	2.3	8.0	9.1	0.4	0.8	1.3
8	48.7	62.3	104.6	2.2	6.9	7.8	0.3	0.6	1.2
9	76.9	91.0	142.4	1.8	8.4	6.2	0.4	0.7	1.4
10	41.1	74.0	90.3	2.9	7.6	16.2	0.5	1.1	0.6
11	39.7	69.7	75.9	1.6	6.2	12.4	0.6	1.8	0.7
12	29.6	78.0	62.4	1.2	4.9	9.1	0.7	2.3	0.9
13	31.7	60.5	79.2	3.1	6.9	14.8	0.4	1.8	0.5
14	29.2	68.0	65.1	3.3	5.3	11.0	0.5	1.3	0.6
15	28.3	80.4	75.5	3.6	4.4	10.4	0.6	1.1	0.7
16	64.4	91.6	74.2	3.4	8.8	8.8	1.0	1.8	0.4
17	45.7	70.6	79.2	2.5	4.3	7.1	0.8	1.6	0.5
18	61.7	55.8	102.0	1.7	7.1	8.5	0.6	1.9	0.6
19	50.6	48.6	70.9	5.9	7.1	8.7	0.6	2.1	1.5
20	28.1	32.9	62.5	4.9	5.1	7.1	0.5	1.7	1.1
21	42.1	34.6	81	3.4	6.8	7.7	0.3	2.4	1.3
22	29.1	29.2	43.2	4.1	5.7	12.2	0.9	2.3	2.1
23	38.9	25.1	55.5	1.6	4.2	8.3	0.6	1.8	0.6
24	27.7	29.6	40.8	3.7	4.2	5.9	0.8	2.3	0.8
25	32.1	50.2	76.9	4.1	4.0	8.6	0.8	0.3	1.6
26	36.4	40.6	56.8	3.8	5.1	7.1	0.7	0.6	1.2
27	23.6	64.7	85.5	2.2	3.8	9.5	0.3	0.3	1.3

The influence of stroke frequency, depth of needle penetration and mass per unit area on the properties of needlepunched nonwoven fabrics are shown graphically as follows, tensile strength in CD: Figures 4.1(a) to 4.1(c); tensile strength in MD: Figures 4.2(a) to 4.2(c); puncture resistance: Figures 4.3(a) to 4.3(c); pore size: Figures 4.4(a) to 4.4(c); water permeability: Figures 4.5(a) to 4.5(c); transmissivity: 4.6(a) to 4.6(c).

4.2.1 Comparison of physical properties

Table 4.2(a) shows the effect of process parameters (depth of needle penetration and stroke frequency) on physical properties (actual weight, thickness and density) of the needlepunched nonwoven fabrics produced from 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres. The actual fabric weight was marginally different with respect to nominal fabric weight due to variations in fibre properties and limitations of the production technique. As expected, the thickness of the nonwoven fabrics increases with the increase in mass per unit area. The variations in the thickness of the fabrics produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres were higher in comparison to that produced from 100% PP fibres, which was attributed to differences in the length and fineness of PP and kenaf fibres as well as breakages of kenaf fibres during the needle punching process. In general, the fabric density of all the needlepunched nonwoven fabrics produced increased with an increase in mass per unit area. In addition, the fabric density of the needlepunched nonwoven fabrics was not following a typical trend with respect to depth of needle penetration, probably due to breakage and reorientation of the fibres during needlepunching process.

4.2.2 Tensile strength in CD

4.2.2.1 Comparison of CD tensile strengths within samples (100% PP fibres)

The tensile strengths of the fabrics were estimated in both machine (MD) and cross-machine (CD) directions. In general, the tensile strength in CD was higher in comparison to that in MD for all the fabrics as shown in Table 4.2(b). This was attributed to the fact that majority of the fibres were oriented in the cross-machine direction as a result of cross-lapping process. The ratios of tensile strengths in MD to CD for all the fabrics, excepting two, were less than 1 as shown in Table 4.2(b), which implied anisotropy in the nonwoven fabrics. However, the values of this ratio for the fabrics produced from 100% PP fibres and one produced from 100% kenaf fibres were close to 1 (sample 2, 10), which implied that the tensile strength in the MD was almost same in comparison to that in the CD. The mechanism of tensile failure of the needlepunched nonwoven fabrics were influenced by fibre-to-fibre friction, tensile strength, bending rigidity and orientation of the fibres and degree of fibre entanglement. The force applied on the fabric has to overcome the frictional forces resulted from degree of entanglement and fibre-to-fibre friction. The entangled fibres become straight and slip from each other when the force applied overcomes the fibre-to-fibre frictional force. With the further increase in tensile force the fibres deform as they have already slipped and the fabric ruptures under the mixed modes of fibre failure and slipping (Anandjiwala and Boguslavsky, 2008).

Figure 4.1(a) shows the influence of stroke frequency and mass per unit area on CD tensile strength of the nonwoven fabrics produced from 100% PP fibres at depths of needle penetration of 4, 7 and 10 mm. At an area weight of 300 g/m^2 and 4 mm depth of needle penetration, the CD tensile strength of the nonwoven fabrics decreased with an increase in stroke frequency up to 350/min, after which it increased with further increase in stroke frequency to 450/min. The decrease in the tensile strength was attributed to lower interlocking and entanglement of the fibres at lower mass per unit area. In addition, the decrease in the tensile strength was attributed to the barbs of the needles carrying fewer number of fibres at lower depth of needle penetration which resulted in poor interlocking of the fibres, therefore, a fabric with higher thickness but lower fabric density. The increase in the tensile strength was attributed to an increase in fabric compactness resulted from better interlocking and entanglement of the fibres at higher stroke frequency (Rawal et al., 2010; Midha and Mukhopadyay, 2005). At an area weight of 300 g/m^2 and 7 mm depth of needle penetration, the CD tensile strength of the nonwoven fabrics increases with an increase in punch density which increases fibre entanglement. In addition, the increase was attributed to the barbs of the needles carrying higher number of fibres with an increase in depth of needle penetration which resulted in adequate interlocking and entanglement of the fibres. The friction contact between the fibres increases with an increase in depth of needle penetration due to higher number of needles acting on the fibres. This results in more compact web while reducing fabric thickness and increasing fabric density (Anandjiwala and Boguslavsky, 2008; Patanaik and Anandjiwala, 2008; Gaunguly, 1999).

At an area weight of 300 g/m^2 and 10 mm depth of needle penetration, the CD tensile strength of the nonwoven fabrics increased with an increase in stroke frequency up to 350/min, however, it decreased with further increase in stroke frequency to 450/min. This decrease in tensile strength above 350/min stroke frequency was attributed to reorientation of the fibres from cross-machine direction to machine direction due to higher depth of needle penetration (Rawal et al., 2010). Amiot et al. (2014) have reported that the tensile strength of the fabrics depend on fibre orientation.

At an area weight of 600 g/m^2 and 4 mm depth of needle penetration, the CD tensile strength of the nonwoven fabrics increased with an increase in stroke frequency up to 350/min, however, it remained the same with further increase in stroke frequency to 450/min as shown in Figure 4.1(a). This lack of change in the tensile strength was attributed to the barbs of the needles carrying fewer number of fibres at lower depth of needle penetration and higher mass per unit area, therefore, resulted in poor interlocking and entanglement of the fibres. Roy and Ray (2009) have reported that lower depth of needle penetration provided an open fabric structure due to insufficient needling. At an area weight of 600 g/m^2 and 7 mm depth of needle penetration, the CD tensile strength of the fabrics increased with an increase in stroke frequency as shown in Figure 4.1(a). This increase was attributed to an increase in the number of finer fibres in the fibrous web which improved web uniformity and fibre interlocking, therefore, increase in fabric density. However, an increase in the fabric density decreases breaking elongation of the fabric (Roy and Ray, 2009). At an area weight of 600 g/m^2 and 10 mm depth of needle penetration, the CD tensile strength of the fabrics increased with an increase in stroke frequency up to 350/min and remained constant with further increase in stroke frequency to 450/min as shown in Figure 4.1(a). This lack of change in the tensile strength was attributed to the crimp of PP fibres and inadequate bonding of some fibres which did not share the load even under maximum stress. In addition, the lack of change in the tensile strength was attributed to variations in fibre curl factor value which resulted in stress differentials and thus affecting breaking strength (Rawal et al., 2010; Adanur and Liao, 1999).

At an area weight of 900 g/m^2 and 4 mm depth of needle penetration, as shown in Figure 4.1(a), a similar trend as observed in the case of area weight of 300 g/m^2 was noticed. At an area weight of 900 g/m^2 and 7 mm depth of needle penetration, the CD tensile strength of the fabric remained the same with an increase in stroke frequency up to 350/min, however, it decreased with further increase in stroke frequency to 450/min as shown in Figure 4.1(a). This lack of change in the tensile strength at higher mass per unit area was attributed to bending resistance and lower fibre-to-fibre friction co-efficient of the PP fibres which may influence interlocking and entanglement of the fibres in the fabric structure (Debnath and Madhusoothanan, 2009).

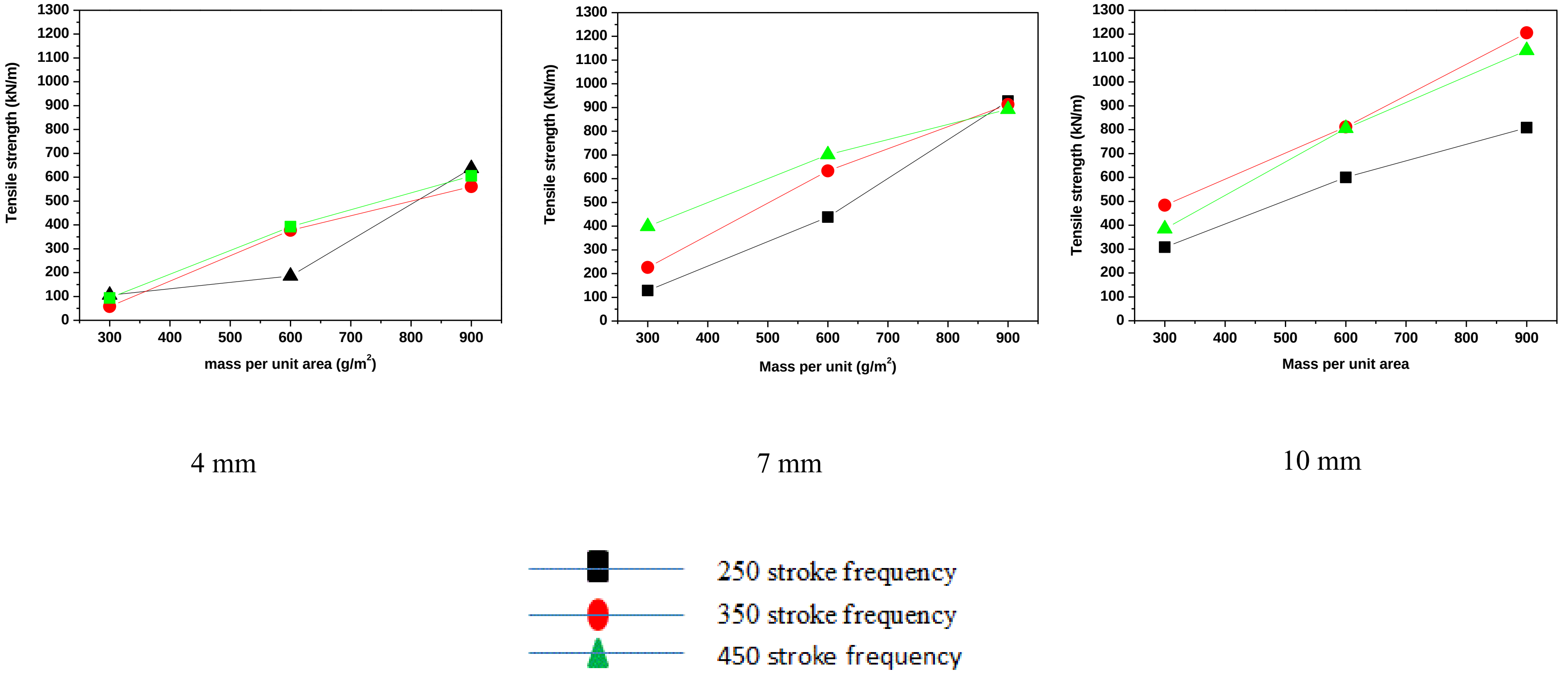

Figure 4.1(a) Effect of stroke frequency and mass per unit area on CD tensile strength of the nonwoven fabrics produced from 100% PP fibres at 4, 7 and 10 mm depths of needle penetration.

The decrease in the tensile strength of the fabrics was attributed to fibre breakages and realignment of the fibres from the MD to CD under the applied force. The applied force has to overcome fibre bonds resulted from interlocking and friction between the fibres (Wang, 2001; Anandjiwala and Boguslavsky, 2008). At an area weight of 900 g/m^2 and 10 mm depth of needle penetration as shown in Figure 4.1(a), a similar trend as observed in the case of area weight of 300 g/m^2 and 10 mm depth of needle penetration was noticed.

4.2.2.2 Comparison of CD tensile strengths between samples (100% PP fibres)

The CD tensile strengths of the nonwoven fabrics between the samples produced at area weights of 300, 600 and 900 g/m^2 but at fixed stroke frequency of 250/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.1(a). The tensile strength increased with an increase in mass per unit area, which was attributed to an increase in the number of layers during fabric formation (Anandjiwala and Boguslavsky, 2008).

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 350 and 450/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.1(a). A similar trend as described in the previous paragraph was noticed.

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250, 350 and 450/min and depths of needle penetration of 7 and 10 mm were compared as shown in Figure 4.1(a). A similar trend as observed in the case 350/min stroke frequency and 4 mm depth of needle penetration was noticed in this case also.

Statistical analysis

The three way ANOVA was performed to determine the interaction effects of the stroke frequency, depth of needle penetration and mass per unit area on CD tensile strength of the nonwoven fabrics. The confidence level of 95 % ($p \leq 0.05$) was chosen to test the significance, if the P-value is less than 0.05, the effect is significant and vice versa. All the parameters and their two-way and three- way interactions showed significant effects on CD tensile strength of the nonwoven fabrics as shown in Table 4.3 below.

Table 4.3: ANOVA on CD tensile strength data of the nonwoven fabrics produced from 100% PP fibres

Nonwoven fabric produced from 100% PP fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	40629985.3	1	40629985.3	70479.3	0.0
Mass per unit area	8378400.1	2	4189200.1	7266.8	0.0
Stroke frequency	536854.5	2	268427.2	465.6	0.0
Needle depth of penetration	3534117.5	2	1767058.8	3065.2	0.0
Mass per unit area x stroke frequency	105632.8	4	26408.2	45.8	0.0
Mass per unit area x Needle depth of penetration	113045.3	4	28261.3	49.0	0.0
Stroke frequency x Needle depth of penetration	256065.0	4	64016.3	111.0	0.0
Mass per unit area x stroke frequency x needle depth of penetration	300338.1	8	37542.3	65.1	0.0
Error	62259.9	108	576.5		

4.2.2.3 Comparison of CD tensile strengths within samples (a blend of 50/50% PP/kenaf fibres)

Figure 4.1(b) shows the influence of stroke frequency and mass per unit area on CD tensile strength of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres at depths of needle penetration of 4, 7 and 10 mm. At an area weight of 300 g/m^2 and 4 mm depth of needle penetration, the CD tensile strength of the nonwoven fabrics decreased with an increase in stroke frequency up to 350/min, however, it increased with further increase in stroke frequency to 450/min. This decrease in the tensile strength was attributed to higher crimp in PP and less crimp in kenaf fibres which resulted in variations in amount of stress (Rawal, 2006c). The increase in the tensile strength of the fabrics was attributed to an increase in punch density which increased interlocking and entanglement of the fibres, therefore, provided a compact fabric. At an area weight of 300 g/m^2 and 7 mm depth of needle penetration, the CD tensile strength of the nonwoven fabrics increased with an increase in stroke frequency. At an area weight of 300 g/m^2 and 10 mm depth of needle penetration, the CD tensile strength of the fabrics increased with an increase in stroke frequency up to 350/min, however, it decreased with further increase in stroke frequency to

450/min. This decrease in the tensile strength was attributed to higher values of punch density and depth of needle penetration which might result in fibre breakages and breakdown of the loop structure in the fabric (Roy and Ray, 2009). The breakages of the fibres may also alter fibre volume fraction and packing density of the fabrics, therefore, fabric tensile strength is also affected.

At an area weight of 600 g/m^2 and 4 mm depth of needle penetration, the CD tensile strength of the nonwoven fabrics increased with an increase in stroke frequency up to 350/min, however, it remained the same with further increase in stroke frequency to 450/min as shown in Figure 4.1(b). The increase in the tensile strength of the fabrics was attributed to the presence of a higher number of fibres per unit area of the fabric, therefore, increased interaction and frictional forces between the fibres which prevented slippage of the fibres from each other. The stress shared by individual fibres before rupture was lower due to higher number of fibres per unit area of the fabric (Çinçik and Koç, 2013). The lack of change in the tensile strength of the fabric was attributed to lower number of kenaf fibres transported by barbs of the needles in the thickness direction in comparison to PP fibres (Rawal and Sayeed, 2013). At an area weight of 600 g/m^2 and 7 mm depth of needle penetration, the CD tensile strength of the nonwoven fabrics increased with an increase in stroke frequency. The increase in the tensile strength of the fabrics was attributed to increases in punch density and depth of needle penetration which increased entanglement of the fibres, therefore, higher fabric tensile strength. At an area weight of 600 g/m^2 and 10 mm depth of needle penetration, a similar trend, as observed in the case of area weight of 300 g/m^2 and 10 mm depth of needle penetration, was noticed.

At an area weight of 900 g/m^2 and depths of needle penetration of 4, 7 and 10 mm, the CD tensile strength of the nonwoven fabrics increased with an increase in stroke frequency up to 350/min, however, it decreased with further increase in stroke frequency to 450/min as shown in Figure 4.1(b). This decrease in the tensile strength might be attributed to some fibres which were not carried by the barbs of the needles in heavier fabrics, therefore, resulted in poor interlocking and entanglement of the fibres in the fabric. In addition, the decrease in the tensile strength at the stroke frequency above optimal level may be due to excessive breakages and reorientation of the fibres. Reorientation of fibres occurs in fabric structure that is sufficiently bonded and the number of bonds in the fabric structure control stress distribution (Rawal et al., 2011c).

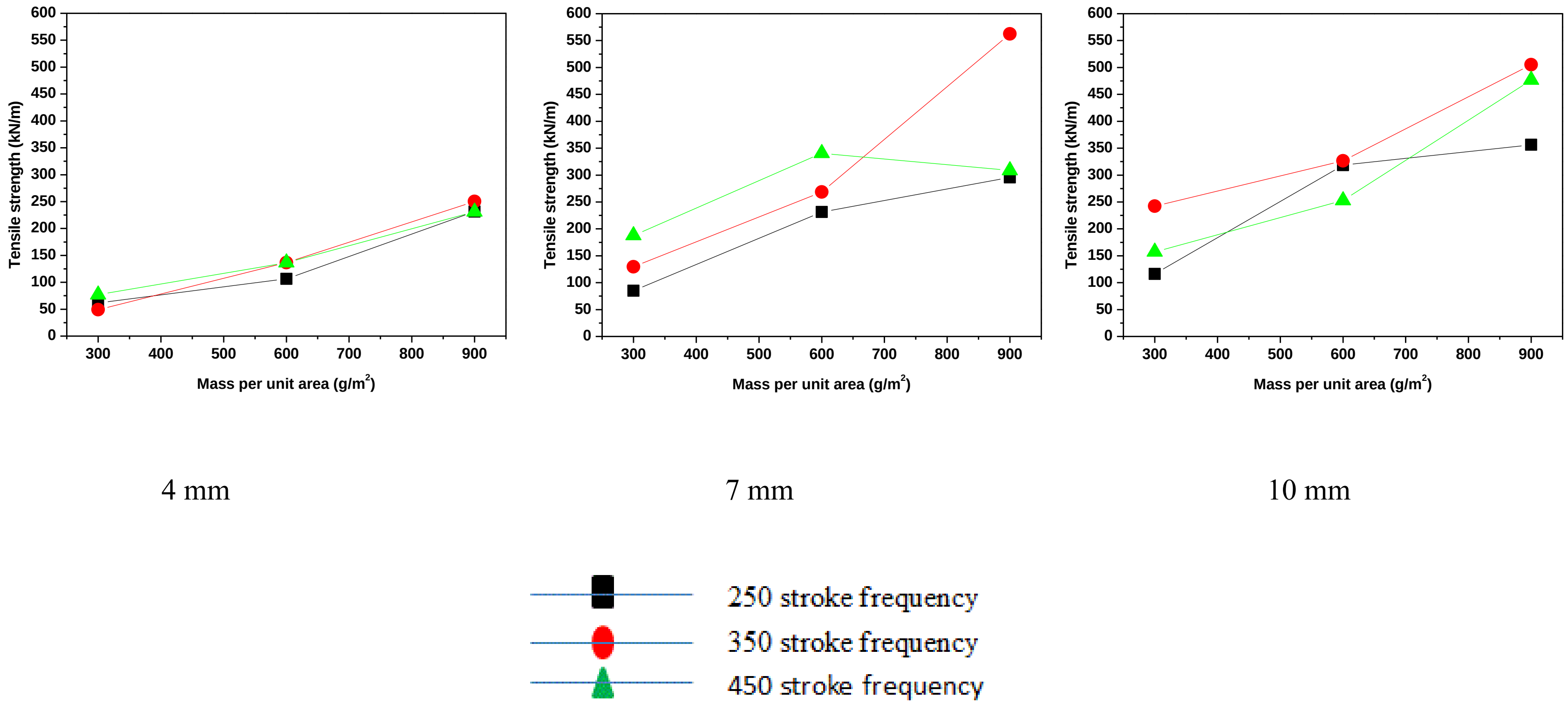

Figure 4.1(b) Effect of stroke frequency and mass per unit area on CD tensile strength of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres at 4, 7 and 10 mm depths of needle penetration.

4.2.2.4 Comparison of CD tensile strengths between samples (a blend of 50/50% PP/kenaf fibres

The CD tensile strengths of the nonwoven fabrics between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.1(b). The tensile strength increased with an increase in mass per unit area due to better fabric compactness resulted from an increase in fibre volume fraction.

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 350 and 450/min at constant depth of needle penetration of 4 mm were compared as shown in Figure 4.1(b). Similar trend as described in the previous paragraph was noticed.

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250 and 350/min at constant depth of needle penetration of 7 mm were compared as shown in Figure 4.1(b). The tensile strength increased with an increase in mass per unit area due to the barbs of the needles carrying higher number of fibres at higher values of depth of needle penetration and mass per unit area which resulted in a consolidated fibrous web with higher fabric tensile strength. The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 but constant stroke frequency of 450/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.1(b). The tensile strength increased with an increase in mass per unit area from 300 to 600 g/m^2, however, it decreased with further increase in mass per unit area to 900 g/m^2. This decrease in the tensile strength was attributed to thicker web which offered more resistance to needle passage, therefore, higher needling force was needed to compact the fabric. Higher depth of needle penetration might unlock the fibres while withdrawing from the fibrous web as well as breaking the fibres and thereby reduction in average fibre length. This, in turn, results in less compact fabric structure (Roy and Ray, 2009).

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250, 350 and 450/min but constant depth of needle penetration of 10 mm were compared as shown in Figure 4.1(b). The tensile strength increased with an increase in mass per unit area as observed by others (Fangueiro et al., 2011).

Statistical analysis

Similar statistical analysis, as presented in Section 4.2.2.2 for the fabrics produced from 100 % PP fibres, was also carried out for the tensile test data of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres. All the tested parameters as well as their two-way and three-way interactions were statistically significant as shown in Table 4.4 below.

Table 4.4: ANOVA on CD tensile strength data of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres

Nonwoven fabric produced from 50/50% PP/kenaf fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	7684728.6	1	7684728.6	42070.7	0.0
Mass per unit area	1239197.4	2	619598.7	3392.0	0.0
Stroke frequency	124258.8	2	62129.4	340.1	0.0
Needle depth of penetration	659524.8	2	329762.4	1805.3	0.0
Mass per unit area x stroke frequency	75143.9	4	18785.9	102.8	0.0
Mass per unit area x Needle depth of penetration	50754.7	4	12688.7	69.5	0.0
Stroke frequency x Needle depth of penetration	50840.9	4	12710.2	69.6	0.0
Mass per unit area*stroke frequency x needle depth of penetration	159635.5	8	19954.4	109.2	0.0
Error	19727.5	108	182.7		

4.2.2.5 Comparison of CD tensile strengths within samples (100% kenaf fibres)

Figure 4.1(c) shows the influence of stroke frequency and mass per unit area on CD tensile strength of the nonwoven fabrics produced from 100% kenaf fibres at depths of needle penetration of 4, 7 and 10 mm. At an area weight of 300 g/m^2 and depths of needle penetration of 4 and 10 mm, the CD tensile strength of the fabrics increased with an increase in stroke frequency up to 350/min, however, it decreases with further increase in stroke frequency to 450/min. This increase in the tensile strength was attributed to better interlocking and entanglement of the fibres resulted from an increase in stroke frequency, whereas the decrease was attributed to higher breakages and reorientation of the fibres at the stroke frequency above the optimal level as observed by others (Debnath and Madhussothanan, 2009). At an area weight of 300 g/m^2 and 7 mm depth of needle penetration, the CD tensile strength of the fabrics increased with an increase in stroke frequency. This increase in the tensile strength was influenced by majority of fibres that were oriented in the cross-machine direction.

At an area weight of 600 g/m^2 and depths of needle penetration of 4 and 10 mm, the CD tensile strength of the nonwoven fabrics increased with an increase in stroke frequency up to 350/min, however, it decreased with further increase in stroke frequency to 450/min as shown in Figure 4.1(c). This increase in the tensile strength was attributed to higher number of fibres per unit area of the fabric which resulted in better interlocking and entanglement of the fibres. However, the decrease in the tensile strength was influenced by shorter fibres that may have been realigned in the bias direction during needlepunching, therefore, affecting interlocking and entanglement of the fibres. At an area weight of 600 g/m^2 and 7 mm depth of needle penetration, the CD tensile strength of the nonwoven fabrics increased with an increase in stroke frequency up to 350/min, however, remained constant with further increase in stroke frequency to 450/min. This lack of change in the tensile strength was attributed to variations in fineness and length of kenaf fibres and anisotropy in the fabric structure.

At an area weight of 900 g/m^2 and 4 mm depth of needle penetration, the CD tensile strength of the nonwoven fabrics decreased with an increase in stroke frequency up to 350/min, however, it increased with further increase in stroke frequency to 450/min as shown in Figure 4.1(c). The decrease in tensile strength was attributed to the structural heterogeneities such as fibre orientation and pore size distributions. The heterogeneities in the fabrics produced from coarser fibres was influenced by fewer number of fibres in comparison to finer fibres present in the fabric structure of similar mass per unit area (Rawal et al., 2010b). The increase in the tensile strength was attributed to better interlocking and entanglement of the fibres resulted from an increase in stroke frequency. At an area weight of 900 g/m^2 and depths of needle penetration of 7 and 10 mm, a similar trend, as observed in the case of area weight of 300 g/m^2 and 4 mm depth of needle penetration, was noticed.

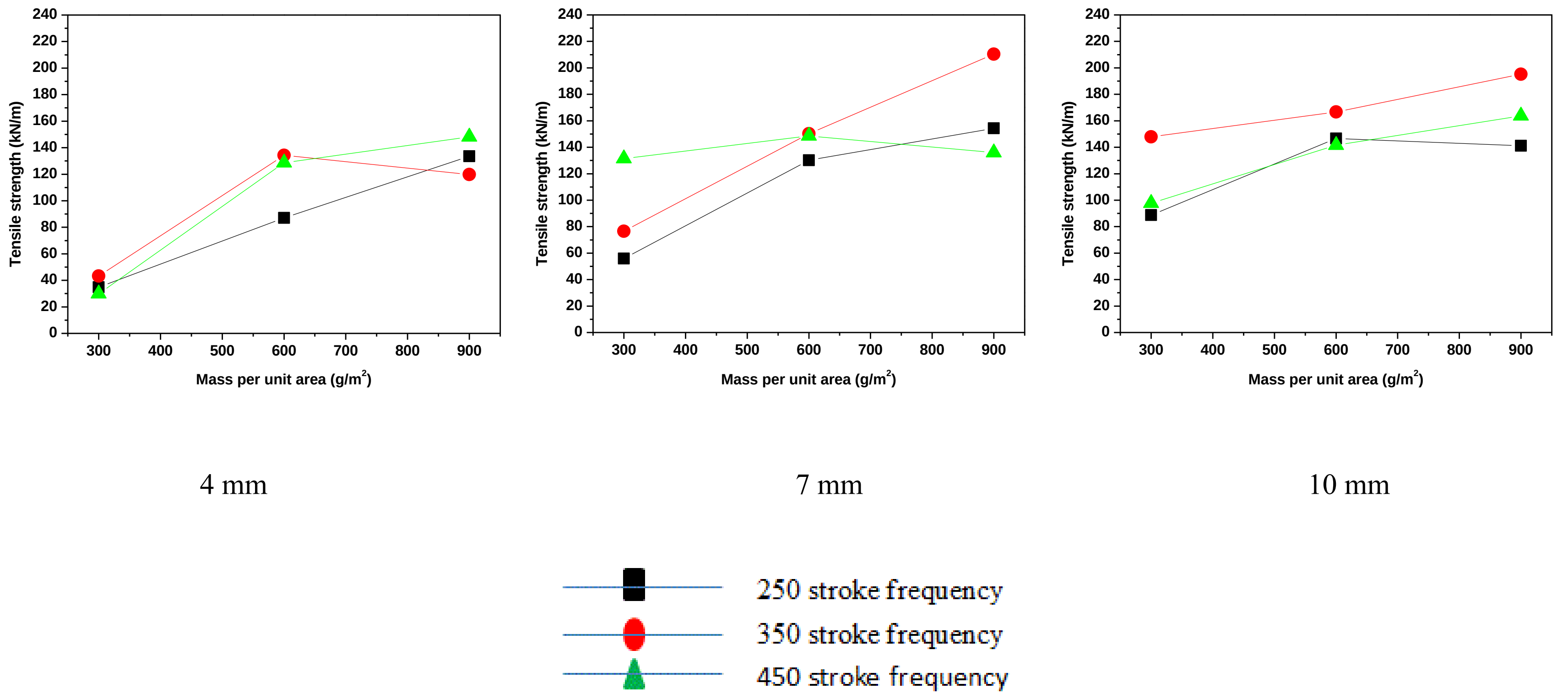

Figure 4.1(c) Effect of stroke frequency and mass per unit area on CD tensile strength of the nonwoven fabrics produced from 100% kenaf fibres at 4, 7 and 10 mm depths of needle penetration.

4.2.2.6 Comparison of CD tensile strengths between samples (100% kenaf fibres)

The CD tensile strengths of the nonwoven fabrics between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250 and 450/min but constant depth of needle penetration of 4 mm were compared as shown in Figure 4.1(c). The tensile strength increased with an increase in mass per unit area due to higher number of fibres per unit area of the fabric.

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.1(c). The tensile strength increased with an increase in mass per unit area from 300 to 600 g/m^2, however, it decreased with further increase in mass per unit area to 900 g/m^2. The decrease in the tensile strength was attributed to variations in fineness and length of natural fibres which influenced their interlocking and entanglement in the fabric.

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250 and 350/min but fixed depth of needle penetration of 7 mm were compared as shown in Figure 4.1(c). Similar trend as observed in the first paragraph of this section was noticed.

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.1(c). The tensile strength increased with an increase in mass per unit area from 300 and 600 g/m^2, however, it decreased with further increase in mass per unit area to 900 g/m^2. The decrease in the tensile strength was attributed to the bending rigidity and specific gravity of kenaf fibres which influenced arrangement of the fibres in the web as well as their interlocking (Çinçik and Koç, 2013).

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 10 mm were compared as shown in Figure 4.1(c). The tensile strength increased with an increase in mass per unit area from 300 to 600 g/m^2, however, it decreased with further increase in area weight of to 900 g/m^2. The decrease in the tensile strength was attributed to lower punching density at higher mass per unit area which resulted in inadequate interlocking and entanglement of the fibres.

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2, stroke frequencies of 350 and 450/min and depth of needle penetration of 10 mm were compared as shown in Figure 4.1(c). The tensile strength increased with an increase in mass per unit area as reported by others (Wojtasik, 2008; Rawal et al., 2010).

Statistical analysis

Similar statistical analysis, as presented in Section 4.2.2.2 for the fabrics produced from 100% PP fibres, was also carried out for the tensile test data of the nonwoven fabrics produced from 100% kenaf fibres. All the tested parameters as well as their two-way and three-way interactions were statistically significant as shown in Table 4.5 below.

Table 4.5: ANOVA on CD tensile strength data of the nonwoven fabrics produced from 100% kenaf fibres

Nonwoven fabric produced from 100% kenaf fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	2069190.7	1	2069190.7	25300.7	0.0
Mass per unit area	146286.4	2	73143.2	894.3	0.0
Stroke frequency	20665.3	2	10332.7	126.3	0.0
Needle depth of penetration	56570.3	2	28285.2	345.9	0.0
Mass per unit area x stroke frequency	2424.4	4	606.1	7.4	0.0
Mass per unit area x Needle depth of penetration	8962.3	4	2240.6	27.4	0.0
Stroke frequency x Needle depth of penetration	7035.2	4	1758.8	21.5	0.0
Mass per unit area x stroke frequency x needle depth of penetration	29744.3	8	3718.0	45.5	0.0
Error	8832.7	108	81.8		

4.2.2.7 Effect of fibre types on CD tensile strength

The effect of 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres on CD tensile strength of the needlepunched nonwoven fabrics is discussed in this section by comparing Figures 4.1(a) to 4.1(c):

(a) Effect of 100% PP fibres

PP fibres influenced the properties of the needlepunched nonwoven fabrics as they were difficult to open at higher roller speeds. However, higher feed rate was needed to produce heavier fabrics. This may result in uneven mass per unit area and thickness of the nonwoven fabrics besides irregularity, therefore, the fabric properties are affected. In addition, uniformity of mass per unit area and thickness of the nonwoven fabrics are also influenced by lower fibre-to-fibre friction and resistance to bending of PP fibres. The fibre-to-fibre friction and bending resistance of PP fibres influence interlocking and entanglement of the fibres, therefore, fabric tensile strength is affected.

The tensile strength of the needlepunched nonwoven fabrics produced from 100% PP fibres was higher in comparison to those produced from a blend of 50/50% PP/kenaf fibres and 100% kenaf fibres. This higher tensile strength was attributed to the properties of PP fibres, such as flexibility, high extensibility, better tensile strength, elastic recovery and lesser fibre deformation during needlepunching process. However, the crimp of PP fibres influences the uniformity in mass per unit area and thickness of the nonwoven fabric on which the tensile strength depends. In addition, crimped fibres occupy more space in the needlepunched nonwoven fabrics in comparison to straight fibres. Furthermore, fabric tensile strength was also influenced by variation in fibre crimp which might result in stress differential within the fabric. In addition, some fibres that were not bonded might not share the load at maximum stress, therefore, the stress was mainly transferred by inter fibre friction mechanism (Ganguly et al., 1999; Simmonds et al., 2007).

(b) Effect of a blend of 50/50% PP/kenaf fibres

The properties of the needlepunched nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres were influenced by differences in the properties of PP and kenaf fibres. When utilizing similar or same feed rate and output speed for producing nonwoven fabrics from a blend of fibres with different fibre specifications, method used to blend PP and kenaf fibres, blend homogeneity and compatibility of the fibres in the blend influences the characteristics of the fabrics. Due to lower bending rigidity of the PP fibres in comparison to that of kenaf fibres more PP fibres were transported in the thickness direction which might influence the tensile strength of the fabrics especially in the machine direction (Rawal and Sayeed, 2013; Chen, 2009).

Longer and finer fibres are known to achieve better interlocking and entanglement in the fabric, therefore, results in better fabric tensile strength. The tensile strength of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres was also influenced by variations in the cross-section of PP and kenaf fibres which resulted in non-uniform fibre distribution within the fabric (Çinçik and Koç, 2013). In addition, variations in the cross-section of PP and kenaf fibres may also influence flexural rigidity of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres. The tensile strength of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres was lower in comparison to that produced from 100% PP fibres, however, higher in comparison to that produced from 100% kenaf fibres.

(c) Effect of 100% kenaf fibres

Fabric properties, such as tensile strength, puncture resistance, pore size, water permeability and transmissivity were influenced by variations in fineness and length of kenaf fibres. The variations in fineness and length of kenaf fibres result in non-uniform mass per unit area and thickness of the nonwoven fabrics. Shorter fibres may be aligned in the cross-machine direction during needlepunching and therefore, contribute to deformation of the fibrous web during drafting in comparison to longer fibres. Therefore, shorter fibres promote irregularity in mass per unit area and thickness of the nonwoven fabrics.

Kenaf fibres were also difficult to entangle due to higher bending rigidity, therefore, results in poor interlocking and entanglement of the fibres with loss in tensile strength. The longer fibres achieve better interlocking and entanglement of the fibres, therefore, variations in fineness and length of the kenaf fibres may result in poor entanglement of the fibres as well as lower fabric tensile strength. Desai et al. (1994) have reported that the staple length of the fibres influence fabric tensile strength. The tensile strength of the nonwoven fabrics produced from 100% kenaf fibres was also influenced by higher breakages of fibres during needlepunching process. This results in less consolidated fabric with lower fabric tensile strength. Higher breakages of the fibres can be attributed to coarseness, brittleness and lower extensibility of the kenaf fibres.

4.2.3 Tensile strength in MD

4.2.3.1 Comparison of MD tensile strengths within samples (100% PP fibres)

Figure 4.2(a) shows the influence of stroke frequency and mass per unit area on MD tensile strength of the nonwoven fabrics produced from 100% PP fibres at depths of needle penetration of 4, 7 and 10 mm. At an area weight of 300 g/m^2 and depths of needle penetration of 4, 7 and 10 mm, the tensile strength of the fabrics increased with an increase in stroke frequency. This increase in the tensile strength was attributed to better interlocking and entanglement of fibres resulted from higher the punch density.

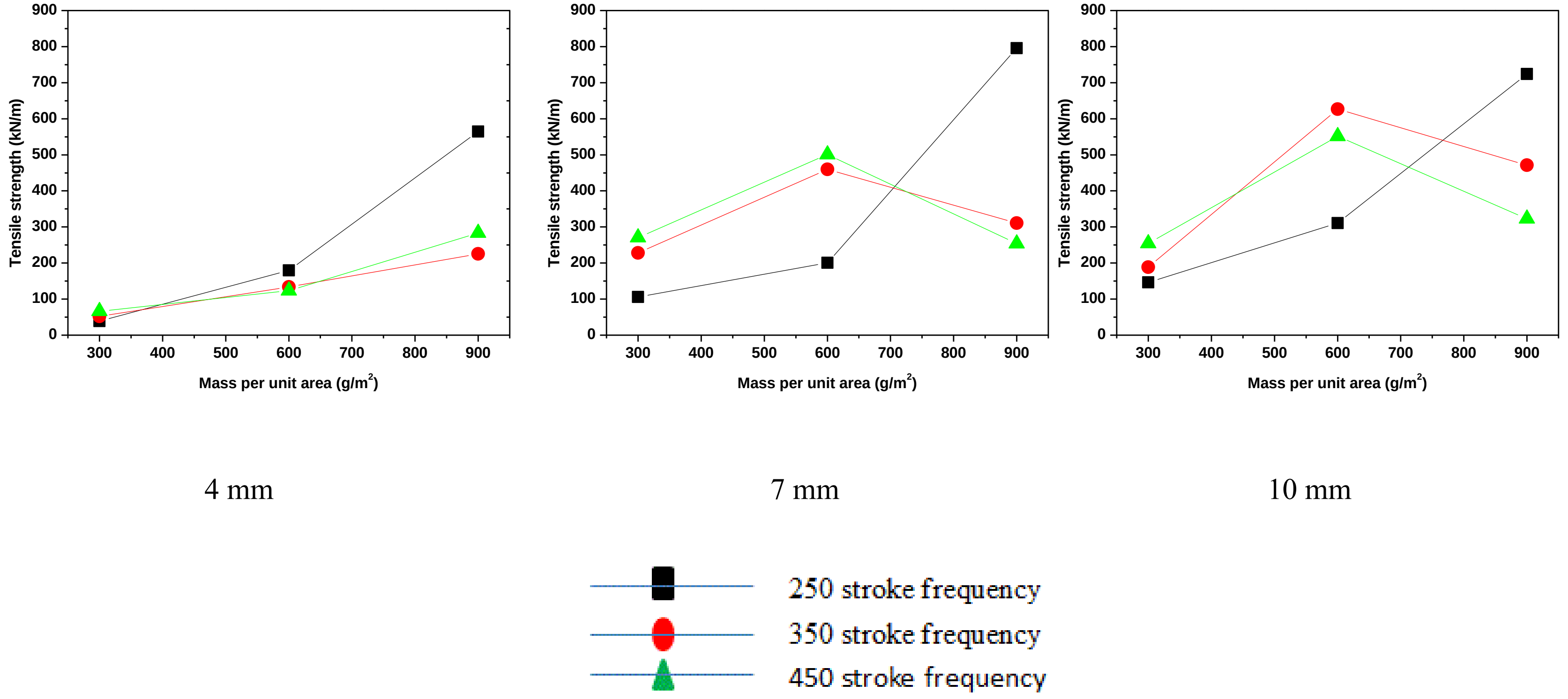

Figure 4.2(a) Effect of stroke frequency and mass per unit area on MD tensile strength of the nonwoven fabrics produced from 100% PP fibres at 4, 7 and 10 mm depths of needle penetration.

At an area weight of 600 g/m^2 and 4 mm depth of needle penetration, the MD tensile strength of the nonwoven fabrics decreased with an increase in stroke frequency as shown in Figure 4.2(a). The lower tensile strength was influenced by lower number of fibres orientated in machine direction due to cross-lapping process (Rawal et al., 2008). At an area weight of 600 g/m^2 and 7 mm depth of needle penetration, the MD tensile strength of the fabrics increased with an increase in stroke frequency. A similar trend, as observed in the case of area weight of 300 g/m^2 and 7 mm depth of needle penetration, was noticed.

At an area weight of 600 g/m^2 and 10 mm depth of needle penetration, the MD tensile strength of the fabrics increased with an increase in stroke frequency up to 350/min, however, it decreased with further increase in stroke frequency to 450/min as shown in Figure 4.2(a). The increase in the MD tensile strength of the fabrics was attributed to better fabric compactness resulted from the increase in stroke frequency. The decrease in the tensile strength was attributed to bending resistance and lower fibre-to-fibre friction of PP fibres which influence interlocking and entanglement of the fibres.

At an area weight of 900 g/m^2 and 4 mm depth of needle penetration, the MD tensile strength of the nonwoven fabrics decreased with an increase in stroke frequency up to 350/min, however, it increased with further increase in stroke frequency to 450/min as shown in Figure 4.2(a). This decrease in the tensile strength was attributed to lower depth of needle penetration in multi-layered nonwoven structure composed of either two or more nonwoven fabrics, therefore, results in insufficient interlocking of the fibres. At an area weight of 900 g/m^2 and depths of needle penetration of 7 and 10 mm, the MD tensile strength of the fabrics decreased with an increase in stroke frequency as shown in Figure 4.2(a). A similar trend, as observed in the case of area weight of 600 g/m^2 and 4 mm depth of needle penetration, was noticed.

4.2.3.2 Comparison of MD tensile strengths between samples (100% PP fibres)

The MD tensile strengths of the nonwoven fabrics between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250, 350 and 450/min and fixed depth of needle penetration of 4 mm were compared as shown in Figure 4.2(a). The tensile strength increased with an increase in mass per unit area, which was attributed to higher number of finer fibres in the fibrous web which promote web uniformity.

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.2(a). A similar trend, as described in the previous paragraph, was noticed.

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 350 and 450/min and constant depth of needle penetration of 7 mm were compared as shown in Figure 4.2(a). The tensile strength increased with an increase in mass per unit area from 300 to 600 g/m^2, however, it decreased with further increase in area weight to 900 g/m^2. The lower tensile strength was attributed to less number of fibres oriented in the machine direction due to cross-lapping process.

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250, 350 and 450/min and constant depth of needle penetration of 10 mm were compared as shown in Figure 4.2(a). A similar trend, as observed in the case of 250, 350 and 450/min stroke frequencies and 7 mm depth of needle penetration, was noticed in this case also.

Statistical analysis

All the tested parameters, their two-way and three-way interactions showed significant effects on MD tensile strength of the nonwoven fabrics produced from 100% PP fibres as shown in Table below 4.6.

Table 4.6: ANOVA on MD tensile strength data of the nonwoven fabrics produced from 100% PP fibres

Nonwoven fabric produced from 100% PP fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	13034368.4	1	13034368.4	65056.4	0.0
Mass per unit area	1948702.1	2	974351.0	4863.1	0.0
Stroke frequency	61677.8	2	30838.9	153.9	0.0
Needle depth of penetration	1124233.6	2	562116.8	2805.6	0.0
Mass per unit area x stroke frequency	1791216.3	4	447804.1	2235.1	0.0
Mass per unit area x Needle depth of penetration	226500.2	4	56625.1	282.6	0.0
Stroke frequency x Needle depth of penetration	101428.3	4	25357.1	126.6	0.0
Mass per unit area x stroke frequency x needle depth of penetration	325303.6	8	40662.9	202.9	0.0
Error	21638.3	108	200.4		

4.2.3.3 Comparison of MD tensile strengths within samples (a blend of 50/50% PP/kenaf fibres)

Figure 4.2(b) shows the influence of stroke frequency and mass per unit area on MD tensile strength of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres at depths of needle penetration of 4, 7 and 10 mm. At an area weight of 300 g/m^2 and 4 mm depth of needle penetration, MD tensile strength increased with an increase in stroke frequency. This increase in the tensile strength was attributed to better fabric compactness resulted from the increase in stroke frequency. At an area weight of 300 g/m^2 and 7 mm depth of needle penetration, MD tensile strength decreased with an increase in stroke frequency up to 350/min, however, it increased with further increase in stroke frequency to 450/min. The lower tensile strength was attributed to differences in the surface properties of both PP and kenaf fibres which influence frictional properties of the fibres in the fabric, therefore, influence fabric tensile strength (Çinçik and Koç, 2013). The increase in the tensile strength was attributed to better interlocking and entanglement of the fibres at higher stroke frequency and depth of needle penetration. At an area weight of 300 g/m^2 and 10 mm depth of needle penetration, the MD tensile strength of the fabrics increased with an increase in stroke frequency up to 350/min, however, it decreased with further increase to 450/min. The increase in the tensile strength was attributed to higher depth of needle penetration that reoriented fibres from cross-machine direction to machine direction, therefore, higher number of fibres in machine direction which resulted in better interlocking and entanglement of the fibres (Rawal et al., 2010). This reduction in the tensile strength was attributed to breakage and reorientation of the fibres during needlepunching process, as a result, the fabric becomes less compact. The MD tensile strength failure mechanism of the fabric was mostly influenced by fibre breakages due to fabric extension (Rawal et al., 2010b).

At an area weight of 600 g/m^2 and 4 mm depth of needle penetration, MD tensile strength of the fabrics increased with an increase in stroke frequency up to 350/min, after which it remained the same with further increase in stroke frequency to 450/min as shown in Figure 4.2(b). This increase in the tensile strength was attributed to higher fabric compactness resulted from the increase in stroke frequency which increases interlocking and entanglement of the fibres. The lack of change in the tensile strength was attributed to differences in the properties of PP and kenaf fibres which influence fabric compactness as well as breakages of mostly kenaf fibres (Adanur and Liao, 1999).

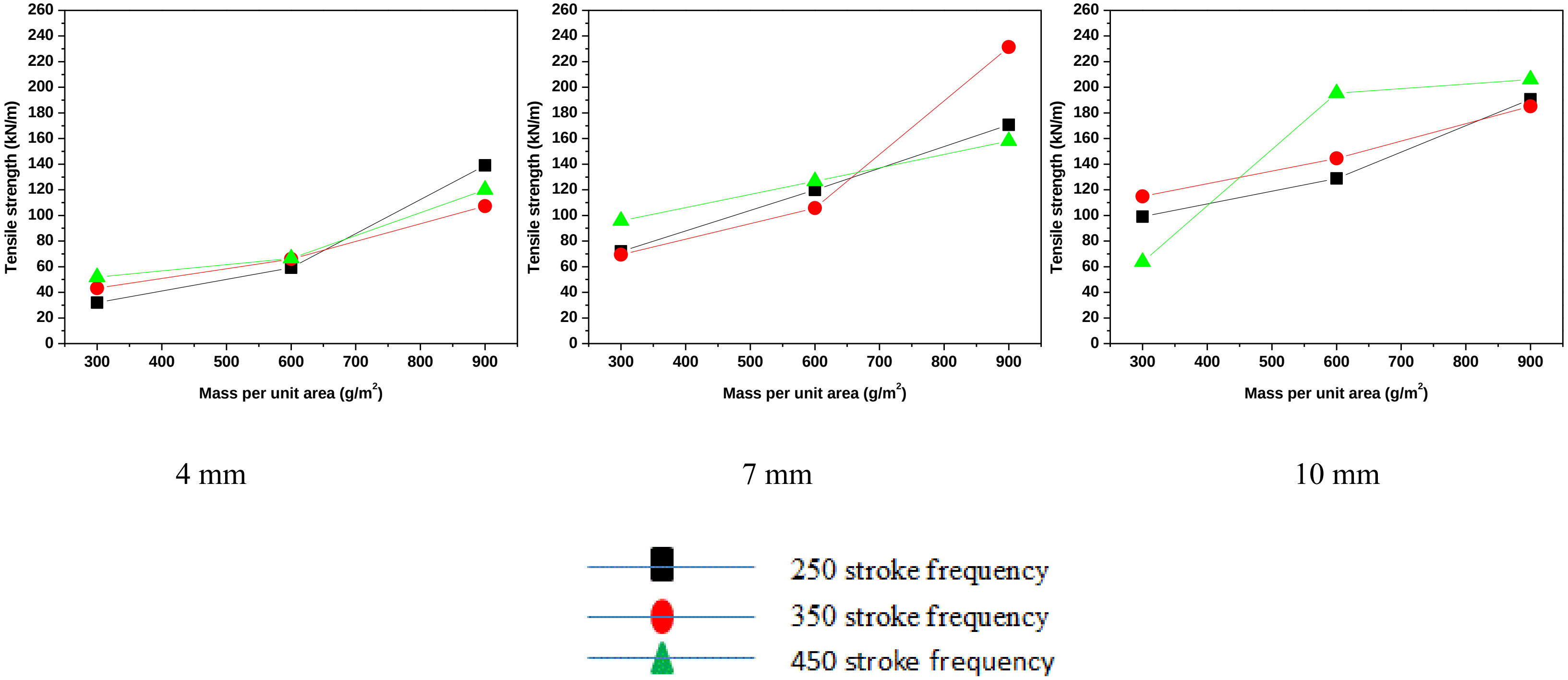

Figure 4.2(b) Effect of stroke frequency and mass per unit area on MD tensile strength of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres at 4, 7 and 10 mm depths of needle penetration.

At an area weight of 600 g/m^2 and 7 mm depth of needle penetration, MD tensile strength of the fabrics decreased with an increase in stroke frequency up to 350/min, however, it increased with further increase in stroke frequency to 450/min. A trend, similar to that observed in the case of area weight of 300 g/m^2 and 7 mm depth of needle penetration, was noticed. At an area weight of 600 g/m^2 and 10 mm depth of needle penetration, MD tensile strength of the fabrics increased with an increase in stroke frequency from 250 to 450/min. The increase in the tensile strength was attributed to better fabric compactness resulted from an increase in stroke frequency and higher depth of needle penetration as well as increase in the number of fibres per unit area of the fabric.

4.2.3.4 Comparison of MD tensile strengths between samples (a blend of 50/50% PP/kenaf fibres)

The MD tensile strengths of the nonwoven fabrics between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250, 350 and 450/min and fixed depth of needle penetration of 4 mm were compared as shown in Figure 4.2(b). The tensile strength increased with an increase in mass per unit area as reported by others (Çinçik and Koç, 2013).

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250, 350 and 450/min and depths of needle penetration of 7 and 10 mm were compared as shown in Figure 4.2(b). A similar trend, as observed in the previous paragraph, was noticed.

Statistical analysis

As shown in Table 4.7, all the tested parameters, their two-way and three-way interactions showed significant effects on the MD tensile strength of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres.

Table 4.7: ANOVA on MD tensile strength data of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres

Nonwoven fabric produced from 50/50% PP/kenaf fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	1853382.2	1	1853382.2	17946.6	0.0
Mass per unit area	210030.0	2	105015.0	1016.9	0.0
Stroke frequency	1609.5	2	804.7	7.8	0.0
Needle depth of penetration	122501.9	2	61250.9	593.1	0.0
Mass per unit area x stroke frequency	6733.3	4	1683.3	16.3	0.0
Mass per unit area x depth of needle penetration	9215.1	4	2303.8	22.3	0.0
Stroke frequency x depth of needle penetration	2233.3	4	558.3	5.4	0.0
Mass per unit area x stroke frequency x depth of needle penetration	31927.9	8	3990.9	38.6	0.0
Error	11153.4	108	103.3		

4.2.3.5 Comparison of MD tensile strengths within samples (100% kenaf fibres)

Figure 4.2(c) shows the influence of stroke frequency and mass per unit area on MD tensile strength of the nonwoven fabrics produced from 100% kenaf fibres at depths of needle penetration of 4, 7 and 10 mm. At an area weight of 300 g/m^2 and 4 mm depth of needle penetration, MD tensile strength of the fabrics increased with an increase in stroke frequency. This increase in the tensile strength was attributed to better interlocking and entanglement of the fibres resulted from an increase in stroke frequency. At an area weight of 300 g/m^2 and 7 mm depth of needle penetration, the tensile strength decreased with an increase in stroke frequency. This lower tensile strength was attributed to breakage and reorientation of the fibres with an increase in stroke frequency and higher depth of needle penetration. Rawal et al. (2010a) have reported that an increase in stroke frequency reduces the number of fibres in the machine direction, therefore, it influences fabric tensile strength.

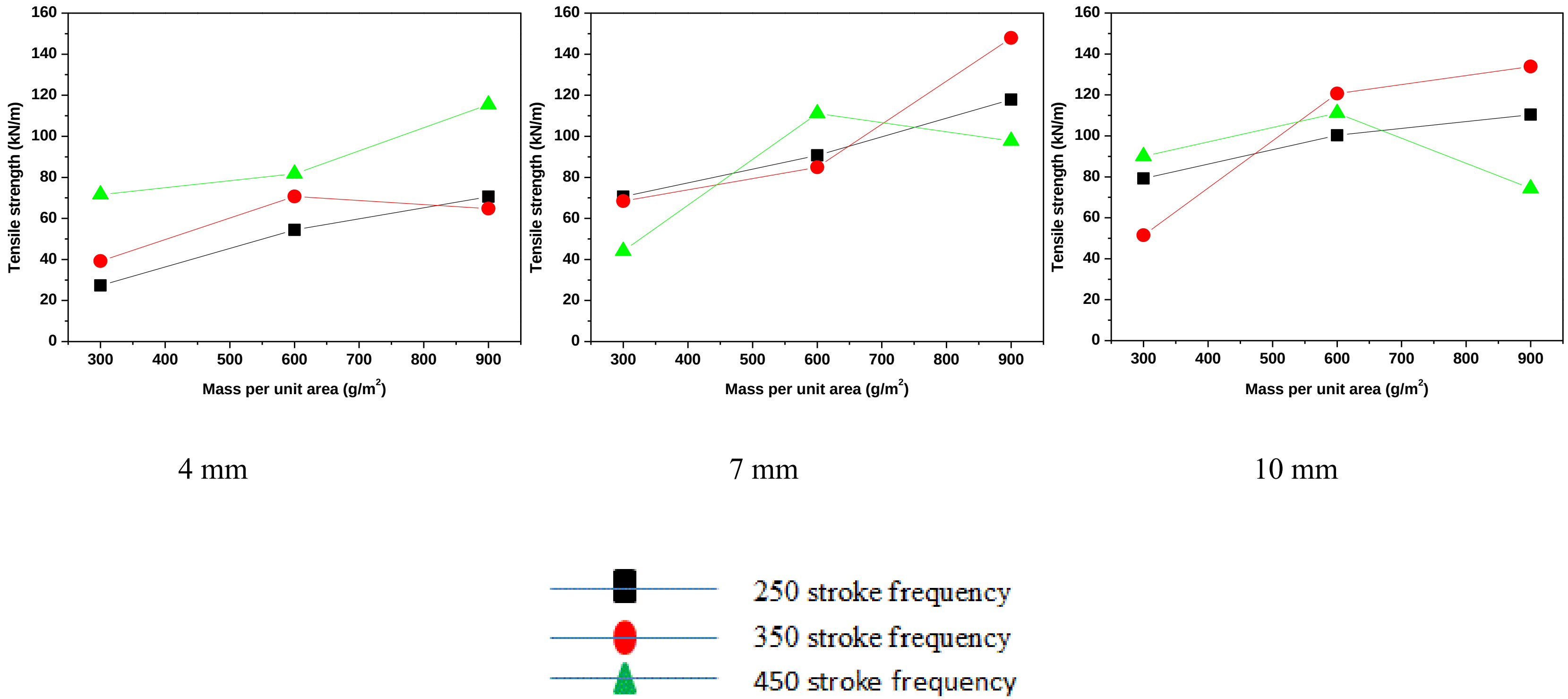

Figure 4.2(c) Effect of stroke frequency and mass per unit area on MD tensile strength of the nonwoven fabrics produced from 100 % kenaf fibres at 4, 7 and 10 mm depths of needle penetration.

At an area weight of 300 g/m^2 and 10 mm depth of needle penetration, MD tensile strength of the fabrics decreased with an increase in stroke frequency up to 350/min, however, it increased with further increase in stroke frequency to 450/min. The lower tensile strength was influenced by variations in fineness and length of kenaf fibres which influence entanglement of fibres and areal density of the fabric. The increase in the tensile strength was attributed to barbs of the needles carrying a higher number of fibres with an increase in stroke frequency and thereby results in better interlocking of the fibres.

At an area weight of 600 g/m^2 and 4 mm depth of needle penetration, the MD tensile strength of the nonwoven fabrics increased with an increase in stroke frequency as shown in Figure 4.2(c). A trend, similar to that observed in the case of area weight of 300 g/m^2 and 4 mm depth of needle penetration, was noticed. At an area weight of 600 g/m^2 and 7 mm depth of needle penetration, MD tensile strength of the fabrics decreased with an increase in stroke frequency up to 350/min, however, it increased with further increase in stroke frequency to 450/min as shown in Figure 4.2(c). The lower tensile strength in MD was attributed to lower number of fibres oriented to the machine direction due to cross-lapping process. The increase in the tensile strength was attributed to barbs of the needles carrying higher number of fibres at higher depth of needle penetration, stroke frequency and mass per unit area, therefore, results in better interlocking of the fibres. This increases interaction and frictional forces between the fibres, therefore, minimises slippage of fibres in the fabrics.

At an area weight of 600 g/m^2 and 10 mm depth of needle penetration, MD tensile strength of the fabrics increased with an increase in stroke frequency up to 350/min, after which it decreased with further increase to 450/min as shown in Figure 4.2(c). The increase in the tensile strength was attributed to higher number of fibres per unit area of the fabric which promotes better interlocking and entanglement of the fibres. The lower tensile strength was attributed to less consolidated fabric resulted from breakages of fibres at highest values of stroke frequency and depth of needle penetration.

At an area weight of 900 g/m^2 and 4 mm depth of needle penetration, MD tensile strength of the fabrics decreased with an increase in stroke frequency up to 350/min, after which it increased with further increase in stroke frequency to 450/min as shown in Figure 4.2(c). A similar trend, as observed in the case of area weight of 600 g/m^2 and 7 mm depth of needle penetration, was noticed.

At an area weight of 900 g/m^2 and depths of needle penetration of 7 and 10 mm, the tensile strength of the fabrics increased with an increase in stroke frequency up to 350/min, after which it decreased with further increase in stroke frequency to 450/min as shown in Figure

4.2(c). A trend, similar to that observed in the case of area weight of 600 g/m^2 and 10 mm depth of needle penetration, was noticed.

4.2.3.6 Comparison of MD tensile strengths between samples (100% kenaf fibres)

The MD tensile strengths of the nonwoven fabrics between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250 and 450/min and fixed depth of needle penetration of 4 mm were compared as shown in Figure 4.2(c). The tensile strength increased with an increase in mass per unit area due to better fabric compactness resulted from the increase in number of fibres per unit area of the fabric.

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.2(c). The tensile strength increased with an increase in mass per unit area from 300 to 600 g/m^2, after which it decreased with further increase in area weight to 900 g/m^2. This decrease in the tensile strength was attributed to variations in fineness and length of kenaf fibres which might cause variation in areal density of the fabric.

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250 and 350/min and fixed depth of needle penetration of 7 mm were compared as shown in Figure 4.2(c). The tensile strength increased with an increase in mass per unit area. A similar trend, as observed in the first paragraph of this section, was noticed.

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.2(c). The tensile strength increased with an increase in stroke frequency from 300 to 600 g/m^2, however, it decreased with further increase in area weight to 900 g/m^2. The decrease in the tensile strength was attributed to breakages of fibres at higher values of stroke frequency, depth of needle penetration and mass per unit area due to thicker web which offered more resistance to needle passage.

The tensile strengths between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250, 350 and 450/min and fixed depth of needle penetration of 10 mm were compared as shown in Figure 4.2(c). A trend, similar to that observed earlier for samples produced at 7 mm depth of needle penetration and discussed above, was observed.

Statistical analysis

As shown in Table 4.8 below, all the tested parameters, two-way interactions and three-way interactions showed significant effects on the tensile strength of the nonwoven fabrics produced from 100% kenaf fibres.

Table 4.8: ANOVA on MD tensile strength data of the nonwoven fabrics produced from 100 % kenaf fibres

Nonwoven fabric produced from 100% kenaf fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	979842.6	1	979842.6	8441.4	0.0
Mass per unit area	45281.1	2	22640.6	195.1	0.0
Stroke frequency	1777.5	2	888.7	7.7	0.0
depth of needle penetration	24822.4	2	12411.2	106.9	0.0
Mass per unit area x stroke frequency	6227.3	4	1556.8	13.4	0.0
Mass per unit area x depth of needle penetration	5037.3	4	1259.3	10.8	0.0
Stroke frequency x depth of needle penetration	13675.6	4	3418.9	29.5	0.0
Mass per unit area x stroke frequency x depth of needle penetration	17600.7	8	2200.1	18.9	0.0
Error	12536.2	108	116.1		

4.2.4 Puncture resistance

4.2.4.1 Comparison of puncture resistance within samples (100% PP fibres)

The puncture resistance of the nonwoven fabrics increases with increases in stroke frequency, depth of needle penetration and actual fabric weight, as shown in Table 4.2(b). However, as expected the increase in the puncture resistance did not follow any specific trend owing to structural anisotropy of the nonwoven fabrics. The puncture resistance of the fabrics depend on mass per unit area and thickness of the fabrics (Rawal et al., 2008). The mechanism of puncture failure of needlepunched nonwoven fabrics depends on fibre-to-fibre contact, frictional properties of the fibres, flexural rigidity and specific surface area and it is shown graphically in Figure 4. 3 (Askari et al., 2012). The force and displacement were zero in the beginning of the test as shown by point A when the plunger just touches the fabric (Figure 4.3). As the plunger begins to penetrate the fabric, the fibres begin to move by compression and tensional forces. The slope shows a slight increase from point A to B due to the fabric tested which was able to withstand force exerted by plunger while moving in downward direction. The layers of sample being tested begin to show signs of deformation with an increase in applied force by a plunger. However, the fibres were still packed together in contact to each other and were unable to move while the frictional forces were increasing as shown from point B to C in Figure 4.3. This was attributed to higher degree of fibre entanglement in the tested sample. As the plunger continues to move downward, tension increases and the fibres breakages and separated from each other by overcoming frictional forces and a puncture in the specimen occurs as shown from point C to D in Figure 4.3 (Hwang et al., 1999; Askari et al., 2012).

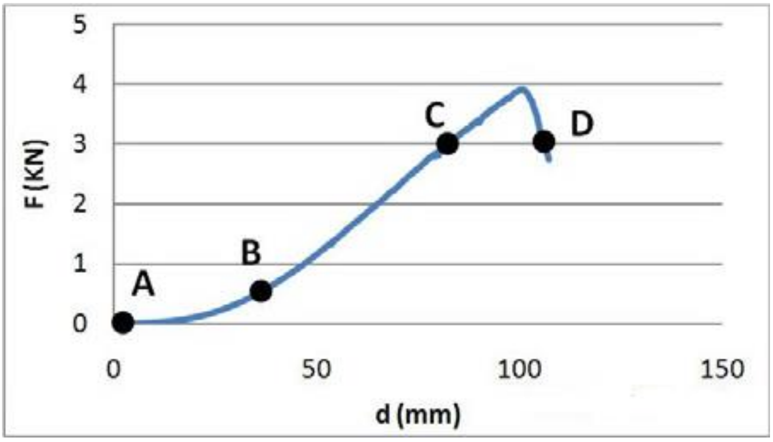

Figure 4.3 Puncture failure of nonwoven fabric (Source: Askari et al., 2012)

Figure 4.3(a) shows the influence of stroke frequency and mass per unit area on puncture resistance of the nonwoven fabrics produced from 100 % PP fibres at depths of needle penetration of 4, 7 and 10 mm. At an area weight of 300 g/m^2 and 4 mm depth of needle penetration, the puncture resistance of the fabrics increased with an increase in stroke frequency from 250 to 450/min. This increase was attributed to better fabric compactness resulted in uniform fibrous web due to fineness of PP fibres and better interlocking and entanglement of the fibres. At an area weight of 300 g/m^2 and depths of needle penetration of 7 and 10 mm, a similar trend, as observed in the case of 300 g/m^2 and 4 mm depth of needle penetration, was noticed.

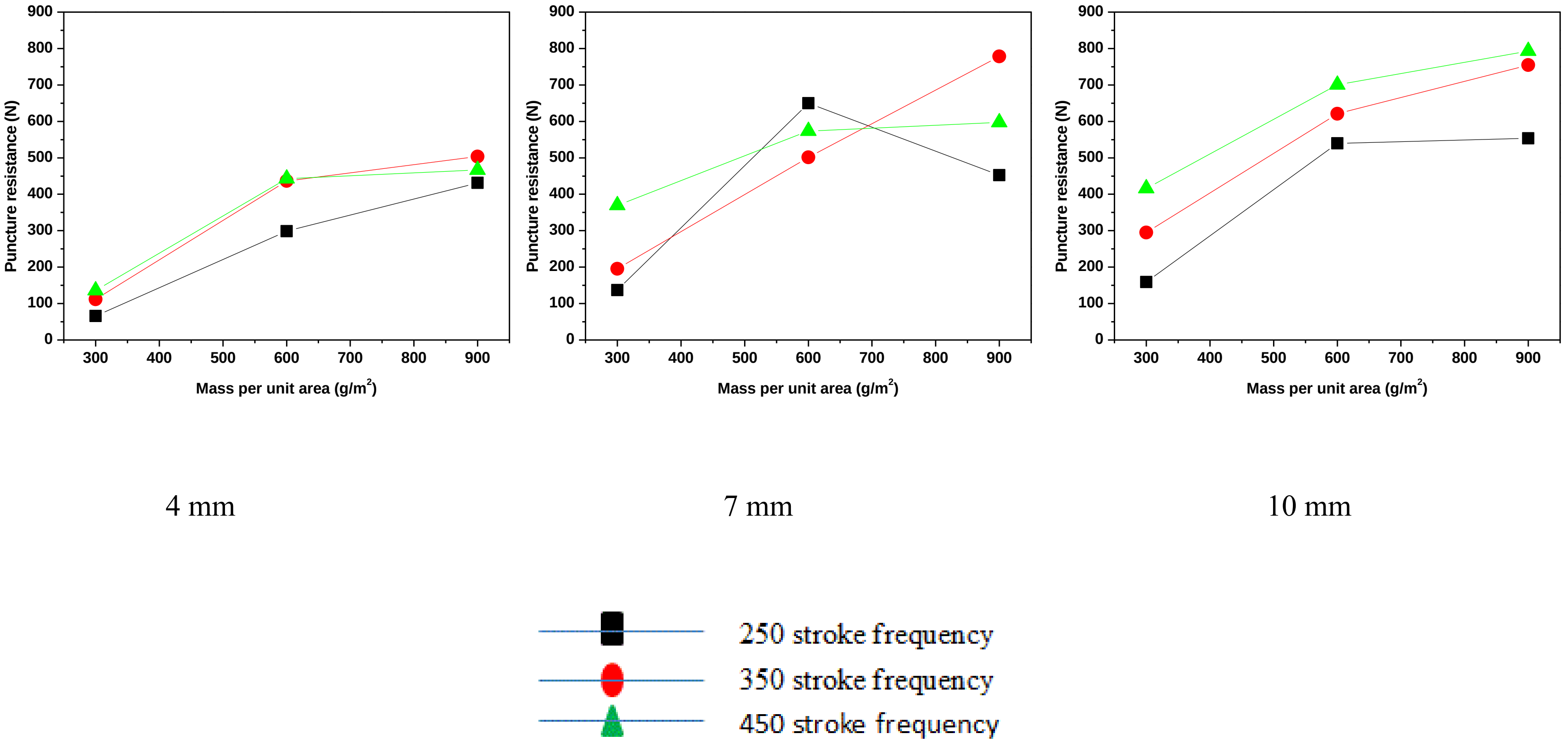

Figure 4.3(a) Effect of stroke frequency and mass per unit area on puncture resistance of the nonwoven fabrics produced from 100% PP fibres at depths of needle penetration of 4, 7 and 10 mm.

At an area weight of 600 g/m^2 and 4 mm depth of needle penetration, the puncture resistance of the fabrics increased with an increase in stroke frequency from 250 to 350/min, after which it remained the same with further increase in stroke frequency to 450/min as shown in Figure 4.3(a). This lack of change was attributed to the barbs of the needles which carried a fewer number of fibres at lower value of depth of needle penetration, therefore, resultant in poor interlocking and entanglement of the fibres provided less compact fabrics.

At an area weight of 600 g/m^2 and 7 mm depth of needle penetration, the puncture resistance of the fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it continued to increase with further increase in stroke frequency to 450/min. This lower puncture resistance was attributed to higher crimp in PP fibres which resulted in lower interlocking and entanglement of the fibres in heavier fabrics. The increase in the puncture resistance was attributed to an increase in stroke frequency and higher depth of needle penetration which increased interlocking and entanglement of the fibres, therefore, increased fabric compactness as observed by others (Rawal et al., 2008). At an area weight of 600 g/m^2 and 10 mm depth of needle penetration, a similar trend, as observed in the first paragraph above, was noticed.

At an area weight of 900 g/m^2 and 4 mm depth of needle penetration, the puncture resistance of the nonwoven fabrics increased with an increase in stroke frequency from 250 to 350/min, after which it decreased with further increase in stroke frequency to 450/min as shown in Figure 4.3(a). This decrease in puncture resistance was attributed to an increase in punch density above the optimal level which might reorient fibres with higher breakages. Wang et al. (2013) have reported that punch density influences puncture resistance of the needlepunched nonwoven fabrics. At an area weight of 900 g/m^2 and 7 mm depth of needle penetration, a trend, similar to that observed in the case of area weight of 900 g/m^2 and 4 mm depth of needle penetration, was noticed. At an area weight of 900 g/m^2 and 10 mm depth of needle penetration, the puncture resistance of the fabrics increased with an increase in stroke frequency from 250 to 450/min as shown in Figure 4.3(a). This increase was attributed to an increase in stroke frequency, higher depth of needle penetration and increase in number of finer fibres per unit area of the fabric which improved interlocking and entanglement of the fibres.

4.2.4.2 Comparison of puncture resistance between samples (100% PP fibres)

The puncture resistance values of the nonwoven fabrics between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.3(a). The puncture resistance increased with an increase in mass per unit area, which was attributed to compactness of the fabrics due to higher number of fibres in the fabric.

The puncture resistance values between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 350 and 450/min and fixed depth of needle penetration of 4 mm were compared as shown in Figure 4.3(a). A similar trend, as observed in the previous paragraph, was noticed.

The puncture resistance values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.3(a). The puncture resistance increased with an increase in mass per unit area from 300 to 600 g/m^2, after which it decreased with further increase in area weight to 900 g/m^2. This lower puncture resistance in heavier fabrics was attributed to lower fibre-fibre friction and bending resistance of PP fibres which resulted in inadequate interlocking and entanglement of the fibres.

The puncture resistance values between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 350 and 450/min but constant depth of needle penetration of 7 mm were compared as shown in Figure 4.3(a). A trend, similar to that observed in the case of 250/min stroke frequency and 4 mm depth of needle penetration, was noticed in this case also.

The puncture resistance values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 10 mm were compared as shown in Figure 4.3(a). The puncture resistance increased with an increase in mass per unit area from 300 to 600 g/m^2, after which it remained the same with further increase in area weight to 900 g/m^2. This lack of change in the puncture resistance was attributed to lower interlocking and entanglement of the fibres at lower punch density and higher mass per unit area as reported by others (Roy and Ray, 2009).

The puncture resistance values between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 350 and 450/min and constant depth of needle penetration of 10 mm were compared as shown in Figure 4.3(a). A trend, similar to that observed in the case of 250/min stroke frequency and 4 mm depth of needle penetration, was noticed in this case also.

Statistical analysis

The statistical analysis similar to that reported in Section 4.2.2.2 on tensile strength was also conducted on the results of puncture resistance as shown below in Table 4.9. All the tested parameters and their three-way interactions showed significant effects on the puncture resistance of the nonwoven fabrics. In addition, the two-way interactions between mass per unit area and stroke frequency and between stroke frequency and depth of needle penetration were significant, however, the interaction between mass per unit area and depth of needle penetration was statistically not significant, (P is 0.326) which was attributed to reorientation and breakages of the fibres and variations in areal density on which the puncture resistance depends.

Table 4.9: ANOVA on puncture resistance data of the nonwoven fabrics produced from 100% PP fibres

Nonwoven fabric produced from 100% PP fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	26580514.1	1	26580514.1	6196.9	0.0
Mass per unit area	3793656.0	2	1896827.9	442.2	0.0
Stroke frequency	440415.1	2	220207.6	51.3	0.0
Needle depth of penetration	1102220.7	2	551110.3	128.5	0.0
Mass per unit area x stroke frequency	183939.8	4	45984.9	10.7	0.0
Mass per unit area x depth of needle penetration	20139.4	4	5034.9	1.2	0.3
Stroke frequency x depth of needle penetration	84140.2	4	21035.0	4.9	0.0
Mass per unit area x stroke frequency x depth of needle penetration	249320.1	8	31165.0	7.3	0.0
Error	463243.9	108	4289.3		

4.2.4.3 Comparison of puncture resistance within samples (a blend of 50/50% PP/kenaf fibres)

Figure 4.3(b) shows the influence of stroke frequency and mass per unit area on puncture resistance of the fabrics produced from a blend of 50/50% PP/kenaf fibres at depths of needle penetration of 4, 7 and 10 mm. At an area weight of 300 g/m^2 and 4 mm depth of needle penetration, the puncture resistance of the fabrics remained constant with an increase in stroke frequency from 250 to 350/min, after which it increased with further increase to 450/min.

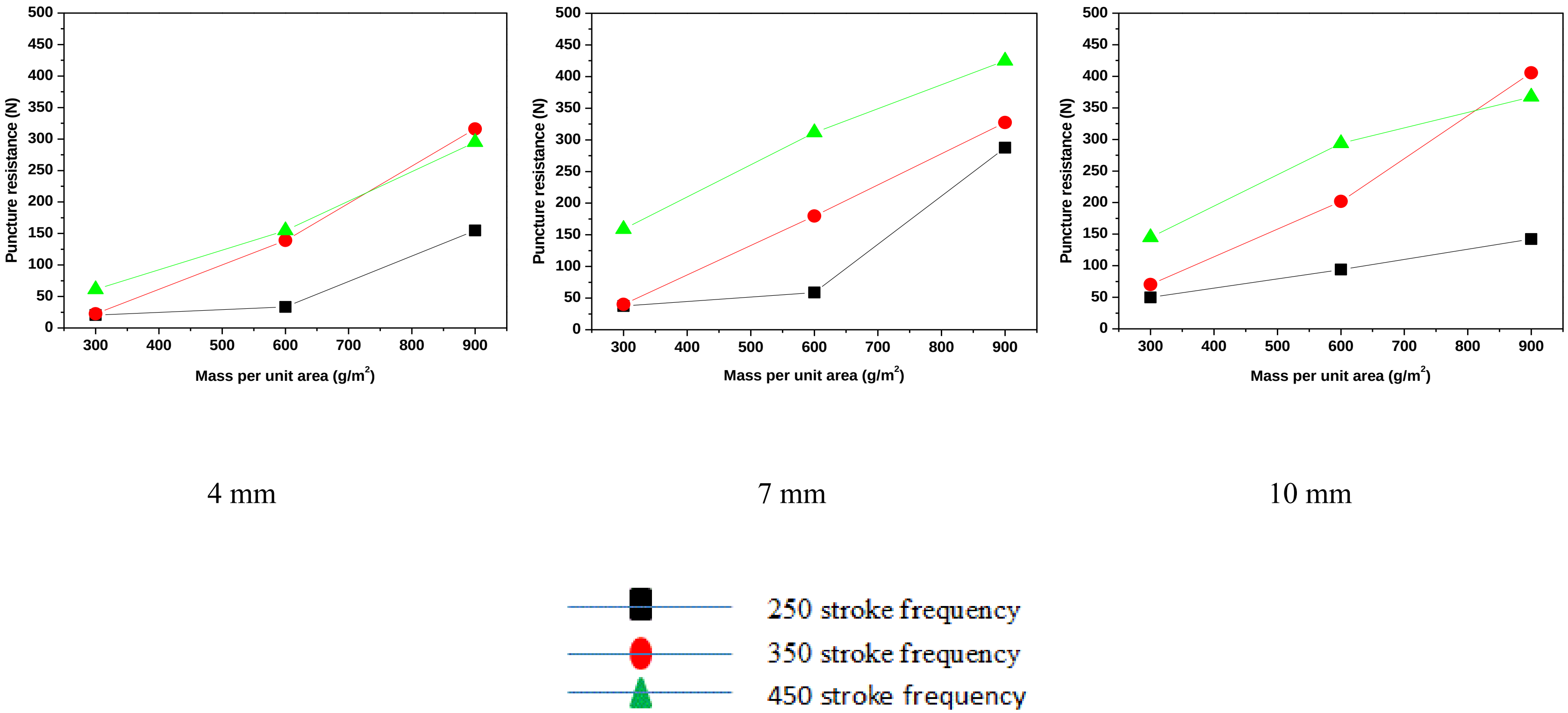

Figure 4.3(b) Effect of stroke frequency and mass per unit area on puncture resistance of the nonwoven fabrics produced from a blend of 50/50 % PP/kenaf fibres at depths of needle penetration of 4, 7 and 10 mm.

This lack of change in the puncture resistance was attributed to variations in fineness and diameter of both PP and kenaf fibres, which influenced uniformity of the fibrous web, therefore, affecting areal density on which puncture resistance depends. In addition, the lack of change in the puncture resistance was attributed to lowest values of depth of needle penetration and mass per unit area which resulted in insufficient interlocking and entanglement of the fibres. The increase in puncture resistance was attributed to an increase in stroke frequency which increased interlocking and entanglement of the fibres to provide a compact fabric. At an area weight of 300 g/m^2 and 7 mm depth of needle penetration, a similar trend, as observed in the case of 300 g/m^2 and 4 mm depth of needle penetration, was noticed. At an area weight of 300 g/m^2 and 10 mm depth of needle penetration, the puncture resistance of the fabrics increased with an increase in stroke frequency as shown in Figure 4.3(b). This increase was attributed to barbs of the needle carrying a higher number of fibres with an increase in stroke frequency and higher depth of needle penetration, therefore, increased interlocking and entanglement of the fibres in the fabric.

At an area weight of 600 g/m^2 and depths of needle penetration of 4, 7 and 10 mm, the puncture resistance of the nonwoven fabric increased with an increase in stroke frequency as shown in Figure 4.3(b). A similar trend, as observed in the case of 300 g/m^2 and 10 mm depth of needle penetration, was noticed in this case also.

At an area weight of 900 g/m^2 and 4 mm depth of needle penetration, the puncture resistance of the fabrics increased with an increase in stroke frequency from 250 to 350/min, after which it decreased with further increase in stroke frequency to 450/min as shown in Figure 4.3(b). The lower puncture resistance was attributed to higher breakages of coarser kenaf fibres at higher stroke frequency.

At an area weight of 900 g/m^2 and 7 mm depth of needle penetration, the puncture resistance of the fabrics increased with an increase in stroke frequency from 250 to 450/min as shown in Figure 4.3(b). The increase in the puncture resistance was attributed to an increase in stroke frequency, higher depth of needle penetration and higher number of fibres per unit area of the fabric which improved interlocking and entanglement of the fibres. At an area weight of 900 g/m^2 and 10 mm depth of needle penetration, a similar trend, as observed in the case of 900 g/m^2 and 4 mm depth of needle penetration, was noticed.

4.2.4.4 Comparison of puncture resistance between samples (a blend of 50/50% PP/kenaf fibres)

The puncture resistance values between the fabric samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.3(b). The puncture resistance increased with an increase in mass per unit area which was attributed to an increase in fibre volume fraction in the fabric.

The puncture resistance values between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 350 and 450/min and fixed depth of needle penetration of 4 mm were compared as shown in Figure 4.3(b). A similar trend, as observed in the previous paragraph, was noticed.

The puncture resistance values between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250, 350 and 450/min and depths of needle penetration of 7 and 10 mm were compared as shown in Figure 4.3(b). A similar trend, as observed in the case of 250, 350 and 450 stroke frequencies and depth of needle penetration of 4 mm, was noticed in this case also.

Statistical analysis

The puncture resistance of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres was analysed in the same way as described in the case of 100% PP fibres in Section 4.2.4.2. The tested parameters, their two-way and three-way interactions showed significant effects on puncture resistance as shown in Table 4.10 below.

Table 4.10: ANOVA on puncture resistance data of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres

Nonwoven fabric produced from 50/50% PP/kenaf fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	4253063.3	1	4253063.3	6815.3	0.0
Mass per unit area	1257056.6	2	628528.3	1007.2	0.0
Stroke frequency	503952.8	2	251976.4	403.8	0.0
depth of needle penetration	134645.5	2	67322.8	107.9	0.0
Mass per unit area x stroke frequency	101858.8	4	25464.7	40.8	0.0
Mass per unit area x depth of needle penetration	19348.3	4	4837.1	7.8	0.0
Stroke frequency x depth of needle penetration	60589.7	4	15147.4	24.3	0.0
Mass per unit area x stroke frequency x depth of needle penetration	45684.4	8	5710.5	9.2	0.0
Error	67397.2	108	624.0		

4.2.4.5 Comparison of puncture resistance within samples (100% kenaf fibres)

Figure 4.3(c) shows the influence of stroke frequency and mass per unit area on puncture resistance of the nonwoven fabrics produced from 100% kenaf fibres at depths of needle penetration of 4, 7 and 10 mm. At an area weight of 300 g/m^2 and 4 mm depth of needle penetration, the puncture resistance of the fabrics remained the same with an increase in stroke frequency from 250 to 350/min, after which it increased with further increase in stroke frequency to 450/min. This lack of change in the puncture resistance was attributed to difficulty in entangling coarser kenaf fibres due to higher bending rigidity and the increase was attributed to an increase in punch density which increased entanglement of the fibres, therefore, resulted in a compact fabric. In addition, the lack of change was also attributed to lower depth of needle penetration and fewer number of fibres per unit area of the fabric which resulted in insufficient interlocking and entanglement of the fibres. At an area weight of 300 g/m^2 and depths of needle penetration of 7 and 10 mm, the puncture resistance of the fabrics increased with an increase in stroke frequency from 250 to 350/min, however, it decreased with further increase in stroke frequency to 450/min. This lower puncture resistance was attributed to less consolidated fabrics resulted from higher breakages of fibres while reducing average fibre length at higher stroke frequency and depth of needle penetration (Roy and Ray, 2009).

At an area weight of 600 g/m^2 and depths of needle penetration of 4, 7 and 10 mm, the puncture resistance of the nonwoven fabric increased with an increase in stroke frequency as shown in Figure 4.3(c). This increase was attributed to an increase in the number of fibres per unit area of the fabric which provided a more compact fabric. In addition, the increase was also attributed to increases in stroke frequency and depth of needle penetration which increased interlocking and entanglement of the fibres.

At an area weight of 900 g/m^2 and 4 mm depth of needle penetration, the puncture resistance of the fabric decreased with an increase in stroke frequency from 250 to 350/min, after which it increased with further increase in stroke frequency to 450/min as shown in Figure 4.3(c). The lower puncture resistance was attributed to variations in fineness and length of kenaf fibres which influenced interlocking and entanglement of the fibres. Maity and Singha (2012) have reported that the length and fineness of the fibres influences mechanical properties of the nonwoven fabrics.

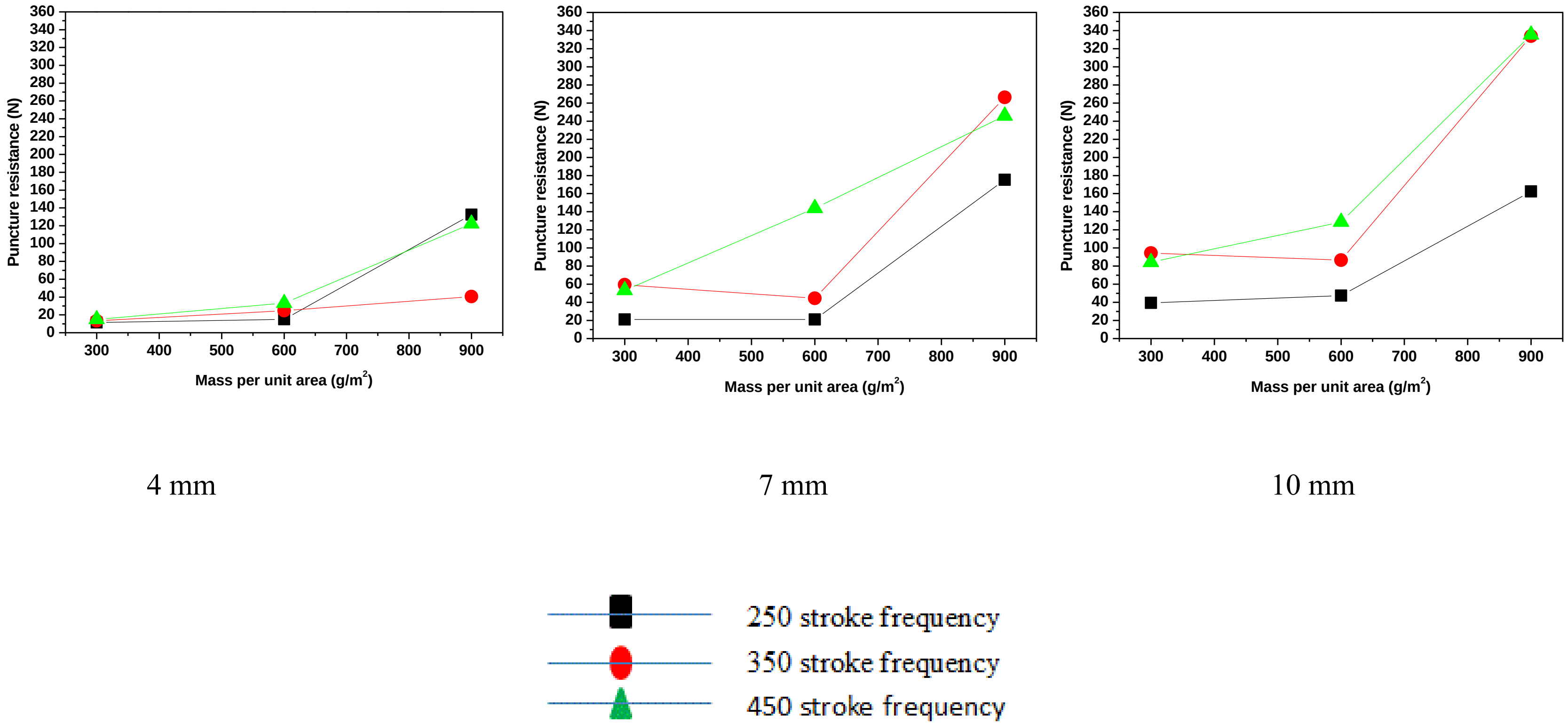

Figure 4.3(c) Effect of stroke frequency and mass per unit area on puncture resistance of the nonwoven fabrics produced from 100% kenaf fibres at depths of needle penetration of 4, 7 and 10 mm.

At an area weight of 900 g/m^2 and 7 mm depth of needle penetration, the puncture resistance of the fabrics increased with an increase in stroke frequency from 250 to 350/min, after which it decreased with further increase in stroke frequency to 450/min as shown in Figure 4.3(c). A similar trend, as observed in the case of 300 g/m^2 and 7 mm depth of needle penetration, was noticed. At an area weight of 900 g/m^2 and 10 mm depth of needle penetration, the puncture resistance of the fabric increased with an increase in stroke frequency from 250 to 350/min, after which it remained constant with further increase in stroke frequency to 450/min as shown in Figure 4.3(c). This lack of change in the puncture resistance was attributed to differences in the diameter of kenaf fibres which resulted in variations in areal density, therefore, influenced fabric puncture resistance.

4.2.4.6 Comparison of puncture resistance between samples (100% kenaf fibres)

The puncture resistance values between the fabric samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.3(c). The puncture resistance of the fabric remained the same with an increase in mass per unit area from 300 to 600 g/m^2, after which it increased with further increase in stroke frequency to 900 g/m^2. This lack of change in the puncture resistance was attributed to lowest values of stroke frequency and depth of needle penetration at higher mass per unit area which resulted in inadequate interlocking and entanglement of the fibres.

The puncture resistance values between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 350 and 450/min and fixed depth of needle penetration of 4 mm were compared as shown in Figure 4.3(c). The puncture resistance of the fabric increased with an increase in mass per unit area from 300 to 900 g/m^2. This increase in the puncture resistance was attributed to an increase in punch density which increased fibre entanglement, therefore, increased fabric density.

The puncture resistance values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.3(c). A similar trend, as observed in the case of 250/min stroke frequency and 4 mm depth of needle penetration, was noticed in this case also. The puncture resistance values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.3(c). The puncture resistance of the fabrics decreased with an increase in mass per unit area from 300 to 600 g/m^2, after which it increased with further increase in area weight to 900 g/m^2. The lower puncture resistance was attributed to shorter fibres which might prefer to be aligned in the cross-machine direction during needlepunching, thereby, promoting variations in web uniformity and areal density. The puncture resistance values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.3(c). A similar trend, as observed in the case of 450/min stroke frequency and 4 mm depth of needle penetration, was noticed in this case also.

The puncture resistance values between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250 and 450/min and fixed depth of needle penetration of 10 mm were compared as shown in Figure 4.3(c). The puncture resistance of the fabrics increased with an increase in mass per unit area. This increase was attributed to improved fabric compactness resulted from a higher number of fibres per unit area.

The puncture resistance values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 10 mm were compared as shown in Figure 4.3(c). A similar trend, as observed in the case of 350/min stroke frequency and 7 mm depth of needle penetration, was noticed in this case also.

Statistical analysis

The statistical analysis similar to that reported in the Section 4.2.4.2 was also conducted on the puncture resistance of the nonwoven fabrics produced from 100% kenaf fibres. All the tested parameters, their two-way and three-way interaction effects were statistically significant as shown in Table 4.11 below.

Table 4.11: ANOVA on puncture resistance data of the nonwoven fabrics produced from 100% kenaf fibres

Nonwoven fabric produced from 100% kenaf fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	1400813.4	1	1400813.4	2142.5	0.0
Mass per unit area	677651.3	2	338825.6	518.2	0.0
Stroke frequency	81757.8	2	40878.9	62.5	0.0
depth of needle penetration	237885.2	2	118942.6	181.9	0.0
Mass per unit area x stroke frequency	18553.9	4	4638.5	7.1	0.0
Mass per unit area x depth of needle penetration	77293.4	4	19323.3	29.6	0.0
Stroke frequency x depth of needle penetration	60315.3	4	15078.8	23.1	0.0
Mass per unit area x stroke frequency x depth of needle penetration	59072.3	8	7384.0	11.3	0.0
Error	70614.1	108	653.8		

4.2.4.7 Effect of fibre types

The effect of 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres on puncture resistance of the needlepunched nonwoven fabrics is discussed below:

(a) Effect of 100% PP fibres

The puncture resistance of the nonwoven fabrics follow a similar trend to the tensile strength - both increases with an increase in mass per unit area of the nonwoven fabric (Wojtasik, 2008; Fangueiro et al., 2011). The nonwoven fabrics produced from 100% PP fibres achieved better puncture resistance in comparison to those produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres. This was attributed to the properties of PP fibres as discussed in Section 4.2.2.7. In addition, the higher puncture resistance of the fabrics produced from 100% PP fibres was attributed to a higher number of finer fibres in the fibrous web which improved web uniformity and fibre interlocking (Rawal et al., 2008).

(b) Effect of 50/50% PP/kenaf fibre blend

The puncture resistance of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres was influenced by the differences in the properties of PP and kenaf fibres which influenced interlocking and entanglement of the fibres. In addition, the variations in the properties of PP and kenaf fibres promote non-uniformity in the web. The puncture resistance of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres was comparatively higher to that produced from 100% kenaf fibres.

(c) Effect of 100% kenaf fibres

The puncture resistance of the nonwoven fabrics produced from 100% kenaf fibres was influenced by variations in fineness and length of kenaf fibres which reduced interlocking and entanglement of the fibres. In addition, the puncture resistance of the nonwoven fabrics produced from 100% kenaf fibres was also influenced by difficulty of entangling coarser kenaf fibres having higher bending rigidity.

4.2.5 Pore size

4.2.5.1 Comparison of pore sizes within samples (100% PP fibres)

Figure 4.4(a) shows the influence of stroke frequency and mass per unit area on pore size of the nonwoven fabrics produced from 100% PP fibres at depths of needle penetration of 4, 7 and 10 mm. At an area weight of 300 g/m^2 and depths of needle penetration of 4, 7 and 10 mm, the pore size of the fabrics increased with an increase in stroke frequency from 250 to 350/min, however, it decreased with further increase in stroke frequency to 450/min. The increase in pore size was attributed to lower fibre-to-fibre friction and lower bending resistance of PP fibres which influenced interlocking and entanglement of the fibres and thus increasing space between the fibres (larger pores). The decrease in pore size was attributed to an increase in stroke frequency which increased interlocking and entanglement of the fibres and resulted in compact fabric with smaller pores (Simmonds et al., 2007; Rawal et al., 2010).

At an area weight of 600 g/m^2 and depths of needle penetration of 4, 7 and 10 mm, the pore size of the nonwoven fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it increased with further increase in stroke frequency to 450/min as shown in Figure 4.4(a).

This decrease was attributed to an increase in punch density which increased fibre entanglement up to an optimal level, therefore, minimised fibre-to-fibre contacts, thus resulted in smaller pore size (Rawal et al., 2010c). The increase in pore size was attributed to an increase in punch density above the optimal level which might reorient fibres with higher breakages. Reorientation and breakage of the fibres alter elementary layers and fibre volume fraction which affect formation of pores.

At an area weight of 900 g/m^2 and 4 mm depth of needle penetration, the pore size of the nonwoven fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it increased with further increase in stroke frequency to 450/min as shown in Figure 4.4(a). A similar trend, as observed in the case of area weight of 600 g/m^2 and 4 mm depth of needle penetration, was noticed in this case also. At an area weight of 900 g/m^2 and 7 mm depth of needle penetration, the pore size of the fabrics increased with an increase in stroke frequency from 250 to 350/min, after which it decreased with further increase in stroke frequency to 450/min as shown in Figure 4.4(a). A similar trend, as observed in the case of area weight of 300 g/m^2 and 4 mm depth of needle penetration, was noticed. At an area weight of 900 g/m^2 and 10 mm depth of needle penetration, the pore size of the fabrics decreased with an increase in stroke frequency from 250 to 450/min as shown in Figure 4.4(a). This decrease in the pore size was attributed to the barbs of the needles carrying a higher number of fibres at higher values of depth of needle penetration, stroke frequency and mass per unit area, therefore, increased interlocking and entanglement of the fibres provided a compact fabric as reported by others (Patnaik and Anandjiwala, 2008, Rawal et al., 2010).

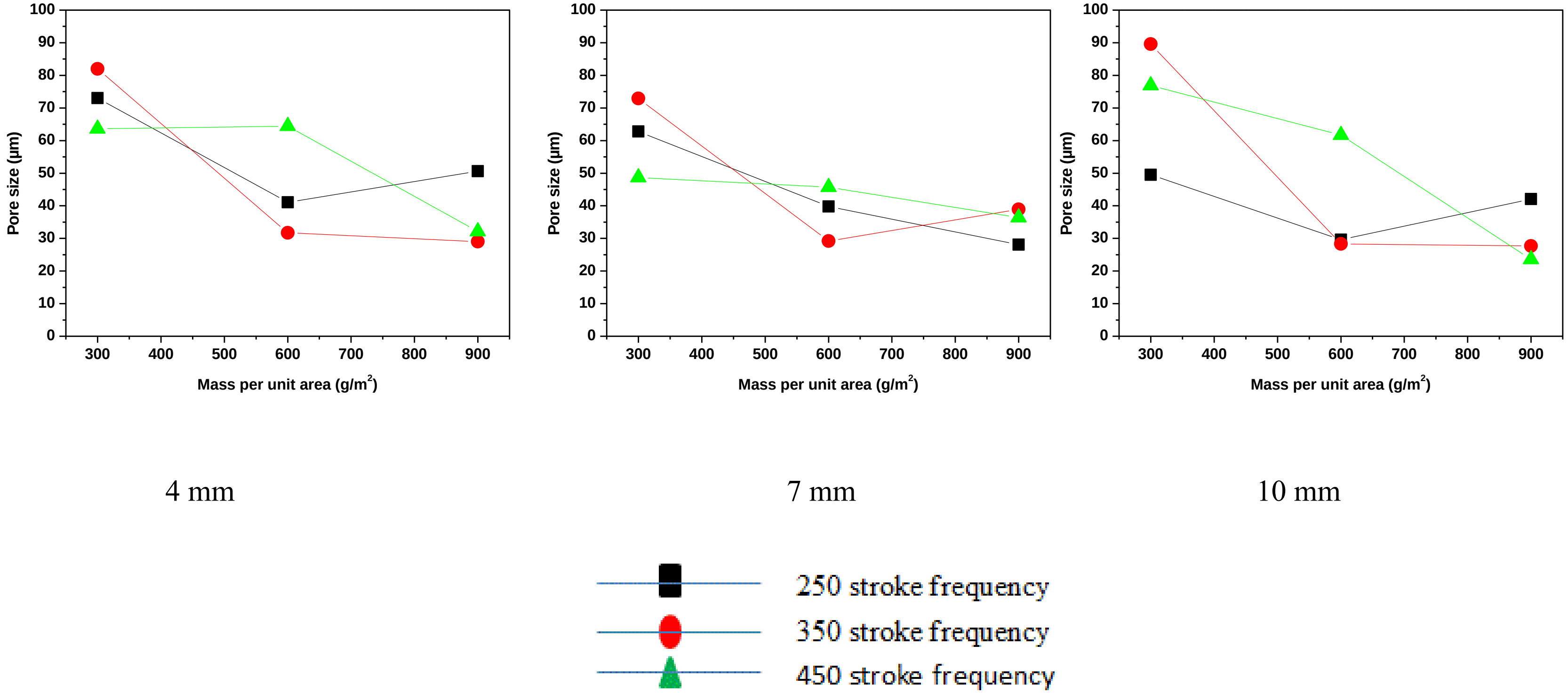

Figure 4.4(a) Effect of stroke frequency and mass per unit area on pore sizes of the nonwoven fabrics produced from 100% PP fibres at 4, 7 and 10 mm depths of needle penetration.

4.2.5.2 Comparison of pore sizes between samples (100% PP fibres)

The pore sizes of the nonwoven fabrics between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.4(a). The pore size of the nonwoven fabrics decreased with an increase in mass per unit area from 300 to 600 g/m^2, after which it increased with further increase in mass per unit area to 900 g/m^2. This decrease in the pore size was attributed to an increase in number of fibres per unit area of the fabric which increased fabric compactness (Majumdar et al., 2012). The increase in the pore size was attributed to lowest values of stroke frequency and depth of needle penetration at higher mass per unit area of the fabric which resulted in inadequate interlocking and entanglement of the fibres. The pore sizes between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.4(a). The pore size of the nonwoven fabrics decreased with an increase in mass per unit area. The decrease in the pore size was attributed to higher punch density and higher number of fibres per unit area of the fabric which increased fibre entanglement, therefore, increased fabric density while decreasing smallest, mean flow and maximum pore diameters (Patanaik and Anandjiwala, 2008). The pore sizes between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.4(a). The pore size of the fabrics remained constant with an increase in mass per unit area from 300 to 600 g/m^2, after which it decreased with further increase in mass per unit area to 900 g/m^2. This lack of change in the pore size was attributed to higher crimp in PP fibres which influenced uniformity of mass per unit area and thickness of the fabric which affect the pore size.

The pore sizes between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250 and 450/min and fixed depth of needle penetration of 7 mm were compared as shown in Figure 4.4(a). A trend, similar to that observed in the case of 350/min stroke frequency and 4 mm depth of needle penetration, was noticed. The pore sizes between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.4(a). A trend, similar to that observed in the case of 250/min stroke frequency and 4 mm depth of needle penetration, was noticed.

The pore sizes between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 10 mm were compared as shown in Figure 4.4(a). A trend, similar to that observed in the case of 250/min stroke frequency and 4 mm depth of needle penetration, was noticed. The pore sizes between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 350 and 450/min and constant depth of needle penetration of 10 mm were compared as shown in Figure 4.4(a). A trend, similar to that observed in the case of 450 stroke frequency and 7 mm depth of needle penetration, was noticed.

Statistical analysis

Similar statistical analysis, as in the case of puncture resistance of nonwoven fabrics, was conducted on pore size of 100% PP fibres and the results are shown in Table 4.12. All the tested parameters, their two-way and three-way interactions showed significant effects on pore size of the nonwoven fabrics.

Table 4.12: ANOVA on the data of pore size of the nonwoven fabrics produced from 100% PP fibres

Nonwoven fabric produced from 100% PP fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	312643.3	1	312643.3	6306.7	0.0
Mass per unit area	29956.6	2	14978.3	302.1	0.0
Stroke frequency	385.4	2	192.7	3.9	0.0
Needle depth of penetration	1193.7	2	596.9	12.0	0.0
Mass per unit area x stroke frequency	10208.1	4	2552.0	51.5	0.0
Mass per unit area x Needle depth of penetration	768.4	4	192.1	3.9	0.0
Stroke frequency x Needle depth of penetration	1604.5	4	401.1	8.1	0.0
Mass per unit area x stroke frequency x needle depth of penetration	4059.3	8	507.4	10.2	0.0
Error	5353.9	108	49.6		

4.2.5.3 Comparison of pore sizes within samples (a blend of 50/50% PP/kenaf fibres)

Figure 4.4(b) shows the influence of stroke frequency and mass per unit area on pore size of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres. At an area weight of 300 g/m^2 and 4 mm depth of needle penetration, the pore size of the fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it increased with further increase in stroke frequency to 450/min. The decrease in the pore size of the fabrics was attributed to an increase in stroke frequency which increased interlocking and entanglement of the fibres up to an optimal level, therefore, provided a compact fabric with smaller pores. The increase in the pore size of the fabrics was attributed to an increase in stroke frequency above the optimal level which reoriented fibres with higher breakages. In addition, the increase in the pore size of the fabrics was attributed to lowest values of depth of needle penetration and mass per unit area which resulted in insufficient interlocking and entanglement of the fibres, therefore, the fabric was less compact with bigger pores. At an area weight of 300 g/m^2 and 7 mm depth of needle penetration, the pore size of the fabrics decreased with an increase in stroke frequency. This decrease in the pore size mentioned above was attributed to the barbs of the needles which carried higher number of fibres at the highest values of depth of needle penetration and stroke frequency and thus resulted in better interlocking and entanglement of the fibres as reported by others (Rawal and Anandjiwala, 2006). At an area weight of 300 g/m^2 and 10 mm depth of needle penetration, the pore size of the fabrics remained the same with an increase in stroke frequency from 250 to 350/min, however, it increased with further increase in stroke frequency to 450/min. The lack of change in the pore size of the fabrics was attributed to fewer number of PP and kenaf fibres at lower mass per unit area as well as variations in the fabric elementary layers due to the following possibilities, PP and kenaf fibres were in contact to each other, PP fibres were in contact to each other and kenaf fibres were in contact to each other (Rawal and Saraswat, 2011a). The increase in pore size was attributed to differences in the fineness of PP and kenaf fibres which influenced fibre orientation and their distributions within the fabric.

At an area weight of 600 g/m^2 and depths of needle penetration of 4 and 7 mm, the pore sizes of the nonwoven fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it increased with further increase in stroke frequency to 450/min as shown in Figure 4.4(b). A trend, similar to that observed in the case of area weight of 300 g/m^2 and 4 mm depth of needle penetration, was also noticed in this case.

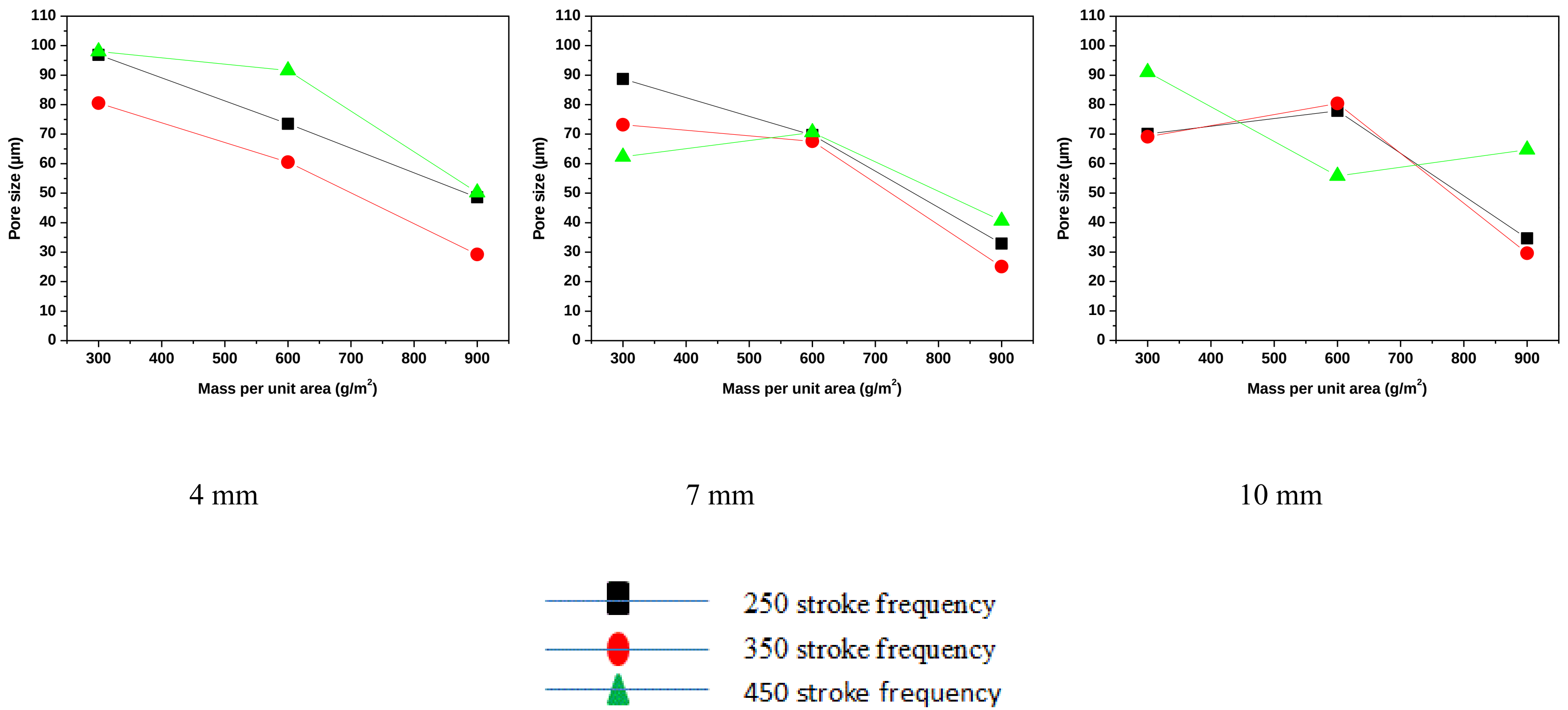

Figure 4.4(b) Effect of stroke frequency and mass per unit area on pore sizes of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres at 4, 7 and 10 mm depths of needle penetration.

At an area weight of 600 g/m^2 and 10 mm depth of needle penetration, the pore size of the fabrics increased with an increase in stroke frequency from 250 to 350/min, after which it decreased with further increase in stroke frequency to 450/min as shown in Figure 4.4(b). This increase in pore size was attributed to differences in the properties of PP and kenaf fibres which might influence fibre volume fraction, blend homogeneity, mass per unit area and thickness of the fabric. In addition, the increase in pore size was attributed to highest value of depth of needle penetration and an increase in stroke frequency which might promote variations in mass per unit area and thickness of the fabrics.

At an area weight of 900 g/m^2 and depths of needle penetration of 4, 7 and 10 mm, the pore sizes of the fabrics decreased with an increase in stroke frequency from 250 to 350/min and it continued to increase with further increase in stroke frequency to 450/min as shown in Figure 4.4(b). A trend, similar to that observed in the case of area weight of 600 g/m^2 and 4 mm depth of needle penetration, was noticed.

4.2.5.4 Comparison of the pore sizes between samples (a blend of 50/50% PP/kenaf fibres).

The pore sizes of the nonwoven fabrics between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.4(b). The pore size of the fabrics decreased with an increase in mass per unit area, which was attributed to increased fabric compactness as more number of fibres per unit area of the fabric were available.

The pore sizes between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 350 and 450/min and fixed depth of needle penetration of 4 mm were compared as shown in Figure 4.4(b). A trend, similar to that observed in the previous paragraph, was noticed.

The pore sizes between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250 and 350/min and constant depth of needle penetration of 7 mm were compared as shown in Figure 4.4(b). The pore size of the fabrics decreased with an increase in mass per unit area. A similar trend, as observed in the first paragraph of this section, was noticed. The pore sizes between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.4(b). The pore size of the fabrics increased with an increase in mass per unit area from 300 to 600 g/m^2, after which it decreased with further increase in mass per unit area to 900 g/m^2. This increase in pore size was attributed to differences in the diameter of PP and kenaf fibres which might induce variations in areal density, therefore, mean pore diameters and pore size distribution were affected (Dhaniyala and Liu, 2001; Rawal et al., 2010). Li et al. (2006) have also reported that the diameter of the fibre influence pore size and pore size distribution.

The pore sizes between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250 and 350/min and fixed depth of needle penetration of 10 mm were compared as shown in Figure 4.4(b). The pore size of the fabrics increased with an increase in mass per unit area from 300 to 600 g/m^2, after which it decreased with further increase in mass per unit area to 900 g/m^2. A similar trend, as observed in the case of 450/min stroke frequency and 7 mm depth of needle penetration, was noticed in this case also. The pore sizes between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 10 mm were compared as shown in Figure 4.4(b). The pore sizes of the fabrics decreased with an increase in mass per unit area from 300 to 600 g/m^2, after which it increased with further increase in mass per unit area to 900 g/m^2. This increase in pore size was attributed to less compact fabric resulted from higher fibre breakages occurring at the highest values of punch density and depth of needle penetration. In addition, the increase in pore size was attributed to random orientation of the fibres in each fabric elementary layer (Rawal and Saraswat, 2011a).

Statistical analysis

A similar statistical analysis, as presented in Section 4.2.2.2 for the fabrics produced from 100% PP fibres, was also carried out on data of the pore size of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres and the results are shown in Table 4.13. All the tested parameters as well as three-way interactions showed significant effects. The interactions between mass per unit area and stroke frequency and between stroke frequency and depth of needle penetration showed significant effects on the pore size of the fabrics, however, the interaction between mass per unit area and depth of needle penetration was not significant, ($P = 0.099$). This non-significant effect was attributed to excessive breakages of coarser kenaf fibres at higher depth of needle penetration as well as shorter fibres which were preferentially aligned to cross-machine direction during the needlepunching process.

Table 4.13: ANOVA on the data of pore size of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres

Nonwoven fabric produced from 50/50% PP/kenaf fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	556230.1	1	556230.1	3827.7	0.0
Mass per unit area	43003.8	2	21501.9	147.9	0.0
Stroke frequency	3520.0	2	1760.0	12.1	0.0
depth of needle penetration	2688.7	2	1344.3	9.3	0.0
Mass per unit area x stroke frequency	1961.6	4	490.4	3.4	0.0
Mass per unit area x depth of needle penetration	1166.7	4	291.7	2.0	0.1
Stroke frequency x depth of needle penetration	2346.2	4	586.5	4.0	0.0
Mass per unit area x stroke frequency x depth of needle penetration	6271.4	8	783.9	5.4	0.0
Error	15694.3	108	145.3		

4.2.5.5 Comparison of pore sizes within samples (100% kenaf fibres)

Figure 4.4(c) shows the influence of stroke frequency and mass per unit area on pore sizes of the nonwoven fabrics produced from 100% kenaf fibres at depths of needle penetration of 4, 7 and 10 mm. At an area weight of 300 g/m^2 and 4 mm depth of needle penetration, the pore size of the fabrics decreased with an increase in stroke frequency. This decrease was attributed to an increase in stroke frequency which increased interlocking and entanglement of the fibres, therefore, a compact fabric with smaller pores was resulted. Medium pores (O_{50}) were converted into smaller pores (O_{10}) while bigger pores O_{95} were converted into medium pores with an increase in interlocking and entanglement of the fibres at higher stroke frequency (Patanaik and Anandjiwala, 2008). At an area weight of 300 g/m^2 and depths of needle penetration of 7 and 10 mm, the pore size of the fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it increased with further increase in stroke frequency to 450/min. This increase in pore size was attributed to less compact fabric resulted from higher depth of needle penetration and an increase in stroke frequency above the optimal level which caused excessive fibre breakages and reorientation of the fibres.

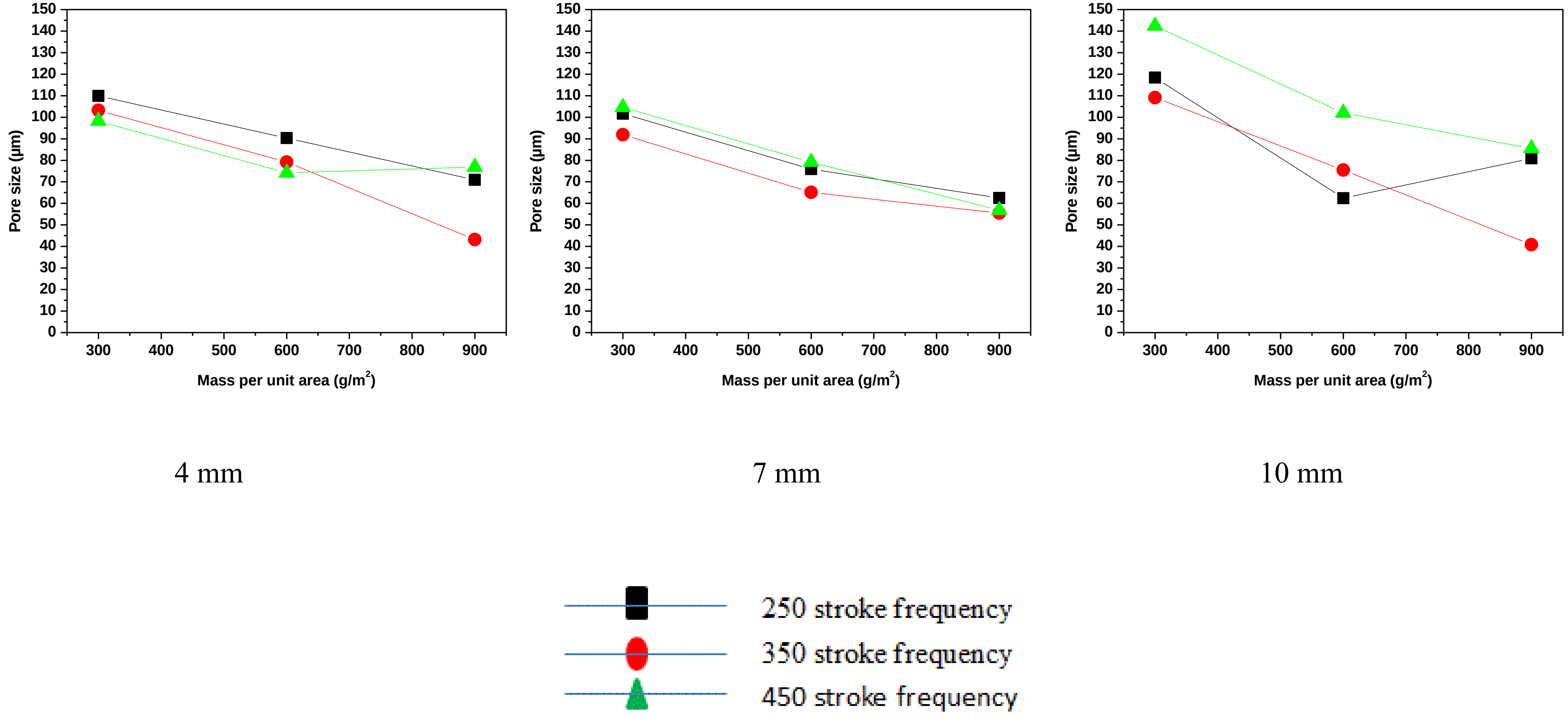

Figure 4.4(c) Effect of stroke frequency and mass per unit area on pore sizes of the nonwoven fabrics produced from 100% kenaf fibres at 4, 7 and 10 mm depths of needle penetration.

At an area weight of 600 g/m^2 and 4 mm depth of needle penetration, the pore size of the fabrics decreased with an increase in stroke frequency as shown in Figure 4.4(c). A trend, similar to that observed in the case of area weight of 300 g/m^2 and 4 mm depth of needle penetration, was noticed. At an area weight of 600 g/m^2 and 7 mm depth of needle penetration, the pore size of the fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it increased with further increase in stroke frequency to 450/min as shown in Figure 4.4(c). A trend, similar to that observed in the case of area weight of 300 g/m^2 and depths of needle penetration of 7 and 10 mm, was noticed. At an area weight of 600 g/m^2 and 10 mm depth of needle penetration, the pore size of the fabrics increased with an increase in stroke frequency as shown in Figure 4.4(c). This increase was attributed to variations in fibre aspect ratio, fineness and length of kenaf fibres which resulted in irregularity of mass per unit area and thickness of the fabrics. Li et al. (2006) have reported that the variations in the fibre size influence space between the fibres and pore sizes between the fibres.

At an area weight of 900 g/m^2 and depths of needle penetration of 4 and 10 mm, the pore size of the fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it continued to increase with further increase in stroke frequency to 450/min as shown in Figure 4.4(c). A trend, similar to that observed in the case of area weight of 300 g/m^2 and 7 mm depth of needle penetration, was noticed. At an area weight of 900 g/m^2 and 7 mm depth of needle penetration, the pore size of the fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it remained constant with further increase in stroke frequency to 450/min as shown in Figure 4.4(c). This lack of change in the pore size was attributed to preferential alignment of shorter fibres to cross-machine direction during needling-punching process.

4.2.5.6 Comparison of pore sizes between samples (100% kenaf fibres)

The pore sizes of the nonwoven fabrics between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250 and 350/min and fixed depth of needle penetration of 4 mm were compared as shown in Figure 4.4(c). The pore size of the fabrics decreased with an increase in mass per unit area. This decrease was attributed to higher number of fibres per unit area of the fabric.

The pore sizes between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.4(c). The pore size of the fabrics decreased with an increase in mass per unit area from 300 to 600 g/m^2, after which it increased with further increase in mass per unit area to 900 g/m^2. This increase in the pore size was attributed to less compact fabric resulted from higher breakages of the fibres at higher stroke frequency which reduced average fibre length (Roy and Ray, 2009).

The pore sizes between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250, 350 and 450/min and fixed depth of needle penetration of 7 mm were compared as shown in Figure 4.4(c). A similar trend, as observed in the first paragraph of this section, was noticed.

The pore sizes between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 10 mm were compared as shown in Figure 4.4(c). The pore size of the fabrics decreased with an increase in mass per unit area from 300 to 600 g/m^2, after which it increased with further increase in mass per unit area to 900 g/m^2. This increase in pore size was attributed to lower stroke frequency at higher mass per unit area which resulted in inadequate interlocking and entanglement of the fibres. In addition, this increase in pore size was also attributed to variations in the diameter and length of kenaf fibres which affected pore size and pore size distribution.

The pore sizes between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 350 and 450/min and constant depth of needle penetration of 10 mm were compared as shown in Figure 4.4(c). The pore size of the fabrics decreased with an increase in mass per unit area as reported by others (Midha and Mukhopadyay , 2005).

Statistical analysis

Similar statistical analysis, as presented in Section 4.2.2.2 for the fabrics produced from 100% PP fibres, was also carried out on the data of pore size of the nonwoven fabrics produced from 100% kenaf fibres. All the tested parameters as well as their two-way and three-way interactions were statistically significant.

Table 4.14: ANOVA on the data of pore size of the nonwoven fabrics produced from 100% kenaf fibres

Nonwoven fabric produced from 100% kenaf fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	942835.9	1	942835.9	5629.3	0.0
Mass per unit area	47815.7	2	23907.8	142.7	0.0
Stroke frequency	7142.6	2	3571.3	21.3	0.0
depth of needle penetration	4303.8	2	2151.9	12.8	0.0
Mass per unit area x stroke frequency	2095.3	4	523.8	3.1	0.0
Mass per unit area x depth of needle penetration	1975.9	4	493.9	2.9	0.0
Stroke frequency x depth of needle penetration	4825.5	4	1206.3	7.2	0.0
Mass per unit area x stroke frequency x depth of needle penetration	4393.6	8	549.2	3.3	0.0
Error	18088.7	108	167.5		

4.2.5.7 Effect of fibre types

The effect of 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres on pore size of the needlepunched nonwoven fabrics is discussed below:

(a) Effect of 100% PP fibres

Needlepunched nonwoven fabrics produced from finer fibres achieve smaller pores. The smaller pores in the fabrics produced from 100% PP fibres in comparison to that produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres, as shown in Figures 4.4(a), 4.4(b) and 4.4(c), were attributed to lower breakages of PP fibres during needlepunching. The pore sizes of the fabrics produced from 100% PP fibres were also influenced by the crimp which might promote variations in pore diameter as well as fibre orientation on which pore size depends (Jena and Gupta, 2002). In addition, nonwoven fabric produced from 100% PP fibres was composed of several elementary layers, therefore, the length of the fibres in the elementary layer influenced the size of pores in the next elementary layer. Furthermore, pore size of the fabrics produced from 100% PP fibres might be influenced by longer fibres which divide pores into two, therefore, the pore size was reduced.

(b) Effect of a blend of 50/50% PP/kenaf fibres

The pore size of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres was influenced by differences in the properties of PP and kenaf fibres, which affected blend homogeneity, web uniformity, interlocking and entanglement of the fibres, therefore, affecting fabric compactness. Variations in the properties of PP and kenaf fibres may also result in irregular pore size. Better filtration efficiency and pressure drop are important in filtration applications, however, it is impossible to achieve both attributes simultaneously. The nonwoven fabrics produced from finer fibres achieve higher filtration efficiency in comparison to that produced from coarser fibres. However, the nonwoven fabrics produced from coarser fibres achieve lower pressure drop in comparison to that produced from finer fibres. The advantage of producing nonwoven fabrics from a blend of 50/50% PP/kenaf fibres is that a better balance between filtration efficiency and pressure drop may be achieved (Fotovati et al., 2010; Pradhan et al., 2014).

(c) Effect of 100% kenaf fibres

The pore size of the nonwoven fabrics produced from 100% kenaf fibres was influenced by the difficulties in entangling kenaf fibres due to their higher bending rigidity and variations in length and fineness. In addition, the variations in the fineness and length of kenaf fibres may increase spaces between the fibres in the elementary layers which affect the pore formation. Furthermore, the pore size of the fabrics produced from 100% kenaf fibres was also influenced by higher depth of needle penetration and stroke frequency which reoriented the fibres and also caused high fibre breakages.

4.2.6 Cross-plane water permeability

4.2.6.1 Comparison of water permeability within samples (100% PP fibres)

Figure 4.5(a) shows the influence of stroke frequency and mass per unit area on water permeability of the nonwoven fabrics produced from 100% PP fibres at depths of needle penetration of 4, 7 and 10 mm. At an area weight of 300 g/m^2 and 4 mm depth of needle penetration, water permeability of the fabrics remained constant with an increase in stroke frequency from 250 to 350/min, after which it decreased with further increase in stroke frequency to 450/min. This lack of change in water permeability was attributed to lower depth of needle penetration and fewer number of PP fibres at lower mass per unit area which influenced interlocking and entanglement of the fibres, therefore, resulted in less compact fabric with bigger pores.

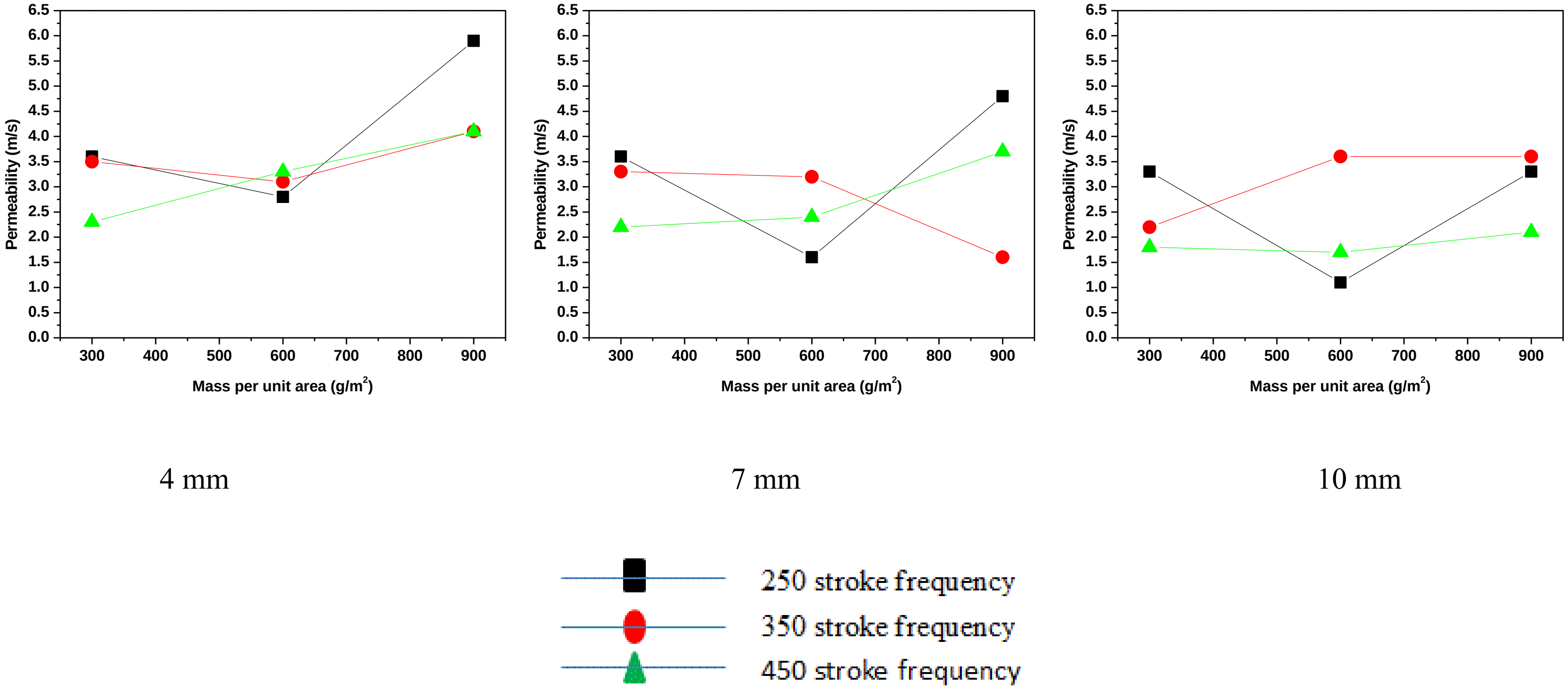

Figure 4.5(a) Effect of stroke frequency and mass per unit area on water permeability of the nonwoven fabrics produced from 100% PP fibres at 4, 7 and 10 mm depths of needle penetration.

The decrease in the permeability was attributed to the compactness of the fabric resulted from better interlocking and entanglement of the fibres at higher stroke frequency (Mao and Russell, 2000; Russell, 2006). At an area weight of 300 g/m^2 and depths of needle penetration of 7 and 10 mm, water permeability of the fabrics decreased with an increase in stroke frequency as shown in Figure 4.5(a). This decrease was attributed to the fabric compactness resulted from higher number of fibres carried by barbs of the needles at higher depth of needle penetration as well as increased stroke frequency. The increase in fabric compactness decreases pore size which results in higher pressure drop.

At an area weight of 600 g/m^2 and 4 mm depth of needle penetration, water permeability of the fabrics increased with an increase in stroke frequency as shown in Figure 4.5(a). This increase was attributed to the crimp of PP fibres which influenced uniformities in mass per unit area and thickness of the fabrics, thus depth and width of pores were affected, which in turn, influenced water permeability.

At an area weight of 600 g/m^2 and depths of needle penetration of 7 and 10 mm, water permeability of the nonwoven fabrics increased with an increase in stroke frequency from 250 to 350/min, after which it decreased with further increase in stroke frequency to 450/min as shown in Figure 4.5(a). This increase was attributed to reorientation of the fibres during needlepunching process. Mao and Russel (2003) have reported that water permeability of the fabric depends on fibre orientation.

At an area weight of 900 g/m^2 and 4 mm depth of needle penetration, water permeability of the fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it remained constant with further increase in stroke frequency to 450/min as shown in Figure 4.5(a). This lack of change in water permeability was attributed to stroke frequency above the optimal level which caused higher breakages and reorientation of the fibres.

At an area weight of 900 g/m^2 and 7 mm depth of needle penetration, water permeability of the fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it increased with further increase in stroke frequency to 450/min as shown in Figure 4.5(a). This increase in the water permeability of the fabrics at higher mass per unit area was attributed to some of the fibres which might not have been carried by the barbs of the needles, therefore, resulted in less compact fabric with bigger pores. At an area weight of 900 g/m^2 and 10 mm depth of needle penetration, water permeability of the fabrics increased with an increase in stroke frequency from 250 to 350/min, after which it decreased with further increase in stroke frequency to 450/min as shown in Figure 4.5(a). A similar trend, as observed in the case of area weight of 600 g/m^2 and 7 mm depth of needle penetration, was noticed.

4.2.6.2 Comparison of water permeability between samples (100 % PP fibres)

The water permeability values of the nonwoven fabrics between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.5(a). The permeability of the fabrics decreased with an increase in mass per unit area from 300 to 600 g/m^2, after which it increased with further increase in mass per unit area to 900 g/m^2. This decrease in water permeability was attributed to higher number of fibres per unit area providing a compact fabric with smaller pores and the increase was attributed to lowest values of stroke frequency and depth of needle penetration at higher mass per unit area which resulted in lower interlocking and entanglement of the fibres with bigger pores.

The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.5(a). A similar trend, as observed in the previous paragraph, was noticed.

The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.5(a). The permeability of the fabrics increased with an increase in mass per unit area. The increase was due to lower fibre-to-fibre friction and bending resistance of PP fibres and higher mass per unit area which might result in less compact fabric with bigger pores and higher water permeability.

The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.5(a). A similar trend, as observed in the case of 250 /min stroke frequency and 4 mm depth of needle penetration, was noticed in this case also.

The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.5(a). The water permeability of the fabrics decreased with an increase in mass per unit area. This decrease in water permeability was attributed to higher values of stroke frequency and depth of needle penetration as well as higher number of fibres per unit area of the fabric which resulted in more compact fabrics due to better interlocking and entanglement of the fibres (Debnath and Madhusoothanan, 2010).

The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.5(a). A trend, similar to that observed in the case of 450/min stroke frequency at 4 mm depth of needle penetration, was noticed.

The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetrations of 10 mm were compared as shown in Figure 4.5(a). A similar trend, as observed in the case of 250/min stroke frequency and 4 mm depth of needle penetration, was noticed. The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 10 mm were compared as shown in Figure 4.5(a). The water permeability of the fabrics increased with an increase in mass per unit area from 300 to 600 g/m^2, after which it remained constant with further increase in mass per unit area to 900 g/m^2. This lack of change in the permeability was attributed to the crimp of PP fibres at higher mass per unit area which influenced uniformity of the fibrous web, promoted variations in areal density and thickness of the fabrics. The crimp in fibres influences orientation of fibres and pore diameter on which the water permeability depends.

The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 10 mm were compared as shown in Figure 4.5(a). A similar trend, as observed in the case of 250/min stroke frequency and 4 mm depth of needle penetration, was noticed.

Statistical analysis

A statistical analysis, as presented in Section 4.2.2.2 for the fabrics produced from 100% PP fibres, was also carried out on the water permeability data of the nonwoven fabrics produced from 100% PP fibres and the results are shown in Table 4.15. All the tested parameters as well as their two-way and three-way interactions were statistically significant.

Table 4.15: ANOVA on the data of water permeability of the nonwoven fabrics produced from 100% PP fibres

Nonwoven fabric produced from 100% PP fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	1274.5	1	1274.5	7907.1	0.0
Mass per unit area	32.0	2	16.0	99.3	0.0
Stroke frequency	11.9	2	5.9	36.9	0.0
depth of needle penetration	27.8	2	13.9	86.2	0.0
Mass per unit area x stroke frequency	41.2	4	10.3	63.9	0.0
Mass per unit area x depth of needle penetration	6.5	4	1.6	10.0	0.0
Stroke frequency x depth of needle penetration	9.6	4	2.4	14.8	0.0
Mass per unit area x stroke frequency x depth of needle penetration	22.9	8	2.9	17.8	0.0
Error	17.4	108	0.2		

4.2.6.3 Comparison of water permeability within samples (a blend of 50/50% PP/kenaf fibres)

Figure 4.5(b) shows the influence of stroke frequency and mass per unit area on water permeability of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres at depths of needle penetration of 4, 7 and 10 mm. At an area weight of 300 g/m^2 and 4 mm depth of needle penetration, water permeability of the fabrics decreased with an increase in stroke frequency from 250 to 450/min. This decrease in water permeability was attributed to an increase in stroke frequency which increased interlocking and entanglement of the fibres, therefore, resulted in a compact fabric with smaller pores. At an area weight of 300 g/m^2 and 7 mm depth of needle penetration, water permeability of the fabrics increased with an increase in stroke frequency from 250 to 350/min, after which it decreased with further increase in stroke frequency to 450/min. This increase in water permeability was attributed to differences in the properties of PP and kenaf fibres which influenced orientation of the fibres, their distributions and blend homogeneity.

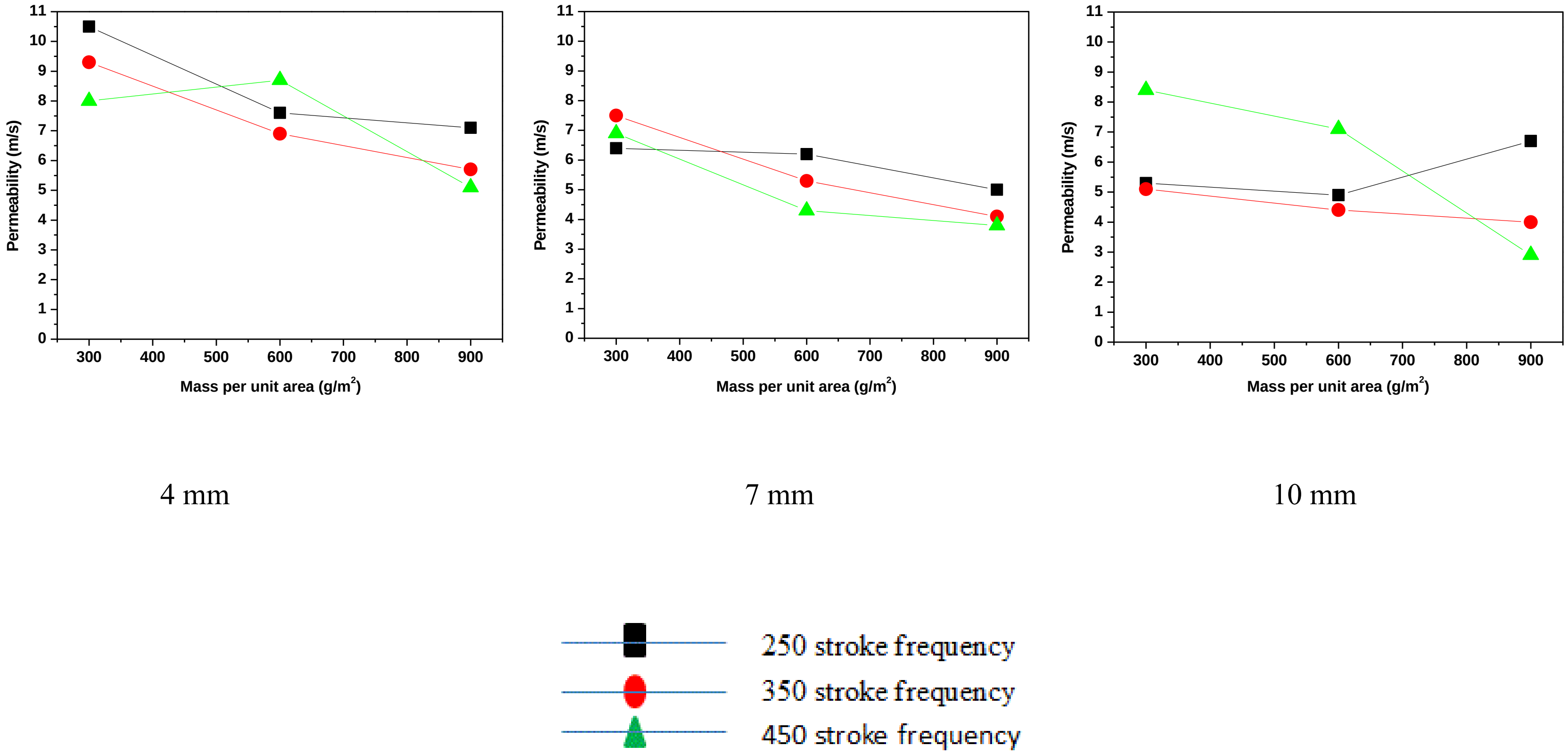

Figure 4.5(b) Effect of stroke frequency and mass per unit area on water permeability of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres at 4, 7 and 10 mm depths of needle penetration.

At an area weight of 300 g/m^2 and 10 mm depth of needle penetration, water permeability of the fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it increased with further increase in stroke frequency to 450/min. The increase in water permeability was attributed to highest values of depth of needle penetration and stroke frequency at lower mass per unit area which might reorient fibres with higher breakages. The increase in water permeability was also attributed to fabric anisotropy which influenced velocity of the fluid. The flow and penetration of a drop of water in the nonwoven fabrics depend on the size and impingement velocity (Jaganathan et al., 2008).

At an area weight of 600 g/m^2 and depths of needle penetration of 4 and 10 mm, water permeability of the fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it increased with further increase in stroke frequency to 450/min as shown in Figure 4.5(b). A similar trend, as observed in the case of area weight of 300 g/m^2 and 10 mm depth of needle penetration, was noticed. At an area weight of 600 g/m^2 and 7 mm depth of needle penetration, water permeability of the fabrics decreased with an increase in stroke frequency as shown in Figure 4.5(b). This decrease in water permeability was attributed to higher number of fibres per unit area of the fabric which provided a compact fabric with smaller pores due to better interlocking and entanglement of the fibres.

At an area weight of 900 g/m^2 and depths of needle penetration of 4, 7 and 10 mm, the water permeability of the nonwoven fabric decreased with an increase in stroke frequency as shown in Figure 4.5(b). A similar trend, as observed in the previous paragraph, was noticed.

4.2.6.4 Comparison of water permeability between samples (a blend of 50/50% PP/kenaf fibres)

The water permeability values of the nonwoven fabrics between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.5(b). The water permeability of the fabrics decreased with an increase in mass per unit area, which was attributed to an increase in fibre volume fraction.

The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.5(b). A similar trend, as observed in the previous paragraph, was noticed.

The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.5(b). The water permeability of the fabrics increased with an increase in mass per unit area from 300 to 600 g/m^2, after which it decreased with further increase in mass per unit area to 900 g/m^2. This increase in water permeability was attributed to disparities in fibre diameters of PP and kenaf fibres as well as ratio of fibres perpendicular to the plane of the fabric (Rawal et al., 2010). Variations in fibre diameters may influence uniformity of mass per unit area and thickness of the fabric which promotes variations in pore diameters on which the water permeability depends (Jena and Gupta, 2002). Chuang et al. (2011) have reported that fibre diameter influence pore size and water permeability of the fabrics.

The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250, 350, and 450/min but fixed depth of needle penetration of 7 mm were compared as shown in Figure 4.5(b). A similar trend, as observed in the first paragraph of this section, was noticed.

The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 10 mm were compared as shown in Figure 4.5(b). The water permeability of the fabrics decreased with an increase in mass per unit area from 300 to 600 g/m^2, after which it increased with further increase in mass per unit area to 900 g/m^2. This increase in water permeability was attributed to lower stroke frequency and higher mass per unit area which resulted in inadequate interlocking and entanglement of the fibres, thus a less compact fabric with bigger pores was produced.

The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 350 and 450/min and constant depth of needle penetration of 10 mm were compared as shown in Figure 4.5(b). A similar trend, as observed in the first paragraph of this section, was noticed.

Statistical analysis

A similar statistical analysis, as presented in Section 4.2.6.2, was also carried out on the water permeability data of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres as shown in Table 4.16. All the tested parameters, their two-way and three-way interactions were statistically significant.

Table 4.16: ANOVA on the data of water permeability of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres

Nonwoven fabric produced from 50/50% PP/kenaf fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	5218.1	1	5218.1	10782.9	0.0
Mass per unit area	146.3	2	73.2	151.2	0.0
Stroke frequency	16.0	2	8.0	16.6	0.0
depth of needle penetration	142.8	2	71.4	147.6	0.0
Mass per unit area x stroke frequency	39.8	4	9.9	20.5	0.0
Mass per unit area x depth of needle penetration	11.0	4	2.8	5.7	0.0
Stroke frequency x depth of needle penetration	24.2	4	6.0	12.5	0.0
Mass per unit area x stroke frequency x depth of needle penetration	63.6	8	7.9	16.4	0.0
Error	52.3	108	0.5		

4.2.6.5 Comparison of water permeability within samples (100% kenaf fibres)

Figure 4.5(c) shows the influence of stroke frequency and mass per unit area on water permeability of the nonwoven fabrics produced from 100% kenaf fibres at depths of needle penetration of 4, 7 and 10 mm. At an area weight of 300 g/m^2 and 4 mm depth of needle penetration, water permeability of the fabrics remained constant with an increase in stroke frequency from 250 to 350/min, after which it decreased with further increase in stroke frequency to 450/min. This lack of change in water permeability was attributed to less compact fabric resulted from lower depth of needle penetration and fewer number of kenaf fibres per unit area of the fabric which influenced interlocking and entanglement of the fibres. The decrease in water permeability was attributed to higher stroke frequency which increased interlocking and entanglement of the fibres, therefore, resulted in a compact fabric with smaller pores. At an area weight of 300 g/m^2 and 7 mm depth of needle penetration, water permeability of the fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it remained constant with further increase in stroke frequency to 450/min. This lack of change in water permeability was attributed to higher values of stroke frequency and depth of needle penetration which might have reoriented fibres with higher breakages.

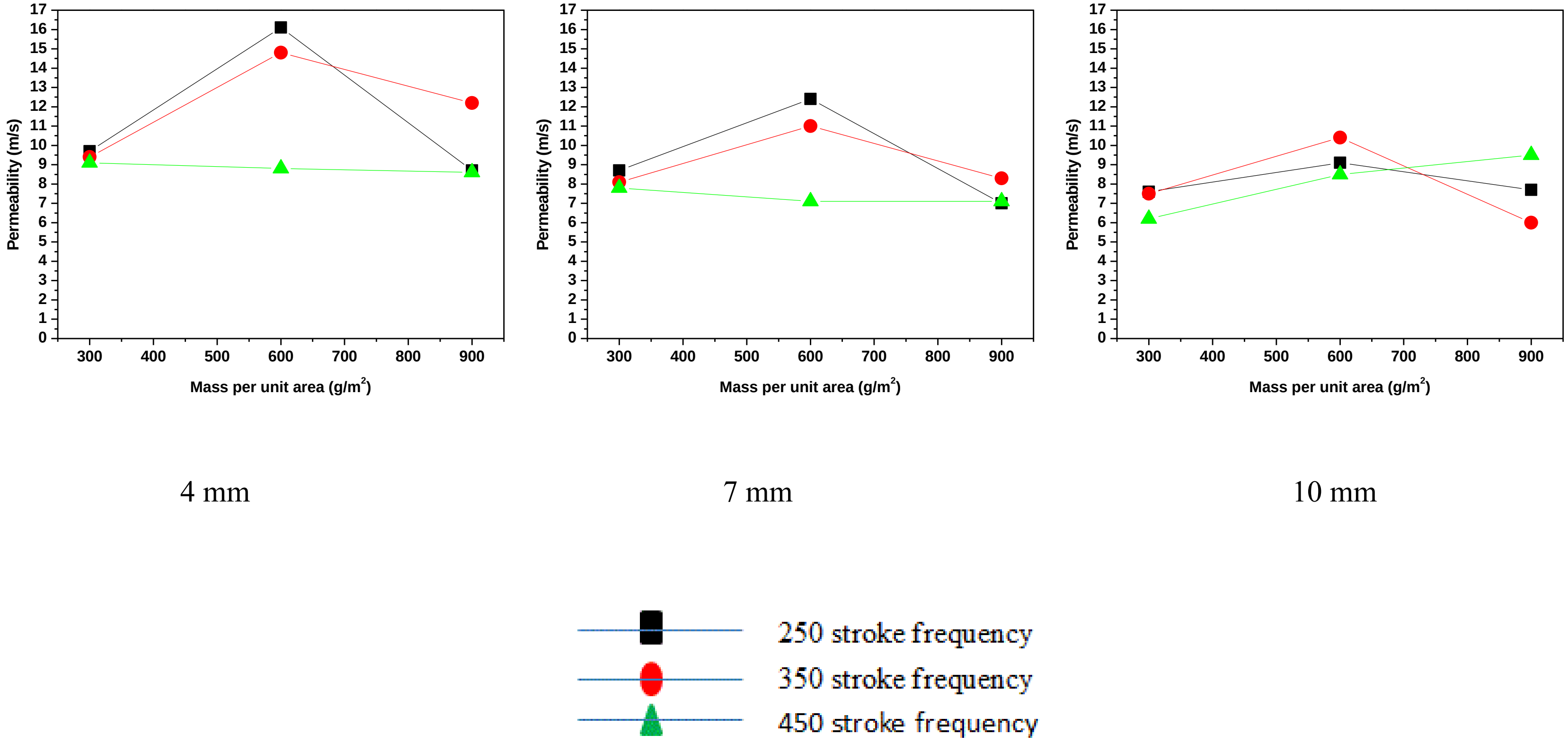

Figure 4.5(c) Effect of stroke frequency and mass per unit area on water permeability of the nonwoven fabrics produced from 100% kenaf fibres at 4, 7 and 10 mm depths of needle penetration.

At an area weight of 300 g/m^2 and 10 mm depth of needle penetration, a similar trend, as observed in the case of area weight of 300 g/m^2 and 4 mm depth of needle penetration, was noticed.

At an area weight of 600 g/m^2 and depths of needle penetration of 4 and 7 mm, water permeability of the fabrics decreased with an increase in stroke frequency due to more compact fabrics resulting from better interlocking and entanglement of the fibres as reported by others (Roy and Ray, 2009) and shown in Figure 4.5(c). At an area weight of 600 g/m^2 and 10 mm depth of needle penetration, water permeability of the fabrics increased with an increase in stroke frequency from 250 to 350/min, after which it decreased with further increase in stroke frequency to 450/min as shown in Figure 4.5(c). This increase in water permeability was attributed to shorter fibres, which were preferentially aligned to cross-machine direction during needlepunching, thus resulting in non-uniform mass per unit area and thickness of the fabrics.

At an area weight of 900 g/m^2 and depths of needle penetration of 4 and 7 mm, a similar trend, as observed in the case of area weight of 600 g/m^2 and 10 mm depth of needle penetration, was noticed. At an area weight of 900 g/m^2 and 10 mm depth of needle penetration, water permeability of the fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it increased with further increase in stroke frequency to 450/min as shown in Figure 4.5(c). This increase in water permeability was attributed to higher punch density and depth of needle penetration which caused breakage of the fibres while reducing average fibre length. This increase in water permeability was also attributed to the variations in water permeability caused by heterogeneous fabric structure (Rawal et al., 2010a).

4.2.6.6 Comparison of water permeability between samples (100% kenaf fibres)

The water permeability values of the nonwoven fabrics between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.5(c). The water permeability of the fabrics increased with an increase in mass per unit area from 300 to 600 g/m^2, after which it decreased with further increase in mass per unit area to 900 g/m^2. This increase in water permeability was attributed to the lowest values of depth of needle penetration and stroke frequency at higher mass per unit area which resulted in inadequate interlocking and entanglement of the fibres. The decrease in water permeability was attributed to an increase in number of fibres per unit area of the fabric.

The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.5(c). A similar trend, as observed in the previous paragraph, was noticed.

The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.5(c). The water permeability of the fabrics decreased with an increase in mass per unit area. This decrease in water permeability was attributed to an increase in number of fibres per unit area of the fabric which provided a compact fabric as reported by others (Midha and Mukhopadyay, 2005).

The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250 and 350/min and constant depth of needle penetration of 7 mm were compared as shown in Figure 4.5(c). A similar trend, as observed in the first paragraph of this section, was noticed. The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.5(c). The water permeability of the fabrics decreased with an increase in mass per unit area from 300 to 600 g/m^2, after which it increased with further increase in mass per unit area to 900 g/m^2. This increase in water permeability was attributed to higher bending rigidity and higher number of kenaf fibres in heavier fabrics which influenced mass per unit area and thickness of the nonwoven fabric.

The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250 and 350/min and fixed depth of needle penetration of 10 mm were compared as shown in Figure 4.5(c). A similar trend, as observed in the first paragraph of this section, was noticed.

The water permeability values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 10 mm were compared as shown in Figure 4.5(c). The water permeability of the fabrics increased with an increase in mass per unit area. This increase in water permeability was attributed to the highest values of stroke frequency and depth of needle penetration which might reorient fibres, therefore, influence water permeability. Mao and Russell (2003) have reported that fibre orientation varies from region to region and it influences water permeability. In addition, the increase in water permeability was also attributed to variations in the length and diameter of kenaf fibres which might influence pore size and water permeability.

Statistical analysis

All the tested parameters, their two-way and three-way interactions showed significant effects on water permeability of the nonwoven fabrics produced from 100% kenaf fibres as shown in Table 4.17 below.

Table 4.17: ANOVA on the data of water permeability of the nonwoven fabrics produced from 100% kenaf fibres

Nonwoven fabric produced from 100% kenaf fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	11395.1	1	11395.1	17902.3	0.0
Mass per unit area	206.6	2	103.3	162.3	0.0
Stroke frequency	81.5	2	40.8	64.0	0.0
depth of needle penetration	192.2	2	96.1	151.0	0.0
Mass per unit area x stroke frequency	111.7	4	27.9	43.9	0.0
Mass per unit area x depth of needle penetration	23.7	4	5.9	9.3	0.0
Stroke frequency x depth of needle penetration	50.4	4	12.6	19.8	0.0
Mass per unit area x stroke frequency x depth of needle penetration	84.1	8	10.5	16.5	0.0
Error	68.7	108	0.6		

4.2.6.7 Effect of fibre types

The effect of 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres on water permeability of the needlepunched nonwoven fabrics is discussed below:

(a) Effect of 100% PP fibres

The water permeability values of the fabrics produced from 100% PP fibres are influenced by the hydrophobic properties of PP fibres, therefore, nonwoven fabrics produced from 100% PP fibres absorb lower amount of water in comparison to that produced from a blend of 50/50% PP/kenaf fibres and 100% kenaf fibres. In addition, the lower water permeability of the fabrics produced from 100% PP fibres was also influenced by fineness of PP fibres which provided a relatively compact fabric with smaller pores. Furthermore, the permeability of the fabrics produced from 100% PP fibres was influenced by the crimp and bending resistance of PP fibres that influences orientation of the fibres, therefore, pore sizes were also affected.

(b) Effect of a blend of 50/50% PP/kenaf fibres

The water permeability of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres was influenced by the hydrophobic and hydrophilic properties of PP and kenaf fibres, respectively. In addition, the permeability of the fabrics produced from a blend of 50/50% PP/kenaf fibres was influenced by numbers of PP and kenaf fibres as well as their orientations in the nonwoven fabric. Variations in the properties of both PP and kenaf fibres may result in non-uniform mass per unit area and thickness of the fabrics on which water permeability depends. Furthermore, the permeability of the fabrics produced from a blend of 50/50% PP/kenaf fibres was influenced by higher stroke frequency and depth of needle penetration which might cause higher fibre breakages and reorientation. The water permeability of the needlepunched nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres was higher in comparison to that produced from 100% PP fibres.

(c) Effect of 100% kenaf fibres

The water permeability of the nonwoven fabrics produced from 100% kenaf fibres was attributed to hydrophilic properties of the kenaf fibres. In addition, a fabric with bigger pores was produced due to coarseness of kenaf fibres. Furthermore, the water permeability of the fabrics produced from 100% kenaf fibres was influenced by majority of shorter fibres which might have reoriented in the cross-machine direction during the needlepunching process (Rawal and Anandjiwala, 2007).

4.2.7 Transmissivity of the nonwoven fabrics

4.2.7.1 Comparison of transmissivity within samples (100% PP fibres)

Figure 4.6(a) shows the influence of stroke frequency and mass per unit area on transmissivity of the nonwoven fabrics produced from 100% PP fibres at depths of needle penetration of 4, 7 and 10 mm. At an area weight of 300 g/m^2 and 4 mm depth of needle penetration, transmissivity of the fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it increased with further increase in stroke frequency to 450/min. The decrease in transmissivity was attributed to higher stroke frequency which reoriented the majority of the fibres from horizontal to vertical (thickness) directions (Rawal and Anandjiwala, 2006). The increase in transmissivity was also attributed to increase in the stroke frequency above the optimal level which results in preponderance of fibre orientation in the horizontal direction.

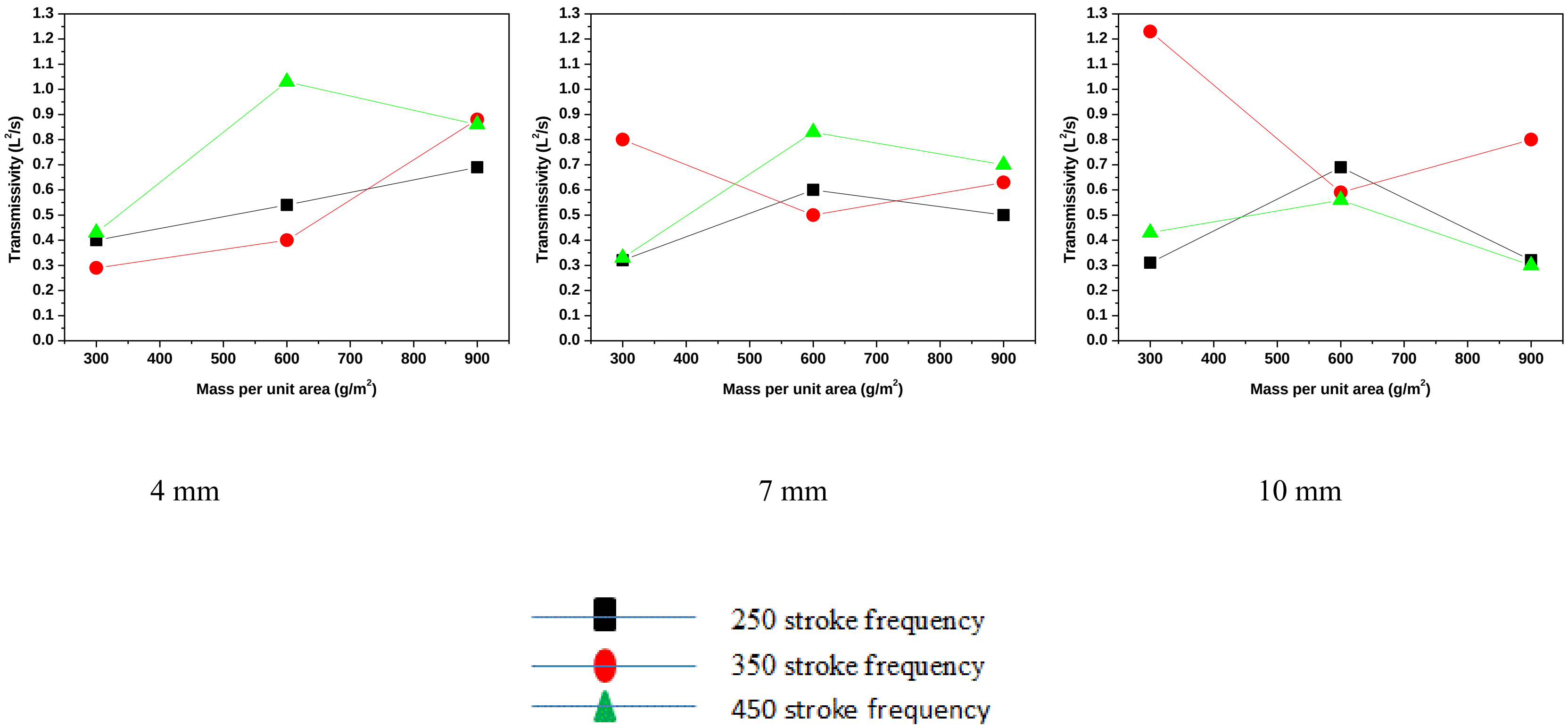

Figure 4.6(a) Effect of stroke frequency and mass per unit area on transmissivity of nonwoven the fabrics produced from 100% PP fibres at 4, 7 and 10 mm depths of needle penetration.

At an area weight of 300 g/m^2 and depths of needle penetration of 7 and 10 mm, transmissivity of the fabrics increased with an increase in stroke frequency from 250 to 350/min, after which it decreased with further increase in stroke frequency to 450/min. This increase in transmissivity was attributed to fewer number of fibres in the fabric with lower mass per unit area which resulted in structural heterogeneity and fabric anisotropies which affected the transmissivity properties.

At an area weight of 600 g/m^2 and depths of needle penetration of 4 and 7 mm, a similar trend, as observed in the case of area weight of 300 g/m^2 and 4 mm depth of needle penetration, was noticed. At an area weight of 600 g/m^2 and 10 mm depth of needle penetration, transmissivity of the fabrics decreased with an increase in stroke frequency as shown in Figure 4.6(a). This decrease in transmissivity was attributed to preferential flow of water caused by fabric anisotropies (Rawal et al., 2010).

At an area weight of 900 g/m^2 and depths of needle penetration of 4 and 10 mm, transmissivity of the fabrics increased with an increase in stroke frequency from 250 to 350 /min, after which it decreased with further increase in stroke frequency 450/min as shown in Figure 4.6(a). A similar trend, as observed in the case of area weight of 300 g/m^2 and 7 mm depth of needle penetration, was noticed. At an area weight of 900 g/m^2 and 7 mm depth of needle penetration, transmissivity of the fabrics increased with an increase in stroke frequency due to preponderance of fibre orientation in the horizontal direction.

4.2.7.2 Comparison of transmissivity between samples (100% PP fibres)

The transmissivity values of the nonwoven fabrics between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250 and 350/min and fixed depth of needle penetration of 4 mm were compared as shown in Figure 4.6(a). The transmissivity of the nonwoven fabrics increased with an increase in mass per unit area, which was attributed to an increase in the number of finer fibres in needlepunched nonwoven fabrics composed of more than one layer (Hwang et al., 1999).

The transmissivity values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.6(a). The transmissivity of the fabric increased with an increase in mass per unit area from 300 to 600 g/m^2, after which it decreased with further increase in mass per unit area to 900 g/m^2. This decrease in transmissivity was attributed to variation in areal densities and composition of the fibres.

The transmissivity values between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250 and 450/min and fixed depth of needle penetration of 7 mm were compared as shown in Figure 4.6(a). A similar trend, as observed in the previous paragraph, was noticed. The transmissivity values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.6(a). The transmissivity of the nonwoven fabrics decreased with an increase in mass per unit area from 300 to 600 g/m^2, after which it increased with further increase in mass per unit area to 900 g/m^2. This decrease in transmissivity was attributed to stroke frequency which might reorient higher number of fibres from horizontal to vertical (thickness) direction as reported by others (Rawal and Anandjiwala, 2006).

The transmissivity values between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 250 and 450/min and fixed depth of needle penetration of 10 mm were compared as shown in Figure 4.6(a). A similar trend, as observed in the case of 450/min stroke frequency for 4 mm depth of needle penetration, was noticed. The transmissivity values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 10 mm were compared as shown in Figure 4.6(a). A similar trend, as observed in the previous paragraph, was noticed.

Statistical analysis

A similar statistical analysis, as presented in Section 4.2.6.6, was also carried out on transmissivity data of the nonwoven fabrics produced from 100% PP fibres and the results are shown in Table 4.18. The tested parameters, namely, mass per unit area and stroke frequency as well as their two-way and three-way interactions showed significant effects on the transmissivity properties as shown in Table 4.18. However, the effect of depth of needle penetration was not significant ($P = 0.572$), which was attributed to variation in areal density, fibre orientation and distribution.

Table 4.18: ANOVA on the data of transmissivity of the nonwoven fabrics produced from 100% PP fibres

Nonwoven fabric produced from 100% PP fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	28.6	1	28.6	1463.5	0.0
Mass per unit area	0.3	2	0.2	7.9	0.0
Stroke frequency	0.5	2	0.3	13.3	0.0
Depth of needle penetration	0.0	2	0.0	0.6	0.6
Mass per unit area x stroke frequency	1.2	4	0.3	15.9	0.0
Mass per unit area x Depth of needle penetration	0.9	4	0.2	11.2	0.0
Stroke frequency x Depth of needle penetration	1.1	4	0.3	14.5	0.0
Mass per unit area x stroke frequency x depth of needle penetration	0.6	8	0.1	3.6	0.0
Error	1.1	54	0.0		

4.2.7.3 Comparison of transmissivity within samples (a blend of 50/50% PP/kenaf fibres)

Figure 4.6(b) shows the influence of stroke frequency and mass per unit area on transmissivity properties of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres at depths of needle penetration of 4, 7 and 10 mm. At an area weight of 300 g/m^2 and depths of needle penetration of 4 and 7 mm, transmissivity of the fabrics increased with an increase in stroke frequency from 250 to 350/min, after which it decreased with further increase in stroke frequency to 450/min. This increase in transmissivity was attributed to predominance of fibre orientation in the horizontal direction. The decrease in the transmissivity was attributed to differences in the fineness of PP and kenaf fibres as transmissivity in the nonwoven fabrics increases with an increase in fibre fineness (Hwang et al., 1999). At an area weight of 300 g/m^2 and 10 mm depth of needle penetration, transmissivity of the fabrics decreased with an increase in stroke frequency due to orientation of higher number of fibres from horizontal to vertical (thickness) direction.

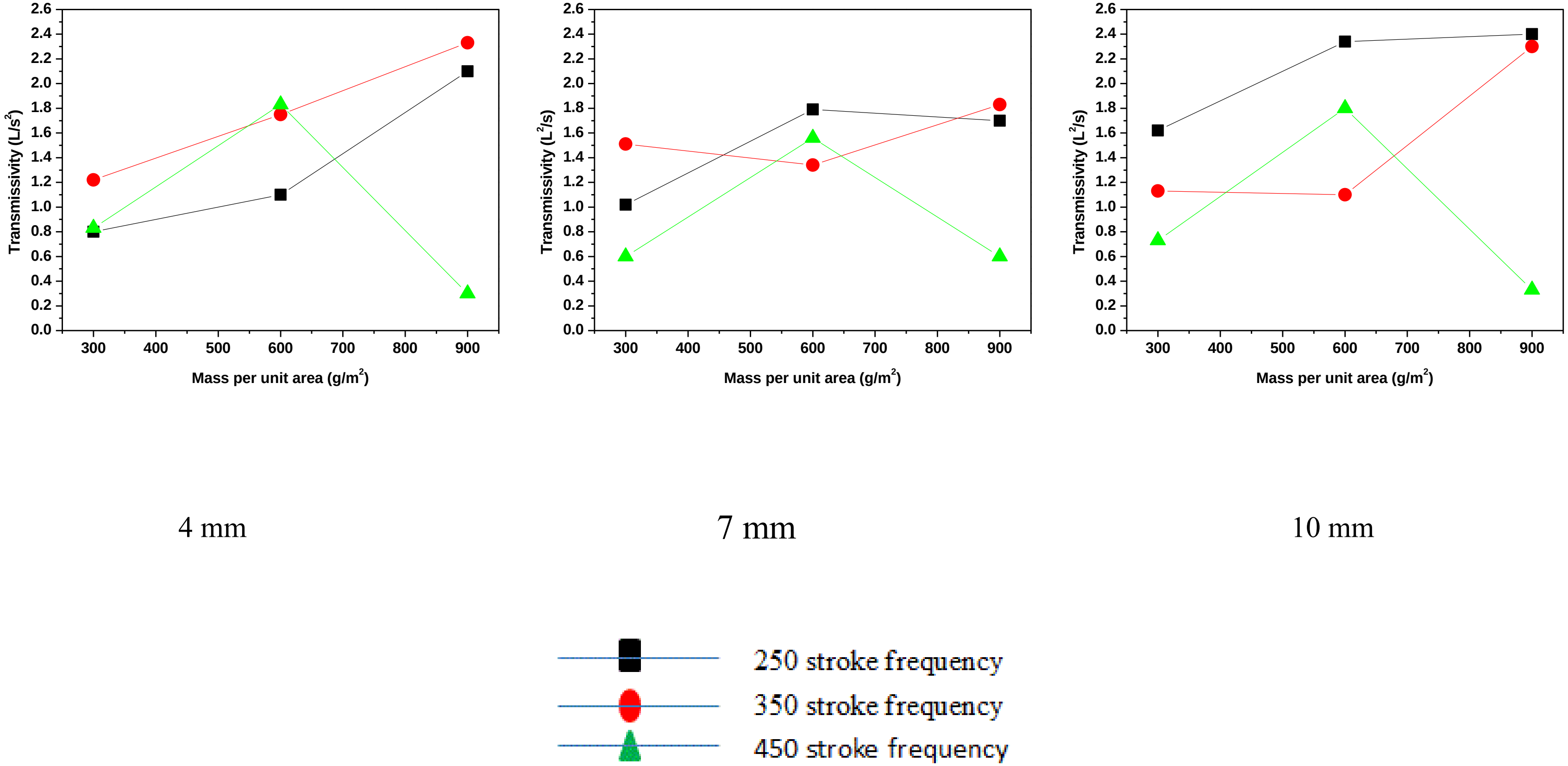

Figure 4.6(b) Effect of stroke frequency and mass per unit area on transmissivity properties of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres at 4, 7 and 10 mm depths of needle penetration.

At an area weight of 600 g/m^2 and 4 mm depth of needle penetration, the transmissivity of the nonwoven fabrics increased with an increase in stroke frequency as shown in Figure 4.6(b). This increase was attributed to an increase in number of finer fibres per unit area of the fabric (Hwang et al., 1999). At an area weight of 600 g/m^2 and depths of needle penetration of 7 and 10 mm, transmissivity properties of the fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it increased with further increase in stroke frequency to 450/min as shown in Figure 4.6(b). This decrease in the transmissivity was attributed to fibre orientation and its distribution.

At an area weight of 900 g/m^2 and depths of needle penetration of 4 and 7 mm, a similar trend, as observed in the case of area weight of 300 g/m^2 and 4 mm depth of needle penetration, was noticed. At an area weight of 900 g/m^2 and 10 mm depth of needle penetration, transmissivity properties of the fabrics decreased with an increase in stroke frequency as shown in Figure 4.6(b). This decrease was attributed to heterogeneous structure of the nonwoven fabric which influenced flow of water.

4.2.7.4 Comparison of transmissivity between samples (a blend of 50/50% PP/kenaf fibres)

The transmissivity values of the nonwoven fabrics between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.6(b). The transmissivity of the nonwoven fabrics increased with an increase in mass per unit area. This increase was attributed to an increase in number of in-plane fibres per unit area of the fabric.

The transmissivity values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.6(b). A similar trend, as observed in the previous paragraph, was noticed.

The transmissivity values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.6(b). The transmissivity of the fabrics increased with an increase in mass per unit area from 300 to 600 g/m^2, after which it decreased with further increase in mass per unit area to 900 g/m^2. The decrease in the transmissivity was attributed to hydrophobic and hydrophilic properties of PP and kenaf fibres, respectively, as well as number of PP and kenaf fibres per unit area of the fabric.

The transmissivity values between the samples produced at area weights of 300, 600 and 900 $g/m^2$and stroke frequencies of 250 and 450/min and fixed depth of needle penetration of 7 mm were compared as shown in Figure 4.6(b). A similar trend, as observed in the previous paragraph, was noticed.

The transmissivity values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.6(b). The transmissivity of the nonwoven fabrics decreased with an increase in mass per unit area from 300 to 600 g/m^2, after which it increased with further increase in mass per unit area to 900 g/m^2. This decrease in transmissivity was attributed to the movement of needles on the web which reorients and breaks fibres, therefore, results in variations in areal densities of the fabric.

The transmissivity values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 10 mm were compared as shown in Figure 4.6(b). A similar trend, as observed in the first paragraph of this section, was noticed. The transmissivity values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 10 mm were compared as shown in Figure 4.6(b). A similar trend, as observed in the case of 350/min stroke frequency for 7 mm depth of needle penetration, was noticed. The transmissivity values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 10 mm were compared as shown in Figure 4.6(b). A similar trend, as observed in the case of 450/min stroke frequency for 4 mm depth of needle penetration, was noticed.

Statistical analysis

A similar statistical analysis, as presented in Section 4.2.7.2, was also carried out on the transmissivity data of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres and the results are shown in Table 4.19. All the tested parameters and their three-way interactions were statistically significant. The two-way interactions between mass per unit area and stroke frequency as well as stroke frequency and depth of needle penetration also showed significant effects on transmissivity of the fabrics. However, the interaction between mass per unit area and depth of needle penetration was not significant ($P = 0.541$), which could be attributed to an increase in depth of needle penetration which might reorient fibres from horizontal direction to vertical (thickness) direction.

Table 4.19: ANOVA on the data of transmissivity of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres

Nonwoven fabric produced from 50/50% PP/kenaf fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	160.2	1	160.2	2355.4	0.0
Mass per unit area	5.1	2	2.5	37.4	0.0
Stroke frequency	8.2	2	4.1	60.6	0.0
Depth of needle penetration	0.6	2	0.3	4.4	0.0
Mass per unit area x stroke frequency	11.4	4	2.9	41.9	0.0
Mass per unit area x Depth of needle penetration	0.2	4	0.1	0.8	0.5
Stroke frequency x Depth of needle penetration	2.9	4	0.7	10.8	0.0
Mass per unit area x stroke frequency x depth of needle penetration	2.3	8	0.3	4.3	0.0
Error	3.7	54	0.1		

4.2.7.5 Comparison of transmissivity within samples (100% kenaf fibres)

Figure 4.6(c) shows the influence of stroke frequency and mass per unit area on transmissivity of the nonwoven fabrics produced from 100% kenaf fibres at depths of needle penetration of 4, 7 and 10 mm. At an area weight of 300 $g/m^2$and depths of needle penetration 4, 7 and 10 mm, transmissivity properties of the fabrics increased with an increase in stroke frequency which was attributed to fewer number of fibres at lower mass per unit area and the difficulty encountered in entangling kenaf fibres due to their high bending rigidity, thus a less compact fabric was produced.

At an area weight of 600 g/m^2 and depths of needle penetration of 4, 7 and 10 mm, transmissivity of the nonwoven fabric decreased with an increase in stroke frequency as shown in Figure 4.6(c). This decrease in transmissivity was attributed to variations in the fineness and length of kenaf fibres as well as orientation of the fibres and fibre distribution which affected transmissivity due to variations in areal density and thickness of the fabric.

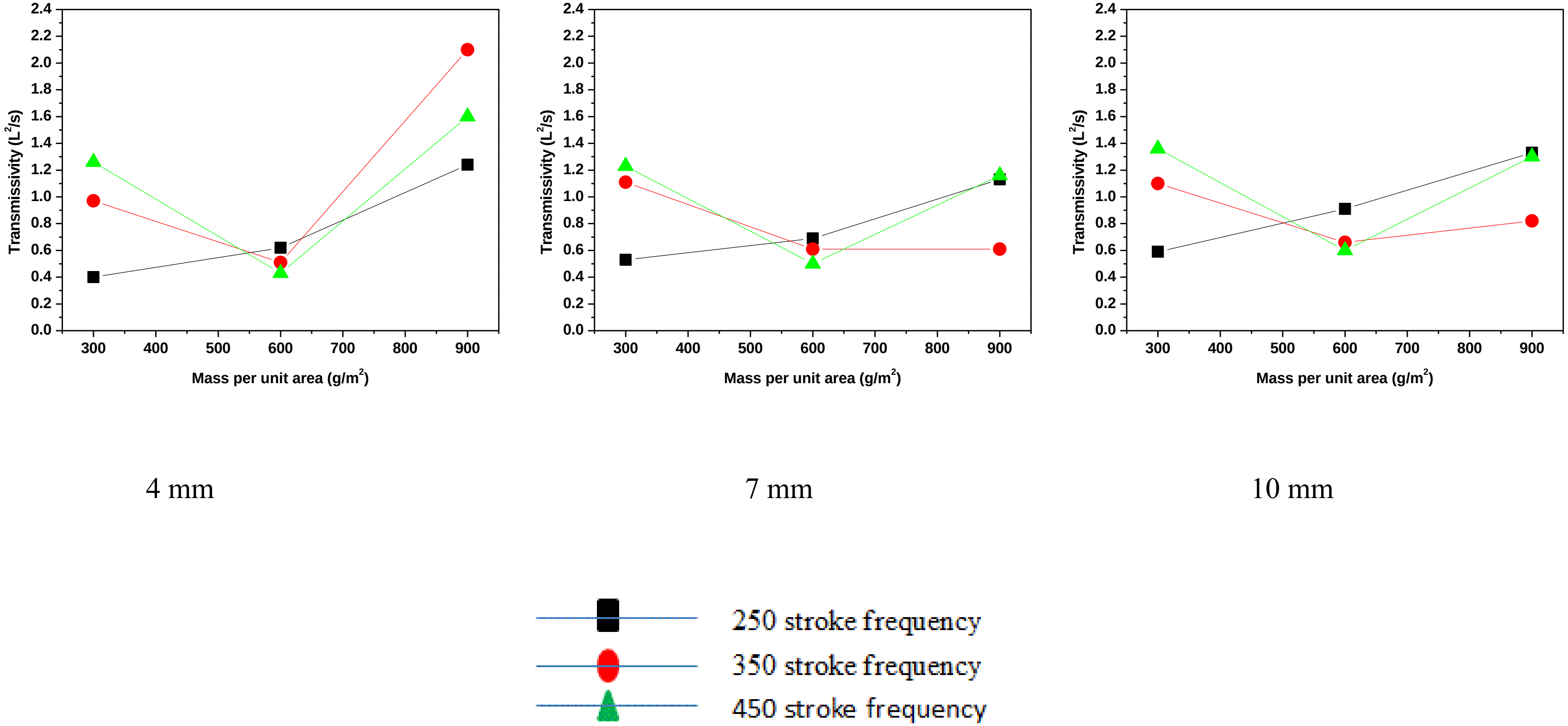

Figure 4.6(c) Effect of stroke frequency and mass per unit area on transmissivity properties of the nonwoven fabrics produced from 100% kenaf fibres at 4, 7 and 10 mm depths of needle penetration.

At an area weight of 900 g/m^2 and 4 mm depth of needle penetration, transmissivity of the nonwoven fabrics increased with an increase in stroke frequency from 250 to 350/min, after which it decreased with further increase in stroke frequency to 450/min as shown in Figure 4.6(c). This increase in transmissivity was attributed to an increase in number of fibres of higher linear density (Hwang et al., 1999). At an area weight of 900 g/m^2 and depths of needle penetration of 7 and 10 mm, transmissivity of the nonwoven fabrics decreased with an increase in stroke frequency from 250 to 350/min, after which it increased with further increase in stroke frequency to 450/min as shown in Figure 4.6(c). This decrease in transmissivity was attributed to irregular orientation of the fibres due to breakages of coarser kenaf fibres during needlepunching (Rawal et al., 2010).

4.2.7.6 Comparison of transmissivity between samples (100% kenaf fibres)

The transmissivity values of the nonwoven fabrics between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 4 mm were compared as shown in Figure 4.6(c). The transmissivity of the fabrics increased with an increase in mass per unit area due to increase in number of fibres oriented in the horizontal direction. The transmissivity values between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 350 and 450/min and constant depth of needle penetration of 4 mm were compared as shown in Figure 4.6(c). The transmissivity of the fabrics decreased with an increase in mass per unit area from 300 to 600 g/m^2, however, it increased with further increase in mass per unit area to 900 g/m^2. This decrease in transmissivity was attributed to preferential alignment of shorter fibres in the cross-machine direction, which in turn affected transmissivity values due to variations in thickness and mass per unit area of the fabric.

The transmissivity values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.6(c). A similar trend, as observed in the case of 250/min and 4 mm depth of needle penetration, was noticed.

The transmissivity values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.6(c). The transmissivity of the fabrics decreased with an increase in mass per unit area from 300 to 600 g/m^2, after which it remained constant with further increase in mass per unit area to 900 g/m^2. This lack of change in transmissivity was attributed to higher bending rigidity of the kenaf fibres which might influence interlocking and entanglement of the fibres, particularly in the heavier fabrics.

The transmissivity values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 450/min and depth of needle penetration of 7 mm were compared as shown in Figure 4.6(c). A similar trend, as observed in the case of 450 /min stroke frequency and 4 mm depth of needle penetration, was noticed.

The transmissivity values between the samples produced at area weights of 300, 600 and 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 10 mm were compared as shown in Figure 4.6(c). A similar trend, as observed in the first paragraph of this section, was noticed. The transmissivity values between the samples produced at area weights of 300, 600 and 900 g/m^2 and stroke frequencies of 350 and 450/min and constant depth of needle penetration of 10 mm were compared as shown in Figure 4.6(c). A similar trend, as observed in the case of 450/min stroke frequency and 4 mm depth of needle penetration, was noticed.

Statistical analysis

A similar statistical analysis, as presented in Section 4.2.7.4, was also carried out on the transmissivity data of the nonwoven fabrics produced from 100% kenaf fibres as shown in Table 4.20. The tested parameters which include mass per unit area and stroke frequency showed significant effects on transmissivity of the fabrics produced from 100% kenaf fibres. However, the effect of depth of needle penetration was not significant ($P = 0.108$) which was attributed to preferential alignment of short fibres in the cross-machine direction during needlepunching, therefore, thickness and mass per unit area of the nonwoven fabrics were affected. The two way interactions between mass per unit area and stroke frequency and mass per unit area and depth of needle penetration also showed significant influence on the transmissivity of the fabrics. However, the effect of two-way interaction between stroke frequency and depth of needle penetration on transmissivity was not significant ($P = 0.103$), which was attributed to higher bending rigidity, variations in fineness and length of kenaf fibres and fibre orientation. The effect of three-way interaction between mass per unit area, stroke frequency and depth of needle penetration was not significant ($P = 0.083$) at 95% confidence interval, however, it was significant at 90% confidence level.

Table 4.20: ANOVA on the data of transmissivity of the nonwoven fabrics produced from 100% kenaf fibres

Nonwoven fabric produced from 100% kenaf fibres					
	Sum of squares	**Degree of freedom**	**Mean square**	**F**	**P**
Intercept	70.9	1	70.9	774.9	0.0
Mass per unit area	5.6	2	2.8	30.7	0.0
Stroke frequency	0.7	2	0.3	3.6	0.0
Depth of needle penetration	0.4	2	0.2	2.3	0.1
Mass per unit area x stroke frequency	2.5	4	0.6	6.7	0.0
Mass per unit area x Depth of needle penetration	2.1	4	0.5	5.7	0.0
Stroke frequency x depth of needle penetration	0.7	4	0.2	2.0	0.1
Mass per unit area x stroke frequency x depth of needle penetration	1.4	8	0.2	1.9	0.1
Error	4.9	54	0.1		

4.2.7.7 Effect of fibre types

The effect of 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres on transmissivity of the needlepunched nonwoven fabrics is discussed below:

(a) Effect of 100% PP fibres on transmissivity

The transmissivity of the fabrics produced from 100% PP fibres was mainly influenced by the hydrophobic properties of PP fibres, therefore, lower amount of water was transported in the in-plane direction in comparison to that produced from a blend of 50/50% PP/kenaf fibres and 100% kenaf fibres. In addition, the transmissivity of the fabrics was also influenced by lower fibre-to-fibre friction and lower bending resistance of PP fibres which caused variations in areal density. The increase in number of finer fibres in the horizontal direction may also improve the transmissivity properties of the nonwoven fabrics.

(b) Effect of a blend of 50/50% PP/kenaf fibres

The transmissivity of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres was influenced by the bending properties of both PP and kenaf fibres which might affect interlocking and entanglement of the fibres as well as their orientation. Hwang et al. (1999)

have reported that transmissivity of the nonwoven fabrics increases with an increase in fibre linear density, therefore, differences in the properties of PP and kenaf fibres also influence transmissivity properties of the fabric. In addition, variations in the properties of PP and kenaf fibres might promote non-uniformity in mass per unit area and thickness of the fabric, thus, affecting the transmissivity.

(c) Effect of 100% kenaf fibres

The transmissivity of the nonwoven fabrics produced from 100% kenaf fibres was influenced by higher stroke frequency and higher depth of needle penetration which might cause breakage and reorientation of the fibres, as a result a less compact fabric would be produced. In addition, the transmissivity of the fabrics produced from 100% kenaf fibres was influenced by variations in fineness and length of kenaf fibres which might influence thickness of the fabric. The transmissivity of the fabrics produced from 100% kenaf fibres was mainly influenced by the hydrophilic properties of kenaf fibres, therefore, it was higher in comparison to fabrics produced from 100 % PP fibres.

4.3 Chemical resistance of the nonwoven fabrics

The effects of chemicals, that is 10% ammonium hydroxide (NH_4OH), 10% sodium chloride (NaCl) and 3% sulphuric acid (H_2SO_4) solutions, on the nonwoven fabrics produced from 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres were studied by analysing tensile strength and mass per unit area of the fabrics before and after treatment. The chemical resistance test was performed for 7, 14 and 31 days. The decrease in the mass per unit area and tensile strength of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres for 7, 14 and 31 days is shown in Tables 4.21 and 4.22. However, mass per unit area and tensile strength of the fabrics produced from 100% PP fibres remain unchanged.

Table 4.21 Effect of chemical treatment on mass of the nonwoven fabrics produced from 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres treated with H_2SO_4 for 7, 14 and 31 days.

Fabric type	Chemical resistance test performed using H_2SO_4								
	7 days			14 days			31 days		
	Average mass before the test (g)	Average mass after the test (g)	% loss	Average mass before the test (g)	Average mass after the test (g)	% Loss	Average mass before the test (g)	Average mass after the test (g)	% loss
100 % PP	17.8	17.8	0	15.6	15.6	0	16.5	16.5	0
50/50 % PP/kenaf fibre blend	12.3	11.9	3.3	11.4	9.8	14.0	13.1	9.1	30.5
100 % kenaf	14.8	13.5	8.8	13.5	9.2	31.9	15.9	10.9	31.4

Table 4.22 Effect of chemical treatment on tensile strength of nonwoven fabrics produced from 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres treated with H_2SO_4 for 7, 14 and 31 days.

Fabric type	Chemical resistance test performed using H_2SO_4								
	7 days			14 days			31 days		
	Tensile strength before the test (kN/m)	Tensile strength after the test (kN/m)	% Loss	Tensile strength before the test (kN/m)	Tensile strength after the test (kN/m)	% Loss	Tensile strength before the test (kN/m)	Tensile strength after the test (kN/m)	% Loss
100% PP	720.1	720.1	0	200.3	200.3	0	615.4	615.4	0
50/50% PP/kenaf fibre blend	570.5	504.8	11.5	122.1	88.1	27.8	519.7	360.5	30.6
100% kenaf	35.3	18.4	47.9	130.6	80.1	38.7	167.6	65.3	61.0

4.3.1 Loss in mass per unit area

4.3.1.1 Nonwoven fabrics produced from 100% PP fibres

The nonwoven fabrics produced from 100% PP fibres were not damaged or deteriorated when treated for 7, 14 and 31 days with all the three chemicals mentioned above due to chemical inertness of polypropylene. Therefore, there was no change in the mass per unit area of the nonwoven fabrics produced from 100% PP fibres.

4.3.1.2 Nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres and 100% kenaf fibres

The fabrics produced from a blend of 50/50% PP/kenaf fibres and 100% kenaf fibres treated with H_2SO_4 were damaged and deteriorated. However, only kenaf fibres were damaged as PP fibres are resistant to chemicals as mentioned above. The deterioration of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres also reduced the mass per unit area of the fabric as shown in Table 4.21. The rate of deterioration increased with an increase in number of days, therefore, higher deterioration was expected in the test performed for 31 days. This was supported by higher loss in mass per unit area of the nonwoven fabric in the tests performed for 31 days in comparison to those performed for 14 and 7 days.

The deterioration and damage of kenaf fibres was attributed to chemical affinity of the presence of hydroxyl groups in lignin and cellulose. Chemicals penetrate in the amorphous region of the cellulose structure, however, it was not easy for them to penetrate the crystalline regions. The surface of the kenaf fibres treated with H_2SO_4 changes as the fibres defibrillate and start to separate into individual fibres, therefore, fibre fineness increases. This is attributed to the removal of smaller portion of hemicellulose, pectin and lignin from kenaf fibres by H_2SO_4 (Johar et al., 2012). Fengel and Wegener (1984) have reported that diluted acid destroys amorphous regions of the cellulosic fibres (Fengel and Wegener, 1984). The deterioration or damage to fibres depends on the concentration of acid, temperature, reaction time, type of fibres tested and the treatment process (Aziz and Ansell, 2004).

No change in the mass per unit area of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres was noticed when treated with NaCl and NH_4OH.

4.3.2 Loss in tensile strength

No change in the tensile strength of the nonwoven fabrics produced from 100% PP fibres treated with H_2SO_4 was noticed. This lack of change in tensile strength was attributed to chemical inertness of PP as reported by others (Szostak-Kotowa., 2004; Rawal et al., 2010). The loss in tensile strength of the fabrics produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres treated with H_2SO_4 are shown in Table 4.22. The decreases in the tensile strength of the tested samples were attributed to the removal of smaller portion of hemicellulose, pectin and lignin from kenaf fibres by H_2SO_4 as reported above in Section 4.3.1.2. In addition, the decrease in the tensile strength was attributed to swelling of fibres due to the presence of water in the test. However, it was noticed that the concentration of the solution used during the test was the major factor for inducing deterioration and damage to fibres. Edeerozey et al. (2007) have reported that the tensile strength of the kenaf fibres treated with 6% NaOH was higher in comparison to that of untreated kenaf fibres, however, the tensile strength decreased with an increase in concentration of NaOH above 6%.

4.3.3 SEM studies

The SEM micrographs, captured at 100x magnification, of untreated and treated samples produced from 100% PP fibres using H_2SO_4 are shown in Figure 4.7. No visual difference was noticeable between the treated and untreated samples.

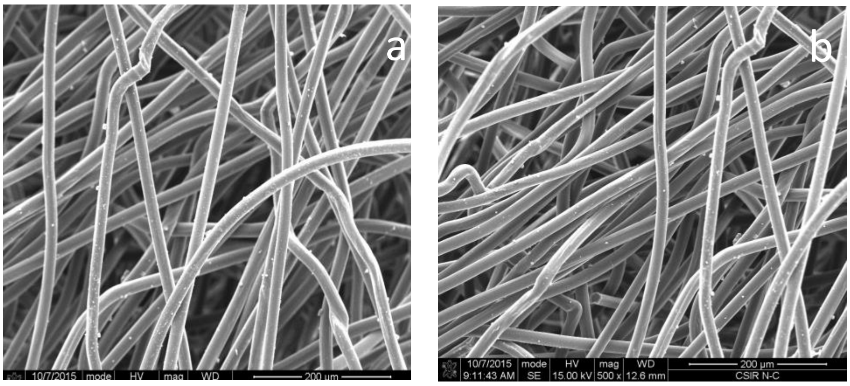

Figure 4.7 SEM micrographs of nonwoven fabrics produced from 100% PP fibres, (a) untreated and (b) treated with H_2SO_4

The SEM micrographs of untreated and treated samples produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres are shown in Figures 4.8 and 4.9, respectively. Kenaf fibres in the fabrics treated with H_2SO_4 were separated from each other and degraded as visible from SEM micrographs in Figures 4.8 and 4.9. The separation of kenaf fibres from each other was attributed to the nature of cellulosic fibres which react with H_2SO_4 due to the presence of hydroxyl groups.

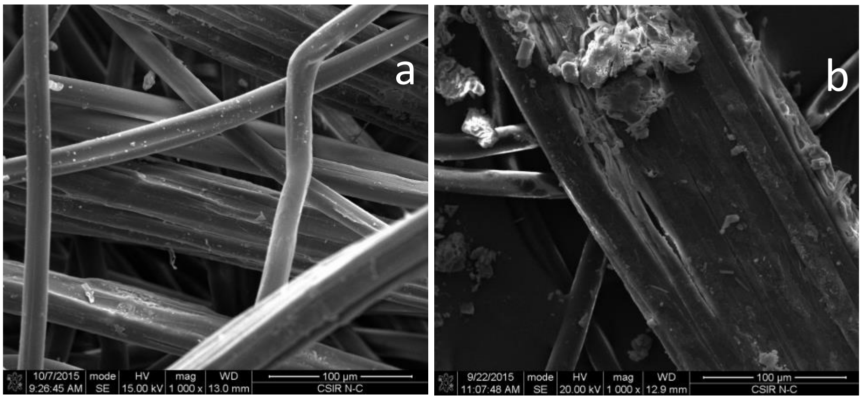

Figure 4.8 SEM micrographs of nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres, (a) untreated and (b) treated with H_2SO_4

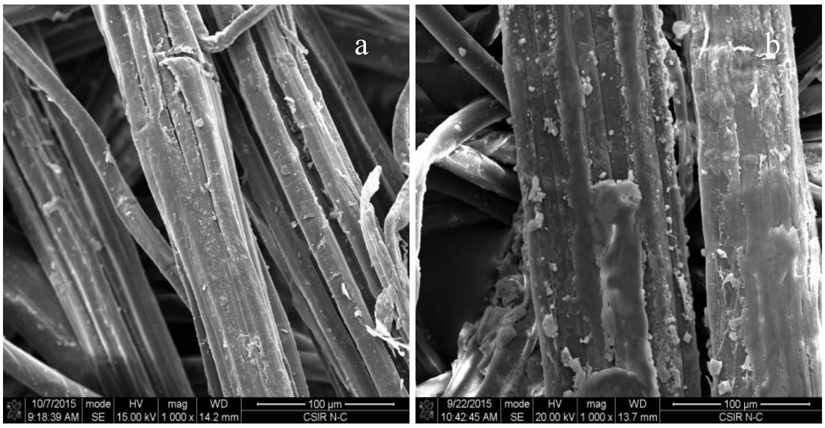

Figure 4.9 SEM micrographs of nonwoven fabrics produced from 100% kenaf fibres, (a) untreated and (b) treated with H_2SO_4

The nonwoven fabrics produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres treated with NaCl solution are shown in the SEM micrographs in Figure 4.10. Smaller particles on the surface of the fibres were noticed, which were thought to be impurities covering kenaf fibres besides salt particles of NaCl. Such smaller particles were also noticed in the samples treated with NH_4OH solution by others (Aziz and Ansell, 2004).

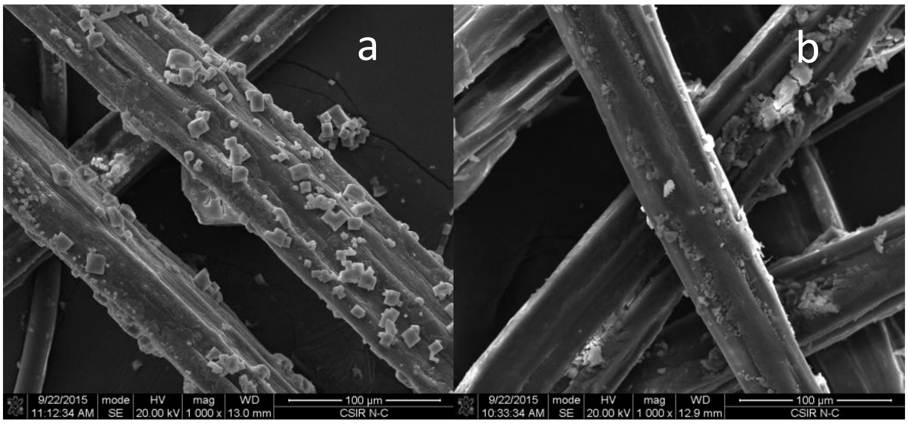

Figure 4.10 SEM micrographs of nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres (a) and 100% kenaf fibres (b) when treated with NaCl

Chapter 5

SUMMARY AND CONCLUSIONS

The aim of this work was to study the effect of process parameters on the properties of needlepunched nonwoven fabrics for geotextile applications. The process parameters, such as stroke frequency and depth of needle penetration and mass per unit area of the fabrics were varied to obtain maximum and minimum values of the fabric properties. The effect of stroke frequency, depth of needle penetration and mass per unit area on the fabric properties, namely, tensile strength, puncture resistance, pore size, water permeability and transmissivity; were studied. In addition, the effect of chemicals on degradation of the fabric was also studied.

The needlepunched nonwoven fabrics were produced from 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres. The three-way ANOVA was conducted to determine the influence of individual and interactive effects of the stroke frequency, depth of needle penetration and mass per unit area on the fabric properties.

The results have shown that density, thickness and weight of the needlepunched nonwoven fabrics were related to each other and they were influenced by stroke frequency, depth of needle penetration and feed rate of the needlepunching process. For example, when comparing the fabrics produced from 100% PP fibres at area weights of 300, 600, 900 g/m^2 but fixed stroke frequency of 350/min and fixed depth of needle penetration of 10 mm, the thickness and density of the fabrics increased by 69% and 2.8%; respectively; with an increase in mass per unit area from 300 to 900 g/m^2. In another case, when comparing the fabric samples produced from a blend of 50/50% PP/kenaf fibres at area weights of 300, 600, 900 g/m^2 but fixed stroke frequency of 250/min and fixed depth of needle penetration of 4 mm, the thickness and density of the fabrics increased by 21.2% and 56.3%; respectively; with an increase in mass per unit area from 300 g/m^2 to 900 g/m^2. However, the thickness values of the fabrics were compared between samples produced from 100% kenaf fibres at area weights of 300, 600, 900 g/m^2 but fixed stroke frequency of 250/min and fixed depth of needle penetration of 10 mm, it decreased with an increase in mass per unit area from 300 g/m^2 to 600 g/m^2 by 7.5%, after which it increased by 51.2% with an increase in mass per unit area from 600 g/m^2 to 900 g/m^2. Similar results, as obtained for the thickness of the fabrics, were also noticed in density of the fabrics.

The increase in nominal weight of the fabrics also increased thickness and density of the fabrics. In general, thickness of the fabric was higher in the fabrics produced from 100% PP fibres in comparison to those produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres. This was expected due to the properties of PP fibres which provides uniform web and better interlocking of the fibres. However, the thickness of the fabric decreases with an increase in depth of needle penetration due to increased interlocking and entanglement of the fibres. This was attributed to the barbs of the needles which carry higher number of fibres with the increase in depth of needle penetration, therefore, more compact fabric is produced.

The tensile strengths of the nonwoven fabrics in the cross-machine direction (CD) were higher in comparison to that in the machine direction (MD) for all the samples studied. This was attributed to pre-dominance of fibre orientation in the cross-machine direction due to cross-lapping process employed during web formation. The tensile strength of the fabrics increases with an increase in stroke frequency, depth of needle penetration and mass per unit area. This increase was attributed to the barbs of the needles carrying higher number of fibres at higher depth of needle penetration, therefore, results in adequate interlocking and entanglement of fibres. In addition, the increase in the tensile strength of the fabric was attributed to higher number of fibres per unit area of the fabrics which improved uniformity and compactness of the fibrous web. For example, when comparing the tensile strengths of the fabrics in CD produced from 100% PP fibres at fixed area weight of 600 g/m^2 and fixed depth of needle penetration of 7 mm and stroke frequencies of 250, 350 and 450/min, the tensile strengths of the fabrics increased with an increase in stroke frequency from 250 to 450/min by 37.6%. However, the tensile strengths of the fabrics did not follow any trend particularly with the increase in stroke frequency at certain fixed mass per unit area and fixed depth of needle penetration. For example, comparison within CD tensile strengths of the fabrics produced from a blend of 50/50% PP/kenaf fibres at fixed area weight of 300 g/m^2 and depth of needle penetration of 4 mm and stroke frequencies of 250, 350 and 450/min, the tensile strength of the fabrics decreased with an increase in stroke frequency from 250/min to 350/min by 21 %, however, increased with an increase in stroke frequency from 350/min to 450/min by 35.9 %.

These variations in tensile strengths of the fabrics were attributed to number of fibres per unit area of the fabrics, fibre properties, orientation and breakages of the fibres caused by downward and upward movements of the needles in the fibrous web. The tensile strength of the fabrics produced from 100% PP fibres was higher in comparison to that produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres. However, better tensile strengths were achieved in the fabrics produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres at higher stroke frequency, higher depth of needle penetration and higher mass per unit area. All the tested parameters and their two-way and three-way interactions showed statistically significant effects on both CD and MD tensile strengths of the nonwoven fabrics.

The puncture resistance values of the fabrics followed similar trends to that of tensile strengths as both increased with increases in stroke frequency, depth of needle penetration and fabric mass per unit area. The puncture resistance of the fabrics produced from 100% PP fibres was higher in comparison to that produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres. However, better puncture resistance was achieved in the fabrics produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres at higher stroke frequency, higher depth of needle penetration and higher mass per unit area. The puncture resistance of the fabrics was highly dependent on areal density and thickness of the fabric, however, the fibre properties also influence the puncture resistance as they influence web uniformity and entanglement of the fibres which affect the compactness and density of the fabrics. For example, when comparing the values of puncture resistance of the fabrics produced from 100% PP fibres at an area weights of 300, 600, 900 g/m^2 but fixed stroke frequency of 250/min and depth of needle penetration of 4 mm, the puncture resistance of the fabrics increased with an increase in mass per unit area from 300 g/m^2 to 900 g/m^2 by 84%. All the tested parameters and their two-way and three-way interactions showed statistically significant effects on the puncture resistance of the fabrics. However, only interaction between mass per unit area and depth of needle penetration on the puncture resistance of the fabrics produced from 100% PP fibres was statistically not significant, (P = 0.326) which was attributed to reorientation and breakages of the fibres at higher depth of needle penetration which promote variations in areal density, thereby, affect the puncture resistance.

Bigger pores were obtained in the nonwoven fabrics produced from 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres at lower depth of needle penetration, lower stroke frequency and lower mass per unit area. This was attributed to fewer number of fibres, inadequate interlocking and entanglement of fibres which resulted in a less compact fabric with bigger pores. However, the pore sizes of the fabrics decreased with the increases in depth of needle penetration, stroke frequency and mass per unit area. This was attributed to the barbs of the needles which carried a higher number of fibres with the increases in depth of needle penetration and stroke frequency, thus better interlocking and entanglement of the fibres occurred and a compact fabric was produced. For example, when comparing the pore sizes of the nonwoven fabrics produced from 100% kenaf fibres at constant area weight of 300 g/m^2 and constant depth of needle penetration of 4 mm and stroke frequencies of 250, 350 and 450/min, they decreased with an increase in stroke frequency from 250/min to 450/min by 10.7%. The pore sizes of the nonwoven fabrics produced from 100% kenaf fibres were bigger in comparison to those produced from a blend of 50/50% PP/kenaf and 100% PP fibres. This was attributed to variations in fibre fineness and fibre length as well as higher bending rigidity of kenaf fibres. The results showed that pore sizes of the fabrics were influenced by fibre properties, orientation of the fibres, elementary layers of the web, areal density and process parameters.

The results have shown that water permeability of the nonwoven fabrics depends on pore size and hydrophilic and hydrophobic properties of the fibres. The higher value of water permeability was achieved at lower values of mass per unit area, depth of needle penetration and stroke frequency, however, it decreased with increases in mass per unit area, depth of needle penetration and stroke frequency. For example, when comparing the values of water permeability of the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres at area weights of 300, 600, 900 g/m^2 but fixed stroke frequency of 350/min and depth of needle penetration of 4 mm, it decreased with an increase in mass per unit area from 300 g/m^2 to 900 g/m^2 by 38.7%. The water permeability of the fabrics produced from 100 % kenaf fibres was higher in comparison to that produced from a blend of 50/50% PP/kenaf and 100% PP fibres which was attributed to bigger pores in the fabrics produced from 100% kenaf fibres.

The results obtained showed that higher value of transmissivity was achieved in the fabrics produced from a blend of 50/50% PP/kenaf fibres in comparison to that produced from 100% kenaf and 100% PP fibres, however, better transmissivity was expected in the fabrics produced from 100% kenaf fibres. This may be attributed to fibre properties, process parameters, variations in areal density and orientation of the fibres which influenced the in-plane water flow.

The results of this study showed that higher values of tensile strength and higher puncture resistance were achieved in the needlepunched nonwoven fabrics produced from 100% PP fibres, therefore, they are suitable for some load-bearing geotextile applications, such as reinforcement and separation. However, higher values of water permeability were achieved in the fabrics produced from 100% kenaf fibres due to their hydrophilicity and bigger pores, therefore, they can be utilized in geotextile applications where good water permeability is required. Higher transmissivity was achieved in the fabrics produced from a blend of 50/50% PP/kenaf fibres, therefore they can be utilized in drainage applications.

The effects of chemicals, such as 10% ammonium hydroxide (NH_4OH), 10% sodium chloride (NaCl) and 3% sulphuric acid (H_2SO_4) solutions on the needlepunched nonwoven fabrics produced from 100% PP, a blend of 50/50% PP/kenaf and 100% kenaf fibres were studied by analysing losses in mass per unit area and tensile strength before and after the treatment. The results obtained showed that the fabrics produced from 100% PP fibres were not damaged or deteriorated when treated with all the three chemicals due to chemical inertness of polypropylene. However, the fabrics produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres were damaged and deteriorated when treated with H_2SO_4 due to the presence of hydroxyl groups in lignin and cellulose of kenaf fibres. This chemical degradation of kenaf fibres is responsible for loss in tensile strength and mass per unit area of the fabrics produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres. The losses in tensile strength and mass per unit area of the fabrics were increasing with the increase in number of days of chemical treatment. Higher decrease in the tensile strength was recorded in the fabrics produced from 100% kenaf fibres, it was 61% for the chemical treatment of 31 days in comparison to 47.9% for 7 days. The decrease in the mass per unit area was higher in the fabrics produced from 100% kenaf fibres, it was 31.4% for the chemical treatment of 31 days in comparison to 8.8% for 7 days. However, lower decreases in tensile strength and mass per unit area were recorded in the fabrics produced from a blend of 50/50% PP/kenaf fibres and subjected to chemical treatment for fewer days, it was 11.5% for tensile strength and 3.3% for mass per unit area. The deterioration and damage to the fibres depends on the temperature, reaction time and types of fibres, however, it has been noticed that concentration of the solution is the major factor for degradation of the fibres. The nonwoven fabrics produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres were not degraded by NaCl and NH_4OH.

In conclusion, the results of this study showed that the fabrics produced from a blend of 50/50% PP/kenaf fibres achieved better values of tensile strength and puncture resistance in comparison to that produced from 100% kenaf fibres, however, lower than those for the fabrics produced from 100% PP fibres. In addition, the fabrics produced from a blend of 50/50%

PP/kenaf fibres achieved bigger pore sizes and higher water permeability in comparison to those produced from 100% PP fibres, however, lower than those for the fabrics produced from 100% kenaf fibres. Therefore, it can be suggested that the nonwoven fabrics produced from a blend of 50/50% PP/kenaf fibres can fulfil almost all requirements of geotextile applications, in filtration, separation, reinforcement and drainage.

The results of this study showed that the properties of the needlepunched nonwoven fabrics are influenced by stroke frequency, depth of needle penetration and mass per unit area. However, it is not guaranteed that the properties will always follow the same trend particularly with an increase in stroke frequency at certain fixed mass per unit area and fixed depth of needle penetration. The results obtained showed that the fabrics produced from 100% PP fibres were not damaged or deteriorated when treated with all the three chemicals due to chemical inertness of polypropylene. However, the fabrics produced from a blend of 50/50% PP/kenaf and 100% kenaf fibres were damaged and deteriorated when treated with H_2SO_4 due to the presence of hydroxyl groups in lignin and cellulose of kenaf fibres, therefore, results in losses in tensile strength and mass per unit area of the fabrics.

5.1 Recommendations for future work

1. It was difficult to match the input speed to the cross lapper with the speed of carded web being fed to the needlepunching machine owing to inherent limitations of the cross-lapping process. Variations in the speeds may result in drafting which will deform the fibrous web. In addition, the variations in speeds may promote non-uniformity in mass per unit area and thickness of the nonwoven fabric. Drafting can be minimised if the input speed is adjusted so that it matches the speed of the carded web.
2. Due to limitations of our pilot production machines, it was impossible to produce needlepunched nonwoven fabrics with higher mass per unit area above 600 g/m^2 in one step. Either two or three layers of the fibrous web were combined together to achieve the desired nominal mass per unit area which has adversely influenced the properties of the fabrics produced. Therefore, a machine that can produce fabrics with nominal mass per unit area above 1000 g/m^2 in one step should be utilized and the results should be compared with those obtained in this study.
3. Only the static puncture test (CBR test) was performed in this work, more tests, such as pin and pyramid puncture tests should to be performed to simulate actual application

conditions. The capillary flow porometer was utilized to analyse pore size, however, future work should include analysis of pore sizes using dry and hydrodynamic sieving. Due to non-availability of the testing equipment, we could not conduct these tests.

4. More tests on the fabric properties should be carried out due to non-uniformity in mass per unit area and thickness of the nonwoven fabrics which may lead to incorrect and unreliable results, however, fewer tests in this research work were carried out due to time constraint.
5. Kenaf fibres were used in this study, however, other natural fibres, such as hemp, flax and coir fibres should be utilized to compare their fabric properties to ascertain their suitability in geotextile applications.
6. This research work was for academic purpose and tests were carried out in the laboratory, however, if possible, field tests should be conducted to compare and verify laboratory results. The results obtained in the field tests can be utilized to minimise problems faced with South African roads, such as potholes and development of cracks.

REFERENCES

AASHTO NTPEP (2002), Laboratory results of evaluations on geotextiles and geosynthetics, Report 02 NTPEP 137, 15th Edition, 6 – 38.

Abramento, M. and Whittle, A. J., 1995. Analysis of pull out tests for planar reinforcements in soil. *Journal of Geotechnical Engineering*, 121(6), 476 – 485.

Adams, K. L. and Rebenfeld, L., 1987. In-plane flow of fluids in fabrics: structure/flow characterization. *Textile Research Journal*, 57(11), 647 - 654.

Adams, K. L. and Rebenfeld, L., 1991. Permeability characteristics of multilayer fibre, reinforcement, part 1: experimental observations. *Polymer Composites,* 12(3), 179 - 185.

Adanur, S., Gowayed, Y. and Elton, D., 1995a. Design and Characterization of Geotextiles for High Performance Applications. In *Proceedings of Hi-Tech Textiles, Exhibition and Conference, Greenville, SC, July.*

Adanur, S., 1995. *Wellington Sears Handbook of Industrial Textiles*. USA, CRC Press, ISBN 1-56676-340-1.

Adanur, S. and Liao, T., 1998. Computer simulation of mechanical properties of nonwoven geotextiles in soil – fabric interaction. *Textile Research Journal,* 68(3), 155 - 162.

Adanur, S. and Liao, T., 1999. Fibre arrangement characteristics and their effects on nonwoven tensile behaviour. *Textile Research Journal*, 69(11), 816 - 824.

Ajayi, J. O. and Elder, H. M., 1997. Fabric friction, handle and compression. *Journal of the Textile Institute*, 88(3), 232 - 241.

Albrecht, W., Fuchs, H. and Kittelmann, W., 2006. *Nonwoven fabrics: raw materials, manufacture, applications, characteristics, testing processes*. Germany, John Wiley and Sons, ISBN 3-527-30406 - 1.

Amiot, M., Lewandowski, M., Leite, P., Thomas, M. and Perwuelz, A., 2014. An evaluation of fibre orientation and organization in nonwoven fabrics by tensile, air permeability and compression measurements. *Journal of Materials Science,* 49(1), 52 – 61.

Anandjiwala, R. D. and Boguslavsky, L., 2008. Development of needle-punched nonwoven fabrics from flax fibres for air filtration applications. *Textile Research Journal,* 78(7), 614 - 624.

American national standard institutes (ANSI)), BS EN ISO 12236:2006, Geosynthetics. Static puncture test (CBR test) (British Standard), accessed on 03 March 2016, http://webstore.ansi.org/RecordDetail.aspx?sku.

American Society for Testing and Materials, ASTM D 3776 -96, ATM D 5034 -96, 1997 Annual Book of ASTM Standards, Vol. 7.01, ASTM, West Conshohocken, PA, U.S.A. (1997).

Antoine, R. and Courard, L., 1996. Perforation strength of geosynthetics and sphericity of coarse grains: a new approach. *Geotextiles and Geomembranes*, 14(10), 585 - 600.

Ariadurai, S. A., Potluri, P. and Whyte, I. L., 1999. Modeling the in-plane permeability of woven geotextiles. *Textile Research Journal*, 69(5), 345 – 351.

Askari, A. S., Najar, S. S. and Vaghasloo, Y. A., 2012. Study the effect of test speed and fabric weight on puncture behaviour of polyester needle punched nonwoven Geotextiles. *Journal of Engineered Fibres and Fabrics*, 7(3).

ASTM D 543-06, Standard practices for evaluating the resistance of plastics to chemical reagents, ASTM International, West Conshohocken, PA, 2006, www.astm.org.

ASTM D1987-07 (2012), Standard Test Method for Biological Clogging of Geotextile or Soil/Geotextile Filters, ASTM International, West Conshohocken, PA, 2012, www.astm.org.

ASTM D4595-86 (2001), Standard test method for tensile properties of geotextiles by the wide-width strip method, ASTM International, West Conshohocken, PA, 1986, www.astm.org.

ASTM D3080 / D3080M-11, Standard test method for direct shear test of soils under consolidated drained conditions, ASTM International, West Conshohocken, PA, 2011, www.astm.org.

ASTM D5493-06(2011), Standard test method for permittivity of geotextiles under load, ASTM International, West Conshohocken, PA, 2011, www.astm.org.

ASTM F 316-03(2011), Standard Test Methods for Pore Size Characteristics of Membrane Filters by Bubble Point and Mean Flow Pore Test, ASTM International, West Conshohocken, PA, 2011, www.astm.org.

ASTM D5101-12 (2012), Standard test method for measuring the filtration compatibility of soil-geotextile systems, ASTM International, West Conshohocken, PA, 2012, www.astm.org.

ASTM D5321 / D5321M-13 (2013), Standard test method for determining the shear strength of soil-geosynthetic and geosynthetic-geosynthetic interfaces by direct shear, ASTM International, West Conshohocken, PA, 2013, www.astm.org.

ASTM C900-15, Standard test method for pull out strength of hardened concrete, ASTM International, West Conshohocken, PA, 2015, www.astm.org.

ASTM D4716, Standard Test Method for Determining the (In-plane) Flow Rate per Unit Width and Hydraulic Transmissivity of a Geosynthetic Using a Constant Head, ASTM International, West Conshohocken, PA, 2013, www.astm.org.

ASTM D4491 / D4491M-15, Standard test methods for water permeability of geotextiles by permittivity, ASTM International, West Conshohocken, PA, 2015, www.astm.org.

Austin, R. A. and Gilchrist, A. J. T., 1996. Enhanced performance of asphalt pavements using geocomposites. *Geotextiles and Geomembranes*, 14(3), 175 - 186.

Ayyappan, T., Indian jute, jute-jute cultivation and fibre extraction process, accessed on 02 May 2016, http://indianjute.blogspot.co.za/p/jute-jute-cultivation-and-fibre.html.

Aydilek, A. H., Oguz, S. H. and Edil, T. B., 2002. Digital image analysis to determine pore opening size distribution of nonwoven geotextiles. *Journal of Computing in Civil Engineering* 16(4), 280 – 290.

Aydilek, A. H. and Kutay, M. E., 2004. Development of an innovative computer-controlled water deairing system for hydraulic testing of geosynthetics. *Journal of Testing and Evaluation,* 32(2), 161 – 166.

Aziz, S. H. and Ansell, M. P., 2004. The effect of alkalization and fibre alignment on the mechanical and thermal properties of kenaf and hemp bast fibre composites: Part 1–polyester resin matrix. *Composites Science and Technology*, 64(9), 1219 - 1230.

Bais-Singh, S., Anandjiwala, R. D. and Goswami, B. C., 1996. Characterizing lateral contraction behavior of spunbonded nonwovens during uniaxial tensile deformation. *Textile Research Journal*, 66(3), 131 - 140.

Barbier, D., Gey, N., Allain, S., Bozzolo, N. and Humbert, M., 2009. Analysis of the tensile behaviour of a TWIP steel based on the texture and microstructure evolutions. *Materials Science and Engineering: A*, *500*(1), 196 - 206.

Bardet, J. P., 1997. *Experimental soil mechanics.* Prentice-Hall, Upper saddles river, New Jersey, ISBN-13: 978-0133749359.

Basu, G., Roy, A. N., Bhattacharyya, S. K. and Ghosh, S. K. 2009. Construction of unpaved rural road using jute–synthetic blended woven geotextile–A case study. *Geotextiles and Geomembranes,* 27(6), 506 - 512.

Basudhar, P. K., 2010. Modelling of soil–woven geotextile interface behaviour from direct shear test results. *Geotextiles and Geomembranes,* 28(4), 403 - 408.

Bathurst, R. J., Geosynthetics classification. International geosynthetics society (IGS), accessed on 11 September 2015, www.geosynthetics-international.com.

Beil, N. B, and Roberts, W. W., 2002. Modelling and computer simulation of the compressional behaviour of fibre assemblies, Part 1: Comparion to Van Wyk's theory. *Textile Research Journal*, 74(4), 341 - 351.

Bergado, D. T., Manivannan, R. and Balasubramaniam, A. S., 1996. Proposed criteria for discharge capacity of prefabricated vertical drains. *Geotextiles and Geomembranes*, 14(9), 481 - 505.

Bergado, D. T., Youwai, S., Hai, C. N. and Voottipruex, P., 2001. Interaction of nonwoven needle-punched geotextiles under axisymmetric loading conditions. *Geotextiles and Geomembranes*, 19(5), 299 - 328.

Bhat, G. S., 1995. Nonwovens as three-dimensional textiles for composites. *Material and Manufacturing Process,* (4), 667 - 688.

Bhatia, S.K., Qureshi, S. and Kogler, R. M., 1990. Long term clogging behaviour of non-woven geotextiles with silty and gap-graded sands. *ASTM Special Technical Publication*, 1081, 285 – 289.

Bhatia, S. K. and Smith, J. L., 1996. Geotextile characterization and pore size distribution: Part 1. A review of manufacturing process. *Geosynthetics International*, 3, 85 – 105.

Bolt, A. and Duszyńska, A., 2010. Static puncture resistance of nonwoven geotextiles.

Bouazza, A., Zornberg, J. G. and Adam, D., 2002a. Geosynthetics in waste containment facilities: recent advances. na, *Geosynthetics*, 7 ICG, Held, 22-27, SEPTEMBER 2002 Delmas, Gourc and Girard, Swets and Zeitlinger, 445 – 507.

Bouazza, A., 2002b. Geosynthetic clay liners. *Geotextiles and Geomembranes*, 20(1), 3 – 17.

Bueno, M. A., Aneja, A. P. and Renner, M., 2004. Influence of the shape of fibre cross section on fabric surface characteristics. *Journal of Materials Science*, 39(2), 557 - 564.

Bueno, B. S., Costanzi, M. A. and Zornberg, J. G., 2005. Conventional and accelerated creep tests on nonwoven needle-punched geotextiles. *Geosynthetics International*, 12(6), 276 - 287.

Camfil, accessed on 23 May 2016, http://www.camfil.com/Filter-technology/Principles-of-Filtration/Interception/.

Canbolat, M. F., 2011. Nonwovens bonding technologies: an overview on mechanisms, properties, application fields. *Electronic Journal of Textile Technologies*, 5(1), 54 – 60.

Capillary flow porometry, accessed on 29 February 2016, https://en.wikipedia.org/wiki/Capillary_flow_porometry.

Cazzuffi, D. A., Mazzucato, A., Moraci, N. and Tondello, M., 1999. A new test apparatus for the study of geotextiles behaviour as filters in unsteady flow conditions: relevance and use. *Geotextiles and Geomembranes*, 17(5), 313 - 329.

Chai, J C., Miura, N. and Nomura, T., 2004. Effect of hydraulic radius on long-term drainage capacity of geosynthetics drains. *Geotextiles and Geomembranes*, 22(1), 3 - 16.

Chatterjee, K. N., Mukhopadhyay, A., Jhalani, S. C. and Mani, B. P., 1996. Performance characteristics of filter fabrics in cement dust control: Part II–Influence of fibre cross-sectional shape and scrim on performance of nonwoven filter fabrics. *Indian Journal of Fibre and Textile Research*, 21, 251 - 260.

Chen, X., 2009. *Modelling and predicting textile behaviour*, Woodhead publishing limited and CRC press LLC, Abington hall, Cambridge, ISBN 978 – 1 – 84569 – 416 – 6.

Chew, S. H., Tian, H., Tan, S. A. and Karunaratne, G. P. 2003. Erosion stability of punctured geotextile filters subjected to cyclic wave loading – a laboratory study. *Geotextiles and Geomembranes*, 21(4), 221 – 239.

Chhabra. R., 2003. Nonwoven uniformity-measurements using image analysis. *International Nonwoven Journal*, 12(1), 43 - 50.

Chuang, S. H., Chang, W. C., Chang, M. C. and Hu, K. L., 2011. Filtration performances of a novel submerged nonwoven filter for particle separation. *Desalination*, 279(1), 163 - 169.

Çinçik, E. and Koç, E., 2013. The effect of blend ratio and process parameters on tensile properties of polyester/viscose blended needle-punched nonwovens. *Fibres and Polymers*, 14(6), 1040 - 1049.

Collins, B. M., Mahoney, J. P. and Holtz, R. D., 2005. FWD Analysis of Pavement Sections with Geotextile Separators. *Advances in Pavement Engineering, American Society of Civil Engineers*, 1 - 14.

Cooley, W. W. and Lohnes, P. R., 1971. *Multivariate data analysis.* John Wiley and Sons, New York, ISBN 978-0471170600.

Corcoran, B. W. and Bhatia, S. K., 1996. Evaluation of geotextile filter in a collection system at fresh kills landfill. *ASTM Special Technical Publication*, 1281, 182 - 195.

Dahiya, A., Kamath, M. G. and Raghavendra, R. H., 2004a. Dry-laid nonwovens, accessed on 25 May 2016, http://www.engr.utk.edu/mse/Textiles/Dry%20Laid%20Nonwovens.htm.

Dahiya, A., Kamath, M. G. and Raghavendra, R. H., 2004b. Spunbond technology, accessed on 25 May 2016, http://www.engr.utk.edu/mse/Textiles/Spunbond%20Technology.htm.

Daniel, D. E. and Koerner, R. M., 1991. Geosynthetic clay liners. *Geotechnical News*, 9(4), 28 - 33.

Das, A., Kothari, V. K., Kumar, A. and Mehta, M. S., 2005. Study on anisotropic creep behaviour of nonwoven geotextiles. *Fibers and Polymers*, 6(4), 313 – 317.

Debnath, S., Kane, C. D., Kadole, P. V. and Patil, C. A., 1994. Needle-punched nonwoven blankets from polyester. *Indian Textile Journal*, 105, 72 - 72.

Debnath, S. and Madhusoothanan, M., 2009. Compression properties of polyester needle-punched fabric. *Journal of Engineered Fibres and Fabrics*, 4(4), 14 – 19.

Debnath, S. and Madhusoothanan, M., 2010. Water absorbency of jute-polypropylene blended needle-punched nonwoven. *Journal of Industrial Textiles*, 39(3), 215 - 231.

Dedov, A. V., Platonov, A. V., Babushkin, S. V. and Nazarov, V. G., 2002. Filtering properties of nonwoven material. *Fibre Chemistry*, 34(4), 301 - 303.

Dedov, A. V., 2004. Nonwoven material with low density and high mechanical strength. *Fibre Chemistry*, 36(2), 126 - 128.

Dedov, A. V., 2005. Formation of the pore structure of needle-punch materials. *Fibre Chemistry*, 37(3), 205 - 207.

Dedov, A. V., 2007. Needle-punch materials with high compressive strength. *Fibre Chemistry*, 39(5), 397 - 399.

Desai, A. N., Jade, B. D. and Balasubramanian, N., 1994. Tensile and absorbency characteristics of cellulosic nonwovens. Indian Journal of Fibre and Textile Research, Vol. 19, 53 – 57.

Dhaniyala, S., 1999. An asymmetrical, three-dimensional model for fibrous filters. *Aerosol Science and Technology*, 30(4), 333 - 348.

Dhaniyala, S. and Liu, B. Y., 2001a. Experimental investigation of local efficiency variation in fibrous filters. *Aerosol Science and Technology*, 34(2), 161 - 169.

Dhaniyala, S. and Liu, B.Y., 2001. Theoretical modeling of filtration by nonuniform fibrous filters. *Aerosol Science and Technology*, *34*(2), 170 - 178.

Dickson, T. C., 1997. *Filters and filtration handbook 4th edition.* Elsevier, New York, USA, ISBN 1 85617 3224.

Dierickx, W. and Van der Sluys, L., 1990. Research into the functional hydraulic properties of geotextiles. In the *Proceedings, of 4th International Conference on Geotextiles, Geomembranes and Related Products*, Rotterdam, Netherlands, Vol. 1, 285-288.

Direct shear test, accessed on 23 February 2016, https://en.wikipedia.org/wiki/Direct_shear_test.

Draper, N. R. and Smith, H., 1998. *Applied regression analysis.* John Wiley and Sons, New York, ISBN 0-471-17082-8.

Dürst, R., Bucher, F. and Schaerer, C., 1981. Permeameter for investigating the hydraulic characteristics of geotextiles. *Matériaux et Construction*, 14(4), 319 - 324.

International association for the nonwovens and related industry (EDANA), accessed on 02 May 2016, http://www.edana.org/discover-nonwovens/how-they're-made/formation.

EDANA WSP 120.6, Standard test methods for the nonwovens and related industries – thickness, European Disposables and Nonwoven Association (EDANA), Brussels, 2005.

Edeerozey, A. M., Akil, H. M., Azhar, A. B. and Ariffin, M. I., 2007. Chemical modification of kenaf fibres. *Materials Letters*, 61(10), 2023 – 2025.

El Mogahzy, Y. E., Gowayed, Y. and Elton, D., 1994. Theory of soil/geotextile interaction. *Textile Research Journal*, 64(12), 744 - 755.

Elsharief, A. M. and Lovell, C. W., 1996. A probabilistic retention criterion for nonwoven geotextiles. *Geotextiles and Geomembranes*, 14(11), 601 - 617.

EN ISO 13433: 2006, Geosynthetics – dynamic perforation test (cone drop test), accessed on 18 August 2015, http://www.centexbel.be/files/PDF_files/geosynthetics/en-iso-13433-2006-conedroptest.pdf.

English, B., 1994. Biobased, biodegradable geotextiles: USDA forest service research update. In steiner PR, comp. *Proceedings of the 2d pacific rim biobased composites symposium*, 6 – 9.

Fangueiro, R., Carvalho, R. and Soutinho, F., 2011. Mechanical properties of needle-punched nonwovens for geotechnical applications. *In the International Conference on Engineering UNI2011*, Covilha, Portugal, 1 - 7.

Faure, Y. H., Baudoin, A., Pierson, P. and Ple, O., 2006. A contribution for predicting geotextile clogging during filtration of suspended solids. *Geotextiles and Geomembranes*, 24(1), 11 - 20.

Finishing process of nonwoven fabrics, printing process of nonwoven fabrics, accessed on 02 May 2016, http://textilelearner.blogspot.co.za/2012/01/finishing-process-of-nonwoven-fabrics.html.

Foster, J. H., Forster needles, needle designs and their effect on the needle nonwoven, accessed on 26 July 2015, http://www.fosterneedleusa.com/tch_pprs/designs.html.

Fotovati, S., Tafreshi, H.V., Ashari, A., Hosseini, S.A. and Pourdeyhimi, B., 2010. Analytical expressions for predicting capture efficiency of bimodal fibrous filters. *Journal of Aerosol Science, 41*(3), 295 - 305.

Fourie, A. B. and Addis, P. C., 1999. Changes in filtration opening size of woven geotextiles subjected to tensile loads. *Geotextiles and Geomembranes*, 17(5), 331 – 340.

F-test, Handling small sample sizes, accessed on 07 May 2016, https**://**explorable.com/f**-**test**.**

Gabr, M. A., Akram, M. H. and Zayed, A. M., 1998. Field versus laboratory filtration performance of a nonwoven geotextile with fly ash. *Geotextiles and Geomembranes*, 16(4), 247 – 255.

Ganguly, P. K., Sengupta, S. and Samajpati, S., 1999. Mechanical behaviour of jute and polypropylene blended needle-punched fabrics. *Indian Journal of Fibre and Textile Research*, 24, 34 - 40.

Gassan, J. and Bledzki, A. K., 1999. Alkali treatment of jute fibres: relationship between structure and mechanical properties. *Journal of Applied Polymer Science*, 71(4), 623 - 629.

Gautier, K. B., Kocher, C. W. and Drean, J. Y., 2007. Anisotropic mechanical behaviour of nonwovens geotextiles stressed by uniaxial tension. *Textile Research Journal*, 77(1), 20 – 28.

Geosynthetics in classified road construction, NAUE, accessed on 15 February 2016, http://www.naue.com/en/applications/civil-engineering/classified-road-construction.html.

Geosynthetics knowledge centre, geosynthetics terminology, accessed on 04 June 2015, http://geosintetik.blogspot.co.za/2007/02/geosynthetics-terminolgy.html.

Geotextile filter design, application and product selection guide, accessed on 03 May 2016, http://www.tencate.com/pt/lam/Images/tn_geofilter_tcm31-11025.pdf.

Geotextile filter fabrics, accessed on 22 February 2016, http://web.mst.edu/~rogersda/umrcourses/ge441/online_lectures/subsurface_drainage/GE441-Lecture5-7.pdf.

Gervais, P. C., Bardin-Monnier, N. and Thomas, D., 2012. Permeability modelling of fibrous media with bimodal fibre size distribution. *Chemical Engineering Science*, 73, 239 - 248.

GE-TE-FLOW, Lenzing instruments GmbH, accessed on 03 March 2016, http://www.lenzing-instruments.com/produkt.infos/ge-te-flow.pdf.

Ghassemieh, E., Acar, M. and Versteeg, H. K., 2001. Improvement of the efficiency of energy transfer in the hydro-entanglement process. *Composites Science and Technology*, 61(12), 1681 - 1694.

Ghosh, T. K., 1988. Puncture resistance of pre-strained geotextiles and its relation to uniaxial tensile strain at failure. *Geotextiles and Geomembranes,* 16(5), 293 – 302.

Ghosh, S., Dever, M., Thomas, H. and Tewksbury, C., 1994. Effects of selected fibre properties and needle-punch density on thermally-treated nonwoven fabrics. *Indian Journal of Fibre Textile Research journal*.

Ghosh, S. and Chapman, L., 2002. Effects of fibre blends and needling parameters on needlepunched mouldable nonwoven fabric. *Journal of The Textile Institute*, 93(1), 75 - 87.

Ghosh, M., Choudhury, P. K. and Sanyal, T., 2009. Suitability of natural fibres in geotextile applications. *IGC, Guntur, India*, 497 - 501.

Giroud, J. P., 1981. Designing with geotextiles. *Materiaux et Construction,* 14(4), 257 - 272.

Giroud, J. P., Ah-Line, C. and Bonaparte, R., 1984. Design of unpaved roads and trafficked areas with geogrids. In *Polymer grid reinforcement,* 116 - 127.

Giroud, J. P. and Bonaparte, R., 1989. Leakage through liners constructed with geomembranes—Part I. Geomembrane liners. *Geotextiles and Geomembranes,* 8(1), 27 - 67.

Giroud, J. P., 2004. Poisson's ratio of unreinforced geomembranes and nonwoven geotextiles subjected to large strains. *Geotextiles and Geomembranes,* 22(4), 297 – 305.

Guicheret-Retel, V., Cisse, O., Placet, V., Beaugrand, J., Pernes, M. and Boubakar, M. L., 2015. Creep behaviour of single hemp fibres. Part II: Influence of loading level, moisture content and moisture variation. *Journal of Materials Science*, 50(5), 2061 - 2072.

Haeri, S. M., Noorzad, R. and Oskoorouchi, A. M., 2000. Effect of geotextile reinforcement on the mechanical behaviour of sand. *Geotextiles and Geomembranes,* 18(6), 385 – 402.

Havlová, M., 2013. Air permeability and constructional parameters of woven fabrics. *Fibres and Textiles in Eastern Europe*, 21(2), 98.

Hearle, J. W. S. and Stevenson, P. J., 1963. Nonwoven fabric studies: Part III: The anisotropy of nonwoven fabrics. *Textile Research Journal*, 33(11), 877 - 888.

Hearle, J. W. and Morton, W. E., 2008. *Physical properties of textile fibres.* England, Woodhead publishing limited, Cambridge, UK, ISBN 978 1 84569 220 9.

Hong, Y. S. and Wu, C. S., 2011a. Filtration behaviour of soil-nonwoven geotextile combinations subjected to various loads. *Geotextiles and Geomembranes,* 29(2), 102 – 115.

Hong, Y. S., Wu, C. S., Yang, Z. Y., Lee, W. F. and Wang, R. H., 2011b. The load type influence on the filtration behaviour of soil-nonwoven geotextile composites. *Tamkang Journal of Science and Engineering,* 14(1), 15r24.

Horrocks, A. R. and Anand, S. C. eds., (2000),'*Handbook of Technical Textiles',* England, Woodhead publishing limited, Cambridge, UK, ISBN 1 85573 385 4.

Horvath, J. S., 1994. Expanded polystyrene (EPS) geofoam: an introduction to material behaviour. *Geotextiles and Geomembranes*, 13(4), 263 - 280.

Hosseinpour, I., Mirmoradi, S. H., Barari, A. and Omidvar, M., 2010. Numerical evaluation of sample size effect on the stress-strain behaviour of geotextile-reinforced sand. *Journal of Zhejiang University SCIENCE A*, 11(8), 555 - 562.

Huang, H. Y. and Gao, X., 1999. *Spunlace (hydro-entanglement),* CSIM, University of Tennessee.

Huang, X. M. and Wang, H., 2009. Comparison between responses of reinforced and unreinforced embankments due to road widening. *Journal of Central South University of Technology*, 16, 857 - 864.

Hufenus, R. and Schrade, U., 2004. An optimized method to measure the hydraulic conductivity of geosynthetics under load. *Geotextiles and Geomembranes,* 24(4), 243 – 253.

Hufenus, R., Rüegger, R., Flum, D. and Sterba, I. J., 2005. Strength reduction factors due to installation damage of reinforcing geosynthetics. *Geotextiles and Geomembranes*, 23(5), 401 - 424.

Hwang, G. S., Hwu, B. L., Hsing, W. H. and Lu, C. K., 1998. Manufacturing effects on the hydraulic properties of needle punched nonwoven geotextiles. *Geotextiles and Geomembranes,* 16(6), 355 – 363.

Hwang, G. S., Lu, C. K., Lin, M. F., Hwu, B. L. and Hsing, W. H., 1999. Transmissivity behaviour of layered needle punched nonwoven geotextiles. *Textile Research Journal*, 69(8), 565 - 569.

ISO 13433: 2006, Geosynthetics – Dynamic perforation test (cone drop test), Accessed on 29 February 2016, http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=36718.

ISO 22088-2:2006, Plastics - determination of resistance to environmental stress cracking (ESC) -- Part 2: Constant tensile load method, accessed on 03 March 2016, http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=34862.

Hwu, B., Koerner, R. M. and Sprague, C. J., 1990. Geotextile intrusion into geonets. International proceeding', *4th International conference on geotextiles, the Hague* , 351 - 356.

ISO 11058:2010, Geotextiles and geotextile-related products - Determination of water permeability characteristics normal to the plane, without load, accessed on 03 March 2016, http://www.iso.org/iso/catalogue_detail.htm?csnumber=54545.

Jaganathan, S., Maze, B., Tafreshi, H. V. and Pourdeyhimi, B., 2008. Simulating liquid flow through virtual glass fibre mats. *Textile Research Journal*, 78(10), 903 – 910.

Jena, A. and Gupta, K., 2002. Characterization of pore structure of filtration media. *Fluid/Particle Separation Journal,* 14(3), 227 – 241.

Jena, A. and Gupta, K., 2003. Liquid extrusion techniques for pore structure evaluation of nonwovens', *International Nonwoven Journal,* 12, 45 –53.

Jena, A. and Gupta, K., 2005. Pore volume of nanofibre nonwovens. *International Nonwoven Journal*, 14 (2), 25 – 30.

Jeon, H. Y., Kim, S. H. and Yoo, H. K., 2002. Assessment of long-term performances of polyester geogrids by accelerated creep test. *Polymer Testing*, 21(5), 489 - 495.

Jeon, H. Y., 2006. Chemical resistance and transmissivity of nonwoven geotextiles in waste leachate solutions. *Polymer testing*, 25(2), 176 - 180.

Jeon, S. S., 2011. Effect of geogrid reinforcement on soft and medium dense soils. *Journal of Central South University of Technology*, 18(5), 1638 - 1645.

Johar, N., Ahmad, I. and Dufresne, A., 2012. Extraction, preparation and characterization of cellulose fibres and nanocrystals from rice husk. *Industrial Crops and Products*, 37(1), 93 - 99.

John, S., 1987. Strong localization of photons in certain disordered dielectric superlattices. *Physical Review Letters*, 58(23), 2486.

Johnston, P. R., 1998. Revisiting the most probable pore-size distribution in filter media: the gamma distribution. *Filtration and Separation*, 35(3), 287 - 292.

Kabeya, H., Karmokar, A. K., Kamata, Y. and Tsunoda, S., 1993. Influence of surface roughness of woven geotextiles on interfacial frictional behaviour-evaluation through model experiments. *Textile Research Journal*, 63(10), 604 - 610.

Kamath, M. G., Dahiya, A. and Hegde, R. R., 2004a. Needle punched nonwovens. accessed on 01 July 2014, http://www.engr.utk.edu/mse/Textiles/Needle%20Punched%20Nonwovens.htm.

Kamath, M. G. Dahiya, A. and Hegde, R. R., 2004b. Spunlace (hydroentanglement). accessed on 01 July 2014, http://www.engr.utk.edu/mse/Textiles/Spunlace.htm.

Karademir, T. and Frost, J. D., 2014. Micro-scale tensile properties of single geotextile polypropylene filaments at elevated temperatures. *Geotextiles and Geomembranes*, 42(3), 201 - 213.

Khedkar, M. S. and Mandal, J. N., 2009. Pull out behaviour of cellular reinforcements. *Geotextiles and Geomembranes*, 27(4), 262 - 271.

Koerner, R. M., Wilson-Fahmy, R. F. and Narejo, D., 1996. Puncture protection of geomembrane Part III: Examples. *Geosynthetics International*, 3, 655 – 675.

Koerner, G. R. and Koerner, R. M., 2011. Puncture resistance polyester (PET) and polypropylene (PP) needle-punched nonwoven geotextile. *Geotextiles and Geomembranes*, 29(3), 360 – 362.

Koerner, R. M., 2012. *Designing with geosynthetics.* United States of America, Xlibris, ISBN 978-1-4628-8289-2.

Koerner, R. M., 2013. *Geosynthetics in filtration, drainage and erosion control.* Elsevier applied science, London, ISBN 1-85166-796-2.

Koerner, R. M., Koerner, G. and Hsuan, Y., 2014. Creep tension testing of geosynthetics. Geosynthetics institute, accessed on 26 July 2014, http://www.geosynthetic-institute.org/papers/paper29.pdf.

Komori, T. and Makashima, K., 1979. Geometrical expressions of spaces in anisotropic fiber assemblies. *Textile Research Journal* 49, 9, 550 - 555.

Kopitar, D., Skenderi, Z. and Rukavina, T., 2013. Influence of pressure on water permeability and characteristic opening size of nonwoven geotextiles. *Journal of Fibre Bioengineering and Informatics*, 6(1), 103 - 115.

Kothari, V. K. and Das, A., 1992. Compressional behaviour of nonwoven geotextiles. *Geotextiles and Geomembranes*, 11(3), 235 - 253.

Kothari, V. K. and Agarwal, G., 2008. Determination of pore size parameters and its distribution of hydro entangled fabrics by image processing. *Journal of The Textile Institute,* 99(4), 317 – 324.

Kuo, C. F. J., Su, T. L. and Tsai, C. P., 2007. Optimization of the needle punching process for the nonwoven fabrics with multiple quality characteristics by grey-based taguchi method. *Fibres and Polymers*, 8(6), 654 - 664.

Kutay, M. E. and Aydilek, A. H., 2005. Filtration performance of two-layer geotextile systems. *Geotechnical Testing Journal*, 28(1), 1 – 13.

Laerd statistics, One-way ANOVA in SPSS Statistics, accessed on 12 May 2016, https://statistics.laerd.com/spss-tutorials/three-way-anova-using-spss-statistics.php.

Lafleur, J., 1999. Selection of geotextiles to filter broadly graded cohesion less soils. *Geotextiles and Geomembranes*, 17(5), 299 – 312.

Landau, S. and Everitt, B. S., 2004. *A handbook of statistical analyses using SPSS.* Chapman and Hall/CRC, London, ISBN 1-58488-369-3.

Lhote, F. and Rigo, J. M., 1988. Study of the effect of the soil bearing capacity on the geotextiles puncture resistance. In *Proceedings of International Nonwovens Fabrics Conference*, 261 - 274.

Lawler, B. and Wilson, H., 2002. *Textiles technology.* Heinemann, UK, ISBN 0 435 41786 X.

Lawrence, C. A. and Shen, X., 2000. An investigation into the hydraulic properties of needle-punched nonwovens for application in wet-press concrete casting Part II: predictive models for the water permeability of needle-punched nonwoven fabrics. *Journal of the Textile Institute*, 91(1), 61 - 77.

Lekha, K. R., 2004. Field instrumentation and monitoring of soil erosion in coir geotextile stabilised slopes - A case study. *Geotextiles and Geomembranes*, 22(5), 399 - 413.

Lennox-Kerr, P. ed., 1972. Needle-felted Fabrics, Textile trade press, England.

Li, D., Frey, M. W. and Joo, Y. L., 2006. Characterization of nanofibrous membranes with capillary flow porometry. *Journal of Membrane Science,* 286(1), 104 – 114.

Li, T. T., Wang, R., Lou, C. W. and Lin, J. H., 2013. Evaluation of high-modulus, puncture-resistance composite nonwoven fabrics by response surface methodology. *Journal of Industrial Textiles*, 43(2), 247 - 263.

Lin, F. J. and Tsai, I. S., 2001. Configuration of PET fibre arrangement in roller drafting air-laid webs. *Textile Research Journal*, 71(1), 75 - 80.

Lin, C. W. and Lin, J. H., 2005. Manufacture and application of high performance geogrids with PP/PET composite covered yarn. *Textile Research Journal,* 75(6), 453 – 457.

Liu, L. F. and Chu, C. Y., 2006. Modelling the slurry filtration performance of nonwoven geotextiles. *Geotextiles and Geomembranes,* 24(5), 325 - 330.

Lombard, G., Rollin, A. and Wolff, C., 1989. Theoretical and experimental opening sizes of heat-bonded geotextiles. *Textile Research Journal,* 59(4), 208 - 217.

Lopes, M. L. and Silvano, R., 2010. Soil/geotextile interface behaviour in direct shear and pullout movements. *Geotechnical and Geological Engineering*, 28(6), 791 - 804.

Luettich, S., Giroud, J. and Bachus, R., 1992. Geotextile filter design guide. *Geotextiles and geomembranes,* 11(4-6), 355 - 370.

Lydon, R., Mayer, E. and Rideal, G. R., 2004. Comparative methods for the pore size distribution of woven and metal filter media. In *9th World Filtration Congress*, 18 April 2004.

Maheshwari, B. K. and Gunjagi, D. A., 2008. Filtration and clogging behavior of geotextiles with roorkee soils. *Geotechnical and Geological Engineering*, 26(1), 101 - 107.

Maitre, K., Pate, M., Cozon, N. and Schlumberger, N., 2001. Needle punch nonwoven primer, capabilities and end uses, market outlook and manufacturing process. Association of the nonwoven fabrics industry, www.Inda.org.

Maity, S. and Singha, K., 2012. Structure-property relationships of needle-punched nonwoven fabric. *Frontiers In Science,* 2(6), 226 - 234.

Majumdar, A., Das, A., Alagirusamy, R. and Kothari, V. K., 2013. *Process control in textile manufacturing.* Woodhead publishing, Cambridge, UK, ISBN 978 –0–85709–02 -0.

Mao, N. and Russell, S. J., 2000. Directional permeability in homogeneous nonwoven structure part 1: The relationship between directional permeability and fibre orientation. *The Journal of The Textile Institute,* 91(2), 235 – 243.

Mao, N. and Russell, S. J., 2003. Anisotropic liquid absorption in homogeneous two dimensional nonwoven structures. *Journal of Applied Physics,* 94(6), 4135 – 4138.

Markets and Markets, Geosynthetics market worth $15,403.7 million by 2019, accessed on 21 May 2015, http://www.marketsandmarkets.com/PressReleases/geosynthetics.asp.

Mazharul, I. K., 2014. Carding process, setting of carding machine, working process of licker-in, cylinder, doffer, accessed on 20 January 2016, http://textilelearner.blogspot.co.za/2012/01/carding-process-setting-of-carding.html.

McCoy., 2014. 'Internal manual for Instron operation, Using the Instron compression/tensile tester in conjunction with the environmental control chamber', accessed on 07 March 2016, http://nmtprg.weebly.com/uploads/3/1/1/0/31101989/instron_procedure.pdf.

Midha, V. K., Alagirusamy, R. and Kothari, V. K., 2004. Studies on properties of hollow polyester needle-punched fabrics. *Indian Journal of Fibre and Textile Research*, 29(4), 391.

Midha, V. K. and Mukhopadyay, A., 2005. Bulk and physical properties of needle-punched nonwoven fabrics. *Indian Journal of Fibre and Textile Research*, 30(2), 218.

Miguel, A. F., 2013. Filtration processes and design of filters. *In Industrial and Technological Applications of Transport in Porous Materials*, Springer Berlin Heidelberg, 63 - 90.

Militký, J., Vik, M., Viková, M. and Křemenáková, D., 2004. Influence of fabric construction on their porosity and air permeability. In *Proceedings of 2nd SIENTEX Conference "International Symposium of Textile Engineering*, 1 - 18.

Montgomery, S. M., Miller, B. and Rebenfeld, L., 1992. Spatial distribution of local permeability's in fibrous networks. *Textile Research Journal*, 62(3), 151 - 161.

Moo-Young, H. K. and Tucker, W. R., 2002. Evaluation of vacuum filtration testing for geotextile tubes. *Geotextiles and Geomembranes*, 20(3), 191 - 212.

Moo-Young, H. K., Gaffney, D. A. and Mo, X., 2002. Testing procedures to assess the viability of dewatering with geotextile tubes. *Geotextiles and Geomembranes*, 20(5), 289 – 303.

Moraci, N. and Recalcati, P., 2006. Factors affecting the pull out behaviour of extruded geogrids embedded in a compacted granular soil. *Geotextiles and Geomembranes*, 24(4), 220 – 242.

Moyo, D. A., Patanaik, A. and Anandjiwala, R. D., 2012. Process control in nonwovens production. *Process Control in Textile Manufacturing* 279.

Mrština, V. and Fejgl, F., 1990. *Needle punching textile technology*. Vol. 8. Wool Research Institute, Brno, Czechoslovakia, Elsevier Science Ltd, ISBN 0-444-98804-1.

Müssig, J. and Martens, R., 2003. Quality aspects in hemp fibre production-influence of cultivation, harvesting and retting. *Journal of Industrial Hemp*, 8(1), 11 - 32.

Muthukumaran, A. E. and Ilamparuthi, K., 2006. Laboratory studies on geotextile filters as used in geotextile tube dewatering. *Geotextiles and Geomembranes*, 24(4), 210 – 219.

Mwaikambo, L., 2006. Review of the history, properties and application of plant fibres. *African Journal of Science and Technology*, 7(2), 121.

Narejo, D., Koerner, R. M. and Wilson-Fahmy, R. F., 1996. Puncture protection of geomembranes, part 2: experimental. *Geosynthetics International*, 3, 629 - 653.

Narejo, D. B., 2003. Opening size recommendations for separation geotextiles used in pavements. *Geotextiles and Geomembranes*, 21(4), 257 - 264.

Neckar, B. and Ibrahim, S., 2003. Theorectical approach for determining pore characteristics between fibres. *Textile Research Journal*, 73(7), 611 – 619.

Ochiai, H., Otani, J., Hayashic, S. and Hirai, T., 1996. The pull out resistance of geogrids in reinforced soil. *Geotextiles and Geomembranes*, 14(1), 19 – 42.

Oosthuizen, P. and Kruger, D., 1994. The use of sisal fibres as natural geotextile to control erosion', proceeding of fifth international conference on geotextile. Geomembrane and related products, Singapore, 871 - 874.

Pagano, M. and Gauvreau, K., 2000. *Principles of biostatistics.* 2nd Edition, Duxbury press, Pacific Grove, CA, ISBN 978-0534229023.

Palmeira, E. M. and Gardoni, M. G., 2000. The influence of partial clogging and pressure on the behaviour of geotextiles in drainage systems. *Geosynthetics International*, 7(4-6), 403 - 431.

Palmeira, E. M. and Gardoni, M. G., 2002. Drainage and filtration properties of nonwoven geotextiles under confinement using different experimental techniques. *Geotextiles and Geomembranes*, 20(2), 97 – 115.

Palmeira, E. M., 2009. Soil-geosynthetic interaction: modelling and analysis. *Geotextiles and Geomebranes*, 27(5), 368 – 390.

Paridah, M. T., Basher, A. B., SaifulAzry, S. and Ahmed, Z., 2011. Retting process of some bast plant fibres and its effect on fibre quality: A review. *BioResources*, 6(4), 5260 - 5281.

Park, J. K. and Nibras, M., 1993. Mass flux of organic chemicals through polyethylene geomembranes. *Water Environment Research*, 227 - 237.

Patanaik, A. and Anandjiwala, R. D., 2008. Water flow through the polypropylene-based geotextiles. *Journal of Applied Polymer Science*, 108(6), 3876 - 3880.

Patanaik, A. and Anandjiwala, R., 2009. Some studies on water permeability of nonwoven fabrics. *Textile Research Journal*, 79(2), 147 - 153.

Patel, M. and Bhrambhatt, nonwoven technology, accessed on date on 28 November 2016, https://textlnfo.files.wordpress.com/2011/10/nonwoven-fabrics1.pdf.

Pilarczyk, K., 2000. *Geosynthetics and geosystems in hydraulic and coastal engineering.* Rotterdam, Netherlands, CRC Press, ISBN 90 5809 302 6.

Placet, V., Cisse, O. and Boubakar, M. L., 2012. Influence of environmental relative humidity on the tensile and rotational behaviour of hemp fibres. *Journal of Materials Science*, 47(7), 3435 - 3446.

Porometer, the principle of capillary flow porometry (CFP), accessed on 29 February 2016, http://www.porometer.com/porometers/technology/.

Prabakar, J. and Sridhar, R. S., 2002. Effect of random inclusion of sisal fibre on strength behaviour of soil. *Construction and Building Materials*, 16(2), 123 - 131.

Pradhan, A.K., Das, D., Chattopadhyay, R. and Singh, S.N., 2014. An approach of optimal designing of nonwoven air filter media: Effect of fibre fineness. *Journal of Industrial Textiles*, 1528083714559566.

Rajagopal, K., 2016. Testing of geosynthetics. accessed on 08 March 2016, http://nptel.ac.in/courses/105106052/downloads/Lecture-7.pdf.

Ramkumar, S. S., Umrani, A. S., Shelly, D. C., Tock, R. W., Parameswaran, S. and Smith, M. L., 2004. Study of the effect of sliding velocity on the frictional properties of nonwoven fabric substrates. *Wear,* 256(3), 221 – 225.

Rakshit, A. K., Desai, A. N. and Balasubramanian, N., 1990. Engineering needle punched nonwovens to achieve desired physical properties. *Indian Journal of Fibre and Textile Research*, 15(1), 41 - 48.

Rawal, A., 2006a. A cross-plane permeability model for needle-punched nonwoven structures. *Journal of The Textile Institute,* 97(6), 527 - 532.

Rawal, A. and Anandjiwala, R., 2006b. Relationship between process parameters and properties of multifunctional needle punched geotextiles. *Journal of Industrial Textiles,* 35(4), 271 – 285.

Rawal, A., 2006c. A modified micromechanical model for the prediction of tensile behaviour of nonwoven structures. *Journal of Industrial Textiles*, 36(2), 133 - 149.

Rawal, A. and Anandjiwala, R., 2007. Comparative study between needles punched nonwoven geotextile structure made from flax and polyester fibres. *Geotextiles and Geomembranes,* 25(1), 61 – 65.

Rawal, A., Anand, S. and Shah, T., 2008. Optimization of parameters for the production of needle punched nonwoven geotextiles. *Journal of Industrial Textiles,* 37(4), 341 – 356.

Rawal, A., 2008. Effect of dynamic loading on pore size of needle punched nonwoven geotextiles. *Journal of The Textile Institute,* 99(1), 9 - 15.

Rawal, A., Shah, T. and Subhash, S. C., 2010a. Geotextiles: production, properties and performance. *Textile Progress,* 42(3), 181 – 226.

Rawal, A., Priyadarshi, A., Kumar, N., Lomov, S. V. and Verpoest, I., 2010b. Tensile behaviour of nonwoven structures: comparison with experimental results. *Journal of Materials Science*, 45(24), 6643 - 6652.

Rawal, A., Kameswara Rao, P. V., Russell, S. and Jeganathan, A., 2010c. Effect of fibre orientation on pore size characteristics of nonwoven structures. *Journal of Applied Polymer Science*, 118(5), 2668 - 2673.

Rawal, A. and Saraswat, H., 2011a. Pore size distribution of hybrid nonwoven geotextiles. *Geotextiles and Geomembranes,* 29(3), 363 - 367.

Rawal, A. and Agrahari, S. K., 2011b. Pore size characteristics of nonwoven structures under uniaxial tensile loading. *Journal of Materials Science*, 46(13), 4487 - 4493.

Rawal, A., Kochhar, A. and Gupta, A., 2011c. Biaxial tensile behaviour of spunbonded nonwoven geotextiles. *Geotextiles and Geomembranes*, 29(6), 596 - 599.

Rawal, A., Sayeed, M. A., Saraswat, H. and Shah, T., 2013a. A comparison of wide-width tensile strength to its axi-symmetric tensile strength of hybrid needle punched nonwoven geotextiles. *Geotextiles and Geomembranes*, 36, 66 - 70.

Rawal, A. and Sayeed, M. M. A., 2013b. Mechanical properties and damage analysis of jute/polypropylene hybrid nonwoven geotextiles. *Geotextiles and Geomembranes*, 37, 54 - 60.

Rollin, A. and Lombard, G., 1988. Mechanism affecting long term filtration behaviour of geotextiles. *Geotextiles and Geomembranes,* 7(1), 119 – 145.

Rowe, R. K. and Li, A. L., 1999. Reinforced embankments over soft foundations under undrained and partially drained conditions. *Geotextiles and Geomembranes*, 17(3), 129 - 146.

Rowe, R. K. and Skinner, G. D., 2001. Numerical analysis of geosynthetic reinforced retaining wall constructed on a layered soil foundation. *Geotextiles and Geomembranes*, 19(7), 387 - 412.

Roy, A. N. and Ray, P., 2009. Optimization of jute needle punched nonwoven fabric properties: Part II-Some mechanical and functional properties. *Journal of Natural Fibres*, 6(4), 303 - 318.

Roy, A. N. and Ray, P., 2009. Optimization of jute needle punched nonwoven fabric properties: Part I—tensile properties. *Journal of Natural Fibres*, 6(3), 221 - 235.

Russell, S. J. ed., 2006. *Handbook of Nonwovens*. Woodhead publishing, Cambridge, UK, ISBN 978-1-85573-603-0.

Saathoff, F., Oumeraci, H. and Restall, S., 2007. Australian and German experiences on the use of geotextile containers. *Geotextiles and Geomembranes*, 25(4), 251 - 263.

Senguptaa, S., Ray, P. and Majumdar, P. K., 2008. Effect of punch density, depth of needle penetration and mass per unit area on compressional behaviour of jute needle-punched nonwoven fabrics using central composite rotatable experimental design. *Indian Journal of Fibre and Textile Research*, *33*, 411 - 418.

Simmonds, G. E., Bomberger, J. D. and Bryner, M. A., 2007. Designing nonwovens to meet pore size specifications. *Journal of Engineered Fibres and Fabrics*, 2(1).

Slater, K., 2003. Design factors in geotextile structures for control of water movement. *Journal of the Textile Institute*, 9(3-4), 99 - 105.

Steve, C. and Mussig, J., 2010. *Industrial applications of natural fibres: structure, properties and technical applications.* (Vol. 10), John Wiley and Sons, UK, ISBN 978-0-470-69501-1.

Subaida, E. A., Chandrakaran, S. and Sankar, N., 2008. Experimental investigations on tensile and pullout behaviour of woven coir geotextiles. *Geotextiles and Geomembranes*, 26(5), 384 - 392.

Szostak-Kotowa, J., 2004. Biodeterioration of textiles’, *International Biodeterioration and Biodegradation*, 53(3), 165 - 170.

Tabachnick, B. G. and Fidell, L. S., 1996. *Using multivariable statistics.* Harper Collins College Publishers, New York, ISBN 978-0205849574.

Tan S A., Chew, S. H. and Wong, W. K., 1998. Sand–geotextile interface shear strength by torsional ring shear tests. *Geotextiles and Geomembranes*, 16(3), 161 - 174.

Tascan, M. and Vaughn, E. A., 2008. Effects of fibre denier, fibre cross-sectional shape and fabric density on acoustical behaviour of vertically lapped nonwoven fabrics. *Journal of Engineered Fibres and Fabrics*, 3(2), 32 - 38.

Textile innovation knowledge platform, accessed on 02 May 2016, http://www.tikp.co.uk/knowledge/technology/nonwovens/under-construction/).

Tholkappiyan, E., 2010. Nonwovens and technical textiles, geotextile degradation under different environ conditions, accessed on 01 July 2011, http://www.indiantextilejournal.com/articles/FAdetails.asp?id=2899.

Van Santvoort., 1994. *Geotextiles and geomembranes in civil engineering.* CRC press, Balkema, Rotterdam, ISBN 9054101725.

Van Wyk, C. M., 1946. 20-Note on the compressibility of wool. *Journal of The Textile Institute Transactions*, 37(12), 285 - 292.

Wambua, P., Ivens, J. and Verpoest, I., 2003. Natural fibres: can they replace glass in fibre reinforced plastics?. C*omposites Science and Technology*, 63(9), 1259 - 1264.

Wang, M. C., Feng, Y. X. and Jao, M., 1996. Stability of geosynthetic-reinforced soil above a cavity. *Geotextiles and Geomembranes*, 14(2), 95 - 109.

Wang, Y., 2001. A Method for tensile test of geotextiles with confining pressure. *Journal of Industrial Textiles*, 30(4), 289 - 302.

Wang, R., Li, T.T., Lou, C.W., Lin, J.Y. and Lin, J.H., 2013. Effect of process parameters on puncture resistance of composites by needle punching and thermal bonding techniques. *Materials and Manufacturing Processes*, 28(9), 1029 - 1035.

Watson, P. D. J. and John, N. W. M., 1999. Geotextile filter design and simulated bridge formation at the soil-geotextile interface. *Geotextiles and Geomembranes*, 17(5), 265 – 280.

Wei, K. Y., Vigo, T. L., Goswami, B. C. and Duckett, K. E., 1985. Permeability of soil-geotextile systems. *Textile Research Journal*, 55(10), 620 - 626.

White, F. M. and Corfield, I., 2006. *Viscous fluid flow.* Vol 3, New York: McGraw-Hill, ISBN 0070697108.

Wilson-Fahmy, R. F., Koerner, G. R. and Koerner, R. M., 1996. Geotextile filter design critique. In *Recent Developments in Geotextile Filters and Prefabricated Drainage Geocomposites*, ASTM International.

Wojtasik, D., 2008. An analysis of physical, hydraulic and mechanic properties of nonwoven needle-punched geotextiles. *Annals of Warsaw University of Life Sciences-SGGW, Land Reclamation*, 40, 115 - 123.

WSP 120.6 (EDANA)), Test standard, accessed on 03 March 2016, https://www.testingmachines.com/standard/wsp-120-6-edana.

Wu, C. S., Hong, Y. S., Yan, Y. W. and Chang, B. S., 2006. Soil-nonwoven geotextile filtration behaviour under contact with drainage materials. *Geotextiles and Geomembranes*, 24(1), 1 – 10.

Wu, C. S., Hong, Y. S. and Wang, R. H., 2008. The influence of uniaxial tensile strain on the pore size and filtration characteristics of geotextiles. *Geotextiles and Geomembranes*, 26(3), 250 - 262.

Xiang, P., 2007. *Numerical modelling and experimental investigation of the hydro entanglement process*, North Carolina State University, ProQuest publishers, ISBN 0549376704, 9780549376705.

Yao, K. M., Habibian, M. T. and O'Melia, C. R., 1971. Water and waste water filtration. Concepts and applications. *Environmental Science and Technology*, 5(11), 1105 - 1112.

Zhai, H., Mallick, S. B., Elton, D. and Adanur, S., 1996. Performance evaluation of nonwoven geotextiles in soil-fabric interaction. *Textile Research Journal*, 66(4), 269 – 276.

Yüksekkaya, M. E., Tercan, M. and Doğan, G., 2010. Filter media research: fabric reinforcement of nonwoven filter cloths. *Filtration and Separation*, 47(3), 36 - 39.