Production and characterization of cotton-chicken feather fibres blended absorbent fabrics

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Abstract

Nonwoven fabrics are mostly used in modern disposable hygienic products where their primary purpose is to offer excellent absorbency as well as comfort to consumers. Scientists, both on the academic and industrial level, have faced numerous challenges in designing nonwoven fabrics of significantly high performance in terms of absorbency and comfort. With the new design, the hygienic products can now be deemed a luxury because of the introduction of superabsorbent polymers. Hence, the need to manufacture these products with either cheap raw materials or reduced production cost and still have excellent performance is vital. Chicken feather fibres have been identified as prospective plentiful fibres that can be used as cheap raw materials in nonwoven production. The problem is that nonwoven fabrics cannot be made entirely from chicken feather fibres due to their poor length. In this work, they were blended with bleached cotton fibres to produce a nonwoven fabric via a needle punched technique used to convert the fibrous web into a coherent fabric structure. The effect of process parameters such as the speed of the conveyor belt, stroke frequency and depth of needle penetration on the absorbency of the fabrics were studied and the optimum conditions were determined. Superabsorbent solutions were used as coatings to improve the absorption behaviour of the new fabrics. The results revealed that the absorbency of the uncoated samples decreased as the speed, stroke frequency and depth of needle penetration increased. Moreover, it was found that the final volume fraction of the fibres used strongly affected the fabric absorbency. Coated fabrics however, had high absorbency compared to uncoated fabrics as well as the samples of absorbent core used in some commercial diapers.

Keywords: superabsorbent, nonwovens, absorption capacity, feathers, fibres

1. INTRODUCTION

Nonwoven absorbent cores (NACs) are layers of highly porous and compressible materials made from short staple fibres or infinite filaments bonded together through mechanical, thermal or chemical process and containing superabsorbent polymers or granules which enable them to absorb and hold large quantities of the liquids at a faster rate (Kakonke *et al.*, 2019). NACs can be characterized by their web forming process and bonding technique; current web forming processes include carded forming, air laying, wet laying, spun bonding, melt spinning, and electrospinning (Raghvendra and Sravanthi, 2017); and commercially available bonding techniques are resin bonding, thermal bonding, solvent bonding, needle-punching, spun lacing and stitch bonding.

The properties of NAC products differ widely from one another, because of the wide variety of available fibrous raw materials and many possible laying techniques used to make NACs. The finished fabrics are usually designed for specific end uses and therefore, the selection of fibre type, binder system, technique and equipment used in their production determines their characteristics (Midha and Mukhopadyay, 2005). Out of various manufacturing techniques of nonwoven fabrics, needle punching is the second most popular technique after spun bonding and is widely used in various applications such as geotextiles, automotive fabrics, home furniture, medical, upholstery industry, gas and liquid filters, and other technical felts. Textile fabrics for high performance applications, such as the various layers used in disposable diapers, are mostly simulated by combining various technologies, especially the combination of needle punched technique with a chemical bonding technique.

A typical way of incorporating recycled products into nonwoven materials is to create needle-punched fabrics produced in part or entirely from waste fibrous materials (Goswami and O'Haire, 2016). CFFs, the recycled fibres from poultry industrial wastes, can be processed into durable nonwoven fabrics because of their various properties, i.e. biodegradable, chemical durability, fineness, high tensile strength (Chinta *et al.*, 2013). Due to their lightweight properties and short lengths, 100 % CFFs cannot be used to produce nonwoven fabrics; but mixing them with other long fibres solved the problem. Hence, fibres from pineapple leaves, sugarcane bagasse, and bamboo, also considered as waste materials with similar properties as CFFs could be blended with

CFFs to successfully prepare a completely bio-based NACs. Raw pineapple leave fibres are strong, silky, hydrophobic and lightweight (Asim *et al.*, 2015) – blending them with CFFs will result in the production of a non-uniform and inconsistent web-structure as most of the fibres will escape from the opener of the carding machine thus resulting in an uneven distribution of fibres through the carded wed . Although, sugarcane bagasse and bamboo fibres are great absorbents containing antibacterial agents (Afrin *et al.*, 2012), the process of converting them into processable fibres for use in disposable diapers is expensive - because in the case of bagasse, special care need to be taken to prevent the fibres from fermenting due to its high sugar content (Bottcher *et al.*, 2013) and since bagasse and bamboo have high content of lignin, more treatment are needed to remove lignin from the fibres before using them in textile fabrics. Bleached cotton fibres (BCFs), on the other hand, are widely used in the textile industries mainly because of their good and excellent mechanical properties; although expensive, BCFs appeared to be suitable fibres to blend with CFFs in the production of nonwovens, especially due to their length and density properties.

Current methods for disposal of waste chicken feathers are unsustainable and effective methods for beneficiating this waste are needed. In this work, the main objective is to use chicken feather fibres in the production of needle-punched nonwoven fabrics as an alternative beneficiation pathway of the poultry waste. Since the municipality has been facing multiple issues related to the waste disposal of disposable diapers (Kakonke *et al.*, 2019), this study attempts for the first time to produce an absorbent core using chicken feather fibres-based needle punched nonwovens – which could help eliminate the problems associated with the degradation of biological inert polymers in sewage treatment plants. From this perspective, the effect of fabric construction parameters such as the speed of the conveyor belt, the stroke frequency as well as the depth of needle penetration were first studied in order to reach the desired characteristics of absorbent cores, i.e. mainly absorption capacity. Thereafter, the proposed needle punched fabrics will be coated with various polymer solution to improve the fabrics' absorption capacity. The effect of these polymer solutions of the fabrics were reported.

2. EXPERIMENTAL

The chemicals utilised in this study were supplied by Sigma Aldrich, each having a unique purpose: 30 % hydrogen peroxide ($H_2 O_2$) was used to clean and decontaminate raw chicken feathers; sodium chloride, molecular weight: 58.44 g/mol, was used to simulate a urine like solution for absorbency test; and sodium hydroxide pellet, ACS reagent, molecular weight: 40 g/mol. Poly vinyl alcohol (PVA), Mw ~ 125 000 and viscosity: 18.5 – 21.5 mPa.s; Poly acrylic acid (PAA), Mv ~ 450 000, ~ 0.1 % cross-linked, Tg 106 °C; N, N – dimethylacrylamide (DMAA), Mw ~ 99.13 g/mol, bp 80 – 81 °C; and Poly (methyl methacrylate-co-methacrylic) acid (PMMCM), Mw ~ 34 000 by GPC, viscosity: 0.19 d*l*/g, Tg: 105 °C were used to prepare the absorbent solutions.

2.1. Extraction process of chicken feather fibres

Raw chicken feathers were collected from Rainbow Chicken Limited (RCL) farms in Hammersdale, KwaZulu-Natal. They contained blood, skin, flesh, bones, and internal organs. They were collected in plastic bags and separated in a lab environment. To facilitate the separation, the mixture was soaked in warm water and the offal was manually removed. The cleaning and decontamination procedure used in this work, was adopted from the work done on the optimization of the decontamination and pre-treatment of waste chicken feathers (Tesfaye *et al.*, 2018). Feathers were then washed thoroughly with hot water and sterilized at a temperature of 121 °C and pressure of 12.5 MPa for 20 minutes prior to drying; this was done to kill most bacteria and avoid worms. Sterilized feathers were dried overnight at ambient temperature and thereafter were decontaminated by soaking the feathers in 25 l aqueous solution of 30 % hydrogen peroxide for a day. They were thereafter thoroughly rinsed with water and oven dried at 50 °C for 3 days. The advantage of using hydrogen peroxide was to dissolve any fat and grease content from the fibres, thereby increasing their strength and improving their degree of whiteness.

Dried feathers were then grinded into fluffy fibres using the modified fluffer, an equipment used in the pulp and paper industry to convert wood pulp into fluff pulp. The "Femco" fluffer is made of multiple blades connected to a shaft with a maximum speed of 2860 rpm and an external motor of a maximum power of 2.2 kW (Figure 1). Its normal safety operating procedure, in the case of wood pulp, involves continuously feeding wood pulp at the inlet (Point A) whilst running the motor, and immediately fluff pulp is collected at its outlet (Point B). To achieve a successful conversion of feathers into fibres, the fluffer outlet (Point B) was closed with a piece of wood. Feathers were feed at point A and collected in containers by switching off the machine and opening the crushing chamber of the pulp fluffer, as illustrated in Figure 1 c.

Bleached cotton fibres were obtained from CSIR – Port Elizabeth.

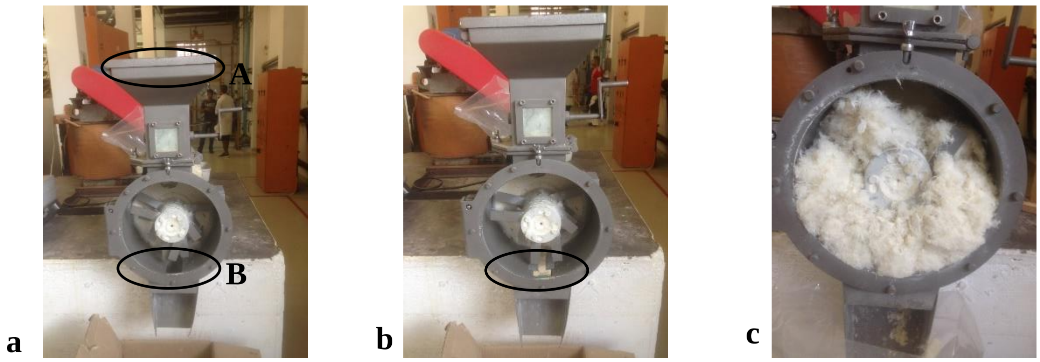

Figure 1: (a) Pulp fluffer setup for cellulose pulp; (b) Pulp fluffer setup for grinding chicken feathers; (c) Collection of CFFs from pulp fluffer

2.2. Selection of parameters and useful parameter values

The process parameters were selected based on the information available in the literature however, the useful parameter values and the blending ratio used in this work were chosen after conducting preliminary experiments with the following volume fractions of CFF:BCF: 90:10, 70:30 and 50:50. The carded webs produced with a CFF:BCF blend ratio of 50:50 passed through the rollers of the cross-lapper unit and that of the needle punched unit without falling apart. The CFF:BCF blend ratios of 90:10 and 70:30 produced carded webs that were not strong and coherent; pieces of the web fell apart, and the bat could not reach the needle punched unit to make a whole fabric. Based on these observations, the blending ratio of CFF:BCF was chosen to be 50:50 since the fabric obtained with this ratio appeared to be condensed. The actual and coded values of the parameters are given in Table 1.

Table 1: Actual and coded needling parameters

Independent variables	Unit	Symbols	Coded values	
			-1	1
Speed (S)	m/min	x_1	0.8	1.2
Stroke frequency (SF)	Hz	x_2	200	350
Depth of needle penetration (D)	mm	x_3	4	7

2.3. Preparation of needle-punched fabrics

A schematic of the production process of needle-punched superabsorbent fabrics is shown in Figure 2. CFFs and BCFs were first blended by hands with a blending ratio of 50:50 , then the fibre blend was run through the opener twice to improve the homogeneity of the fibre mixture that was then carded in a carding machine equipped with a main cylinder (800 mm diameter x 600 mm width) to form a web. The cylinder, surrounded by pairs of rollers, distributes the fibres during the process by accomplishing the dual function of blending and carding. The carded webs were then fed to the lattice of the cross-lapper unit to layer up the web and form a batt. The carding machine and cross-lapper unit were perpendicular to the needle-punched machine; consequently, the fibre orientation in the web was perpendicular in line with orientation to the direction of the web movement. Nonwoven fabrics were produced by mechanically reorienting and interlocking the fibres, by repeatedly punching and penetration actions of an array of double reduction felting barbed needles into the carded web. Fabrics were produced using the needling parameters shown in Table 1. Figure 3 shows the machines used in the production of needle punched fabrics: the carding machine is on the right, in white and blue; the cross-lapper unit is the part connecting the carding machine to the needle punched machine on the left, in green.

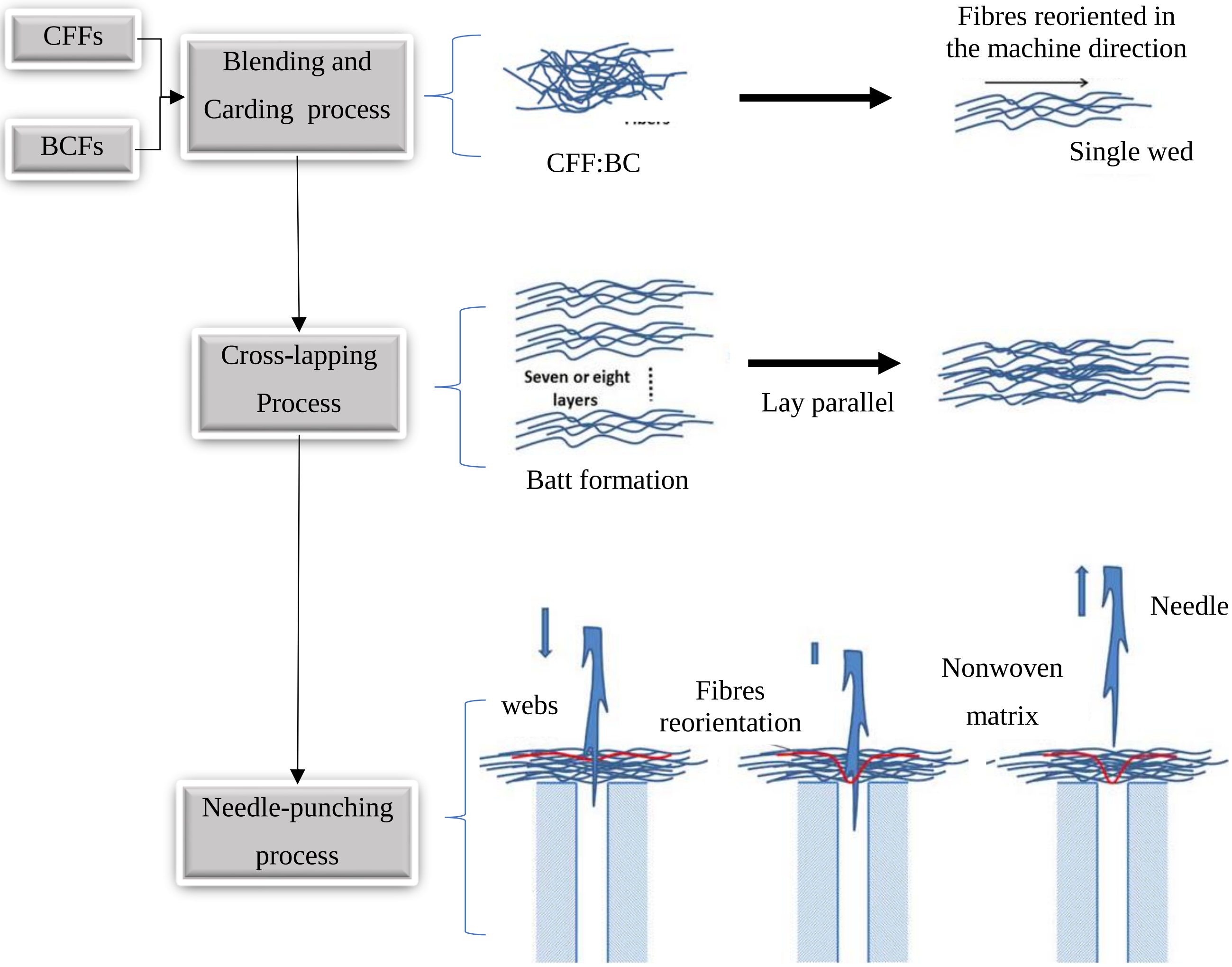

Figure 2: Schematic diagram of needle-punch process

Figure 3: Machines used for needle-punched fabrics (on the left); CFF:BCF nonwoven fabrics leaving the needle puncher (on the right)

2.4. Statistical analysis

To investigate the individual and interactive effects of the independent variables (S (m/min), SF (Hz) and D (mm)) on the fabric weight, thickness and absorbency, the samples were produced according to a randomized regular two-level factorial design (Oehlert, 2010). A Design Expert software generated a matrix of 8 experimental combinations under which the fabrics were produced. The coded and actual values considered for each independent variable are given in Table 2.

Table 2: Randomized regular 2-level factorial matrix design.

	Level of variables					
	x_1 level		x_2 level		x_3 level	
Run	Coded	Actual	Coded	Actual	Coded	Actual
1	$+1$	1.20	-1	200.00	-1	2.00
2	-1	0.80	$+1$	350.00	$+1$	4.00
3	-1	0.80	-1	200.00	$+1$	4.00
4	$+1$	1.20	$+1$	350.00	-1	2.00
5	$+1$	1.20	$+1$	350.00	$+1$	4.00
6	$+1$	1.20	-1	200.00	$+1$	4.00
7	-1	0.80	$+1$	350.00	-1	2.00
8	-1	0.80	-1	200.00	-1	2.00

x_1 : Throughput speed in m/min
x_2 : Stroke frequency in Hz
x_3 : Penetration depth in mm

2.5. Preparation of superabsorbent nonwoven fabrics

A fabric was produced using the optimum conditions obtained during the production process of CFF:BCF blended nonwoven fabrics described in section 2.3. The same production technique was utilized except that the formation of a batt was achieved by feeding a double carded web to the lattice of the cross-lapper unit to layer up the web and obtain a more consolidated fabric prior to the padding method. Hydrophilic fabrics are commonly produced by coating the surface with a superabsorbent solution typically PVA, PAA or DMAA (Hundorf *et al.*, 2013). Thus, four polymer solutions were prepared using PVA, PAA, DMAA and a DMAA:PAA mixture. The PVA coating mixture was prepared by dissolving 5 g of PVA in 100 ml of distilled water at a temperature of 100 ℃ and stirring rate of 100 rpm for 3 hours to obtain a clear PVA solution. When PVA was completely dissolved, 0.2 g of the crosslinker was gradually added to the mixture and stirred until the crosslinker was completely dissolved. Thereafter, 0.1 g of the radical initiator was added and stirred to complete dissolution. PAA solution was prepared at room temperature in the same fashion as PVA solution (2^{nd} coating solution). For the third solution, 100 ml of DMAA was measured into a beaker and placed on a magnetic plate at 100 rpm. Because DMAA is light sensitive, the beaker was completely covered with an aluminium foil and the stirring process was done at room temperature. The same amount of crosslinker and initiator used in solution 1 was added to the DMAA solution in the same fashion. Finally, for the last solution, 3 g of PAA was dissolved in 100 ml of distilled water at 100 rpm for a minute. Thereafter, 50 ml of the PAA solution was mixed with 10 ml of DMAA; the resulting solution was then vigorously stirred for 10 minutes to obtain a homogenous solution to which 0.2 g of crosslinker and 0.1 g of the initiator were added as described in the solution 1. These solutions were separately sprayed onto the four fabrics with the help of a syringe; a manual padding technique was then used to evenly distribute the solution onto each fabric – rollers were used to spread the chemical on the fabrics and pressure was applied on the rollers to ensure that chemical penetrates inside the fabric as well. Thereafter, each fabric was placed in the oven at 80 ℃ for polymerization reaction to take place. Once the fabric was dried, it was removed and kept in an aluminium foil prior to absorbency test.

2.6. Fibre blend ratio

A chemical analysis procedure was used to determine the exact amounts of fibres in the fabric after the whole production process. Three samples were cut from 3 random fabric samples and immersed in 1.5 % sodium hydroxide solution at 80 ℃ with stirring speed at 100 rpm (Nagai and Nishikawa, 2014) for an hour to dissolve CFFs. After complete dissolution, the sample was filtered through a dried weighed fritted crucible and the residues were thoroughly washed with distilled water to remove excess sodium hydroxide and then oven-dried at 100 ℃ to a constant weight to calculate the weight of dried residues.

2.7. Weight per unit area

The ASTM D6242 Standard Test Method for determination of mass per unit area of fabric was followed. Test samples measuring $60 \times 60\ mm$ were randomly cut from different areas of fabric samples, conditioned at 20 ± 2 ℃, and 65 ± 2 % relative humidity for 24 h and then weighed on a precision weighing balance. An average of 10 readings was recorded and the weight per unit area was estimated using equation 1.

$$\text{weight per unit area}\left(\frac{g}{m^2}\right) = \frac{mass}{length \times width} \quad (1)$$

2.8. Thickness

The thickness of 12 different specimens from each needle-punched fabric was measured using a digital thickness gauge, in accordance with the *European Disposables and Nonwovens Association (EDANA) –WSP 120.6 (05)* standard test for the measurement of nonwoven fabric thickness. A pressure of 1 kPa and pressure foot area of $19.6\ cm^2$ was applied on the fabric while the thickness was recorded in mm. An average value of 10 thickness readings was then recorded. The pressure level was set low (1 kPa), on the assumption that the superabsorbent samples were highly compressible, to avoid inaccurate thickness reading.

2.9. Density

The density of the fabrics was measured in accordance with the ASTM D 3776. Ten samples from each material were conditioned at 20 ± 2 ℃ temperature and 65 ± 2 % relative humidity for 24 h and weighed on a precision balance to an accuracy of $0.001\ g$. The length and width of each test specimen was measured using SANS 83 and SANS 81. The density was estimated using equation 2 and the average value was recorded.

$$\text{density}\left(\frac{g}{cm^3}\right) = \frac{mass}{length \times width \times thickness} \quad (2)$$

2.10. Water permeability

Water permeability of the fabrics was analysed using a GE-TE-FLOW-K permeameter according to the EN ISO11058-10 standards (International Standard Institution, 2010. ISO 11058). The GE-TE-FLOW-K permeameter measures water permeability based on the principle of falling hydraulic head with a hydraulic difference height between 0 mm and 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 maintained at 20 °C. Three specimens from each 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 was used to measure the fabric permeability and the average value of each sample was recorded in $l/\ s\ m^2$.

2.11. **Morphology and structure analysis**:

The surface and cross-section of CFF:BCF blended nonwoven fabrics were visualized by an optical microscope (Nikon H600L). The specimens were coated with platinum and examined at varying accelerating voltage.

2.12. Absorption capacity

The absorption test determines how much fluid can be held inside a fabric. The test was done with saline water to simulate urine properties in hygienic products because the evaporative characteristics of saline water and urine are reported to be similar (Karantanis *et al.*, 2004). Five pre-weighted conditioned specimens from each nonwoven sample were soaked in a 0.9 % saline solution for 60 minutes and then hanged for 15 minutes to allow excess fluid to run off. The weights of the specimens before (W_1) and after (W_2) absorption were recorded and used in equation 3 to estimate the absorption capacity of the NAC samples. The standard temperature and relative humidity at which the samples were conditioned were in the range of $24.4 - 20.9$ ℃ and $58.5 - 48.7$ % due to the fluctuation of the hygrometer in the humidity control room. The absorption capacity was determined for both coated and uncoated nonwoven fabrics.

$$\text{Absorption capacity}\ \left(\frac{g\ of\ liquid\ absorbed}{\text{g of fabrics}}\right) = \frac{W_2 - W_1}{W_1} \quad (3)$$

3. RESULTS AND DISCUSSIONS

Nonwoven fabrics were characterized for their different structural properties such as: area weight, thickness and density as well as their end-use properties such as liquid permeability and absorption capacity. These properties are mostly dependent on the needle-punched machine parameters, viz., needle-punched speed, stroke frequency, and penetration depth of the needles. The composition of CFFs in the fabrics had also an important influence, especially for water permeability and liquid absorbency of the core products.

3.1. Thickness

Fabric thickness is considered as one of the important properties when evaluating the performance of nonwoven products (Senthil and Punitha, 2017). Table 3 shows the various dimensional parameters of needle-punched fabrics produced from a CFF:BCF blend. A thicker fabric was obtained in run 8 with a thickness of 13.73 mm, whereas a thinner one was obtained in run 2 with 6.95 mm thickness. In addition, the results indicated that as the penetration depth increased, the thickness decreased. When the penetration depth increases during the needling process, there is an increase in the number of barbs participating in fibre transport through the thickness of the web (Patanaik and Anandjiwala, 2009). Single fibres on top of the batt are pulled through a long distance – from 2 mm to 4 mm distance – resulting in less consolidation of the batt and a decrease in its thickness. Needle punched fabrics made at a lower penetration depth were therefore more open with higher thickness than the ones made at a higher penetration depth, which were less open with a lower thickness.

The speed of the conveyor belt reduced the thickness of the fabrics: as S increased, more fibres are fed to the needle action area resulting in a decrease in the effectiveness of needle-punching through the thickness of the web since there is a high chance that some fibres may escape the needling action (Patanaik and Anandjiwala, 2008). Hence, nonwoven fabrics produced at a lower S are more open with a lower thickness than fabrics produced at a higher speed, which are less open with higher thickness.

It is known that the thinner the absorbent core, the more comfortable it feels. Literature reports indicate that absorbent core thicknesses between 3 mm and 8 mm were perceived to be more comfortable than other thicknesses (Miao, 2012). However, product experience is a complex concept since some people perceive thinner products to be more comfortable whereas others would prefer thicker ones. Hence, the fabrics obtained in this work with a thickness varying between 6.95 mm to 13.76 mm can be deemed comfortable.

3.2. Area weight and density of fabrics

The variation of the fabric area weight was mostly driven by its weight, while the density was affected by both the fabric weight and thickness. The area weight varied between 124.25 g/m^2 and 220.92 g/m^2, while the fabric density was in the range of 0.072 g/cm^3 – 0.188 g/cm^3. The results of absorbent core area weight and density are given in Table 3. At lower penetration depth, the fabrics were more open giving space for more fibres to be stored, thus resulting in an increase in fabric weight.

3.3. Water permeability

The liquid permeability values of the CFF/BCF blend nonwovens are given in Table 3. Sample 6 had the maximum water permeability while the minimum was obtained for sample 8. These two samples were produced at a constant frequency, but the different S and different depth of needle penetration had the greatest effect on their permeability characteristics. Although sample 6 and 8 had almost similar thickness, the latter was more compact and heavier than the former, which was lighter and more open on average. It was therefore easy for water to pass through the specimen without applying any pressure. It is acknowledged by many authors that water permeability is greatly influenced by the nonwoven fabric porosity. The more compact the fabric is, the lesser the voids that can be filled by the cross-over fibres hence, the harder the liquids pass through the fibrous structure.

Table 3:Dimensional properties and permeability characteristics of needle-punched CFF/BCF blend nonwoven fabrics

Sample ID	S (m/min)	SF (Hz)	D (mm)	Fabric weight per unit area (g/m^2)	Fabric thickness (mm)	Fabric density (g/cm^3)	Water permeability $(l/s\,m^2)$
Sample 1	1.20	200.0	2.00	170.56 ± 36.81	11.05 ± 2.01	0.155 ± 0.003	116.2
Sample 2	0.80	350.0	4.00	129.45 ± 11.89	6.95 ± 0.88	0.186 ± 0.003	88.93
Sample 3	0.80	200.0	4.00	155.10 ± 11.0	8.31 ± 0.97	0.188 ± 0.002	52.45
Sample 4	1.20	350.0	2.00	124.25 ± 32.4	9.80 ± 1.32	0.127 ± 0.003	84.19
Sample 5	1.20	350.0	4.00	131.51 ± 17.78	8.13 ± 0.63	0.162 ± 0.002	129.9
Sample 6	1.20	200.0	4.00	96.94 ± 70.78	13.46 ± 3.34	0.072 ± 0.002	267.4
Sample 7	0.80	350.0	2.00	194.93 ± 30.89	12.34 ± 0.61	0.158 ± 0.002	54.05
Sample 8	0.80	200.0	2.00	220.92 ± 19.71	13.73 ± 1.27	0.169 ± 0.002	40.78

S: Speed of the conveyor belts

SF: Stroke frequency

D: Depth of needle penetration

During the needle punching process, there are changes in pore sizes: some of the medium pores are converted into smaller ones and larger pores are converted into medium pores due to the entanglement action of the needles (Patanaik and Anandjiwala, 2009). It is therefore important to further study pore size characteristics and their distributions to better understand liquid permeability behaviour.

3.4. Absorption capacity

The wettability of chicken feather fibres was proven to be poor compared to bleached cotton fibres (Tesfaye *et al.*, 2017). CFF:BCF blended nonwoven fabric is expected to have improved saline holding capacity due to the presence of BCFs. It is also expected that the structural properties mainly the fabric thickness may play an important role in the saline absorbency of these nonwoven fabrics because of their variation with respect to the process parameters. The following section studies the effect that the fibre blend ratio and the process parameters had on the CFF:BCF blended nonwoven fabrics. Coated nonwoven fabrics were also analysed and the influence of the coating polymers on the saline absorbency of these fabrics were compared.

3.4.1. Effect of fibre blend ratio on absorbency

During the production of nonwoven fabrics, there was some loss of CFFs due to their lower density compared to cotton. It was therefore important to determine the actual fibre volume fraction achieved in the fabrics and analyse its effect on the absorbency of the fabrics. Based on the properties of CFFs and BCFs shown in Table 4, it can be concluded that the volume fraction of these fibres in the nonwoven fabrics will affect the rate of liquid absorption through the fibrous batt.

Table 4:Properties of the used fibres

Properties	**Chicken feather fibre [(a)]**	**Bleached cotton fibre [(b)]**
Density, (g/cm^3)	0.89	1.5[*]
Moisture regain, %	16	7.3
Moisture content, %	12.33	6.8
Fineness, dtex	76	1.5
Elongation at break, %	7.7	8.6

[(a)] (Tesfaye *et al.*, 2018)

[(b)] (Shanmugasundaram and Gowda, 2010)

[*] (Rong and Bhat, 2004)

Figure 4 shows the resultant fibre volume fraction for each run and their corresponding liquid absorption capacity values. The results indicate that the actual CFF:BCF ratio averaged about 46:54 with the highest composition obtained in run #3 and the lowest in run #5. The highest fibre volume fraction of chicken feather fibres exhibited the lowest absorption capacity. This was probably caused by the poor affinity of CFFs with water.

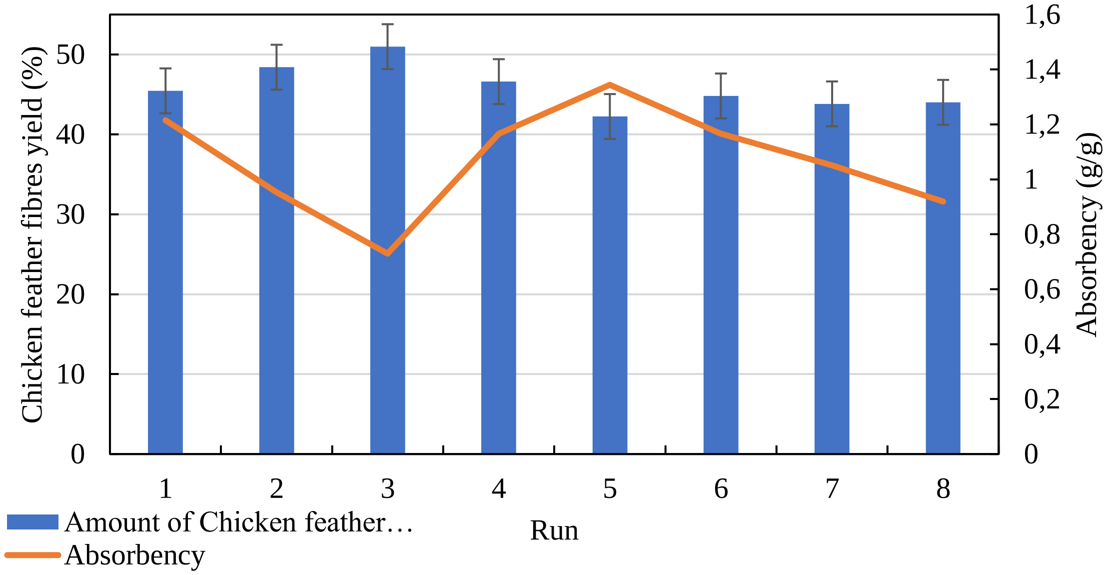

Figure 4: Actual ratio achieved per run and absorption ability of nonwovens produced in each run

The structure and properties of nonwoven fabrics are mainly determined by the fibre properties, the bonding method, the bonding interfaces between the fibres and the binder elements, and the fabric structural architecture (Russell, 2007). A large volume fraction of hydrophobic fibres (CFF) present in a nonwoven sample will result in a decrease of the fluid handling property (absorbency) of the sample analysed, as depicted in Figure 4. However, this observation is valid for the samples analysed in run 1, 2, 3, 4 and 5 because despite the approximately equal volume fraction of CFF in run 6, 7 and 8, the absorption capacity decreased. The reason for this decrease in absorbency was probably due to the variation in process parameters (S, SF and D) during the web formation process which resulted in anisotropic samples in terms of both the fabric structure (Figure 5) and absorption property due to the alignment of fibres as well as the arrangement of bonding points in the structure of the fibrous web.

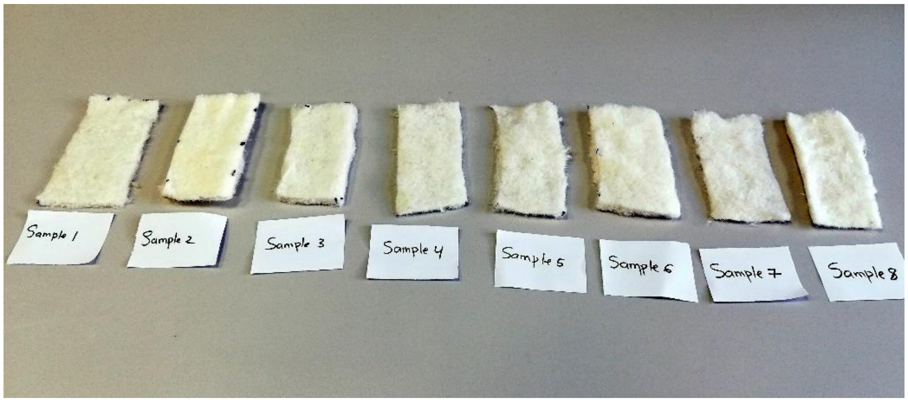

Figure 5: Samples of CFF:BCF nonwoven fabrics produced at different run

Fibre volume faction plays an important role in controlling the diffusion of liquid through the fibrous structures. However, in many cases, the liquid transmission cannot be adequately explained on the basis of fibre volume fraction alone. This is because of the complex interaction between fibre volume fractions and other parameters such as fabric thickness, web porosity structure, which is influenced by the process parameters.

3.4.2. Effect of process parameters on the absorbency of uncoated nonwoven fabrics.

Wettability of chicken feather fibres is poor compared to cotton fibres (Tesfaye *et al.*, 2017). The blended needle-punched fabrics are expected to have a slightly improved saline holding capacity due to the presence of BCFs in the matrix. It is also expected that the fabric thickness may play a significant role in the saline-absorbing capacity of the blended fabrics. The 3-D surface diagrams (Figure 5, 6 and 7) show the effect of stroke frequency, speed of the conveyor belt and depth of needle penetration of the blended needle-punched fabrics.

When the depth of needle penetration is not applied, the saline absorbency gradually increases with an increase in the speed of the conveyor belt from lower values of the stroke frequency to higher values (Figure 5). Fabrics produced at higher speeds were thinner than those produced at lower speeds and, hence, thinner fabrics had more open voids to transport and hold the liquid than thicker fabrics. The depth of needle penetration has an opposite effect on the saline absorbency of the fabrics compared to the speed. With an increase in the speed of the conveyor belt, saline absorbency decreases from higher value of depth of needle penetration to lower values (Figure 6).

Similarly, as the stroke frequency increases, saline absorbency decreases from high values to low values of the depth of needle penetration (Figure 7). This could be attributed to the reduction of pore sizes which could be caused by the breakage of fibres from the matrix as a result of severe action of the needles. These breakage of fibres into small constituents results in a significant reduction of larger pore sizes. As a consequence, the blended nonwoven fabrics' ability to retain the liquid significantly decreases.

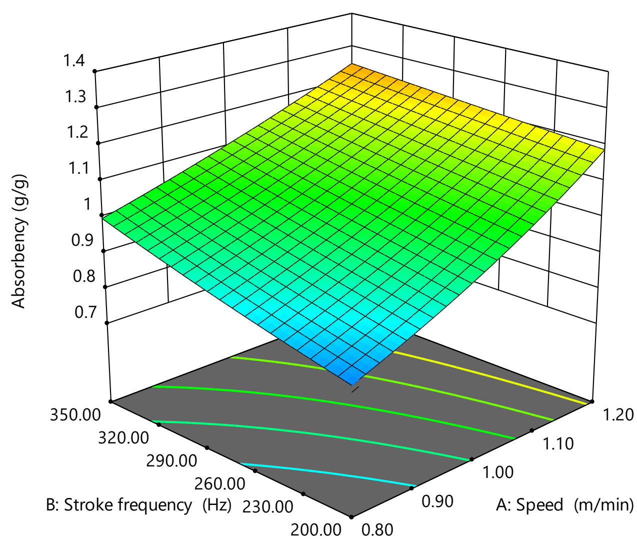

Figure 6: Effect of speed and stroke frequency on saline absorbency of CFF:BCF fabrics

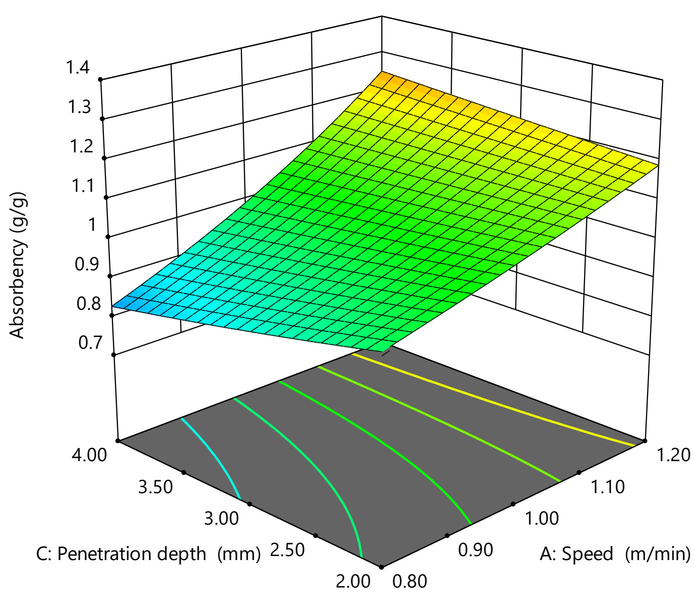

Figure 7: Effect of speed and depth of needle penetration on saline absorbency of CFF:BCF fabric

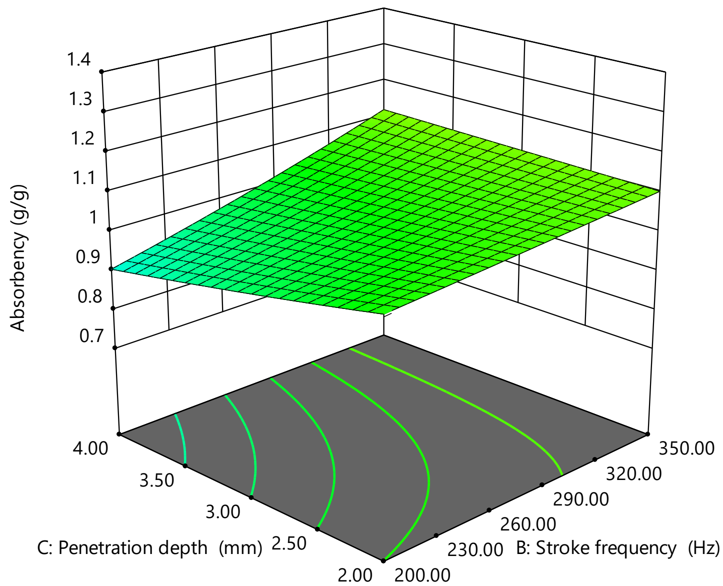

Figure 8: Effect of stroke frequency and depth of needle penetration on saline water absorbency of CFF/BCF fabrics

Stroke frequency refers to the rate at which the needle board moves per second, forcing the needles through the bed plate and penetrating the web (MOYO *et al.*, 2012). As the stroke frequency increases, more fibres are reoriented from the horizontal to the vertical direction, which also results in significant reduction of large voids in the structure (Rawal and Anandjiwala, 2006), thus resulting in a more consolidated fabric with reduced liquid absorption capacity. However, in this work: with an increase in stroke frequency, saline-holding capacity of the fabric increased. This was probably because at higher stroke frequencies, the fabrics were less consolidated than at lower frequencies. Although some of the large pores collapsed during needling process due to the breakage of BCFs, the fabrics still maintained few large pores created between CFFs. This was probably because CFFs might have escaped the action of needle barbs thus allowing the nonwoven fabric to maintain the large pores formed by feather fibres (Figure 9). It is postulated that as the fabric thickness decreased due to the collapse of large voids between the fibrous layers and entanglement of the fibres, the fibres were pulled down from the top layer to the base of the web to form consolidated fabrics. However, some fibres escaped the process due to their light weight. Therefore, a less consolidated fabric was formed at higher frequencies.

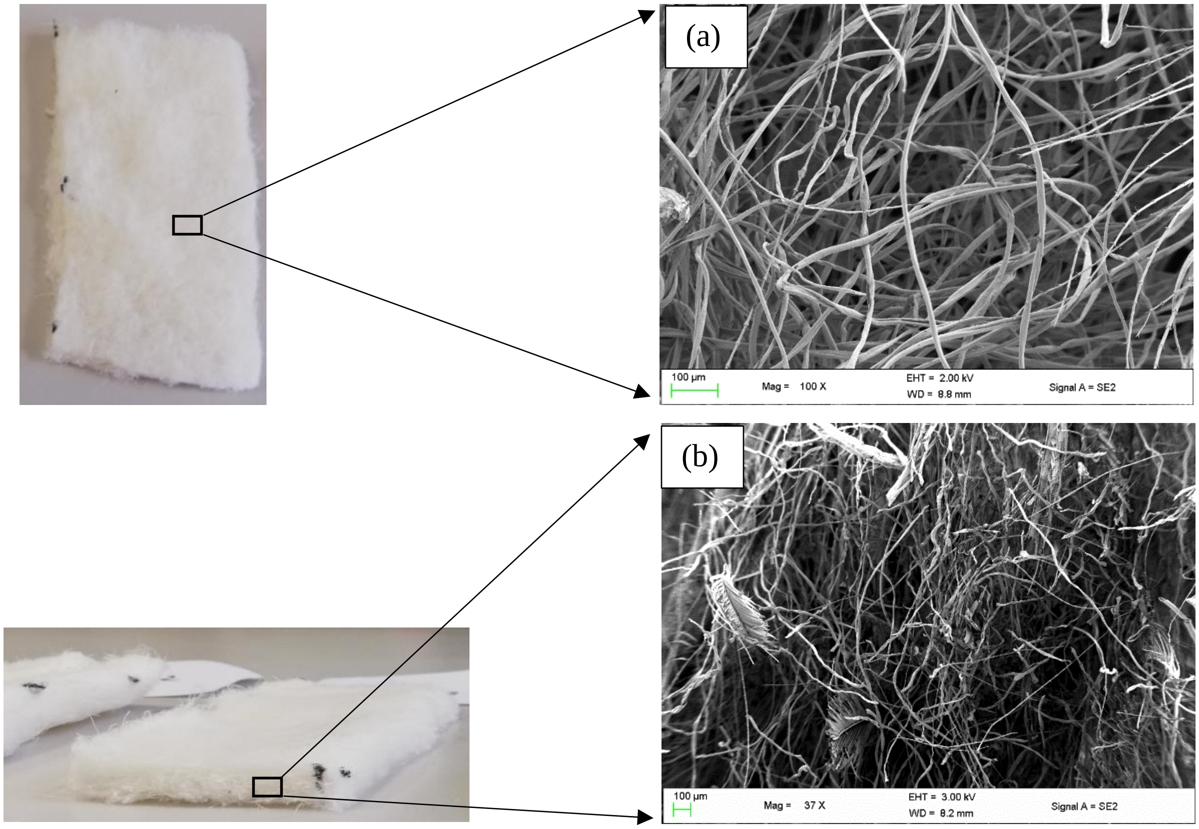

Figure 9: SEM images of uncoated CFF:BCF blended needle punched fabric; (a) surface area and (b) cross-section area

Instead of investigating the individual effect of process parameters on the saline absorbing capacity of CFF:BCF nonwoven fabrics, the most important information regarding the proposed product with CFFs is how to combine the process parameters in order to achieve high saline absorption capacity. The observations mentioned above provides nonwoven fabric producers with guidelines when developing chicken feather fibres-based needle-punched fabrics with the desired absorption capacity. In general, uncoated chicken feather fibres-based nonwoven fabrics are not absorbent due to the hydrophobic nature of the fibres in use. However, a higher saline absorption capacity of these uncoated fabrics can be achieved at higher speed, higher stroke frequency and lower depth of needle penetration as seen in the Figure 5, 6 and 7. The depth of needle penetration is a significant factor in the production of CFF:BCF blended nonwoven fabrics since it determines the number of barbs penetrating needle-punched fabrics on each stroke, and thus the level of fibre entanglement and bonding to be achieved (Russell, 2007). In addition, it influences the speed of the conveyor belt and/or the relative frequency of the fibres reoriented in the machine direction as seen in Figure 2.

3.4.3. Optimization of process variables by Plackett-Buman design

The effect of process variables as well as the interactions of them on saline absorbency were examined. About thirty-six preliminary and eight experimental runs were conducted in this study and the results enabled the calculation of the coefficient of regression. Based on the experimental results on saline absorbency and the different interaction terms of the variables, a mathematical model equation was regressed (Eq. 4).

$$(Absorbency)^{-0.6} = 1.2 - 0.42 * x_1 - 0.0012 * x_2 + 0.28 * x_3 + 0.0017 * x_1 x_2 - 0.167 * x_1 x_3 - 0.0003 * x_2 x_3 \quad (4)$$

where x_1, x_2 and x_3 represent speed (m/min), stroke frequency (Hz) and depth of needle penetration (mm).

Analysis of the regression equation helped in concluding that the criterion of saline absorbency optimization is negatively influenced by the speed of the conveyor belt and the stroke frequency of the punching unit and is positively influenced by the depth of needle penetration. The negative sign in front of the coefficient implies that an increase in the value of the given factor leads to a decrease in saline absorbent capacity, whereas a positive sign implies that an increase in the values of the factors leads to an increase in absorbency; this is confirmed in the surface and contour plots shown in Figures 5, 6 and 7. Table 5 shows the statistical significance of the mathematical model equation (Eq. 4) and the model terms that were assessed in ANOVA by the F- and p- values .

A significant large F-value (F-value $>$ 1) would indicate that the mathematical model or the model term is statistically significant. This indicate that the experimental data does fit the model and does describe the mean structure adequately (Oehlert, 2010). It is observed from the ANOVA results shown in Table 5 that the F-values of the first and second-order factors were high, indicating that the model was significant and there was 0.2 % chance that the F-values this large would occur due to noise Similarly, p-values less than 0.05 indicate that the model or the factor is significant (Oehlert, 2010). In this case, all the factors and the interactions between the factors were significant model terms. Therefore, the "lack of fit" is not significant, so the mathematical model equation (Eq. 4) should be a reasonable approximation to the mean structure in the region of the experimentation.

Table 4: Analysis of Variance (ANOVA) for the fitted linear model for optimization of process variables for the production of CFF:BCF blended nonwoven fabric

Source	Sum of squares	Degree of freedom	Mean square	F-value	p-value	
Model	0.0975	6	0.0162	1.473E+05	0.0020	Significant
x_1	0.0630	1	0.0630	5.711E+05	0.0008	Significant
x_2	0.0122	1	0.0122	1.107E+05	0.0019	Significant
x_3	0.0033	1	0.0033	30005.01	0.0037	Significant
x_1x_2	0.0054	1	0.0054	48666.94	0.0029	Significant
x_1x_3	0.0089	1	0.0089	80808.21	0.0022	Significant
x_2x_3	0.0047	1	0.0047	42718.25	0.0031	Significant
Residual	1.103E-07	1	1.103E-07			
Cor Total	0.0975	7				
$R^2 = 1.0$	Adjusted	$R^2 = 1.0$		Std. Dev	0.0003	
Mean	0.9764			C.V. (%)	0.034	

The suggested model in Eq. 4 was investigated to assess its veracity by comparing the R^2 value and the adjusted R^2 value. Figure 7 shows the correlation between the experimental and predicted values of saline absorbency: there were no differences between the experimental values and the predicted model. This was also confirmed by the R^2 and the adjusted R^2 (Table 5) and further confirmed by the closeness between the actual and predicted data as shown in Figure 8. Hence, there is a satisfactory correlation between the actual and predicted values.

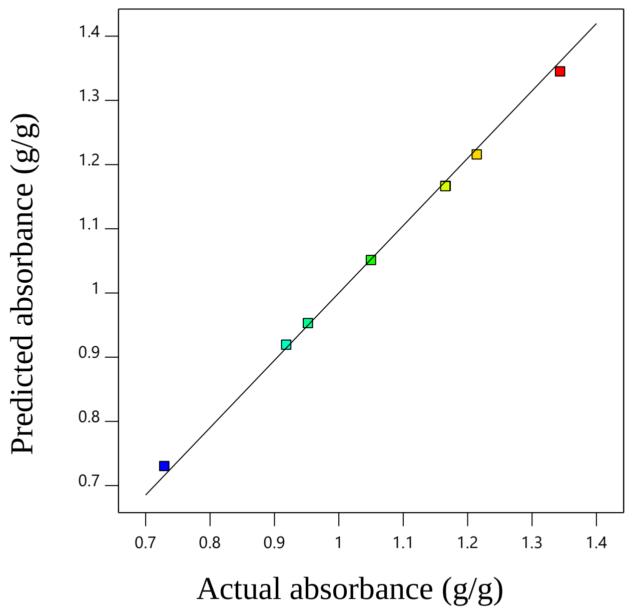

Figure 10: Correlation between the actual experimental data and the predicted model data for the absorption of CFF:BCF blended nonwoven fabrics.

The coefficient of variance (CV %) is a statistical measure of the dispersion of experimental data points around the mean. A lower CV value indicates that the experiments conducted were precise and reliable. The ANOVA CV value of 0.034 % showed a good precision and reliability of the experiments for absorbency test of the fabrics in saline water. The optimum conditions resulting in highest absorbency were: 1.187 m/min for speed, 265.42 Hz for stroke frequency, and 2.92 mm for depth of needle penetration.

3.4.4. Effect of coating solutions on absorbency of fabrics

Four coating solutions were applied on eight specimens from the fabric samples produced at the optimum conditions given above. The absorbency of the specimens was determined and compared with the absorbency of the NAC samples found in a commercial diaper.

Figure 7 shows the variation of the saline absorbency values of the coated NACs produced in this work. Approximately 18.16 g/g of saline liquid was absorbed by the samples coated with PAA+DMAA. This absorbency was more than the absorbency of the core fabric found in the commercial diaper tested in the lab (Figure 7). Samples coated with PVA exhibited lower absorbency than samples coated with DMAA and higher absorbency than PAA samples. In addition, samples containing PAA, DMAA or combinations of PAA and DMAA were softer than the samples containing PVA, making them to be able to absorb saline laterally and longitudinally because of these polymers did not form a layer on the fabric surface but rather they coated the fibres. However, PVA samples had a thick and hard outer layer on their surface preventing saline water to migrate through the fabrics. The coated layer was formed because of the high viscosity of PVA that do not allow it to transgress trough the fibres matrix to coat the fibres.

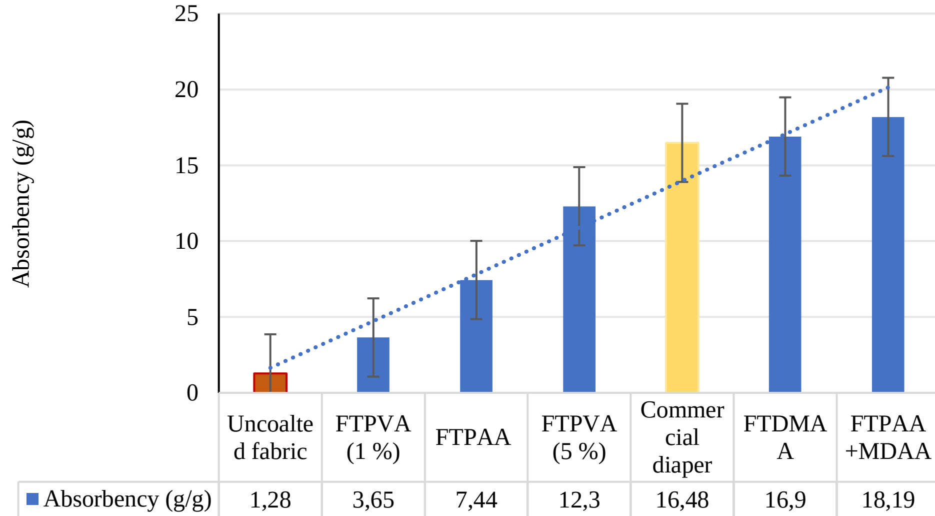

Figure 11: Effect of chemistry of coating solution on absorbency of CFF:BCF blended nonwoven fabrics.

The absorption mechanism of the NACs can be explained at three different levels. The fabrics can absorb and retain the liquid through (1) pores by capillary absorption (Figure 12), (2) fibres by diffusion (Azeem *et al.*, 2017) or (3) coating granules or solution. Capillary absorption is a phenomenon by which a liquid enters the fabrics' pores, which are initially filled with moisture at ambient temperature (Azeem *et al.*, 2017). Capillary absorption of the coated NACs produced in this work was minimal since most of the open pores were filled with the polymer solution as seen in Figure 12 a and c. Uncoated fabrics produced under optimum conditions were placed on the surface of saline water to visually assess their wettability. After 2 hours, there was no transport of the liquid from the surface in contact with the liquid to the opposite surface. Despite the influence of the process variables as mentioned above, the fabrics' surface was made mostly of CFFs which prevented the absorption process to occur as seen in Figure 9. Hence, the uncoated fabrics exhibited lower absorption capacity.

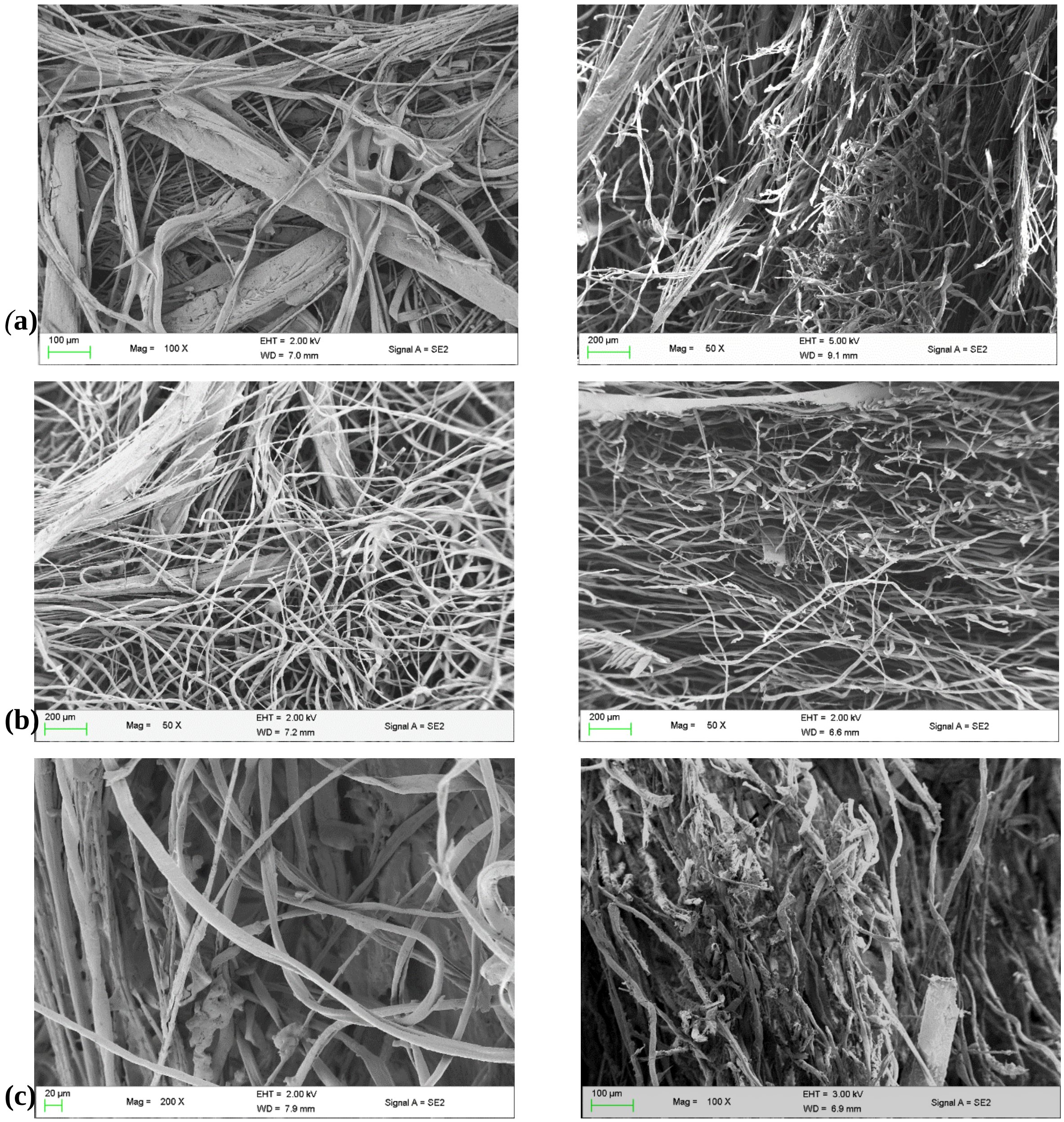

Figure 12: SEM images of selected coated CFF:BCF blended needle punched nonwoven fabrics; (a) Surface (left) and cross-section (right) SEM images of nonwoven sample coated with PVA; (b) Surface (left) and cross-section (right) SEM images of nonwoven sample coated with PAA and (c) Surface (left) and cross-section (right) SEM images of nonwoven sample coated with PAA+ DMAA

Absorption through fibres is mainly dependent on the chemical properties of the fibres present in the nonwoven structure as well as the interaction between the absorbent liquid and the fibres. Textile fibres used in AHPs are naturally occurring fibres containing functional groups in their molecules which enable them to absorb water or any liquids; depending on the amounts of these functional groups whose hydrophilic strength is in the order – OH > – COOH > – COO^- > C=O > – NH_2 > – $CONH_2$ > – SO_3H, etc (Gun'ko *et al.*, 2017). BCFs are inherently hydrophilic since their chemistry consists of glucose units, each containing three hydroxyl groups (- OH) (Mather and Wardman, 2015), whereas CFFs are 60 % hydrophobic (Seawright *et al.*, 2017) as they contain a significant amount of amino (-RNH_2) and amide groups (-$RCONR_2$) than carboxylic acid (-COOH) groups which are less hydrophilic than – OH groups. It is therefore difficult for saline molecules to penetrate the CFFs and be absorbed into the amorphous part of the fibres.

Consequently, there was no direct interaction between NACs and saline water since the fabrics were coated with the polymers. The high absorption capacity observed in this work, was mainly attributed to the electrochemical interactions between the solvent and the polymers, that are ultimately related to the ionic strength of each coating solution (Quintero *et al.*, 2010). Although PVA solution (contains -OH group) had high ionic strength, samples coated with 1 % PVA solution had low saline absorption capacity (Figure 11) than the 5 % PVA coated samples. this was because of the limited -OH molecules in 1 % PVA solution to form hydrogen bonds with saline water. PAA solution did not close the open pores of the fabric samples as seen in Figure 12 b, however DMAA solution and PAA+DMAA solution coated the fibres and filled the open pores of the fabrics resulting in the fabrics having enough molecules to bond with the molecule present in saline water. Thus, resulting in higher absorbency of the fabrics coated with DMAA or PAA+DMAA. It is therefore important to note that the sensitivity of superabsorbent coating polymer to monovalent saline solution is mainly due to the reduction of osmotic pressure difference inside and outside the coating polymer (Zohuriaan-Mehr and Kabiri, 2008) .

4. CONCLUSIONS

This report demonstrates that one route of beneficiation of waste chicken feathers is via production of NACs from fibres extracted from the feathers. However, the production process needs a blend of CFFs and BCFs for effective needle-punching into nonwoven fabrics. Fabrication of novel NACs was achieved by coating the novel needle-punched nonwoven fabrics with superabsorbent polymers. Uncoated fabrics exhibited lower absorption capacities than coated fabrics, whose absorption capacity varied depending on the coating polymer used. The results revealed that the nonwoven chicken feather fibres blended fabrics coated with DMAA and PAA are promising alternatives for applications where high absorbency is required, especially as core products in the production of AHPs.

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AUTHORS CONTRIBUTIONS

G.K. and T.T. conceived and planned the experiments. G.K. carried out all of the experiments. T.T. contributed to test for the fabrics’ absorbency. G.K took lead in interpreting the results and in writing the manuscript in consultation with B.S. and M.N. T.T. conceived the original idea and helped shaped the research and analysis. B.S. supervised the projects.

DECLARATION OF COMPETING INTERESTS

I declare that there is no conflict of financial, professional or personal interests that might have influenced the presentation of the research work described in this manuscript.

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