Spunlaced and chemically bonded nonwovens for filtration applications:
Performance evaluation and comparison

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Abstract

The main function of textile filter media in air filtration is to control air pollution. Air filtration plays an important role in improving air quality and hygiene. The demands for air quality and hygiene at work places have increased greatly due to new regulations and a change in health consciousness.

Spunlaced nonwovens offer various performance advantages compared to more traditional technologies used in air filtration.
Chemical bonding process with the light weight foam will result in the binder bonding of the fabric surface. Very little energy is required for evaporation of the water contained in the binder.
Nonwoven fabrics for filtration application were produced from polypropylene (PP) and polyester (PET) fibres using the hydroentanglement and chemical bonding techniques.

Three different pressures of AquaJet, 60, 120 and 200 bar were selected as variable parameters for the trial. The chemical binder applied by the weight of material was 25% and 40%, with 30% of solid in the resin.

The physical, mechanical and performance properties were measured and compared.
It was concluded that chemical bonding had a higher effect on the fabric structural changes, such as pore size and its distribution.

The results showed an improvement in dust holding capacity and pressure drop for the chemically bonded material as a result of consolidation of the material's structure. The fibres became more tightly packed, making it more difficult for particles to pass through the body of the fabric.

The developed filtration materials were compared with industrial filtration material acquired from filter manufactured company Filtermac in Eastern Cape,
Port Elizabeth

1. Introduction

The filter media is defined as the permeable material used to separate particles passing through it. Textile filters are an essential part of industrial processes, contributing to product purity, savings in energy, production cost and to a cleaner environment. Main importance of textile filter media in air filtration is to control air pollution. Air filtration plays an important role in improving air quality and hygiene at work. The demands on air quality and hygiene at work increased greatly due to new regulations, new scientific knowledge and a change in health consciousness (Kothari 2007).

Textile fabrics are the most important and widely acceptable groups of materials used for filter media. The basic advantage is the wide range of pore size and fibre configuration. Two or more types of fibres can be combined in a single fabric to provide a combination of good strength and filtration characteristics.

The fabric filter media may be woven, knitted or nonwoven. Nonwovens are the major media for air filtration and compose almost 70% of the total filter media. A random arrangement of fibres in nonwovens providesmore favorable conditions for the trapping and precipitation of particles than the same quantity of tightly bundled fibres made into weft and warp yarn. Nonwovens have higher filtration efficiency, no chance of yarn slippage and good cake discharge property (Kothari 2007).

In nonwovens single fibres characteristics may effect and control filtration performance by their geometric properties, such as diameter, shape, surface finish, electrical charge and hardness. For maximum capture ability, fibres should have small diameters and be made of material with a low Young’s modulus.

Dry filtration of particles is based on four main principles:

- Inertial impaction
- Direct interception

- Brownian diffusions
- Electrostatic enhancement

Typically nonwoven filtration media have 1-500 µm mean flow pore (MFP) rating. Smaller MFP can be achieved by utilising the bonding technologies, such as hydroentanglement, and finishing processes namely, calendering and chemical bonding. The present work illustrated the combination of two bonding technologies such as hydroentanglement and chemical bonding.

Spunlace technology (hydroentanglement) utilised high speed water jets to entangle fibres of webs. This bonding technology is illustrated by Figure 1. The resulting nonwoven fabric is soft, drapeable and has relatively high strength. The turbulence of the water causes rearrangement and entanglement of the fibres with resulting consolidation of the material structure. The fibres are pushed and pulled by the water always in the direction of its flow. Open areas in between the fibres are removed and filled up with the fibre strands. That leads to a homogeneous fabric that has not been damaged through the mechanical action. The absence of the mechanical damage prevents the passing of dust particles through the bulk of the filter media and leads to the increased resistance of the fabric (Lorentz 2007).

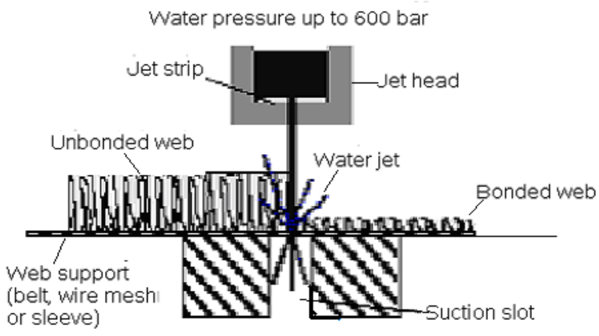

Fig. 1
Hydroentanglement process

One of the methods of fibre bonding is by chemical binders. **The binder is applied first and the bonding process takes place during the following treatment in the oven. As a result, the crosslinks between fibres are developed.**
Different nonwoven fabrics can be produced from the same web by using the different binder recipes. The different polymer based emulsions can be used as a binder. The resulting polymer emulsion can contain various additives in different concentration which can influence coagulation temperature, foamability, wettability, migration behaviour etc.
During the foam application, the same binder liquids are used as for bonding with liquid binders. Foamability is achieved by adding the foaming agent and foam stabiliser. The foam stability influences the disintegration speed of the foam bubbles and the processing behavior.
Depending on the effect desired, the liquor is beaten to foam 5, 10 or 20 times its volume with a weight per litre of foam between 30 and 300 g/l (Watzl 2007).

The schematic diagram of the foam bonding is illustrated in Fig. 2

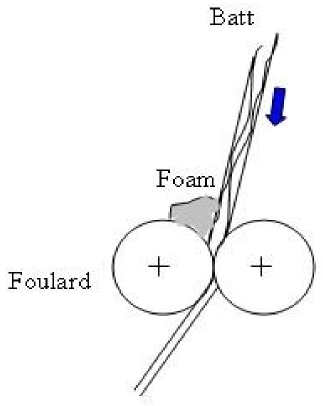

Fig. 2
Foam bonding

Application of chemicals as a foam was developed with the aim of using less water during application with the resultant energy saving on drying and decreasing a risk of binder migration.

The binder solution and a measured volume of air are passed continuously through the pump which beats the two components into a consistent foam. The foamis then delivered to the horizontal nip of the impregnating roller and foam applied on the one side of the fabric. The foam delivery has to be traversed because the foam does not flow easily.
The rollers squeeze the foam into the batt and then it goes to the oven for drying and curing.
The foam can be applied from both sides, if the batt entered vertically. In present work a foam was delivered on the one side of the material.

The objective of this research was to make nonwovens suitable for high efficiency filtration application from PP and PET fibres by using spunlacing and chemical (foam) bonding technologies. The effect of percentage of binder application, such as 25 and 40 % and AquaJet water pressures, 60, 120 and 200 bars on the performance properties, as pore size and its distribution and also on the filtration properties, were investigated and analysed.

2. Experimental

Polypropylene (PP) and polyester (PET) fibres with thefollowing fibre parameters were selected for this experiment: PP fibres of 2.2 dtex linear density and 40 mm staple length, PET fibres of 3.6 dtex linear density and 60 mm staple length. The selection of finer fibres can be explained by the aim to produce more homogeneous structure by using hydroentanglement technique resulting in thinner fabric with the finer pore opening. That will lead to better filtration efficiency compared to more traditional needle-punched filter media with a bigger pore size. The PET and PP fibres provide the necessary strength and durability for the filtration material.

Fibres were opened first by carding, then carded again and cross-lapped. The resulting batt was transported to the hydroentanglement unit containing three manifolds of water jets where the first bonding took place. Chemical coating was then applied on spunlaced wet fabric by traversed foam delivery unit. It is critical to apply the resin on the wet fabric for the creation of a better bond between fibres and the binder. The bonded fabric is then passed through the oven for drying and curing. Process parameters, such as speeds of conveyors were kept constant, but the water jet pressure was increased according to the plan of experiment.

Three different pressures of AuaJet, 60, 120 and 200 bars were selected as variable parameters for this trial during hydroentangling process.

The chemical binder applied by the weight of material was 25% and 40% with 30% of solid in the resin. It is the recommended concentrations of the binder for this specific application which provided the stability of the foam and required degree of bonding. Acronal 32 D was used as a chemical binder for this experiment. The wetting agent and foam stabiliser Kieralon was used as 1% of resin weight.
Twelve samples were selected for the evaluation and comparison of properties according to the plan of the experiment.

3. Testing of properties

Samples were tested for physical, mechanical and performance properties under standard laboratory conditions. All fabric samples were conditioned under atmospheric conditions at 22 ± 1^{o}C temperature and 65 ± 2% relative humidity for at least 24 hours before testing.

The area weight of fabric was measured according to the ASTM D 3776 test method by using an electronic balance.

The measurement of fabric thickness was performed according to ASTM D5729-95 with digital Thickness Gauge for Textiles EV- 06 under the weight of 1 kPa. This was achieved by applying a metal disk with weight of 170g and 50 mm in diameter.

Tensile strength and elongation were measured on Titan according to the Test method ASTM 5034.
PMI Capillary Flow Porometer was utilised for the measurement of pore size and its distribution according to Test method 6212005-134 which corresponds to ASTM E 1294.

Filtration properties were measured on Dust Filtration Device (DF-1) manufactured in house. The tests were conducted according to ASHRAE 52.1– 92 Standard Method.

Table 1 illustrates the measured physical-mechanical properties, such as area weight, thickness, calculated fabric density of the samples and applied variable processing parameters namely water jet pressure and binder concentration. “T2” in all samples identification refers to the second trial on this application.

4. Results and discussion

4.1 Fabric Density

Fabric weight, thickness and density are interrelated physical parameters for the nonwovens using carding and cross-lapping for web formation. In general, with an increase in fabric weight, the thickness of the fabric also increased (Anandjiwala 2008). The turbulence of high pressure water jets causes rearrangement, shifting and entanglement of the fibres. That led to consolidation of fibre structure and increased fabric density with the increase in water jets pressure.

This trend is applicable to all samples with 25% and 40% binder in PP and PET fibres. The highest value was observed for the sample N3 – PP fibres with water jet pressure of 200 bars. The thicker PET fibres tend to have a higher bending stiffness, resulting in the lower fabric density. However, the samples of PET fibres (samples N10, 11 and 12) demonstrated the higher values of fabric density in comparison to PP samples for all water jet pressures with 40% binder.

Table.1 Physical and mechanical properties of spunlaced and chemically bonded samples

Sample ID	Fibres compos.	AquaJet pressure (bar)	Binder application (%)	Average area weight (g/m²)	Actual area weight (g/m²)	Thickness (mm)	CV (%)	Fabric density (kg/m³)
N1-T2	PP	60	25	125	120-130	1.48	2.67	84.46
N2-T2	PP	120	25	140	130-150	1.36	2.90	102.94
N3-T2	PP	200	25	165	160-170	1.13	2.68	146.02
N4-T2	PET	60	25	160	150-170	1.7	5.86	94.11
N5-T2	PET	120	25	140	130-150	1.35	1.44	103.7
N6-T2	PET	200	25	130	120-140	1.01	4.12	128.71
N7-T2	PP	60	40	210	200-220	2.28	6.22	92.11
N8-T2	PP	120	40	160	145-180	1.31	6.55	122.14
N9-T2	PP	200	40	145	140-150	1.05	1.56	138.1
N10-T2	PET	60	40	170	145-200	1.6	1.87	106.25
N11-T2	PET	120	40	180	150-210	1.36	2.44	132.35
N12-T2	PET	200	40	240	200-275	1.35	5.52	177.78

However, the samples of PET fibres (samples N10, 11 and 12) demonstrated the higher values of fabric density in comparison to PP samples for all water jet pressures with 40% binder.

4.2 Tensile Properties.

The tensile properties, such as breaking strength and elongation were measured for all samples cut in machine (MD) and cross machine direction (CD). The summary of results are shown in Table 2 and graphically in Figures 3 and 4, for PP and PET samples with 25% binder.

The tensile properties of nonwoven fabrics are different in different directions of the fabric due to structural anisotropy resulting from the process of fibres alignment during web formation. The strength of the samples in cross machine direction (CD) is higher than that in the machine direction (MD) for all samples.

For samples in MD, the breaking strength increased with the increase in applied water jet pressure in all PP samples (samples N1,2 and 3). For samples containing PET fibres, the strength is higher for the 60 bars water jet pressure in MD. It was the same trend for the PET samples in CD. It can be explained by the structural characteristic of the fabric by being the thicker and heavier one among all PET samples. The higher value was detected in CD in sample N2 – PP with 120 bars pressure of water jet.

Table 2. Breaking strength and elongation with 25% binder application

Sample ID	Fibre composition	Max force, N MD	CV, %	Max force, N CD	CV, %	Elongation,% MD	CV, %	Elongation, % CD	CV, %
N1-T2	PP	95.94	18.86	232.22	10.85	163.33	13.09	124.64	7.25
N2-T2	PP	166.61	8.33	404.17	6.87	170.24	8.45	123.71	6.83
N3-T2	PP	202.48	3.27	371.22	7.77	140.96	13.93	121.03	9.46
N4-T2	PET	282.49	9.18	363.43	23.77	89.23	8.01	88.93	4.16
N5-T2	PET	194.35	17.48	220.41	9.51	85.0	7.05	94.48	4.51
N6-T2	PET	152.95	4.22	313.15	3.22	135.03	5.87	123.49	7.6

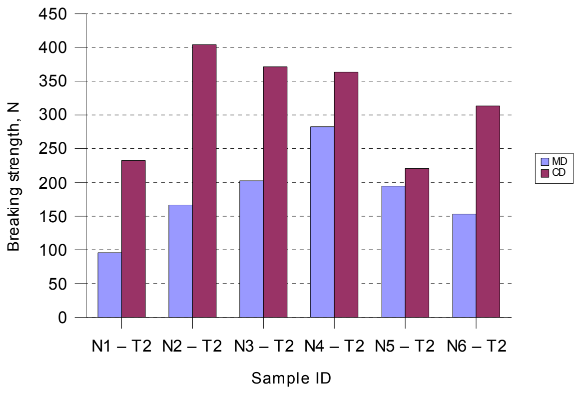

Fig. 3 Breaking strength in MD and CD

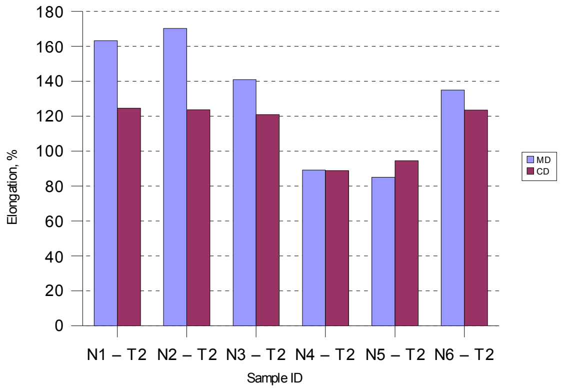

Fig. 4 Elongation in MD and CD

One can imagine that increasing of the water jet pressure would inevitably cause the increase in breaking strength of nonwovens. But that was only applicable for the PP samples in MD. The opposite effect was observed for the PET samples in MD and CD, except N6 (PET) in CD.

The strength of the samples in CD is higher than in MD for all samples which can be attributed to carding and cross-lapping processes and alignment of fibres during it.

Decrease of the strength in the PET samples could be explained by the weaker nonwoven structure due to poorer interlocking of more coarser and rigid PET fibres as compared to PP fibres. In MD higher value showed by the PET sample (N4) at 60 bars water jet pressure. But it can be attributed to the more thicker structure of the sample (with thickness of 1.7 mm) compare to the rest of the samples.

The thickness of the material can directly effect the tensile strength which was reported in the previous work (Anandjiwala 2008). As a result, the samples with the lower tensile strength showed higher results of fabric extension.

The samples cut in CD are significantly stronger and less extensible due to predominance of fibre orientation resulting from the web formation techniques applied in this work.

The tensile properties of the samples N7 to N12 are summarised in the Table 3 and illustrated by Figures 5 and 6.

Table 3. Breaking strength and elongation with 40% binder application

Sample ID	Fibre	AquaJet press, bar	MaxForce,N (MD)	CV, % (MD)	Max Force, N (CD)	CV % (CD)	Elong, % (MD)	CV % (MD)	Elong, % (CD)	CV, % (CD)
N7-T2	PP	60	68.89	2.24	177.33	23.69	97.06	11.15	65.1	4.37
N8-T2	PP	120	189.54	5.65	414.37	4.69	169.27	8.57	131.93	6.44
N9-T2	PP	200	179.28	8.23	385.85	7.89	158.21	2.74	123.04	7.24
N10-T2	PET	60	188.39	7.23	203.17	8.15	72.08	13.82	108.87	7.58
N11-T2	PET	120	294.78	5.34	307.8	5.57	71.5	7.56	88.11	5.43
N12-T2	PET	200	270.89	7.17	290.61	11.25	65.72	10.34	80.11	9.63

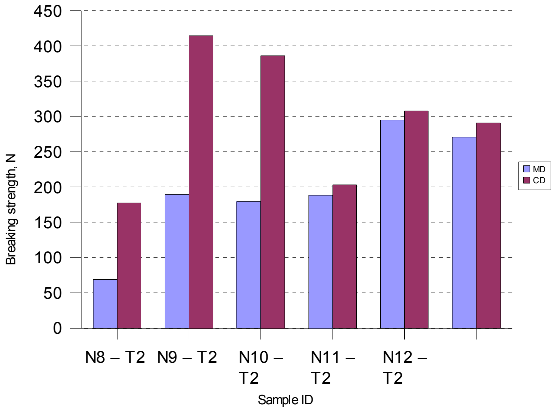

Fig. 5 Breaking strength in MD and CD

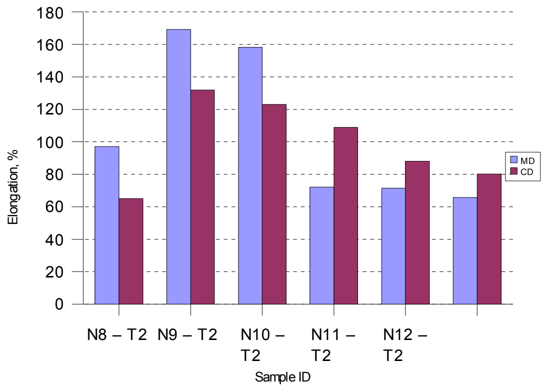

Fig. 6 Elongation in MD and CD

As it was established before, the orientation of fibres in the web contributed to the higher strength of the fabric in cross machine direction (CD) compared to that in machine direction (MD). The breaking strength increased with increasing water jet pressure but was higher for the samples of 120 bars, than for samples of 200 bars. This trend was observed for PP and PET samples in both MD and CD. The higher water jet pressure caused the higher entanglement and interlocking of the fibres, but also attributed to the development of more stiff fabric (compare to fabric spunlaced with 60 and 120 bars water jets) which tends to break more easily.

4.3 Pore Size and its Distribution

The pore size and its distribution are very important parameters in filtration application. The smallest pores contribute to higher filtration efficiency and higher dust holding capacity. The liquid extrusion technique can be used for the evaluation of pore size in nonwovens. In this technique, a wetting liquid (Galwik with known surface tension parameter such as 15.9 dynes/cm) fills the pores of the sample and a pressurised gas extrudes the liquid from pores. Differential gas pressure and flow rates through wet and dry samples were measured and from that the most constricted through pore diameters, the largest pore diameter and the mean flow pore diameter were calculated.

The biggest pores opened first at the lowest pressure as the smallest pores required higher pressure for the liquid extrusion with resultant decreasing of volume of flow rate. The pressure at which flow starts through the wet sample (bubble point) is determined and pore diameter calculated from this pressure (Jena 2003). The mean flow pore (MFP) diameter is such that fifty percent of flow is through pores larger than MFP diameter and the rest of the flow is through smaller pores. The mean flow pore diameter is a measure of permeability.

The pore size and its distribution for the samples with 25% binder application are summarised in Table 4 and illustrated by Figure 7.

Table 4. Pore size and its distribution (25% binder)

Sample ID	Min, µm	MFP, µm	Max, µm
N1 – T2 PP	7.48	71.83	135.63
N2 – T2 PP	7.56	48.02	104.95
N3 – T2 PP	6.91	29.09	67.61
N4 – T2 PET	7.57	81.99	155.47
N5 – T2 PET	7.50	73.11	151.69
N6 – T2 PET	7.38	29.37	77.7

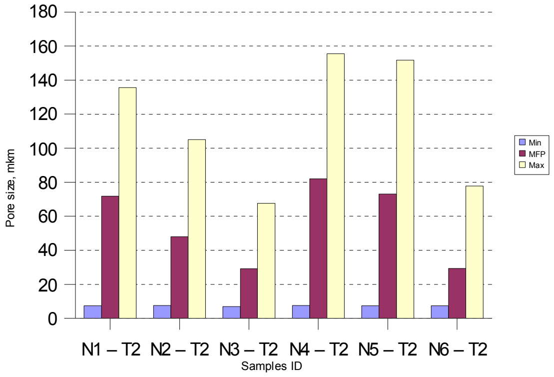

Fig. 7 Pore size and its distribution (25% binder)

The maximum pore reduction showed by the sample N3-T2 (PP) of 200 bars water jet. PP samples of 120 bars (N2-T2) also showed a big reduction of pore size in MFP and Max pore compare to PP sample N1-T2.
In case of PET samples, the pores of PET sample (N5-T2) with applying 120 bars didn't show much difference, compared to pores of samples with applied water jet pressure of 60 bars. However, the pores (MFP and Max) significantly decreased with applied 200 bars water jet pressure (N6-T2).
Porosity of nonwoven fabric depends on the fibres specific surface area when finer fibres will create the smaller pores. That can explained the smaller pores for all PP samples compare to PET samples as PP fibres are finer than PET fibres. It was also observed that the smaller pores were created during more intense interlocking of fibres with the higher pressure water jets (200 bars) for PP and PET samples with 25% binder application.

The pore size and its distribution for the samples with the 40% binder are summarised in Table 5 and illustrated by Figure 8.

Table 5. Pore size and its distribution (40 % binder)

Sample ID	Min, µm	MFP, µm	Max, µm
N7 – T2 PP	6.6	68.33	128.46
N8 – T2 PP	7.2	45.45	98.94
N9 – T2 PP	7.18	31.45	82.17
N10 – T2 PET	7.21	101.26	179.77
N11 – T2 PET	7.20	83.15	150.35
N12 – T2 PET	7.42	74.31	153.86

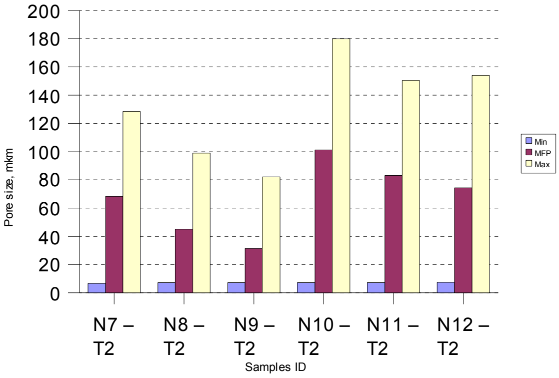

Fig. 8 Pore size and its distribution (40% binder)

The smallest pores were achieved in sample N9 - T2 of PP with water jet pressure of 200 bar.
The same trend on decreasing of MFP and Max pores was observed for both PP (N7 - N9) samples and PET (N10 – N12) samples with increase of water jet pressure. However, the sample N12-T2 did not show a differencein terms of Max pore size, compare to N11-T2.

4.4 Filtration Properties

The samples were tested for Filtration properties, such as filtration efficiency (dust arrestance), dust holding capacity and resistance (pressure drop). The method and applied technique was described elsewhere (ASHRAE 52.2 - 1999). The arrestance is a type of efficiency measurement that determines the amount of particulate matter retained in filter when introduced in air stream. Dust holding capacity is the amount of dirt or contaminant that a filter will hold before it reaches a predefined pressure rise and point. Pressure drop is an indication of the resistance to air flow through it. It is measured in Pascals in the SI system. Pressure drop has a direct relationship to the amount of energy required to flow air through the filter. In almost all applications lower pressure drop is better.

The results on filtration properties for samples with 25 % binder are illustrated in Table 6.

Table 6. Filtration properties (25% binder application)

Filtration Properties	N1-T2 PP	N2-T2 PP	**N3-T2 PP**	N4-T2 PET	N5-T2 PET	N6-T2 PET
Water jet pressure, bar	60	120	**200**	60	120	200
Dust arrestance, %	90.9	93.7	**99.4**	95.8	94.5	96.9
Dust holding capacity, g	62.7	45.6	**74.4**	48.7	59.4	68.1
Pressure drop, Pa	25	37.5	**25**	37.5	12.5	25

Within the samples with 25 % binder application, sample N3-T2 (PP) showed the best performance properties in terms of all filtration parameters.

Dust holding capacity improved for the PET samples with the increase in water jet pressure. A pressure drop decreased for PET samples , but the dust arrestance for all samples remained almost the same.

The filtration properties, such as dust arrestance, dust holding capacity and resistance (pressure drop) were evaluated on samples with 40% binder application. The results are summarised in Table 7

Table 7. Filtration properties (40 % binder application)

Filtration Properties	**N7-T2 PP**	N8-T2 PP	N9 -T2 PP	N10 -T2 PET	N11-T2 PET	N12-T2 PET
Water jet pressure, bar	**60**	120	200	60	120	200
Dust arrestance, %	**97.3**	97.7	98.6	88.62	90.4	93.9
Dust holding capacity, g	**75.35**	52.48	72.84	49.65	64.21	37.16
Pressure drop, Pa	**37.5**	37.5	62.5	37.5	25	50

Dust arrestance parameter was higher for all PP samples but didn't change with the increase in water jet pressure. Dust holding capacity decreased for the sample with 120 bars water jet pressure, but increased for the sample of 200 bars pressure (N9-T2). Despite of that, the pressure drop increased for the sample of 200 bars pressure which is not desirable in this application.

For the PET sample N 11-T2 dust arrestance parameter increased as well as dust holding capacity with the decrease of the pressure drop. However, that trend was not observed for the sample N12-T2 with the higher water jet pressure of 200 bars.

The increase of the binder application does not always improve the performance of filters. The increase in binder concentration can cause the clogging of empty spaces between the fibres. **That will result in an increase of the pressure drop - not desirable for this application.**

5. Comparison of developed filtration material with industrial filters

Two samples of so called disposable filters supplied by filters manufactured company Filtermac in Port Elizabeth, were tested for the performance properties, such as filtration properties and pore size and its distribution. No technical specifications were provided on these samples, but visual examination allowed to characterized one sample (N1 in our research) as a thermobonded needle-punched fabric from PP fibres.
The second one (N2 in our research) could be described as a chemically bonded (on one side) needle-punched fabric from PP fibres.

The results given in Tables 8 and 9 showed the comparison of industrial filters with our developed filtration material in terms of pore size and its distribution and filtration properties. These two industrial samples were compared with our "best" performed filtration samples such as N3-T2 (PP) and N7-T2 (PP) what illustrated by Figure 9 and in Table 9.

Table 8. Pore size and its distribution

Sample ID	Pore size, μm		
	Min	MFP	Max
N1 (Filtermac)	7.55	60.06	131.52
N2 (Filtermac)	7.59	30.46	93.74
N3-T2	6.91	29.09	67.61
N7-T2	6.60	68.33	128.46

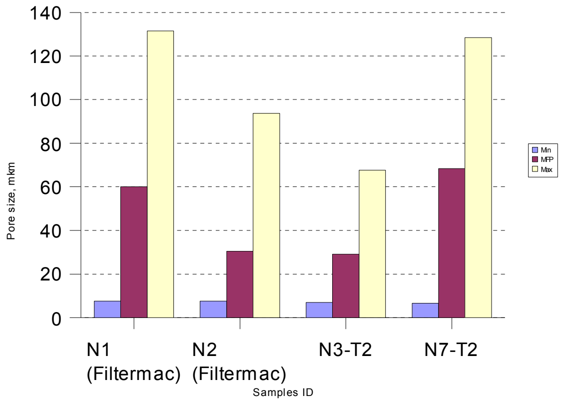

Fig. 9 Pore size (Industrial vs developed filters)

Table 9. Filtration Properties

Filtration Properties	N1 (Filtermac)	N2 (Filtermac)	N3-T2	N7-T2
Dust arrestance%	97.8	98.2	99.4	97.3
Dust holding capacity, g	99.8	87.9	74.4	75.35
Pressure drop, Pa	37.5	50.0	25	37.5

6. Conclusions

The hydroentaglement process binds the fibres in a homogeneous way. With the use of finer fibres, the surface area of the filter media shows an increasing number of finer pores. The improved surface of the media and homogeneous cross-section lead to better filtration efficiency. The absence of the mechanical damage of fibres leads to increased filtration performance as dust cannot penetrate the filter media.

The results in this study showed an improvement in filtration properties, such as arrestance and dust holding capacity for the spunlaced and chemically bonded material with increase of pressure of water jet as a result of consolidation of material's structure. The fibres become more tightly packed, making it more difficult for particles to pass through the body of the fabric.

Sample with 25 % binder application such as N3-T2 (PP) showed the best performance properties in terms of all filtration parameters. The results on good filtration properties were nicely correlated with the best results on their pore size and its distribution.

For samples with 40 % binder application the best filtration properties were demonstrated by sample N7-T2 (PP) in terms of all filtration parameters and by sample N11-T2 (PET) in terms of dust holding capacity and pressure drop. But the results on their pore size did not support the theory on the decreasing of pore size with the increase of water jet pressure and the binder application.

It could be concluded that optimum parameters for the manufacture of filters from PP fibres, were 200 bars pressure of water jets and 25 % of binder application.

The improved surface characteristics from the finer pores of finer fibres will result in the reduction of raw material for manufacturing of light filtration fabric with high filtration efficiency. Hydroentangled and chemically bonded nonwovens can be an alternative to the traditional filter media.

7. References

KOTHARI, V. K., DAS A. and SINGH S., 2007. Filtration Behavior of Woven and Nonwoven Fabrics. *Indian Journal of Fibre and Textile Research*, **Vol.32:** 214-220.

LORENTZ, V., 2007. Spunlaced Nonwovens – Advantageous Alternative for Filtration Media. *Technical Textiles, **Vol.*** **3:** E 186 – E 187.

WATZL A., 2007. Value Added Technology for Spunlace Nonwovens. *Textile Asia*, **Vol. 38:** 23 – 25.

ANANDJIWALA, R. D. and BOGUSLAVSKY, L., 2008. Development of Needle-punched Nonwoven Fabrics from Flax Fibres for Air Filtration Application. *Textile Research Journal,* **Vol. 78(7):** 614 - 624

JENA, A., GUPTA, K., 2003. Liquid Extrusion Techniques for Pore Structure Evaluation of Nonwovens. Porous Materials, *INJ Fall* , 45 - 53.

American Society for Testing and Material, 1997. ASTM D 1440-96, ASTM D 3776, ASTM D5729-95, ASTM D 5034. *Annual Book of ASTM Standards,* **Vol. 7.01.**

American Society of Heating, Refrigeration, and Air Conditioning Engineers, Inc., 1999. Method of Testing General Ventilation Air-cleaning Devices fro Removal Efficiency by Particle Size. *ANSI/ASHRAE Standard 52.2*

8. Acknowledgement

The authors wish to express gratitude to Dr. R. Anandjiwala for the guidance and review of the paper.