Grażyna Bartkowiak

Central Institute for Labour Protection
- National Research Institute,
Department of Personal Protective Equipment
ul. Wierzbowa 48, 90-133 Łódź
tel +42 678-18-63
e-mail: grbar@ciop.lodz.pl

Liquid Sorption by Nonwovens Containing Superabsorbent Fibres

Abstract
Working in tight protective clothing causes considerable discomfort, because it is impossible to expel high quantities of intensively secreted sweat out of the garment, among other reasons. The sweat accumulates on the skin and on the internal surface of tight clothing. Research work was undertaken with the aim of developing materials containing superabsorbents, which are characterised by high sorption capacity and dynamics, and could be applied in protective clothing structures to absorb sweat. The paper presents the results of research concerned with the development and testing of the liquid sorption of nonwoven materials designed for sweat-absorbing inlays.

Key words: *protective clothing, tight protective clothing, superabsorbent fibres, nonwoven materials, sweat-absorbing inlays.*

Introduction

Working in tight protective clothing made from coated fabrics, which are not permeable to water vapour, causes considerable discomfort, among other reasons because it is impossible to expel high quantities of intensively secreted sweat from the garment [1]. The sweat accumulates on the skin and on the internal surface of tight clothing, and so fails to play its physiological role, as it cannot evaporate because the undergarment microclimate is saturated with humidity. The high humidity content of the undergarment microclimate leads to sensations of stuffiness and sultriness, increasing the user's discomfort associated with the presence of liquid sweat on the skin and clothing layers. A similar situation takes place when wearing tight shoes and gloves.

Previous studies [2] have demonstrated that undergarment layers worn under tight protective clothing exert considerable influence on the intensity of heat and sweat transport. However, the textile materials currently used have limited sorption capacity, both for water vapour and for liquid sweat. Therefore, research work has been undertaken with the aim of developing materials containing superabsorbents, characterised by high sorption capacity and dynamics, which could be applied in protective clothing structures to absorb sweat. The paper presents the results of research concerned with the development and testing of nonwoven materials designed for sweat-absorbing inlays.

Objectives for modelling sweat-absorbing inlays designed for use under tight protective clothing

The main aim of the research work was to develop new absorbent structures, containing superabsorbents designed for sweat-absorbing inlays. It was presumed that textile inlays containing superabsorbents would be used for clothing elements which are not tightly fit, such as absorbent vests, tops, and single sweat-absorbing elements, as well as for inlays placed inside protective gloves and footwear. They would be also used for elements fastened to the internal surfaces of protective clothing by means of bilaterally adhesive tapes. In view of the fact that the use of disposable sweat-absorbing inlays was primarily planned, it was decided to develop a nonwoven cloth which would be a suitable material for them. The technology of nonwoven cloth production is relatively inexpensive, and allows different structures with variable material composition to be obtained.

As the sweat-absorbing inlays are used primarily in a standing position, it was presumed that they should contain highly absorbent fibres which would give them stable structure, rather than powders which could be displaced and slide down in such a position. Highly absorbent fibres have many characteristics predisposing them for use in textile sweat-absorbing inlays worn under tight protective clothing. First of all, they are characterised by high sorption of water vapour and salty water. They can also be processed using traditional textile industry technologies, providing that they are processed under appropriate climatic conditions.

The following presumptions concerning sweat-absorbing material structures were adopted:
- The structures should allow sweat absorption in both gaseous and liquid phase, also taking into consideration the fact that under actual usage conditions, the sweat will be absorbed under the pressure of the outer garment;
- They will be used primarily as exchangeable (disposable) inlays;
- The user's body should not come into direct contact with the superabsorbent, in order to avoid the sensation of wetness after sweat absorption and potential irritation of the skin; therefore, the user of tight protective clothing should wear an undergarment clothing layer next to the skin, which will be made of hydrophobic fibres, ensuring the dynamic transport of sweat (in vapour and liquid form) to the materials containing superabsorbents.

Tested materials

Superabsorbent fibre

Based on analyses of fibre properties, especially with respect to salty water sorption [3], Oasis 102 fibres were selected for the technological tests aimed at the development of sweat-absorbing inlays as part of this research task. Chemically, Oasis fibres are cross-linked acrylate copolymer, partially neutralised by the sodium salt. They demonstrate very good sorption properties for salty water, both load-free and under pressure, which is

Table 1. *Sorption properties of Oasis fibres, based on own research.*

Salty water (0.9% NaCl) free sorption for Oasis 102 fibres, g/g	
after 15 s	after 30 s
20	25

very important in view of the pressure exerted by protective clothing on sweat-absorbing inlays. A high sorption rate (the complete sorption time is 15 s) is a positive feature of the Oasis fibres.

Another very important characteristic of the Oasis fibres is their satisfactory absorption of water vapour over the whole range of relative air humidity. The fact that the Oasis fibres are manufactured by a company from the European Union (based in the UK), which may impact on their imports to Poland, was also important for the decision. The 102-type Oasis fibres were selected also because of their length (52 mm), which was most appropriate for the technological process used by as.

In order to analyse the properties of Oasis 102 fibres which are important from the point of view of their use for sweat-absorbing inlays, water vapour and salty water sorption tests were performed. Figure 1 presents the changes of humidity of Oasis 102 fibres over time for different relative air humidity values, based on the results of our own research.

The results presented indicate that Oasis fibres demonstrate very good sorption of water vapour over a wide range of relative air humidity values. After 30 min of exposure to air of 80% humidity, they have already absorbed c. 25% of the water vapour in relation to their own weight. This property is very important from the point of view of their target use in sweat-absorbing inlays under tight protective clothing, where humidity may reach even 100% after 10-20 min of work.

The results of our own tests of free salty water sorption by Oasis 102 fibres are presented in Table 1. However they are lower than the values specified by the manufacturer, they are relative good compared with other fibres, and are satisfactory considering our demands.

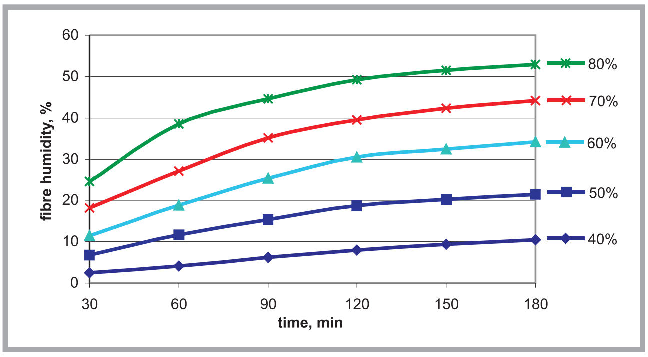

Figure 1. Changes of Oasis 102 fibre humidity over time, under different relative air humidity conditions, based on our own research.

Nonwoven materials containing superabsorbent fibres

The tests were carried out on needled nonwoven materials containing highly absorbent Oasis 102 fibres. Ten needled nonwoven variants with different material composition and variable contents of highly absorbent Oasis 102 fibres were produced. In order to assess the effect of highly absorbent fibre content and material composition on sweat transfer properties under tight protective clothing, we produced nonwoven cloth variants containing 50% or 30% of Oasis fibres in combinations with cotton (CO) – 1.7 dtex, polyester (PET) - 1.5 dtex and polypropylene (PP) - 1.7 dtex.

As a result of the hot pressing of the needled nonwoven (the sorptive layer) marked with the symbol **G** (with thermoplastic PP fibre content), a material **M**, resembling thick paper in appearance, was obtained. The characteristics of nonwoven materials tested within the framework of the study are presented in Table 2.

Testing methodology

Liquid sorption tests

The sorption of liquid sweat by materials containing superabsorbents was determined using the method of contacting the material surface with the liquid. The method reflects the actual conditions of use [4] of the garment contacting sweating human skin, and allows the sorption phenomenon to be assessed over time.

The tests were carried out using the device [4] presented schematically in Figure 2. Prior to the tests, the material samples had been stored for 24 h in a tightly sealed exsiccator with anhydrous calcium chloride at 20 ±2 °C. Sorption tests were carried out under normal climatic conditions (temperature 20 ±2 °C, relative humidity 65 ±2%).

A material sample was placed on the porous plate of a Schott funnel, whose upper surface lies at the level of liquid surface, which is constantly maintained by an automatic control system. The liquid absorbed by the sample is continuously supplemented by a hydraulic system. The amounts of liquid supplied by that system in the form of regulated impulses in the function of time is recorded and plotted into a curve, which forms the basis for the analysis of parameters defining the course of the sorption process (Figure 3).

The proper sorption time is characterised by a rapid (rectilinear) increase of liquid mass in the sample volume. The tangent of the inclination angle of the AB segment to the X-axis defines the sorption velocity V_{30-70}, in µl / cm^2 s.

The saturation stage begins at the moment of abrupt decrease of the sorption velocity, and lasts until the complete cessation of the liquid mass's increase. At that point, the maximum sorption S_{max}, expressed as µl of the absorbed liquid per cm^2 of the sample, is determined. The time corresponding to that point is defined as the total sorption time t_{max}, in seconds.

Assuming that during continuous use of tight protective clothing, intensive sweat secretion takes place, and that the clothing is used under the pressure of the outer barrier clothing layer, the following measurement conditions have been adopted:
- pulsative liquid supply: 0.2423 µl
- pressure exerted on the sample: 0.5 kPa
- range of the AB curve interval used for the determination of the sorption velocity: 30 to 70% S_{max},
- pre-set time: 20 s (i.e. the time of termination of the measurement, after which, if no subsequent liquid supply is absorbed, the hydraulic system switches off).

In order to approximate the actual conditions associated with sweat secretion, the tests were carried out using acid sweat substitute according to PN-P-4913:1996 [5], based on literature concerning the chemical composition of sweat [6].

For comparative analysis of particular material variants which differ in surface mass values, the **'sorption effectiveness index' (*E*)** was calculated by relating the maximum sorption value to the unit area mass of the material, in µl of sweat/mg of fabric [7]:

$$E = \overline{S}_{max} / m_p, \ \mu l/mg$$

where:

S_{max} - average value of 10 measurments of maximum sorption, µl/cm^2,

m_p - unit area mass of the given layer, in mg/cm^2, according to Table 2 where it is listed in g/m^2.

Preliminary tests demonstrated that the sorption value is not directly proportional to the content of highly absorbent Oasis fibres in the material. That is why we have introduced an additional parameter, referred to as the '**Oasis sorption effectiveness index**' (**E_{oasis}**), characterising the quantity of liquid absorbed by the sample in relation to the unit mass of Oasis fibres m_o in the given material:

$$E_{oasis} = \overline{S}_{max} / m_o, \ \mu l/mg$$

Test results

Liquid sorption

The results of investigation of sorption parameters are presented in Table 3. The table contains no data concerning sweat sorption for material **H**, which did not absorb any liquid under the test conditions.

The maximum sorption value is of crucial importance from the point of view of the sorption of the given material. The highest sorption capacity, reaching over 340 µl/cm^2, was demonstrated by nonwoven materials **A** and **I** composed of Oasis and cotton. The nonwoven materials **D**, **E**, **F** containing Oasis and PET fibres were also characterised by very high sorption capacities (ranging from 298.3 to 321.5 µl/cm^2). All the nonwoven materials except for **G** and **M** were characterised by high sorption velocity. Low maximum sorption (141.4 µl/cm^2) and sorption velocity (0.44 µl/cm^2 s) were found for variant **G**, a nonwoven material composed of 50%Oasis/50%PP. It is noteworthy that variant **H**, consisting of 30%Oasis/70% PP, did not demonstrate any sweat sorption capacity at all. However, the sorption value for variant **M** (obtained as a result of the hot pressing of the needled nonwoven **G**) can be regarded as satisfactory. The hot pressing of the needled nonwoven **G** resulted in an increase of liquid sorption.

Analysis of test results

The results of our determination of sorption parameters clearly indicate the significant influence of the composition of the nonwoven materials both on the maximum sorption value and on the indexes characterising the effectiveness and dynamics of sorption.

The analysis of nonwoven materials composition was carried out on the basis of sorption effectiveness parameters (E, E_{oasis}), because the impact of surface mass is then eliminated.

Considering the impact of material composition on the effectiveness of sorption, attention should be paid to the properties of Oasis fibres and associated liquid

***Table 2.** Basic variants of needled nonwoven materials.*

Variant	Fibres composition	Mass per square meter, g/m^2	Thickness, mm
A	50% Oasis 102 50% cotton	150.6	3.32
B	30% Oasis102 70% cotton	131.8	3.37
D	50% Oasis 102 50% polyester	204.7	2.32
E	30% Oasis 102 70% polyester	276.7	3.71
F	15% Oasis 102 85% polyester	197.3	3.02
G	50% Oasis 102 50% polypropylene	226.3	3.57
H	30% Oasis 102 70% polypropylene	203.9	3.01
I	34% Oasis 102 33% cotton 33% polypropylene	240.9	-
M	Nonwoven G (50% Oasis 102, 50% PP) after hot pressing	230.5	0.83

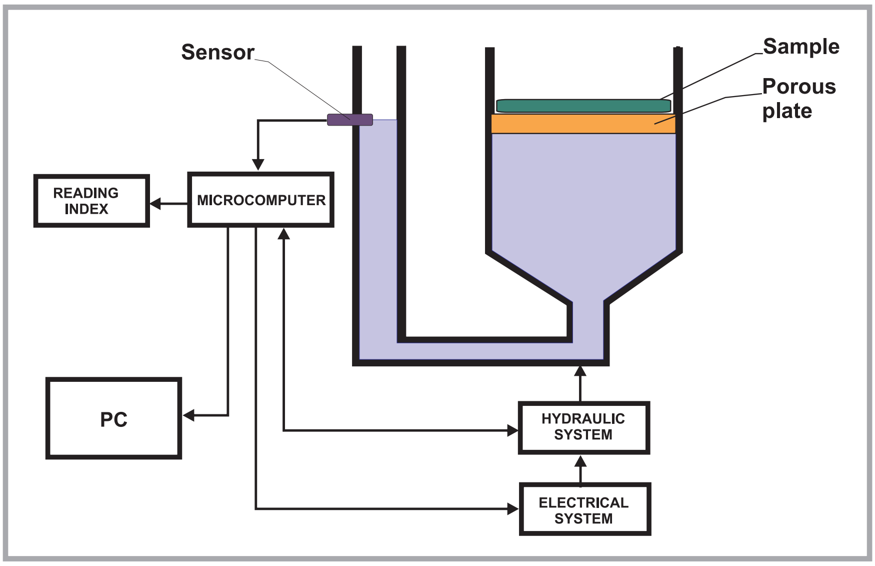

***Figure 2.** Scheme of the device for liquid sorption measurements [4].*

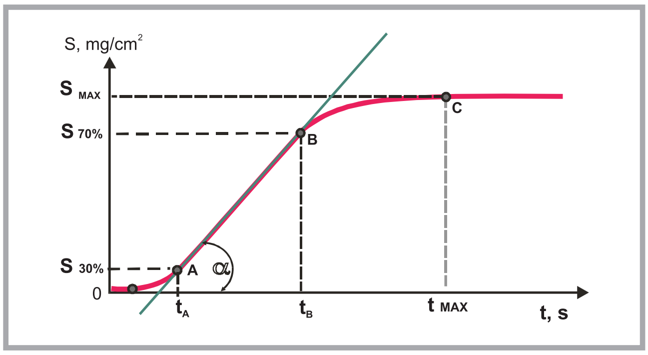

***Figure 3.** Typical sorption curve.*

transport. The Oasis fibres after liquid absorption assume a gel-like form, retain the liquid inside and do not transfer it to the surrounding fibres. Thus, material structures containing Oasis fibres can only absorb liquids as a result of:

- direct contact of the Oasis fibres with the liquid,
- transport of the liquid deeper inside the material by the fibres which absorb it and transfer it to the Oasis fibres (wicking),
- capillary transport of the liquid along the fibres possessing a hydrophilic surface and transferring it to the Oasis fibres situated deeper in the material.

Analysing the influence of cotton fibres on the effectiveness of sorption, it can be stated that, when used in combination with Oasis fibres, they have a positive impact on sorption capacity. Variants (**A**, **B**) are characterised by the highest sorption effectiveness and the most effective utilisation of Oasis fibres (E_{oasis}). Reducing the proportion of the Oasis fibres in Oasis/cotton composite from 50% to 30% (sample B) decreases the sorption effectiveness from 23.2 µl/mg to 18.3µl/mg. Considering the sorption effectiveness in relation to the quantity of Oasis (E_{oazis}), the nonwoven variant **B** (30% Oasis/70% cotton) is characterised by higher sorption effectiveness than nonwoven A (50% Oasis/50% cotton). Thus, the positive role of cotton fibres in nonwoven materials containing Oasis fibres results from their ability to transport the absorbed liquid deeper inside the nonwoven structure and transfer it to Oasis fibres, which do not come in direct contact with the liquid. Variant **I** with Oasis, cotton and PP also demonstrates a very good effectiveness of sorption.

On further analysis of the raw materials used in superabsorbent nonwoven, the satisfactory sorption and sorption dynamics demonstrated by the nonwoven variants composed of Oasis/PET (in contrast to nonwoven variants composed of Oasis/PP) should be emphasised.

The nonwoven variants **D**, **E**, **F** demonstrate very high maximum sorption values (298.3µl/cm^2 – 321.5µl/cm^2). Variants D and F are characterised by high sorption effectiveness (14.5µl/mg – 16.3µl/mg).

Further comparison of the variants **D** and **F** leads to the finding that reducing Oasis fibre proportion from 50% to 15% increased sorption effectiveness (E), as well as sorption effectiveness as related to Oasis fibre content (E_{oazis}). This in turn leads to the conclusion that in the case of nonwoven materials composed of Oasis/PET, increasing the percentage content of Oasis fibres does not result in any increase of the material sorption capacity. When Oasis fibres are packed too densely, they do not transfer liquid to one another, which makes liquid penetration through the material pores more difficult.

Table 3. Results of sweat sorption tests for basic nonwoven materials and nonwoven composites.

Variant	Maximum sorption S_{max}, µl/cm^2		Sorption velocity $V_{30-70\%}$, µl/cm^2 s		t_{max}, s	Sorption effectiveness index E, µl of sweat/mg of fabric	Oasis sorption effectiveness index E_{Oasis}, µl of sweat/mg of Oasis
	$\bar{S}_{max}$	Standard deviation	$\bar{V}$	Standard deviation			
A	349.70	16.83	8.32	0.41	81.0	23.20	46.41
B	239.60	11.48	20.90	1.40	49.0	18.32	60.60
D	298.30	9.75	14.77	2.02	74.5	14.57	29.16
E	301.10	19.71	11.02	0.90	67.5	10.88	36.37
F	321.50	12.06	15.30	1.99	34.3	16.29	108.62
G	141.40	30.82	0.46	0.06	342.5	6.26	11.98
H	No liquid sorption		-	-	-	-	-
I	342.40	12.47	9.06	0.53	81.0	14.27	43.23
M	217.17	14.24	1.43	0.23	194.0	8.99	30.59

Table 4. The results of sweat sorption tests for nonwoven materials (OA) with comparison with cotton knitted material (CO).

Variant	Maximum sorption S_{max}, µl/cm^2		Sorption velocity $V_{30-70\%}$, µl/cm^2 s		t_{max}, s	Sorption effectiveness index E, µl of sweat/mg of fabric	Oasis sorption effectiveness index E_{Oasis}, µl of sweat/mg of Oasis
	$\bar{S}_{max}$	Standard deviation	$\bar{V}$	Standard deviation			
OA	492	11.7	26.1	2.95	56	19.68	65.6
CO	111	2.58	31.6	2.74	8	6.76	-

Analysing nonwoven materials with the same Oasis fibre content (equal to 50%), and differing in the complementary synthetic fibres used, the definite superiority of variant **D** (using PES) over variant **G** (containing PP) should be emphasised. The nonwoven variant **D** is characterised by a twofold-higher sorption effectiveness, which becomes threefold higher in relation to Oasis fibre content E_{oazis} (Figure 4, 5). The very high sorption effectiveness of nonwoven materials containing only 30 and 15% of Oasis should be emphasised here, although this is only true with respect to Oasis/PET composites, whereas the nonwoven variant **H** containing 30% Oasis and 70% PP demonstrates no sweat absorption.

The reason for the phenomena we have observed is the surface characteristics of the fibres used to produce the nonwoven composite with Oasis. Polyester fibres with a hydrophilic surface facilitate capillary transport of liquid in the material structure, as a result of which, it reaches the fibres while having no contact with the liquid. This is impossible in the case of polypropylene fibres with a hydrophobic surface, which does not promote capillary transport. In Oasis/polypropylene nonwoven materials, only the fibres coming into direct contact with the liquid can absorb it, while the others are inaccessible for the liquid and are not utilised at all. Such conclusions are confirmed by the results of liquid sorption by nonwoven variant **I** (34% Oasis/33% Cotton/33% PP). This variant is characterised by very high sorption effectiveness E and E_{oasis}, which is only owedto the content of cotton, and transports the liquid to deeper highly absorbent fibres. The nonwoven variant with similar Oasis content combined with polypropylene only (**H**) did not demonstrate any liquid sorption capacity, since only a few Oasis fibres came into contact with the sweat, which could not be transported deeper into the structure because of the hydrophobic character of the polypropylene fibres.

Pressing the nonwoven **G** considerably improved its sorptive properties. As a result of pressing, the material surface was flattened, and more Oasis fibres came into direct contact with the wet plate surface during the sorption test. For this reason, an increase in the maximum sorption value (variant **M** - sorption 217 µl/cm^2) was observed, as well as a decrease in the total sorption time (from 342.5 s to 194 s), for variant **G** samples after pressing.

Summing up the results of sweat sorption tests, it can be stated that the most favourable parameters characterising the dynamics of sweat sorption were obtained for the following nonwoven variants:

- for nonwoven materials, Oasis fibres and cotton (variants **A**, **B**, **I**), and
- for nonwoven materials containing PET (variants **D**, **E**, **F**).

The sweat-absorbing inlays to be used in close contact with the skin (next to the skin or on underwear capable of sweat transport away from the skin surface) can be made of nonwoven **M**, which was obtained as a result of hot pressing with a mangle of needled nonwoven **G**. Liquid sorption by **M** at the level exceeding 200 μl/cm2 should promote dynamic sweat transport away from the user's skin, and high water vapour absorption should facilitate the creation of appropriate microclimate around the user's body under tight protective clothing. Nonwoven **M** is characterised by low thickness and smooth surface. It should not constitute any additional thermal load, and, because of its low thermal resistance, should allow heat transfer from the user's body and out of the garment.

Taking into account the above results and conclusions, a new variant (**OA**) of a needled, hot pressed nonwoven for sweat absorption inlays was produced. It consisted of 33% Oasis 102, 33% PET (transferring liquid) and 34% PP (binding nonwoven during hot pressing). The material is characterised by a liquid sorption which is fourfold higher than the cotton knits (**CO**) traditionally used in the production of underwear (Table 4). The sweat sorption results of this nonwoven are very satisfactory, and they confirm the conclusions given below.

Conclusions

1. Tests of needled nonwoven materials containing superabsorbentsfibres demonstrated that the extent of liquid sorption depends primarily on their composition, and is not directly proportional to the quantity of superabsorbent fibres.
2. The best properties with respect to sorption are demonstrated by needled nonwoven materials containing superabsorbent fibres and cotton or polyester. In the case of nonwoven materials containing superabsorbent fibres with polypropylene, the liquid sorption properties can be improved by hot ironing, as a result of which their structure is flattened and a form more appropriate for sweat-absorbing undergarment inlays is obtained.
3. As follows from the assessment of conditions associated with the use of tight protective clothing, while also considering the results concerning sweat sorption, nonwoven materials with a content of Oasis 102 superabsorbent fibres can be applied for sweat-absorbing undergarment inlays, which would then serve a double function:
   - collecting sweat directly from the skin or from the clothing layer adjacent to the skin, and absorbing water vapour from the microclimate over the skin,
   - collecting sweat from the inner surface of tight protective clothing, and absorbing water vapour from the undergarment space.

Nonwoven textile inlays containing superabsorbents can be used for clothing elements, such as absorbent vests, tops, and single sweat-absorbing elements, as well as for inlays placed inside protective gloves and footwear.

Sweat-absorbing inlays to be worn under tight protective clothing should, for practical reasons, be installed in such places on the user's body that are particularly associated with sweat secretion.
Research on testing microclimates under tight protective clothing with sweat-absorbing inlays on men in a climatic chamber will be presented in another publication.

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