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Investigation of Sealed Seams Properties of Moisture Barrier Layer in Firefighters Clothing

Diana GRINEVIČIŪTĖ *, Lina VALASEVIČIŪTĖ, Violeta NARVILIENĖ, Kristina DUBINSKAITĖ, Regina ABELKIENĖ

Textile Institute of Center for Physical Sciences and Technology, Demokratu str. 53, LT-48485 Kaunas, Lithuania

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This study presents an experimental investigation of sealed seams performance of two types of nonwoven fireproof fabrics laminated with bicomponent and hydrophilic membrane, which are used for moisture barrier layer in firefighters clothing. Seam strength in longitudinal and cross direction and resistance to water penetration were determined for investigation of quality of sealed seams with thermoplastic polyurethane tape. Determining the efficiency of sealed seams, optimal sealing parameters (temperature, sealing speed and quill pressure) were identified in order to achieve good seam performance. The experimental relations and empirical equations for the seam strength and resistance to water penetration determined in this research can be used to predict efficiency of seams quality applying different parameters of seam sealing process.

Keywords: moisture barrier, firefighters clothing, nonwoven fabrics, membrane strength, resistance to water penetration, seam sealing efficiency, sealing parameters.

1. INTRODUCTION

The multilayer system for firefighters clothing usually consists of several layers: an outer shell, moisture barrier of water resistant and water-vapour permeable membrane, a thermal insulation layer and lining. Each layer of clothing must meet different security requirements. Under outer shell a moisture resistant layer is integrated. Fabric properties of this layer must secure from water penetration from outside and at the same time to help transmit moisture from the clothing system to the environment. Contemporary moisture resistant firefighters' clothing layer is made of breathable, coated or laminated with membranes fabrics, which are fire resistant [1]. As it is presented in literature [1, 2] hydrophilic membranes are highly resistant to water penetration, and bicomponent membranes have enhanced strength and elongation properties. In order to ensure good characteristics of firefighter‘s protective clothing, it is important not only a proper selection of textile material properties of the separate layers, but also to ensure the integrity of the characteristics, which are significantly influenced by the structural properties of seams.

Many studies [3 – 6] shoved that the seam performance (seam strength, elongation, seam efficiency) depends on the interrelationship of fabrics, threads, the stitch and seam type selection and sewing conditions, which include the needle size, stitch density and etc. It was investigated [5] that type of fabric finishing improves wear behaviour (slippage resistance of yarns at a seam, friction) of sewn fabrics. In case of breathable waterproof fabrics, the seamed fabrics must be sealed with waterproof sealing tape to prevent water from penetration through the holes caused by stitching of needle. In study [7] it is presented the influence of sealing process on seams characteristics of breathable waterproof fabrics made by various finishing methods – the authors state that sealing of seams improves their strength properties comparing to sewn ones.

Investigations of mechanical properties of fabrics and seams in different fabrics direction, which usually are during wear processes of the clothing, are presented in research [8 – 10]. Authors of study [11] investigated that in both of parallel and perpendicular (warp and weft) directions tensile characteristics of seams of breathable waterproof fabrics were significantly changed with variability of seaming and sealing processes condition. Data obtained from other researchers' works showed lack of investigations concerning evaluation of seams mechanical properties in different seam directions, despite the fact that constructional seams are affected by multiaxial deformations.

With increasing use of coated and laminated fabrics in functional protective clothing, also various technologies for joining of these materials with the seams are developed [12]. It is evident that quality of bonded seams depends on bonding parameters. In [13] authors investigated the performance of bonded seams of some thermoplastic materials with additional layer of silicone paper. As the results of investigation showed delamination of created seams, it was determined that bonding strength of textile depends on fabrics structure characteristics as well. Authors in [3 – 13] analyse seams' behaviour of knitted and woven textile materials. In a part of these studies seam properties of laminated textile fabrics, where the base layer is woven or knitted material, are analysed. In order to improve fire resistance properties in moisture impervious clothing insulation new constructions of fire resistant aramid fabrics with nonwoven base layer, laminated with different membranes are developed [14]. Application of nonwoven aramid fabrics for firefighter's insulation layers

*Corresponding author. Tel.: +370-37-308660, fax: +370-37-308668.
E-mail address: *grineviciute@lti.lt* (D. Grinevičiūtė)

is also based on economical and ecological aspect: recyclability and reuse of this expensive raw material.

It is lack of research information where complex investigation of protective and comfort properties of sealed seams of waterproof moisture barrier layer was performed. Hereby the objective of this study is to evaluate the differences of constructional seams formation of protective clothing for firefighters' moisture impervious layer. For this layer nonwoven fire resistant aramid materials with different polymer membranes are used and seams are constructed applying different technological modes of sealing with tape. Also influence of sealing process parameters on constructional seams maximal strength and resistance to water penetration values will be determined.

2. MATERIALS AND METHODS

Two contemporary commercially available laminated nonwoven aramid fabrics of different structure – with hydrophilic and bicomponent membranes, having different properties (tensile strength, resistance to water penetration, thickness) – were selected for the moisture barrier investigation. Table 1 provides basic information about the tested fabrics.

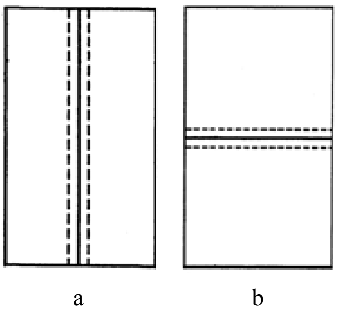


Fig. 1. Schematic view of seams: a – longitudinal direction, b – cross direction

Based on test results of water proof breathable fabrics evaluation [11], that showed the differences between seams tensile properties (after sealing process) in both directions – parallel and perpendicular – to the seam line, analogous specimens (as in [11]) for seams preparation in two directions were selected for our tests. Specimens for the seam tests were prepared from nonwoven textile fabrics cut in longitudinal direction. The test samples for mechanical properties investigation (tensile strength) were sewn in longitudinal (a) and cross (b) directions (Fig. 1).

For the investigation of resistance to water penetration specimens were sewn only in longitudinal direction.

The seaming was performed with a sewing machine "Brother DB2-B101" with an average sewing speed of 3150 stitch/min (stitch type 301, stitch density 3 ±0.5 stitch/cm). For sewing of samples 100 % meta-aramid yarns (16.7×3 tex) were used.

Samples for seam bonding were prepared as it is usually required for joining of details of water resistant layer for firefighter's clothing, i. e. making reinforced joining of 2 seams. Then, the seamed samples of both fabrics were sealed with waterproof thermoplastic polyurethane sealing tape (which was recommended by fabric manufacture) with silicone paper (the thickness was 0.05 mm) applying seam sealing machine "Ardmel MK5" (Fig. 2).

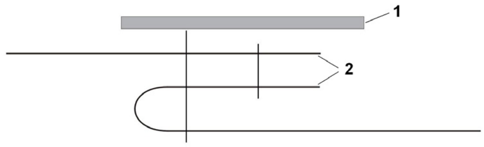


Fig. 2. Scheme of stitched and sealed seams test samples: 1 – sealing tape, 2 – fabric of moisture barrier layer

For investigation of influence of factors of sealing process with tape on mechanical and protective seams properties an experimental design was applied. In this research an orthogonal plan of three factors was used [16]. Factors numbering is shown in Table 2.

Test samples for the seams investigation (strength and water resistance) were prepared applying different technological parameters of sealing process of "Ardmel" machine (Table 2).

Applying experimental design the values of tested seams' optimization criterions (Y_1 – maximal tensile force in longitudinal direction, Y_2 – maximal tensile force in cross direction, Y_3 – resistance to water penetration) were determined.

Experimentally seam strength was measured according to the standard [17] applying "SDL International Textile Testing Solutions" ZT-400 tension machine. The specimens

Table 1. Characteristics of moisture barrier fabrics laminated with different membranes

Fabric code	Characteristic							
	Content	Area density, g/m^2	Thickness, mm	Tensile strength, N		Tensile elongation, %		Resistance to water penetration, kPa
				Longitudinal direction	Cross direction	Longitudinal direction	Cross direction	
MB1	Textile: 50 % para-aramid 50 % meta-aramid Membrane: 100 % bicomponent PTFE/PU	140	1.35	541	342	46.1	73.4	89.3
MB2	Textile: 50 % melamine resin 25 % para-aramid 25 % meta-aramid Membrane: 100 % hydrophilic PES	110	0.87	181	149	43.3	65.7	95.0

Table 2. Identification of sealing process factors

No.	Factor code	Factor and variability levels
1	X_1	Temperature (400 – 500) °C
2	X_2	Sealing speed (2.5 – 4.5) m/min
3	X_3	Quill pressure (1.0 – 4.0) kPa

were extended to their breaking point, and their breaking modes were registered. The dimensions of specimens were (100 × 250) mm. The gauge length was 100 mm and the rate of extension was 50 mm/min. This test was performed for specimens with seams in longitudinal and cross direction.

Seam resistance to water penetration was determined according to the standard [18]. The size of specimen with the seam in the middle was 100 cm^2. The rate of the pressure increase of the water was (60 ±3) cm head of water per minute. The test result of the pressure being taken at the appearance of the third drop on the surface of the seam.

The efficiency of seam sealing was determined using the following equation [11]:

$$\text{Seam sealing efficiency (\%)} = \frac{\text{Seam parameter}}{\text{Fabric parameter}} \times 100 . \quad (1)$$

3. STATISTICAL ANALYSIS

During the test mean values of optimization criterions for investigated fabrics were calculated and experimental relationships were determined. Values of the coefficient of variation did not exceed 7 % for both fabrics (MB1 and MB2).

For tests, performed according to the experimental design, polynomial non-linear relationships were calculated and significance of regression coefficients of the relationships was determined.

Statistical analysis of relationships between parameters of the seam strength in longitudinal direction, resistance to water penetration, and sealing process factors revealed that regression coefficients were significant for both fabrics. However in relationships between the seams strength in cross direction of both fabrics and sealing factors the number of insignificant coefficients was obtained higher.

In order to determine the relevance of empirical equations, Fisher's criterion was calculated, which revealed that mathematical models were adequate.

Mathematical models are presented in following form:

For fabric MB1:

Seam strength in longitudinal direction:

$$y_1 = 716 - 3.37x_1 + 9.07x_2 + 6.13x_1x_2 + 15.88x_1x_3 + 13.38x_2x_3 - 74.75x_1^2 - 67.66x_2^2 - 69.44x_3^2 + 6.13x_1x_2x_3 . \quad (2)$$

Seam strength in cross direction:

$$y_2 = 565.9 + 3.09x_1 + 6.41x_2 - 0.07x_3 + 4.88x_1x_2 - 9.88x_1x_3 - 2.63x_2x_3 - 31.85x_1^2 - 52.75x_2^2 - 37.16x_3^2 - 7.38x_1x_2x_3 . \quad (3)$$

Resistance to water penetration:

$$y_3 = -20.86 - 0.01x_1 + 1.01x_2 + 0.15x_3 + 1.27x_1x_2 + 0.07x_1x_3 - 0.28x_2x_3 + 8.47x_1^2 + 8.67x_2^2 + 8.99x_3^2 - 0.19x_1x_2x_3 . \quad (4)$$

For fabric MB2:

Seam strength in longitudinal direction:

$$y_1 = 211.5 - 9.56x_1 - 4.16x_2 - 7.27x_3 - 5.00x_1x_2 - 2.50x_1x_3 - 2.50x_2x_3 + 20.73x_1^2 + 20.73x_2^2 + 12.04x_3^2 + 7.50x_1x_2x_3 . \quad (5)$$

Seam strength in cross direction:

$$y_2 = 127.1 - 8.72x_1 - 1.21x_2 - 2.13x_3 - 1.13x_1x_2 - 1.38x_1x_3 + 6.13x_2x_3 + 38.44x_1^2 + 34.90x_2^2 + 31.54x_3^2 - 1.13x_1x_2x_3 . \quad (6)$$

Resistance to water penetration:

$$y_3 = -8.15 - 0.58x_1 + 0.99x_2 + 0.35x_3 - 0.01x_1x_2 - 0.09x_1x_3 + 0.53x_2x_3 + 3.20x_1^2 + 3.67x_2^2 + 3.15x_3^2 + 0.16x_1x_2x_3 . \quad (7)$$

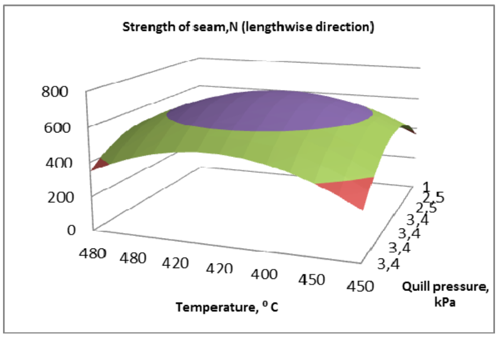
The statistical analysis proved that the coefficient of determination for the three models of fabric MB1 is 0.92, 0.94 and 0.82 respectively, and for the three models of fabric MB2 are 0.93, 0.63 and 0.86 respectively, which means that these models fit the data very well.

4. RESULTS AND DISCUSSION

In addition to the determination of relationships of optimization criterions (seam strength in longitudinal and cross direction, resistance to water penetration) and factors (temperature, sealing speed, and quill pressure), comparative analysis of experimental and calculated values of empirical equations was performed. It was also evaluated the efficiency of seam properties of MB1 and MB2 fabrics.

4.1. Seam strength in longitudinal direction

Relationships between the seam strength in longitudinal direction of fabrics MB1 and MB2 and sealing regime factors are presented in Figures 3 and 4 respectively.



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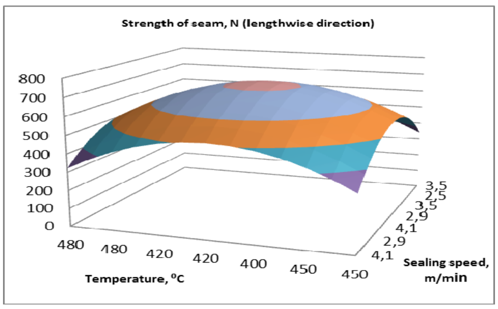
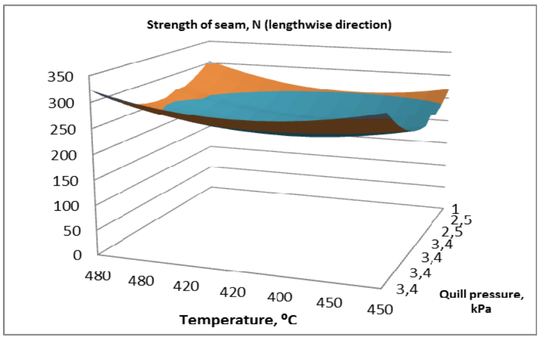


b

Fig. 3. Response surface of seam strength of fabric MB1 at different levels of temperature, quill pressure (a) and sealing speed (b)

As it can be seen from relations presented in Figures 3 and 4, influence of sealing factors on mechanical parameters of both fabrics is expressed by different diagrammatic nature. Analysis of recent relations showed that clearly expressed maximal seam strength values of fabric MB1 can be obtained using a particular set of factors. On the contrary, a range of minimal seam strength values of fabric MB2 can be expressed by wider diapason of factors investigated.



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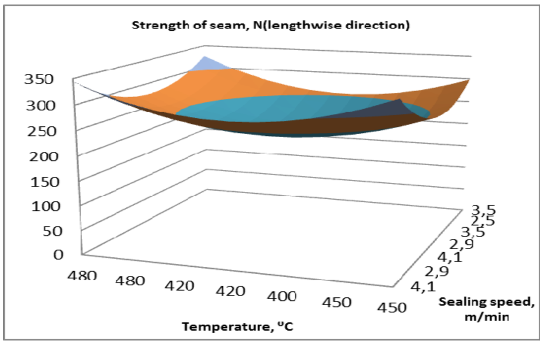


b

Fig. 4. Response surface of seam strength of fabric MB2 at different levels of temperature, quill pressure (a) and sealing speed (b)

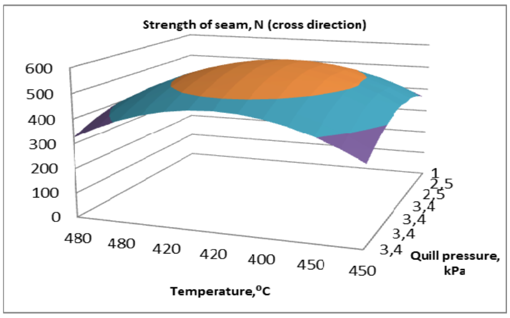
4.2. Seam strength in cross direction

Influence of sealing regime factors on seam strength in cross direction of fabrics MB1 and MB2 are presented in Figures 5 and 6 respectively.

Analysis of relations between seam strength in cross direction of fabrics MB1 and MB2 and regime factors showed identical diagrammatic nature as it was for seam strength in longitudinal direction. The difference is that a range of maximal seam strength values of fabric MB1 can be expressed by wider diapason of factors investigated (Fig. 5), and minimal seam strength values of fabric MB2 are clearly expressed and can be obtained using a particular set of factors (Fig. 6).

4.3. Resistance to water penetration

In order to optimize protective properties of moisture resistant layer of firefighters' protective clothing it is very important to ensure not only good seams strength, but also their resistance to water penetration. Different relations of optimization criterions identified in this study pose a challenge to optimize sealing process factors in order to ensure optimal seams performance.



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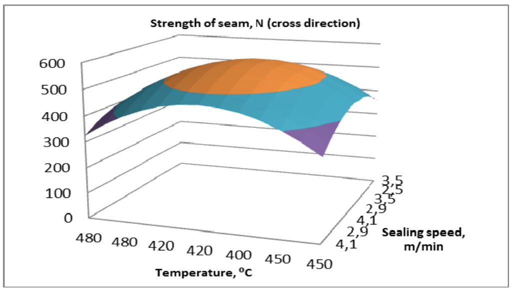
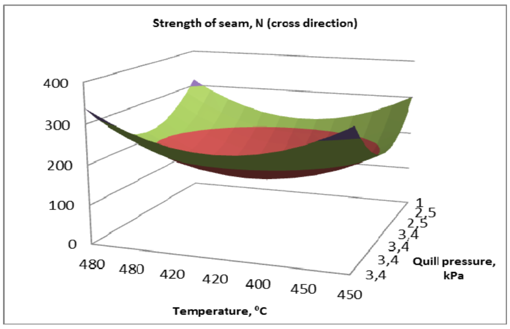


b

Fig. 5. Response surface of seam strength of fabric MB1 at different levels of temperature, quill pressure (a) and sealing speed (b)



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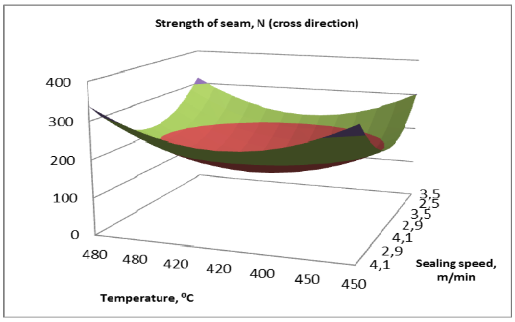
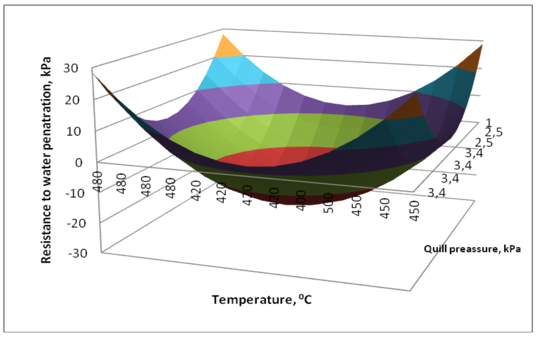


b

Fig. 6. Response surface of seam strength of fabric MB2 at different levels of temperature, quill pressure (a) and sealing speed (b)

Parameters relations presented in Figures 7 and 8 show similar diagrammatic nature for both fabrics evaluated, still differences between fabrics evaluation exist. Variation range of MB1 quill pressure and sealing speed factors is evenly distributed, and diapason of minimal values of resistance to water penetration is expressed equally (Fig. 7). However variation of sealing speed factor of MB2



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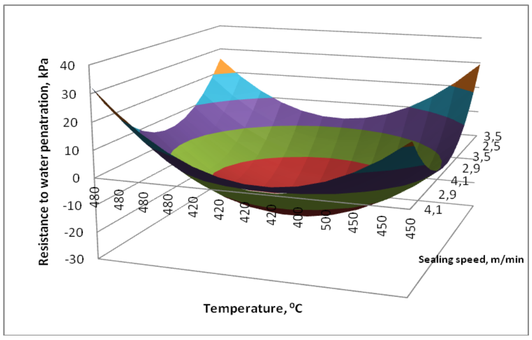
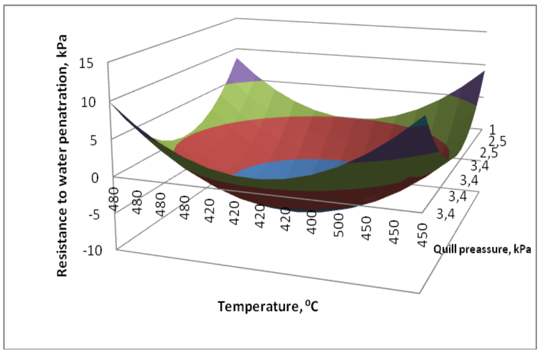


b

Fig. 7. Response surface of resistance to water penetration of seams of fabric MB1 at different levels of temperature, quill pressure (a) and sealing speed (b)



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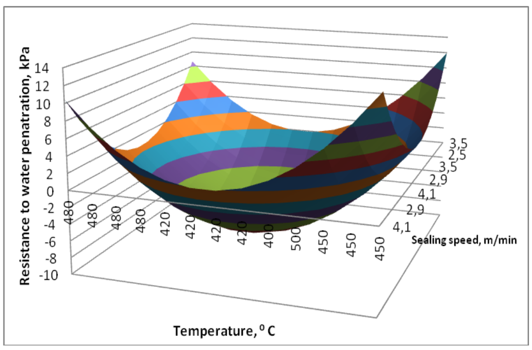

b

Fig. 8. Response surface of resistance to water penetration of seams of fabric MB2 at different levels of temperature, quill pressure (a) and sealing speed (b)

(Fig. 8, b) is located in narrow ranges and limits of minimal resistance to water penetration can be obtained using a particular set of factors. On the contrary to sealing speed factor's variation, limits of quill pressure factor's variation are wider, still minimal values of fabric resistance to water penetration are clearly expressed (Fig. 8, a).

4.4. Seam efficiency

Comparative analysis between experimental parameters of seam strength and resistance to water penetration and initial characteristics of fabrics MB1 and MB2 also determination of seam efficiency according to each optimization criterion are presented in Tables 3 and 4.

Table 3. Comparison of fabric MB1 seams efficiency

Sample code	Efficiency of seam strength, %		Efficiency of seam resistance to water penetration, %
	Longitudinal direction	Cross direction	
MB1J1	103.5	81.7	92.7
MB1J2	89.1	89.1	96.5
MB1J3	89.1	81.9	44.1
MB1J4	89.1	81.9	26.9
MB1J5	94.4	83.5	54.9
MB1J6	96.3	78.1	53.6
MB1J7	89.1	81.9	54.6
MB1J8	96.3	80.0	49.2
MB1J9	94.4	89.1	49.2
MB1J10	92.6	87.2	19.3
MB1J11	96.3	74.4	31.2
MB1J12	98.1	80.0	49.6
MB1J13	92.6	85.4	50.0
MB1J14	100	85.4	51.4

Table 4. Comparison of fabric MB2 seams efficiency

Sample code	Efficiency of seam strength, %		Efficiency of seam resistance to water penetration, %
	Longitudinal direction	Cross direction	
MB2J1	136.1	125.5	36.4
MB2J2	136.1	125.5	7.05
MB2J3	141.7	114.4	2.94
MB2J4	152.8	125.5	2.84
MB2J5	147.2	141.7	50.2
MB2J6	158.3	136.1	23.6
MB2J7	158.3	125.5	22.9
MB2J8	147.2	136.1	11.9
MB2J9	158.3	136.1	16.4
MB2J10	141.7	125.5	2.31
MB2J11	152.8	136.1	3.58
MB2J12	147.2	114.4	43.1
MB2J13	147.2	120.0	12.8
MB2J14	125.6	120.0	2.73

Comparing test results presented in Tables 3 and 4 with other researchers' data [7, 11], it was determined that seam strength after sealing process of nonwoven fabrics with membrane and the derivative index – efficiency of seam strength – were different in both directions (longitudinal and cross), as well as test results achieved by researchers [7, 11] of three-layer laminated fabrics with knitted and woven base layers. Results of this investigation confirm that seam strength of both fabrics is lower in cross direction than in longitudinal.

Results presented in Table 3 show that seam strength efficiency of MB1 varied between 74.4 % and 103.5 %, still variation of efficiency of resistance to water penetration had wider range (19.3 % – 96.5 %). Summarizing results of all three optimization criterions evaluated, optimal values were determined for sample MB1J2.

As it can be obtained from Table 4, seam strength of fabric MB2 was achieved higher comparing to initial fabric strength, hereby efficiency of MB2 seam strength varied from 114.4 % to 158.3 %. Evaluation results of efficiency of resistance to water penetration showed significantly lower values and their range of variation was wide (2.31 % – 50.2 %).

Summarizing results of all three optimization criterions evaluated, optimal values should be expressed for sample MB2J5.

As it was stated in literature [1, 2], that bicomponent membranes are characterized by advanced strength properties comparing to hydrophilic ones, our research revealed that the same tendency was obtained also comparing strength properties of sealed seams of nonwoven fabrics with bicomponent and hydrophilic membranes.

Comparing test results presented in Tables 3 and 4 and data in literature [15], it could be stated that quality of the sealing seams depended on their sealing processes parameters, such as temperature, pressure intensity and sealing speed as well as quality of joined layers depended on their bonding processes parameters, such as temperature, pressure intensity and pressing duration.

After optimizing mathematical models there were determined optimal parameters of technological process for seams sealing with tape (Table 5).

Table 5. Optimal parameters of technological process for seams sealing with tape with "Ardmel" machine

Sample code	Temperature X_1, °C	Sealing speed X_2, m/min	Quill pressure X_3, kPa
Fabric MB1 with bicomponent membrane			
MB1J2	480	4.1	1.6
Fabric MB2 with hydrophilic membrane			
MB2J5	420	4.1	3.4

It's a matter of top relevance that the parameters of strength properties and resistance to water penetration of solid fabric as well as joining (sealed) seams were as high as possible for firefighters' clothing. Hereby it should be mentioned that in contrary to investigations of mechanical properties of sealed seams (seams strength in longitudinal and cross direction) performed in [7 – 13], additional tests of seams resistance to water penetration were performed in this work. Also the way of selection of optimal set of technological process parameters is presented.

Considering that seam resistance to water penetration is essential factor for moisture barrier layer of firefighter's clothing, the results analysis (Tables 3 and 4) revealed that better protective performance would be achieved using fabric MB1 with bicomponent membrane for firefighter's system. Test results also showed that applying optimal seam sealing process seam strength and resistance to water penetration were achieved almost the same as initial fabric parameters.

Whereas significantly worse results would be achieved integrating fabric MB2 with hydrophilic membrane for firefighter's clothing system. Despite high resistance to water penetration of fabric MB2 seam resistance to water penetration applying optimal seam sealing process was achieved only 50.2 % comparing to initial fabric parameter value.

Experimental relations and empirical equations for seam strength and resistance to water penetration determined in this research can be used to predict efficiency of seams quality applying different parameters of seam sealing process.

5. CONCLUSIONS

1. Experimental and statistical analysis showed that seam sealing parameters of textile materials should be selected according to a complex investigation of seam quality (i. e. using a particular set of factors: seam strength and resistance to water penetration).
2. Investigation revealed different behaviour of seams made of nonwoven fabrics with bicomponent and hydrophilic membranes when optimal parameters of seam sealing with tape process were applied.
3. It was determined that better protective performance would be achieved using nonwoven fabric with bicomponent membrane for firefighter's system. After application of optimal seam sealing process seam strength and resistance to water penetration were achieved almost the same as initial fabric parameters.
4. Significantly worse protective properties of firefighter's clothing would be achieved integrating nonwoven fabric with hydrophilic membrane in the system. Because of structure of the fabric resistance to water penetration of sealed seams was achieved significantly worse comparing to initial properties of the fabric when optimal seam sealing process was applied.

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