Innovative Technical Textiles

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Monographs
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INTRODUCTION

Marcin Barburski, Katarzyna Pieklak

The complexity of the functions and requirements for innovative products is a big challenge, especially when the time between the birth of the concept and development of the product is drastically shortened. Innovative solutions aimed at enhancing the attractiveness of the product significantly help to meet these requirements.

It is also necessary to harmonize processes, the cooperation of people, to assure easy and fast information flow, so that the risk of failure in launching innovative products onto the market is minimal. The monograph presents innovative solutions and textile products, using achievements and ideas related not only to textile industry.

Nowadays, more often than before, interesting and innovative ideas formed in other fields of science and technology are applied in textiles, creating the image of modern textile industry directed at humans; protecting them, improving health conditions and the quality of life, increasing their satisfaction. Here a specific function of textile products is used, i.e. their direct contact with humans to comprehensively support them and provide optimal and friendly environment.

This environment can be extended to areas not related so closely to the human being. Textiles are everywhere, because it is difficult to identify the areas of everyday life, or science and technology, in which textiles are not used. Medicine, biology, aviation, transportation, construction, composites, defence system and many other areas reflect the versatility of these products, whose innovation is increasing, allowing to accelerate general development of civilization.

Faced with an increasing demand for mechanical structures with improved properties, advanced materials offer a promising perspective. In the book the most recent scientific studies in textile including: Proetex – protection of life and health in the working environment textile, solutions for personal protection, textiles for the protection of the working environment, Techtex – innovative technical textiles, textiles for composites, footwear and leather industry and for special applications, Budtex – healthy home, textiles for the construction industry and interior decoration, Geotex – safe transportation, textiles for means of transport, geotextiles, textiles for road protection and Medtex – everyday protection, improving the quality of everyday life, medical and hygienic textiles, rehabilitation and recreational textiles.

The monograph includes 4 chapters divided into 15 subchapters.

The first chapter is focused on the field of PROETEX.

Protective clothing is a very important group of garments, as it allows the employees in many branches of the economy to work safely in an environment characterized by health- and life risk factors. The requirements for personal
protective equipment, including protective clothing, are contained in Directives. There was presented the aspect of research associated with functionality and overall comfort of use of the selected protective clothing.

Also this chapter presents the underlying reasons for amending the Council Directive 89/686/EEC, inter alia, a lack of clarity with regard to the range of products and conformity assessment procedures covered by the Directive, as well as the need for introducing clear and detailed rules which do not give room for divergent transposition by the Member States. Furthermore, the chapter discusses the basic provisions of the new regulation in the context of changes in comparison to the requirements of the existing legal document, such as a five-year validity of an EU type-examination certificate, simplifying the procedures for renewal of the certificate validity, changes or extension of categories with reference to some of PPE, e.g. products protecting against cuts by hand-held chainsaws, bullet wounds or knife stabs.

Bulletproof vests hidden wearing belongs to products intended for usage by police officers responsible for the security of the citizens. Ballistic products used by the police should comply with specific requirements in terms of protective and ergonomic as well as functional properties. The third subchapter was dedicated for evaluating the multifunction bulletproof vest hidden wearing designed for the police in terms of ergonomics, ease of use and functionality, on the basis of laboratory tests.

Recently is observed a trend of increase of safety and hygiene significance at the work stations, where there are many factors dangerous for the human health. One of such places, where the dangerous factors like the high temperature, pollution, noise, sharp edges or other items occur, is the welder work station. Therefore the next subchapter presents the innovative material solution relying on replacement of aluminized glass protective clothing, which has been applied so far in the welding company, by the aluminized basalt protective clothing, which additionally warns the user about too high temperature. In the project the modelling of material package content and integrated sensors of thermal shock were carried out. In the next stage the virtual sewing process of clothing model with the use of aluminized basalt fabric content was done.

In recent years, individual ballistic shields have become widespread so that it is hard to imagine modern army of soldiers without their use. The development of technology meant that they have become significantly lighter and stronger than at the beginning of their existence. The purpose of research in five subchapter was comparison of ballistic resistance of soft ballistic package with the KEVLAR 29 plain weave fabric and KEVLAR 29 base weave triaxial fabric.

**The second chapter is focused on the field of MEDTEX.**

Head trauma constitute a big part of injuries resulting from traffic accidents of different type. People with this kind of injuries form a significant group of patients who are treated by maxillofacial surgeons. In the last few years
there has been a constant, repetitive growth in the number of maxillofacial trauma. CODUBIX® ORBITAL WALL/ CODUBIX® ORBITAL WALL 3D prostheses, presented in subchapter one, are modern implantation materials made with the use of knitting technique out of polypropylene yarn characterised by low specific weight and low melting point which enables assuring the prosthesis’ adequate stiffness and toughness.

Textiles are now widely applied not only in garments for everyday use, but also in technical and medical products. Textiles, including knitted fabrics are used among others to produce orthoses, that is products for orthopedic rehabilitation. The second subchapter analyzes the construction of orthoses for diverse applications in terms of determining, among others, the types of stitches of the knitted fabrics and raw materials used to produce them. It also presents some selected utility properties of knitted orthoses used mainly to secure different sections of the spine: lumbar-sacral and thoracolumbar-sacral.

The third chapter is focused on the field of TECHTEX.

In the first subchapter a problem of the influence of composite lamina constituents on its strength properties is considered with the aim to get possibly simple and easy to apply formulas describing basic strength characteristics. Analysis is confined to the fiber composites with epoxy matrix i.e. the most widely used type of composite materials. The most important factor, which has to be taken into account is heterogeneity of a laminate’s ply, though fibers and matrix are – separately - homogenous materials. In some cases, depending on type of fibres (e.g. carbon fibers, Kevlar, etc.), their anisotropy should also be considered.

Woven composites are a type of material which appeared some years ago. This new technology consists of combining resin and fabric, mixing them in order to achieve better mechanical properties. Moreover, this technique has been improved over the years owing to technological advances. Therefore, more and more objects are manufactured with composite materials replacing heavier metal parts. This advancement resulted in 3D woven composites products. When replaced with these textile perform mechanical properties can improve and reduce manufacturing cost of highly advanced technical structures, for example, engine rotors, aircrafts and turbines. The aim of this research work in second subchapter was design and realize a 3D shape woven fabric. The ladder has been done in one of the weaving process using technology to produce fabric shapes. The aspiration was to make a ladder with better properties than traditional rope ladders.

An important or even fundamental utility feature of many assortment of textiles is flame-retardant. This applies to textiles intended for many applications, for example, products for interior furnishings, fabrics used in protective clothing, and numerous textile technical materials, including some filtering and thermal insulating materials. Above mentioned textiles, during normal use, are exposed to many factors, which can have destructive effects on the fibres. The aim of the third subchapter was to determine the effects of
chemical contamination on the flammability and tensile strength of flame resistant fabrics. The changes in mechanical properties and burning behaviour of contaminated fabrics caused by thermal radiation were also investigated.

Textiles in the automotive industry are very important. They are used both as decorative and aesthetic products, as well as functional materials, for example carpets damping sounds and vibrations while driving, reinforcing yarns for high-pressure hoses and belts and other. In the case of the first group of textiles they can be mainly used as materials for the upholstery of car seats. The development of textile technologies, including knitting techniques, led to the creation of structures that directly in the manufacturing process have a spatial structure. In the subchapter four were described specific properties of 3D knitted spacer fabrics in the context of their use in automobile seat covers.

The fourth chapter is focused on the field of BUDTEX AND GEOTEX. There is a steady increase in the number of architectural projects that contain the maximum area of glazing in the form of window openings, as well as the whole facades. Massive use of architectural glass by the designers is conditioned by the development of innovative manufacturing technologies and processing of this material. The tendency is also present in public objects, where using the glass is reasonable, as a material safer and lighter than concrete, considering the trend to high-rise constructions. Glass architecture promotes the production of protective systems, and creates innovative structural solutions. This raised the need to develop a systematic naming for this group of products as well as standardization of requirements and methods of measurement in accordance with the current state of the technology. In the first subchapter, an analysis of the relevant Polish and European standards was performed within the scope of architectural screens in the form of woven curtains: terminology, utility and special properties. The legal and technical regulations regarding the fabrics used in the hotel interiors for the sun shields were also reviewed.

Concrete is generally the most used material in the field of construction. Despite its extensive use in structures, it represents some drawbacks related to its properties including its low tensile strength and low ductility. To solve this problem, the use of steel reinforcement in concrete structures is possible. Another possibility is the introduction of different types of continuous fibers. The objective of study, described in second subchapter, is to examine concrete reinforcement by inserting reinforcements in the form of bidirectional (2D) or three-dimensional (3D) wovens made of polyester.

The third subchapter concerns the technology of multilayer functional knitted fabrics, whose construction refers to the phenomenon of sorption and desorption of water vapor from the air. Target application area of these fabrics are wallpapers used in interior decoration. The primary function of a wallpaper is self-regulation of humidity in the room, but its properties can be expanded to include self-regulation of temperature. The above – mentioned factors – relative humidity (and temperature) are supposed to change within a certain range,
and the wallpaper cannot replace actively operating air conditioning and heating systems.

The last subchapter is focused on textile wastes used for the production of geotextiles designed for protection of steep slopes. The geotextiles were obtained from meandrically arranged Kemafil ropes. Segments of geotextiles were installed on the steep slope in the gravel pit. The behaviour of the slope during exploitation was observed. It was stated that the geotextiles ensure immediate protection of the slope and initiate the growth of protective vegetation. The application of geotextiles efficiently protects the slope against sliding.
Chapter I

PROETEX
1. Introduction

Protective clothing is a very important group of garments, as it allows the employees in many branches of the economy to work safely in an environment characterized by health- and life risk factors.

The requirements for personal protective equipment, including protective clothing, are contained in Directive 89/686 / EEC [1]. According to this Directive, such equipment should be designed so as to preclude risks and other inconveniences under the foreseeable conditions of use. Any problems associated with mobility, performance of professional activities, changes in body position and sensory perception should be eliminated as far as possible.

It happens that products which, although they meet the requirements concerning their protective properties, are not ergonomic enough are introduced to the market [2-5]. For this reason, workers are sometimes unwilling to use them, thus exposing their lives or health to occupational hazards [6]. Therefore, the appropriate assessment of ergonomic properties of protective clothing before launching it on the market is very important.

Full ergonomic assessment of protective clothing should take into account such aspects as the impact of clothing on psychomotor skills of the users, their physiological comfort and freedom of movements [4]. Such methodology was developed in CIOP-PIB within the framework of the National Programme “Safety and working conditions improvement”. It allows to classify protective garments to the appropriate ergonomics class.

The aim of the study presented in this publication was to investigate the ergonomic properties of firefighters clothing (available on the market) according to the developed methodology. The publication presents the aspect of research associated with functionality and overall comfort of use of the selected protective clothing.
2. Materials and methods

The ergonomic assessment of protective clothing was carried out on the basis of the results of practical performance tests, which consist of a series of exercises performed by selected volunteers. The assessment was conducted from two points of view, i.e. by a test participant and by the person conducting the study, based on the questions contained in a questionnaire survey specially prepared for this purpose. The practical performance tests included the use of a reference clothing variant, with which the test results obtained for the assessed clothing were compared. The assessed clothing was compared with the reference clothing based on the same series of tests, carried out with the participation of the same volunteers.

Test results were the questionnaires completed by the test participants and the clothing assessment questionnaire filled in by the person conducting the test constituted the results of the study. Based on the results of questionnaires completed by the study participants, the ergonomics class of protective clothing was determined.

2.1. Test objects

The object of the study was protective clothing used by firefighters, made of the following material system: aramide outer fabric, PU membrane, thermal insulation layer: aramide-viscose fabric (50% Aramide, 50% Viscose FR) quilted with aramide nonwoven. The assessed set of firefighters’ protective clothing consisted of a jacket with a stand-up collar, fastened with a front zipper, covered with a flap fastened with metal snaps and Velcro tape, and trousers with a waist bib. Reflective tape strips were sewn on the jacket and trousers.

The protective clothing was compared with the reference clothing, developed in CIOP-PIB in accordance with the basic requirements of ergonomics using selected lightweight woven polyester – cotton fabric (65% PES / 35% cotton) with satisfactory biophysical and sensorial properties. The reference clothing set consisted of a jacket with a collar, fastened with buttons in the front, with ventilation holes under the arms and air vents at the back at the level of the shoulder blades to ensure thermal comfort, and trousers finished with the top bar.

The size of the firefighters’ clothing and the reference clothing was fitted to the body dimensions of each volunteer. During the test, the same underwear – cotton T-shirts, was worn under the assessed protective clothing and the reference clothing. In addition, clothing was supplemented with protective gloves and footwear, typically used with a set of clothing for firefighters. When performing additional activities, typical of the profession of a firefighter, a set of garments was supplemented with an oxygen bottle. Fig. 1 shows the appearance of the tested firefighters’ clothing (ZK) and reference clothing (R).
2.2. Study participants

The ergonomic tests of protective clothing were carried out with the participation of 5 volunteers (firefighters). Table 1 shows their average age, body height and weight.

Table 1. Characterization of the participants of the ergonomic tests of protective clothing

<table>
<thead>
<tr>
<th>Mean value and standard deviation</th>
<th>Age [years]</th>
<th>Body height [cm]</th>
<th>Body weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>34.40±8.04</td>
<td>178.80±4.66</td>
<td>83.20±8.98</td>
</tr>
</tbody>
</table>

Before the commencement of the tests, each of the participants remained in a sitting position for 5 min after putting on the test garments to be assessed.

2.3. Research tools

The basic research tools used in ergonomic studies of protective clothing included:

A) Survey questionnaire for the study participant – consisting of a set of 10 closed questions, the first 9 of which are questions scored according to the validity rank. The answers to these questions are taken into account in qualification of the assessed protective clothing into the appropriate ergonomics
class. Question 1 concerns the functionality of protective clothing during specific movements, whereas the remaining 8 questions allow to assess the overall comfort of use. Question 10 allows to establish which clothing variant, i.e. protective clothing vs. reference clothing is more ergonomic.

**B) Survey questionnaire for the investigator** – consisting of a set of 8 open questions with the content similar to that in the questionnaire designed for the participants of the study. The task of the investigator conducting the study is to assess the functionality and comfort of use of protective clothing on the basis of observation of the study participants testing a specific protective clothing type.

The scope of questions in the questionnaire completed by the study participants and the investigator conducting the study is presented in Table 2.

Table 2. The scope of survey questions to the study participants and the investigator

<table>
<thead>
<tr>
<th>Question No.</th>
<th>Scope of the questions</th>
<th>Questionnaire</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Limitations of mobility:</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Basic exercise set</td>
<td>x</td>
</tr>
<tr>
<td>a)</td>
<td>going up and down the stairs (10 steps) – (3 repetitions),</td>
<td></td>
</tr>
<tr>
<td>b)</td>
<td>raising both arms – (3 repetitions),</td>
<td></td>
</tr>
<tr>
<td>c)</td>
<td>sitting position, grasping with both hands any object (e.g. a ruler) lying opposite to the study participant at 70 cm distance – (3 repetitions),</td>
<td></td>
</tr>
<tr>
<td>d)</td>
<td>reaching up with one hand in standing position for a small object (e.g. a pencil) lying at the height of 2 m – (3 repetitions),</td>
<td></td>
</tr>
<tr>
<td>e)</td>
<td>reaching up with both hands in standing position for a small object (e.g. a pencil) lying at the height of 2 m – (3 repetitions),</td>
<td></td>
</tr>
<tr>
<td>f)</td>
<td>flexion of the arm in the elbow joint and extension in standing position – (3 repetitions),</td>
<td></td>
</tr>
<tr>
<td>g)</td>
<td>bending and lifting from the floor a small object (e.g. a pencil) in a standing position – (3 repetitions),</td>
<td></td>
</tr>
<tr>
<td>h)</td>
<td>in a standing position, rotation of the trunk to the right with the right arm extended backward, and then turning the trunk to the left with the left arm extended backward – (3 repetitions),</td>
<td></td>
</tr>
<tr>
<td>i)</td>
<td>5 squats,</td>
<td></td>
</tr>
<tr>
<td>j)</td>
<td>kneeling on the right knee, kneeling on the left knee, kneeling on both knees and then rising from a kneeling position – (3 repetitions),</td>
<td></td>
</tr>
<tr>
<td>k)</td>
<td>assuming position with the legs apart, the body leaning forward, the arms bent at the elbows – (3 repetitions),</td>
<td></td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>1)</th>
<th>walking on the treadmill in upright position – with 6 km/h velocity for 5 min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional exercise set</td>
<td></td>
</tr>
<tr>
<td>a)</td>
<td>walking on a horizontal treadmill in upright position at a constant speed of 6 km/h for 5 min, 1 min running at a speed of 8.0 km/h, crawling on a horizontal surface under an obstacle of (0,7±0,05 m) height for 5 min (over approximate total distance of 70 m),</td>
</tr>
<tr>
<td>b)</td>
<td>climbing up and going down a ladder and a single pass in both directions through a square hole of 460 mm dimensions – (3 repetitions),</td>
</tr>
<tr>
<td>c)</td>
<td>unwinding and rewinding a fire hose – (3 repetitions).</td>
</tr>
<tr>
<td>2</td>
<td>Problems with putting the clothing on and taking it off</td>
</tr>
<tr>
<td>3</td>
<td>Functionality of fastening devices</td>
</tr>
<tr>
<td>4</td>
<td>Fit of the clothing to the body</td>
</tr>
<tr>
<td>5</td>
<td>Compression/blood flow impairment during the tests of clothing</td>
</tr>
<tr>
<td>6</td>
<td>Appropriate location of garment construction elements (e.g. armpits, crotch)</td>
</tr>
<tr>
<td>7</td>
<td>Sharp edges, protruding elements, rough surfaces, fastening devices, seams, etc. limiting the user’s mobility</td>
</tr>
<tr>
<td>8</td>
<td>Appropriate coverage of the body surfaces to be protected: a) at rest, b) during the execution of movement</td>
</tr>
<tr>
<td>9</td>
<td>Compatibility of protective clothing with other PPEs</td>
</tr>
<tr>
<td>10</td>
<td>Comparison of protective vs. reference clothing in terms of ergonomics</td>
</tr>
</tbody>
</table>

Source: own work.

2.4. Clothing acclimation and testing conditions

Before the tests, the protective clothing, the reference clothing and the underwear was acclimated for 24 hours in a laboratory room at constant ambient air temperature (20.0±3.0)°C, relative humidity (50.0±5.0)%.

The ergonomic tests were conducted under the same climatic conditions. In order to obtain reliable results, the tests of protective clothing and reference clothing with the participation of the same volunteer were carried out at the time interval no longer than one hour.
2.5. Test procedure

Prior to the exercise, each participant put on the appropriate set of clothes and other personal protective equipment; the reference clothing variant was tested in the first place, before the assessed protective clothing.

While the participant was putting the clothing on, the person conducting the study recorded in the questionnaire own observations concerning, among others, the ease of dressing, functionality of fasteners, fit, clothing compatibility with PPEs, etc.

Ergonomic class of protective clothing

After completion of the study and summation of the scores in the individual questionnaires of the study participants (for reference clothing and protective clothing separately), the difference between the number of points awarded to the reference clothing and protective clothing was calculated. The obtained results (the differences) were averaged and provided the basis for qualification of protective clothing to a particular class according to the following criteria:

**Ergonomics class I** – difference of up to 6 pts. (only the answers scoring 0-2 pts. should be taken into account, with max. 3 answers scoring 2 pts. to questions other than Question 1 acceptable) **Ergonomics class II** – difference of 7-15 pts. (only the answers scoring 0-2 pts. should be taken into account, with max. 6 answers scoring 2 pts. to questions other than Question 1 acceptable).

**Ergonomics class III** – difference of 16-24 pts. (only the answers scoring 0-2 pts. should be taken into account, with max. 3 answers scoring 2 pts. to questions other than Question 1 acceptable).

**Ergonomics class IV** – difference of 16-24 pts. only the answers scoring 0-2 pts. should be taken into account, with max. 6 answers scoring 2 pts. to questions other than Question 1 acceptable).

**Unacceptable product** – difference exceeding 34 pts.

According to the developed procedure lower ergonomics class indicates more ergonomic, and consequently more comfortable clothing.

3. Test results

The test results are presented in figs. 2, 3 and 4.
Results of protective clothing functionality tests – basic exercise set

During the activities marked with symbols (b), (c), (e) and (g) in protective clothing (ZK) even 80% of the respondents reported limitations of mobility in the shoulders and underarms (Fig. 2a). The investigator also saw this problem in study participants (Fig. 2b). On the other hand, in the case of reference clothing mobility limitations were observed only in the case of one participant.

As many as 80% of study participants testing protective clothing (ZK) felt discomfort when bending and lifting a small object from the floor (g) and during the activities marked with symbol (k). In addition to the above limitations, the respondents complained about restrictions at the site of the arm flexion, resulting from the excess material and tension of the trousers material at the level of the thigh. The investigator conducting the study also pointed to the existence of such problems. On the other hand, while performing squats (i) in the protective clothing (ZK), it was noticed that 3 of out of 5 participants (60%) had a problem with excessive build-up of material under the knees. The observations of the investigator were confirmed by the participants.

Some of the respondents (40%) testing protective clothing (ZK) commented on too wide and too short legs of the trousers, which rubbed against each other, thereby limiting the freedom of movement while climbing stairs (a) and walking on the treadmill (l). As rightly observed by the investigator, the problem escalated during the activities typically associated with the assessed type of protective clothing.
Results of protective clothing functionality tests – additional exercise set

The selected clothing was also subjected to additional evaluation using a set of exercises reflecting the characteristic actions performed in the actual conditions of firefighters’ work.

The results (Fig. 3 a and 3 b) show that most of the difficulties were associated with crawling on the horizontal surface (b) and climbing up and going down the ladder (c). Movement (b) in protective clothing (ZK) was observed to be restricted by accumulation of fabric under the arms, and the sleeves pulling on the forearms in 60% of the participants, which was confirmed by them. In the case of the reference clothing, two participants (40%) reported minor limitation in the shoulders.

The investigator observing the performance of protective clothing (ZK) during the activities marked as (c) noticed that in 3 of the participants (60%) there was a problem with the shoes catching on the reflective tape sewn on the trousers legs. This was also remarked by the research participants.

While walking on the treadmill (a) in protective clothing (ZK) with a load in the form of oxygen bottle, the same problems as when performing basic exercises (activities a, l), which intensified during the run, were found in 60% of the participants. In the case of the reference clothing, limitations of movement were reported by only one participant.

During unwinding and rewinding the fire hose (in protective clothing ZK) minor restrictions on the shoulders were reported by two of the respondents; the problem had been noticed by the investigator only in one of them. During tests
performed in the reference clothing, a similar problem was reported by only one participant.

**Assessment of the comfort of use of protective clothing**

![Graphs showing comfort assessment](image)

Fig. 4. Assessment of the comfort of use of protective clothing as compared with reference clothing: a) according to the study participants, b) according to the investigator

*Source: own work.*

According to the observations made by the investigator, 40% of the study participants had difficulty putting on the protective clothing (ZK) (question 2), but only 20% of them confirmed that observation. The difficulties resulted from inconvenient adjustment of the braces length.

In the case of protective clothing (ZK), 2 participants (40%) had also problems with zipping and unzipping the jacket (question 3). In the case of reference clothing, all fastening elements functioned properly. According to the investigator, the problem of inappropriate fit of the protective clothing (question 4) concerned 3 out of 5 study participants, but only one of them confirmed it. The observations revealed that in the case of one participant the sleeves and legs of the garments were too short, and in the case of 2 others – the clothing was too loose. In the case of reference clothing, the aforementioned elements were positioned correctly.
The conducted surveys did not demonstrate the presence of any sharp edges, protruding elements, rough surfaces, fasteners or other junctions which could result in the user’s experience of discomfort (question 7), either in the protective clothing (ZK) or in the reference clothing (R)

The observations of both the investigator conducting the tests and the test participants indicate that the problem of uncovered wrists and/or ankles applies to 40% of the participants testing the protective clothing ZK (at rest). The problem is exacerbated during exercise. In the case of reference clothing, uncovered wrists were noticed in 40% of the participants, but only while they were moving.

As far as the compatibility of protective clothing with other PPE, used with the firefighters’ clothes set (question 9), is concerned, the irregularities were found only in the case of one participant. The problem of incompatibility with PPE does not occur in the reference clothing.

**Ergonomic class of ZK protective clothing**

According to the procedure of ergonomic assessment of protective clothing, developed in CIOP-PIB, the tested protective clothing was classified to the appropriate ergonomics class. After analyzing the responses of the study participants, the average score for reference clothing was found to be 4 pts., whereas the assessed protective clothing (ZK) scored 15 pts. Therefore, the difference between the variants is equal to 11 pts., which qualifies the assessed protective clothing to ergonomics class II.

**4. Conclusions**

The methodology of ergonomic studies developed in CIOP-PIB, owing to the use of the reference clothing variant, allowed for quantitative assessment of the tested protective clothing by qualifying it to the appropriate ergonomics class. The assessed firefighter’s clothing was classified as ergonomics class II, which indicates that under the actual conditions of use certain problems may arise, resulting, e.g. from jamming of the jacket zipper, or inconvenient adjustment of the length of the trousers braces. The practical performance tests conducted with the participation of volunteers and the investigator (acting as an observer) made it possible to localize the defects in garment construction, as well as to assess the selection of design and size of protective clothing to fit the users’ anatomy. The obtained results provide valuable information for the manufacturers of protective clothing and can serve as the guidelines for improvement of the ergonomic properties of the assessed garments.
Acknowledgements

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Bibliography

1. Introduction

Personal protective equipment (PPE) is any device or appliance designed to be worn or held by an individual for protection against one or more health and safety hazards [1]. Before PPE is placed on the EU market, it is subject to an appropriate conformity assessment procedure to confirm the compliance with the provisions of Directive 89/686/EEC relating to the harmonisation of the Member States legislation in the scope of personal protective equipment.

Council Directive 89/686/EEC was adopted in the context of creating an internal market intended to harmonise the occupational safety and health requirements in the scope of personal protective equipment in all Member States and to remove trade barriers in personal protective equipment between Member States [1].

The PPE Directive has been in force since 1st December 1989 but the experience with its application revealed shortcomings and non-compliance as regards the scope of products covered by the requirements of the Directive and conformity assessment procedures.

Hence, work on amending this basic legal act on personal protective equipment was pursued for many years. It was completed with the adoption of the Regulation (EU) 2016/425 of the European Parliament and of the Council of 9 March 2016 on personal protective equipment and repealing Council Directive 89/686/EEC. The Regulation No. 2016/425 came into force on 20 April 2016 and it shall be applied from 21 April 2018 with some exceptions.

The Regulation lays down requirements for the design and manufacture of personal protective equipment which is to be made available on the market, in order to ensure protection of the health and safety of users and establish rules on the free movement of PPE in the Union.
It covers PPE which is new to the Union market when it is placed on the market (new PPE made by a manufacturer established in the Union or PPE, whether new or second-hand, imported from a third country). The Regulation also applies to all forms of supply, including distance selling.

According to the Regulation personal protective equipment (PPE) means [2]:
- equipment designed and manufactured to be worn or held by a person for protection against one or more risks to that person's health or safety,
- interchangeable components for the above-mentioned equipment which are essential for its protective function,
- connexion systems for the above-mentioned equipment that are not held or worn by a person, that are designed to connect that equipment to an external device or to a reliable anchorage point, that are not designed to be permanently fixed and that do not require fastening works before use.

The current Directive 89/686/EEC provides a more elaborated definition of PPE, notwithstanding the fact that the basic scope of this definition is similar in both documents. According to Directive [1], PPE means, apart from the basic definition referred to at the beginning of this chapter, a unit constituted by several devices or several types of protective appliance which have been integrally combined by the manufacturer for the protection against risks as well as a protective device or appliance combined, separably or inseparably, with personal non-protective equipment worn or held by a user for the execution of a specific activity, and interchangeable PPE components or system which are essential to its satisfactory functioning and used exclusively for such equipment.

According to Directive 89/686/EEC, PPE also covers any system placed on the market in conjunction with PPE for its connection to another external, additional device shall be regarded as an integral part of that equipment even if the system is not intended to be worn or held permanently by the user for the entire period of risk exposure [1].

The following PPE has been excluded from the scope of Regulation 2016/425:
- specifically designed for use by the armed forces or in the maintenance of law and order;
- designed to be used for self-defence, with the exception of PPE intended for sporting activities;
- designed for private use to protect against:
  - atmospheric conditions that are not of an extreme nature,
  - damp and water during dishwashing;
- for exclusive use on seagoing vessels or aircraft that are subject to the relevant international treaties applicable in Member States;
- for head, face or eye protection of users, that is covered by Regulation No. 22 of the United Nations Economic Commission for Europe on uniform provisions concerning the approval of protective helmets and their visors for drivers and passengers of motorcycles and mopeds [2].
When comparing exclusions from the scope of application of Directive 89/686/EEC, it is clear that the Regulation in explicit terms indicates that PPE intended for sporting activities is subject to its provisions. PPE intended for private use to protect against heat, falls outside of the scope of this Regulation.

2. Main changes introduced by the new Regulation

2.1. Definitions of economic operators and their obligations under the new Regulation

One of the most important changes in the Regulation, as compared to the Directive, is provision of the definition for the concept of economic operators responsible for placing of PPE on the Union market. So far the basic legal act stipulating requirements for personal protective equipment (Directive 89/686/EEC) imposes obligations mainly on manufacturers of PPE and/or their authorised representatives, it fails however to define these basic concepts [3]. The Regulation indicates, inter alia, obligations of manufacturers, authorised representatives, importers, distributors and cases in which manufacturers’ obligations apply to importers and distributors [2].

Under the Regulation:
- ‘manufacturer’ means any natural or legal person who manufactures PPE or has it designed or manufactured, and markets it under his name or trademark;
- ‘authorised representative’ means any natural or legal person established within the Union who has received a written mandate from a manufacturer to act on his behalf in relation to specified tasks;
- ‘importer’ means any natural or legal person established within the Union who places PPE from a third country on the Union market;
- ‘distributor’ means any natural or legal person in the supply chain, other than the manufacturer or the importer, who makes PPE available on the market;
- ‘economic operators’ means the manufacturer, the authorised representative, the importer and the distributor.

With the definitions of economic operators in place, the obligations imposed on each of them should be also noted. In general terms, the manufacturers are obliged to:
- ensure that PPE is designed and manufactured in such a way as to satisfy the essential health and safety requirements set out in the Regulation;
- draw up the technical documentation and have a conformity assessment procedure carried out. Where compliance of PPE with the applicable essential health and safety requirements has been demonstrated by the appropriate procedure, manufacturers draw up the EU declaration of conformity and affix the CE marking;
- keep the technical documentation and the EU declaration of conformity for 10 years after the PPE has been placed on the market;
- ensure that PPE which they place on the market bears a type, batch or serial number or other element allowing its identification, or, where the size or nature of the PPE does not allow it, that the required information is provided on the packaging or in a document accompanying the PPE;
- indicate, on the PPE, their name, registered trade name or registered trade mark and the postal address at which they can be contacted or, where that is not possible, on its packaging or in a document accompanying the PPE. The address must indicate a single point at which the manufacturer can be contacted;
- ensure that the PPE is accompanied by the instructions and information set out in the Regulation in a language which can be easily understood by consumers and other end-users, as determined by the Member State concerned. Such instructions and information, as well as any labelling, must be clear, understandable, intelligible and legible;
- further to a reasoned request from a competent national authority, provide it with all the information and documentation, in paper or electronic form, necessary to demonstrate the conformity of the PPE with this Regulation, in a language which can be easily understood by that authority. The manufacturers are required to cooperate with that authority, at its request, on any action taken to eliminate the risks posed by PPE which they have placed on the market.

The authorised representative is obliged to perform the tasks specified in the mandate received from the manufacturer. The mandate allows the authorised representative to perform at least the following [2]:
- keep the EU declaration of conformity and the technical documentation at the disposal of the national market surveillance authorities for 10 years after the PPE has been placed on the market;
- further to a reasoned request from a competent national authority, provide that authority with all the information and documentation necessary to demonstrate the conformity of the PPE;
- cooperate with the competent national authorities, at their request, on any action taken to eliminate the risks posed by PPE covered by the authorised representative's mandate.

Importers are obliged, inter alia, to do the following:
- place only compliant PPE on the market;
- ensure that the manufacturer has subjected the PPE which is placed on the market to the appropriate conformity assessment procedure referred to in the Regulation, that the manufacturer has drawn up the technical documentation, and that the PPE bears the CE marking and is accompanied by the required documents set out in the Regulation;
- indicate, on the PPE, their name, registered trade name or registered trade mark and the postal address at which they can be contacted or, where that is
not possible, on its packaging or in a document accompanying the PPE. The contact details should be in a language easily understood by end-users and market surveillance authorities;

- ensure that the PPE is accompanied by the instructions and information set out in the Regulation in a language which can be easily understood by consumers and other end-users, as determined by the Member State concerned;

- ensure that, while the PPE is under their responsibility, storage or transport conditions do not jeopardise its conformity with the applicable essential health and safety requirements set out in the Regulation.

Importers who consider or have reason to believe that PPE is not in conformity with the applicable essential health and safety requirements set out in the Regulation do not place such PPE on the market until it has been brought into conformity. Furthermore, where the PPE presents a risk, importer immediately informs the manufacturer and the market surveillance authorities [2].

Before making PPE available on the market, distributors are obliged to verify that it bears the CE marking, is accompanied by the required documents, instructions and information set out in the Regulation in a language which can be easily understood by consumers and other end-users in the Member State in which PPE is to be made available on the market, and that the manufacturer and the importer have complied with the requirements set out in the Regulation.

As is the case with importers, if a distributor considers or has reason to believe that PPE is not in conformity with the applicable essential health and safety requirements, he does not make the PPE available on the market until it has been brought into conformity. Furthermore, where the PPE presents a risk, the distributor informs the manufacturer or the importer to that effect as well as the market surveillance authorities.

Distributors ensure that, while PPE is under their responsibility, its storage or transport conditions do not jeopardise its conformity with the applicable essential health and safety requirements set out in the Regulation.

The regulations stipulates cases in which obligations of manufacturers apply to importers and distributors.

An importer or distributor is considered a manufacturer for the purposes of the Regulation and he is subject to the obligations of the manufacturer set out in the Regulation where he places PPE on the market under his name or trademark or modifies PPE already placed on the market in such a way that compliance with this Regulation may be affected.

2.2. Other definitions under the Regulation No. 2016/425

It should be noted that Regulation No. 2016/425 contains other definitions, which so far have not been covered by the Directive. The definitions that apply under the new Regulation are the following:
‘Making available on the market’ – any supply of PPE for distribution or use on the Union market in the course of a commercial activity, whether in return for payment or free of charge;
‘Placing on the market’ – the first making available of PPE on the Union market;
‘Recall’ – any measure aimed at achieving the return of PPE that has already been made available to the end-user;
‘Withdrawal’ – any measure aimed at preventing PPE in the supply chain from being made available on the market [2].

2.3. Other changes introduced by the Regulation No. 2016/425

Another change arising from the Regulation is the specification of the period of validity and a minimum content of the EC-type examination certificate WE [2].

Under the new Regulation, EC-type examination certificates will be issued for a period of five years, whereas a minimum content of the certificates will include the following:

– name and identification number of the notified body the name and address of the manufacturer and, if the application is lodged by the authorised representative, his name and address as well;
– identification of the PPE covered by the certificate (type number);
– a statement that the PPE type complies with the applicable essential health and safety requirements;
– where harmonised standards have been fully or partially applied, the references of those standards or their parts;
– where other technical specifications have been applied, their references;
– where applicable, the performance level(s) or protection class of the PPE;
– for PPE produced as a single unit to fit an individual user, the range of permissible variations of relevant parameters based on the approved basic model;
– the date of issue, the date of expiry and, where appropriate, the date(s) of renewal;
– any conditions attached to the issue of the certificate;
– for category III PPE, a statement that the certificate will only be used in conjunction with one of the conformity assessment procedures (Module C2 or Module D).

Directive 89/686/EEC did not specify the period of validity of the EC-type examination certificates, neither did it determine the required minimum content of the certificate. The period of validity of EC-type examination certificate set at five years, adopted by many European notified bodies and content which should be in the certificate arise from the so-called Recommendations for use, i.e. CNB/P/00.136 and CNB/P/00.138 [3]. The said documents however are not legally binding.
A comparison of the Regulation and the Directive also shows changes with regard to the EU declaration of conformity. Under the new Regulation the document concerned:
- states that the fulfilment of the applicable essential health and safety requirements has been demonstrated;
- has the model structure set out in Annex;
- is continuously updated;
- is translated into the language or languages required by the Member State in which the PPE is placed or made available on the market.

Another provision set out in the Regulation refers to the renewal of the EC-type examination certificate. Under the Regulation a simplified procedure should be applied in the case of renewal of the EU-type examination certificate where the manufacturer has not modified the approved type and the harmonised standards or other technical specifications applied by the manufacturer have not been changed and continue to meet the essential health and safety requirements in the light of the state of the art. In such cases, additional tests or examinations should not be necessary and the administrative burden and related costs should be kept to a minimum.

The Regulation also provides for derogations, i.e. for PPE produced as a single unit to fit an individual user and classified according to Category III, the Regulation stipulates that the conformity assessment procedure for PPE classified according to Category II be used.

Another two changes introduced by the new Regulation are also noteworthy. They refer to establishing of PPE categories and new conformity assessment procedures. The two new regulations will be discussed in the next part of the chapter.

2.4. Risk categories of PPE

Under the existing Directive 89/686/EWG, categorisation of PPE is only limited to two groups of PPE, i.e. PPE models of simple and complex design, respectively. The common practice however is to classify PPE as: Category I, II, III, where Category I means simple design PPE, Category III – complex design PPE and Category II – PPE which is neither simple nor complex.

The new Regulation changes this approach and, instead of defining PPE on the basis of its construction, it introduces definitions of risk categories of PPE [2]. Under the Regulation, PPE is classified according to risk categories against which users should be protected, as described below.

**Category I** includes exclusively the following minimal risks:
- superficial mechanical injury;
- contact with cleaning materials of weak action or prolonged contact with water;
- contact with hot surfaces not exceeding 50°C;
d) damage to the eyes due to exposure to sunlight (other than during observation of the sun);
e) atmospheric conditions that are not of an extreme nature.

**Category III** includes exclusively the risks that may cause very serious consequences such as death or irreversible damage to health relating to the following:

a) substances and mixtures which are hazardous to health;
   b) atmospheres with oxygen deficiency;
   c) harmful biological agents;
   d) ionising radiation;
   e) high-temperature environments the effects of which are comparable to those of an air temperature of at least 100°C;
   f) low-temperature environments the effects of which are comparable to those of an air temperature of –50°C or less;
   g) falling from a height;
   h) electric shock and live working;
   i) drowning;
   j) cuts by hand-held chainsaws;
   k) high-pressure jets;
   l) bullet wounds or knife stabs;
   m) harmful noise.

**Category II** includes risks other than those listed in Categories I and III. This means that when comparing interpretation of the existing Directive 89/686/EEC and the provisions of Regulation 2016/425, some of PPE change a category or new risks are added to a given category. For example, PPE protecting against drowning, cuts by hand-held chainsaws, high-pressure jets, bullet wounds or knife stabs, harmful noise or harmful biological agents.

### 2.5. Conformity assessment procedure

The changes of PPE also concern the concepts related to the conformity assessment procedure. The new Regulation introduces modules which are compliant with the Decision No. 768/2008/EC of the European Parliament and of the Council of 9 July 2008 [4].

The conformity assessment procedures to be followed for each of risk categories are as follows:

- for Category I: internal production control (module A);
- for Category II: EU type-examination (module B), followed by conformity to type based on internal production control (module C);
- for Category III: EU type-examination (module B) and either of the following:
  - conformity to type based on internal production control plus supervised product checks at random intervals (module C2),
  - conformity to type based on quality assurance of the production process (module D).
In case of risk category I the manufacturer carries out the Internal production control (module A). In this module, the manufacturer ensures and declares on his sole responsibility that the PPE concerned satisfies the applicable requirements of this Regulation. Furthermore, the manufacturer establishes the technical documentation, draws up EU declaration of conformity and affixes the CE marking to each individual PPE.

For Category II PPE, the manufacturer contacts a chosen notified body, which examines the technical design of PPE, verifies and attests that the technical design of the PPE meets the requirements of this Regulation that apply to it. Such examination is carried out on the basis of the assessment of the technical documentation, examination of a specimen, and ascertainment of compliance with the provisions of the applicable harmonised standards, in case they were applied by the manufacturer or conformity with other technical specifications.

The manufacturer is obliged to lodge an application for the EC-type examination with a single notified body of his choice. The application should include the specimen(s) of the PPE representative of the production envisaged.

Where the type meets the applicable essential health and safety requirements, the notified body issues an EU type-examination certificate to the manufacturer. As was already mentioned earlier, the manufacturer is obliged to keep a copy of the EU type-examination certificate, its annexes and additions, together with the technical documentation at the disposal of the national authorities, for 10 years after the PPE has been placed on the market.

Activities under Module C are the part of a conformity assessment procedure whereby the manufacturer fulfils the obligations set out in the Regulation as regards manufacturing of PPE affixing of the CE marking, and drawing up of a written EU declaration of conformity. Furthermore, the manufacturer ensures conformity of the manufactured PPE with the type described in the EU type-examination certificate and with the applicable requirements of the Regulation.

For risk category III, the manufacturer is required to submit a specimen of a PPE item for the EU-type examination, described above, and to select either of the modules attesting the conformity to type: based on internal production control plus supervised product checks at random intervals (module C2) or based on quality assurance of the production process (module D). As a part of the procedure described in Module C2, the manufacturer is obliged to take all measures necessary so that the manufacturing process ensures the homogeneity of production and conformity of the manufactured PPE with the type described in the EU type-examination certificate and with the applicable requirements of the Regulation. A notified body chosen by the manufacturer carries out product checks in order to verify the actions undertaken by the manufacturer.

As part of Module D, in turn, the manufacturer operates an approved quality system for production, final product inspection and testing of the PPE.
concerned, and is subject to surveillance of the notified body which carries out periodic audits.


3. Summary

According to the provisions of Regulation No. 2016/425, Directive 89/686/EWG is repealed with effect from 21 April 2018 r. EC-type examination certificates and approval decisions issued under Directive 89/686/EEC will remain valid until 21 April 2023 unless they expire before that date. The Regulation will apply from 21 April 2018 with some exceptions, inter alia, concerning notification of conformity assessment bodies, which will take effect from 21 October 2016.

Acknowledgements

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Programme coordinator – Central Institute for Labour Protection – National Research Institute

Bibliography

1. Introduction

Concealable bullet-proof vest belongs to products intended for usage by police officers responsible for the security of the citizens. Ballistic products used by the police should comply with specific requirements in terms of protective and ergonomic as well as functional properties. One of the major problems affecting the ergonomics and functionality of personal protections is that they should adjust to the individual size of the user. A good solution is to design a product for each officer individually [1].

To ensure the safety of police staff, it is important for a bulletproof vest, apart from the basic scope of protection associated with bulletproof equipment, to provide additional protection against a knife or other sharp tool, cuts or a blow with a blunt object that may occur in a traffic accident. However, such an increase of the protection scope will affect the type of materials used in the vest construction, as well as increase the weight and the number of ballistic layers [1, 2]. Bulletproof vests must meet the ergonomic requirements which can be evaluated on the basis of appropriate studies. Therefore, to evaluate a product of this type, it was necessary to conduct laboratory practical performance tests with the participation of future users [3-5]. Appropriate methodology for this purpose has been developed at the Central Institute for Labour Protection – National Research Institute [6, 7].

The primary objective of the study was to evaluate on the basis of laboratory tests the multifunction concealable bullet-proof vest designed for the police in terms of ergonomics, ease of use and functionality.
2. Materials and methods

Test objects
The study was carried out on a prototype of concealable bullet-proof vest developer by ITB Moratex and Maskpol S.A. within the framework of the project entitled Individualization of multifunctional concealable ballistic vests design (contract No. DOBR-BIO4/045/13067/2013).

The bullet-proof vest prototype was studied in 3 versions:
- Version 1 – a vest designed and made for each participant of the study individually, using the „body scanner” type technique (Figs. 1, 2 a,b) with front and rear ballistic inserts as well as front and rear stab-proof inserts (Fig. 3); the total weight of the vest prototype amounted to ca. 4.5 kg.
- Version 2 – a concealable bullet-proof vest with dimensions averaged from 4 sizes; construction such as described for Version 1.
- Version 3 – a vest personalized like in Version 1 – without stab-proof inserts; the total weight of the vest prototype amounted to ca. 2.5 kg.

Fig. 1. A front view of the vest – right side
Source: own work.

Fig. 2. A front view of the vest – wrong side, a – back, b – front
Source: own work.
Study participants

The subjects for the study were selected from among the employees of the Police Academy in Szczytno (Polish acronym WSPol) after cardio-pulmonary exercise tests (CPET) and 3D scanning process (for personalization of ballistic vests construction). Laboratory practical performance tests were conducted with the participation of a group of 12 police officers from WSPol. Each police officer was wearing the following clothing items, fitted individually to the body dimensions: Helikon UTP Cotton Beige (SP-UTL-CO-13) trousers, a Fazzini SLIM FIT D167 long-sleeved shirt fastened with buttons, a 5.11 Double Duty TDU Belt 1.5" Coyote Brown (59568-120) KR, Fjord Nansen Trek Kevlar Black/Olive F socks, cotton boxer shorts and a T-shirt. The belt of each study participant was equipped with a holster, a handgun (a model school), an ammunition bag and a handcuffs pouch.

Practical performance test procedure

The practical performance tests to which the prototypes of concealable bullet-proof vests were subjected involved performance by a participant of a sequence of activities simulating the use of these products under the expected actual conditions of their use. The sequence of test activities is presented in Table 1.

Table 1. The exercise set for laboratory practical performance tests

<table>
<thead>
<tr>
<th>#</th>
<th>Type of exercise</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Walking on a treadmill with 6 km/h velocity – 5 min</td>
<td></td>
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<tr>
<td>2</td>
<td>Running on a treadmill with 8 km/h velocity – 3 min</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Walking alternately in inclined (under obstacles of 1.3 m height) and in upright position with lifting from the ground and putting back 4 light objects while walking upright (halting with straight legs, bending forward) – 3 min</td>
<td>Activities with energy expenditure measurements</td>
</tr>
<tr>
<td>#</td>
<td>Type of exercise</td>
<td>Comments</td>
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<tr>
<td>4</td>
<td>Climbing and going down the ladder – 5 repetitions (total height 15 m)</td>
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<tr>
<td>5</td>
<td>Filling a basket with rubber scraps using the right and left hand alternately (simulation of forced, stationary working position) – 3 min</td>
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<tr>
<td>6</td>
<td>Sitting down to cross-legged position on the floor from erect standing position and standing up from the floor back to erect position – 5 repetitions</td>
<td></td>
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<tr>
<td>7</td>
<td>Crawling in a tunnel of 70 cm height – 3 x 10 m</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Simulation of prone shooting stance with a handgun: rolling to the sides from prone shooting stance with hands extender horizontally Beyond the head holding a handgun (with both hands) – 5 repetitions 360° to either side, after the 3rd cycle – reloading the gun in prone position, 3 cycles.</td>
<td></td>
</tr>
</tbody>
</table>
| 9 | Simulation of an element of detention/arrest procedure – incapacitation of the subject and low-kneeling shooting stance with a handgun:  
   - standing position facing the ATLAS weight training machine (ca. 20 kg load)  
   - gripping the handle on the right side with the right hand and 90° rotation towards oneself in the horizontal plane (from the side in medial direction), holding in that position, then, gripping the handle on the right side with the left hand and 90° rotation towards oneself in the horizontal plane (from the side in medial direction), holding in that position, then, still holding the handles, slow deflection to the original position |          |
<p>| 10| Assuming a low-kneeling shooting stance with a handgun while hiding behind a curtain in the following arrangement: kneeling low behind the right curtain edge with the gun in the dominant hand, hiding back behind the curtain, kneeling low behind the right curtain edge with the gun in the dominant hand; exit from behind the curtain and putting the gun back into its holster |          |</p>
<table>
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<tr>
<th>#</th>
<th>Type of exercise</th>
<th>Comments</th>
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</table>
| 11 | Simulation of an element of detention/arrest procedure – „handcuffing” of the subject and standing shooting stance with a handgun:  
- standing position facing the ATLAS weight training machine (ca. 20 kg load),  
- Gripping the central handle with the right hand and pulling it from the height of ca. 0.8 m to the ground, kneeling down at the same time, changing the hand holding the handle, while the right hand takes the handcuffs out of the pouch directs them towards the handle and clamps on the handle,  
- return to the standing posture and release of the handle to return to the initial height (inversely in the case of the dominance of the left side of the body) | 5 cycles 2 repetitions Activities w/o energy expenditure measurements |
| 12 | Assuming a standing shooting stance with a handgun while hiding behind a curtain in the following arrangement: standing behind the right curtain edge with the gun in the dominant hand, hiding back behind the curtain to reload the gun, standing behind the right curtain edge with the gun in the dominant hand; exit from behind the curtain and putting the gun back into its holster | 2 cycles 2 repetitions |
| 13 | Evacuation of a casualty – dragging the vest user held under the arms over the distance of 5 m |  |
| 14 | Simulation of getting in and out of the car (a minivan with open door of rectangular shape) – 5 cycles |  |

Source: own work.

To perform the scheduled exercise set (Table 1) an ATLAS type weight training equipment was used. This ensured the reproducibility of motion and exercise characteristics (constant, fixed load through the use of standard weights). Before the tests, the vests were acclimated to temperatures: -40°C, 20°C i 50°C for a period of 5 h for each temperature.

**Performance test questionnaire**

A questionnaire containing 18 questions regarding the functionality of the concealable bullet-proof vest was developed. The survey was consulted with the employees the Police Academy. The study assessed the ergonomics, comfort and functionality of a prototype concealable bullet-proof vest developed in 3 versions. The functionality of the particular vest variants was analyzed on the basis of subjective user reviews, presented in the form of answers to the questions according to the developed questionnaire, as well as on the basis
of the opinion of the person conducting the tests, who evaluated the correctness and the ability to perform the scheduled types of exercise efficiently.

**Energy expenditure**

To estimate the energy usage by the participants during the test exercise, a method of measuring energy expenditure, and thus the amount of energy expended per unit of time by the human body, was selected [8-11]. Energy expenditure during physical activity was evaluated by indirect calorimetry on the basis of oxygen consumption in metabolic processes taking place in the subject during exercise. There is a high correlation coefficient and a nearly linear relationship between the amount of oxygen consumption during exercise and the volume of minute ventilation of the lungs. In this study, we used an MWE-1 energy expenditure meter [10]. The principle of the meter operation is based on measurements of pulmonary ventilation by an air flow sensor. The meter calculates the energy expenditure automatically from minute pulmonary ventilation using Datta-Ramanathan [10] method taking into account the ambient temperature, atmospheric pressure ratio (averaged on Polish territory) and a correction factor, which verifies the measurement to the standard indirect calorimetry method. After inputting the weight, age, body height and gender of the subject it is possible to obtain the net energy expenditure result.

**3. Results and discussion**

The results of practical performance tests obtained on the basis of answers to the survey questions (Table 2) given by the participants of the tests are presented in Fig. 4.

Table 2. Contents of the survey questions to the test participants

<table>
<thead>
<tr>
<th>Question No</th>
<th>Question content</th>
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<tbody>
<tr>
<td>1</td>
<td>Perceptible discomfort of the musculo-skeletal system, e.g. in the form of pain in the nuchal muscles or the spine.</td>
<td>10</td>
<td>Perceptible limitation while raising hands in pitting and standing position.</td>
</tr>
<tr>
<td>2</td>
<td>Presence of sharp edges, rough surfaces, fastening devices and junctions which can cause skin scratches or traumas during professional activities.</td>
<td>11</td>
<td>Perceptible limitation while crawling prone and supine.</td>
</tr>
<tr>
<td>3</td>
<td>Putting the vest on and taking it off easily without the help of other persons.</td>
<td>12</td>
<td>Perceptible limitation while turning from prone/supine position to side-lying one.</td>
</tr>
<tr>
<td></td>
<td>Correct functioning of fastening devices.</td>
<td></td>
<td>Perceptible limitation while climbing and going down the ladder.</td>
</tr>
<tr>
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<td>----------------------------------------</td>
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<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td>5</td>
<td>Sensation of compression, blood flow impairment.</td>
<td>14</td>
<td>Perceptible limitation while bending the arms and picking up small objects.</td>
</tr>
<tr>
<td>6</td>
<td>Adequate covering of the body surfaces by the protective material.</td>
<td>15</td>
<td>Perceptible limitations while using handguns in various shooting stances.</td>
</tr>
<tr>
<td>7</td>
<td>Perceptible limitation while kneeling, including kneeling on one knee.</td>
<td>16</td>
<td>Perceptible limitations during transport of a casualty.</td>
</tr>
<tr>
<td>8</td>
<td>Perceptible limitation while sitting down, including squatting on the floor.</td>
<td>17</td>
<td>Perceptible limitations while executing incapacitation techniques.</td>
</tr>
<tr>
<td>9</td>
<td>Perceptible limitation while getting in and out of the car.</td>
<td>18</td>
<td>Perceptible limitations while executing handcuffing techniques.</td>
</tr>
</tbody>
</table>

Source: own work.

![Bar chart](image)

Fig. 4. Comparison of the results of a questionnaire survey concerning three vest variants

Source: own work.

In terms of subjective feelings of comfort and functionality, Version 3 in the form of a personalized vest without the stab-proof insert, whose total weight is approx. 2.5 kg, was assessed most positively. The difference in mass of the various versions of concealable bullet-proof vests influenced on the subjective feelings in the evaluation of ergonomics, ease of use and functionality. In this
respect, Version 1 with stab-proof inserts, weighing approx. 4.5 kg, was assessed most negatively by the study participants. Most of the negative comments concerned:

- protective vest material failure to provide adequate cover for the body surfaces which should be protected by a correctly chosen size of the vest,
- presence of rough surfaces, fastening devices, seams and junctions which might cause traumas while carrying out professional activities,
- limitation of the ability to sit down, including sitting down in cross-legged position,
- limitation of the possibility to use handguns in various shooting stances,
- impossibility of easy putting on and taking off the vest without the help of another person,
- compression exerted by the construction elements of the vest.

It is possible to average the sizes of the vests on the basis of anthropometric studies, which will not affect negatively the overall assessment of functionality and ergonomics of concealable bullet-proof vests, as indicated by the results of the questionnaire survey concerning variants 1 and 2.

Most of the answers concerning the subjective sensations of warmth and humidity [12] after completing the test exercises demonstrated that the sensation of „heat” over the whole body as well as very high humidity level, both with respect to clothing and to the user’s skin, was an important reported problem. Such assessment did not depend significantly on the vest variant.

The results of energy expenditure tests are presented in Table 3.

Table 3. Energy expenditure during exercise in three variants of the vests

<table>
<thead>
<tr>
<th>Test variant</th>
<th>Mean gross energy expenditure value [kJ/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W/o the vest</td>
</tr>
<tr>
<td>1</td>
<td>31.58 ± 2.55</td>
</tr>
<tr>
<td>2</td>
<td>31.58 ± 2.55</td>
</tr>
<tr>
<td>3</td>
<td>31.58 ± 2.55</td>
</tr>
</tbody>
</table>

Source: own work.

Assessment of energy expenditure by the test participants wearing all three vest variants demonstrated that the use of the vests in all three variants did not have a significant effect on the increase in energy expenditure resulting from using the prototype of concealable ballistic vest together with the stab-proof insert.

4. Conclusions

There were significant differences in the survey results with respect to the assessment of variants 1, 2 and 3. The above result indicates that the total weight
of the vest, together with the protective inserts, was of the key importance for subjective assessment of functionality and ergonomics of the personalized vest. Reduction of the vest mass by 2 kg as a result of removal of stab-proof inserts (variant 3) eliminated significantly such inconveniences as: discomfort due to sharp edges and rims, difficulty in putting the vest on and taking it off without help of other persons, compression and problems with the use of short firearms.

In the case of necessity to use the full set of ballistic inserts (including stab-proof ones) it is necessary to pay particular attention to the time and organization of work of the WSPol, with a focus on limited duration of the vest use and intensification of practical training.

Acknowledgements

The publication has been based on the results of Phase III of the National Program “Safety and working conditions improvement”, funded in the years 2014-2016 in the area of tasks related to services for the State by the Ministry of Family, Labour and Social Policy (The Program coordinator: Central Institute for Labour Protection – National Research Institute) and project Individualization of multifunctional concealable ballistic vests design acronym: SECRET, funded in the competition No. 4/2013 in the area of research and development for defense and national security.

Bibliography


1. Introduction

There is an observed trend of increase of safety and hygiene significance at the work stations, where there are many factors dangerous for the human health. One of such places, where the dangerous factors like the high temperature, pollution, noise, sharp edges or other items occur, is the welder work station. Many dangers and harmful factors in the welder company cause the worsening of physiological and psychological comfort of welder workers. Therefore, the specialist protective clothing is used to prevent the harmful activity of high temperature. Modern technological material solutions are used for the protective clothing to assure the better physiological comfort of the user and his work ergonomics. Innovative fabric solutions aim at a minimization of heat radiation effect leading to an improvement of protection against harmful heat factors.

In the frame of research and development activity the innovative material solution relying on replacement of aluminized glass protective clothing, which has been applied so far in the welding company, by the aluminized basalt protective clothing, which additionally warns the user against too high temperature. In the project the modelling of material package content and integrated sensors of thermal shock were carried out. In the next stage the virtual sewing process of clothing model with the use of aluminized basalt fabric content was done (Fig. 1).
2. The research object

The research on the thermal resistance aluminised glass fabrics commonly used in the manufacturing the protective clothing and commercially available aluminised basalt fabric was carried out. The criterion of selection aluminized basalt fabric was the mass per square which should be close to the mass per square of aluminized glass fabric (Table 1).

Table 1. Characteristics of the research object

<table>
<thead>
<tr>
<th>No.</th>
<th>The name of object</th>
<th>Mark of object</th>
<th>The mass per square [g/m²]</th>
<th>Thickness [mm]</th>
<th>The weave</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Aluminized glass fabric</td>
<td>S1</td>
<td>250</td>
<td>0.47</td>
<td>Plain weave</td>
</tr>
<tr>
<td>2</td>
<td>Aluminized glass fabric</td>
<td>S2</td>
<td>430</td>
<td>0.56</td>
<td>Twill weave</td>
</tr>
<tr>
<td>3</td>
<td>Aluminized basalt fabric</td>
<td>B1</td>
<td>319</td>
<td>0.35</td>
<td>Plain weave</td>
</tr>
<tr>
<td>4</td>
<td>Aluminized basalt fabric</td>
<td>B2</td>
<td>440</td>
<td>0.49</td>
<td>Twill weave</td>
</tr>
<tr>
<td>5</td>
<td>Aluminized basalt fabric</td>
<td>B3</td>
<td>880</td>
<td>0.70</td>
<td>Plain weave</td>
</tr>
</tbody>
</table>

Source: own work.
3. Selecting the best materials in terms of heat insulation properties

In order to develop the new protective clothing, it was necessary to select aluminised basalt fabrics, for which the thermal insulation parameters were similar to those of aluminised glass fabric. The values of parameters of thermal insulation for aluminised glass fabric provide a reference point to the creation of package of aluminised basalt fabrics. The parameters, which determine the choice of aluminised basalt fabrics, as a component of protective clothing, were the values of thermal conductivity and thermal resistance. The values of these parameters influence the characteristics of thermophysical use of the protective clothing.

4. Research on the thermal insulation properties on the device Alambeta

Research on the thermal insulation properties allowed for selecting the aluminised fabrics basalt fabrics, which made it possible to develop a model of protective clothing using aluminised basalt fabrics. In the first step of research measurements of thermal insulation on the available fabrics: basalt and glass were made. Results of studies are presented in Table 2.

Table 2. The average values of thermal insulating parameters of the aluminized basalt and glass fabrics from Alambeta

<table>
<thead>
<tr>
<th>Mark of object</th>
<th>Thermal conductivity coefficient $\lambda$ [Wm$^{-1}$K$^{-1}$*10$^{-3}$]</th>
<th>Thermal diffusivity $a$ [m$^2$s$^{-1}$*10$^{-6}$]</th>
<th>Thermal absorption $b$ [Ws$^{1/2}$m$^{-2}$K$^{-1}$]</th>
<th>Thermal resistance $R$ [m$^2$KW$^{-1}$*10$^{-3}$]</th>
<th>Thickness $h$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>59.27</td>
<td>0.08</td>
<td>231.57</td>
<td>4.76</td>
<td>0.28</td>
</tr>
<tr>
<td>S2</td>
<td>63.19</td>
<td>0.08</td>
<td>232.43</td>
<td>7.39</td>
<td>0.47</td>
</tr>
<tr>
<td>B1</td>
<td>62.44</td>
<td>0.08</td>
<td>231.57</td>
<td>5.66</td>
<td>0.35</td>
</tr>
<tr>
<td>B2</td>
<td>67.16</td>
<td>0.10</td>
<td>228.70</td>
<td>7.72</td>
<td>0.49</td>
</tr>
<tr>
<td>B3</td>
<td>60.80</td>
<td>0.12</td>
<td>186.43</td>
<td>11.58</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Source: own work.

For further research of thermal properties there have been selected the aluminized basalt fabrics B1 and B2. The selected fabrics are characterized by a similar mass per square to the aluminized glass fabric. Aluminized basalt fabric B1 of surface mass equal 319 g/m$^2$ is compatible with aluminized glass fabric S1 of surface mass equal 250 g/m$^2$. Both of fabrics have a plain weave.
5. The concept of print temperature sensors

The development of textronics has allowed to design smart protective clothing, which includes clothing for a foundry worker. The clothing provides protection before overheating, the possibility of continuous monitoring and activating alarm systems in the case of exceeding limit values. The measurement range of temperature sensors in the under-clothing region has to result from the body's response to high temperatures. On the base of the literature [1, 2] the skin damage occurs at the temperature of 42°C. For this temperature after 6 hours the skin necrosis occurs. This time is reduced at the higher temperatures. At 55°C the epidermal necrosis occurs after 3 minutes and at 70°C in just one second. Each of the higher temperatures, acting on a surface of the body causes the skin tissue damage and mostly irreversible damage and necrosis. Detailed studies on the pain perception by the human body were presented in the article [3]. The threshold value of the hot air temperature causes the pain perception amounts to 44°C depending on the exposed parts of the body. Therefore, it is assumed that the temperature of 44°C is a critical value, which can occur in the layers of under-clothing. The textronics system integrated into the protective clothing and monitoring the temperature under-clothing region should be characterized by possible small size, weight and flexibility. The new construction of temperature sensor from the electro-conductive polymers and digital printing were developed. Figure 2 shows a model of the particular layers on the surface of the basalt fabric.

![Fig. 2. Model of layers of the printed temperature sensor](source: own work)
6. The technology for manufacturing printed temperature sensors

In order to develop the temperature sensor in the first place geometric model of electrodes were made. The distance between the electrodes was 12 mm. On the basis of geometric model the map control jet of the print head digital was developed using the Raster Image Processor.

The electrodes of temperature sensors were made by printing dispersions of silver nanoparticles directly on the surface of the basalt fabric by the digital printing through type head drop on demand made by company ReaJet (Germany). After the printing process the samples were placed in the chamber, which had the temperature 140°C within 1 hour.

In the second stage on the surface of fabric with printed electrodes the thermo-sensitive layer of dimensions 15 mm x 6 mm was deposited (Fig. 3). The thermo-sensitive layer temperature sensors in three variants of electro-conductive polymers were made of:

a) Polyaniline (PANI),
b) Polypyrrole (PPy),
c) Poly(3,4-ethylenedioxythiophene) (PEDOT).

![Fig. 3. The thermo-sensitive polymer layer with the system of electrodes](source: own work)

7. Research methodology for monitoring the temperature under-clothing region

The construction of the test stand is presented in the Fig 4. The test stand consisted of: the portable temperature calibrator Microcal T-100, precise thermometer Tempmaster T100, precise multimeter Agilent 34410A and computer PC.
8. Results of metrological properties of printed temperature sensors

The static characteristics $R = f(T)$ of the sensors measuring their resistance values in the steady states during increase process and decreasing the temperature in the range of from 10 to 70°C. For each of these processes the separate static characteristics were found. The measurements were repeated twice for each sensor.

In the initial stage of research on the static characteristics IT was stated, that the temperature sensor with the thermo-sensitive layer made of polypyrrole is not suitable for the use because of the very large hysteresis, which is not observed in the remaining two types of sensors. Therefore, the calculation of the metrological parameters for sensors with thermo-sensitive layers made of polyaniline (PANI) and PEDOT was carried out. For each of standard value an arithmetic average resistance value ($R_r$) and standard deviation were calculated. The set of actual values of characteristics $R_i(T)$ approximated by the method of least squares was found.

The highest value of the standard deviation for the sensor PANI was equal to $21.99\ \Omega$ at the temperature $10^\circ$C. The maximum value of difference between the actual value resulting from the approximation is the value $117.19\ \Omega$ in the temperature $10^\circ$C. On the base of observations sensor parameters presented in table 3 were calculated. The static characteristics are shown in Figure 5.
Table 3. The sensor parameters PANI

<table>
<thead>
<tr>
<th>Range of actual resistance values</th>
<th>PWR</th>
<th>1812.6</th>
<th>Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-linearity</td>
<td>N</td>
<td>6.46</td>
<td>%</td>
</tr>
<tr>
<td>The sensitivity of the sensor</td>
<td>s</td>
<td>-30.21</td>
<td>Ω/°C</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>P_C</td>
<td>1.21</td>
<td>%</td>
</tr>
</tbody>
</table>

Source: own work.

Fig. 5. The static characteristics of the sensor PANI

Source: own work.

A similar calculation was applied to sensor PEDOT. The test results are shown in Table 4 and Fig. 6

Table 4. The sensor parameters PEDOT

<table>
<thead>
<tr>
<th>Range of actual resistance values</th>
<th>PWR</th>
<th>1812.6</th>
<th>Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-linearity</td>
<td>N</td>
<td>6.46</td>
<td>%</td>
</tr>
<tr>
<td>The sensitivity of the sensor</td>
<td>s</td>
<td>-30.21</td>
<td>Ω/°C</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>P_C</td>
<td>1.21</td>
<td>%</td>
</tr>
</tbody>
</table>

Source: own work.

The relative changes of resistance of the sensor referenced to the initial resistance at the temperature 10°C were analysed. Obtained in this way parameters were signed by the subscript “w”. The results are shown in Tables 5, 6 and Figures 7, 8.
Protective clothing made with the use of aluminized basalt fabrics

Fig. 6. The static characteristics of the sensor PEDOT

Source: own work.

Table 5. The parameters of the sensor PANI in relative values

<table>
<thead>
<tr>
<th>Range of actual resistance values</th>
<th>$PWR_w$</th>
<th>0.384854</th>
<th>–</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-linearity</td>
<td>$N_w$</td>
<td>6.42</td>
<td>%</td>
</tr>
<tr>
<td>The sensitivity of the sensor</td>
<td>$s_w$</td>
<td>-0.0064</td>
<td>1/°C</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>$P_{cw}$</td>
<td>1.13</td>
<td>%</td>
</tr>
</tbody>
</table>

Source: own work.

Fig. 7. The static characteristics of the sensor PANI in relative values

Source: own work.
Table 6. The parameters of the sensor PEDOT in relative values

<table>
<thead>
<tr>
<th>Range of actual resistance values</th>
<th>( PWR_w )</th>
<th>0.33714</th>
<th>–</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-linearity</td>
<td>( N_w )</td>
<td>6.72</td>
<td>%</td>
</tr>
<tr>
<td>The sensitivity of the sensor</td>
<td>( s_w )</td>
<td>-0.0052</td>
<td>1/°C</td>
</tr>
<tr>
<td>Reproducibility</td>
<td>( P_{Cw} )</td>
<td>0.84</td>
<td>%</td>
</tr>
</tbody>
</table>

*Source: own work.*

![Function approximation](image)

Fig. 8. The static characteristics of the sensor PEDOT in relative values

*Source: own work.*

The presented result of research shows that both sensors have properties eligible for the use in the foundry clothing for the temperature measurement underclothing. The static characteristics of nonlinearity are about 6.5%. This results in the adoption of subjective characteristics of the ideal linearity. The adoption of ideal characteristics in the form of second-degree polynomial radically improves nonlinearity, but complicates the signal processing in the future research.

9. Summary

The parameter deciding on the selection of the basalt fabric was surface mass. The parameter deciding on the selection of the basalt fabric was surface mass and the thermal insulation properties which were measured by Alambeta device. Based on results of aluminized basalt fabrics B1 and B2 were selected. The application of digital printing technology and suitable inky compositions
allowed for the execution of a fully functional print temperature sensors based on electro-conductive polymers. The different layers were applied directly on the surface of the basalt fabric. The use of outer aluminized layers of foil allowed to effectively eliminating the impact of changes in the humidity for a change in the resistance of thermo-sensitive layers. The research of sensor properties fully confirmed the suitability for their use for monitoring the temperature under-clothing. The presented results are statistically significant. The repeatability of measurements equal to 1% was obtained. The results statistically significant was. A static characteristics of non-linearity is about 6.5%, which can be significantly reduced by adopting the characteristics of ideal in the form of polynomial of the second degree.

Bibliography

1. Introduction

In recent years, individual ballistic shields have become so widespread that it is hard to imagine a modern army of soldiers without their use. Since the development of technology they have become significantly lighter and stronger than at the beginning of their existence. The contemporary armed conflict inextricably connected with the use of individual ballistic protection considerably contributes to reducing the percentage of dead and wounded soldiers, but do not protect against all threats present on the battlefield. The manufacturers of bulletproof vests implement to produce more and more modern, lighter and more efficient enclosure, and on the other hand – it is the presently constructed ammunition with ever-increasing capacities of destruction.

Constantly growing military conflict leading to the reduction of the sense of security has become one of the arguments for scientific research. The assumption that the fabric will differ only in the type of structure, while maintaining the similar surface weight of ~200 g/m² and the thickness of 1500 dtex yarn was adopted. Experimental and numerical analysis of dynamic phenomenon of the impact bullet in the structure of the textile are constantly published. The model of physical bullet impact into the ballistic package by Chocron-Benloulo [1, 2] et al was presented. The proposed model was based on the theory of Smith. A team of researchers conducted by Smith made both experimental and theoretical research. The results of these studies are widely published. A series of articles under the title of Stress-Strain Relationships in Yarns Subjected to Rapid Impact Loading [3-11] were issued. In the physical model it was considered that the fabric as a layer of ballistic package, which had two independent systems of weft and warp, and did not have impacts
between them. The studies did not include interlaces. For the simulation and experimental research the parameters of threads of aramid KEVLAR 29 were adopted. The bullet both in the experimental and simulation research had a weight equal to 1.04 g. The authors studied the residual velocity of the projectile as a function of the impact velocity for different numbers of layers of the protective package.

In the literature many examples of numerical modeling of ballistic fabrics can also be found, but mainly these are of biaxial structures. The simulation research of the impact bullet into a single layer of ballistic package made of TWARON was conducted by Lim et al. [12]. Numerical research has been carried out in an LS-DYNA. The material parameters on the basis of published experimental studies were adopted. Based on the calculation the velocity and residual kinetic energy of the bullet absorbed by the layer was marked. The authors drew attention to the omission of the model of discrete friction between the threads of the warp and weft and the effect of pulling out from the structure the threads of fabric during contact with the bullet. Ting et al. [13] were engaged in numerical modeling of the phenomenon of the bullet impact into the multi-layered ballistic package. The discrete model was taken into account the slip between the points interlacing threads. For the analysis of multilayer packages the model of variable parameter defining initial distance between adjacent layers was introduced. The simulation research included the determination of the residual velocity as a function of the impact velocity for different friction coefficients. It has been found that the ballistic effectiveness decreases with decreasing coefficient of friction between threads at the interlacing point.

A wide range of numerical research was presented in articles Neelakantan et al. (2008, 2010a, 2010b). In the presented chapter multiscale modeling technique was proposed. This included modeling fabric, which takes into account three areas: the first area of impact bullet – plain weave 3D object, the second area – plain weave 2D object, the third area – the structure of homogenized 2D object. This solution carries the benefit of reducing the number of finite elements, and this is associated with the shortening of computing time. The authors developed discrete model the KEVLAR S706 fabric plain weave and the weight of 180 g/m². Based on the detailed analysis under the microscope of the fabrics KEVLAR S706 the necessary parameters representing a single thread were designated. The simulation research in an LS-DYNA was carried. The spherical bullet with a mass of 0.63 g and a diameter of 5.55 mm, the impact velocity of 40 m/s, 100 m/s, 200 m/s was used. The boundary condition was adopted in the simulation limit the degrees of freedom for all four edges of the sample. For object of research three variants of dimensions were adopted depending on the applied areas: a 3D object, the object 2D, 2D structure homogenized. The authors analyzed the velocity of the projectile, deformation layer, the amount of energy absorbed by the layer and the contact force between the projectile and the fabric. The approach proposed by the
authors have contributed to the reduction in the cost calculations either in terms of computing power and memory, and at the same time enabled the precise ballistic answer.

The possibility of modeling warp and weft in the fabric allows to explore in detail the phenomenon occurring between the bullet and the fabric and between threads in the fabric. However, simulation research of this type is related with having large resources of computer hardware performance. In the present chapter simulation research for textile structures mirroring the actual geometry of the thread in the structure of biaxial and triaxial fabrics KEVLAR 29 was conducted. In contrast to the studies submitted by Nilakantan et al. layer over the entire surface was a 3D object having a weave. This resulted into the number of nodes on a single layer, which was more than 1 million, and in turn it affected the simulation time of one packet of the multilayer structure which, depending on the number of layers lasted for about one month.

2. Object of research

The primary materials used for personal ballistic shields are textile structures based on aramid fibers such as KEVLAR®, TWARON® and polyethylene DYNEEMA®, SPECTRA®. In chapter the results of ballistic textile packages are made from the same raw material, namely the first generation aramid yarn KEVLAR 29 was presented. Table 1 shows the basic parameters of the yarn used on the basis of catalog data from the company DuPont.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>KEVLAR 29 1500 dtex</td>
<td>1.44</td>
<td>338</td>
<td>2.99</td>
<td>70.5</td>
<td>3.6</td>
</tr>
</tbody>
</table>

*Source: the data comes from catalogue of DuPont company.*

For research of the bullet resistance of the soft ballistic packages two different fabric structures were used. The parameters of the structures of ballistic fabrics in Table 2 are presented.
Table 2. Basic parameters of the structures of ballistic fabrics biaxial and triaxial KEVLAR 29

<table>
<thead>
<tr>
<th>THE WEAVE FABRIC</th>
<th>PLAIN WEAVE</th>
<th>KEVLAR 29 BIAXIAL FABRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>YARN THICKNESS, dtex</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>NUMBER OF THREADS PER 10 CM</td>
<td>WEFT</td>
<td>70±2</td>
</tr>
<tr>
<td></td>
<td>WARP</td>
<td>70±2</td>
</tr>
<tr>
<td>SURFACE MASS, g/m²</td>
<td>200±10</td>
<td></td>
</tr>
<tr>
<td>THICKNESS FABRIC, mm</td>
<td>0.28±0.03</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>THE WEAVE FABRIC</th>
<th>TRIAXIAL WEAVE BASE</th>
<th>KEVLAR 29 TRIAXIAL FABRIC STRUKTURZE TRÓJOSIOWEJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>YARN THICKNESS, dtex</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>NUMBER OF THREADS PER 10 CM</td>
<td>WEFT</td>
<td>70±2</td>
</tr>
<tr>
<td></td>
<td>WARP</td>
<td>AA 33±2</td>
</tr>
<tr>
<td>SURFACE MASS, g/m²</td>
<td>200±10</td>
<td></td>
</tr>
<tr>
<td>THICKNESS FABRIC, mm</td>
<td>0.27±0.03</td>
<td></td>
</tr>
</tbody>
</table>

Source: own work.

3. 9 x 19 mm Parabellum bullet

9 x 19 mm Parabellum bullet made by company Winchester was used. The ammunition made by the company Winchester guarantees precision and high quality workmanship. The company has set the standard for operating parameters and innovation in the production of the most reliable ammunition. Currently Parabellum bullets are the most popular weapon among the uniformed
services. The exemplary types of arms are a Mini Uzi, MAG-98, PM-84P, PM-98, PM-98S and Glock. Based on the data of bullet factory 9 x 19 mm Parabellum geometric model of the jacket and the core of bullet, as shown in Fig. 1 were developed.

![Fig. 1. A) The geometrical model of 9 x 19 mm Parabellum bullet, B) core bullet, C) jacket bullet](image)

Source: own work.

The geometrical model of 9 x 19 mm Parabellum bullet of discretization process in the software ANSYS ICEM CFD was subjected. For the core and jacket the finite element mesh size of 0.5 mm was generated. The material parameters for core and jacket bullet on the base of the literature [14] were adopted. The detailed description of the development of a discrete model of the bullet in literature [15] was presented.

4. Methodology of research

4.1. Experimental research

The experimental research was carried out in the Laboratory for Ballistic Research. The laboratory is equipped with the ballistic gun for shooting bullets, a system of gates for measuring the impact velocity and the residual velocity of the bullet as well as the camera to record dynamic phenomena CORDIN 535D. The packages consisting of 6, 12, 16, 18, 22 and 24 of the biaxial and triaxial KEVLAR 29 fabrics were prepared. The dimension of the prepared samples was 30 x 30 cm. For each variants of packages the three of the sample were carried out.

Textile ballistic packages with biaxial and triaxial fabrics before firing were attached to the holder as shown in Fig. 2. This parameter was chosen deliberately because ballistic package in simulation research also have the same dimension.
During the experimental research in the Laboratory for Ballistic Research each package was given one shot, at zero angle of impact in the middle of samples for $x = 0$ and $y = 0$. At the moment of the bullet impact measurement system gates measured the impact velocity of the bullet and the velocity after passing through the gate that is to say residual velocity when the ballistic package was streaked. A series of measurements for each ballistic package were conducted four times, and the measured velocity calculated arithmetic averages. During the firing the phenomenon of deformation of ballistic packages was recorded using the camera CORDIN 535D.

4.2. Simulation research

In the first stage of the simulation research geometric models of single thread fabrics of biaxial and triaxial based on the actual dimensions were developed. The fabrics were subjected to detailed analysis performed under a stereoscopic microscope OLYMPUS SZ-10. As a result of microscopic analysis of the average values of the height and width of the cross section of threads, the average values of the amplitude and the period of the sine wave of threads for the actual triaxial and biaxial fabrics (Fig. 3 and 4) were designated.
Fig. 3. Geometrical model of triaxial fabric: A) dimensions of height and width of the cross-section of thread B) dimensions of the amplitude and period of the sine wave thread

*Source: own work.*

Fig. 4. Geometrical model of biaxial fabric: A) dimensions of height and width of the cross-section of thread B) dimensions of the amplitude and period of the sine wave thread

*Source: own work.*

Based on the determined dimensions of the cross sections and the parameters sinusoidal wave of threads, in the next step 3D models using ANSYS ICEM CFD was developed. Fig. 5 and 6 show a view of the geometrical structure of the triaxial and biaxial fabrics. Ultimately, for further simulation research the geometric model of triaxial fabric measuring 20 x 20 cm was developed.

Fig. 5. The geometric structure of the triaxial fabric

*Source: own work.*
The computer simulations in an LS-DYNA were carried out. 9 x 19 mm Parabellum FMJ bullet hit centrally in the ballistic package and the velocity of the bullet was 406 m/s. Each of the layers at the edges of the package was mounted, so as not to move in any direction of the coordinate system XYZ. For this purpose, the SPC BOUNDARY - SET was set. In the computer simulation of the type of contact AUTOMATIC SURFACE_TO_SURFACE was used. The material parameters for the discrete model of KEVLAR 29 fabric based on the literature [16, 17] were adopted.

![Image of the geometric structure of the biaxial fabric](image)

**Fig. 6. The geometric structure of the biaxial fabric**

*Source: own work.*

5. The results of experimental and simulation

The results of experimental and simulation have allowed to assess the studied multi-layer packages for two safety criteria. The first criterion refers to not penetration of ballistic package and the second safety criterion defines that the maximum height of the cone deformation cannot exceed 44 mm.

In the first steps of the experimental research for packages which with biaxial and triaxial fabrics residual velocity of the projectile as a function of the number of layers was analyzed. For each variants of packages the three of the sample was carried out. Next the average value of residual velocity of bullet and the maximum deformation of soft package were calculated. Fig. 7 shows images from the camera, which recorded the phenomenon of bullet impact in the packages and the penetration packets of biaxial and triaxial fabrics consisting of 12 layers.
Chapter I. Proetex

A)

B)

Fig. 7. B) Penetration biaxial package consisting of 12 layers of KEVLAR 29 fabrics at time \( t = 139.7 \) µs, B) a triaxial puncture package consisting of 12 layers of KEVLAR 29 fabrics at time \( t = 139.7 \) µs

Source: own work.

The ballistic package with a biaxial fabric has not been streaked for the layers 16, 18, 22 and 24 (Fig. 8). Whereas for ballistic packages composed of the triaxial fabric the total absorption of the energy carried by a bullet occurred for the 22 and 24 layers. The analysis of the results of the residual velocity of the projectile for the first criterion of security led to the conclusion that the structure of the textile of a plain weave has better puncture resistance than triaxial fabric packages.

Fig. 8. The dependence of the residual velocity as a function of the number of layers of ballistic package for the biaxial and triaxial fabrics

Source: own work.
Then, the maximum value of the deformation of the cone as a function of the number of layers was analyzed (Fig. 9). Thus, with the increase of the number of layers followed by the increase in cone deformation, as a result of ever-increasing energy dissipated through the structure of the textile ballistic package. The increasing character of the curve was detained for the 16 layers of biaxial package, while for the packages of triaxial fabric for the number of layers equal to 22. Further increasing the number of layers contributes to the reduction of the value of deformation of the cone.

![Fig. 9. The dependence of the maximum height of the cone as a function of the number of layers of ballistic package for biaxial and triaxial fabrics](image)

Source: own work.

However, it should be emphasized that in case of ballistic package consisting of the structured biaxial fabric of the number of layers equal to 16 the maximum cone reaches the value of 60 mm. Also, from the ballistics package of biaxial fabric consisting of 24 layers, the maximum value of the cone is 50 mm in contrast to the ballistic package of a triaxial fabric consisting of 24 layers, where the value of the cone deformation reaches the value 36 mm (Fig. 10). This is the basis to conclude that the structure of the textile of triaxial satisfies the second criterion of safety in contrast to multilayer packages made of biaxial fabric.
Fig. 10. A) Non-penetrative bullet hit in a package of 24 layers of KEVLAR 29 biaxial fabrics at the time \( t = 922.6 \, \mu s \), B) Non-penetrative bullet hit in a package of 24 layers of KEVLAR 29 triaxial fabric at the time \( t = 931.4 \, \mu s \)

*Source: own work.*

In Fig. 11 change the size of the deformation of a package consisting of 24 layers of biaxial and triaxial fabrics over time was presented. In the case of the package comprised of 24 layers of biaxial fabrics maximum deformation was achieved at time \( t = 0.66 \, ms \), in opposed to the package consisting of triaxial fabrics where time was equal \( t = 0.53 \, ms \). For the package triaxial fabric character of the curve increasing during time it faster reaches the maximum value of deformation.

![Graph showing the dependence of the maximum height of the cone as a function of time for the package consisting of 24 layers of biaxial and triaxial fabrics.](source)

*Fig. 11. The dependence of the maximum height of the cone as a function of time for the package consisting of 24 layers of biaxial and triaxial fabrics*

*Source: own work.*
Numerical and experimental analysis of resistance of soft ballistic packages consisting…

Because of the time consuming simulation research in the chapter the results for a minimum number of layers of ballistic biaxial and triaxial package, which in the experimental research were not-penetrated, are presented. A biaxial fabric package consisting of 16 layers and triaxial fabric package consisting of 22 layers were studied.

Fig. 12. Impact bullet in the package of 16 layers of biaxial fabric: A) t = 50 µs, B) t = 100 µs  
*Source: own work.*

Fig. 13. Impact bullet in the package of 22 layers of triaxial fabric: A) t = 50 µs, B) t = 100 µs  
*Source: own work.*
Fig. 12 and 13 show images of impact of 9 x 19 mm FMJ Parabellum bullet in the ballistic package of the biaxial fabric 16 layers and the package consisting of 22 layers of triaxial fabric. The maximum height of the cone deformation in the function of time for a packet with biaxial and triaxial fabrics was analyzed.

The results presented in Fig. 14 show that for the package with a biaxial fabric the value of deformation increases more rapidly than for a packet with a triaxial fabric. However Fig. 14 shows only the first stage of deformation pack time of 0.10 ms. The simulation research will be continued in order to obtain a final maximum value of the deflection of the cone. This allows to evaluate the effectiveness of ballistic packages and compare the results of experimental and simulation results.

![Graph showing cone deformation](image)

Fig. 14. The dependence of the height of the cone as a function of time for a ballistic package consisting of 16 layers of biaxial fabric and 22 layers of triaxial fabric

*Source: own work.*

6. Summary

The conducted experimental tests of the effectiveness of ballistic packages revealed that the structure of biaxial textile have better puncture resistance than the triaxial structures. The experimental analysis of the maximum cone of deformation has shown that the structure of triaxial provide much smaller value of the maximum deformation of the cone. This is the conclusion which gives the basis for further experimental and simulation research of biaxial and triaxial structures. Experimental research on the model of the human body made of ballistic gelatin, which will have a model of the heart; lung model and a model of the skeletal system are also planned. The results of the research will allow to verify in detail the impact of the triaxial fabric subjected to non-penetration impact 9 x 19 mm Parabellum bullet on ballistic trauma.
Bibliography


Chapter II
MEDTEX
Head trauma constitute a big part of injuries resulting from traffic accidents of different type. People with this kind of injuries form a significant group of patients who are treated by maxillofacial surgeons. In the last few years there has been a constant, repetitive growth in the number of maxillofacial trauma. The reasons for that are the increased motorisation, the mechanisation of everyday life and the higher incidence of cancerous diseases. According to the literature (Uliasz et al., 2006) and on the basis of clinical observations it may be stated that the main reasons for fractures of maxillofacial bones are batteries and traffic accidents.

In 1885, Mules as the first person in the world used an orbital implant (Prost, 2007). The implant was made of glass with rings of gold and silver. In the next years different materials were used for production of orbital implants; the grafts were also shaped differently (Sami, 2007). Due to the fact that such implants were not well-tolerated by the orbital wall tissues, they were either too expensive or too heavy, the grafts were often prone to implosion when subjected to temperature changes (glass implants or hollow implants). The majority of those grafts are not used nowadays.

It needs to be emphasised that in the last decade, owing to a significant progress in technology and surgical techniques, the treatment of maxillofacial fractures has been subjected to many important changes. The reconstruction of bone defects resulting from comminuted fractures still constitutes a major problem in the treatment of maxillofacial fractures, especially in the case of orbital wall fractures. The methods currently used for such reconstruction include transplants and implants of different materials: titanium mesh,
hydroxyapatite, polymethyl methacrylate (PMMA), fat, silicon, polyethylene, and polypropylene (CODUBIX® ORBITAL WALL 3D).

CODUBIX® ORBITAL WALL/ CODUBIX® ORBITAL WALL 3D prostheses are modern implantation materials made with the use of knitting technique out of polypropylene yarn characterised by low specific weight and low melting point which enables assuring the prosthesis’ adequate stiffness and toughness. Each implant has a factory-given convex shape corresponding with the anatomy of an orbital wall and is available in 3 sizes or in a custom-made version (the prosthesis is manufactured on the basis of the CT scan of patient’s head). Owing to the right curvature, elasticity and resilience the knitted material adheres tightly to the orbital wall which excludes the necessity of the fixation of the graft.

Reconstructive surgeons confirm that CODUBIX® material is safe and shows no local inflammatory or purulent complications after implantation. High biocompatibility of polypropylene and its high processing capacities make it one of the most recognised and keenly used material for manufacturing of implants used, among others, in urogyneacology, hernia surgeries, cranioplasty, and orthopaedics. CODUBIX® implants are characterised by adequate biological parameters and fixed mechanical parameters which significantly influences the safety and efficacy of implantation.

1. Introduction

Maxillofacial injuries are a special group of fractures, mainly due to the presence of many organs within a small area; the organs include not only the central nervous system (CNS), but also vision, hearing and balance organs [1-6]. Although CNS and hearing and balance organs are protected by quite strong bone structures, the same cannot be said in the context of vision organs, even despite the fact that the ‘massive shackle’ of zygomatic bone protects the eyeball from the consequences of lateral mechanical injuries.

This ‘shackle’, in spite of its constructive importance and the distribution of the force of the trauma into many constituent forces, is placed in between much weaker structures of smaller resistance; the structures in question are the orbit with soft tissues and the maxillary sinus which is filled with air and its size depends on an individual. These facts deserve to be emphasised because the mentioned construction solution leads to the situation in which this part of the cranium may be much more susceptible to damages. It may result in orbitozygomatic fractures, zygomaticomaxillary fractures or isolated fractures of orbital floor. All these fractures are often followed by complications and in modern traumatology they are gathered under a common name of midfacial bone fractures.
Despite the fact that in dynamic and static tests the resistance of bone tissue often determines the consequences of an injury, the mechanical resistance of cranial bone, which is very important from the point of view of the mechanics of trauma, is rarely a subject of research. Latkowski’s research shows that in resilience tests the least resilient are parietal bone and maxillary sinus wall (0.03 kG/mm$^2$), in bend tests – frontal bone (0.2 kG/mm$^2$), in tensile test – zygomatic bone (0.36 kG/mm$^2$), and in crushing test – maxillary sinus wall (10 kG/mm$^2$). Due to the toughness of natural bone, the search for an adequate implantation material was carried out within the range of synthetic polymers.

Fibre-forming polymers, the fibres, the threads and the knitted fabrics made out of them constitute a wide and separated branch of knowledge of plastic materials which is very important from the point of view of medicine. Synthetic fibres are made out of macromolecular compounds which are either to be found in the nature or are created synthetically. The polymers used for that purpose have to possess certain properties, out of which high molecular weight (high degree of polymerisation), elongated asymmetrical shape of the macromolecules, the presence of polar groups in macromolecules, and the ability to dissolve or melt without degradation are of great importance.

At present, the thermoplastic properties of synthetic fibres enabling modifications of their primary shape are used more and more often. Straight fibres after the forming are subjected to mechanical deformations in the temperature approximate to their melting point.

The CH$_2$ = CH – CH$_3$ propylene is one of the most widespread polymers in medicine (Fig. 1). It is used for creation of continuous fibres (mono- and multifilament silk) or for the creation of staple fibres. The fibres made of polypropylene solutions can be shaped with the use of dry or wet method. One of its advantages is the possibility of creating the fibres which are less thick and have better physical and mechanical properties. This method is used for manufacturing the fibres to be used for technical purposes; such fibres have to be of much resistance [8].

\[
\begin{align*}
\text{CH}_2 = \text{CH} \rightarrow \text{CH}_2 - \text{CH} \\
\text{polimer} & \quad \text{monomer}
\end{align*}
\]

Fig. 1. The outline of polymer synthesis

*Source: own work.*
In Poland polypropylene yarn has been used in medicine for many years. At present, the yarn and the products made of it are successfully used in such medicine branches as: vascular surgery, general surgery, orthopaedics, laryngology, gynaecology and plastic surgery.

2. Materials and methods

Orbital wall prostheses are a product used for many years in the treatment of orbital floor fractures. The materials most commonly used in the treatment are: autografts of ala of ilium (Fig. 3a), bioactive glass plates shaped as ‘kidney’ or ‘sphere’, stainless steel (Fig. 3b), titanium meshes (Fig. 3c), porous polyethylene plates (Fig. 3d), polylactic acid implants, polylactic acid and polyglycolide composite implants (Fig. 3f), polylactic acid and polydioxanone patches (Fig. 3g), and titanium mesh and polyethylene composite (Fig. 3h).
A modern orbital wall prosthesis made of polypropylene yarn was first used in oral surgery in 2000 in the Oral and Maxillofacial Surgery Clinic of Surgery Institute of Medical Academy in Łódź. The knitted fabric has the form of rectangular or square fragments measuring 2.5x4.0 cm and 4.0x4.0 cm; the fragments can later be freely adjusted (Fig. 2b). At present it is possible to make a 3D prosthesis which is compliant with individual needs of the patient. The implant is prepared on the basis of the CT scans (Fig. 2a).

Fig. 4. Orbital floor defect visible in the CT scan
Fig. 5. Virtual model of filled-in orbital floor
Fig. 6. The form used for shaping the orbital floor prosthesis

Source: own work.

Computer modelling. CODUBIX 3D orbital wall prostheses, which were created to answer the needs of individual patients, were designed with the use of computer standardisation [9-12]. On the basis of the images obtained by CT scanning (Fig. 4) three sizes of the graft were obtained; the grafts are manufactured in two versions: right side and left side one.

The anthropometric analysis of CT scans of a group of patients allowed for choosing 3 representatives for each of the defined sizes. What is more, on the basis of the literature it was assumed that the shape of both orbits is symmetrical – the left being the mirror image of the right – which facilitated the designing procedure of the implants. Virtual models of the orbits were prepared with the Mimics software. The software created a cloud of points describing the edge of the orbit; it was later used to prepare a virtual model of a cranium in the 3D computer imaging system (Fig. 5). On the basis of the 3D model the forms were prepared with the use of incremental extrusion (Fig. 6).

The next step was designing and preparing the forms for shaping the orbital wall prosthesis. After the manufacturing of the grafts, the physical, chemical and structural tests were done for each lot of the prostheses.

The determination of chemical parameters was done by carrying out the tests in acc. with the following norms: pH of the sample – PN-EN ISO 3071, permanganate oxidability – PN-P 04896, UV absorbance at a wavelength of 230 and 245 nm – PN-P 04990, content of substances soluble in petroleum ether – PN-P 04607. All the tests were done on the basis of water extract prepared in acc. with the requirements of PN-P 04894.

Testing the physical parameters was an important element in the evaluation of the usefulness of the yarn in terms of mechanics. The following parameters were
tested: surface mass (in acc. with the manufacturer’s instructions), thickness (in acc. with PN-P-04890-01 norm), bursting strength (in acc. with ISO 7198 norm).

In order to assess the surface of the polypropylene orbital wall prostheses the tests were done with microscopic instruments with the use of scanning electron microscope (SEM); the device Nova NanoSEM by FEI was located in Lodz University of Technology. It was equipped with FEG type electron gun (field electron emission) and with the X-ray EDS microanalyser Apollo 40 manufactured by EDAX. The sample was placed on the microscope stage with the use of conductive carbon tape.

3. Results and discussion

In the tests discussed in this chapter constitute a comparison of different orbital floor prostheses manufactured accordingly with the standard production technology and the prostheses manufactured on the basis of 3D model of an orbit was presented.

The test methods were based on European norms and Polish harmonised norms. In the cases where it was not possible to select an appropriate testing methodology, the research instructions were applied. All the tests were carried out in the Quality Control Laboratory of TRICOMED S.A. The research instruction of Textile Research Institute in Łódź was used as referential methodology for bursting strength tests; the test itself was carried out in this institution. Owing to the results obtained from different research methods it was possible to assess their adequacy, accurateness and repeatability.

4. Conclusions

An adequate choice of the prosthesis aiming at good cosmetic result constitutes a major problem in reconstructive and plastic surgery. Reconstructive Engineering solves the above-mentioned problem due to the fact that it is an ideal tool for designing medical devices adjusted to the individual needs of a patient. The result of 3D effect is the implant which does not need to be manually adjusted intra-operatively to the shape of the bone defect which reduces the time of the surgery and, as a consequence, hospitalisation costs and the risk of medical incident occurrence. What is more, it needs to be emphasised that the prostheses made with the use of computer modelling are equally good as the standard grafts (Tables 1, 2). According to the surgeons, polypropylene material is well-tolerated and the widespread medical use of the material, among others, in the polypropylene surgical meshes seems to prove it. For instance, in this chapter there were presented, for the needs of the comparison, scanning images of a surgical mesh and an orbital wall prosthesis (Fig. 7). The type of polymer used for the manufacturing of orbital wall prosthesis is much different from the polymer used for surgical meshes. The reason for that is the fact that it is a multifilament. Moreover, it should be recognised that CODUBIX ORBITAL WALL prostheses do not require additional fixing due to its excellent adjustment to the size of the defect.
<table>
<thead>
<tr>
<th>No.</th>
<th>Tested parameter</th>
<th>Unit</th>
<th>Requirements</th>
<th>Test method</th>
<th>Test results</th>
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<td>CODUBIX ORBITAL WALL 3D</td>
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<td></td>
<td>TRI result</td>
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*Source: own work.*

Fig. 7. SEM scanning images of polypropylene knitted fabric for CODUBIX ORBITAL WALL prostheses compared with the knitted fabric used for hernia meshes

*Source: own work.*
Table 2. Chemical properties test results for orbital wall prostheses

<table>
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Source: own work.
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1. Introduction

Textiles, including knitted fabrics, are now widely applied not only in garments for everyday use, but also in technical and medical products. Medical textiles known as med-textiles belong to a group of textile products, which in the recent years have enjoyed a very rapid development. Knitting technologies are widely used in the production of such textiles, as they allow the production of diverse structures, both flat and spatial ones. Textiles, including knitted fabrics are used among others to produce orthoses.

Orthoses are different kinds of medical or prophylactic products used to support orthopedic rehabilitation. They possess a broad range of applications in the treatment of human locomotor system – bones, joints, ligaments and muscles. Orthoses are defined [1, 2, 3] as different kinds of external constructions supporting particular anatomical regions of the human body, which are used to modify the structural features and operation of motor organs, the neuromuscular system. Nowadays, orthoses are lightweight, ergonomic, comfortable and aesthetic constructions and constitute an alternative to the classical methods of immobilizing parts of the human body using plaster casts.

Orthoses can be classified according to the following three main criteria: anatomical area of the body subjected to treatment, design and construction of the product and the function it is intended to perform [4].

Taking into account the anatomical area of the body subjected to treatment, there are three basic groups of orthoses, which include [4]:
- trunk orthoses:
  - orthoses of cervical spine,
- orthoses of cervico-thoracic spine,
- orthoses of cervico-thoraco-lumbar-sacral area,
- orthoses of thoraco-lumbar-sacral area,
- orthoses of lumbar-sacral spine, supporting the whole or only a part of the lumbar and sacral trunk,
- orthoses of the sacro-iliac area, supporting the whole or only a part of sacroiliac area,
- orthoses of upper limbs:
  - hand orthoses – of fingers or wrist,
  - elbow joint orthoses,
  - shoulder joint orthoses,
- orthoses of lower limbs:
  - orthoses of hip joint and thigh,
  - orthoses of knee joint and lower leg,
  - orthoses of ankle and foot.

Due to the construction and design orthoses can be divided into [4]:
- soft products – made of knitted or woven fabrics, foams and elastic bands, which press the soft tissues from the outside,
- rigid products – made of solid and semi-solid materials, such as light alloys (mainly aluminium, magnesium and titanium), carbon fibers, chrome steel, carbon and Kevlar composites, laminates, solid foamed plastics,
- semi-rigid products - with supporting elements made of metal or plastics, and a soft textile "lining".

In terms of their functions orthosis can be divided into [4]:
- restricting motion,
- stabilizing,
- relieving,
- corrective,
- functional corrective.

A wide range of orthoses makes it possible to use them in case of damage to bones and joints, but also after surgery, in case of neurological and rheumatic disorders, to prevent possible injury during sports, both amateur and competitive.

Design and construction of orthosis should primarily take account of the anatomy of the body section, which will undergo treatment. On the market of medical devices there is a huge selection of ready-made orthoses from mass production, whose sizes are normalized on the basis of standardized anthropometric data on human body construction. In special cases it is also possible to make a customized product for individual patient.
2. Material and research program

The chapter analyzes the construction and design of the assortment of soft and semi-rigid orthoses from the viewpoint of materials used in their manufacturing. Among others, the types of raw materials and stitches of the knitted fabrics were determined.

Fig. 1. Variants of orthoses subjected to tests of selected utility properties
Selected properties of five orthoses (Fig. 1) made of knitted fabrics and used primarily to protect lumbar-sacral and thoraco-lumbar-sacral segments of the spine were also presented. Such properties as thermal resistance, air permeability and unit pressure on the user’s body were determined. The research was conducted as part of the thesis [5]. The tested orthoses are used, among others, in the following medical cases: discopathy, posture defects, degenerative diseases of the spine in the LS region, pain syndrome, congenital anomalies of the lumbar spine, osteoporosis, while stabilizing the patient in functional treatment and after surgery.

3. Construction of orthoses

Analysis of the construction of soft and semi-rigid orthoses revealed their layered structure. Structures composed of at least two, or more often three layers made of knitted or woven fabrics or flexible foams can be distinguished in the construction of these products. Orthoses can be manufactured on flat weft-knitting machines as fully-fashioned elements of a specific shape and dimensions or as seamless products (seamless, Knit & Wear), but they can also be made-up of different kinds of knitted piece goods. Knitted fabrics used in manufacture of orthoses can be made of both weft- and warp-knitted stitches and have flat (Fig. 2, Fig. 3) or spatial form (Fig. 4). They are characterized by different surface structures e.g. smooth (Fig. 2), openwork (Fig. 3, Fig. 4) – enabling rapid moisture absorption from the skin while ensuring proper air permeability, looped, velour – providing adequate heat insulation and sensory comfort.

Orthoses are equipped with tightening bands – rigid or flexible, for better adjustment and control of the pressure exerted on the body during use. Some orthoses are mainly made of orthopedic warp-knitted tapes (Fig. 5), joined together in the making-up process. As a result, their construction is very light, well suited to the curvature of the spine.

Additional non-textile components of orthoses made of metal- the so-called rigid ones, or made of plastics-flexible or semi-flexible (including liners, underwire, clamps and splints) are responsible for stiffening and stabilization of the treated body part.

In case of elements made of plastics manufacturers use two production methods – injection molding and thermoform method. Plastic parts are often made of composite materials, for instance containing glass fibers or carbon fibers improving their quality and durability [8]. Metal parts are produced from structural steels of the highest quality, special high-strength aluminum alloys and spring steel. A very important step in the production of metal elements are finishing processes consisting of a number of operations including galvanic treatment and lacquering to protect steel components against the harmful effects of human sweat [8]. In some orthoses these elements are removable and in others permanently fixed, which greatly complicates the maintenance of these products.
Fig. 2. Weft-knitted fabric with plain stitches

Fig. 3. Warp-openwork structure

Fig. 4. Warp-knitted spacer fabric

Fig. 5. Warp-knitted orthopedic tape

*a*) Lumbo-sacral orthosis made of warp-knitted orthopedic tapes connected in the making-up process [9]

*b*) Lumbo-sacral orthosis made on a flat weft-knitting machine in a fully-fashioned form with rib stitches with a silicone massaging pad [10, 14]

Source: own work.
Fig. 6. Examples of knitted orthoses for treating different body parts

In addition to the elements mentioned above, orthoses may possess additional equipment e.g. silicone or carbon pelottes for better adjustment and massaging pads made of technogel or silicone, ensuring pain relief and reducing swelling.

Analysis of the composition of fabrics used in various types of orthoses showed that textured polyamide yarns of linear density in the range 156–235 dtex and different number of filaments are most frequently used for their production.
In addition, elastomeric yarn is introduced into the knitted structure, as its elastic properties are important for the adjustment and stabilization of the treated body part, but also for shape stability of the orthosis itself. In order to increase the users’ comfort, but most of all their sensory feelings, bare elastomeric yarns are rarely used in the knitted fabrics for manufacturing orthoses. Most often elastomeric threads are chosen, whose core is braided with a polyamide yarn. Linear densities of these yarns vary depending on whether they form knitted loops – lower linear densities e.g. 130 dtex, or whether they are introduced into the structure in the form of weft threads – thicker yarns e.g. 400 tex. The selection of raw material in the form of polyamide yarn is mainly dictated by its positive properties such as high strength and higher abrasion resistance comparing to yarns of natural fibers [3]. These features of polyamide translate into high abrasion and pilling resistance of the finished products, which is especially important during intensive use of the orthoses. Modified polyamide yarns for example Meryl Skinlife with bacteriostatic properties are also frequently used.

Another type of synthetic yarn used in knitted fabrics for manufacturing orthoses is a polypropylene yarn, which is also characterized by high resistance to abrasion, just like the polyamide one. Polypropylene has density equal to 0.90-0.91 g/cm$^3$, which is the lowest of all the natural and chemical fibers, and thus the products made of it are lightweight and give a pleasant grip, which improves the comfort of use [7]. Other advantages of polypropylene, which are of particular importance in manufacturing medical devices is good biological resistance - the material does not cause allergic reactions and reduces the growth of microorganisms, mold and fungi, thus preventing unpleasant odors and skin irritation [7]. Polypropylene yarns are also used in orthopedic rubbers, which are used in the manufacturing of certain types of orthoses.

In addition to synthetic materials, cotton yarns of linear density in the range of 15-30 tex are also used for the production of orthoses to ensure high hygienic comfort.

In the connecting layer of knitted spacer fabrics and in orthopedic rubbers polyamide monofilament yarns are used, with linear density of 33-57 dtex.

All textile raw materials used in medical devices including orthoses should possess all necessary certificates for contact with human skin.

4. Analysis of the tests of selected utility properties of orthoses

Orthoses used to support the lumbosacral sections of the spine should exert pressure on the abdominal wall, so as to increase pressure in the abdomen, which helps to relax the back muscles and sets the spine in the correct position [6]. Only in this way can the orthoses fulfill their therapeutic function. Based on the above premises, measurements were made of unit pressure exerted by the orthoses on the user’s body.

The test of unit pressure was performed by in vivo method – that means in real conditions on volunteers, using a mobile device Kikuhime. The pressure
was measured by means of a sensor (small cushion) made of ultra-thin, biocompatible material into which air was introduced. The sensor was placed between the body and the orthosis in the following places: the side, abdomen and the back – at a proper point of the spine, corresponding to the intended function of the orthosis. The tests were conducted in standing and sitting positions. The pressure detected by the sensor as a result of the action of the product was measured by a digital meter. The study was performed on five users, whose waist circumferences were previously measured, to check whether the value falls within the range specified by the manufacturer of the orthoses. The results of this study are shown in Table 1 and graphs 1 and 2.

Table 1. Measurements results of unit pressure exerted by orthoses (for trunk treatment) on the user’s body

<table>
<thead>
<tr>
<th>Variant</th>
<th>Waist circumferences</th>
<th>Unit pressure values P [mmHg]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Waist circumference of the user [cm]</td>
<td>Circumference of the orthosis in free state [cm]</td>
</tr>
<tr>
<td></td>
<td>side abdomen spine side abdomen spine</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>72 64</td>
<td>16 20 2</td>
</tr>
<tr>
<td>II</td>
<td>83 76</td>
<td>18 32 3</td>
</tr>
<tr>
<td>III</td>
<td>83 78</td>
<td>33 38 1</td>
</tr>
<tr>
<td>IV</td>
<td>83 76</td>
<td>18 20 1</td>
</tr>
<tr>
<td>V</td>
<td>99 86</td>
<td>41 24 4</td>
</tr>
</tbody>
</table>

Source: own work.

Graph 1. Values of unit pressure between the orthosis and the body measured on the abdomen and the side of the user’s body in standing position

Graph 2. Values of unit pressure between the orthosis and the body measured on the abdomen and the side of the user’s body in sitting position

Source: own work.
The study showed that orthoses used for orthopedic support in the trunk area are characterized by different values of unit pressure exerted on the user's body. The pressure values vary, depending on the position of the user during the test i.e. standing or sitting, and the point of measurement, i.e. the side, abdomen or spine. The highest values of pressure on the user's body are observed on the abdomen in sitting position. An exception is the thoraco-lumbar-sacral orthosis (variant V), in case of which the pressure takes higher values on the side in both standing and sitting position. It should be noted that this orthosis possesses in its structure a larger number of flexible tightening bands than the other tested products. These bands significantly increase the pressure exerted on the user’s body, especially on the sides. The lowest pressure values were recorded on the spine, which results from the construction of the human body, as the spine is situated in the back recess (natural curvature of the spine).

The study showed that orthoses can be regarded as compression products as the pressure exerted on the abdomen in standing position was in the range from 20 to 38 mmHg, while in the sitting position - in the range from 23 to 45 mmHg. Taking into account the obtained results, the tested orthoses can be included in the I or II compression class.

Orthoses should ensure proper body temperature in the spine area, which speeds up the healing process. The heat causes loosening of tight muscles and reduces pain. Therefore, thermal resistance of the products was determined using the Alambeta device [15], and the measurements were made in ten points on each orthosis. Average values of the tests results are given in Table 2 and on graph 3.

### Table 2. Average values of thermal resistance for tested orthoses

<table>
<thead>
<tr>
<th>Variant</th>
<th>Thermal resistance $R*10^{-3}$ [W$^{-1}$Km$^2$]</th>
<th>Standard deviation [W$^{-1}$Km$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>94,380</td>
<td>5.45</td>
</tr>
<tr>
<td>II</td>
<td>101,520</td>
<td>6.99</td>
</tr>
<tr>
<td>III</td>
<td>60,120</td>
<td>3.37</td>
</tr>
<tr>
<td>IV</td>
<td>57,060</td>
<td>3.17</td>
</tr>
<tr>
<td>V</td>
<td>57,060</td>
<td>3.17</td>
</tr>
</tbody>
</table>

The analysis of thermal resistance measurements results showed that the greatest values of this parameter were achieved for variants I and II made in fully-fashioned form on flat weft-knitting machines, from polyamide textured
yarns and braided yarns, whose core constituted elastomeric yarn and the braid-polyamide yarn. Thermal resistance \( R \) for these products equals respectively \( 94.380 \times 10^{-3} \) W\(^{-1}\)Km\(^2\) and \( 101.520 \times 10^{-3} \) W\(^{-1}\)Km\(^2\). These two variants of orthoses were twice as thick as the other products, they also possessed in the inner layer an additional warp-knitted spacer fabric. From the above characteristics it follows that protection against heat loss during use of such products is greater than in case of the three remaining orthoses.

Air permeability is one of the factors influencing hygienic properties of the products and shaping the parameters of the microclimate under it. It improves the ventilation of the body, and accelerates the removal of perspiration from the skin to the environment. Therefore air permeability values were measured for each variant [16].

<table>
<thead>
<tr>
<th>Variant</th>
<th>Air permeability ( P ) [dm(^3)/m(^2)s]</th>
<th>Standard deviation [dm(^3)/m(^2)s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>318.64</td>
<td>17.17</td>
</tr>
<tr>
<td>II</td>
<td>369.47</td>
<td>17.31</td>
</tr>
<tr>
<td>III</td>
<td>1558.46</td>
<td>93.90</td>
</tr>
<tr>
<td>IV</td>
<td>322.25</td>
<td>12.91</td>
</tr>
<tr>
<td>V</td>
<td>304.19</td>
<td>11.08</td>
</tr>
</tbody>
</table>

*Source: own work.*

Analysis of the tests results showed that air permeability \( P \) for each orthosis falls in the range from 318.64 to 1558.46 dm\(^3\)/m\(^2\)s. Comparison of the results shown in Table 3 and graph 4 proves that the third variant made of warp-knitted orthopedic tape has the highest average value of air permeability. This is due to the structure of the tape, which possesses free spaces between the wales, significantly increasing air permeability. Based on the classification of textile materials in terms of air permeability [17], it can be concluded that variants I, II, IV, and V are characterized by medium, and variant III by good air permeability.

5. Conclusions

1. Orthoses are characterized by complex, layered structure. They are made of textile materials, knitted and woven fabrics, elastic orthopedic tapes made with different stitches of synthetic and natural yarn, as well as with non-textile parts, which may include liners, underwire, clamps and splints.
Non-textile details are made of metal or plastics, composite materials containing glass or carbon fibers. In addition to the items listed above, orthoses may have additional equipment in the form of silicone or carbone pelottes and massaging pads made of technogel or silicone, bringing pain relief and reducing swelling. Due to their complex structure, orthoses can fulfill their healing functions and ensure high comfort for the user.

2. The study showed that orthoses used to support the lumbar-sacral segment of the spine can be regarded as compression products. Their function is to exert pressure on the abdominal wall, which relieves back muscles and sets the spine in correct position. The results showed that products used for orthopedic treatment in the trunk area are characterized by different values of unit pressure of the orthosis on the abdomen. The obtained pressure values are in the range from 20 to 38 mmHg in standing position, and from 23 to 45 mmHg in sitting position. Accordingly, the tested products may be classified as I (mild) or II (moderate) compression class.

3. The study showed that the best protection against heat loss is provided by orthoses made on flat weft-knitting machines from polyamide yarns with the participation of elastomeric yarn, additionally reinforced in the inner layer with a warp-knitted spacer fabric. Providing adequate thermal protection of the spine area is an important characteristic of such products, because heat accelerates the healing process.

4. Tests have proven that orthoses can be classified as products of medium and very good air permeability. As a result, they provide adequate ventilation close to the skin.

Bibliography

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Chapter III
TECHTEX
MICROMECHANICAL DESCRIPTION
OF THE STRENGTH OF COMPOSITE LAMINATES

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1. Introduction

In the chapter a problem of the influence of composite lamina constituents on its strength properties is considered with the aim to get possibly simple and easy to apply formulas describing basic strength characteristics. Analysis is confined to the fiber composites with epoxy matrix i.e. the most widely used type of composite materials. The most important factor, which has to be taken into account is heterogeneity of a laminate’s ply, though fibers and matrix are – separately – homogenous materials. In some cases, depending on type of fibres (e.g. carbon fibers, Kevlar, etc.), their anisotropy should also be considered.

The issue of the impact of composite ply ingredients distinguishable at microscopic level on macroscopic composite properties is possible in the frame of micromechanics of composite materials. It is now well developed branch of the mechanics of composites. However, it must be emphasized, that microscopic strength analysis is significantly less recognized than e.g. stiffness analysis and is in fact confined to the tensile and compressive strength. The present chapter gives a general review of fundamental ideas and solutions in this field and is thought as a kind of brief „user’s manual” for people who are customized with composite materials, but not necessarily with their mechanics and micromechanics.

Macroscopic analysis of the laminate load carrying capacity is based on the on-axis characteristics of a single laminate’s ply. Therefore, the basic goal of micromechanics relevant for that class of composites is to determine on-axis strength parameters as a functions of the characteristics of fibers and matrices. It can be written in the following form:

$$X = X(X_m, X_f, v_m, v_f)$$

where: $X$ denotes given strength characteristic of a ply, $X_m$, $X_f$ – appropriate strength constants for matrix and fibers, $v_m$ and $v_f$ denote the volume fraction of matrix and fibers, respectively.
At the present time the perfectly accurate and simultaneously simple, theoretical model suitable for determination of the lamina’s strength parameters depending on matrix and fibers characteristics does not exist. An approach presented in the chapter, based on the mechanics of materials appears to be the simplest and therefore it is the most frequently used in practical applications.

The readers being interested in that subject can find more details in e.g. monograph by Jones [3] and in Delaware Composite Encyclopedia [1], [7], [8], [9].

2. Tensile strength $X_t$ in fiber direction

2.1. Fibers of equal strength

Let us consider a single ply od unidirectional fiber composite subjected to the tensile force $F$ in fiber direction. The theoretical idealization of a real ply is based on the separation of the fibers and matrix. Constituents are concentrated in two separated areas i.e. there is no contact between those two regions. In terms of the theory of so-called structural material models it means the parallel connection of fiber region and matrix region. It is shown in Fig. 1. Notation used in the chapter is as follows:

- $X_f$ tensile strength of fibers,
- $X_m$ tensile strength of matrix,
- $X_t$ tensile strength of the composite lamina,
- $\varepsilon_f^*$ ultimate tensile strain for fibers,
- $\varepsilon_m^*$ ultimate tensile strain for matrix.

![Fig. 1. The ply of fiber composite and its micromechanical model](image)
The analysis of the theoretical model of a composite ply is based on the following assumptions:

- both fibers and matrix are linearly-elastic up to the failure (see Fig. 2),
- the fibers are of equal strength,
- longitudinal strain of the matrix and fibers is the same,
- the failure of fibers and matrix does not influence the unidirectional state of stress within the ply.

Micromechanical model is generally accepted, despite simplifying assumptions, because it gives reasonable description of the composite ply strength as a function of the strength and volume fraction of the matrix and fibers.

Fig. 2. Linear-elastic relationship stress vs. strain for fibers and matrix

Source: own work.

The unidirectional state of stress in fibers and matrix is described by the Hooke’s relations:

$$\sigma_f = E_f \varepsilon_f, \quad \sigma_m = E_m \varepsilon_m$$  \hspace{1cm} (2)

External force $F$ is distributed among fibers and matrix, as follows:

$$F_f = \sigma_f A_f = E_f v_f \varepsilon A, \quad F_m = \sigma_m A_m = E_m v_m \varepsilon A$$  \hspace{1cm} (3)

where: $A$, $A_f$, $A_m$, $v_f$, $v_m$ denote the area of a ply cross-section, total area of fibers, total area of matrix, volume fraction of fibers and matrix, respectively. Therefore, we have:

$$F = \varepsilon A \left( E_f v_f + E_m v_m \right)$$  \hspace{1cm} (4)
The ultimate forces corresponding to the ultimate tensile strains for matrix and fibers are equal:

\[ F'_m = E_m \nu_m \varepsilon'_m A = X_m \nu_m A, \quad F'_f = E_f \nu_f \varepsilon'_f A = X_f \nu_f A \]  \hspace{1cm} (5)

The composite constituents are intact until strain at given load \( F \) does not reach the ultimate value for fibers or matrix. The subsequent “scenario” of a composite ply behaviour depends on which of constituents reaches the strength as the first one. The three cases are potentially possible, namely:

- case I – \( \varepsilon_f^* < \varepsilon_m^* \) (fiber “more brittle” than matrix),
- case II – \( \varepsilon_f^* > \varepsilon_m^* \) (matrix “more brittle” than fibers),
- case III – \( \varepsilon_f^* = \varepsilon_m^* \) (matrix and fibers “equally brittle”).

**Case I – “brittle” fibers, “ductile” matrix**

Inequality \( \varepsilon_f^* < \varepsilon_m^* \), which is equivalent to the relation:

\[ \left( \frac{E_m}{E_f} \right) < \left( \frac{X_m}{X_f} \right) \]  \hspace{1cm} (6)

means, that failure occurs in fiber first. Note, that in real composites fibers strength is strongly greater than matrix strength and as a consequence we get an inequality between elasticity moduli \( E_m < E_f \).

The external load \( F' \) resulting in fibers failure is equal:

\[ F' = \varepsilon'_f A \left( E_f \nu_f + E_m \nu_m \right) = X_f A \left[ \nu_f + \left( \frac{E_m}{E_f} \right) \nu_m \right] \]  \hspace{1cm} (7)

The external load can be now carried out only by the matrix, but it depends on the ratio of the load \( F' \) and the ultimate force \( F_m^* \). There are possible two situations, namely:

1. load \( F' > F_m^* \) – matrix failure occurs simultaneously with fibers failure i.e. ultimate load for a composite ply is equal load \( F' \),
2. load \( F' < F_m^* \) – external load can increase up to the value \( F_m^* \) and therefore failure of the matrix means also ply failure.

The above two possibilities are dependent on fibers volume fraction. The threshold value \( \nu_f^* \) one can obtain from the condition \( F' = F_m^* \). After simple calculations we get the tensile strength of a composite ply reinforced “brittle” fibers \( X_f \) in the following form:

\[ X_f = \begin{cases} \frac{F'}{A} = X_m \nu_m = X_m (1-\nu_f) & \text{for } 0 \leq \nu_f < \nu_f^* \\ \frac{F'}{A} = X_f \left[ \nu_f + \left( \frac{E_m}{E_f} \right) (1-\nu_f) \right] & \text{for } \nu_f^* < \nu_f \leq 1 \end{cases} \]  \hspace{1cm} (8)

It is shown in Fig. 3.
Micromechanical description of the strength of composite laminates

Fig. 3. Tensile strength of a composite ply as a function of the fibers volume fraction (“brittle” fibers, “ductile” matrix)

Source: own work.

Figure 3 allows conclude that influence of the fibers on composite ply strength is following:

- if fiber volume fraction is smaller than $v_f^*$ the tensile strength of a ply is worse than tensile strength of matrix alone. Taking into account that the fibers strength is many times greater than matrix strength – it must be seen as curious and unexpected result. Fibers are in this case a kind of stress concentrators making material weaker. Within the range $0 \leq v_f < v_f^*$ composite strength is basically controlled by matrix,

- adding the fibers in a volume bigger than $v_f^*$ causes the strength growth, but the composite ply strength is bigger than matrix strength beginning from a critical fibers volume fraction $v_f^{cr}$. It means, that fibers in a real way improve a composite strength. Within the range $v_f^* \leq v_f \leq 1$ composite strength is controlled by the fibers.

**Case II – „brittle“ matrix, „ductile“ fibers**

This case is defined by an inequality $\varepsilon_f^b > \varepsilon_m^*$, which means that the matrix fails first and the subsequent composite’s behaviour is determined by the volume fraction of fibers. The analysis is very similar to that for case I. We limit ourselves to give only the results of calculations. Tensile strength of a composite ply is given by the equation:

$$X_t = \begin{cases} X_m \left[1 - v_f \left(1 - E_f / E_m\right)\right] & \text{for} \quad 0 \leq v_f < v_f^{*}\lor\ \varepsilon\lor\ v_f^{*} < v_f \leq 1 \\
X_f v_f & \end{cases}$$

(9)
Relation (9) is shown in Fig. 4 for the ratio $E_f / E_m$ greater than one. It is obvious that any volume fraction of fibers causes growth of composite ply strength. This effect is more strongly visible if $v_f$ is over the limit value $v_f^{**}$. The critical volume fraction of fibers does not exist in that case.

**Fig. 4.** Tensile strength of a composite ply as a function of the fibers volume fraction (“brittle” matrix, “ductile” fibers) for $E_f > E_m$

*Source: own work.*

**Case III – matrix and fibers equally “brittle”**

The condition $\varepsilon_f^* = \varepsilon_m^*$ is equivalent to the condition:

$$\left(\frac{E_m}{E_f}\right) = \left(\frac{X_m}{X_f}\right)$$

The failure occurs simultaneously both in fibers and matrix. The solution results directly from eq. (8b) and is valid for any value of $v_f$ and has the following form:

$$X_t = X_m v_m + X_f v_f$$

Equation (11) is called rule of mixture for the tensile strength of a ply of the composite laminate. It is shown in Fig. 5.
Micromechanical description of the strength of composite laminates

Fig. 5. Tensile strength of a composite ply as a function of the fibers volume fraction (matrix and fibers equally „brittle”) for \( E_f = E_m \)

*Source: own work.*

Tensile strength of the typical fibrous composites

Let us illustrate the results obtained in point 2.1 applying data for typical fibrous composites with polymeric matrix reinforced with most often used fibers. They are given in the Table 1.

Table 1. Tensile strength, elasticity moduli, ultimate strains, threshold and critical volume fractions for typical fibers and epoxy matrix

<table>
<thead>
<tr>
<th>FIBERS</th>
<th>MATRIX</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Graphite UHM *)</td>
</tr>
<tr>
<td>( X ) [MPa]</td>
<td>1030</td>
</tr>
<tr>
<td>( E ) [GPa]</td>
<td>520</td>
</tr>
<tr>
<td>( \varepsilon^* ) [%]</td>
<td>0.2</td>
</tr>
<tr>
<td>( v_f^* ) [%]</td>
<td>5.33</td>
</tr>
<tr>
<td>( v_f^{**} ) [%]</td>
<td>–</td>
</tr>
<tr>
<td>( v_f^{cr} ) [%]</td>
<td>5.68</td>
</tr>
</tbody>
</table>

*) Ultra High Modulus ***) High Modulus ***) High Strength

*Source: different literature sources – e.g. (1, 3, 6 and own work).*
From the data in Tab. 1 follows that:

- $E_t > E_m$, $X_t > X_m$
- the case of "brittle matrix" (i.e. when $\varepsilon_m^* < \varepsilon_f^*$), is possible for both glass fibers and for Kevlar 29. Taking into account previous considerations – it can be concluded that fibers of any volume improve tensile strength of a composite ply,
- the case of "brittle fibers" (i.e. when $\varepsilon_m^* > \varepsilon_f^*$), is possible for graphite fibers and for Kevlar 49. Taking into account previous considerations – it can be concluded that fibers improve tensile strength of a composite if volume fraction of fibers exceeds the critical values given in Table 1.

Normalised (dimensionless) tensile strength $X_t/X_m$ of a composite ply is shown in Fig. 6, which is based on data taken from Table 1. Fig. 6B shows the results for the range $0 \leq v_f \leq 0.2$.

Fig. 6. Normalized strength of composite ply as a function of the fiber volume fraction

Source: own work.

Fig. 6 shows, that formulation of general conclusions regarding effectiveness of the specific fibers by means of their influence on growth of composite ply tensile strength is possible only for $v_f$ above approx. 0.4 (note, that in real fibrous composite $v_f$ is within the range (0.4-0.7). Let us conclude that:
Micromechanical description of the strength of composite laminates

- the largest increase of a composite ply strength comparing with matrix strength for a given fibers volume fraction we get reinforcing matrix with glass fibers „S”, graphite HS and then subsequently Kevlar 49, graphite HM and finally glass „E”,

- in order to get the same increase of a composite ply strength we have to use the smallest amount by volume of fibers: glass „S”, graphite HS, Kevlar 49, graphite HM and finally glass „E”.

Interesting observations follow from the correlation of those qualitative conclusions with the material characteristics of fibers and matrix given in Table 2. One can conclude that:

- the strength of a composite ply is determined mainly by the strength characteristics of matrix and reinforcement. The bigger ratio of fibers strength to the matrix strength (see Table 2) the bigger fibers effectiveness (see Fig. 6A) i.e. it is reasonable to reinforce “weak” matrix with the “strongest” fibers. In the real composites the mentioned ratio is so large that it can be stated that composite strength is determined substantially entirely by fibers,

- elastic properties of the matrix and fibers are of secondary importance from the point of view of a composite strength.

Table 2. Normalized (dimensionless) strength and elasticity modulus of the typical fibers

<table>
<thead>
<tr>
<th>FIBERS</th>
<th>Glass ”S”</th>
<th>Graphite HS</th>
<th>Kevlar 49</th>
<th>Graphite HM</th>
<th>Glass ”E”</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_f / X_m$</td>
<td>38.5</td>
<td>38.2</td>
<td>34.9</td>
<td>27.5</td>
<td>26.2</td>
</tr>
<tr>
<td>$E_f / E_m$</td>
<td>0.040</td>
<td>0.015</td>
<td>0.028</td>
<td>0.0095</td>
<td>0.049</td>
</tr>
</tbody>
</table>

Source: own work.

Summary

Let us summarize the most important conclusions regarding the tensile strength in fiber direction of the fibrous composite ply of plastic matrix. They are as follows:

- the relations between elastic and strength characteristics of the fibers and matrix are always following:
  \[ E_t > E_m \quad \text{and} \quad X_t > X_m, \]  
  (12)

- taking into account a real volume fraction of fibers of order 40-70% – the threshold values $v_f^*$ and $v_f^{**}$, as well as critical value $v_f^{cr}$ – being much smaller – do not have much meaning for the choice of the relationship defining composite ply,

- if the elastic and strength characteristics satisfy the inequality $(E_m/E_f) < (X_m/X_f)$ the composite ply strength is equal:
  \[ X_t = X_t \left[ v_t + \left( \frac{E_m}{E_t} \right) v_m \right] \]  
  (13)
• if the elastic and strength characteristics satisfy the inequality \((E_m/E_f) > (X_m/X_f)\) the composite ply strength is equal:
\[
X_i = X_f \nu_i \quad (14)
\]
• if the elastic and strength characteristics satisfy the equality \((E_m/E_f) = (X_m/X_f)\) the composite ply strength is described by the rule of mixture:
\[
X_i = X_f \nu_i + X_m \nu_m \quad (15)
\]
• taking into account that the ratio \(E_m/E_f\) is of order 0.01-0.05, \(X_f/X_m\) is of order 26-40 (see Table 2) and volume fraction of the matrix is within range (0.3-0.6) the rule of mixture can be seen as the suitable formula for each of the listed above cases.

2.2. Fibers with random distribution of the strength

The analysis presented in point 2 were based on the assumption, among others, that the strength of each fiber is the same. It means that all fibers are subjected to failure simultaneously. In a real composite materials situation is more complex, as strength of fiber is changing along its length due to e.g. the existence of a surface defects, thus the strength of a ply is random variable. It is obvious that some fibers to be broken under lower load, while the other ones under higher load. It causes that after failure of some fibers there are possible different mechanisms of subsequent damage of a composite depending on the characteristics of a matrix and its connection with the fiber. Basically, they are two possible mechanisms of the composite damage. If the matrix-fiber interface is very strong and the matrix is brittle – the cracks initiating on the broken fibers propagate through the matrix and then they “cut” another fibers. This process leads to the final destruction of a composite. The second mechanism relates to the composites with weak interface between matrix and fibers or the matrix is relatively ductile (i.e. the yield stress of the matrix is low). In this case the cracks reaching the matrix-fiber interface start to propagate along the fiber direction and cause the debonding effect. Both mechanisms are shown in Fig. 7.

![Fig. 7. The mechanisms of the failure of a composite ply under tension: A. transverse cracking, B. longitudinal debonding on the matrix-fiber interface](image)

*Source: different literature sources – e.g. (1, Vol. 2).*
The second type of a ply failure under tensile load in fiber direction is characterised basically by the separation of broken fibers and intact fibers, thus a composite starts to behave like a fiber bundle. Let us assume, that for a given external load the strain in all fibers is identical and equal $\varepsilon$. The probability that the fiber does not break at the strain level $\varepsilon$ is following:

$$R(\varepsilon) = \exp\left[-L(\varepsilon/\varepsilon_0)^\alpha\right]$$

(16)

where: $L$ means the fiber length, $\varepsilon_0$ and $\alpha$ are constants. Schematic diagram of a probability function is shown in Fig. 8.

![Fig. 8. Probability of the fiber is intact as a function of strain](Source: own work.)

The net stress (i.e. related to the area of intact fibers) in the bundle fibers is equal:

$$\sigma = E_r \varepsilon R(\varepsilon) = E_r \varepsilon \exp\left(- L \varepsilon_0^{-\alpha} \varepsilon^{\alpha}\right)$$

(17)

The fiber bundle is assumed to be broken if it will not able to take any further increase in load. Using statistical distribution by Weibull and conducting relevant calculations we get relationship between fiber bundle strength $X_b$ and single fiber strength $X_f$ in the following form:

$$\frac{X_b(L)}{X_f(L)} = \frac{1}{(\alpha \varepsilon)^{\frac{1}{\alpha}}} \frac{\Gamma\left(1+\frac{1}{\alpha}\right)}{\Gamma\left(1+\frac{\alpha}{\alpha}\right)}$$

(18)

where $\Gamma$ denotes Euler’s gamma function.
The graph of equation (18) is shown in Fig. 9. The values of the gamma function are taken from work [4].

Fig. 9. The ratio of the fibers bundle strength to a single fiber strength as a function of a variation coefficient

*Source: own work.*

Tsai and Hahn [6] proved, that a coefficient $1/\alpha$ is very close to the value of the coefficient of fiber strength variation $^{*}$ i.e. it is a measure of its dispersion. Fig. 9 shows, that the bigger fiber strength dispersion, the strength of fibers bundle is becoming smaller relative to the strength of a single fiber.

Using statistical approach to the tensile strength of a composite ply, presented in the present chapter, Rosen [5] considered a mixed model combining both mechanisms i.e. transverse and longitudinal cracking. He assumed, that failure occurs partially transversely to the fiber direction and partially in fiber direction. Rosen’s model is based on the assumption, that composite is destroyed if within the interaction zone of broken fibers of the length $\delta$ - the remaining fibers being earlier intact are going to be also destroyed. Rosen calculated the length of interaction zone $\delta$ in the form:

$$
\delta = 2D \left( \frac{X_f}{4S_m} \right)^{\alpha+1} \left[ (\alpha + 1) \frac{L}{D} \right]^{\frac{1}{\alpha+1}}
$$

(19)

where: $D$ denotes fiber diameter, $S_m$ means shear strength of the matrix.

---

$^{*}$ The coefficient of a variation of the random variable is equal to the ratio of standard variation of that variable and its expected value.
The tensile strength of a composite ply is assumed to be equal the strength of fibers bundle of length $\delta$, plus the matrix strength. The tensile strength calculated in the described manner is given by the following equation:

$$X_t = X_b(\delta) \nu_t + \sigma_m^* \nu_m$$  \hspace{1cm} (20)

where $\sigma_m^*$ denotes the stress in matrix associated with the composite ultimate stress:

$$\sigma_m^* = \left(\frac{E_m}{E_t}\right) X_t$$  \hspace{1cm} (21)

The calculations made for a case being analysed lead to the following equation for tensile strength:

$$X_t = \frac{1}{\left(\alpha \beta\right)^{\eta \alpha}} \frac{L}{(1+1/\alpha)} \left(L \frac{\nu_t}{\delta}\right)^{\psi \alpha} X_t(L) + \frac{E_m}{E_t} X_t \nu_m$$  \hspace{1cm} (22)

3. Compressive strength $X_c$ in fiber direction

The failure of a composite ply subjected to the compressive load in fiber direction is associated with in-plane fibers buckling. The matrix plays in that case much more important role than for tensile load, because it is kind of support for the fibers impeding their buckling.

There are two types of fibers buckling, they are shown in Fig. 10.

![Fig. 10. Fibers buckling in compressed composite ply: A. transverse mode, B. shear mode](source)

*Source: different literature sources e.g. (2, 3).*
Type A is characterized in that adjacent fibers are buckling symmetrically with respect to the center line running between fibers. Mode A of buckling is called transverse (or extensional) because the matrix between the fibers due to their buckling is subjected to the tension and compression in transverse direction to the fibers.

In mode B of buckling the fibers are in phase one to each other i.e. they are antisymmetric with respect to the center line running between fibers. It causes that the matrix is subjected to shear. It justifies the term „shear mode”. Each type of buckling leads to different estimates of a composite ply strength under compressive load. The lower value is assumed to be the authoritative one.

Theoretical model is based on the following assumptions: the fiber is a rod of rectangular cross-section dimensions $h \times t$ and the length $L$ and is entirely embedded in the matrix, the fiber is subjected to the compressive force $F$, the fiber buckling occurs in the linear elastic range in a plane $(x, y)$. The shear effect of the fibers is omitted being of the secondary importance comparing with matrix shear (it is justified by the relationship between matrix shear modulus and fiber shear modulus $G_f >> G_m$).

Summary

- the compressive strength of a fibrous composite ply is determined by the critical stress at buckling of the fibers, which can be of the two types, namely transverse and shear type,
- the compressive strength corresponding to the transverse mode is determined basically by the fibers deflection,
- the compressive strength corresponding to the shear mode is primarily associated with the matrix shear,
- depending on the buckling mode – the compressive strength $X_c$ of a composite ply is given by the following relations:

$$X_c = \begin{cases} 
2 \frac{\nu_f E_f E_m}{3(1-\nu_f)} \left[ \nu_f + \frac{E_m}{E_f} (1-\nu_f) \right] & \text{for } 0 \leq \nu_f \leq \bar{\nu}_f \\
\frac{G_m}{1-\nu_f} & \text{for } \bar{\nu}_f \leq \nu_f
\end{cases}$$

(23)

In the chapter only basic concepts for tensile and compressive strength in frame of the micromechanics of composite have been discussed. The reader who is interested in wider and detailed micromechanical analysis of such a problems as e.g. stiffness characteristics, thermal properties, effective fibers length and other can find a variety of solutions in [1-3], [6-9] and many other monographs on mechanics of composites.
Bibliography


1. Introduction

In order to improve the interlaminar properties of 2D laminates, three dimensional structures where developed by using different manufacturing techniques such as weaving, knitting, braiding and stitching. A structure woven over all three axes (X-axis, Y-axis and Z-axis) is called a 3D woven structure. With this type of structure, materials with fiber volume fraction up to 70% can be created. Also, a very wide selection of shapes and sizes can be manufactured.

In these 3D structures, yarns may be woven into several layers in order to join these layers together. This gives them a great advantage over laminated materials because of their excellent resistance to layer delamination.

A composite material, is a solid material which is a result of combining two or more different substances. Each individual substance has its own characteristics, and when put together they create a new substance whose properties are superior to those of the original components in a specific application [1, 2].

There are a lot of different kinds of composites:
- Composite building materials like cement and concrete,
- Metal composites,
- Ceramic composites.
- Fiber-reinforced polymers [3].

The last one “fiber-reinforced polymer” is the composite which is used very often in different applications. There are different kinds of fiber reinforced polymers, each with their own advantages and disadvantages as can be seen in Figure 1.
Composites produced from 3D woven structure have higher delamination resistance, ballistic damage resistance and impact damage tolerance. These properties have been a major issue in the composites produced with traditional 2D weaving, and they will increase the number of available applications for 3D woven composites. Moreover, nowadays 3D woven composites are mostly found in engine parts, beams of civil infrastructure and aircrafts.

The aim of this work was to design and realize a 3D shape woven fabric. In order to achieve our objective, first it was necessary to find an application, second designed the shape and finally produced it. Moreover, once built, it was possible to study its mechanical properties and improve it.

The ladder was chosen because the ladder is an original idea where all the aspects of 3D structure of woven composite are involved. The ladder can be very useful innovation.

The ladder could be used in helicopter, escape and mountain ladder. This type of ladder has a soft part (the rail) and a stiff part (the rung).

2. Specification of the ladder

In order to find fibres, resins and how to make the ladder, specifications are required.

They are based on conventional ladder founded on the market and focus on its rolling function and ecological footprint.
Chapter III. Techtex

Table 1. Specifications of the ladder

<table>
<thead>
<tr>
<th>Functions</th>
<th>Criteria</th>
<th>Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be able to carry 2 people</td>
<td>Strength</td>
<td>200 kg</td>
</tr>
<tr>
<td></td>
<td>Size of a square</td>
<td>50x34</td>
</tr>
<tr>
<td></td>
<td>Rung</td>
<td>Strong</td>
</tr>
<tr>
<td></td>
<td>Robust</td>
<td>Good impact strength</td>
</tr>
<tr>
<td>Adapt to a shape</td>
<td>Rope</td>
<td>Soft</td>
</tr>
<tr>
<td></td>
<td>Long</td>
<td>10 m</td>
</tr>
<tr>
<td>Respect environment</td>
<td>Life</td>
<td>5 years</td>
</tr>
<tr>
<td></td>
<td>Weather resistant</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ecologic</td>
<td>80% of recyclable materials</td>
</tr>
<tr>
<td>Transportation</td>
<td>Weight</td>
<td>1 kg/m</td>
</tr>
<tr>
<td></td>
<td>Rollable</td>
<td>In box 60 cm x 60 cm x 60 cm for 5 m ladder</td>
</tr>
</tbody>
</table>

Source: own work.

Table 1 shows some specifications:
- Strength of the ladder is thought to carry two people at the same time, each weighing maximum 200 kg.
- To decide the size, some research was conducted and some regulations about the dimensions were found [4]. For example, the minimum distance between rails is 29 cm.
- The application has been thought to have a negligible environmental impact, so the materials used have to be 80% recyclable.
- The final product should be light to be easy to carry.

These are the specifications to be achieved. However, when the prototype is finalized some analysis or tests will be done to check if the ladder is able to fits these requirements.

3. Materials

Natural fibres have some advantages. Indeed, the production has low cost, less chemicals products are used for the manufacturing more over those fibres can be recyclable. The research was focused on density, tensile strength, young’s modulus, elongation at failure and price [5, 6, 7]. Synthetic fibres are based on synthesized polymers. The compounds used to make these fibres come from raw materials such as chemicals or petrochemicals molecules or minerals. Different molecules are used to make diverse types of fibres. They also have a better life expectancy than natural fibres. Properties are also better against external aggression such as the weather, water, moisture, oil or sunlight. The same research was conducted for synthetic fibres as for naturals.
Finally, after comparing fibres, the flax fibre was chosen. It is the best compromise between price and properties. Indeed, this fibre has a low price when compared with synthetic fibres. Also it has the best properties of natural fibres. Moreover, synthetic fibres have really high properties that they are not necessary in the application. Also, they are less respectful for the environment [8, 9, 10].

**Strength test of yarns**

Three types of flax fibres yarn from Safilin company was tested: Tex 200, Tex 400 and Tex 2000. Tests were done with a strength machine in order to determinate the average strength of a single yarn. The maximum force of this machine is 1 kN and the speed was 250 mm/min. The test was done according to the standard EN ISO 2062:1995 [11]. The test has been done in laboratory of Institute of Architecture of Textile. Each test has been done 10 times.

![Strength test of flax fibres yarn](source: own work)

Tex 2000 is the most suitable fibre with an average strength of 119.4N. It will be used to weave the ladder. The strength and strength per amount of material (called specific strength) is the best of Tex 2000 yarn.
Table 2. Figure of specific strength

<table>
<thead>
<tr>
<th>Linear density [Tex]</th>
<th>Strength average [N]</th>
<th>Specific strength average [N*km/g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>7.6 ± 1.2</td>
<td>0.038</td>
</tr>
<tr>
<td>400</td>
<td>20.9 ± 5.2</td>
<td>0.0523</td>
</tr>
<tr>
<td>2000</td>
<td>119.4 ± 37.5</td>
<td>0.0597</td>
</tr>
</tbody>
</table>

Source: own work.

Table 2 shows that the specific strength of the Tex 2000 yarn is the best. Secondly, the Tex 2000 yarn is the biggest and strongest one, this means that also the cheapest one to use for manufacturing. If Tex 200 yarns were used, the amount of warp yarns would be more than 10 times as much, this production would consume more time, which makes manufacturing more difficult and expensive.

Woven structure

The ladder consists on rails on each side and one rung connecting the two rails, as shown in figure 24. To perform it, it is necessary to calculate how many yarns are needed or know how the structure should be [12, 13, 14].

![Fig. 3. Draft of ladder](source: own work)

The rails will have only a tensile load, this means that the shape of the rail will have no influence on its strength. Both rails will have a square shape, this makes it easier to go from rail to rung and back. For the weaving, Tex 2000 is used both warp and weft. The ladder has to be able to carry 200 kg (2000 N) so this means the number of strings in the rail is 32 yarns 16 on each side.

For the rung, it is important to be very stiff. This means that the shape of the rung is of significant importance. The parameter for the stiffness is bending resistance also known as surface moment of inertia. The H-shape is the most
suitable, because it has relatively has the most material on the outer side. On the other hand, it is necessary to know how many yarns it is needed to do the rung shape. The rung will be made with 20 yarns.

4. Production of ladder

The weaving stand has the ability to weave in 3D, unlike most other machines which can only produce in 2D. This weaving frame is old, but relatively easy to use. The weaving stand is in the Institute of Architecture of Textile laboratory.

![Image of weaving stand](source: own work.)

Fig. 4. The weaving stand for 3D woven stricture production

Source: own work.

![Weave structure on the: A) rail 16+20 yarns, B) rail 16 yarns, C) rung in H shape 16 yarns](source: own work.)

Fig. 5. Weave structure on the: A) rail 16+20 yarns, B) rail 16 yarns, C) rung in H shape 16 yarns

Source: own work.
The best way to make a good structure without cutting the yarns, so all the ladder will be made in the same peace of yarn. The process of weaving of ladder was divided for few steps:
- Weave the two rails separately,
- Weave the rung along one rail,
- Move the rung to the opposite side,
- Attach the rung to the second rail,
- Continue weaving the rails,
- Do the same with the rung (weave it and attach to the other rail).

In one rail will be 16 yarns and in the second rail 16+20 (to make rung) yarns. Secondly, to make the 3D structure the yarns have to be connected. Figure 5 show how the yarns were connected. The figure 6 show the process of weaving.

![Image of weaving process](image)

**Fig. 6. The process of weaving**

*Source: own work.*

Once finish, in order to make the rungs strong have been put epoxy resin. The resin has to enter inside the rung because all the fibres should be impregnated of resin, so some force should be done with the brush. When the resin is mixed, it is solidifies in 45/60 minutes. When the resin is applied it needs 24 hours to completely harden out and obtain its full strength (Figure 7B).
Fig. 7. A) 3D textile ladder B) Ladder with stiff rung

*Source: own work.*

5. Ladder analysis

When the prototype was made, some minor errors were noticed. First one is that the rails will be different length extensions. This is because of the elongation of the fibres. There are more yarns on one side, so this side will not elongate as long as other side. The result is inclined rungs. The solution for this problem is to take this elongation in consideration. Calculate the length of it and weave this length of the elongation shorter on the thinner rail. This way the rungs will stay straight.

After making the ladder, it was analysed in order to improve the ladder and its mechanical properties. Firstly, the ladder has been made by hand instead of a weaving machine so there are some human errors. The solution would be to use a machine weave it, with this, the ladder would be more uniform which results in better mechanical properties.

However, in the prototype it is possible to clearly see the 3D woven structure for as well the rung as the rail. In the prototype on the rung is possible to see the H shape very clearly.

When the resin and the hardener are mixing to prepare epoxy resin, some bubbles are caught in the preparation and the viscosity is too high. This will cause problems during applying the epoxy on the fiber. Indeed, the section of the rung is large; therefore, insides fibres will not be penetrated by the resin.
In order to reduce this problem, it is possible to put the epoxy under vacuum to expel bubbles from the liquid.

To continue, the rung had to be tested. The tests consisted of apply a weight on the middle of the rung to simulate the weight of a person. The weight was applied on a piece of wood as large as a foot. Once the resin is solidified the rung is really strong, it is capable of holding 45 kg. In order to keep the ladder in good state, the heaviest weight test was done with 45kg because the rung started to emit cracking noise. However, in the future, should find a way to improve the mechanical properties and appearance of ladder.

6. Conclusions

Firstly, the ladder made of 3D woven composite is an innovative idea, which makes it a good addition to the current selection of available ladders. Manufacturing with this new technologies, makes the application stronger, lighter and more environmental friendly.

Secondly, the design is unique in shape, material and manufacturing. Combining the best of each design property, resulting in a state of the art ladder. Moreover, producing the prototype was a success. In the prototype is visible that it is made by hand but you can see improvement and a good uniform structure. It is proof that is possible use 3D shaped fabric to the construction of the composite and always is opportunity find new applications.

Bibliography


1. Introduction

Textile materials, which play an important role in our everyday life, consist in the main of organic polymers. Due to chemical structure of fibers, both natural and man-made origin, they are relatively high flammable and thus can present a fire risk. This applies to textiles intended for many applications, for example, products intended for interior furnishings, fabrics used in protective clothing, and numerous textile technical materials, including some filtering and thermal insulating materials.

The flame-retardant textiles may be obtained in various ways:
- chemical treatment of the fabrics made from flammable fibres (e.g. cotton, wool, polyester),
- use of fibres which have been flame retarded during manufacture (e.g. Trevira CS®, Lenzing FR®),
- use of inherently flame retarded fibres (e.g. Nomex®, Kevlar®, Rhovyl®).

Currently a lot of flame retardant and methods of their application are used, but much work still needs to be undertaken in this area. Improving the fire retardant behavior of many kinds of textile products is a major challenge for scientists and engineers.

Several studies are devoted to the development of new methods of flame retardant treatment of textiles and plastics as well as to better understand the flame retardant action of some nanoparticles, namely, montmorillonite, carbon nanofiber, multiwalled carbon nanotube [1, 2, 3, 4]. A novel method to improve flame retardant properties of textile fabrics using multilayered thin films was evaluated by Carosio et al. [5]. In this work, PET fabrics were coated with silica nanoparticles using layer-by-layer assembly. The nano-coating of
PET fabrics dramatically reduced after-flame time, eliminated melt dripping and decreased heat release rate by about 20%.

The flame retardant textiles, during normal use, are exposed to many factors, which can have destructive effects on the fibres. The fabrics may be subjected to occasional exposure to a heat radiation of a relatively low or moderate intensity level as well as to action of small ignition source. It is well known that thermal energy (IR radiation, convective heat) has a destructive impact on fiber-forming polymers. Heat causes significant changes in the molecular and supramolecular structure of polymer materials, both in the case of thermoplastic and thermosetting fibres. The tests performed by Rossi et al. [6] showed the destructive effect of heat radiation on flame retardant fabrics and membranes commonly used for firefighters’ protective clothing. Heat exposure decreased tensile strength and water vapour permeability of tested products.

Slater [7] additionally found that selected important properties of textile products may be reduced before any changes in this material are visible to the naked eye. It should be noted that such situations may cause a potential hazard to the user of protective clothing and reduce the level of fire safety in the building.

Protective clothing, as well as other types of textiles can be exposed to different chemicals, when in use. This can lead to contamination of fabrics with many chemical substances. The presence of contaminants on a fabric may affect the number of its properties, including burning behavior, tensile strength, air permeability and other. For determining the quantity and distribution of oily contaminants in the flame retardant fabrics intended for protective clothing against heat and flames radiotracer analysis and SEM method were used [8]. It was found that the fibre morphology, type of flame retardant treatment and both yarn and fabric structure may affect contaminants retention and distribution as well as their release from fabric during washing process.

It can be assumed that any type of contaminants, especially those that are highly flammable, may deteriorate the flame resistance of a fabric. Mettananda et al. found that oily contaminated flame retardant fabrics showed significantly higher heat release rate (HRR), and effective heat of combustion (EHC) compared to uncontaminated ones [9].

Protective characteristics of flame resistant textiles are commonly assessed for the new products (never used before) according to the appropriate ISO and CEN standards. The changes in these fabrics properties – essential in providing protection to workers in high-risk environments – which occurred during their use are rarely considered.

The aim of this work was to determine the effects of chemical contamination on the flammability and tensile strength of flame resistant fabrics. The changes in mechanical properties and burning behavior of contaminated fabrics caused by thermal radiation were also investigated.
2. Experimental Part

Materials:

- Five commercial flame resistant fabrics of different structure and raw material composition were used. They were intended for flame and heat resistant clothing, for interior furnishings and as technical materials. The general description of the textiles tested is given in Table 1.
- Three chemical substances (industrial liquids) which may be potential contaminants of fabrics.
  - Hydraulic oil: mineral, HLP100, used as pressure fluid for power transmission and control (Liqui Moly, Polska).
  - Ammonium phosphate dibasic (NH\(_4\))\(_2\)HPO\(_4\), wide variety of uses (POCh, Gliwice, Polska);
  (in this study an aqueous solution of 10% was used as a contaminant).

Table 1. Description of tested fabrics

<table>
<thead>
<tr>
<th>No.</th>
<th>Raw material</th>
<th>Mass per unit area [g/m(^2)]</th>
<th>Thickness, [mm]</th>
<th>Porosity [%]</th>
<th>Type of finishing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Cotton 100%</td>
<td>280</td>
<td>0,95</td>
<td>81,0</td>
<td>untreated</td>
</tr>
<tr>
<td>2.</td>
<td>Cotton 100%</td>
<td>260</td>
<td>0,62</td>
<td>72,9</td>
<td>FR*, non-permanent finishing</td>
</tr>
<tr>
<td>3.</td>
<td>Cotton 100%</td>
<td>280</td>
<td>0,55</td>
<td>67,2</td>
<td>FR, Pyrovatex; waterproof</td>
</tr>
<tr>
<td>4.</td>
<td>Cotton 100%</td>
<td>316</td>
<td>0,63</td>
<td>67,6</td>
<td>FR, Proban</td>
</tr>
<tr>
<td>5.</td>
<td>PET 100%</td>
<td>210</td>
<td>0,37</td>
<td>59,2</td>
<td>FR, phosphonic acid derivative</td>
</tr>
<tr>
<td>6.</td>
<td>Meta-aramide 100%</td>
<td>215</td>
<td>0,72</td>
<td>78,7</td>
<td>FR, waterproof</td>
</tr>
</tbody>
</table>

* flame retardant

Source: own work.

Methods:

- Fabrics exposition to heat radiation: Fabric samples with dimensions of approximately (160 x 210 cm), were fastened on a metal holder and installed in vertical position. Uncontaminated and contaminated fabric specimens were exposed to thermal radiation of intensity 10 kW/m\(^2\) for 30 s using a testing stand according to PN-EN ISO 6942 [10] (Figure 1). The radiation source consists of six silicon carbide (SiC) heating rods, which reach a temperature of about 1100°C.
- Testing of mechanical properties: The tensile strength tests of fabric samples were performed to estimate strength property changes due to the
contaminants presence and heat radiation. The uncontaminated and contaminated fabric samples, conditioned for 24 hours at a temperature of 20°C and RH 65%, were tested by using a tensile testing machine, INSTRON Model 5944 (Instron, USA). The breaking force and elongation at break were determined for samples (measured 25 x 160 mm) according to PN-EN ISO 13934-1 [11]. The results are given in table 2.

Testing of flammability: Two methods were used to examine changes in the burning behavior of fabrics due to the contaminants presence and heat radiation:
- method for determination of easy of ignition of vertically oriented specimens, according to PN-EN ISO 6940 (bottom edge ignition) [12],
- method for determination of burning behaviour by Limiting Oxygen Index (LOI), according to PN-EN ISO 4589-2 [13]. The results are given in Table 3.

- Analysis of fabrics structure and fibers surface: The SEM investigations were performed to observe cotton and PET fibers surface morphology and also to observe the presence and distribution of contaminants in the structure of the fabrics. SEM images of longitudinal fibres were obtained at magnification 1000x, with a voltage of 10 kV. These studies were carried out with the use of a scanning electron microscope, NOVA NANOSEM 230 (FEI).

![Fig. 1. View of testing stand used for fabrics exposition to heat radiation: R – radiator; S – fabric sample](image)

*Source: own work.*
Table 2. Tensile strength of contaminated fabrics before and after radiant heat exposure (heat flux density – 10 kW/m², time – 30 s)

<table>
<thead>
<tr>
<th>No.</th>
<th>Raw material/ type of finishing</th>
<th>Contaminant</th>
<th>Contaminant content in fabric [%]</th>
<th>Breaking force [N] (Elongation at break [%])</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>before exposure after exposure</td>
</tr>
<tr>
<td>1.</td>
<td>Cotton 100%, untreated</td>
<td>uncontaminated –</td>
<td>675,2 (9,2) 659,5 (8,9)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor oil 48,2</td>
<td>697,0 (7,8) 608,4 (8,7)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydraulic oil 44,1</td>
<td>704,6 (7,9) 578,1 (8,3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(NH₄)₂HPO₄ * 7,3</td>
<td>671,4 (11,0) 187,5 (7,6)</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Cotton 100%, FR, non-permanent finishing</td>
<td>uncontaminated –</td>
<td>271,4 (12,2) 212,8 (11,1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor oil 56,5</td>
<td>256,3 (11,3) 261,0 (10,1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydraulic oil 41,3</td>
<td>263,2 (12,3) 252,2 (11,2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(NH₄)₂HPO₄ * 6,7</td>
<td>275,7 (13,2) 200,3 (11,3)</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Cotton 100%, FR, Pyrovatex</td>
<td>uncontaminated –</td>
<td>558,3 (12,2) 169,1 (8,1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor oil 17,3</td>
<td>551,1 (11,3) 198,7 (8,8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydraulic oil 18,7</td>
<td>508,4 (10,7) 439,3 (8,4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(NH₄)₂HPO₄ * 2,1</td>
<td>539,5 (12,1) 68,7 (5,7)</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Cotton 100%, FR, Proban</td>
<td>uncontaminated –</td>
<td>674,2 (11,2) 378,6 (10,8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor oil 54,3</td>
<td>676,8 (10,9) 674,9 (10,5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydraulic oil 42,7</td>
<td>662,7 (11,3) 643,7 (11,3)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(NH₄)₂HPO₄ * 6,5</td>
<td>671,4 (10,2) 647,8 (10,2)</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>PET 100% FR, phosphonic acid derivative</td>
<td>uncontaminated –</td>
<td>641,8 (28,1) 665,7 (37,0)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor oil 26,2</td>
<td>674,0 (31,3) 620,3 (39,2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(NH₄)₂HPO₄ * 4,1</td>
<td>635,9 (28,4) 584,4 (37,4)</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Meta-aramide fibres, 100%</td>
<td>uncontaminated –</td>
<td>907,4 (25,6) 896,2 (23,8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor oil 48,1</td>
<td>921,3 (26,5) 897,5 (24,2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydraulic oil 59,4</td>
<td>932,4 (25,9) 822,8 (23,6)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(NH₄)₂HPO₄ * 3,8</td>
<td>917,1 (24,7) 821,7 (23,2)</td>
<td></td>
</tr>
</tbody>
</table>

* expressed on a dry weight basis

Source: own work.
Table 3. Burning behavior (according to PN-EN ISO 4589-2 and PN-EN ISO 6940) of contaminated fabrics before and after radiant heat exposure (heat flux density – 10 kW/m², time – 30 s)

<table>
<thead>
<tr>
<th>No.</th>
<th>Raw material/ type of finishing</th>
<th>Contaminant</th>
<th>Contaminant content in fabric [%]</th>
<th>LOI [%]</th>
<th>Minimum ignition time* [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>before exposure</td>
</tr>
<tr>
<td>1.</td>
<td>Cotton 100%, untreated</td>
<td>uncontaminated</td>
<td>–</td>
<td>18,7</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor oil</td>
<td>48,2</td>
<td>20,6</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydraulic oil</td>
<td>44,1</td>
<td>21,1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(NH₄)₂HPO₄ **</td>
<td>7,3</td>
<td>31,2</td>
<td>non ignition</td>
</tr>
<tr>
<td>2.</td>
<td>Cotton 100%, FR, non- permanent finishing</td>
<td>uncontaminated</td>
<td>–</td>
<td>35,8</td>
<td>non ignition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor oil</td>
<td>56,5</td>
<td>21,3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydraulic oil</td>
<td>41,3</td>
<td>24,5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(NH₄)₂HPO₄ **</td>
<td>6,7</td>
<td>38,7</td>
<td>non ignition</td>
</tr>
<tr>
<td>3.</td>
<td>Cotton 100%, FR, Pyrovatex</td>
<td>uncontaminated</td>
<td>–</td>
<td>30,2</td>
<td>non ignition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor oil</td>
<td>17,3</td>
<td>23,6</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydraulic oil</td>
<td>18,7</td>
<td>28,8</td>
<td>non ignition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(NH₄)₂HPO₄ **</td>
<td>2,1</td>
<td>32,9</td>
<td>non ignition</td>
</tr>
<tr>
<td>4.</td>
<td>Cotton 100%, FR, Proban</td>
<td>uncontaminated</td>
<td>–</td>
<td>29,8</td>
<td>non ignition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor oil</td>
<td>54,3</td>
<td>22,4</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydraulic oil</td>
<td>42,7</td>
<td>26,2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(NH₄)₂HPO₄ **</td>
<td>6,5</td>
<td>37,4</td>
<td>non ignition</td>
</tr>
<tr>
<td>5.</td>
<td>PET 100% FR, phosphonic acid derivative</td>
<td>uncontaminated</td>
<td>–</td>
<td>32,3</td>
<td>non ignition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor oil</td>
<td>26,2</td>
<td>24,1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(NH₄)₂HPO₄ **</td>
<td>4,1</td>
<td>34,7</td>
<td>non ignition</td>
</tr>
<tr>
<td>6.</td>
<td>Meta-aramide fibres, 100%</td>
<td>uncontaminated</td>
<td>–</td>
<td>28,8</td>
<td>non ignition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor oil</td>
<td>48,1</td>
<td>23,3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydraulic oil</td>
<td>59,4</td>
<td>21,7</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(NH₄)₂HPO₄ **</td>
<td>3,8</td>
<td>31,1</td>
<td>non ignition</td>
</tr>
</tbody>
</table>

* bottom edge ignition
** expressed on a dry weight basis

Source: own work.
3. Results and discussion

The results given in Table 2 indicate that the mechanical parameters of contaminated fabrics after radiant heat exposure depend on the chemical nature of contaminant, kind of fibres and type of finishing performed. Among the uncontaminated cotton fabrics tested, it is the untreated fabric that shows the highest resistance to the applied heat radiation. The breaking force of this fabric after radiant heat exposure is decreased only by about 2%, while the cotton fabric finished with Pyrovatex loses, at the same conditions, almost 70% of its tensile strength. This means that the flame resistant cotton textiles show a lower resistance to heat than the without flame resistant finishing. The value of tensile strength of uncontaminated fabrics made from PET fibres and from aramid fibres virtually did not decrease, when exposed to radiant heat. The results listed in Table 2 demonstrate that among the three chemical substances tested, it is ammonium phosphate dibasic that shows the most destructive effect on all fabrics subjected to heat radiation.

The amount of oily contaminants in individual fabrics because of the differences in fibres chemical structure and type of flame retardant treatment varies in different fabrics from 18% to 59%. The smallest amount of contamination, as expected, absorb PET fabric and cotton fabric flame retardant finished with Pyrovatex which was also waterproof. Based on the results, one can state that the oily contaminated cotton flame retardant fabrics after radiant heat exposure showed significantly lower extent of destruction compared to uncontaminated ones. It can be assumed that in the case of the presence of large amounts of oily contaminants on the fabric during heat radiation occurs the cooling effect of oily contaminants evaporation.

All the cotton fabrics tested showed a trend toward reduced elongation of samples due to radiant heat exposure (Table 2). This is a characteristic symptom of the aging process in polymeric materials. Both the chain scission and cross-linking of the cellulose molecules may cause a decrease in the elongation at break of fabrics.

All the uncontaminated flame resistant fabrics tested in accordance with the PN-EN ISO 6940 showed the resistance to ignition (Table 3). Flame resistant properties has also gained the unfinished cotton fabric as a result of contamination by ammonium phosphate dibasic. All the flame resistant fabrics, both flame-retardant finished cotton fabrics and fabric made from inherently flame resistant polyaramide fibres, contaminated with motor oil (17-54% on weight of fibres) showed an ignition after only 1 s of exposure of a fabric sample to an ignition source. The results obtained by method for determination of easy of ignition, according to PN-EN ISO 6940, were confirmed by testing the fabric specimens according to the Limiting Oxygen Index method. The results of these tests clearly show that the flammability of all the tested fabrics increased dramatically with oily contamination. The LOI values for the uncontaminated flame resistant fabrics are 28.8-35.8%; the LOI values for the oily contaminated fabrics are reduced to 21.3-23.3%. Burning behavior of fabrics tested by LOI
and PN-EN ISO 6940 methods, did not show any significant influence of radiant heat exposure on their flammability properties.

The results of the examination of fibres surface morphology in cotton and PET fabric samples before and after radiant heat exposure are presented in the form of SEM images in Figures 2-10. The microscopic images of the surface of cotton and PET fibres after the thermal exposure show no visible differences in comparison with fibres before exposure. This applies to fibres both from uncontaminated and contaminated fabrics. This seems to indicate that the decrease in the mechanical strength (by more than 40%) of uncontaminated cotton fabric finished with Proban® due to its radiant heat exposure is not reflected by changes in the fibres surface morphology (Figures 5a and 5b).

The SEM images of the contaminated fabric samples show a very high motor oil content in both cotton and PET fabrics. Detailed analysis of SEM images reveal that most or all available inter-yarn and inter-fiber spaces within the yarns are filled with oil (Figures 4, 7 and 10). It can be considered that in the case of cotton fabrics (Figures 4 and 7) a significant quantity of oil remained in the lumens and crevices of cotton fibres, while no motor oil penetrated to the interior of the PET fibres.

4. Conclusions

The flame retardant cotton fabrics show a lower resistance to heat radiation than the fabrics without finishing. For example, the breaking force of untreated fabric after radiant heat exposure (10 kW/m², 30 s) is decreased only by about 2%, while the cotton fabric finished with Pyrovatex loses, at the same conditions, almost 70% of its tensile strength and fabric finished by Proban technology deteriorate its tensile strength by about 44%.

The textiles susceptibility to contamination with different liquids for industrial application depends on fibres chemical structure, structure of textile products and type of their flame retardant finishing. Among the three industrial liquids (as a possible contamination of the tested fabrics) it is ammonium phosphate dibasic that show the most destructive effect on fabrics subjected to radiant heat.

The tests performed to determination of easy of ignition and the test results obtained by LOI method show that the flammability of all the tested fabrics increased dramatically with oily contamination. The flame resistant finished cotton and PET fabrics and fabric made from inherently flame retardant meta-aramide fibres contaminated with tested oils showed an ignition after only 1 s of exposure of a fabric sample to the test flame.

The analysis of SEM images of both uncontaminated and contaminated cotton fabrics allowed to state that even a dramatic decrease in tensile strength of fabric (by about 70%) caused by radiant heat exposure is not reflected by changes in the surface morphology of cotton fibres constituted this fabric.
Fig. 2. SEM images of fibres in cotton fabric, non-permanent FR finishing – uncontaminated (a) before radiant heat exposure (b) after radiant heat exposure  

*Source: own work.*

Fig. 3. SEM images of fibres in cotton fabric, non-permanent FR finishing, contaminated with (NH₄)₂HPO₄ (a) before radiant heat exposure (b) after radiant heat exposure  

*Source: own work.*
Changes in some properties of flame resistant textiles during their use

Fig. 4. SEM images of fibres in cotton fabric, non-permanent FR finishing, contaminated with motor oil (a) before radiant heat exposure (b) after radiant heat exposure

*Source: own work.*

Fig. 5. SEM images of fibres in cotton fabric, FR finishing (Proban®) – uncontaminated (a) before radiant heat exposure (b) after radiant heat exposure

*Source: own work.*
Fig. 6. SEM images of fibres in cotton fabric, FR finishing (Proban®) – contaminated with $(\text{NH}_4)_2\text{HPO}_4$ (a) before radiant heat exposure (b) after radiant heat exposure

*Source: own work.*

Fig. 7. SEM images of fibres in cotton fabric, FR finishing (Proban®) – contaminated with motor oil (a) before radiant heat exposure (b) after radiant heat exposure

*Source: own work.*
Changes in some properties of flame resistant textiles during their use

Fig. 8. SEM images of fibres in PET fabric, FR finishing – uncontaminated (a) before radiant heat exposure (b) after radiant heat exposure

Source: own work.

Fig. 9. SEM images of fibres in PET fabric, FR finishing – contaminated with (NH₄)₂HPO₄ (a) before radiant heat exposure (b) after radiant heat exposure

Source: own work.
Chapter III. Techtex

Fig. 10. SEM images of fibres in PET fabric, FR finishing – contaminated with motor oil (a) before radiant heat exposure (b) after radiant heat exposure

*Source: own work.*

**Bibliography**


10. **PN-EN ISO 6942.** Protective clothing – Protection against heat and fire – Method of test: Evaluation of materials and material assemblies when exposed to a source of radiant heat.
1. Introduction

Textiles in the automotive industry are very important [1-5]. They are used both as decorative and aesthetic products, as well as functional materials, for example carpets damping sounds and vibrations while driving, reinforcing yarns for high-pressure hoses or belts and other. In the case of the first group of textiles they can be mainly used as materials for car seats upholstery. Nowadays, in less luxury vehicles, as automotive upholstery materials are used flat textiles, i.e. woven or knitted fabrics. These textiles in order to increase the comfort of the driver and passengers, on the underside are taped by foam. As a result, the external (functional) part of the car seat is softer. Despite the use of this type of upholstery packages for many years, this solution is not enough good. The structure of above mentioned upholstery materials prevents the free airflow, leading to the discomfort. In addition, these products have a limited ability to moisture transport (draining of a liquid), and as time went on using them significantly decline the mechanical characteristics connected among others with destruction of the internal layer – the foam.

The research carried out at the Department of Knitting Technology of TUL confirmed the above the above-defined characteristics of traditional upholstery fabrics [6]. These studies included both knitted and woven fabrics in the form of non laminated and laminated structures with surface mass at the level of 156 g/m² to 368 g/m². Their thickness was varied from 0.75 mm to 4.19 mm, wherein for the un laminated products it was lower compared to the laminated knitted fabrics because they were taped by foam. Abrasion resistance for the analyzed nine variants of different types of knitted fabrics ranged from 403 cycles to 9823 cycles. The air permeability for not laminated and laminated knitted fabrics fluctuated within the following ranges: from 350 mm/s to 1208 mm/s. By studying the individual components of the material like foam
and fabric, following results were obtained: for foam itself with a thickness of 3.5 mm the air permeability was 1.169 mm/s; for fabric itself with a thickness of 1.25 mm the air permeability was 1.928 mm/s; while the whole tested material having a thickness of 4.73 mm was characterized by air permeability at the level of 1002 mm/s. According to the above it can be concluded that with increasing number of material layers increases the thickness of the product and thus its air permeability decreases.

The development of textile technologies, including knitting techniques, led to the creation of structures that directly in the manufacturing process have a spatial structure [7−12]. An example of this type of textiles are 3D distance warp-knitted fabrics. Their main advantages are: maintainability, high porosity and permeability of air, good mechanical properties, ie. the stiffness of compression, absorption of the impact energy, return to their original shapes and many others. In addition, the technological process in a relatively simple manner allows intervention in changing the properties of the finished product adapting them for specific applications. These characteristics caused that automakers noticed high application potential of 3D spacer warp-knitted fabrics in the automotive industry.

2. Materials and methods

The object of the research was distance warp-knitted fabric composed of three layers: two external layers and one internal layer. Fabric was manufactured on the warp-knitting machine, type RD6/1-12, with needle guide E24. The structure was made of polyester yarn. External layers of fabric were different from each other. One of the layers was an openwork structure, and the other one was full covered. The all variants were manufactured on the basis the same stitches using four guide bars. The finishing process of each knitted fabric was different. The white sample called W1 was only the subject of the thermal stabilization process. The second sample, that was finished by process of thermal stabilization and dyeing process, was called W2. The last fabric named W3 was finished by process of thermal stabilization and printing process. The above characterized knitted fabrics were measured before and after washing process. Therefore, after the sign of sample, a mark as a subscript was introduced: "bw" – for the samples tested before washing process and “aw” – for the samples examined after washing process.

The research was conducted as part of the diploma thesis [13]. For the above-characterized knitted fabrics were determined following parameters: thickness g [mm] [14], surface mass Mp [g/m²] [15], course density P_r [courses/10 cm] and wale density P_k [wales/10 cm] [16], relative dimensional change along courses Z_r [%] and along wales Z_k [%], abrasion resistance Ls [cycles], air permeability R [mm/s], compression stiffness modulus E [kPa] and plastic deformation index Δg [%]. The first three parameters were determined according to the standards. In order to identify relative dimensional change,
based on the measured values of the directional density of the knitted fabrics before and after wet treatment, were used the following dependences:

\[ Z_r = \left( \frac{P_{r,bw}}{P_{r,aw}} - 1 \right) \cdot 100\% \]  

(1) and

\[ Z_k = \left( \frac{P_{k,bw}}{P_{k,aw}} - 1 \right) \cdot 100\% \]  

(2)

where: \( Z_r \) – relative dimensional change along courses [%]; \( Z_k \) – relative dimensional change along wales [%]; \( P_{r,bw} \) – wale density before washing process [wales/10 cm]; \( P_{r,aw} \) – course density before washing process [courses/10 cm]; \( P_{k,bw} \) – wale density after washing process [wales/10cm]; \( P_{k,aw} \) – course density after washing process [courses/10 cm]. Abrasion resistance was determined based on the polish standard [17], however the test was carried out using two different abrasive materials. In the first step it was plain weave fabric made of cotton, and in the second time was used the material with a grain size of 240 in order to diversify the resistance of samples to the friction process. The air permeability was determined using new measuring position built at the Department of Knitting Technology in cooperation with prof. Leszek Zawadzki [8]. The new device allows the measurement of air permeability of textile having large thickness and large porosity. Figure 1 presents this device. Measured high of the column of manometer liquid was converted to a value of air permeability based on the Polish standard dedicated to flat textiles [18].

![Fig. 1. Real view of a measuring device for testing air permeability of knitted spacer fabrics (1 – connecting pipeline with measuring reducer, 2 – element measuring pressure drop, 3 – suction system and vacuum control system, 4 – pressure gauges) [8]](image-url)
Compression stiffness modulus was determined using Haunsfield H50K-S type testing machine. During tests was measured non-linear character of analyzed 3D distance warp-knitted fabrics. The characteristics were divided into four ranges, ie. initial phase, main area of compression, compression phase with a significant increase in the compressive force and the phase of "crushing" the material (Fig. 2) [19]. The methodology of measurements and calculations based on diploma thesis written by Natalia Mateuszuk [8].

![Graph showing non-linear character of the hysteresis loop](image)

Fig. 2. Visualization of non-linear character of the hysteresis loop, ie. compression and relaxation curve of a distance knitted fabric [19]

The last parameter called as plastic deformation index was defined in two ways by the following formulas:

\[
\Delta g_{t1} = \frac{g - g_z}{g} \times 100\%
\]

(3)

and

\[
\Delta g_{t2} = \frac{g - g_r}{g} \times 100\%
\]

(4)

where: \( g \) – the initial thickness of the sample (before compression process) [mm]; \( g_z \) – thickness of the sample after three cycles of compression and relaxation process [mm]; \( g_r \) – sample thickness after 30 minutes of relaxation [mm], \( \Delta g_{t1} \) – plastic deformation index between the thickness of the sample before compression process and the thickness of the sample after three cycles of compression process [%], \( \Delta g_{t2} \) – plastic deformation index between the thickness of the sample before compression process and the thickness of the sample and after 30 min of relaxation [%] [13].
3. Results and discussion

– Evaluation of thickness of 3D spacer knitted fabrics

The thickness of the analyzed 3D knitted structures was in the range of 4.67 mm to 3.80 mm (Fig. 3). The highest thickness was noted for the sample W1 for which the finishing process only based on the thermal stabilization, where \( g = 4.55 \) mm, and the lowest thickness was achieved for the sample W3 with printed pattern, where \( g = 3.80 \) mm (\( \Delta g,_{w1-w3} = 0.75 \) mm). Taking into account the impact of preservation process to the change of thickness, an increase of the analyzed parameter of 0.12 mm was observed for knitted fabrics W1 and a decrease of 0.18 mm for the dyed knitted fabric W2 was noted. In the case of printed fabric W3 the process of washing was not affected by thickness (\( g = 3.80 \) mm; \( \Delta g,_{w3bw-w3aw} = 0.00 \) mm). Analyzing the obtained results, it should be noted that the washing process does not significantly affect the thickness of the knitted fabric because for the same types of structures (both before washing and after washing) the results do not differ a lot – approximately about 3.6%. The spread of obtained thickness values of samples at the level of 1.5% can be caused by the fact that during thermal stabilization process of the spacer knitted fabric varies in thickness through a flattening on the section reaching up to 30 cm from the edge of the fabric.

Fig. 3. Thickness of 3D spacer knitted fabrics

Source: own work.

– Evaluation of surface mass of 3D spacer knitted fabrics

Figure 4 presents the distribution of the surface mass in the analyzed 3D distance knitted fabrics. The obtained values of the surface mass of the samples before and after washing process are very similar. Before wet treatment these values vary from 240 g/m\(^2\) to 267 g/m\(^2\), and after washing from 255 g/m\(^2\) to 270 g/m\(^2\). The highest values were recorded for the dyed sample, and the lowest for printed fabric. It should be mentioned that for all variants of knitted fabrics was observed an increase of surface mass as a result of the washing process that for knitted fabric W1 was equal to \( \Delta Mp = 2 \) g/m\(^2\) and for sample
W2 $\Delta M_p = 3 \text{ g/m}^2$. The highest increase of surface mass was noted for the structure W3, where $\Delta M_p = 15\text{ g/m}^2$.

![Fig. 4. Surface mass of 3D spacer knitted fabrics](source: own work)

**Evaluation of relative dimensional change of 3D knitted fabrics after washing**

Based on the measurements results it can be concluded that the value of the relative dimensional change after washing both along courses and wales has changed (Fig. 5). Regarding the values of the relative dimensional change after washing process along wales, all samples shrank as follows: $Z_{k,W1} = -2.32\%$; $Z_{k,W2} = -2.97\%$ and $Z_{k,W3} = -1.87\%$. However, in the results of the relative dimensional change after washing process along courses in variant W2 (dyed fabric) was observed the stretching the sample about $Z_{r,W2} = 0.71\%$. The other two variants of knitted fabrics in this test were shrunk respectively by: $Z_{r,W1} = -0.99\%$ and $Z_{r,W3} = -2.70\%$.

![Fig. 5. Relative dimensional change of 3D knitted fabrics after washing process](source: own work)
Evaluation of abrasion resistance of 3D knitted fabrics

Abrasion resistance test was carried out in two ways. In the first case the measurements were carried out using plain weave fabric (made of cotton) as an abrasive material. The study was conducted to the number of cycles equal to 45,000. According to industry standards the material dedicated to the car seats upholstery should endure up to 35,000 cycles. Despite continuing the measurement to the value of 45,000 cycles, there was no damage of threads that caused formation of holes on the surface of the article.

![Fig. 6. 3D distance knitted fabrics before and after friction process](source: own work).
On the surface of dyed knitted fabric was observed field, followed by the moving abrasive material. These results are due to the fact that some dye was wiped off from the surface of the fabric. It was noted that the printed fabric has been destroyed the most comparing to other structures. To illustrate these changes on the surface of samples the pictures under the microscope were taken (Fig. 6). Pictures show the structure of the fabrics before and after friction process.

In order to diversify the resistance of samples to the friction process as an abrasive material was used the material with a grain size of 240. The results are shown in Figure 7. As a result of analysis, it was observed that variants W3 before and after washing were the weakest and sequentially achieved following values: 1350 cycles and 1479 cycles. This results from the fact that the printing process has a destructive effect on the surface of the 3D knitted fabrics, which is more susceptible to abrasion damage. It was noted an increase of friction resistance after washing for white fabric W1\textsubscript{aw} (an increase of 153 cycles) and printed fabric W3\textsubscript{aw} (an increase of 129 cycles). For dyed knitted fabrics W2\textsubscript{aw} after washing process the resistance for friction has decreased by 129 cycles. Based on the analysis it can be concluded that the fabric after thermal stabilization process is the most resistant to friction in comparison with the fabrics after other finishing processes such as dyeing and printing.

![Graph showing resistance of 3D knitted fabrics to friction process](image)

**Fig. 7. Resistance of 3D knitted fabrics to the friction process**

Source: own work.

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**Evaluation of air permeability of 3D knitted fabrics**

The average value of air permeability for 3D knitted fabrics before washing process was at the level of 5427 mm/s (Fig. 8). For white and dyed fabric achieved values were similar ($R_{W1,bw} = 5000$ mm/s and $R_{W3,bw} = 4748$ mm/s). In the case of printed fabric W3 the value of air permeability is higher than the other samples and is equal 6535 mm/s.
During the results analysis for the samples after the washing process the average value of air permeability was 5037 mm/s. The highest value was obtained for the printed fabric, where $R_{W3,aw} = 5718$ mm/s. This value is higher than in the case of white fabric, for which the air permeability was observed at the level of 4238 mm/s and for dyed fabric, where $R_{W2,aw} = 5157$ mm/s. Therefore, it can be concluded that as a result of washing process the value of air permeability has declined in the case of white fabric by 18% and for printed fabric by 14%. For the dyed knitted fabric there was observed an increase of air permeability up to about 9%.

Fig. 8. The air permeability of 3D knitted fabrics

Source: own work.

Evaluation of compression stiffness modulus of 3D knitted fabrics

In the first stage of measurement of compression stiffness modulus for 3D knitted fabrics the maximum forces $F_{\text{max}}$ were determined. Furthermore, the values equal 25%, 50% and 75% of maximum compressive forces were calculated (Table 1).

Table 1. The results of measuring the maximum compressive force and compressive forces for 25%, 50% and 75% of the maximum force

<table>
<thead>
<tr>
<th>Variant</th>
<th>$F_{\text{max}}$ [N]</th>
<th>$F_{25%}$ [N]</th>
<th>$F_{50%}$ [N]</th>
<th>$F_{75%}$ [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before washing process</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W1$_{\text{bw}}$</td>
<td>149.10</td>
<td>37.27</td>
<td>74.55</td>
<td>111.82</td>
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<tr>
<td>W2$_{\text{bw}}$</td>
<td>240.00</td>
<td>60.00</td>
<td>120.00</td>
<td>180.00</td>
</tr>
<tr>
<td>W3$_{\text{bw}}$</td>
<td>154.00</td>
<td>38.50</td>
<td>77.00</td>
<td>115.50</td>
</tr>
<tr>
<td>After washing process</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W1$_{\text{aw}}$</td>
<td>132.20</td>
<td>33.05</td>
<td>66.10</td>
<td>99.15</td>
</tr>
<tr>
<td>W2$_{\text{aw}}$</td>
<td>203.00</td>
<td>50.80</td>
<td>101.65</td>
<td>152.50</td>
</tr>
<tr>
<td>W3$_{\text{aw}}$</td>
<td>111.00</td>
<td>27.80</td>
<td>55.50</td>
<td>83.30</td>
</tr>
</tbody>
</table>

* bw – before washing process, aw – after washing process, $F_{\text{max}}$ – maximum compressive force [N]; $F_{25\%}$ – 25% of maximum compressive force [N]; $F_{50\%}$ – 50% of maximum compressive force [N]; $F_{75\%}$ – 75% of maximum compressive force [N].

Source: own work.
On the basis of the maximum compressive force was observed that for dyed fabric were reported the highest results both before and after washing process: for $F_{\text{max;W2,bw}} = 240.00 \text{ N}$ and for $F_{\text{max;W2,aw}} = 203.00 \text{ N}$. In the case of white and printed fabric before wet treatment the maximum compression forces amounted to $151.50 \text{ N} \, (\Delta F_{\text{max;W1,bw-W3,bw}} = 4.90 \text{ N})$. The difference between results for samples after washing process was significantly higher and differed by 19%.

The “percentage compressive forces” were used for the defining compression stiffness of 3D knitted fabrics in three hysteresis loops. The measurement results were used for determination of values of compression stiffness modules for each compression curves (both before and after washing process) (Fig. 9).

The analysis showed that the average values of the compression stiffness modulus for variants before washing process did not differ significantly from each other ($\Delta E_{\text{W2,bw-W3,bw}} = 4.199 \text{ kPa}$). In the case of variants after washing process, it was noted that sample W3,aw (11.912 kPa) differs its value nearly three times from fabric W2,aw (29.306 kPa) and two times from W1,aw (23.007 kPa), ($\Delta E_{\text{W2,aw-W3,aw}} = 17.394 \text{ kPa}$). Furthermore, the values for the white fabric, both before and after washing proces, were at a similar level, ie. $E_{\text{W1,bw}} = 23.796 \text{ kPa}$ and $E_{\text{W1,aw}} = 23.006 \text{ kPa}$, (there was a slight decrease in the value of 0.790 kPa). Comparing the variations before and after the washing process, the printed sample was characterized by the greatest distribution of results ($\Delta E_{\text{W3,bw-W3,aw}} = 9.838 \text{ kPa}$).

In addition for printed fabric after washing process was noted decrease in the value of compression modulus of 9.838 kPa, and for dyed fabric an increase of these parameter of 3.357 kPa. It can be concluded that most stable structure was white fabric (fabric after the process of thermal stabilization).

![Fig. 9. The compression stiffness modulus of 3D knitted fabrics](image)

*Source: own work.*
### Evaluation of plastic deformation index for 3D knitted fabrics

Based on the results shown in Figure 10, it was observed that the plastic deformation index $\Delta g_1$ for samples before washing had the highest value for dyed knitted fabric and was equal to 8.17%. The values for the other two fabrics were similar ($\Delta g_{1,W1,bw} = 3.30\%$ and $\Delta g_{1,W3,bw} = 2.98\%$). Among the samples after wet treatment, the highest value of plastic deformation index $\Delta g_1$ was noted for printed fabric ($\Delta g_{1,W3,aw} = 6.36\%$). White and dyed fabric had values close to each other ($\Delta g_{1,W1,aw} = 3.87\%$ and $\Delta g_{1,W2,aw} = 3.17\%$).

![Fig. 10. Plastic deformation index of 3D knitted fabrics: bw – before washing process, aw – after washing process, $\Delta g_1$ – plastic deformation index examined immediately after three compression cycles, $\Delta g_2$ – plastic deformation index examined after 30 minutes of relaxation Source: own work.](image)

In the case of plastic deformation index $\Delta g_2$ for knitted fabrics before wet treatment, the highest value was achieved for the sample W1 ($\Delta g_{2,W1,bw} = 1.97\%$), and the lowest for sample W3 ($\Delta g_{2,W3,bw} = 0.27\%$). Setting the parameter $\Delta g_2$ for variants after washing, the highest value was recorded for the sample W3 (aw ($\Delta g_{2,W3,aw} = 3.81\%$)), then for the first sample it was $\Delta g_{2,W1,aw} = 1.93\%$, and the lowest for dyed sample ($\Delta g_{2,W2,aw} = 1.71\%$).

To summarize, the printed fabric before washing process had the greatest susceptibility to return to their original dimensions, almost in 100%. It should also be noted that each of the tested variants of knitted fabrics returned to their original dimensions approximately of 98%.

The largest difference in the value of deformation $\Delta g_{1}$ and $\Delta g_2$ was in variant W2_bw. Change of this parameter immediately after three compression cycles was 8.17%, whereas after 30 minutes of relaxation it was 1.44%. Both for W1_bw and W1_aw, the plastic deformation index $\Delta g_1$ and $\Delta g_2$ were close to each other and were equal: 3.30%, 3.87% and 1.97%, 1.93%, wherein, after 30 minutes, this ratio decreased on average by 1.8 times. Summing up at the end, all variants of knitted fabrics after 30 minutes of relaxation have returned more to its
original dimensions, than those that have been examined immediately after three compression cycles (on average by 2.5 times).

4. Results and discussion

a) The review of the literature indicates a large variety of textiles used in the automotive industry. Due to the requirements of national, European and industry standards for this type of products, there are still searched materials characterized by high aesthetic and functional parameters. Developing group of textiles, which has a high potential for application as automotive upholstery materials, are 3D distance knitted fabrics. These fabrics through their special characteristics can improve the comfort of vehicle users.

b) The object of the study were 3D knitted spacer fabrics produced on the warp-knitting machine, type RD6/1-12, with needle guide E24. The variants were diversified by finishing process: only after process of thermal stabilization, after dyeing process and after printing process. In addition measurements were carried out for two groups of knitted fabrics: both before and after wet treatment.

c) Based on the analysis of the obtained results, it was found that:

- Thickness of the tested samples before washing process was varied in the range of 3.80 mm to 4.55 mm ($\Delta g_{bw} = 19\%$) and after washing process from 3.80 mm to 4.67 mm ($\Delta g_{aw} = 23\%$). In addition the various processes of textile finishing, like reheating or washing may change the structure of the fabric, including thickness.

- Surface mass for considered knitted fabrics fluctuated in the range of 240g/m$^2$ to 270g/m$^2$ ($\Delta M_p = 12\%$). In the case of printed fabric, due to wet treatment, an increase of surface mass of 6% was observed. For the other variants this influence is at the level of 1%.

- After washing process, all samples along wales were shortened by about 2%. For the measurement along courses – samples white and printed shrunk by 1.82%, and dyed sample increased its size by 0.71%.

- Analyzing the results of fabrics resistance to friction, using as an abrasive material plain weave fabric made of cotton, after 45000 number of friction cycles there were not observed damages to threads causing breakdown of the knitted structure. In case of using as an abrasive material the structure with a grain size 240, the resistance of 3D textiles on the friction process was in the range of 1415 cycles to 2080 cycles.

- The knitted fabrics before washing process had the air permeability at the level of 5428 mm/s ($\Delta R_{bw} = 37\%$) and after the washing process the average value was equal 5037 mm/s ($\Delta R_{aw} = 35\%$). As a result of the wet treatment the white sample decreased permeability of air about 18% and printed sample about 14%. In the case of dyed fabric an increase of permeability of air by 8.5% was noted.
The study of process compression for spacer knitted fabrics allowed to note that the nature of the finishing process affects the value of the maximum compressive force (difference about 60%). After washing process the maximum value of the compressive force decreases from 13% to 38%. The process of wet treatment affects the value of compression modulus. Before washing process the value of the module was 23.832 kPa ($\Delta E = 4.199$ kPa) and after washing process the change of the compression resistance was 150%. The lowest value was recorded for printed fabric (11.912 kPa). The largest value of the compression modulus, both before and after wet treatment, achieved the dyed fabrics (on average: $E = 27.628$ kPa, difference 13%). For white knitted fabric, there were no significant effect of wet treatment to the value of the compression modulus (difference 3%).

On the basis of the measurement results of plastic deformation index of fabric it can be seen that its values range between 3% to 8% when measured directly after three times compression cycles and from 0.3% to 4% after 30 minutes of relaxation in the free state. These data may suggest that with an increase of the relaxation time of 3D distance knitted fabrics, the plastic deformation index is expected to decrease.

d) Regarding the obtained results for 3D distance knitted fabrics to the parameters of traditional upholstery materials, mentioned in the literature review, it can be concluded that: spatial knitted structures are characterized by significantly better values of utility properties such as: air permeability (for spacer knitted fabrics it is about 5232 mm/s, and for traditional textile is in the range of 350 mm/s to 1208 mm/s) and resistance to the friction process (3D knitted structures after the process of friction, using as an abrasive material the textile made of cotton, did not damaged after 45000 cycles, and the maximum strength for traditional upholstery products is 9823 cycles). In addition, the obtained results can be an important source of information about the use of distance warp-knitted fabrics as a material for car seat covers.

Bibliography


Chapter IV

BUDTEX
SUN SHIELD SYSTEMS – USAGE AND SPECIAL REQUIREMENTS FOR THE BLACKOUT CURTAINS

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1. Introduction

Since the 3rd of April, 1993, the Act on the Standardisation has abolished the mandatory standards and according the Art. 19, Par. 5 of the Act, applying the Polish Standards is now entirely voluntary, which commitment Poland accepted within the Association Agreement with the UE. On the 28th of October 2010, during the meeting of the Standardization Council of PKN the proposal was accepted, to make PKN management adopt an official position on the voluntary use of standards, therefore item 3 states: „Applying Polish Standards is voluntary” [1]. The lack of necessity to apply the standards does not preclude the use of them, they serve in practice to providing the guidelines at designing, or for determining the quality and applicability of many products. Lack of uniform requirements, test methods and unambiguous naming may lead to wrong response from manufacturer or service provider to the needs of customer and user. On the other hand, those who formulate descriptions of public procurement, or to subcontract, have a need for referring the standards, as they are present in the tender and contract documents, at the commissioning and implementation of contract investments.

Due to the situation of the standardisation linked with the withdrawal of national standards, introduction of new PN-EN Standards, there is a need to verify the state of standardisation, taking into account the state-of-the-art, as well as practical considerations.

General Technical Specification (Pol. OST) and Technical Specifications (Pol. ST) for execution of the service works refer in their content to the standards: Polish Standards (Pol. PN), Branch Standards (Pol. BN), European Standards in the collection of Polish Standards (PN-EN) and possibly other foreign standards. Beside the standards, the OSTs and STs comprise also the
references to other documents, like guidelines, standardisation regulations, the Acts, the directives of Ministers etc. [2].

The work focuses on the problem of lacking the standards for blackout curtain fabrics applicable in the public buildings. The need for standardization in this field is illustrated. The problem analysis was conducted on the basis of available standards associated with these products, and technical specification for service works execution, linked to the implementation of window decorations in a four-star hotel belonging to an American network. This really encountered problem confirms that the blackout fabrics as a product present on the market are not adequately described.

2. Standardisation background concerning the blackout-type curtains

There is a steady increase in the number of architectural projects that contain increased area of glazing in the form of window openings, as well as the whole facades. Massive use of architectural glass by the designers is conditioned by the development of innovative manufacturing technologies and processing of this material. This trend also occurs in public buildings, where due to the trend of high constructions, it is reasonable to use glass since it is safer and lighter material than concrete. Glass architecture promotes the production of curtain systems, and creates their innovative design solutions. Therefore a need appeared to develop a systematic naming for this group of products and to standardise the requirements and measuring methods, according to the present state of the art.

The exploratory research was carried out on the basis of available objective norms in the field of architectural covers in the form of woven internal curtains: terminology, usage and special properties. Also the technical requirements for the fabrics applicable as the sun shields in the hotel interiors were tracked. Especially the barrier properties of the curtains against the external radiation applicable inside the public buildings are not defined precisely, and the blackout-type products are not adequately specified.

In 2005, the European Commission gave the European Committee for Standardisation (CEN) a mandate to develop standards in the scope „Doors, windows, shutters, building hardware and curtain walling, including the blinds, both external PN-EN(U)13561:2005 and internal PN-EN(U)13120:2005 [3].

Within the meaning of the standards, the inner curtain is a product that covers the window, and is attached anywhere on the interior surface of a building. Such a general definition comprises covers made of plastic, metal, wood or fabrics. Hence the PN-EN (U) 13120: 2005 "Internal blinds. Performance requirements including safety "describes all kinds of covers. It gives the requirements to be met by internal blinds installed in the building. The Standard is applicable for jalousie, roller and vertical shutters as well as the curtains like the roll up, Roman type pleated, Austrian, panels, including the
blind curtains. In addition, the Standard embraces internal rack blinds including inter-pane type, and the indoor shutters. It gives the performance requirements that should be met by internal blinds, taking into account potential risks that relate mainly to systems controlled manually or electrically.

No Standard has been developed so far, dedicated to sunlight-screening curtains, and the meaning of the word "curtain" in the Polish language usually refers to a fabric hanged vertically on the support system, i.e. curtain rod. The basic Standard PN-EN 12216:2004 „Shutters, External Blinds, Internal Blinds - Terminology, Glossary And Definitions“ [4] gives the definitions of all kinds of the internal blinds, i.e. internal blinds, awnings, roller blinds, vertical blinds, pleated curtains, shutters and mosquito nets - internal blinds, awnings, roller blinds, vertical blinds, pleated blinds, shutters and mosquito nets - depending on their use, design and component materials, widely used and applicable in buildings. For these products, the basic functions, modes of operation, working movements, control and drive systems are listed and the characteristic dimensions are specified. The Standard contains also a comprehensive dictionary of terms and names of components and parts of the individual types of curtains and jalousies illustrated with numerous figures. The Standard states, that the jalousies and curtains constitute a separated group of construction hole products, installable both inside and on the outer side of a building in order to provide an additional cover and/or additional protection for a hole in building, i.e. a hole already equipped with a window, door or gate. Such a general definition is the reason of terminological confusions; according to the Standard the internal curtains are the wide range of window screens. Concerning curtains that are the subject of this work consideration, the safety functions are out of the question. Also, the term "vertical curtain" used in this standard for a range of products known in Poland as vertical jalousie, or verticals, may raise false connotations. Thus, in the PN-EN 12216:2004 and PN-EN(U) 13120:2005 Standards we won't find the terminology, functional requirements or evaluation methodology for the blackout fabrics applicable in buildings as the vertical, freely hanging curtains. The PN-EN 12216:2004 Standard gives the terminology of window blackout of dimout covers only regarding of the roller shutters with the guiding system, presented on a detailed drawing.

According to recent information provided by the Polish Committee for Standardization, there are no separate standards for issues of the textile curtains in vertical applications [5]. For example, upholstery fabrics have their dedicated document PN-EN 14465:2005P Textiles – Upholstery fabrics – Specification and methods of test [6]. No wonder that standards for curtains – understood as the textile products featuring barrier properties against sunlight – weren’t found.

The basic feature of the more generally defined curtain system: darkening or dimming, quoted in the PN-EN 12216:2004 Standard, is defined in the EN 14501:2005 [7]. According to the latter, there are two kinds of the darkening fabrics and products: blackout and dimout types. Classification for covering properties of the curtains was based on the characteristics of the source of the light to be blocked by the textile product. Figure 1 presents the classification of
shading fabrics and products by transparency, included to the above Standard in the Tables 6 and 7 on the page No. 14.

<table>
<thead>
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<th>Table 6. Opacity of fabrics – Classification</th>
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<tr>
<td>Opacity control of fabric</td>
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<td>No light perceived when tested under 1 000 Lux</td>
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<tr>
<td>No light perceived when tested under 100 000 Lux</td>
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<table>
<thead>
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<th>Table 7. Opacity control of products – Classification</th>
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<td>Product performance</td>
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<tr>
<td>No light perceived when tested under more than 1 000 Lux</td>
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<tr>
<td>No light perceived when tested under more than 75 000 Lux</td>
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</tbody>
</table>

Fig. 1. Shading products and fabrics classification, part of EN 14501:2005 Standard [7]

It is well known that the blackout products should block the external radiation and create darkened conditions. Defining characteristics of darkening should refer to physically existing radiation, external, mainly the sunlight.

The first standards in the field of evaluating the properties of sunscreen clothing were developed in Australia and New Zealand [AS/NZS 2604:1986 Sunscreen products – Evaluation and classification], and on that basis the national standards were developed in other countries, for example AATCC 183:2004, ASTM D6544 and ASTM D6603 in the United States, EN 13758-1 in Europe, and GB/T18830:2009 Evaluation for solar ultraviolet radiation protective properties (Japan Garment Association Standard) [8]. Both in Poland and in Europe, to assess the optical properties of textiles, the point measurements (with a spectrophotometer) of the coefficient of light transmittance T [%] are commonly used. The process of identifying the optical properties of blackout fabrics is conducted on the basis of the PN-EN ISO 13758-1 Standard [9]. The arithmetic mean of the transmittance of radiation that passes through the sample is the test result. Based on such measurements the value of transmittance of radiation, the value of SPF (Sun Protection Factor) or UPF (Ultraviolet Protection Factor) is calculated as the unit for the protective properties. The level of SPF or UPF index qualifies a given product to relevant protection class. The highest level of protection comprises the products with the SPF or UPF above 50. None of these standards, where the spectrophotometric measurements are used, has any reference to the intensity of the light source, which is the basis for the classification of fabrics and blackout products.

American Association of Textiles Chemists & Colorists (AATCC) gives two technical specifications that concern the methods of defining the effect
of shielding the window covers. The AATCC TM148 [10] and AATCC TM203 [11] Standards, are standards dedicated to cover products. The methods are different in the measuring systems. TM148 uses a photo-detector to determine the level of barrier properties by measuring the amount of light that passes through various textiles, including coated fabrics. The method consists in measurement of quantity of light emitted by a source (measurement without a sample), and the light quantity emitted by the source with a sample. Then, the amount of light blocked by a product is calculated as the quantity of light passing through the product and registered by the photometer (B) divided by the mean quantity of the light measured without sample (A) minus one and is expressed in percents (% of Light Blocked = 100 x [1- (B/A)]). Wherein the blocking of a light is defined as the capability to prevent the transmission of light through the textile product.

Procedure TM203 defines a method of measuring the light passing through the windows covers carried out with a spectrophotometer. The measurement principle is compatible with the PN-EN ISO 13758-1 Standard described above. Since 2001 in USA tests of a product with sun-screening UV capabilities are carried out according to the AATCC 183 Standard which presents the assessment methods using a spectrophotometer [12]. It describes the new conditions of preparing the samples, which should first be washed, exposed to sunlight and chlorinated water. It also introduces the condition, which eliminates the use of the integrating sphere smaller than 150 mm.

The standards cited above do not include the two basic types of blackout fabric: coated fabrics and blackout construction textiles. Blackout fabrics exist on the fabrics market as the coated fabrics or the layered fabrics. The range of coated blackout fabric obtains their barrier properties against sunlight in the process of finishing. The range of coated blackout fabric obtained barrier properties against sunlight in the process of finishing, while the layered blackout fabrics acquire their properties only in the weaving process. For curtains for interiors of public buildings, the weaving blackout product is preferred, in which the barrier properties are created by the special conditions of constructing the fabric, in combination with the parameters and properties of warp and weft yarns.

Among the textile covers used in the interiors of public buildings, the woven blackout curtains are common. Features such as the ability to wash and maintenance became an advantage of this type of blackout curtains. The advantage of vertical blind is a simple suspension system, and the control without a complex manual mechanism. So we have a system composed of a fabric and suspension elements in the form of curtain ceiling track and the runners (a piece of plastic, acting as a joint between fabric and track, critical for the mobility of a curtain).

The primary function of the darkening products in the form of a vertical blinds, covered by this publication is to protect against the unfavourable effects of sunlight. Moreover, the products provide protection features of visibility,
improve the thermal and sound insulation, as well as protect against excessive contrast and dazzle [13].

Secondary importance is the isolation from an unattractive surrounding or maintaining users' comfort and privacy. It is known that the multifaceted requirements for curtain fabrics refer to both decorative and special functionalities. The complexity of the special features of such products requires description and standardization.

Two technologies for producing blackout fabrics mean different levels of barrier properties and different indicators of evaluation. And so – in the case of coated fabrics the assessment of barrier performance may be unnecessary, while for the weave blackout, the detailed rules for evaluating the optical properties need to be defined.

The lack of references to the standards for blackout curtain fabrics is reflected in the content of the technical specifications for hotels.

The analysed technical specifications for textile products applicable in the interior of the four-star hotel, including the curtains is document that governs range of requirements for designers and contractors on the significant special features which allow the fabric to be applied in the interiors, ie. flammability, blackout and mechanical resistance. The specification lists the requirements for the fabrics, and the conditions for service works (forms of decoration, production/preparation and mounting). Specification consists of 7 pages, and the contents is presented in the Table 1.

Table 1. The scope of technical specification for the fabrics in a four-star hotel

<table>
<thead>
<tr>
<th>No.</th>
<th>Scope</th>
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<tr>
<td>2</td>
<td>Fabric standards</td>
</tr>
<tr>
<td>3</td>
<td>Specification for fabrics: Construction, size, samples, industrial standards</td>
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<tr>
<td>4</td>
<td>Specification for fabrics, Fabrics all areas: Drapes, Valances &amp; Sheers</td>
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<tr>
<td>5</td>
<td>Specification for fabrics: cleaning, certificates</td>
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<tr>
<td>6</td>
<td>Specification for fabrics: Fire regulation</td>
</tr>
<tr>
<td>7</td>
<td>Recommended Suppliers for fabrics</td>
</tr>
</tbody>
</table>

Source: own materials.

First – the flame retardancy, as a mandatory requirement for the textile in buildings. The feature can easily be described with the common European or national standards. A list of acceptable standards the table lists in the section "Requirements for Fabric" on No. 6. A view of listed standards is shown in Figure 2.
Fig. 2. Acceptable standards for flame retardancy of the decorative fabrics, technical specification for the fabrics in a four-star hotel

Source: own materials.

A comprehensive list of standards presented in Figure 1 proves a sufficient recognition of the topic and broadly understood compliance, regardless of the place of service.

After the flame retardancy, the second important feature of the fabric for curtains in buildings is a barrier capability against visible light. The hotel buildings are equipped with the blind curtain fabrics. They provide comfort to the hotel guests, by protecting them against unwanted external light both natural and artificial. Unfortunately, the above technical specification does not cite any standard defining the barrier properties of fabrics. Specification does not define any requirement for darkening. The word "blackout" does not appear. The question of sunscreen and barrier functionalities against the visible light is ignored and is not included to the specifications due to the lack of recognition of reference sources. The fact is, that in the above-mentioned hotel the blackout curtains have been mounted beside the jacquard curtain fabrics.

Another part of the work analyzes the distributors-provided certificates of blackout fabrics available on the market of the fabrics for buildings. On their basis, two test procedures have been identified – national PB/15/2007 [14] and American AATCC Method 148/2015. Figures 3 and 4 present available methods for assessing the barrier action currently applicable for blackout fabrics.
Chapter IV. Budtex

Fig. 3. Part of the certificate that confirms the level of darkening by a blackout fabric, document shared by the trading company Rad Pol Sp. Z o. o.

Source: own materials.

Fig. 4. Part of the certificate that confirms the level of darkening by a blackout fabric, document shared by the trading company S.I.C. Co. Ltd.

Source: own materials.

The problem of lack of reference in the technical specifications regarding the blackout properties can be caused by the inconsistency between the assessment methodologies described in the standards AATCC TM148 or testing procedure PB/15/2007 compliant with the EN ISO 13758-1 and the suggested methodology for classifying the darkening fabrics into the two
basic groups – blackout and dimout. Such a classification refers to the characteristics of the power of the light source to be screened by a textile. In the latter standards the light source is the optical system of a spectrophotometer, while the AATCC TM 148 does not specify the light source. The conditions of sample illumination have not referred to the conditions of EN 14501:2005 Standard which classifies such a kind of products. It can be concluded that the described standards for defining barrier properties against sunlight are not equivalent. Classification of the screening textile products does not correspond with applicable methods of assessing these products.

3. Summary and conclusions

A characteristic feature of the EN standards and PN-EN standards adopted on their basis is that they often are very general and vague compared to the old PN Standards.

Woven blackout fabrics commonly applicable in public buildings gain their barrier properties against visible light from their complex structure. They are textiles of complex design and produced with the technology of layered threads system or the technology of multi-layer fabrics. Fabrics of the barrier design cannot be compared with the coated barrier fabrics. They demand dedicated testing procedure.

Manufacturers offer a variety of blackout fabrics, where the structure determines their optical barrier properties. New construction and technological solutions appear constantly due to the high demand for this type of product range. This justifies the need for a normative assessment systems for blackout fabrics.

The exploratory research carried out on the basis of available standards as well as on the technical specifications for curtain fabrics at a reputable hotel, confirm the lack of harmonized terminology, procedures for assessing the performance and special properties. In particular, the special properties of fabrics applicable in the interiors of public buildings should be clearly defined.

The analysis of the technical specification of a four-star hotel, and the certificates of curtain fabrics applicable in public buildings justify a statement that there is a need to identify conditions of using and classifying the curtain fabrics for their special optical properties, and approving the fabrics to the use in the interiors.

The need was identified to develop effective standards for curtain fabrics, featuring the barrier capabilities against the visible light, including the assessment indicators for each type of blackout fabric.
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STUDY OF CONCRETE REINFORCEMENT BY WOVEN REINFORCEMENTS

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1. Introduction

The fibres, when added to concrete, could allow its strengthening opposing crack propagation and thus they increase its ductility. This solution provides a composite with superior traction capacity in ordinary concrete. With the random disposition of the fibres, the use of single fibres varies largely. This lack of order in the arrangement of the fibres causes some fibres become positioned perpendicular to the direction of the load while others are found in small sections solicited as shown in figure (Fig. 1).

Fig. 1. Fibres arrangement

\textit{Source: own work.}
To remedy this, the use of textile structures to organize more orderly fibre has been studied and evaluated RWTH Aachen University and Dresden University of Technology [1]. This solution has therefore been developed in order to increase the load bearing capacity of the structure with the same amount of reinforcing or reducing the amount of reinforcement required for the same load capacity.

In the same vein the use of woven reinforcements ("textile reinforced concrete" TRC) has been the subject of scientific research to produce high performance concrete composites with controlled geometry that could allow the construction of sustainable structures, more economical and more environmentally friendly.

Concrete reinforced with textile or textile-mortar composite (TRC) is a new class of sustainable building materials with high tensile strength, better toughness, higher ductility and good energy absorption under static and dynamic [2].

Resistance and improved ductility are governed mainly by the fibres which retard cracks in the matrix and to transfer loads, allowing the development of a microcrack system distributed (Fig. 2).

![Fig. 2. Cracks distribution](source: own work.)

A comparative study between the tensile strength of a cement matrix reinforced with glass fabric and that of the same matrix reinforced by glass fibres revealed that the woven reinforcements provide the superior tensile strength [3]. (Figure 3). Subject to loads, these composites exhibit a better performance than the composite reinforced with short fibres (glass) (Fig. 3) [5].
The modern textile technology offers a variety of fabrics produced by different methods, which allows great flexibility in the design of the fabric. This flexibility allows precise control of the geometry and design of the fabric, thread geometry, orientation of the wire, and the combination of thread materials. These many options in designing the fabric create an opportunity to produce new building products that are structurally safe and durable.

Several publications [3] [4] discuss the state of the art on the subject of concrete reinforced by textiles (TRC). The following paragraphs present our own description of a bibliographic review of previous studies.

2. Mechanics characterization of woven reinforcements

The behaviour of a fabric is mainly controlled by three types of rigidities: stiffness voltage which is related to the extension of the fibre, shear stiffness that comes from the variation in angle between the strands and their crush on each the other, and the flexural rigidity which is very low compared to the other two forms of rigidities. One can determine the behaviour of a tissue either by experimentation, either by analytic methods or by simulation at the scale of representative unit cells (REC). [5] A REC is defined as a pattern for a simple translation to reconstruct the entire weaving.

The diameters of fibers constituting the strands are very small in relation to their lengths. Therefore, the wicks cannot be subjected to tension in their longitudinal direction. The tension in the wicks depends mainly on two factors: stretching of the fibres, but also the shrinkage (corresponding to the difference between the actual length of a wick once extracted from the tissue and the length which it occupies in the fabric, expressed as a percentage).
The drawing a fibre in an orientation will lead to the withdrawal of the fibre in the other direction. Thus, the voltage in a wick will depend on the deformation of the wick, but also the deformation of the wick is located in the other orientation.

To characterize the behaviour of a tension fabric we use is experimental techniques, either finite element simulations at the mesoscopic scale. [6] For the experimentation, one of the techniques is to define the law of behaviour of the tissue using a biaxial tensile testing machine (Fig. 4). This is to perform tensile tests in a direction while maintaining a constant deformation in the other direction. Thus, for each ratio \( k \) is obtained a traction diagram (Fig. 5 (a)), and that finally allows to draw tension surfaces (Fig. 5 (b)).

\[
    k = \frac{\varepsilon_{warp}}{\varepsilon_{weft}}
\]

(Eq. 1)

![Fig. 4. Biaxial tension to a fabric in Croix [7]](image)

![Fig. 5. Biaxial traction surface [7]](image)
The second method mentioned is to perform a 3D simulation of a REC at the mesoscopic scale (Figure 6), and further define once the tensile curves. The experimental results agreed well with the results from finite element.

![Fig. 6. Representative unit cell of an unbalanced fabric](source: own work)

The third method is, starting from the geometry of the weave profile to describe stress-strain curves analytically [8-9].

**ONCRETE REINFORCED TEXTILE (TRC)**

### 2.1. Concre
c

The requirements on the concrete may vary depending on the geometry and the textile mesh properties. Aggregates of sizes are often limited by the size of the mesh layer.

The cement matrix CRT is different from that generally used in reinforced concrete with steel bars. Concrete grained, also defined as mortar, is the type of concrete required for the TRC, where the maximum aggregate size is less than 2 mm. The fluid concrete is needed to adequately penetrate the openings of the textile reinforcing structure, to provide sufficient binding and to allow transfer of the load of the matrix to the reinforcement (Fig. 7).

In addition, the cement matrix must be chemically compatible with the selected textile reinforcement, while providing the desired load bearing capacity, mechanical characteristics and behaviour appropriate to the geometry of the specimen and the production method [2].

![Fig. 7. Overview of the textile composite mortar: casting process (left) and the cured TRC component (right)](source: own work)
2.2. Textile

There are a large number of variations of wicks constituting the reinforcing material. Various materials can be used such as carbon fibre, glass or basalt fibre. A textile thread consists of many single fibres in a range of 800 (typically glass fibre) to 24,000 (carbon fibres) [2]. A thread may vary in cross section, shape and circumference as well. Son these can then be arranged in the meshes of different types and sizes; 2D or 3D, sparse or dense, woven, glued or held together using additional son. How the stitches are arranged can affect mainly the ability to pull and the mechanical behaviour of the composite [2].

In our study, we will use polyester fibres as a reinforcing material and we will discuss the different types of 2D and 3D weaving to identify, initially, their influence on the mechanical behaviour of the resulting fabric. The treated textile fiber is a synthetic fiber. She has good qualities of mechanical strength and is easily recyclable. Also, it is known for its fire retardant properties.

2.3. Mechanics of TRC

Many composite materials, such as polymer matrix have a strong adhesion matrix wire. Their behaviour laws expressed in tensile deformation, stress can then be modelled easily and accurately between the textile and the matrix. In this case, the intrinsic properties of the materials present sufficient to account for the behaviour.

In contrast, in the case of textile-mortar composites, filaments adhesion-matrix remains usually very limited. In addition, the impregnation of the thread (consisting of hundreds of filaments) is essentially restricted to filaments located on the periphery. The forces applied to the matrix are thus transmitted to the "external" filaments impregnated by the matrix (matrix adhesion filament) which themselves redistribute, in part, to the filaments 'internal' (membership filament-filament). Understanding these mechanisms of adhesion is thus required to take the behaviour of TRC traction. Given the complexity and importance of these mechanisms of adhesion between the textile and mortar, they were studied at different scales.

Fig. 8. Illustration of a coated filament in its matrix. Viewing not impregnated and external inner filaments impregnated [12-13]
Also, in order to improve this adhesion, the thread can be pre-impregnated with various products. Their influence on the resistance to adhesion between the son and the matrix will also be considered [11].

3. Conclusion

The literature review highlighted the growing interest of the scientific community for the textile-mortar composites (TRC) and thus their credibility in the performance-oriented terms (tensile strength of up to tens of mega Pascal, coupled with low openings cracks Service tenth of a millimetre).

In addition, a general explanation of the two main constituents of the TRC namely the concrete matrix and the textile reinforcement, was exposed in this chapter. Also, experimental methods applied to characterize the mechanical properties on the textile reinforcement were also cited. In the end, other factors (membership, impregnating son, etc.) can affect the behaviour of textile-mortar composite, were mentioned and will also be considered in carrying out the tests.

Bibliography


MULTILAYER, RELIEF KNITTED FABRICS AS WALLPAPERS WITH A FUNCTION OF MOISTURE CONTROL

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The subject of the chapter is the technology of multilayered functional fabrics, whose construction refers to the phenomenon of sorption and desorption of water vapor from the air.

Target application area of these fabrics are wallpapers used in interior decoration of living spaces.

The primary function of a wallpaper is self-regulation of humidity in the room, but its properties can be expanded to include self-regulation of temperature. The above-mentioned air regulating parameters will change within a certain range, and cannot replace actively operating air conditioning and heating systems. The structure of the textile wallpaper was based on a multilayered jacquard weft-knitted fabric. Two alternative solutions were presented- the first one was based on a double-layer tuck knitted fabric and a three-layer structure, filled with additional weft threads, and the second one was a spacer 3D channel knitted fabric, having a thickness of about 3 mm.

Fig. 1. Double-layer tuck weft-knitted fabric

Source: own work.
Both considered structures will be produced on cylindrical or computer-controlled flat weft-knitting machines. The outer surface of the fabric will serve a decorative function, and that is why this layer will contain a plain jacquard color stitch or relief of unlimited size of stitch repeat. In terms of properties, the structure will be hydrophobic and will possess certain porosity, so that the air will be able to contact successive layers of the fabric. For utility reasons this layer will be built of synthetic polyester yarns or, alternatively, polyamide or polypropylene ones. The subsequent layers of the fabric will function as controllers of microclimate in the room, in terms of changing relative humidity. Depending on the moisture content in the atmosphere, these layers will take up vapor molecules acting as absorbents, or give up the stored moisture, according to the desorption principle.

Hygroscopicity of the inner layers of the fabric will be obtained by using hydrophilic yarns, made of natural materials (wool, cotton, silk). In addition, in case of three-layer weft knitted fabrics and spacer channel fabrics it is intended to fill the inner layer with absorbents in the form of granulated crystals of silicon dioxide SiO$_2$ (water absorption up to 36% of its own weight), aluminium oxides, salts of polyacrylic montmorillonite and others [1, 2].

The inner layer, because of the function of storing moisture, will possess antibacterial (anti-virus) and anti-fungal properties, providing chemical and biological purity. By appropriate selection of materials and percentage participation of individual component fabric layers it will be possible to control the capacity of the absorbed water vapor, thereby regulating the microclimate in the room.

In the analyzed process of sorption and desorption of moisture from the air through a knitted wallpaper we use the well described basic phenomena occurring in the process of ventilation and air conditioning [3, 4]. During heat and moisture transformations the mass of dry air ($m_p$) does not change, while
the moisture mass \( (m_w) \) may vary (process of humidification or dehumidification of the air). The physical state of moisture can also change (evaporation or condensation).

The basic characteristic of humid air is the moisture content, called specific humidity \( x = m_w/m_p \) [g/kg of dry air] or absolute humidity described by the proportion of moisture mass \( m_w \) to the volume occupied by the air \( V \) \((\rho = m_w/V)\). Other important parameters include relative humidity \( \varphi \) – the ratio of partial pressure of water vapor in humid air \( P_p \) to the pressure of saturated vapour \( P_s \), enthalpy of humid air \( h_p \) (specific enthalpy \( h \)), wet bulb temperature, dew point temperature, temperature of dry air, mass of air stream.

The parameters of indoor air in residential and public premises are regulated by the following laws and standards [5]:

- Regulation of the Minister of Infrastructure of 12 April 2002 on technical conditions to be met by buildings and their locations. Dz. Ustaw (Journal of Laws) nr 75 from 15 June 2002 item 690.
- PN-89/B-10425: Smoke flues, gas passes and ventilation ducts made of brick. Technical requirements and final acceptance tests.

Recommended general parameters of indoor warmth and humidity, guaranteeing thermal comfort for people, take the following values specified by PN-EN 13779:2008 and the Regulation of the Minister of Infrastructure:

- air temperature \( 20 \pm 26^\circ C \),
- air speed in the occupied zone \( 0,15 \pm 0,2 \) m/s, in summer up to \( 0,6 \) m/s,
- relative air humidity at a temperature of \( \varphi = 30-60\% \) do \( 80\% \),
- average temperature of thermal radiation by \( 2 \) to \( 3^\circ C \) lower than the ambient temperature.

Relative humidity of indoor air should be jointly dependent on temperature, and so in summer at \( 23 \pm 25^\circ C \) humidity should fall between 40 to 60% (preferably 50%), while in winter at air temperature of \( 21-22^\circ C \) relative humidity should equal \( 35-55\% \).

Maintaining proper quality of indoor air is the task for ventilation [6]. As a result of poor ventilation and thus poor quality of indoor air excess relative humidity increases, causing various ailments. One of the solutions for changing the state of humid air (dehumidification, humidification, mixing, heating, cooling) is hybrid ventilation [7]. It is a mechanically assisted natural ventilation...
using an inlet fan or a balanced system. Proper design of hybrid ventilation is tailored to air parameters, changing during the year and even throughout the day. In literature concerning indoor climate of building facilities attention is drawn to the fact of excess moisture accumulation. The impact of moisture on factors such as the growth of bacteria > 60%, viruses > 70%, fungi > 60%, mites > 47%, respiratory infections < 45%, allergic inflammations, asthma > 46%, chemical effects > 30%, ozone production < 90%, demonstrates that the preferred range of air humidity in an indoor space falls between 30% and 55% [8].

Different methods can be used in order to reduce humidity levels in indoor spaces where people are staying. They include moisture absorption by building structures and elements of interior decoration [9].

The concept of "moisture buffering" [10, 11] can be defined as hygrothermal interaction between building materials, room equipment and internal air. The interaction may contribute to maintaining air quality by reducing momentary values of humidity, which can affect thermal comfort. Peak changes of air humidity may occur e.g. at night in the bedroom.

Among the building materials, the biggest capacity for moisture buffering is possessed by: spruce boards 1.2 g/m$^3$, cellular concrete 1.0 g/m$^3$, birch boards 0.78 g/m$^3$, concrete foundations with stucco 0.76 g/m$^3$, plaster 0.6 g/m$^3$ (brick and concrete - the smallest values of the order of 0.4 g/m$^3$) [10].

The advantage of the capability of moisture buffering possessed by some building materials is reducing the peak values of humidity in indoor spaces while people are staying inside. The buffering effect is essential for balancing daily fluctuations of humidity.

According to the concept described in the chapter, the process of natural ventilation is supported by moisture buffering (sorption drying) realized by textile material made of natural fibers, forming the multi-layered knitted wallpaper.

The developed technology brings new solutions in the field of technical textiles used in building industry in the area of interior decoration of residential interiors.

In the first phase of technological research a jacquard double-layer knitted wallpaper was designed using a CAD programme called M1plus by Stoll company. The outer layer of the wallpaper was made of PE threads with thickness of 188 dtex x 2, and the inner layer was formed of cotton yarns of linear density of 150 (200) dtex x 2. Tuck stitch was used in three different variants of connecting the layers, on every 8th, 4th and 2nd needle, which changes the percentage of threads in the fabric. The fabric was made on Stoll computer-controlled weft-knitting machine CMS 530 HP with needle gauge E16. Three variants of the knitted fabric were prepared, differing in surface density and surface mass. Parameters of the knitting process: knitting speed 0.8 m/s, density NP$_{PE}$ = 11.5, NP$cotton$ = 11.0, lift off WM = 6.6. The fabric was made on 299 needles, pattern repeat on the face of the wallpaper – 768 courses / 24 wales. In the designed structure, for one course on the face of the fabric there are two courses on the fabric back, for variant 1a two additional structures were made, wherein for one course of the wallpaper pattern, there is one course of
cotton on the fabric back in case of variant 1b, and in variant 1c for one course on the fabric face there are three courses on the fabric back.

Fig. 3. Printout of the designed stitch and fabric pattern in the M1plus system

Fig. 4. Stitches variant in the knitted fabric

Source: own work.

Fig. 5. View of a numerically controlled weft – knitting machine Stoll, type CMS

Fig. 6. Photographs of the face and back of the wallpaper (fabric face – variant 1b, fabric back – variant 1c)

Source: own work.
Basic structural parameters of the knitted wallpapers were measured and the level of moisture absorption was determined.

Table 1. Structural parameters of knitted fabrics (PE1 – orange, PE2 – violet, grey – fabric face, violet – fabric back)

<table>
<thead>
<tr>
<th>Fabric variant</th>
<th>Surface mass $M_m$ [g/m²]</th>
<th>Percentage of threads masses $%M_n$ [%]</th>
<th>Fabric thickness g [mm]</th>
<th>Course density $P_r$, number of courses /100 mm</th>
<th>Wale density $P_k$, number of wales /100 mm</th>
<th>Loop shape coefficient C = $P_k/P_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>w1a</td>
<td>492.25</td>
<td>PE 1 18</td>
<td>2.58</td>
<td>90 72</td>
<td>122 72</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PE 2 18</td>
<td></td>
<td>100 76</td>
<td>144 72</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cotton 64</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>w1b</td>
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<td>PE 1 27</td>
<td>2.05</td>
<td>96 74</td>
<td>100 76</td>
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<td></td>
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<td>100 76</td>
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<td></td>
<td></td>
<td>cotton 55</td>
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</tbody>
</table>

Source: own work.

Moisture absorption test was performed using a moisture analyzer (Fig. 7) of MAC series produced by Radwag. Moisture content was determined in relation to the initial mass of samples acclimatized in the following conditions: a) temp. = 18°C, relative humidity 58% b) temp. = 30°C, relative humidity 75%.
Drying conditions: air temp. 95°C, air velocity $V_{pow.}=1$ m/s.
Measurement results of hygroscopicity of fibers are shown in Table 2.

![Fig. 7. Conditioning apparatus (schematic diagram) [15]](image)

Literature data [12, 13] shows that hygroscopicity of fibers at air humidity of 65% equals as follows: 15.5% for wool fibers, 11.2% for natural silk, 8.2% for cotton, 5.1% for polyamide, 4.1% for polyacrylonitrile, 0.5% for polyester and 0.2% for polypropylene.
The research confirms literature reports.

<table>
<thead>
<tr>
<th>Yarn type</th>
<th>Dry sample mass $M_0$ [g]</th>
<th>Sample mass at 18°C and humidity of 58% [g]</th>
<th>Percentage of moisture mass in the yarn [%]</th>
<th>Sample mass at 30°C and humidity of 75% [g]</th>
<th>Percentage of moisture mass in the yarn [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE1</td>
<td>88.68</td>
<td>88.97</td>
<td>0.33</td>
<td>89.02</td>
<td>0.038</td>
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<td>PE2</td>
<td>88.28</td>
<td>88.60</td>
<td>0.36</td>
<td>88.67</td>
<td>0.44</td>
</tr>
<tr>
<td>BV</td>
<td>60.84</td>
<td>65.43</td>
<td>7.02</td>
<td>67.44</td>
<td>9.77</td>
</tr>
</tbody>
</table>

Source: own work.

Assumptions for the analysis of moisture sorption and desorption by a knitted wallpaper:
1. Changes in the mass of water vapor were referred to the average size of a living space with dimensions of 5 m x 5 m which gives an area of 25 m$^2$. Such a room with assumed height of 2.8 m has a cubature of $V_w = 70$ m$^3$. The surface of the walls in the room possible to be covered with a knitted wallpaper is 56 m$^2$. Deducting the surfaces of window and door openings we accept for calculations $P_{pom} = 50$ m$^2$. 
2. According to the above specified standards of indoor climate we accept boundary conditions of temperature and relative humidity.

a) Boundary variant min.: $t_p = 20^\circ C$, relative humidity 30% for which the dew point temperature $DP = 1.92^\circ C$, the volume content of water vapor in dry air $PPMV = 7004.09$ ppm, the ratio of water vapor to the mass of dry air $PPMW = 4356.54$ ppm, moisture content, the ratio of water vapor mass to the mass of dry air $X = 4.36$ g/kg (5.181 g/m$^3$), enthalpy of the mixture of dry air and water vapor $(x) I = 7.43$ kcal/kg, the pressure of water vapor contained in humid air $WVP = 704.58$ Pa, the pressure of saturated water vapor in the air $SWVP = 2348.6$ Pa, wet bulb temperature in psychrometer $T_w/T_1 = 10.94^\circ C$.

b) Boundary variant max.: $t_p = 26^\circ C$, relative humidity 60% for which $DP = 17.64^\circ C$, $PPMV = 20415.19$ ppm, $PPMW = 12698.25$ ppm, $X = 12.7$ g/kg (14.598 g/m$^3$), $I = 13.93$ kcal/kg, $WVP = 2026.68$ Pa $SWVP = 3377.81$ Pa, $T_w/T_1 = 20.36^\circ C$.

Optimum variant possesses the following parameters: $t_p = 22^\circ C$, relative humidity $RH = 50\%$, other parameters: $DP = 11.11^\circ C$, $PPMV = 13283.57$ ppm, $PPMW = 8262.38$ ppm, $x = 8.26$ g/kg (9.7 g/m$^3$) $I = 10.28$ kcal/kg, $WVP = 1327.99$ Pa $SWVP = 2655.97$ Pa, $T_w/T_1 = 15.49^\circ C$ [14].

The results of the analysis are shown in Table 3.

Table 3. Surface masses of fabric variants and absorbed moisture mass

<table>
<thead>
<tr>
<th>Fabric variant</th>
<th>Surface mass [g/m$^2$]</th>
<th>Mass of PE in 1 m$^2$ [g]</th>
<th>Mass of BV in 1 m$^2$ [g]</th>
<th>Moisture mass absorbed by BV for 1 m$^2$ [g]</th>
<th>Maximum moisture mass absorbed by BV for 50 m$^2$ of wallpaper [g] (*)</th>
<th>Max. Moisture volume in 70 m$^3$ of air</th>
</tr>
</thead>
<tbody>
<tr>
<td>w1a</td>
<td>492.25</td>
<td>177.21</td>
<td>315.04</td>
<td>26.46</td>
<td>1323.0</td>
<td>679g (t$_p$ = 22°C, humidity 50%)</td>
</tr>
<tr>
<td>w1b</td>
<td>352.42</td>
<td></td>
<td>165.64</td>
<td>13.91</td>
<td>695.5</td>
<td></td>
</tr>
<tr>
<td>w1c</td>
<td>597.08</td>
<td></td>
<td>429.90</td>
<td>36.11</td>
<td>1805.5</td>
<td></td>
</tr>
<tr>
<td>w2a</td>
<td>432.24</td>
<td></td>
<td>250.69</td>
<td>21.05</td>
<td>1052.5</td>
<td></td>
</tr>
<tr>
<td>w3a</td>
<td>431.99</td>
<td></td>
<td>237.59</td>
<td>19.96</td>
<td>997.88</td>
<td></td>
</tr>
</tbody>
</table>

* after calculations we assume average moisture absorption by cotton yarns of 8.4%.

Source: own work.
Knitted wallpapers have the potential of maximum moisture absorption of 1175 g at maximum air saturation with moisture in the range 679–1022 g (possibility of full air drying). This means that knitted wallpapers possess a significant capacity of moisture sorption from the air, which is the basis to consider them as a factor of natural regulation of the parameters of ventilated air in the hybrid system.

One of the dangerous characteristics is high dew point temperature, which in case of air temperature of 26°C and relative humidity of 60% equals: \( DP = 17.6°C \), and for optimum parameters \( tp = 22°C \) and relative humidity of 50%, \( DP = 11.1°C \). The danger lies in the fact that the moisture absorbed in the inner layer of the fabric may be condensed, particularly when the fabric is put on the outer wall of low thermal insulation, where low temperatures occur. In this case, it is essential to provide adequate thermal insulation of the residential building, either in the form of an additional layer of high thermal resistance between the wall and the wallpaper or outer insulation.

In further works analytical analysis will be conducted of parametric changes of absolute and relative air humidity, moisture content in the air, specific enthalpy of humid air for isobaric transformations for a specific mass balance of moisture and heat. In case of dehumidification and humidification of air given off or absorbed by the sorption layer of the knitted wallpaper the changes will be illustrated on graphs I-x.

**Bibliography**


Chapter V
AGROTEX
1. Introduction

The production and usage of textiles and clothing generate a significant amount of textile wastes. In current practice, a large part of the wastes is deposited on a landfill, what is the cause of serious environmental problem. The substantial portion of the wastes, both post-industrial as well as post-consumer, is a source of raw materials, which can be used for production of new valuable products. The production of such products effectively extends the active life of the constituent fibres potentially by many years beyond the first use phase. In this way the environmental problem connected with landfilling of wastes can be significantly reduced.

For the production of textiles from recycled fibres usually nonwoven technologies are applied. In this way thermal and acoustic insulating materials used in construction or automotive industry are obtained. Alternative technique for the processing of recycled fibres is the Kemafil technology.

The Kemafil technology was developed in the 70’s in the Institute for Industrial Textiles in Dresden (Germany) [1]. The technology enables production of thick ropes with a core-mantle structure, which can be filled with various materials. For the formation of ropes a small circular knitting machine is used. The machine is equipped with four hooked loopers arranged around a guide tube. The four threads guided by loopers form around the rope tubular knitted sheath, which is formed by four stitch courses running parallel to the longitudinal axis of the ropes and the stitch wales running spirally around the rope [2].
For many years the Kemafil technology has been used for production of various products, which found broad application in construction, agriculture and transport. In the 90's technology has been used in Beskidian Textile Institute in Bielsko-Biala (Poland) for the production of ropes designed for erosion protection of slopes. The ropes from textile wastes with a diameter $\phi = 50 \text{ mm}$ were obtained and spread on the slope diagonally to form 60-70 cm sided squares. The grid created from the ropes was fastened to the ground with wooden or steel pins and covered with the soil. The ropes forming the geogrids were successfully used for the protection of sandy roadside slopes as well as banks of an expansion tank [3].

Some years ago in Saxon Textile Institute in Chemnitz (Germany) innovative geotextiles from the coarse Kemafil ropes with a diameter $\phi = 130 \text{ mm}$ were invented. The geotextiles forming segments built from meandrically arranged Kemafil ropes were produced. The segments were stabilised with additional knitted chains, which linked subsequent turns of the ropes. In previous years the meandrical geotextiles were successfully used in Germany for land reclamation of post-mining area and the protection of the steep slopes at road construction [4].

Recently, in Institute of Textile Engineering and Polymer Materials in Bielsko-Biala (Poland) in co-operation with Saxon Textile Institute the geotextiles made from Kemafil ropes were obtained. The geotextiles were used for the protection of roadside and drainage ditches in the clay ground [5]. The behaviour of protected ditches and geotextiles installed in the ditches during one year of the exploitation was observed. It was revealed that the geotextiles eliminate the formation of erosive channels and well protect the banks of the ditches against sliding. Simultaneously, during exploitation the gradual biodegradation of materials used for the production of ropes was observed [6].

Based on the positive experience with the use of the meandrical geotextiles in the erosion protection of roadside and drainage ditches the next attempts of using geotextiles in new application were undertaken. The results of investigations aiming the protection of slopes threatened by a landslide are presented in the chapter.

2. Materials and methods

The coarse Kemafil ropes with a diameter 12 cm were produced. For the production of ropes the waste strips of woollen nonwoven and a stitch-bonded nonwoven from recycled fibres were used. For the production of the nonwoven the blend of natural and synthetic fibres obtained by the shredding of textile wastes was used. The nonwoven was produced by the Maliwat system. For stitching of the web a polyester multifilament thread with a linear mass density of 148 dtex was applied. To the nonwoven from recycled fibres grass seeds were incorporated.
The thickness and mass per square meter of nonwovens were measured in accordance with PN-EN ISO 9863-1:2007 and PN-EN ISO 9864: 2007 standards. The measured parameters of the nonwovens are presented in Table 1.

Table 1. Parameters of nonwovens used for the production of ropes

<table>
<thead>
<tr>
<th>Row material</th>
<th>Way of bonding</th>
<th>Thickness [mm]</th>
<th>Mass per square meter [g/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>wool</td>
<td>needle punching</td>
<td>5.8</td>
<td>406</td>
</tr>
<tr>
<td>recycled fibres</td>
<td>stitch bonding</td>
<td>3.0</td>
<td>265</td>
</tr>
</tbody>
</table>

Source: own work.

The sheath of the ropes was made from the polypropylene twine with a diameter of 2 mm. The number of rows on the length of 1 meter of the sheath for woollen nonwoven and nonwoven from recycled fibres was 25 and 28 m⁻¹, respectively.

The segments of meandrically arranged ropes of a width 2 m were prepared (Fig. 1). The subsequent turns of meandrically arranged ropes spaced apart about 0.5 m were connected with five linking chains. The chains were formed from the polypropylene three-wire twine from fibrillated fibres with a linear density of the 310 dtex.

3. Installation of geotextiles

The geotextiles were installed near Raciborz in Upper Oder Valley close to the Czech-Polish border. The area has been often flooded by the river. Due to the high risk of flooding some years ago in the region the construction of the Raciborz Dolny dry flood protection reservoir was initiated. The reservoir is to
be a key element of the Oder River flood protection, which will reduce the impact of the river on the creation of flood waves from Raciborz to Wroclaw.

Within the reservoir the Oder valley exhibits specific geological structure. Under the soil and a thin layer of sand or clay the thick layer of gravel and sand occurs. The gravel layer possesses large thickness, which locally exceeds 15 m. The gravel has very good characteristics and can be successfully used in road construction and for production of concrete.

The rich gravel deposits accumulated in the valley are intensively exploited. In the vicinity several open mines exist, which use various extraction methods (Fig. 2a). As a result of gravel extraction, irrespective of the extraction method, deep pits are formed, which are naturally fill with water to form smaller or greater ponds. On the banks of the pits steep slopes prone to local sliding and slipping are generated (Fig. 2b). Simultaneously in some places collapse following undermining of the bank toe is observed. Due to the high risk of landslide the protection of slopes ensuring their stability is highly desirable.

In order to stabilize the slope the geotextiles were installed in the western part of the gravel pit Nieboczowy. The geotextiles were used for the protection and stabilisation of the steep slope with a length ca. 5 m and slope ratio between 1:0.9 and 1:1.8. The part of the slope with a total area of approximately 150 m$^2$ was secured.

Before installation the slope was properly profiled. The surface of the slope was levelled and cleaned from the bigger stones or roots. Then the segments of the meandrically arranged ropes were rolled out and spread on the surface of the slope (Fig. 3b). The subsequent segments of geotextiles laid next to one another were connected with additional links made from the polypropylene twine.
The segments were anchored in the crown of the slope and fastened at the surface with steel “U-shaped” pins (Fig. 4a). The long pins made from ribbed bars of diameters $\phi = 8$ mm were used. The pins were hammered to a depth of 40 cm. After installing of geotextile the slope was covered with local soil (Fig. 4b).

4. Exploitation of the slope

After installation during several weeks the behaviour of the slope was regularly monitored. In the first period of exploitation the consolidation of the soil covering the geotextiles was observed. In the steepest part of the slope only initially consolidated soil located between the turns of the ropes was partially removed. The soil loosely connected to solid ground poured over the ropes and slide down to lower part of the slope. As a result the certain portion of the meandrically arranged ropes was uncovered (Fig. 5a). Contrary to steepest part of the slope in sections with lower slope ratio the soil covering the geotextile was kept between the turns of the ropes (Fig. 5b).
Chapter V. Agrotex

The ropes arranged laterally on the slope formed a network of micro-dams, which slow down the flow of water and reduce the transport of material detached from the soil by rain drops (Fig. 6a). Moreover, the ropes installed on the slope exhibit high water absorption capacity. For ropes produced from the woollen nonwoven the absorption capacity equals 535%. During drying in the free state the water absorbed in the ropes is slowly released and after one month its content is systematically decreased to approximately 100%. For ropes made from recycled fibres the absorption capacity is much lower and amounts to 205%. In this case after one month of drying the water is completely removed from the ropes. Thanks to forming a system of micro-dams and high water absorption capacity during several weeks of exploitation no erosive channels on the surface of the slope were formed and no sliding of the slope was noticed.

Source: own work.

Fig. 5. The first period of exploitation of the protected slope: a) uncovered ropes in the steepest part of the slope, b) the geotextiles covered by the soil

Source: own work.

Fig. 6. The exploitation of geotextiles on the slope: a) the rope made from woollen nonwoven, b) germination and growth of grass on the ropes from recycled fibres

Source: own work.
In spring with the start of the new growing season on the slope the first signs of vegetation became visible. In the section protected with ropes containing seeds the germination and growth of grass was initiated (Fig. 6b).

The incorporation of seeds into ropes prevents the washout of seeds by the water flowing on the surface of the slopes. By absorbing rain water the ropes ensure humid environment and good conditions for seeds germination. Later the ropes function like a storage system for water, which supply the grass vegetation. As a result in next weeks on the slope the transverse strips of grass were grown.

Thanks to seeds germination on the ropes and retaining of water the geotextiles help to initiate growth of the protective plants on the steep slope in difficult field conditions. In next weeks the geotextiles facilitate the development of protective vegetation, which gradually takes over the protective function.

5. Conclusions

The performed investigations revealed that the Kemafil technology can be successfully used for the production of valuable products from the textiles wastes. The geotextiles built from the segments of meandrically arranged Kemafil ropes can be used for the stabilisation of the steep slopes in gravel pits. The geotextiles can be easily installed on the slope. After installation the geotextiles protect the slope immediately and help to establish protective vegetation in difficult field conditions. The application of geotextiles efficiently protect the slope against sliding.

Acknowledgment

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Bibliography


SUMMARY

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Facing an increasing demand for mechanical structures with improved properties, advance materials offer a promising perspective. In the book the most recent scientific studies in textile including: Proetex – protection of life and health in the working environment textile, solutions for personal protection, textiles for the protection of the working environment, Techtex – innovative technical textiles, textiles for composites, footwear and leather industry and for special applications, Budtex – healthy home, textiles for the construction industry and interior decoration, Geotex – safe transportation, textiles for means of transport, geotextiles, textiles for road protection and Medtex – everyday protection, improving the quality of everyday life, medical and hygienic textiles, rehabilitation and recreational textiles.