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Stability of the Performance and Safety of the Ballistic Body Protections Used in Humanitarian Demining

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Abstract
This paper focused on analysing actual state-of-the-art personal protective equipment (PPE) used in humanitarian demining for the determination of potential gaps to provide improvements to increase the safety and, simultaneously, performance of PPE. The essential requirements and technical standards for PPEs used in humanitarian demining operations were analysed as a basis for gap identification. Furthermore based on the defined gap and risk analysis, the effect of accelerated ageing and simulation of the use of soft ballistic inserts designed with p-aramid woven fabrics was performed. The research provided new inputs for improvements in the standardisation of PPE with respect to performance and safety validation in a laboratory environment. Moreover the gap analysis resulted in strictly identified gap areas for PPE improvement in usability, functionality and safety.

Key words: *use simulation, accelerated ageing, fragment-proof personal protections, humanitarian demining.*

Introduction

Landmines and cluster munitions still kill or maim civilians every day in an indiscriminate manner (civilian or military, men, women or children), even long after conflicts are over.

All employees involved in humanitarian demining should be provided with comfortable and serviceable clothing and footwear appropriate to the task and local conditions. Personal protective equipment (PPE) used in humanitarian demining includes body protection, face or eye protection, trousers, leggings, a helmet and blast-resistant boots.

The minimum requirements of PPE for use in mine action are given in the International Mine Action Standards (IMAS) [1]:

a) body armour capable of satisfying the ballistic test outlined in STANAG 2920 [2], achieving a V50 rating (dry) of 450 m/s. It must also be capable of protecting the chest, abdomen and groin area against the blast effects of 240 g of TNT at 60 cm from the closest part of the body;
b) eye protection that is held over the eyes in a frame that prevents blast ingress from beneath. The eye protection must be capable of retaining integrity against the blast effects of 240 g of TNT at 60 cm and must provide protection equivalent to not less than 5 mm of untreated polycarbonate.

To minimise/eliminate the risks associated with a demining operation or the clearance of mines and/or cluster munitions, the contractor must equip staff properly with the selected PPE to reduce the possible effects related to an explosion. PPE shall be treated as a last opportunity to protect against the risks associated with the operation of the explosives found in demining actions. PPE rarely achieves the maximum level of protection, whereas the actual level of protection is difficult to quantify [3].

Moreover PPE should not restrict the mobility, visibility and focus of the personnel participating in the demining action. It is necessary to take into account that PPE effectiveness is dependent on its proper use and exploitation.

The subject of the present publication is a PPE which is in accordance with Directive 89/686/EEC, Annex 1: "Exhaustive list of PPE classes not covered by this directive". The essential requirements and technical standards for PPEs used in demining operations (IMAS) should be specified in the European standards determining requirements for the design, performance and safety as well as personal hygiene. The EU standards should cover:

- general requirements;
- an assessment of the usefulness and relevance of the selection for a person, weather conditions, cultural practices and the risks involved;
- the requirements in terms of the properties of the materials used, taking into account the requirements for materials that enhance visibility;
- the minimum requirements for protection against shock waves associated with the explosion (anti-blast behaviour);
- fragment resistance (V50);
- trauma resistance;
- resistance to chemicals and biological agents;
- requirements for the determination of the period of the use guarantee without significant reduction in the safety and performance;
- ergonomic requirements.

Separate, detailed standards should include:

- frontal body protector requirements;
- requirements for footwear protectors for the legs and feet;
- hearing protection requirements;
- requirements for clothing used in demining activities;
- head protection requirements;
- requirements for protection of the limbs;
- requirements for eye protection.

The standards describing the research methodology, including ergonomic studies and the impact of ballistic shock waves, should also be elaborated.

PPE is required to include a warranty period (the period in which a protective device has parameters unchanged in relation to the level designed and the terms of use). This is particularly important when used in high temperatures and humidity and due to the use of UV-degradation susceptible materials, i.e., aramids or polycarbonate (if not protected against direct exposure to sun-light and high humidity).

Nevertheless there is no information about the durability of such PPE. In the case of body armour, few researchers have studied the accelerated ageing of ballistic fibres [4-6]. Researchers from DSM [4-6] showed that the properties of Dyneema® fibres and the ballistic resistance of Dyneema® UD retain their values after being conditioned for 8 weeks at 65°C and 80% relative humidity. Using the Arrhenius shift factor of 2 presented, it was found that armour made of Dyneema® maintains its long-term performance when used in ambient weather conditions. The performance of armour based on ultra-high molecular weight polyethylene (UHMWPE) fibre at high temperatures (above 65°C) has also been studied. The results showed that products made of Dyneema® maintain their performance even after being exposed to temperatures far above the usage temperatures for body armour. This study [7] tested the effect of the ageing processes (real-time and accelerated) on the usage properties and safety of ballistic inserts made of a polyethylene fibrous sheet called Dyneema® UD SB21.

Gap analysis was performed as part of the D-BOX project (project No. 284996 "Demining tool-BOX for humanitarian clearing of a large scale area from anti-personal landmines and cluster munitions") within the scope of PPE in humanitarian demining use and indicated that improvement in personal protection needs to be implemented in the following areas:

- training;
- designing process aspects (new designs, ergonomics aspects, implementation of new materials, material systems or material bonding technologies resulting in a reduction in the mass with an improved level of protection);
- protection level identification for each part of the protected body regions;
- manufacturing process optimisations (including principles of sustainable growth);
- standardisation of PPE in the EU area (essential requirements);
- correct identification of the threats and associated risks, especially in the scope of the use, transportation and storing of PPE.

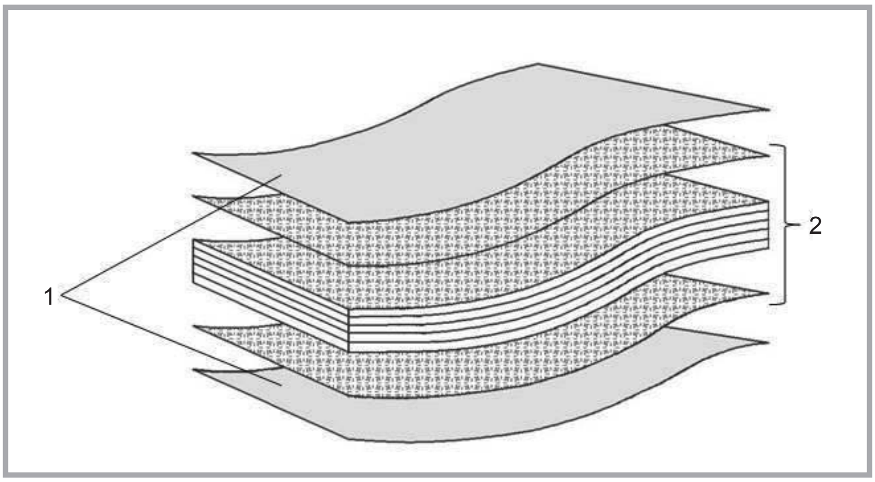

Figure 1. Structure of multi-layer ballistic insert: 1 – air-permeable textile cover, 2 – ballistic inserts consisting of 14 layers of p-aramid woven fabric.

Table 1. Specification of Style 363 p-aramid woven fabric.

Areal density, g/m² PN-EN ISO 3801:1993	Tensile strength, N PN-EN ISO 13943-1:2013		Elongation, % PN-EN ISO 13943-1:2013	
	warp	weft	warp	weft
207 ± 1	8300 ± 450	8900 ± 380	7.2	4.9

The risk analysis, taking into account the aspects of PPE application in humanitarian demining, indicates the need for verification of the stability of performance and safety during PPE use and storage, resulting in the necessity for the elaboration of research procedures for estimation, in simulated conditions, of the period and condition limitations of PPE use. The aim of this study was to investigate, based on the gap prepared and risk analysis, the effect of accelerated ageing and simulation of the use of soft ballistic inserts designed with p-aramid woven fabrics on the structural and ballistic properties.

Based on the risk analysis performed, the conditions of measurement i.e., the factors and intensities of their effect on the samples to be tested, were specified, and the groups of properties examined were defined as the criteria for assessing the resistance to ageing [8].

Materials

The subject of research was "soft" multi-layer ballistic inserts made of p-aramid woven fabric (Style 363, DuPont/USA). The main parameters of the textile material are shown in ***Table 1***.

Within the framework, a ballistic multilayer system – ballistic inserts (testing sample) was prepared consisting of 14 layers of fabric 250 x 250 mm in size, located inside air-permeable covers (***Figure 1***).

The test sample was designed taking into account the ballistic resistance requirement described in the IMAS Standard.

Methods

The methodology of preparing a research programme for the simulation covered the importance of the impact of usage conditions that were characterised based on the risk analysis prepared and gap analysis.

Elaboration of a programme of research on simulation of the use of soft composite ballistic inserts under conditions of accelerated ageing required proper selection of the simulation parameters, which allowed for maximum recreation of the normal conditions of use, as described in [8].

Simulation of the usage of soft ballistic inserts was performed according to ***Table 2*** (see page 90) and [8].

Simulation of mechanical load

The wear of ballistic inserts (test sample) resulting from mechanical deformation (cyclic local deformations coming from the structure and profile of the user's activities) was simulated on a stand developed for fatigue tests (Lodz University of Technology, Poland) [7, 8].

The research device required a power source of 230 V +N + PE, 50 Hz and was controlled by a panel with a display located at the top of the device. Programming the measurement consisted of entering the following parameters into the control system:
- number of cycles within the range of 1-100 000 000;
- time of cycle within the range of 1-60 seconds;
- testing angle within the range of 10°C-90°C (increments of 10°C).

In ***Table 3***, we provide the simulated usage conditions.

Simulation of the mechanical load and thermal effect

The test samples were subjected to the effect of temperature, and a single cycle involved storing a sample at a temperature of 70°C in a TK 720 thermal chamber – (BINDER GmbH Austria). A temperature displacement of ± 2°C was permissible. In ***Table 4***, we provide the usage conditions simulated.

Assessment of the ballistic properties

The research was performed according to the requirements and testing methodology included in the NATO STANAG 2920:1996 standard. Ballistic packets (test sample) of p-aramid woven fabric were weighed before testing and stabilised at a temperature of 20±3°C and relative humidity of 65±5% for not less than 12 hours. After the necessary number of shots, the V_{50} velocity was calculated as the arithmetical mean of the three highest recorded hit velocities that resulted in partial piercing and the three lowest recorded hit velocities that resulted in full piercing, with a requirement that the difference between these velocities should not exceed 40 m/s.

FTIR-ATR study

The progress of ageing of the p-aramid woven fabric from the test sample was assessed on the basis of changes to the structure. Research was performed with a Nicolet iS10 spectrophotometer (Thermo Scientific/USA) with the attenuated total reflection (ATR) technique, within the range of 400-4000 cm^{-1}. The first stage of the research was cutting 20 x 20 mm samples of the woven fabric of p-aramid fibres tested, putting them in a special handle, and measuring the spectrum with the FTIR spectrometer.

Before the main measurements of the spectra, the background (baseline) was registered to subtract it automatically from the sample's FTIR spectra. After the measurement, the spectra of the aged samples were compared to those of samples before the ageing process. That analysis allowed for evaluation of the impact of the ageing processes on the changes to the structure of the objects tested.

Table 2. *Simulation of usage of soft ballistic inserts according to [8].*

Number of deformation cycles, N	Relation to real time of use, years
1650	1
3300	2
4950	3
6600	4
8250	5
9900	6

N = n*x*k; n – number of days the vest is used during a year; x – simulated time of use; k – number of deformations per day; Based on the data from direct end-user: n was 33 and k 50 days

Table 3. *Time periods and conditions of ageing ballistic inserts exposed to mechanical load.*

Symbol of sample	Simulated time of ageing, years	Simulation of mechanical deformations		
		Time of the cycle, s	Testing angle, °	Number of cycles, pcs.
M1	1	4	90	1650
M2	2	4	90	3300
M3	3	4	90	4950
M4	4	4	90	6600
M5	5	4	90	8250
M6	6	4	90	9900

Table 4. *Time periods and conditions of ageing ballistic inserts exposed to mechanical load and temperature of 70°C.*

Symbol of sample	Simulated time of ageing, years	Simulation of mechanical deformations			Simulation of the effect of temperature at 70°C
		Time of cycle, s	Testing angle, °	Number of cycles, pcs.	
MT1	1	4	90	1650	+
MT2	2	4	90	3300	+
MT3	3	4	90	4950	+
MT4	4	4	90	6600	+
MT5	5	4	90	8250	+
MT6	6	4	90	9900	+

Results & discussion

The impact of ageing factors on the test sample made of aramid fibres was intensified over time during the experiment. The results of action of such factors either compensate or escalate, and the behaviour of the material is a result of all of the effects. At every stage of the experimental work, tests of the ballistic properties of the packets exposed to the action of selected ageing agents were performed. Results of the research performed are presented below (***Figure 2***).

Analysis of the research for the V_{50} ballistic resistance limit of the ballistic inserts based on the material made of aramid fibres – p-aramid woven fabric exposed to 1) a mechanical load, and 2) a mechanical load and the temperature proved that with an increasing number of ageing factors acting simultaneously on the material, the ageing process becomes more intense.

V_{50} reached 509.8 m/s for the ballistic packets exposed to the impact of two ageing factors. The V_{50} of the new ballistic insert reached V_{50} = 502.7 m/s. When test samples were exposed to a mechanical load, an initial decrease in V_{50} was observed. The lowest value of V_{50} of the ballistic insert exposed to a mechanical load was 466.6 m/s. Then the value increased to 475.3 m/s.

According to the current state-of-the-art structure of polymers, the fundamental element of the supermolecular structure is a fibril, which consists of alternating areas of ordered (crystalline) and disordered (amorphous) regions. The fibrils are linked by macromolecules belonging to adjacent fibrils. At moderate deformations of polymers, there is virtually no deformation of the crystalline regions. Therefore in areas of amorphous fibrils, molecular deformation occurs, with the elongation and breaking of chemical bonds, as well as the forming and enlarging of the molecular defects. An increase in the number of polymer deformations and the additional impact of temperature cause further destruction of the crystalline regions, which is reflected in the higher values of V_{50} for test samples subjected to two ageing factors. In the case of ballistic inserts, the differences are not significant. The results of the FTIR-ATR confirm this hypothesis.

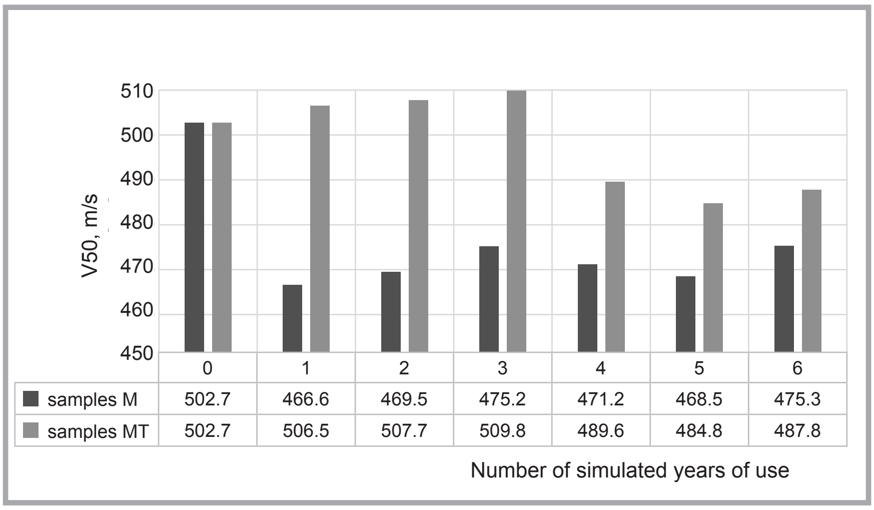

Figure 2. *Results of tests for V_{50} (mean value) of ballistic inserts made of p-aramid woven fabric exposed to M – a mechanical load, MT – a mechanical load, and temperature.*

The process of accelerated ageing using a mechanical load or both a mechanical load and temperature did not influence changes in the chemical structure of the woven fabric (***Figures 3-4*** and ***Table 5-6***).

The initial FTIR spectra of the p-aramid woven fabric are characterised by the presence of:

- a broad absorption band at λ = 3312 cm^{-1} corresponding to -NH stretching of the secondary amide;
- a peak at approximately λ = 2925 cm^{-1} corresponding to =C-H stretching of the aromatic (benzene) ring band;
- a peak at approximately λ = 1640 cm^{-1} corresponding to C=O stretching of the primary amide band;
- a peak at approximately λ = 1538 cm^{-1} corresponding to N-H (Amide II) and C-N stretching coupled modes;
- a peak at approximately λ = 1303 cm^{-1} corresponding to C-N, N-H and C-C combined vibration bands;
- a peak at approximately. λ = 821 cm^{-1} corresponding to C-C stretching vibration in the aromatic ring.

The research indicated that accelerated ageing under a mechanical load and temperature resulted in the absence of influence on the value of the V50. The FTIR spectra did not show any significant changes in the absorption band (either shifts or changes in the intensity), confirming the lack of changes in the structure of the polymer. According to results of the simulation, the ballistic insert prepared, should be stable over time (6 years of usage).

Summary

The main goal of the research work was to investigate the effect of accelerated ageing and simulation of the use of soft ballistic inserts based on ballistic properties. Simulation using soft ballistic inserts made of aramid fabric was performed. Accelerated ageing is a research method that allows for assessing the functionality and safety of a product by determining the period of usability. The method is applicable for products that maintain their properties with no remarkable chang-

Table 5. *Absorption bands for p-aramid woven fabric before and after accelerated ageing under mechanical load.*

Functional group	Number of cycles/Wavenumber, cm^{-1}								
	Initial	825	1650	3300	4950	6600	8250	9900	11550
N-H stretching of secondary amide	3312	3312	3312	3312	3312	3312	3312	3312	3312
=C-H stretching of aromatic ring	2925	2924	2925	2923	2923	2924	2924	2935	2924
C=O stretching of primary amide	1640	1637	1639	1639	1637	1636	1639	1640	1639
N-H deformation and C-N stretching coupled mode (Amide II)	1538	1537	1537	1537	1538	1538	1538	1539	1538
C-N, N-H and C-C combined vibration	1303	1304	1302	1305	1304	1304	1303	1303	1304
C-C stretching in aromatic ring	821	821	821	821	821	821	821	821	821

Table 6. *Absorption bands for p-aramid woven fabric before and after accelerated ageing under mechanical load and at 70°C.*

Functional group	Number of cycles/Wavenumber, cm^{-1}						
	Initial	1650	3300	4950	6600	8250	9900
N-H stretching of secondary amide	3312	3312	3312	3312	3312	3312	3312
=C-H stretching of aromatic ring	2925	2925	2924	2925	2925	2935	2925
C=O stretching of primary amide	1640	1636	1639	1640	1639	1640	1639
N-H deformation and C-N stretching coupled mode (Amide II)	1538	1538	1538	1538	1538	1538	1538
C-N, N-H and C-C combined vibration	1303	1304	1305	1302	1304	1303	1305
C-C stretching in aromatic ring	821	821	821	821	821	821	821

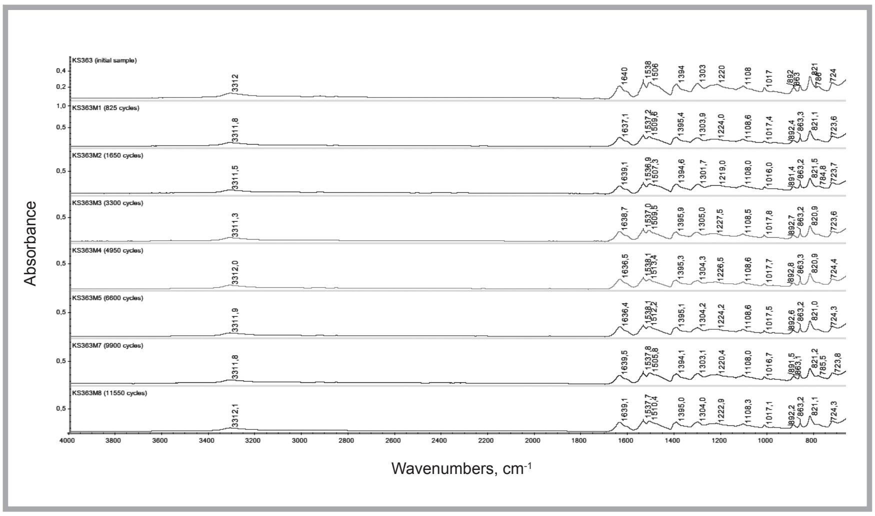

***Figure 3.** FTIR spectra of p-aramid woven fabric before and after cycles of accelerated ageing under mechanical load.*

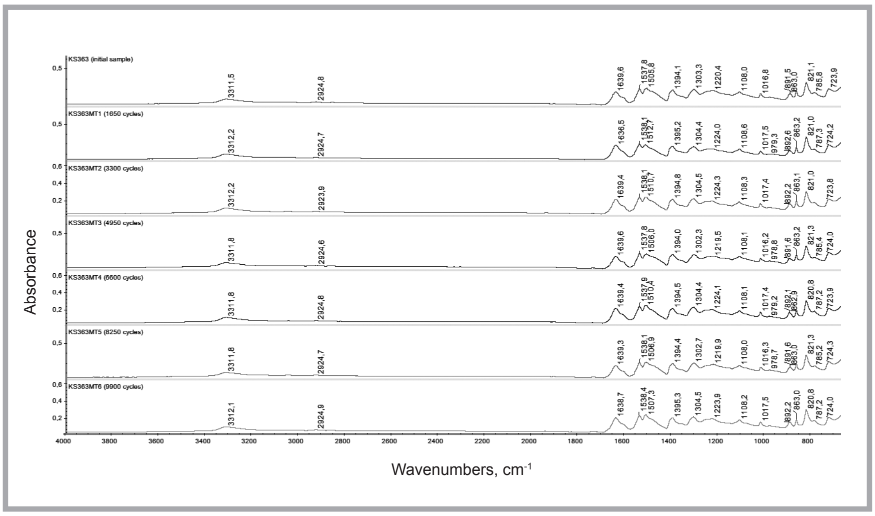

***Figure 4.** FTIR spectra of p-aramid woven fabric before and after cycles of accelerated ageing under mechanical load at 70°C.*

es for longer time periods – counted in years.

The results prove that the mechanical load and temperature cycle did not have any significant effects on the ballistic properties. The ballistic tests assessed the performance of ballistic protection based on the ballistic limit velocity V_{50}. Changes to the structure of ballistic materials exposed to the ageing process under laboratory conditions were assessed by thermal analysis by means of FTIR spectroscopy.

The simulation testing of soft ballistic inserts made of aramid fabric can be used as a new addition to the IMAS Standard to help determine the durability of PPE as well as in European standards.

Moreover we suggest that for clarification of the indicators and their levels of performance and safety testing of PPE, the following aspects should be considered regarding the simulated use:

- the introduction of procedures to control the performance and safety of commercially available protection, especially for products used in conditions that may influence the reduction of the key properties;
- accurate and parameterised definition of the types of threats resulting from contact with hazardous materials to select the most appropriate type and level of protection;
- a review of existing research methodologies for verification of the protection level of properties and the possible introduction of changes to the standardisation scheme within the EU;
- taking into the account the effect of the standard use of PPE.

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