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DESIGNING AND TESTING MULTILAYER STRUCTURES FOR CBR AIR PERMEABLE PROTECTIVE SUIT, WITH IMPROVED THERMAL BURDEN

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Abstract: *Protection is crucial not only for ensuring the safety of military personnel and other professionals regularly exposed to various threats but also for the broader population. Globally, the development of new protective gear focuses on several key objectives: minimizing stress during the use of personal protective equipment, providing reactive and extended protection (such as through filtered and air-permeable structures that guard against a wide range of CBR/TIC threats), and developing intelligent protective equipment that incorporates detection, self-decontamination, and revitalization functions. Given the diversity of threats that specialized anti-terrorism units face, particularly in chemical, biological, radiological, and nuclear (CBRN) domains, it is imperative that they are equipped with effective CBRN protection. Within the framework of strategic, operational, and tactical security measures, CBRN Defense is recognized by NATO as a distinct and critical area. Consistent with the standards of NATO and the specific regulations of the Romanian Army, every member of the NATO/national forces is required to be equipped with an air-permeable CBR protective suit. This study aims to design and test, according to NATO standards, multilayer structures that will protect combat personnel under conditions of reduced stress, addressing these vital needs.*

Keywords: air-permeable PPE, thermal comfort, CBRN protection

1. Introduction

The current state of the art in low burden protective equipment for CBRN (chemical, biological, radiological, and nuclear) purposes focuses on optimizing the balance between protection and wearer comfort, particularly concerning thermal strain and physiological load. Studies emphasize the development of adaptable protective clothing systems that allow modifications based on the environmental and operational needs, thereby reducing heat stress while maintaining high protection levels [1, 2]. Innovations also include the integration of biophysical assessments to evaluate the thermal and vapor permeability properties of CBRN suits, aiding in the reduction of thermal burden without compromising the protective efficacy [3, 4]. The present study consists in NATO standardized tests (AEP-38 and STANAG 4563) of several multilayer structures, to be used for designing a new personal protective suit for CBRN incidents, with improved properties regarding thermal burden.

2. Materials

The tested multilayer structures are made of an outer layer with superior physical and mechanical properties, an intermediate layer that provides, together with the outer layer, protection against toxic compounds

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in the form of droplets, vapours or aerosols and an inner layer for increasing the wearer's thermal comfort. *The outer layer* consisted of 4 types of materials as follows: type M fabric (code M) obtained from mixed modacrylic fibres, cotton and para-aramid fibres, and fireproof; fabric type XA (code XA) obtained from mixed fibres of polyacrylonitrile, cotton, para-aramid and polyamide, water and petroleum products repellent and fireproof; Ripstop1 type fabric (code Rip1) obtained from mixed fibres of cotton with filamentary polyester, with oleophobic and hydrophobic treatment; Ripstop2 type fabric (Rip2 code) obtained from laminated mixed fibres. Nomex type fabric (code Nom) is a leakproof, flame retardant and anti-static fabric obtained from polyaramid fibres. *The intermediate layer* consisted of 4 types of materials as follows: fabric (code C1) from activated carbon in the form of woven fibres, deposited on a non-woven layer, with a woven textile support; fabric (code C2) from a tricot of activated carbon fibres, deposited on a polyester support; fabric (code C3) made of carbon fibres with a woven textile backing; fabric (code C4) made of carbon fibres with a non-woven textile backing. For *the inner layer*, 5 types of fabrics were used as follows: mesh type fabric (code P); Coolmax fabric (code Cool) obtained from mixed polyester and cotton fibres, which, thanks to the capillarity of the material, has the property of absorbing and removing sweat very quickly, allowing the user to feel dry and comfortable; 3 Tebox fabrics (code TebN, code TenK, code TebFl) three-dimensional honeycomb type.

3. Methods and Results

The CBR air-permeable protective suits must meet a series of protection requirements formulated by the NATO manual AEP-38 “Operational requirements, technical specifications and evaluation criteria for CBRN protective clothing” [5] and, additionally, comply with the requirements of the NATO standard STANAG 4563 “Tropical Field Clothing” System” [6]. In this sense, several laboratory tests were carried out to validate the functionality and capability of the newly developed equipment. The testing strategy consisted in checking the physico - mechanical, protection and comfort parameters on all possible multilayer structures, obtained with the mentioned materials.

3.1 Physical and Mechanical Characterization

The resistance to the physical and mechanical factors of the analysed materials was achieved by evaluating warp and weft tear resistance (Figure 1) and tensile strength (Figure 2), the degree of water and oil repellency, as well as their combustion behaviour (Figure 3). Warp is the long yarn running vertically along the fabric roll, determining the vertical pattern repeat, while weft represents the shorter yarn running horizontally, determining the horizontal pattern repeat.

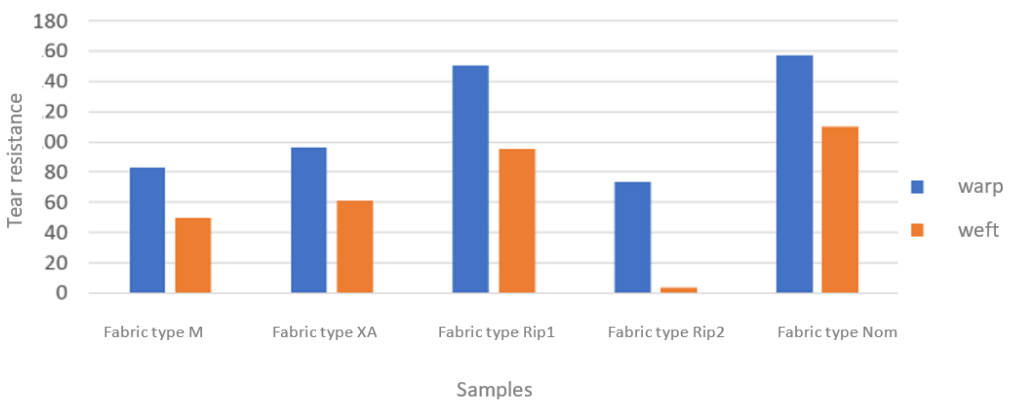

Figure 1: Tear resistance tests for outer layer

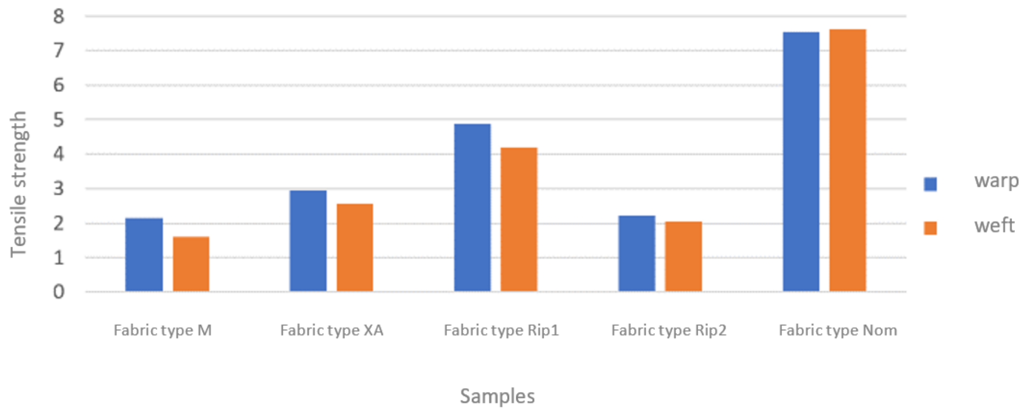

Figure 2: Tensil strenght tests for outer layer

Figure 3: Burning behavior of outer layer materials (M-left, XA-center, Nomex-right)

Following the evaluations made on the materials with possible use for the outer layer, it is recommended to use the Nomex material, due to its superior physico-mechanical characteristics. Regarding the materials that can be used to make the intermediate layer and the inner layer, their physico-mechanical properties have a low impact in evaluating the physico-mechanical characteristics of the set of materials, because their primary role is that of protection against toxic agents and ensuring thermal comfort.

3.2 The Capacity to Protect against Droplets of Chemical Warfare Agents

The tests were performed with real chemical warfare agents (mustard gas) in accordance with AEP 38. The method used to determine the protection time against droplets of chemical agents was the static test with mustard gas dropplets with a contamination density of 5 g/m^2, for the set of outer – intermediate - inner layer materials. The tests were carried out at a temperature of 36.5±1°C, in a thermostated oven. Toxic substances diffuse through the protective material in the direction of decreasing concentration gradient, until they pass through the entire thickness of the material and come out on the side opposite to the contaminated one. In contact with indicator fabric impregnated with a pH indicator and a chloramine, the toxic substance is chlorinated, with the formation of hydrochloric acid, which causes the color of the indicator to change.

The multilayer structures provide protection against toxic vapours combat agents for durations between 11 and over 24 hours (Figure 4).

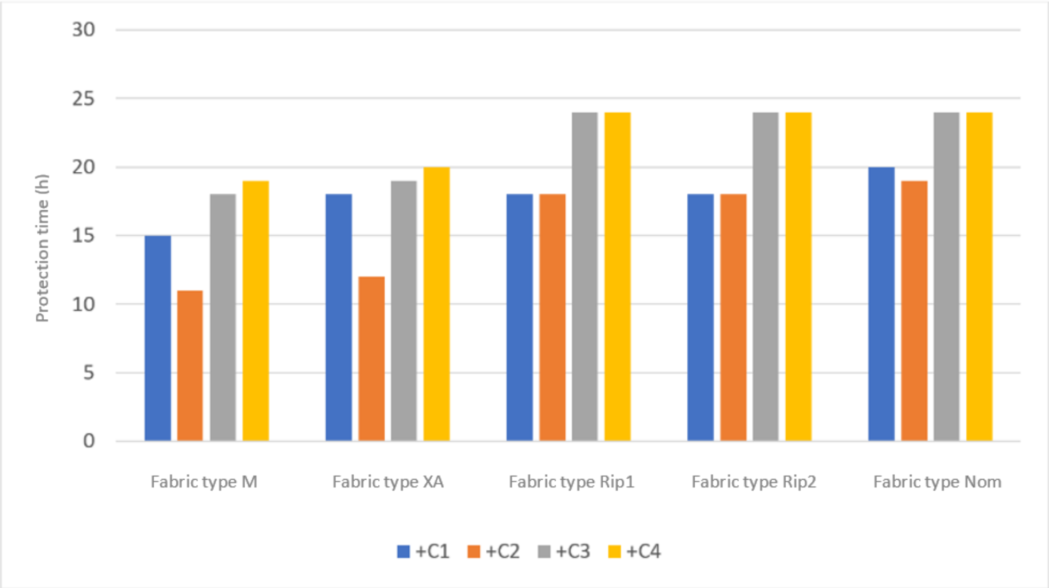

Figure 4: Tests for protection against droplets of sulphur mustard

3.3. Thermal Comfort Characteristics of Innovative Multilayer Structures

For the costume model, a new geometry was created, of the "surface" type, obtained by defining an offset from the surface of the main model, of 2 mm. After defining it, the two models were used in the simulation, keeping the initial solid type, and the "shell" type surface geometry, where we defined the thickness and material properties (Thermal resistance 0.08 m^2K/W). Interaction between each element in the main body assembly was set "bonded", and the inner surface of the suit against the body with the related thermal resistance. To generate the heat source, we defined the main body as the heat source (Figure 5). The power was distributed throughout the body, on each surface, and was varied between 80-1000 W. At the same time, the radiative heat loss was defined on each surface, with an emissivity of 0.98. Radiative heat was set as surface-to-ambient loss, as well as surface-to-surface interaction, both between body elements and body-interior suit surface. For the ambient temperature, a temperature variation curve was defined to capture the level of insulation produced by the suit in different situations. The discretization of the model was achieved using the "blended curvature-based mesh" method, due to the geometry of the model. The critical results are presented in Figure 6, where only the results for a power of 130 W (the equivalent of a moderate effort) and an ambient temperature of 15-25°C were presented. It can be seen that for high temperatures and sustained effort, the thermal discomfort zones have a considerable effect, but for lower values of the outside temperature, the discomfort zones are kept at an agreeable level.

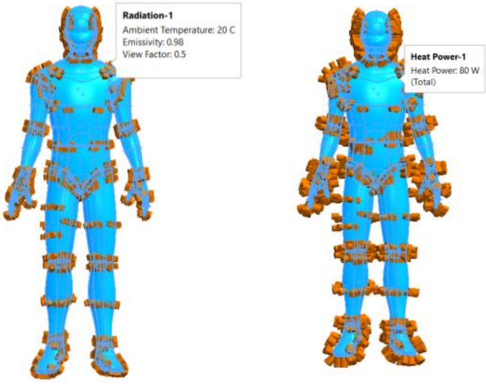

Figure 5: Heat sources and radiative emission

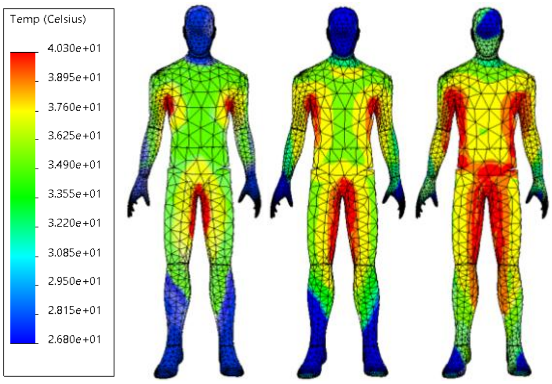

Figure 6: Results for an average sustained effort, at an ambient temperature of 15, 20, 25°C

The evaluation of the degree of thermal comfort was carried out by performing a series of experimental determinations on the multilayer structures with regard to thermal and water vapor resistance (in accordance with EN ISO 11092:2015 - Textile material. Physiological effects.) [7] Measurement of thermal and water vapor resistance in steady state (heated plate test held in a sweaty state). These parameters represent measurements of heat transfer and water vapor transport through fabric structures. A high level of thermal comfort must present the highest possible thermal resistance and the lowest possible water vapor resistance. The direct comparison between thermal resistance and water vapor resistance will be made using the notion of permeability index, which represents the ratio between thermal resistance and water vapor resistance (Figure 7). From the point of view of thermal comfort, all the analysed structures could be used in the fabrication of the air-permeable CBR protective suit.

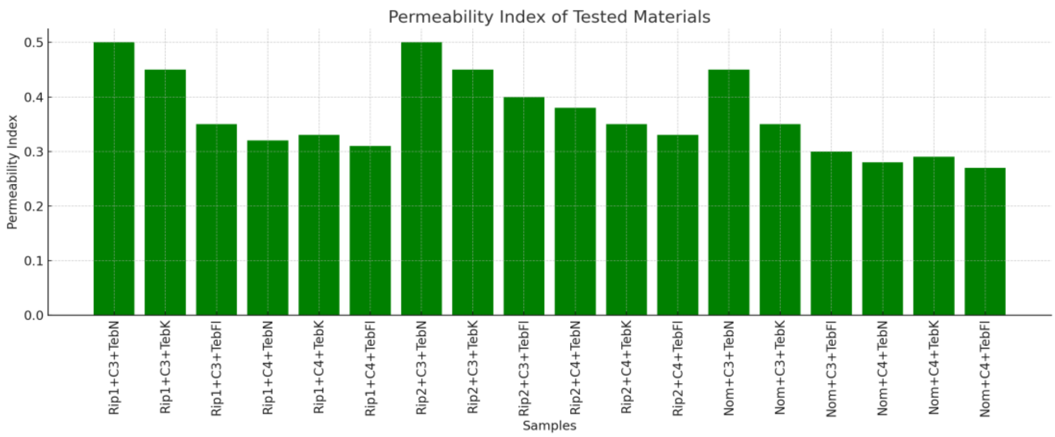

Figure 7: Permeability index of tested materials

4. Conclusions

Analysing all the data presented, we conclude the following:

A. for the creation of an air-permeable CBR protective suit, which requires high fire resistance while ensuring the degree of thermal comfort for hot climate areas, the Nom+C3+TebK multilayer structure is recommended (Nom+C3+TebN - alternative version), ensuring high physical-mechanical characteristics, high ignition type, high protection capacity and average level of comfort.

B. for the creation of an air-permeable CBR protective suit, which does not require high fire resistance while ensuring the degree of thermal comfort for areas with a warm climate, the multi-layer structure Rip+C3+TebK (Rip+C3+TebN - alternative version) ensuring average physical-mechanical characteristics, low ignition type, high protection capacity, high level of comfort.

Regarding the cost, the structures mentioned in point A have a higher cost than those in point B, the price being imposed by the value of the outer layer.

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