

Design & characterisation of laminated activated carbon fabric for critical military applications

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This study aims to prepare activated carbon fabric (ACF) and laminated activated carbon fabric (LACF) from a commercially available rayon-based carbon fabric using CO₂ activation, and to evaluate their functional and physical performance for potential military applications. In the present work, the carbon fabric is activated in a CO₂ atmosphere to produce ACF, which is subsequently characterised for Brunauer–Emmett–Teller (BET) surface area, internal porosity, pore size distribution, average pore diameter and adsorption isotherm behaviour. LACF is then prepared by laminating the ACF with suitable textile substrates on both sides to enhance structural stability and performance. The functional properties of LACF are evaluated through measurements of dichloropropane breakthrough time (DCP-BTT), sulphur mustard breakthrough time (HD-BTT), air permeability and water vapour transmission rate (WVTR). Physical properties in terms of mass, thickness, bending length, flexural rigidity, peel strength, and tensile/bursting strength are also assessed. Durability is examined by comparing these properties before and after six wash cycles. The findings indicate that the prepared LACF exhibits promising adsorption efficiency, robust physical performance and satisfactory durability. Such materials demonstrate strong potential for use in critical military protective systems, which include chemical protective suits, facemasks and breathable gloves, offering effective protection for personnel operating in chemical warfare environments.

Keywords: Adsorption, Breakthrough time, Chemical protective clothing, Chemical warfare agents, Laminated activated carbon fabric

1 Introduction

In modern warfare, soldiers are increasingly exposed to hazardous toxic chemicals, including chemical warfare agents (CWAs). Agents such as sulphur mustard, phosgene and nerve agents are widely recognised as weapons of mass destruction¹. Their penetration into the human body can cause severe physiological damage and may even lead to death². CWAs can enter through the oral, respiratory or dermal routes, with dermal exposure considered the most critical, as it is often the primary pathway for chemical ingress³. To mitigate such risks, chemical protective clothing (CPC) - which includes suits, gloves, over-boots, face masks and related components is used to safeguard military personnel⁴. CPC is broadly classified into permeable and impermeable systems. Permeable protective clothing provides protection against aerosolised CWAs while allowing perspiration to escape, thus offering greater comfort to the wearer⁵. In contrast, impermeable

protective clothing prevents direct contact with liquid contaminants but restricts moisture transmission, leading to heat stress and reduced working efficiency⁶. Therefore, it is unsuitable for prolonged use. In all forms, CPC acts as a barrier between the human body and external contaminants. Protection may be achieved through: (i) incorporating reactive chemicals into garments; (ii) using air-impermeable materials to isolate the wearer; or (iii) integrating a breathable, highly adsorbent layer within the clothing. Of these methods, the third is preferred because it reduces heat stress while maintaining adequate protection⁵.

Activated carbon plays a central role in this breathable protection approach. In the form of beads, powders or fabrics, it serves as the main adsorbent layer in permeable protective clothing due to its high surface area, developed porosity, hydrophobic nature, chemical stability, long lifespan and relatively low cost⁷⁻¹⁰. Laminated activated carbon fabric (LACF) has recently emerged as a superior alternative to conventional carbon-powder-coated fabrics, offering enhanced durability, breathability and comfort.

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Current trends in military protective systems indicate a shift towards lightweight permeable clothing with adequate chemical protection and reduced physiological burden⁹.

Activated carbon is produced through carbonisation followed by activation¹¹. Carbonisation of organic raw material is carried out in an inert atmosphere at 750–900 °C, while activation is performed using carbon dioxide, steam or a combination of both¹². Although carbonisation alone yields porous carbon, the pore structure remains underdeveloped, resulting in low adsorption capacity. Activation significantly enhances the pore network, producing a material with a highly extended surface area suitable for adsorption applications¹³. While natural raw materials such as coconut shell, wood and coal are commonly used for commercial activated carbon production¹⁴, military applications require adsorbents with superior and highly consistent properties¹⁵.

In this context, ACF in fabric form is an advanced form of carbon adsorbent produced from viscose rayon, PAN, pitch or phenolic-resin-based textile fabrics. Its preparation involves stabilisation, carbonisation and activation. ACF offers several advantages over conventional activated carbon:

- extremely fine fibre diameter (5–10 micron), enabling rapid adsorption through surface-accessible pores;
- high surface area and homogeneous pore size distribution;
- well-defined porous structure;
- availability in tow, fabric and felt forms; and
- ease of handling¹⁶.

Due to these features, ACF is used in pollutant removal, deodorisation, solvent recovery, water purification and as an electrode material in capacitors¹⁷⁻¹⁹. It is also employed as a functional filler in high-performance polymer composites, providing stability, antistatic behaviour, and electromagnetic interference shielding²⁰⁻²¹.

Extensive research is currently underway to develop advanced adsorbent materials for future generations of chemical protective clothing. In this context, ACF/LACF has emerged as a material of choice for military applications, with lamination further enhancing tensile strength, durability, and handling properties. In light of the above, this study aims to investigate the suitability of viscose rayon-derived ACF and laminated ACF for permeable chemical protective clothing applications.

Accordingly, the chemical endurance, physical, and functional properties of LACF, before and after six wash cycles, have been measured and studied.

2 Materials and Methods

2.1 Materials

The preparation of LACF involved first producing Activated Carbon Fabric (ACF), which was subsequently laminated with a 30 gsm polypropylene (PP) nonwoven on one side and a 90 gsm knitted polyester fabric on the other. Rayon-based carbon fabric was procured from M/S Kristaa Clean Carbon Pvt. Ltd., Coimbatore, for the preparation of ACF. CO₂ gas was arranged locally for the activation process. A polyurethane-based hot-melt thermoplastic adhesive (-NH-COO-, Jowatherm Reaktant 630.99) was obtained from M/s Pidilite Industries Limited, Mumbai, for lamination of the ACF.

2.2 Preparation of ACF

The detailed process for preparing rayon-based activated carbon fabric has been described by Dhyani *et al.*²². Building on that work, a large-sized sample was prepared for lamination and subsequently evaluated in the present study. The ACF was prepared in a furnace equipped with a Programmable Integrated Derivative (PID) temperature controller and fitted with an arrangement for the upward flow of CO₂ gas from the bottom. After completing the activation process, the ACF sample was cooled to room temperature under a nitrogen atmosphere before being removed from the furnace. The schematic of the furnace is shown in Fig. 1.

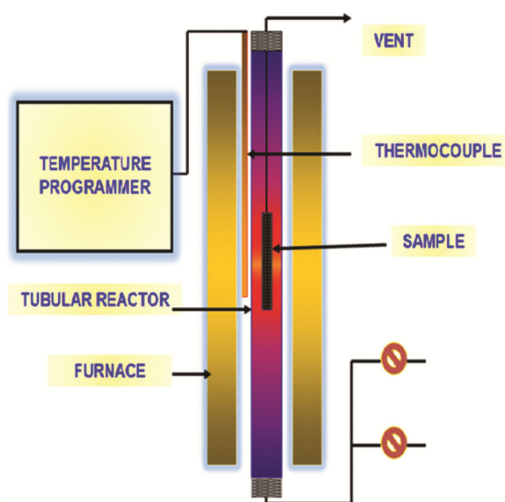


Fig. 1— Schematic representation of the furnace used for CO₂ activation

2.3 Preparation of LACF

LACF was prepared by sandwiching the ACF between two layers of textile materials (Fig. 2) with the help of a two-stage industrial lamination process using commercially available hot melt thermoplastic adhesive.

During lamination, the reactive hot-melt adhesive was heated to its molten state before application. The lamination machine consisted of a gravure roller, a pressure roller, and a laminating roller (Fig. 3). In the first stage, the ACF was passed between the gravure and pressure rollers, where predefined quantities of adhesive dots were transferred onto the fabric. A doctor blade ensured the engraved roller surface remained clean. In the second stage, the adhesive-printed ACF was passed between the pressure and laminating rollers, where heat and pressure facilitated lamination with the 30 g/m² PP nonwoven. The same process was then repeated to laminate the 90 g/m² knitted polyester fabric on the opposite side of the ACF.

A commercially available Jowatherm Reaktant 630.99 reactive hot melt adhesive, with a processing temperature range of 110°C to 140°C, was used in the lamination process. The adhesive coating density was selected based on the g/m² and the required bond strength. For lamination, 10 g/m² of adhesive was applied for bonding the ACF to the PP nonwoven, and another 10 g/m² for bonding the ACF to the knitted polyester. Upon cooling, the adhesive developed green strength through physical hardening.

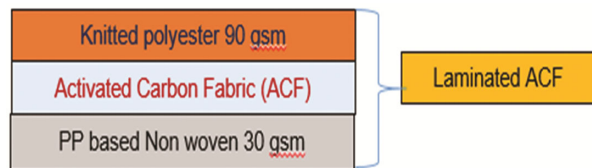


Fig. 2 — Schematic representation of the laminated ACF

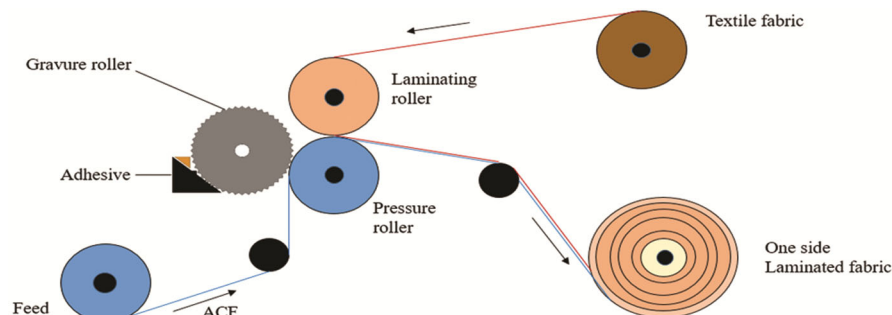


Fig. 3 — Schematic of a laminating machine used for fabric lamination

2.4 Characterisation Techniques

2.4.1 Measurement of Weight

Fabric weight is measured in grams per square metre (g/m²), commonly referred to as GSM of a fabric. GSM is measured by cutting the fabric with a cutter and weighing it on an electronic balance. The average GSM before and after six washing cycles was measured in accordance with ASTM D 3776 standard.

2.4.2 Thickness

The thickness of LACF before and after six wash cycles was measured using a thickness gauge under 200 g/cm² pressure according to the ASTM D1777-96 standard.

2.4.3 Bending Length and Flexural Rigidity

A bending length measurement is carried out using a cantilever in which the material is allowed to bend under its own weight. The bending length before and after six wash cycles was measured using a stiffness tester in accordance with the BS 3356 standard. The flexural rigidity was calculated using the following formula:

$$G = M \times C^3 \\ = M \times C^3 \times 9.8 \times 10^{-6}$$

where G is the flexural rigidity (μNm); M, mass of sample (g/m²); and C, bending length (mm).

2.4.4 Breaking Strength

LACF was evaluated for breaking strength measurement (50mm x 200mm gauge length) using a Universal Testing Machine (UTM) (Make: Dak System Inc., Model: Series 9000) before and after six wash cycles, according to the ASTM D5034 standard.

2.4.5 Bursting Strength

Bursting strength before and after six wash cycles was measured according to ASTM D3786/D3786M-2018 standard using the PRESTO bursting strength tester. For this measurement, the sample was placed on an extendable diaphragm using a circular gripper,

and gas pressure was applied under the diaphragm at a constant rate until the sample ruptured.

2.4.6 Peel Strength

Peel strength was measured using a Universal Testing Machine (UTM) (Make: Dak System Inc., Model: Series 9000) according to the ASTM D1876 standard. The peel strength was evaluated before and after six wash cycles.

2.4.7 BET Surface Area Analysis

An Autosorb C-1 BET surface area analyser (Anton Par, USA) was used to measure the internal porosity, adsorption capacity, and pore size distribution of ACF. The surface area measurement is based on the Brunauer-Emmett-Teller (BET) theory using N₂ gas as an adsorbate. Before measurement, the samples were degassed at 200°C under vacuum for 2 h. Finally, nitrogen gas at its boiling point (77K) was entered into ACF to fill the entire porosity. The BET Surface area analyser was equipped with powerful software, which provides data for BET Surface area, pore volume, micro-pore volume, and pore size distributions.

2.4.8 Water Vapour Transmission Rate (WVTR) Measurement

WVTR simulates the breathable performance of textiles and measures the passage of water vapour through the material. This is directly related to sweat evaporation through the fabric from the human body, indicating the comfort level during prolonged use. WVTR measurements were performed on samples before and after six washes, as per the ASTM E-96 standard. The WVTR through the unit area of the sample may vary due to changes in temperature and humidity.

2.4.9 Air Permeability

Air permeability is determined by measuring the rate of airflow through a known area of material. This is achieved by applying a known pressure differential across a set area of material. The average air permeability (based on ten readings) before and after six wash cycles was measured using the Shirley air permeability tester, according to the ASTM D 737 standard.

2.4.10 FESEM Analysis

FESEM analysis was performed to observe the surface morphology of LACF before and after six wash cycles. Samples were mounted on stubs, sputter-coated with gold, and imaged using FESEM. The micrographs were used to assess the changes in the surface.

2.5 DCP-BTT and HD-BTT Test

To access chemical endurance and suitability for use in Nuclear Biological and Chemical (NBC) protective clothing, the LACF was subjected to functional tests, namely the 1, 3-Dichloro-propane Breakthrough Time Test (DCP-BTT), followed by the Mustard Breakthrough Time Test (HD-BTT), according to British Specification (Specification No. UK/SC/3346G).

DCP-BTT measurements were performed on LACF samples in accordance with the test protocol, which was based on an instrument designed by DMSRDE, Kanpur. The test was conducted using DCP, a simulant of sulphur mustard, which exhibits similar behaviour on carbon adsorbent during diffusion. The test overcomes the requirement of highly toxic chemical sulphur mustard and can be used safely in conditions where it is not feasible to carry out the test with sulphur mustard.

The test assembly consists of a diffusion cell, in which the LACF sample is held firmly between a donor and a receptor compartment [Fig. 4 (a)]. The donor chamber is filled with DCP vapour, whereas the receptor chamber is connected to a gas chromatographic detector that continuously monitors vapour penetration. The breakthrough time is defined as the time required for DCP vapour to be detected in the receptor chamber, indicating diffusion through the LACF specimen. DCP-BTT measurements were conducted using a standard diffusion test apparatus (Model: Newchrom Technologies, Version 2.03), as shown in Fig. 4 (b). The measured breakthrough time (in seconds) provides a quantitative indication of the fabric's resistance to chemical vapour permeation.

Further, the protective performance of the LACF against live sulphur mustard (HD) was evaluated using the HD-BTT, a recognised method for assessing barrier materials against chemical warfare agents. The principle of the test is based on the colour change of a sensitive indicator paper upon exposure to permeating mustard vapour. The test setup consisted of a multilayer assembly comprising a mustard-soaked cotton pad as the challenge layer, the ACF specimen as the protective barrier and a detector paper impregnated with sulphur mustard-sensitive indicator paper. These components are held tightly between brass plates and rings to prevent lateral vapour leakage. A schematic of the test configuration is shown in Fig. 4 (c), and the actual HD-BTT test apparatus used in the study is illustrated in Fig. 4 (d). The breakthrough time was recorded as the interval

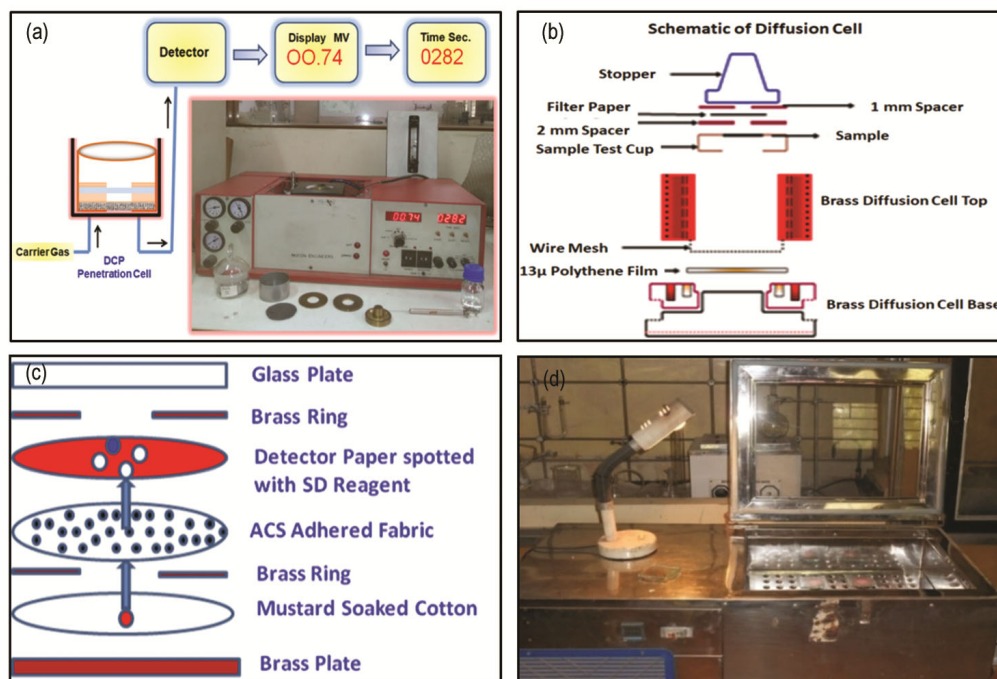


Fig. 4 — Test setups for chemical breakthrough evaluation: (a) DCP breakthrough test assembly; (b) DCP test apparatus; (c) HD breakthrough test assembly; (d) HD breakthrough test apparatus

between exposure and the first observable colour change on the detector paper. This parameter serves as a direct measure of the fabric's resistance to HD vapour permeation.

3 Results and Discussion

The technical parameters of carbon fabric and ACF are described in Table 1. As seen from the Table, the physical properties, viz., mass, thickness, bending length, flexural rigidity, and tensile strength decrease, whereas the air permeability and water vapour transmission rate of the carbon fabric increase after conversion into ACF. On the other hand, the surface area is substantially increased from 14g/m^2 to 1544g/m^2 due to the development of porosity.

3.1 BET Surface Area and Porosity Measurements

For the porous carbon fabric (ACF) sample RSM-5, a burn-off of 46.4% is recorded, along with a BET surface area of $1544.23\text{ m}^2/\text{g}$. A micropore volume of 0.56 cc/g and a total pore volume of 0.71 cc/g are obtained, while the average pore diameter is measured as 18.5 \AA . Furthermore, the adsorption and desorption isotherms for the representative ACF sample (abbreviated as RSM-5) are shown in Fig. 5.

According to the Brunauer–Deming–Deming–Teller (BDDT) classification²³, the isotherm corresponds to Type I. The initial region of the

Table 1 — Technical parameters of carbon fabric and ACF

Parameter	Carbon fabric	ACF
Mass, gsm	320 ± 5	200 ± 5
Tensile strength, kgf/cm^2	80.5	28
Thickness, mm	0.34	0.28
Bending length, mm	23	19
Flexural rigidity, μNm	38.15	13.77
Surface area (BET) m^2/g	≈ 14	>1544
Avg. WVTR, $\text{g/m}^2/24\text{ h}$	187	209
Avg. air permeability, $\text{cm}^3/\text{cm}^2/\text{s}$	22	26

isotherm reflects micropore filling in narrow micropores, characterised by a steep uptake at very low relative pressures, after which the amount adsorbed approaches a limiting value. The shape of the adsorption curve therefore confirms the microporous nature of the ACF, indicating that the material is highly suitable for gas-phase adsorption.

3.2 FESEM Analysis

Different layers of the LACF were examined using FESEM before and after six wash cycles at varying magnifications (ACF at $50\text{K}\times$, knitted polyester at $5\text{K}\times$, and nonwoven at $200\times$), as shown in Fig. 6. The images before and after washing are denoted as BWACF and AWACF for the ACF layer; BWKP and AWKP for the knitted polyester; and BWNW and AWNW for the nonwoven layer. The FESEM images

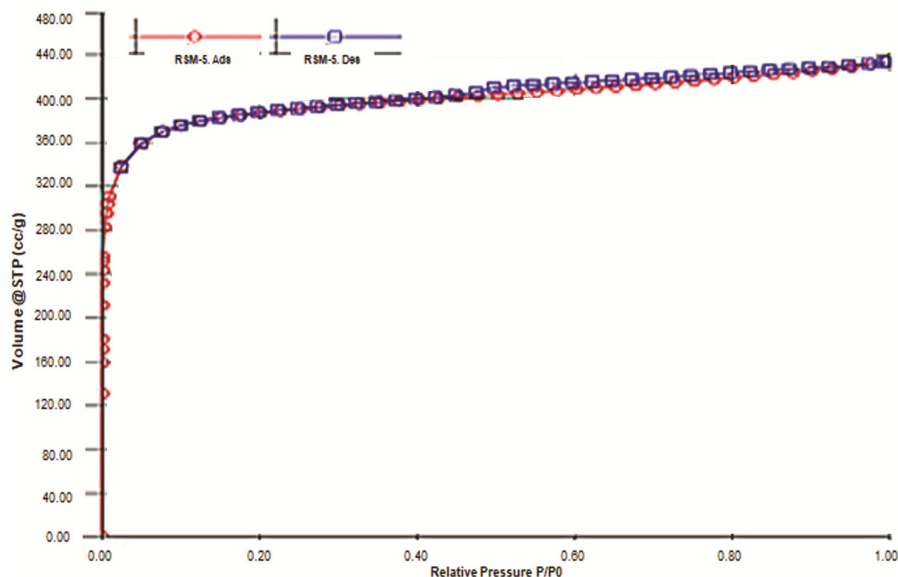


Fig. 5 — Adsorption and desorption isotherm at 77 K for rayon-based ACF in CO₂ activation

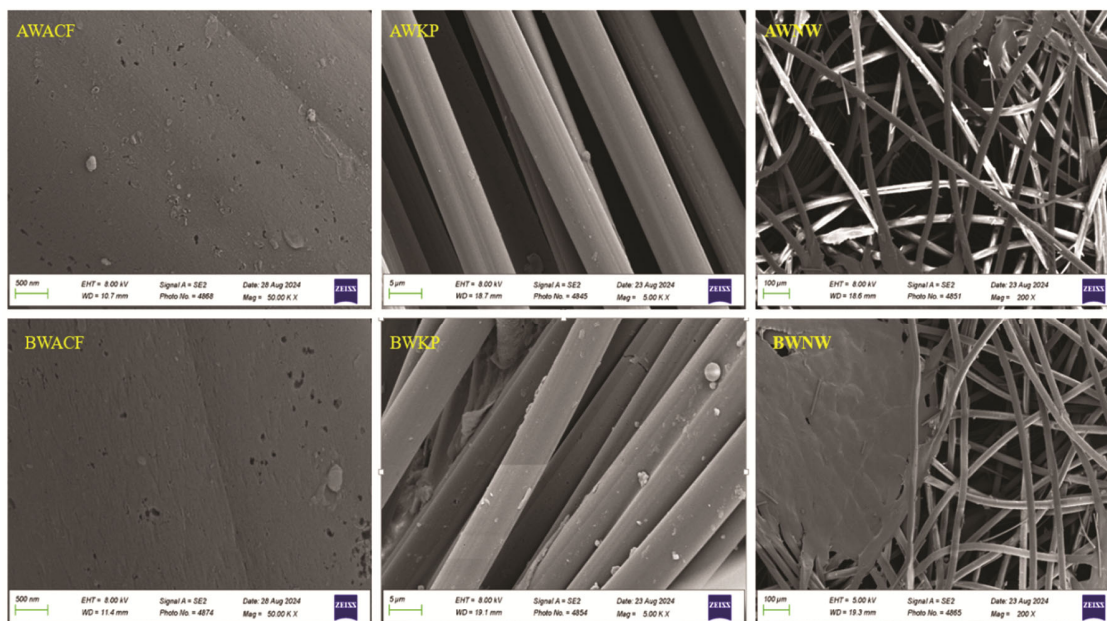


Fig. 6 — FESEM images of ACF, knitted polyester and nonwoven polypropylene layers before and after six wash cycles

indicate that there is no significant change in the morphology of any of the component materials after six wash cycles. A few internal cavities are visible on the ACF surface, and adhesive dots can be observed on the nonwoven surface (BWNW). The structural integrity of the layers appears to remain largely unaffected by repeated washing.

3.3 Effect of Launderability on Physical & Functional Properties

LACF is a critical component of military chemical protective clothing, including Nuclear Biological and

Chemical (NBC) suits and facelet masks. This fabric provides essential protection against potential chemical warfare agents such as sulphur mustard and nerve agents. Beyond operational use, such protective garments are also worn during training exercises, mock drills, and emergency preparedness activities. For hygiene and economic reasons, it is neither practical nor advisable to use new garments for each of these activities. According to general practice, a garment is expected to be worn continuously for a minimum of 45 days under non-contaminated

conditions, necessitating at least one wash per week. This implies that the garment must withstand a minimum of six wash cycles without significant deterioration in its functional or physical properties. Therefore, assessing its performance before and after washing becomes essential. The key physical properties relevant to chemical protective clothing were evaluated to determine the garment's durability and service life. The measured properties before and after six wash cycles are presented in Table 2.

According to the data presented in Table 2, the mass and thickness of the composite fabric increase after six wash cycles, from 380 g/m² to 400 g/m² and from 0.84 mm to 0.91 mm, respectively. The increase in mass and thickness may be attributed to shrinkage in the composite fabric. This behaviour has also been reported by Soleman *et al.*²⁴

Further, a decrease in bending length and flexural rigidity is observed after six wash cycles. One possible reason for this reduction may be due to increased softness and flexibility of the fabric resulting from repeated washing. The decline in these parameters in both warp and weft directions corroborates the findings of Belinda *et al.*²⁵

A reduction in breaking strength is also noted—from 63 kg to 59 kg in one direction and from 33 kg to 30 kg in the other. This change may be associated with weakened bonding between the component layers of the composite fabric, consistent with the observations of Song *et al.*²⁶ During breaking strength measurement, the ACF and nonwoven PP layers in the composite fabric rupture together, while the knitted polyester layer remains intact and undergoes elongation along the loading direction [Fig. 7 (a)].

A decrease in peel strength from 270 g/cm to 253 g/cm is recorded after six wash cycles. The nonwoven layer separates with residual ACF fibres adhering to its surface, indicating weaker bonding between these two layers. In contrast, the knitted polyester layer remains firmly bonded to the ACF [Fig. 7 (b)]. This suggests variability in interlayer bonding strength within the composite.

Given that bursting strength is widely regarded as a more reliable indicator of strength in multilayer and composite fabrics, this parameter was evaluated to determine the overall structural integrity of LACF. A marginal decrease is observed—from 16 kg/cm² to 15 kg/cm²—after six wash cycles (Table 2).

Functional properties, including chemical protection endurance, air permeability, and WVTR, are critical for

military protective clothing. Air permeability and WVTR significantly influence comfort and mobility during activities such as running, walking, and crawling. Chemical endurance is crucial, as any decline in protection could expose the wearer to harmful chemical warfare agents. Therefore, rigorous evaluation is essential prior to field deployment.

The functional performance of LACF is shown in Table 3. WVTR increases slightly from 78.93 g/m²/24 h to 83.47 g/m²/24 h, and air permeability rises from 9.57 cm³/cm²/s to 12.30 cm³/cm²/s after six washes. This marginal increase may be due to a minor weakening of the adhesive bonds within the laminate, leading to slight loosening and the formation of minor gaps that facilitate the easier transmission of air and moisture vapour.

Table 2 — Physical properties of LACF

Property	Before wash	After wash
Mass, g/m ²	380	400
Thickness, mm	0.84	0.91
Bending length, mm (One direction)	42	39
(Other direction)	30	28
Flexural rigidity, μ Nm (One direction)	276	232
(Other direction)	101	86
Breaking strength, kg (One direction)	63	59
(Other direction)	33	30
Bursting strength, kg/cm ²	16	15
Peel strength, g/cm	270	253

Table 3 — Functional properties of LACF

Property	Before wash	After wash
DCP-BTT, s	> 300	> 300
Mustard-BTT, h	> 24	> 24
Avg. WVTR, g/m ² /24h	78.93	83.47
Avg. air permeability, cm ³ /cm ² /s	9.57	12.30

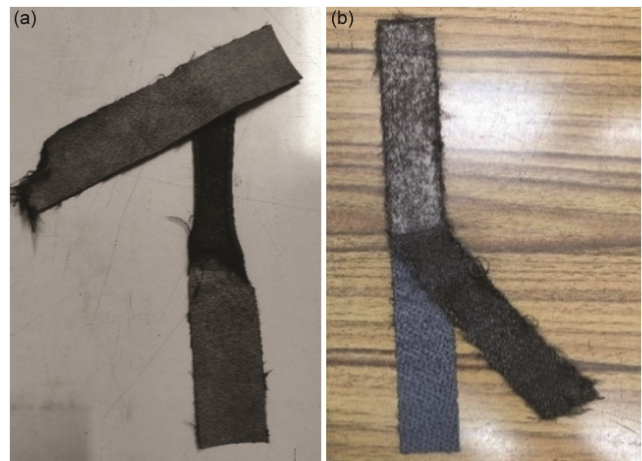


Fig. 7 — Sample after (a) tensile strength testing and (b) peel strength testing

Importantly, the breakthrough times for both DCP and sulphur mustard remain unchanged before and after washing (>300 s and >24 h, respectively). This indicates that neither the ACF nor the composite structure undergoes significant degradation, and their adsorption and chemical protection capabilities remain fully intact after six wash cycles.

4 Conclusion

Activated carbon fabric (ACF) continues to emerge as a superior adsorptive material for chemical protective applications, offering clear advantages over conventional powdered or granular forms. In this study, a highly microporous rayon-based ACF (RSM-5) is developed through CO₂ activation to generate the desired porosity and internal surface area, and its suitability as a protective layer against the chemical warfare agent sulphur mustard is evaluated. To enhance durability and handling performance, the ACF is laminated with knitted polyester and nonwoven polypropylene, resulting in a composite structure suitable for military garments. The functional and physical performance of the laminated ACF is assessed before and after six wash cycles, reflecting realistic usage conditions in non-contaminated environments. The results show no significant deterioration in breakthrough time, air permeability, water vapour transmission rate, mass, thickness, bending behaviour, tensile strength, bursting strength, or peel strength. These findings indicate that the laminated ACF retains both its protective efficacy and structural integrity after repeated washing.

The study demonstrates that suitably laminated ACF is a viable and effective chemical protective layer for use in lightweight, breathable military garments such as NBC suits and facelet masks. Beyond defence applications, the prepared ACF also holds potential for wider commercial use, including pollution-control masks, air and water purification systems, and antibacterial wound dressings. There remains considerable scope for further development of ACF from alternative, cost-effective precursors

and for designing lighter LACF with enhanced performance.

References

- 1 Singh K, Kumar A & Rao P, *Carbon*, 168 (2020) 1.
- 2 Prasad G K, Pandey K S, Singh B & Vijayaraghavan R, *J Hazard Mater*, 391 (2020) 122123.
- 3 Semple S, *Occup Environ Med*, 79 (2022) 376.
- 4 Van Wijk E, *Industrial health*, 55 (6) (2017) 485.
- 5 Bhuiyan M A, Wang L, Shaid A, Shanks R & Ding J, *J Ind Text*, 49 (1) (2019) 97.
- 6 Potter A W, Gonzalez J A & Xu X, *PLOS ONE*, 10 (11) (2015) e0142345.
- 7 Hasdi N D, Ahemad N, Ahya M K & Puasa S W, *J Sci Res*, 20 (1) (2023) 51.
- 8 Mishra K & Dedhia E, *Int J Home Sci*, 8 (3) (2022) 7.
- 9 Xuezhi D & Jingkai X, *E3S Web of Conf*, ICESCE, 267 (2021) 02072.
- 10 Sharma G, Sharma S & Kumar A *et al*, *Adsorp Sci Technol*, (2022) 1.
- 11 Yue Z & Economy J, *Wood Publishing Series Text*, (2021) 61.
- 12 Chavan M P, Slovak V, Zelenkova G & Dominko D, *Materials (Basel)*, 15 (7) (2022) 2431.
- 13 Zhao C, Ge L, Li X, Zuo M, Xu C, Chen S, Li Q, Wang Y & Xu C, *Energy*, 273 (2023) 127177.
- 14 He H, Zhang R, Zhang P, Wang P, Chen N, Quin B, Zhang L, Yu J & Dai B, *Adv Sci*, 10 (2023) 2205557.
- 15 Yahya M A, Qodah Z A & Ngah C W, *Chemosphere*, 263 (2021) 128163.
- 16 Chen H, Zhang Y J, He P Y, Li C J & Liu L C, *J Appl Catal B*, 274 (2020) 117804.
- 17 Yellappa M, Modestra J A, Reddy Y R & Mohan S V, *Bioresour Technol*, 320 (2021) 124340.
- 18 Forintos N & Czigany T, *Compos Part B Eng*, 162 (2019) 331.
- 19 Hu J, Mubarak S, Li K, Huang X, Huang W, Zhuo D & Wang J, *Polymers*, 14 (2022) 301.
- 20 Mousavi S M, Hashemi S A, Kalashgrani M Y, Omidifar N, Bahrani S, Vijayakameswara R N & Chiang W H, *Polymers*, 14 (2022) 617.
- 21 Li W & Liu S, *J Porous Mater*, 28 (1) (2021) 567.
- 22 Dhyani H, Adivarekar R V, Thakare V B, Bharati S, Dixit A, Vimal M, Kumar V & Garg P, *J Indian Chem Soc*, 102 (4) (2025) 101635.
- 23 Brunauer S, Emmett P H & Teller E, *J Am Chem Soc*, 60 (1938) 309.
- 24 Rout S A, Rasel S & Khalil E, *J Text Sci Tech*, 1 (3) (2015) 45.
- 25 Orzada B T, Moore M A, Collier B J & Chen J Y, *Int J Clothing Sci Tech*, 21 (1) (2009) 44.
- 26 Song E, Kim M & Chang S, *J Text Res*, 94 (3-4) (2024) 375.