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Effects of salt water on the ballistic protective performance of bullet-resistant body armour

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Abstract

Bullet resistant body armour is used by law enforcement agencies and military personnel worldwide, often in inclement weather. Some fibre types used in body armour perform poorly when wet resulting in a reduced level of protection; this is why most body armour protective elements are water-repellent treated and / or protected by a water-resistant cover. Some of the users operate in the maritime environment. The effect of salt water on body armour performance has not been previously reported. In this work the effect of soaking body armour in salt water and exposing body armour for up to ten soaking and drying cycles in salt water was investigated. The effectiveness of the water-resistant cover was investigated by considering three cover conditions i) intact, ii) cut and iii) removed. Wet armour was heavier and provided significantly less protection from 9mm Luger FMJ ammunition when compared to not-conditioned armour irrespective of cover condition. The presence of a cover (intact or cut) resulted in heavier armours and poorer protection as the water was less able to drain out of the armour. A degradation in performance of armours exposed to soaking and drying cycles was noted, but this was similar across all regimes considered (one, three, five and ten cycles) and not as great as for wet armours.

Keywords

Burden; Backface signature; Behind armour blunt trauma; Perforation; Degradation

Introduction

Bullet resistant body armour is used by law enforcement agencies and military personnel worldwide. Body armours typically consist of two major elements i) soft armour which provides protection from targeted threats including fragmentation, sharp-weapons and pistol ammunition (depending on intended end-user) and ii) hard body armour plates

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(dependant on threat these are either ceramic faced / composite backed or 100% composite) that provide protection from high velocity rifle ammunition (Lewis et al., 2017). Protection is 'measured' by considering whether or not the ammunition of interest perforates the armour (i.e. passes through the armour into the body) and by measuring the backface signature (BFS) which is the amount of deformation of the rear of the armour due to a non-perforating event (Croft and Longhurst, 2007). BFS cannot be directly correlated to behind armour blunt trauma (BABT), but standard test methods provide a maximum allowable BFS (Croft and Longhurst, 2007). BABT injuries that body armour wearers suffer are typically bruises to the skin and to some underlying organs, and broken ribs (Carr et al., 2016). Soft armours are made using fabrics containing para-aramid (e.g. Kevlar®, Twaron®) or ultra-high molecular weight polyethylene (UHMWPE e.g. Dyneema®, Spectra®) fibres and provide protection from a range of projectiles dependent upon construction (Lewis et al., 2017).

The properties of para-aramid fibres are affected by moisture; UHMWPE fibre as less susceptible (Li et al., 2015). The ballistic protective performance of wet para-aramid fabrics is reportedly up to 40% lower than dry para-aramid fabrics (Laible, 1980; Gibb, 2005). To minimise the risk of moisture affecting the protective performance of para-aramid fabrics used in body armour they are often water repellent treated and/or enclosed in water resistant covers, which are typically made from polyvinyl chloride (PVC). However, with everyday usage the covers can become damaged and potentially split, allowing the ingress of moisture in to the ballistic protective element. In addition, if the body armour becomes submerged in water (for example the wearer falls into a body of water) it is possible that water will permeate through the PVC cover resulting in the para-aramid fabric becoming saturated.

Within the UK, there are a number of in-shore and off-shore police marine units who have a responsibility for patrolling the waterways around the UK, including providing specialist firearms support during operations (Ministry of Defence, 2018).These patrols are often conducted using Rigid Hulled Inflatable Boats (RHIBs) which expose the occupants to the effect of salt water spray, especially in rough sea conditions; potentially resulting in the body armour they are wearing becoming wet. There is always a risk of the RIB occupants entering the water. How salt water affects the ballistic performance of body armour is not

known. Although the body armour is dried between patrols, the effect of regular soakings with salt water and drying has also not been previously studied. Laundering (washing and drying cycles) can affect the ballistic protective performance of fabrics (Helliker et al., 2014).

The salinity of sea water varies worldwide between 31 g/L and 38 g/L with pH varying between 7.5 and 8.4; the mean salinity of sea water at Harwich over a 12-month period was 34.48 g/L (Centre for Environment Fisheries and Aquacultre, 2018).

This paper investigates the effect of soaking and soaking and drying cycles in saline water typical of UK sea water on the ballistic performance of a typical UK Police Authorised Firearms Officer (AFO) para-aramid body armour.

Method

Plastic containers were filled with a salt water solution of 35 g/L salinity. The water was monitored using an Extech® RF20 portable salinity refractometer and pH paper to ensure it was between 34 – 35 g/L and a pH of 8 throughout the soaking regimes investigated (see below).

Body armours were selected that were certified to the UK Home Office standard HG2 / KR2 protection level that is typically worn by AFOs (Croft and Longhurst, 2007). The armours contained front and rear panels in an outer cover; each panel contained a protective pack with a water-resistant cover. The protective packs of the armours consisted of a HG2 element with a KR2 element located at the rear[1]. The body armours had been previously issued to officers and were beyond their shelf-life expectancy, however all panels were inspected prior to testing for signs of damage and only those classified with no visible damage were used for this work. The panels were prepared in pairs for testing in one of three 'cover' conditions:

1. water-resistant cover intact,
2. water-resistant cover cut on the edges with 50 mm slits at 6 locations (Figure 1) and
3. water-resistant cover completely removed.

[1] HG2 = handgun protection level 2; KR2 = knife protection level 2

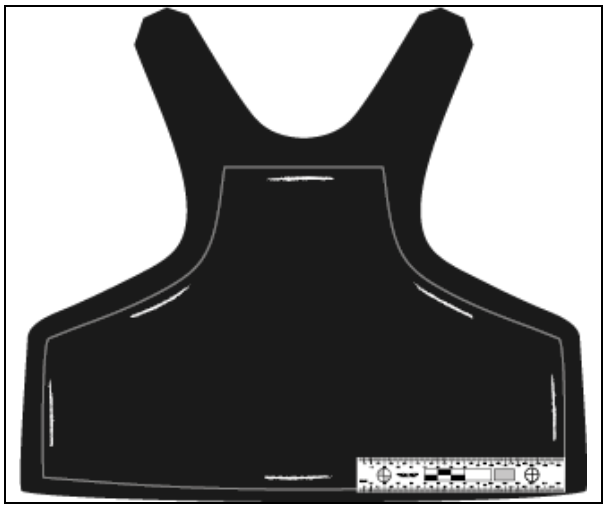

Figure 1 Location of cuts in body armour covers

To provide baseline data, two test panels were tested as-received with covers on and two tested as-received with the covers removed (i.e. test panels were not subjected to an 'exposure' regime). For each cover condition described above, two test panels were subjected to one, three, five or ten cycles of 3-hours soaking and 45-hours drying. Test panels were dried vertically at 20 ±3 ˚C with the final drying process timed to enable the armour panels to be tested within 30-minutes of completion of the final 45-hours drying period. An additional set of two test panels were prepared for each cover condition and subjected to ballistic testing 'wet' by soaking in salt water for 3-hours and then drying vertically for 5-minutes before the first test shot was taken. The test schedule is presented in Table 1.

Table 1 Test schedule (*n* = 2 for each cover condition / exposure combination)

cover	**exposure regime**
Intact	as-received
removed	as-received
Intact	soaked (3-hours) and dried (45-hours) for one cycle
Intact	soaked (3-hours) and dried (45-hours) for three cycles
Intact	soaked (3-hours) and dried (45-hours) for five cycles
Intact	soaked (3-hours) and dried (45-hours) for ten cycles
Cut	soaked (3-hours) and dried (45-hours) for one cycle

Cut	soaked (3-hours) and dried (45-hours) for three cycles
Cut	soaked (3-hours) and dried (45-hours) for five cycles
Cut	soaked (3-hours) and dried (45-hours) for ten cycles
removed	soaked (3-hours) and dried (45-hours) for one cycle
removed	soaked (3-hours) and dried (45-hours) for three cycles
removed	soaked (3-hours) and dried (45-hours) for five cycles
removed	soaked (3-hours) and dried (45-hours) for ten cycles
Intact	soaked (3-hours) and dried (5-minutes)
Cut	soaked (3-hours) and dried (5-minutes)
removed	soaked (3-hours) and dried (5-minutes)

Before and after the defined soaking and drying or soaking regimes, the test panels were weighed to two decimal places (i.e. 0.01 g) to determine any change in mass.

The test panels were marked with shot locations one to five in accordance with the HOSDB 2007 standard and mounted on trays of calibrated Roma Plastilina No 1 (Croft and Longhurst, 2007). Each test panel was shot five times from a distance of 5 m with 9mm FMJ Luger DM11A1B2 bullets using a proof housing fitted with a 580 mm barrel (1 in 11 twist). The impact velocity of each shot was recorded using a Weible W-700 Doppler radar. Between each shot the test panel was checked for perforation by the bullet and the backface signature (BFS) recorded by measuring the depth of the indentation in the Plastilina using a calibrated depth gauge. The test panel was smoothed between shots and repositioned on the tray.

Results

Effect of conditioning on mass of panel

Mean mass data for pairs of front and back test panels across all variables are presented in Table 2. All exposed test panels were heavier than not-exposed test panels. Wet test panels were the heaviest for all cover conditions. For all soaking and drying regimes except one cycle, test panels with the cover removed had the smallest increase in mass; for test panels exposed for one soaking and drying cycle the intact cover set had the smallest increase in mass, but this was very similar to the increase in mass for panels exposed to one soaking and drying cycle with the cover removed (12% and 14% respectively). Considering the mean

mass across all test panels exposed to soaking and drying regimes, similar changes in mass were observed after exposure for one, five and ten soaking and drying cycles (15%, 14%, 15% respectively); a heavier change in mean mass was observed after exposure for three soaking and drying cycles (25%). Test panels that had their water-resistant covers intact or cut were heavier irrespective of having been exposed to a soaking and drying or soaking regime.

Table 2 Mean mass data (%) for test panels (*n* = 2 per variable combination)

Cover	exposure	mean change in mass (%)
Intact	not-conditioned	0
removed	not-conditioned	0
Intact	one cycle	12
Cut	one cycle	19
removed	one cycle	14
Intact	three cycles	30
Cut	three cycles	24
removed	three cycles	20
Intact	five cycles	18
Cut	five cycles	17
removed	five cycles	8
Intact	ten cycles	21
Cut	ten cycles	16
removed	ten cycles	8
Intact	wet	70
Cut	wet	61
removed	wet	25

Ballistic testing

Mean impact velocity for the ammunition used was 415 m/s (SD = 4 m/s). One of the 170 impacts resulted in a perforation of the complete test panel i.e. both the HG2 and KR2 portions (cover removed, exposed to three soaking and drying cycles, 412 m/s). All ammunition expanded on impact with the test panels irrespective of other variables considered.

The ballistic protective performance of the test panels was assessed by considering the proportion of shots that perforated the HG2 packs (*n* = 2 packs, *n* = 5 shots per pack

across all variables) i.e. whether the bullet was retained in the HG2 pack or in the KR2 pack located towards the rear of the test panel. Summary data across the two variables of cover condition and exposure regime are given in Table 3. No shot perforated the HG2 packs of the not-exposed test panels irrespective of the cover being present or not. However, the majority of shots on wet test panels perforated the HG2 packs (mean = 87%); further analysis suggested that presence of the water-resistant cover reduced this degradation, 70% of shots perforated the protected HG2 packs compared to 100% of shots when the cover was removed. A large degradation in ballistic protective performance was also noted for test panels that had been exposed to one or three cycles of soaking and drying in saline water when the cover was removed. However, this degradation was reduced as the number of exposure cycles increased. Cycled test panels with covers intact typically provided a higher level of protection than test panels with the covers damaged or removed. The exception to this was for three soaking and drying cycles with the cover intact.

Table 3 Percentage of shots that perforated HG2 packs (*n* = 10 per variable condition)

Cover	**exposure**	**% of shots that perforated HG2 packs**
Intact	not-conditioned	0
removed	not-conditioned	0
Intact	one cycle	0
Cut	one cycle	10
removed	one cycle	100
Intact	three cycles	50
Cut	three cycles	0
removed	three cycles	100*
Intact	five cycles	0
Cut	five cycles	0
removed	five cycles	10
Intact	ten cycles	0
Cut	ten cycles	0
removed	ten cycles	30
Intact	Wet	70
Cut	Wet	90
removed	Wet	100

*one bullet perforated the test panel

The BFS values were measured for each shot and summary statistics are provided in Table 4. Data variability (expressed as CV) ranged from 5% to 33% with no obvious trend due to the variables considered (Table 4). Fourteen of 169 shots (one perforation) resulted in a BFS of greater than 25 mm (the maximum allowable in the standard the armours were designed against). Of these, 11 shots were on wet armours; i.e. 37% of shots on wet armour resulted in a BFS greater than that allowed in the standard. In comparison no shots onto the not-exposed armours resulted in a BFS greater than 25 mm. Considering the mean BFS across each variable, only one exposure regime resulted in a mean BFS greater than 25 mm, that was for armours with intact covers shot while wet (5 out of 10 shots resulted in a BFS greater than 25 mm). Considering the two variables of cover condition and exposure regime in greater detail, the lowest mean BFS was observed for not-exposed test panels, the highest for wet test panels. With respect to increasing numbers of soaking and drying cycles similar values for mean BFS were observed for one, three and five cycles irrespective of cover condition with a slight decrease for ten cycles (20 mm, 19 mm, 19 mm and 17 mm respectively). The condition of the water-resistant cover did not appear to affect the measured BFS in test panels exposed to soaking and drying regimes.

Table 4 Summary statistics for backface signature (*n* = 10 per variable condition)

Cover	Condition	mean (mm)	SD (mm)	CV (%)
Intact	not-conditioned	14	4	29
removed	not-conditioned	18	2	11
Intact	one cycle	19	1	5
Cut	one cycle	21	2	10
removed	one cycle	18	4	22
Intact	three cycles	19	4	21
Cut	three cycles	17	4	24
removed	three cycles	19*	3	16
Intact	five cycles	18	3	17
Cut	five cycles	20	2	10
removed	five cycles	19	4	21
Intact	ten cycles	21	2	10
Cut	ten cycles	17	4	24
removed	ten cycles	12	4	33
Intact	Wet	26	2	8
Cut	Wet	23	5	22
removed	Wet	24	3	13

*one bullet perforated the test panel

Discussion

There are several points that require discussion i) mass of test panels, ii) perforation of test panels and iii) effect on backface signature.

The wet test panels were the heaviest as expected. Water ingress occurred into the individual fabric layers. Wet test panels with the covers intact or slit were much heavier (up to 70%) than all other test panels presumably due to the water being trapped in the covers and not being able to drain out; this is further evidenced by the wet test panels with covers removed having a lower mass (25%) than the other wet test panels. Other work has demonstrated large increases in mass when various fabrics and garments are wet e.g. (Laing et al., 2010; Crow and Osczevski, 1998; Laing et al., 2008). That mass of the test panels increased after soaking and drying exposure cycles in a saline solution was also expected and is likely due to salt crystallising and being trapped within the fabric and panel structure during the drying process. Residual moisture may have also remained trapped in the fabric packs. It was noticeable that test panels with intact covers exposed for three soaking and drying cycles had a higher mass (30%) than other test panels exposed to soaking and drying cycles with their covers intact (12%, 18% and 21%); this may be due to degradation of the seams of the covers before testing resulting in a greater ingress of moisture which became trapped during the drying phase. Excluding the test panels exposed for three soaking and drying cycles, an upward trend in mass was observed suggesting increased amount of trapped crystalline salt in the panels with an increasing number of soaking and drying cycles.

Previously published research (for fresh not saline water) suggested that a degradation in performance of up to 40% occurred for wet compared to dry ballistic protective fabrics (Laible, 1980; Gibb, 2005). Degradation in protection was observed in the current work for wet test panels, although at a higher level; this might be due to the different projectiles used. The previous work used non-deforming 1.1 g steel fragment simulating projectiles at similar impact velocities to the current work which used 9mm Luger FMJ ammunition that expanded on impact with the test panels. The 1.1g FSPs will be more penetrative due to the concentration of the kinetic energy over a smaller strike face. Higher

levels of degradation were also observed for specimens with covers removed that had been exposed to soaking and drying cycles; this suggested that the covers provide some protection from the degradative effects observed. It is noticeable that the higher level of HG2 element perforation observed for test panels with intact covers exposed for three soaking and drying cycles correlated with the increased mass for these panels further suggesting trapped moisture due to seam disruption (Tables 2 and 3).

That a higher number of shots on wet panels compared to dry panels resulted in a BFS greater than that allowed in the standard was expected; similar results have been observed in test laboratories worldwide for decades, but are rarely reported openly. Whether such increases in BFS would lead to more severe BABT is difficult to comment on, however, given an increase in BFS by as much as 25% it does seem likely that a more injurious event would occur. When considering test panels that had been exposed to cycles of soaking and drying, a slight increase in BFS compared to not-exposed panels was observed, but this was still within the limit of 25 mm in the standard giving confidence in the protection offered by armours that had been exposed in such a way.

Limitations

This work was conducted using one type of body armour and one type of ammunition at a given velocity. The results are not necessarily transferable to other armour systems, ammunition and exposure conditions. However, the work suggests that these other situations should be considered.

Conclusions

Wet armours provide less protection than dry armours. If the armour gets wet ensuring that is has completely dried is important as this work suggested that residual moisture can affect ballistic protective performance with respect to an increased likelihood of more severe BABT. Armour exposed to soaking and drying cycles (up to ten) in saline water was affected with respect to the protection levels offered, but the results suggested that a satisfactory level of protection would still be provided.

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