Testing light-weight personal protection impacted with sand particles

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Abstract. Regarding the evolution of combat scenarios, it is necessary to comprehend the challenges provided by improvised explosive devices (IEDs), it is vital to investigate the sand that is ejected during an explosion. Due to the absence of primary components, the IEDs principal risks come from the explosion and secondary fragmentation. For dismounted soldiers, the explosion itself and the debris released could result in severe injuries to the exposed, unprotected body parts, primarily the limbs. More protective mass is not advantageous because the limbs need to be highly mobile. The addition of mass would reduce the ability to move which should be avoided. The Allied Engineering Publication (AEP) 2920, which focuses on primary fragments as they are the principal concern for the majority of explosives devices, is the reference standard for testing fragmentation threats. These primary fragments are represented by steel Fragment Simulating Projectiles (FSPs). Therefore, this threat is faster and denser when compared with a cloud of sand ejected from an explosion. Thus, a methodology tailored to IEDs must be developed or modified. The major goal of this project is to create a method for consistently releasing a cloud of sand, which will enable testing light personal protective equipment. Controlling the sand cloud's velocity, dispersion, and the ability to precisely measure these events as they occur, when the cloud hits the target, are essential. Secondly, it is crucial to be able to measure various targets' properties in order to research how well the sand grains are stopped by them. The AEP 94 "Skin penetration assessment of non-lethal projectiles" was used to evaluate the damage and potential skin wounds in order to assess the damage and possible skin wounds.

1. INTRODUCTION

The number of Improved Explosives Devices (IEDs) has increased. During the decade 2010-2020, there have been around 28,800 incidents involving IEDs, resulting in more than 35,000 casualties [1]. The main difference between IEDs and other explosive devices, such as shells or grenades, is the lack of primary fragmentation produced during the explosion. IEDs are often packed inside plastic containers, which limits the production of primary fragments. The dangers of IEDs are due to the explosion itself, but also the secondary debris (or fragmentation) from the soil surrounding the explosion site.

This secondary fragmentation can cause a variety of injuries to the unprotected parts of the human body, particularly the limbs. Due to the nature of the threat and the extremities, it is critical to increase the level of limb protection, without adding heavy armour that would severely restrict the user's movements.

The Allied Engineering Publication (AEP) 2920 [2] is the primary reference standard for testing fragmentation threats. 1.1 g Fragment Simulating Projectiles (FSPs) are typically required for armour and personnel protection. Other minor threats described in the standard, such as 0.16 g FSP or Right Circular Cylinder (RCC), are quite unstable in flight, making obtaining accurate results during testing difficult. Furthermore, as a reflection of typical primary fragments, all of these fragment-simulating projectiles are made of metal. These facts make it difficult to relate the test results to the actual protection provided by armour impacted with secondary fragmentation.

The study of the secondary fragmentation has been already addressed. Some systems have been developed to consistently launch projectiles with masses between 0.004 and 54 g, at velocities up to 1,600 m/s [3]. Several attempts have successfully developed different systems to launch different sand and fragments larger than 4 mm and 0.12 g [4, 5]. Smaller particles might be of special interest in sandy conditions or even to represent components of the IED itself [6]. The probability of hit by small (0.61 g) stones is similar to larger stones in a certain region (from 30° to 80° from the explosion point) [7], showing the necessity of being protected effectively for smaller threat.

For this reason, this work aims to expand the work in the literature and studies how to accelerate and eject sand and small debris particles at different light-weight fabrics, to obtain a methodology that is able to classify the fabrics. The main objective of this work is to test the ability of several light-weight armour systems to defeat a cloud of small debris and compare the results with the protection offered against FSPs.

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2. METHODOLOGY

2.1 Test samples

The test samples are ten different fabrics of interest for comparison. These materials have been provided by different manufacturers and involve prototype fabrics and fabrics already used as uniform in different militaries. These light-weight fabrics have different areal densities and 2 different constructions, knitted and woven. Most of the samples are manufactured from aramid – viscose, while three of them use a high-performance ultra-high molecular weight polyethylene (UHMWPE) yarn (Table 4). The differences in areal density are mainly due to a tighter knit. An example of weave comparisons is shown in Figure 15.

Table 4. Tested samples

Sample	Material	Areal Density (g/m^2)	Fabric Construction
1	100 % UHMWPE	95	Knit
2	98 % UHMWPE	260	Knit
3	90 % UHMWPE	270	Knit
4	Aramid - Viscose	180	Knit
5	Aramid - Viscose	204	Woven
6	Aramid - Viscose	205	Woven
7	Aramid - Viscose	210	Woven
8	Aramid - Viscose	250	Woven
9	Aramid - Viscose	384	Woven

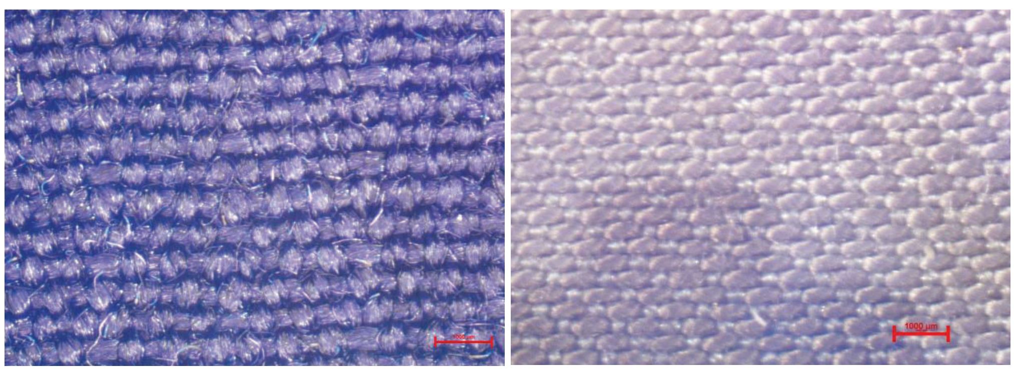

Figure 15. Comparison of fabrics: Sample 6 (left) and sample 8 (right)

2.2 Experimental set-up

The first part of this research is to estimate the ballistic resistance of the different fabrics when impacted with FSPs. For conducting the ballistic tests, a universal receiver with interchangeable barrel is used to fire the projectiles, and the target is positioned 5 m ahead of the muzzle. For the first series of tests, 1.1 g FSPs were used, with projectile velocity measured using optical chronographs. The target is the test fabric backed by 20% gelatine. Perforated fabric was assessed with the help of a high-speed camera, as the fragment might perforate the fabric but rebound out of the gelatine (Figure 16). During the testing the fabric was placed over the gelatine and pressed into a metal frame, which has an opening of 1,50 x 150 mm (Figure 17). This frame holds the fabric around its entire perimeter, with a single central shot for each test.

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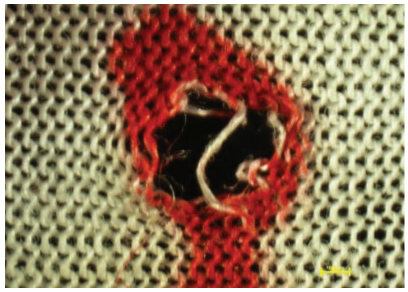

Figure 16. Example of hole in the fabric

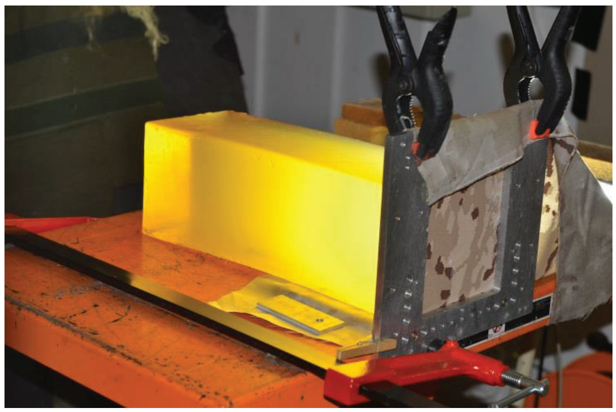

Figure 17. Frame support

For the second round of tests, the ammunition used was a 12 gauge shell, filled with 6.37 g of sieved sand of between 1 and 2 mm (around 0.01 g) placed in a sabot. The sand remained in the cartridge after closing, and there were no issues regarding leaking of the sand outside the cartridge. These sizes were selected to provide a good compromise of mass and perforation effect without reaching the mass of an FSP. For that grain size it would need a complete ballistic or fragment protection. Small debris size was chosen to try to replicate small particles up to 2 mm size, a common size secondary fragment [6], as well as being a typical sand particle size in beach or desert environments. At this size, the sand ejected might find an easy way to get through the gaps of the fabrics. As shown in the example, there are gaps in the regular fabric of around 0.5 mm (Figure 4).

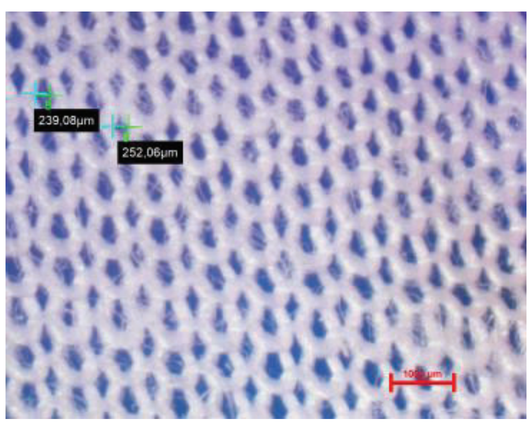

Figure 4. Gaps in the fabric (Sample 1)

The velocity of the particles was calculated from the recording of a high-speed camera placed orthogonally to the impact point. Five different particles were measured and averaged. The target is placed 3 m in front of the muzzle. The velocity of the cloud is controlled by varying this distance.

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Different configurations of propellant have been tested and it is possible to achieve velocities up to 900 m/s at 2 m. The goal is to have a configuration able to fire sand in a controllable way from 300 m/s up to around 1,000 m/s. Below 300 m/s, there is very little interest as it has been observed that the particles in the target tend to rebound from the gelatine.

The test fabric is backed with natural chamois skin with an optimum thickness of 1.39 mm, a 6 mm closed cell foam and 20% gelatine (figure 5), as per AEP 94 [8]. Cameras were used to record the depth of perforation of the sand grains into the gelatine. The samples were held in place upon testing by stapling the fabric directly to the foam. This was enough to retain the fabric during testing.

It is possible to modify the impact velocity by modifying the distance between the muzzle and the target. This also modifies the density of the impacts in the back-face material. As the idea is to develop a quantitative method to rank the different materials, it should be possible to analyse the data and extract conclusions from the comparison between the different samples.

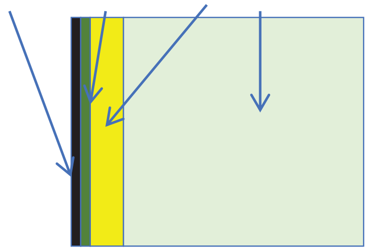

Figure 5. Lay-up of the test sample

It was not possible to always use the same backing material, as the material defined in the AEP 94 is no longer available, therefore available stocks were limited. An alternative solution is being sought in order to update the standard.

3. RESULTS AND DISCUSSION

3.1 FSP tests

The ballistic resistance of each sample backed with gelatine was estimated following the Probit method when impacting with FSPs (Table 5 and Figure 6). An average of 17 shots were fired per sample.

Table 5. Ballistic resistance of the samples impacted with FSP.

Sample	Material	Areal density (g/m^2)	Type of fabric	V_{50} (m/s)	σ (m/s)
1	100 % UHMWPE	95	Knit	137	11
2	98 % UHMWPE	260	Knit	194	0
3	90 % UHMWPE	270	Knit	161	15
4	Aramid - Viscose	180	Knit	92	5
5	Aramid - Viscose	204	Woven	92	3
6	Aramid - Viscose	205	Woven	94	0
7	Aramid - Viscose	210	Woven	96	0
8	Aramid - Viscose	250	Woven	97	2
9	Aramid - Viscose	384	Woven	106	2

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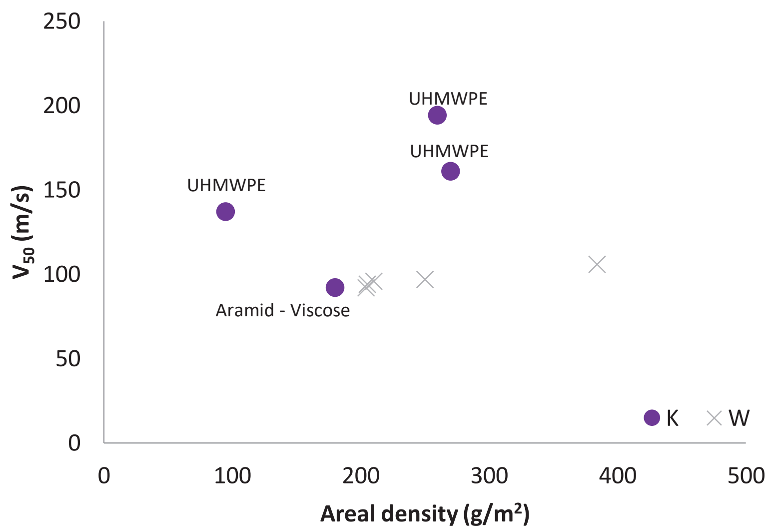

Figure 6. V_{50} versus areal density of the fabrics.

As shown in Figure 6; the higher the V_{50}, the higher the ballistic resistance of the sample. For woven fabrics, the ballistic resistance seems to increase slightly with the increment of the areal density for the considered range. This may happen because the level of the threat is too high for this type of material. Due to the low areal density of the structures, these samples are able to dissipate only limited quantities of kinetic energy. This may happen because of limitations on the response of the structure, e.g. in terms of deformation, to absorb the incoming kinetic energy. Adding a small quantity of material, even if it is almost double, may not have a visible effect in the protective characteristics of the fabric.

For knitted fabrics, it is more difficult to set conclusion due to the reduce number of samples. There seems to be an increase in resistance when increasing the areal density. The fabric is able to deform and dissipate significantly larger quantities of kinetic energy. The fabrics with polyethylene (Sample 1, 2 and 3) exhibit a higher performance than the regular yarns, as they have greater mechanical properties than the other woven sample.

3.2 Sand tests

When impacted with sand, the number of holes in the rear of the foam were counted, in order to differentiate the fabrics. This parameter was identified as a useful indicator to rank the different fabrics (Figure 7).

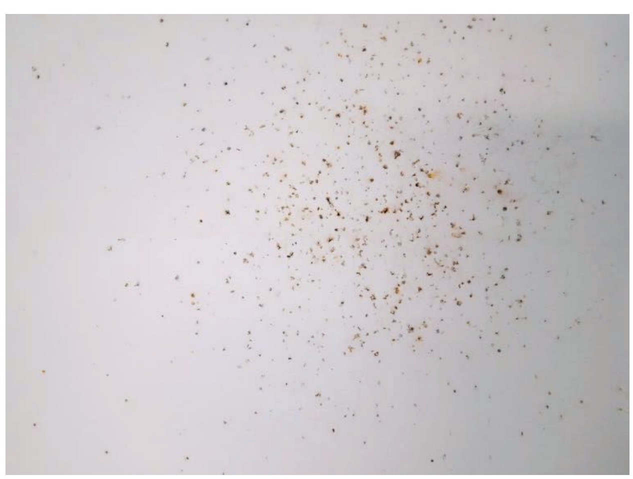

Figure 7. Example of the back face of the foam after a test (Sample size 305 x 225 mm).

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Due to the inherent variability and dispersion of the ejection of different sand grains, there were differences in the density and velocity of the sand cloud. It is possible to observe a variation of around 10 % in the number of total holes in the rear of the foam for the test without samples, and a variation of around 20 % of the velocity of the sand cloud (Table 6). Results of the testing are shown in Table 6, Figure 8 and Figure 9. Currently, no study of variability has been performed, but it is possible to observe some differences in the behaviour of the fabrics. Only one shot per sample has been conducted.

Table 6. Ballistic results of the samples impacted with sand cloud.

Sample	Material	Weight (g/m^2)	Type of fabric	Impact velocity (m/s)	Holes
1	100 % UHMWPE	95	Knit	433	48
2	98 % UHMWPE	260	Knit	443	43
3	90 % UHMWPE	270	Knit	447	72
4	Aramid - Viscose	180	Knit	400	85
5	Aramid - Viscose	204	Woven	400	17
6	Aramid - Viscose	205	Woven	477	51
7	Aramid - Viscose	210	Woven	467	59
8	Aramid - Viscose	250	Woven	478	50
9	Aramid - Viscose	384	Woven	392	36
No sample	Backing material AEP94	-	-	470	83
No sample	Backing material AEP94	-	-	430	94

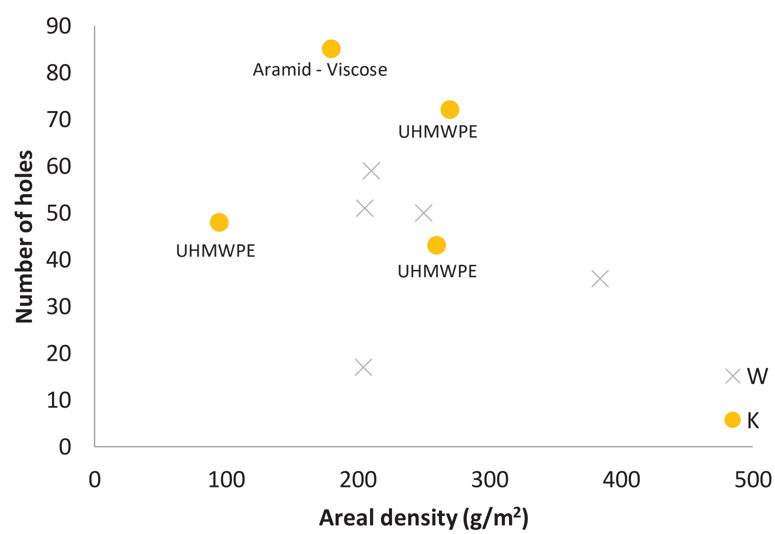

Figure 8. Number of holes in the foam regarding the areal density of the fabrics.

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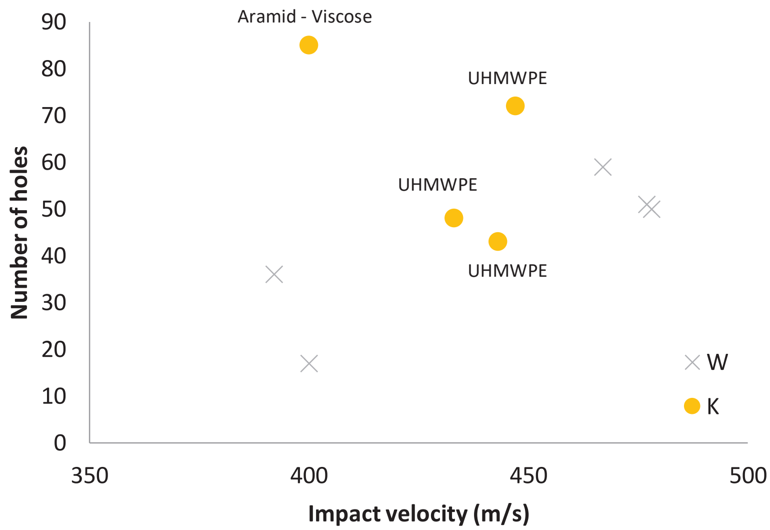

Figure 9. Number of holes in the foam regarding the impact velocity of the sand.

Despite the limited number of tests conducted, it is possible to observe some trends, which need to be confirmed with more testing. In Figure 8 and Figure 9, the lower the number of holes, the better the ballistic resistance of the sample, as there will be less sand debris perforating the fabric, causing potentials wounds. A criterion should be developed which relates the depth of penetration in the gelatine with the potential for wounding. The depth of penetration can be measured with the high-speed camera (Figure 10). The deepest sand impact is approximately 13 mm. Despite there being no clear wound criteria available to determine the possible damage upon the impact of sand, it seems plausible that it would be related to the number of impacts and the depth of the impacts. It has been previously postulated that the risk of skin perforation corresponds with impacts in excess of 24 J/cm^2. This value can be related to the number of impacts [9]. The depth of the impacts in gelatine may be related to an abrasion or more important wounds, but a reference needs to be established.

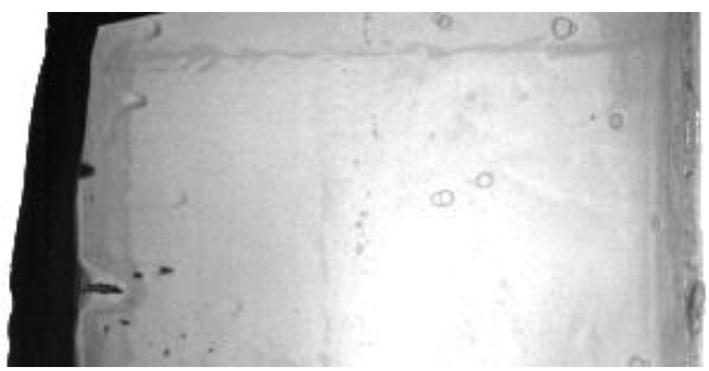

Figure 10. Sand impacts into a block of gelatine.

In Figure 8 and Figure 9, it is possible to observe the different points for all the different materials. This means that assessment of the holes in the fabric can lead to a ranking and allow the study of the best characteristic required to defeat this particular threat. Assessing the number of perforations is much easier with backing foam than in gelatine. These small perforations in gelatine tend to collapse, therefore the backing prescribed by the AEP 94, or a similar one, is of great importance.

Even though, it is difficult to obtain some conclusions due to the few samples shown, the number of holes increases with the impact velocity for knitted fabrics. There is still insufficient data for woven fabrics. The fabrics with polyethylene (Sample 1, 2 and 3) exhibit a higher performance than the regular yarns, as they suffer fewer perforations in comparison with the other woven sample.

It is noticeable the different behaviour of the samples when facing both samples. As an example, in Figure 6 and Figure 8, it is possible to observe that the knitted samples behaves better upon impact of the FSP's compared with the woven sample. But for the sand threat, knitted samples can only behave as good as the woven sample. This difference shows the importance of developing this technique to be able to study the different fabrics and improve them when facing small threats.

4. CONCLUSIONS

In this study, a methodology was proposed to test light-weight fabrics upon impact of secondary fragmentation in the form of sand debris ejected from an IED. Although a greater understanding of the mechanism of the perforation of multiple projectiles into a lightweight fabric is required, it is possible to identify some characteristics that would make this methodology suitable for classifying the fabrics. This methodology allows classification of the different fabrics, by counting the number of perforations in the foam. Trends observed include greater perforation with higher impact velocities and lower perforation with higher areal densities of fabrics. However, it is desirable to increase the control of the ejection of the sand, in order to enhance the repeatability in terms of velocity and dispersion of the sand cloud. The repeatability of a perforation pattern of a fabric when face a similar debris cloud should be studied.

Once the methodology has been refined, it will be possible to rank the fabrics and study in depth the different parameters that affect the ballistic resistance of a fabric, for this particular threat. It is not yet part of this work to establish the best characteristic of a fabric to defeat this type of threat. The difference of the results of the samples when facing the regular FSP's or a sand cloud shows a different behaviour that should be analysed developing this technique.

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References

[1] I. Overton, 'A decade of global IED harm reviewed', *AOAV*, Oct. 15, 2020. https://aoav.org.uk/2020/a-decade-of-global-ied-harm-reviewed/ (accessed Mar. 03, 2023).

[2] NATO, 'STANAG 2920 - Procedures for the evaluation and classification of personal armour-Bullets and fragmentation threats', Sep. 2016.

[3] J. Weir *et al.*, 'Fragment Characterisation & Threat Modelling - A Multinational Study to Re-Define & Represent the Fragment Threat', *Proc. Pers. Armour Syst. Symp. 2020*.

[4] G. Pageau and S. Ouellet, 'Development of soil ejecta surrogate projectiles for laboratory testing of lightweight protective materials', *Proc. Pers. Armour Syst. Symp. 2020*.

[5] M. J. Van den Jagt-Deutekom and T. A. T. Westerhof, 'Assessment of the secondary fragments from buried explosives', *Procedings Pers. Armour Syst. Symp. 2018*.

[6] B. Wilks, R. M. Morgan, and N. L. Rose, 'An experimental study addressing the use of geoforensic analysis for the exploitation of improvised explosive devices (IEDs)', *Forensic Sci. Int.*, vol. 278, pp. 52–67, Sep. 2017, doi: 10.1016/j.forsciint.2017.06.028.

[7] C. A. Couldrick, T. A. Ringrose, P. L. Gotts, and M. J. Iremonger, 'ASSESSMENT OF SECONDARY FRAGMENTS FROM BURIED AP BLAST MINES', *Procedings Pers. Armour Syst. Symp. 2004*.

[8] NATO, 'AEP- 94: Skin penetration assessment of Non-lethal projectiles', Jul. 2021.

[9] L. Koene, M. L. Van Essen, A. Oukara, and A. Papy, 'ASSESSMENT OF SKIN PENETRATION OF KINETIC NON-LETHAL PROJECTILES USING THE SURROGATE METHOD', *Proc. Int. Symp. Ballist. 2014*.

 https://doi.org/10.52202/080042-0034