Development of soil ejecta surrogate projectiles for laboratory testing of lightweight protective materials

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Abstract. This paper presents the development of Rock Simulating Projectiles (RSP) that simulate natural fragments accelerated during the explosion of a buried charge. The key features of the projectile (shape, sectional density, edges) are based on a detailed morphological study of natural fragments. Ballistic tests (V_{50} and overmatch) were conducted on a novel lightweight ballistic fabric to compare the relative penetrating capability of the proposed 2 gr RSP with 2 gr natural rocks and a 2 gr steel Right Circular Cylinder (RCC). The RSP was successfully launched with minimum yaw at low and high velocities using a 0.17 calibre gun without sabots. For the fabric tested, the lowest V_{50} value and smallest absorbed energy (from overmatch tests) were obtained with the RCC, leading to an underestimation of the actual protective capability against natural fragments. Scaling techniques, typically used for armour material with higher Areal densities (***Ad***) against FSPs and RCCs, were shown to be inappropriate for very low ***Ad*** armour materials against projectiles with a different shape. The results obtained with the RSP suggest that it is an adequate surrogate for soil ejecta, enabling a conservative assessment of the effective ballistic resistance of protective fabrics against this threat and leading to more reliable estimation of safe operating distances.

1. INTRODUCTION

In the context of asymmetric warfare, dismounted soldiers are facing a broad and complex spectrum of threats. Most current fragment protective armours were designed to defeat high-velocity fragments from air-burst warheads at long standoff distances. However, the close proximity exposure to the detonation of a buried Improvised Explosive Device (IED) leads to a very different scenario involving non-metallic natural fragments (i.e. soil ejecta), a high number of close impacts, negative impact angles and potential synergy with the blast wave [1]. While the severity of the threat may remain driven by the physical attributes of the projectiles (i.e. mass, shape, material) and their impact velocities, the specificities of the IED scenario warrants an adapted ballistic test method to evaluate potential protective strategies. Unfortunately, replicating more realistic conditions (e.g. projectile simulating soil particles, close multi-hit, etc.) has not yet been standardized in laboratory testing. In addition, the emergence of the buried IED threat has led to redefining armour coverage to include zones that were typically unprotected such as extremities, joints and urogenital areas which extends the range of materials to consider for protection. Until better-defined test methods with relevant performance metrics are implemented, the development of protective systems against the buried IED threat may not lead to the intended protection levels.

Since 2014, Defence Research & Development Canada (DRDC) has been conducting work to address this buried IED test methodology gap. Specifically, DRDC has developed complementary and rigorous test methods for full-scale explosive testing and laboratory testing of protective materials. For the full-scale tests, the method is built around test beds made of two types of narrow-graded standardized soils in order to represent two operational severity levels. The lower severity test uses a test bed made of BC 2.5-5mm crushed aggregates [2], where BC is the designation for cement concrete aggregates. This aggregate grading is meant for testing protective clothing and under garment (Tier-1 Pelvic Protection Systems (PPS)). A test bed with coarser aggregates (BC 2.5-10 mm) is used to conduct the high severity test meant for testing protective over garments (Tier-2 PPS). Well-graded soils with larger particles, such as the STANAG soil [3] specified for vehicle mine resistance testing, were found to be too severe for **PPS** testing. Because the ballistic performance of a material is sensitive to the supporting conditions (e.g. clamped or backed), a biofidelic backing replicating the "as-worn" condition and developed to test soft armour material is used to support material samples during testing [4,5]. The backing has a layered structure, ideal for recovering fragments, and comprises of an outer skin (epidermis/dermis), an under layer (hypodermis) and a soft tissue simulant. The layered backing is also used in laboratory ballistic testing of protective materials. For end-items testing (e.g. boxers, PPS), the layered backing can be easily assembled into quasi-anthropomorphic shapes. Post-test analysis of full-scale experiments is done using a CT-scanner and the *FragFinder* software [6] which enables automatic measurement of fragment properties and depth of penetration (***DoP***) in the layered backing. From these

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measurements and the laboratory calibration of the layered backing, a fragment's residual velocity (***V_r***) is estimated and used for evaluating armour system effectiveness in operational scenarios.

Using the layered backing for both laboratory and full-scale explosive test leads to coherent ballistic data sets, which can then be cross-correlated. To maintain a high level of correlation between full-scale and laboratory tests, it is necessary to use an adequate surrogate projectile and reproduce the spatial distribution of impacts on the armour. A number of laboratories [7-8] have explored using the "sand cannon" technique where multiple non-metallic projectiles are launched in a sabot to replicate the spatial and temporal distribution of impacts from soil ejecta. This method typically has a low level of reproducibility in terms of impact dispersion and velocity of the aggregate projectiles, making comparative performance assessment difficult. Multi-projectiles launchers have also been used for multi-hit testing [9-10] where the effect of near-simultaneous impacts can be evaluated. However, this method is not easy to implement due to the required specialized equipment. Using multi-hit shot-patterns is thought to be a good compromise between realism of the simulated threat, repeatability and ease of use, keeping in mind that in the context of buried IED, laboratory tests will always be limited as the combined effect of blast overpressure and ballistic impacts cannot be reproduced. The validation of the performance of protection systems against buried IEDs will always require full-scale explosive tests.

Standardized fragments simulating those from fragmenting munitions are routinely used in body armour testing [11]. The main categories are the chisel-nose fragment-simulating projectiles (FSP) and the flat-nose right circular cylinder (RCC). Both are available in a number of homologous sizes. For pre-formed fragmenting munitions, the filler fragments (RCC, spheres, cubes) are sometime directly used. The failure mechanisms of armour and the ballistic resistance are highly influenced by fragment geometry. Therefore, choosing a shape that adequately replicates the buried IED threat would appear important. Unfortunately, end items aimed at protecting against energized natural fragments still have protection levels defined using the 2 gr steel RCC or the 2.5 gr steel FSP. Soil particles are however different from the standard FSPs and RCCs. They have significantly different compositions (e.g., densities), and are often asymmetrical with numerous edges. Soil ejecta surrogates, using alternative materials, have been explored by other researchers. Glass spheres [7] have been proposed for testing lightweight fabrics, and silicon nitride balls [12] have been specified for the low-velocity testing of transparent armours. However, spheres are far from the shape of soil particles and are known to interact much differently with woven targets compared to projectiles with edges where shear cutting may dominate. Glass cannot be easily machined into complex shapes making skirted designs impossible. Cubes and parallelepipeds would potentially provide a closer match to the geometry of natural fragments, but are rarely used because their striking orientations (e.g. corners, faces and edges) and penetration capability cannot be controlled reliably. Linden [13] proposed using aluminium RCCs (3 mm and 6 mm) which led to the adoption by CEN [14] of a 4 mm diameter/length aluminium RCC (2.2 gr) for testing deminer's protection systems. An aluminium cylindrical projectile with a conical nose is also specified for testing of railway glazing against rock strike [15].

2. SURROGATE DESIGN

To support the development of a better soil ejecta surrogate projectile, a study was conducted on particle size distribution and morphology of rocks from three types of soil used in buried IED testing. The study used standard sieve analysis, 3D laser scanning and 2D image analysis. Thirty individual samples were taken from 6 different sieve opening sizes for each of the three soils (crushed granite, crushed limestone, natural granite) for 90 samples in total. The morphology parameters obtained included mass, outer surface area, minimum, maximum and average presented areas, average shape factor, and mean edge radius. The relative density with respect to water, or Specific Gravity (***SG***), was measured using a solid density tester and yielded values ranging from 2.65 to 2.72 for the three aggregate types, which is comparable to the value of 2.62 reported by Thomas [16]. The following correlations between mass (***m*** in grams), diameter (***D*** in mm), length (***L*** in mm) and elongation ratio (***L/D***) were found from the analysis:

$$\boldsymbol{m = 0.003 * D^{2.58}} \quad \textbf{(1)} \qquad\qquad \boldsymbol{\frac{L}{D} = 2.1 * D^{-0.42}} \quad \textbf{(2)}$$

Using Equation 1, the average mass for a 4.3 mm diameter (0.17 calibre) rock is 0.13 gram or 2 gr. The 4.3 mm size was chosen as it corresponds to the smallest barrel rifling available, making possible the use of skirted projectiles. It also corresponds to the upper end of the BC 2.5-5 mm aggregate grading selected for Tier 1 PPS testing making possible future performance correlations between laboratory and full-scale testing. A Rock Simulating Projectile (RSP) was designed (Figure 1) based on the standard FSP geometry and the 0.17 calibre Hornet rifling specifications. To better replicate the geometry and

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numerous edges of natural rocks, the nose of the RSP includes four bevel planes instead of two. The planes are at an angle of 45° (version 1) instead of the standard 35° on FSPs.

The edges are also sharp with no radius, making the RSP more severe and leading to more consistent and conservative assessments of the ballistic resistance of personal armour materials. For firing at low velocity with short target distance, an un-skirted variant was also designed which can be launched using a smoothbore gas gun. For specific gravity, the closest material to natural rock is aluminium followed by soda lime glass (***SG*** of 2.5). Magnesium (***SG*** of 1.77 vs 2.7 for aluminium) was finally selected since its lower ***SG*** allows for artificially increasing the RSP length by 52% while keeping the sectional density constant (Figure 2 left). The greater elongation ratio (1.53 for magnesium vs 1.13 for aluminium) ensures better in-bore and in-flight stability (i.e. low yaw).

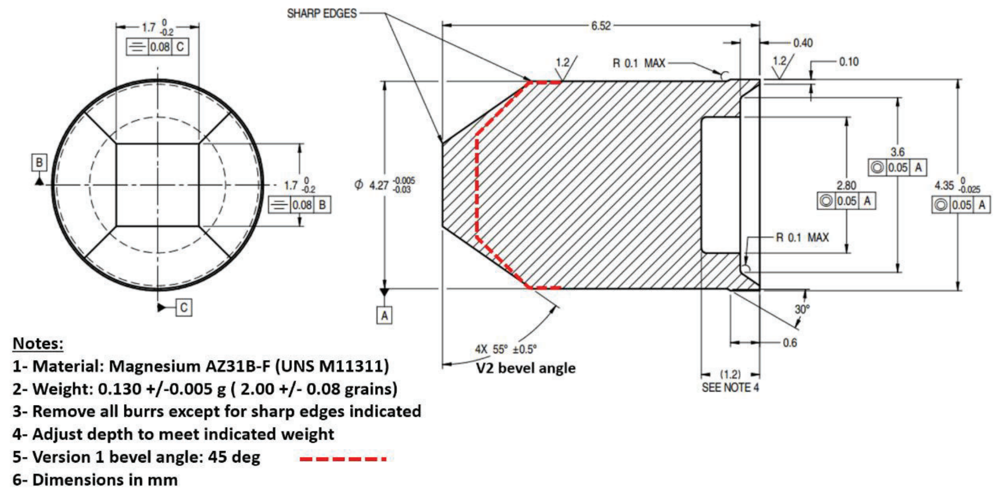

Figure 1. Drawing of magnesium RSP

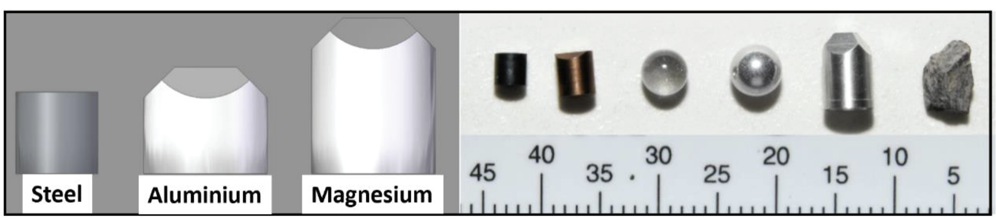

Figure 2. 2 gr steel RCC vs aluminium and magnesium RSP (left)
2 gr RCC, 3.7 gr FSP, 4 mm glass sphere, 4.5 mm aluminium sphere, 2 gr RSP, 2 gr rock (right)

A 6 gr and 16 gr variant are also proposed for representing coarser soils. The 2 gr and 16 gr masses are commonly used for testing body armour and are part of the RCC homologous family [17]. The corresponding diameters for the 6 gr and 16 gr, calculated using Equation 1, are 6.6 and 9.7 mm respectively. These values correspond closely to two standard gun calibres: the 0.270 Weatherby magnum and the 40 Smith and Wesson. The corresponding elongation ratio from Equation 2 are: 0.95 and 0.81 respectively. Although the nose geometry for the 6 gr and 16 gr variants would be the same as for the 2 gr, the 3 variants would not be fully homologous because of the different elongation ratios. This could limit scaling of ballistic data based on sectional density. To validate the integrity and flight stability of the proposed 2 gr RSP, an initial quantity of 30 units was produced. The bevel angle was subsequently changed from 45° to 55° (RSP version 2) such that the resulting edges angles are 45° as initially planned.

3. BALLISTIC TESTS: MATERIALS AND METHODS

Table 1 summarizes the four ballistics tests series conducted to validate the suitability of the proposed 2 gr RSP for replicating soil ejecta. Two types of soft armour materials were used: a 500-denier woven aramid fabric (Twaron®) typically used in fragment protective vests and a novel lightweight fabric designed for combat uniforms. Four projectiles were tested (Figure 2) namely the 4 mm glass spheres

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(*Cospheric* precision grade soda lime), the 2 gr steel RCC, the 2 gr limestone gravel stones (rock), and the proposed 2 gr RSP machined from 6.35mm diameter magnesium alloy AZ31F rod (*Buymetal.com*). A first test series was conducted as an initial proof of concept for the RSP design (v1) where two-shots V_{50} firings could be performed against 1, 3 and 26 plies of the Twaron® fabric. The 4 mm glass spheres were only tested against the one ply Twaron® samples. Test series 2 to 4 were conducted with the 2 gr RSP (v2), 2 gr RCC and 2 gr rock against two plies of the novel fabric material selected. V_{50} tests of the novel fabric were conducted following the standard conditions (shot pattern, up-and-down method) of AEP-2920 while ballistic overmatch tests were done according to the guidelines of TOP-10-2-506 [18]. Residual velocity (***V_r***) testing was done with impact velocities (***Vi***) up to twice the V_{50}. Impact velocity was measured using a Doppler radar and two orthogonal *Photron SAZ* cameras. Rebound velocities (negative ***V_r***) were also measured for the non-penetrating impacts for better fitting the ***V_r*-*V_i*** data. The *ProAnalyst* image analysis software was used to compute the total projectile yaw upon target impact using the two orthogonal views. The target size for V_{50} and overmatch tests was 400 mm x 400 mm with the fabric samples stitched together at their four corners. Tests using twelve plies of the novel fabric targets (200 x 200 mm) were also conducted to measure the number of layers penetrated as a function of ***V_i*** for both the RCC and RSP. All targets were affixed with two nylon bands to the biofidelic backing.

Table 1. Ballistic tests conditions

Series	Test types	Projectiles	Target materials
1a	V_{50}	RSP 2 gr v1	Twaron® 500 den: 1, 3, 26 plies
1b	V_{50}	Sphere glass 4mm	Twaron® 500 den:1 ply
2a	V_{50} skin, ***DoP-V_i***	RSP 2 gr v2	Bare backing
2b	V_{50} &overmatch	RSP 2 gr v2	New fabric: 2 plies
2c	Perforated layers vs ***V_i***	RSP 2 gr v2	New fabric: 12 plies
3a	V_{50} skin, ***DoP-V_i***	Rock 2 gr	Bare backing
3b	V_{50} &overmatch	Rock 2 gr	New fabric: 2 plies
4a	***DoP-V_i***	RCC 2 gr (sabot)	Bare backing
4b	V_{50} & overmatch	RCC 2 gr (sabot)	New fabric: 2 plies backing & frame
4c	Perforated layers vs ***V_i***	RCC 2 gr (sabot)	New fabric: 12 plies
4d	V_{50} multi-hit	RCC 2 gr (sabot)	New fabric: 2 plies

For the V_{50} tests, the complete and partial perforation assessment was performed using three criteria: perforation of the armour sample, perforation of the backing epidermis/dermis layer and perforation of the hypodermis layer, leading to a different V_{50} value for each condition. The up-and-down procedure was driven by the perforation status of the armour to avoid removing the layered backing components after each firing. The layered configuration of the backing allowed for the precise determination of the Depth of Penetration (***DoP***) of the projectiles. This was done only after all the firings on a sample were completed. Calibration tests (***DoP*** vs ***V_i***) were conducted on the bare layered backing (series 3a and 4a) to enable the estimation of ***V_r*** from ***DoP*** data when the armour sample is perforated. The 2 gr RSP and 4 mm glass sphere were launched using a 0.17 calibre Hornet barrel chambered for receiving 0.22 calibre long rifle cartridges. Three barrels lengths were available, i.e.: 250, 400 and 660 mm for the RSP. The 250 mm barrel was used to cover the lower velocity ranges (130 to 550 m/s) while the 660 mm barrel allowed to reach up to 1450 m/s. *Hilti* 0.22 calibre single shot powder blanks (brown, green, yellow) and *Victory* crimped start blanks were used to propel the fragments. For each blank cartridge type, a velocity-distance calibration curve was generated by varying the initial position of the projectile within the barrel by steps of 12 mm up to the barrel mid-length. Projectile velocity adjustment was then done by selecting the right blank type and insertion distance.

The 2 gr rock projectiles were selected from a 15-litre container of BC 2-5mm crushed limestone aggregates. The rocks were launched using a 6.35 mm smoothbore gun tube dimensioned for firing the 16 gr steel spheres. A neoprene obturator disc was placed behind each rock to provide a gas seal and gain adequate control on impact velocity. The 2 gr RCC test series was conducted by an external laboratory using plastic sabots and short barrels which unfortunately prevented reaching the lower end of the desired velocity range. To replicate the effect of multiple close impacts (Figure 3 left), ballistic tests were also conducted using the multi-hit pattern shown in Figure 3 (test series 4d). A single-hit V_{50} value is obtained first using the AEP-2920 [11] standard shot pattern with a 64 mm spacing. A second test series is then performed where shots are placed in pairs at close distance (18 mm) from the first

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series to generate a second V_{50} value. A third series is finally conducted using an equilateral triangle pattern for obtaining the third V_{50} value with a minimum distance between each triangle of about 50 mm.

Ballistic resistance degradation from overlapping damage may then be quantified by comparing the three V_{50} values. Although this approach only replicates the spatial and not the temporal distribution of the impact of soil ejecta, it should help identify fabric architectures and material systems that are better suited for the soil ejecta threat. From Figure 3 (centre), it can be seen that for the same projectile mass, the diameter of the RSP is 1.5 times larger than for the steel RCC and the presented area is 2.3 times larger. The larger RSP area will translate into more yarn damage. For the multi-shot pattern proposed (Figure 3 right), the RSP may lead to more overlapping damage and greater relative severity compared to the RCC. Meanwhile, the 2 gr RCC will likely be more penetrating against low thread density fabrics due to its smaller size.

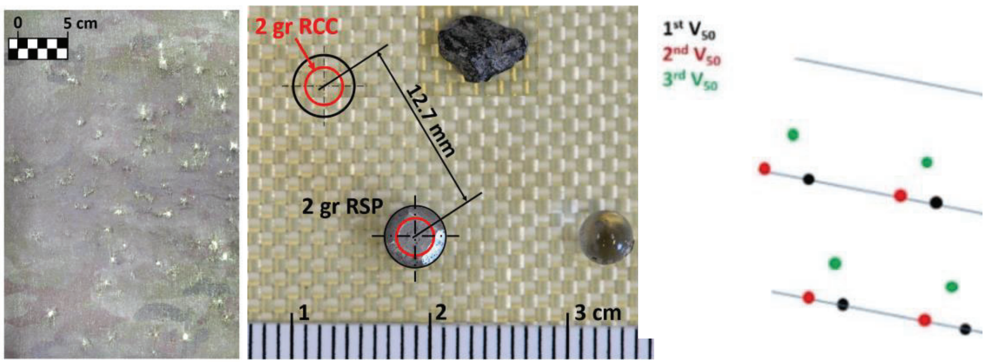

Figure 3. Typical soil ejecta spatial density (left)
RCC, RSP, Rock, and 4 mm sphere vs aramid yarn sizes (centre), multi-hit shot pattern (right)

4. BALLISTIC TESTS RESULTS

Figure 4 illustrates the level of flight stability obtained with the RSP design. The average total yaw at impact was 2.5° with 73% of the shots having yaw lower than 3° and only 5% with yaw above 5°. The yaw behaviour is quite similar to what is obtained with the 17 gr FSP, but much less than typically yaw values observed when launching the 2 gr RCC and the 2.5-gr FSP using sabots.

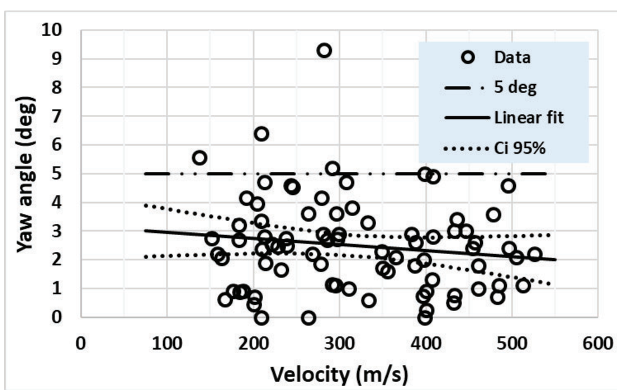

Figure 4. RSP yaw angle vs velocity

Figure 5 (left) illustrates a test where the 4 mm glass sphere penetrated the one-ply aramid fabric and remained entangled in the aramid yarn. This type of yarn pull-out did not occur with the RSP or rock projectiles as shear cutting appears to be the dominating failure mechanism. For the tests with the target made of 26 plies of Twaron®, velocities up to 1425 m/s were reached. At that point, the RSP projectiles were partly eroded with a reduction of mass of 20% and nose expansion of 5% (Figure 5 right). For all tests below 900 m/s, no erosion occurred and the projectiles remained intact. Since the 2 gr RSP is intended mainly for assessing Tier-1 PPS, erosion at very high velocities is not a concern. For the 2 gr rocks, no erosion was observed during tests at velocities around 300 m/s, but the rocks sometimes fractured into pieces upon impact. Such behaviour was also observed during full-scale buried IED trials.

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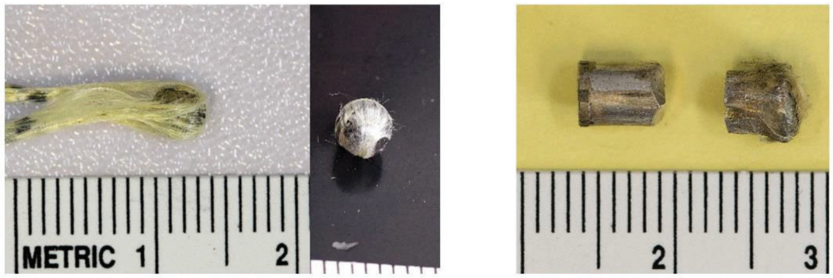

Figure 5. Twaron® yarn slippage 4mm sphere (left), recovered RSP(v1) at 500 and 1400 m/s (right)

Figure 6 shows the results obtained for test series 1 with the 4 mm glass sphere and the 2 gr RCC. Although the number of shots was limited, V_{50} values with one partial and one complete penetration within 50 m/s (2 shots V_{50}) were obtained. Results obtained previously for the same fabric against the 1 and 16 grain steel spheres and the standard FSPs and RCCs are included for comparison. To illustrate some of the scaling and testing issues involved with low areal density fabrics and non-steel fragments, the armour ***Ad*** have been normalized by the projectile sectional densities (***Sd***) as proposed by Cunniff [17]. Ballistic data for Kevlar® K706 against FSP, RCCs [19] and glass spheres [20] are also shown in Figure 5. Data from Steier [21] for Twaron® CT709 against 5.5 mm spheres of 4 densities is shown to scale well with the ***Ad/Sd*** ratio. All spheres demonstrate more severe penetrating capability than their FSP-RCC counterparts. The RSP is shown to be less penetrating than its FSP-RCC counterparts, equivalent to increasing the FSP-RCC presented areas by 39%.

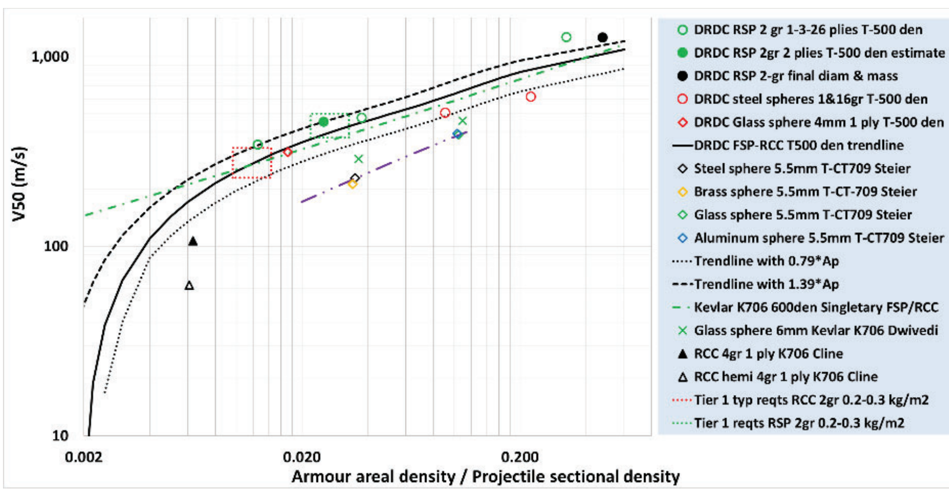

Figure 6. Ballistic test results with woven aramid fabrics

Data from Cline [22] for 1 ply Kevlar® K706 against the 4 gr RCC illustrates the effects of edge sharpness/nose radius on ballistic performance. The data does not follow the scaling trend for larger fragments and higher armour ***Ad*** for the same fabric material, suggesting that the energy absorption mechanism is changed. Figure 6 also illustrates the typical requirements (V_{50} of 230-300 m/s for 2 gr RCC) for Tier-1 PPS which are shown to increase to 375-500 m/s when scaled for the 2 gr RSP. The 2 gr RCC also appears to underestimate the protection levels of armour systems from the soil ejecta threat. The ballistic limit results obtained for the skin components of the layered backing are presented in Figure 7 (left) for the RSP and rock projectiles. The raw data was analysed using the *Stats.Blue* logistic regression calculator [23] for computing the logit penetration probability curve fits and the corresponding 95% confidence intervals. For the RCC, it was not possible to obtain a V_{50} value for the backing skin due to the lower velocity limit achievable by the firing equipment. Instead, a threshold perforation velocity V_{th} was obtained (109 m/s) by extrapolating the V_i vs ***DoP*** data (Figure 7 right). The RSP is found to be slightly more penetrating than the rock projectile with a V_{50} of 187 m/s compared to 233 m/s. For the rock projectile, a much larger standard deviation is observed which is expected since

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each natural rock has a slightly different shape and hit the target with different orientations, making the penetration process less repeatable.

Figure 7 (right) presents the results obtained for the $\boldsymbol{V_i}$-***DoP*** calibration of the layered backing with the 2 gr RCC, RSP and rock. The three projectiles are shown to have a similar slope with the main difference being the $\boldsymbol{V_{th}}$ measured from the $\boldsymbol{V_i}$-***DoP*** fits at ***DoP* = 0**. The $\boldsymbol{V_{th}}$ values are found to be close to the V_{50} values.

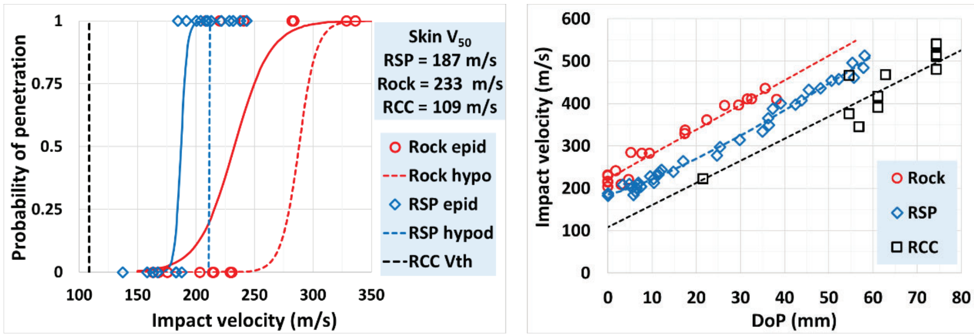

Figure 7. Ballistic limit response of backing skin layer for 2 gr RCC, RSP and Rock (left)
Calibration of layered backing ($\boldsymbol{V_i}$ vs ***DoP***) for 2 gr RCC, RSP and Rock (right)

The $\boldsymbol{V_i}$-***DoP*** best fits are used in the armour overmatch test series for converting the measured ***DoP*** into $\boldsymbol{V_r}$. To further interpret the ***DoP*** results in terms of probability of incapacitation, an analysis was done using the ***DoP*** data of Breeze [24]. The data from Breeze is for ***DoP*** in goat tissues against the 0.16, 0.49 and 1.1g steel FSPs. The data was found to be best fitted by Equation 3 (R^2 of 84%) where the ***DoP*** is normalized using projectile sectional density ***Sd*** to make the correlation usable for fragments of similar shapes but made with different materials (e.g. glass, aluminium).

$$\boldsymbol{Vi} = \left(\frac{\boldsymbol{DoP}}{\boldsymbol{Sd}}\right) * (-\mathbf{1176} * \boldsymbol{Sd} + \mathbf{108950}) + \mathbf{484} * \boldsymbol{Sd}^{-\mathbf{0.4}} \qquad (\mathbf{3})$$

The ***DoP*** curve obtained for the RSP with the layered backing is plotted again in Figure 8, this time with ***DoPs*** in goat tissue computed from equation 3 for the 2 gr steel RCC and 2 gr RSP. The layered backing is shown to be softer than goat tissue, thus providing better resolution for determining impact velocity. From the figure, a given ***DoP*** in foam (e.g. 55 mm) can be translated into a ***DoP*** (26 mm) in goat tissue, from which the equivalent velocity of a 2 gr steel RCC having the same ***DoP*** in goat tissue can be calculated (250 m/s). This process is needed to obtain predictions for the associated probability of incapacitation ($\boldsymbol{P_i}$). $\boldsymbol{P_i}$ is calculated using the Kokinakis model [25], which was formulated for steel fragments only. The example yields a $\boldsymbol{P_i}$ of 45% (6 impacts). The black curve in Figure 8 is the result of this process for any ***DoP*** of the 2 gr RSP in the layered backing. It is also shown that no incapacitation is occurring for ***DoPs*** in the backing material less than 20 mm.

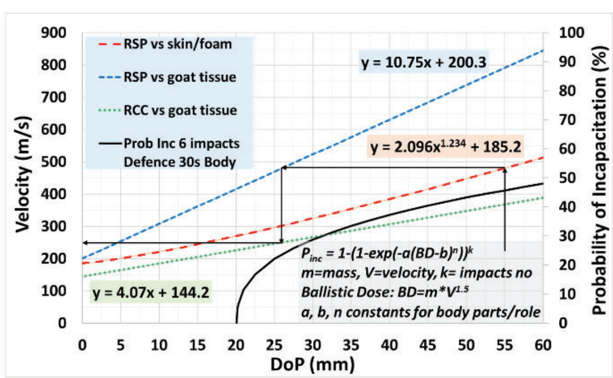

Figure 8. 2 gr RSP & RCC ***Vi*** vs ***DoP*** response for foam and goat tissue & related incapacitation

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Figure 9 (left) presents the ballistic response curves (logit fit) of the novel fabric material against the 2 gr RCC, RSP and rock. Based on the full perforation of the skin component of the layered backing, the RCC is found to be more penetrating than the RSP.

For the RCC, the V_{50} obtained with the clamping fixture (338 m/s) is found to be much higher than that obtained with the layered backing (246 m/s). The target being allowed to deform without any restriction (air backed) and the use of the 0.5 mm aluminium witness plate which must be perforated to count as a complete penetration contribute to artificially increasing the measured ballistic resistance. For the multi-hit series with the RCC, a slight decrease of ballistic resistance was obtained for the 2nd shot V_{50} (237 m/s) with no degradation for the 3rd shot V_{50} (245 m/s) using an 18 mm triangular shot pattern. The good multi-hit performance of the novel fabric may be due to its architecture which led to very localized damage. The response of the fabric against the rock projectile demonstrates a much larger variance compared with the RSP, which was also expected given the high level of rock shape and impact angle variability. Figure 9 (right) presents the number of layers penetrated as a function of $\boldsymbol{V_i}$ for the 2 gr RCC and RSP, based on tests using samples of 12 layers of fabric. Based on a linear fit of the data, a velocity of 350 m/s would be required to penetrate two plies of fabric material, which is more than the measured V_{50} value of 291 m/s. In other words, a higher number of plies would be needed to defeat the projectile at a given impact velocity than the value estimated from semi-infinite targets. This is in agreement with the findings of Anderson [26] for metallic targets. Results for the 2 gr RCC also follow the same trend.

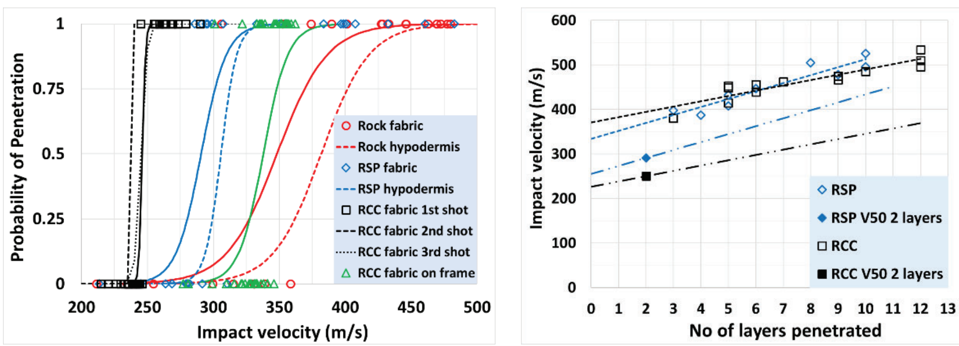

Figure 9. Ballistic limit response of novel fabric vs 2 gr RCC, RSP and Rock (left) Number of fabric layers penetrated vs impact velocity for 2 gr RSP and RCC (right)

Figure 10 (left) presents the results obtained during the overmatch test series. The ***DoP*** data for each projectile was converted into residual velocities, from which the residual kinetic energies ($\boldsymbol{E_r}$) were computed. The absorbed energies by the fabric was obtained by subtracting $\boldsymbol{E_r}$ from the initial kinetic energy of the projectile ($\boldsymbol{E_i}$). The energy absorption ratio is given by $\boldsymbol{E_a/E_i}$. Best fits were obtained for the energy absorption ratio data using the *Xuru* open-source software [27], which searches through more than 100 nonlinear regressions functions and ranks the resulting fits from best to worst.

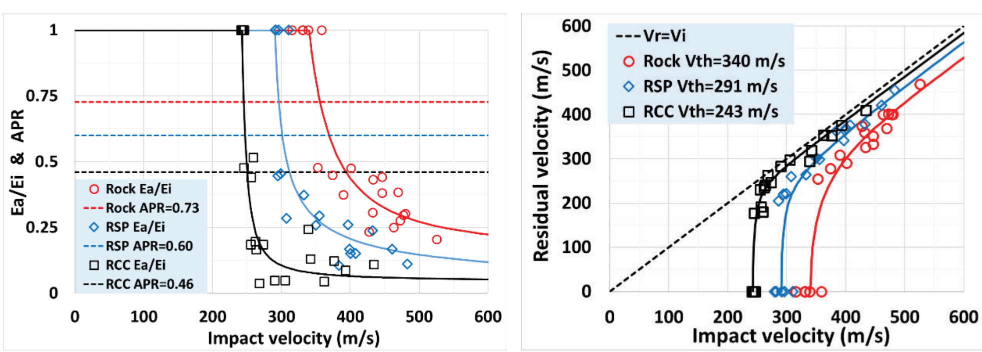

Figure 10. Energy absorption response of 2 gr RCC, RSP, and Rock (left) vs impact velocity (left) $\boldsymbol{V_r}$-$\boldsymbol{V_i}$ overmatch response of novel fabric for 2 gr RCC, RSP and Rock (right)

The best fit models for the energy absorption ratio were integrated over the 0-600 m/s velocity range to obtain the Armour Protection Rating (***APR***). The ***APR*** represents the average energy absorption capability of a given armour over a range of velocity. The ***APR*** captures in a single value both the

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ballistic resistance and the overmatch response of the armour. It is similar to the *effective ballistic resistance* concept proposed by Bourget *et al.* [28]. The best fit models were converted back into V_r-V_i space (Figure 10 right), which provides key input data for vulnerability modelling tools.

Interestingly, this method of generating V_r-V_i fits was found to generate better models for the V_r-V_i data than fitting the data directly using models such as Haque and Gillepsie [29]. The obtained V_r-V_i data reproduced the typical vertical jump in V_r near V_{th} very well. Naturally, this jump is more pronounced when using the layered backing method since the projectile must penetrate both the armour and the skin component of the backing before any measurable ***DoP*** values are obtained. The ***APR*** relative ranking for the 2 gr RCC, RSP and Rock follows the one obtained from the V_{50} tests.

The operational significance of choosing the RSP instead of the RCC as a fragment surrogate for protection systems assessment can be demonstrated by analysing the fabric penetration data in the context of an explosive event producing natural fragments. First, impact velocities for a 2 gr fragment were estimated for standoff distances of 0 to 18 m from the detonation centre using the deceleration model of Thomas [15] and assuming cubic geometry and an initial velocity of 1000 m/s. The three V_r-V_i models of Figure 10 were used independently for computing corresponding V_r values. The process explained in Figure 8 was then followed to generate incapacitation predictions and the probabilities of survival (P_s =1-P_i) using the Kokinakis model [24] for the defence tactical role, 30 seconds post wounding time, with ten impacts over the entire body area. The probability of survival curves obtained are plotted relative to standoff distance for the three projectile types in Figure 11, where within a hypothetical crater radius of 1.5 m a kill probability of 100% (P_s = 0%) was assumed. For the 2 gr RCC, a safe standoff distance (P_s = 100%) of 15.9 m is obtained, which is 45% more relative to the natural rock value (11 m). For the RSP, the survival-incapacitation trendline is shown to follow much more closely to that of natural rock with a safe standoff distance of 12.6 m.

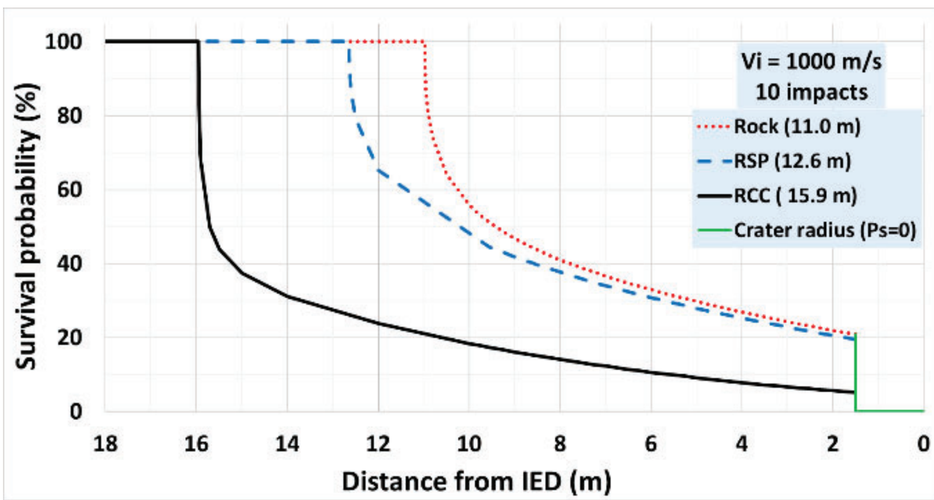

Figure 11. Estimated probability of survival vs standoff for 2 gr RCC, RSP and rock

5. CONCLUSIONS

Ballistic test results (V_{50} and overmatch) with the 2 gr Rock Simulating Projectile demonstrated that it is a suitable surrogate for soil ejecta while providing a conservative assessment of the ballistic resistance (i.e. lower V_{50}) of armour materials. The RSP can be launched in a stable manner without sabot at the low velocities required for assessing the ballistic resistance of Tier-1 personal armour systems. The results generated for the woven aramid fabric showed that the RSP V_{50} data did not follow the same scaling laws as the steel FSP and RCC data, especially for the one-ply system. Tests conducted with the 4 mm glass sphere on woven fabrics showed evidence of yarn pull-out as a dominating failure mechanism, which is different than the typical shear cutting seen with natural rocks and with the RSP. The 2 gr steel RCC was shown to be much more penetrating than the 2 gr Rock (lower V_{50} and ***APR***) leading to significant underestimation of the actual protection capability of armour systems. Additional laboratory tests (single and multi-hit) with the 2 gr RSP will be conducted to further confirm the observed trends and the scalability with the results obtained during full-scale buried IED trials. Future analyses are also planned for validating threshold and objective ballistic protection requirements (2, 6, 16 grain

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RSPs, and impact velocities) representing the lower and upper bounds of the buried IED threat severity (levels 1 and 2).

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