Impact of mechanical stress on ballistic performance of body armour materials

C. Boettger[1], M. Dombrowski [2], M. Fietkau[1], H. Knoester[3]

[1]Teijin Aramid GmbH, Kasinostrasse 19-21, 42103 Wuppertal, Germany
[2] Pro-Systems S.p.A., Via al Corbé 63/65, 22076 Mozzate, Italy
[3] Teijin Aramid BV, Tivolilaan 50, 6824 Arnhem, The Netherlands

Abstract. Ballistic resistant vests usually are used for a period of 5 – 10 years and in some cases even longer. It is of the utmost importance to the user that the vest, over the course of its wearable lifetime, offers reliable protection in accordance with the performance standard it had originally been designed and certified to.
With the introduction of the NIJ 0101.06 standard in the year 2008 a tumble test was instituted with the intention to provide some indication of the armor's ability to maintain ballistic performance after being exposed to conditions of heat, moisture and mechanical wear. This test requires the tumbling of bullet resistant vests for 10 days at a climate of 65°C and 80% RH, simulating mechanical stress potentially introduced to such vests during real use. While the protocol does not predict the service life of the vest nor does it simulate an exact period of time in the field, the belief is that if the sample armor can still stop a bullet after the tumble test, then the production armor *should* withstand normal use wear and tear and still be strong enough to protect the wearer.
Teijin Aramid utilizes the tumble test to investigate and compare the impact of mechanical stress at elevated temperature and humidity on various armor materials and panel constructions.
During a first series of baseline trials, monolithic ballistic panels were constructed from both woven and Uni-Directional (UD) fabrics made from Teijin Aramid's Twaron® para-aramid as well as several ballistic UDs made from Ultra-High Molecular Weight Polyethylene (UHMWPE). In a second series of tests, several hybrid panel constructions were made from a combination of woven Twaron® fabrics in conjunction with UHMWPE UD. All armor panels were subject to the tumble test in accordance with the NIJ 0101.06 standard. Ballistic testing of panels was then conducted with the 9mm DM41 in both "new" (un-tumbled) and post-tumbled conditions and analyzed utilizing logistic regression.
Test results observed by Teijin Aramid reveal statistically significant differences in tumbler (aging) resistance of the individual ballistic materials. The same holds true for the different hybrid constructions, even though the ratio of woven Twaron® fabric to UHMWPE-UD material content was held constant between them.
Details about the test method will be provided and all ballistic results generated are compared in graphical form using S-curves, followed by final conclusions.

1. BALLISTIC PERFORMANCE MEASUREMENT METHOD

During ballistic limit testing, test articles are repetitively subjected to projectiles in a range of impact velocities. This range is balanced in the sense that both complete and partial perforations are required. Generally, the objective is to measure a specific impact velocity, called V_{50}, for which the probability of observing a complete perforation is 50%. There are methods providing procedures for such testing including methodologies to calculate V_{50}. V_{50} is a good measure to enable calculation of the specific energy absorption, which allows comparison of the ballistic efficiency of different materials. V_{05} is a better indicator to assess the safety margin of body armour. It represents the impact velocity for which the probability of a complete perforation is 5%. We use the method of logistic regression to determine V_{50} and V_{05}, which boils down to applying linear regression to the logarithm of the odds of a complete perforation. The quality of the logistic model can be checked afterwards by a goodness-of-fit test (chapter 1.2), testing how well model predictions mirror observed data.

1.1 Logistic regression

The method of logistic regression allows estimation of the probability of complete perforation $p(v)$ for any impact velocity v. Another advantage is that logistic regression comes with instruments to determine confidence boundaries. By definition, $0 \le p(v) \le 1$, and $p(v)$ must have a sigmoidal, non-linear character. Therefore, applying logistic regression, the probability is linearized by transformation to the logit of the probability $\ln(p/1-p)$, which is unbounded to the positive and negative side. The logit is approximated by a straight line where impact velocity is the independent variable:

$$\ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 v, \quad \text{or: } p(v) = \frac{e^{\beta_0+\beta_1 v}}{1+e^{\beta_0+\beta_1 v}} \tag{1}$$

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The above, explicit solution for $p(v)$ is a sigmoid function which we henceforth denote as S-curve. Standard linear regression is not possible because, for individual observations, probability p takes on two values ($p = 0$ and $p = 1$) only. Estimation of the parameters β_0 and β_1 can be done by, for instance, maximum likelihood estimation. This method also renders the variances of the estimates (σ_0^2, σ_1^2) and their covariance (σ_{01}). The standard deviation σ of the estimate for the logit $\beta_0 + \beta_1 v$ itself can be expressed in terms of these variances and covariance:

$$\sigma = \sqrt{\sigma_0^2 + 2v\sigma_{01} + \sigma_1^2} \tag{2}$$

The true logit corresponding to velocity v is contained in the interval $\langle \beta_0 + \beta_1 v \pm z_{\alpha/2} \cdot \sigma \rangle$ with probability $1 - \alpha$ and $z_{\alpha/2}$ is the z-score defining how many standard deviations one has to be away from the center of the interval to have a probability of only $\alpha/2$ for the logit to be even further away from the mean. Since the sigmoid function is strictly increasing, the predicted $p(v)$ will be contained (again with probability $1 - \alpha$) within the boundaries:

$$p_{LB}(v) = \frac{e^{(\beta_0 + \beta_1 v - z_{\alpha/2} \cdot \sigma)}}{1 + e^{(\beta_0 + \beta_1 v - z_{\alpha/2} \cdot \sigma)}} < p(v) < \frac{e^{\left(\beta_0 + \beta_1 v + z_{\frac{\alpha}{2}} \cdot \sigma\right)}}{1 + e^{\left(\beta_0 + \beta_1 v + z_{\frac{\alpha}{2}} \cdot \sigma\right)}} = p_{UB}(v) \tag{3}$$

Functions $p_{LB}(v)$ and $p_{UB}(v)$ are chosen as confidence bounds of the S-curve. Figure 1 visualizes the S-curve of a ballistic armor, including its confidence bounds. Clearly, the uncertainty in V_{05} is larger compared to V_{50}. Meaningful estimation of V_{05} requires a large amount of measurements, particularly for impact velocities with low probability of complete perforation. Figure 1 also shows other characteristics of the ballistic test results:

VLCP the lowest velocity for which a complete perforation was observed
VHPP the highest impact velocity for a partial perforation was observed
ZMR Zone of Mixed Results ranging from VLCP to VHPP
velocity range where partial and complete perforations alternate

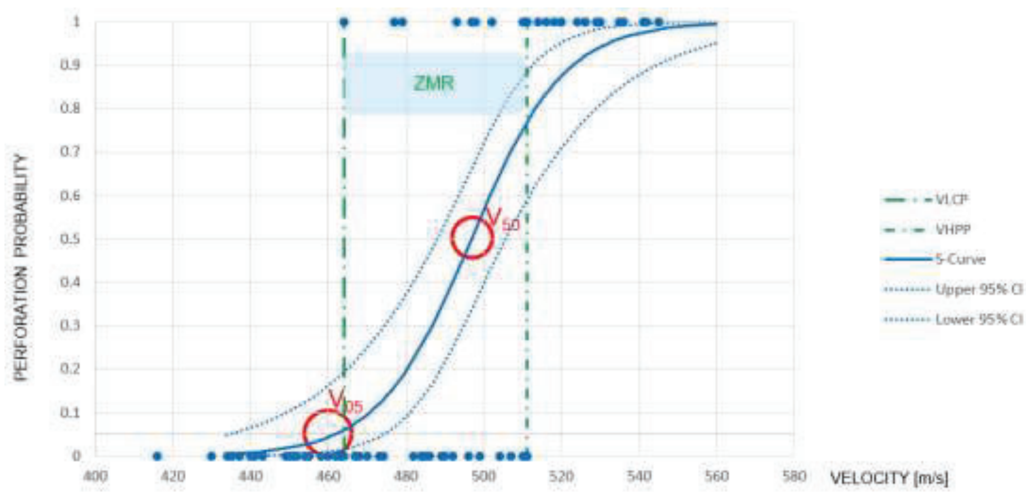

Figure 1. S-curve with 95% confidence intervals and ZMR

Ballistic articles with a steep S-curve, or narrow ZMR, are more desirable, as the confidence bounds for V_{50} and V_{05} will be relatively narrow and therefore the ballistic performance of the armor is well predictable. As can be seen from Figure 2, not just V_{50}, but also the slope of the S-curve determines the safety margin of an armour. While the V_{50} of the blue and yellow armour are the same, the slope of the yellow armour, due to a smaller Zone of Mixed Results (ZMR), is steeper, resulting in a substantially higher V_{05}. The figure also contains V_{ref} and V_{refmax} which illustrate the required and maximum test velocities specified in the official test standard (e.g. VPAM). The figure below illustrates the test velocities typically used for 9 mm DM41. While the yellow armour has a V_{05} substantially higher than

$V_{refmax,}$ the blue one has a V_{05} below V_{refmax}. Even so the V_{50} is similar, safety margin of the yellow armour is much higher compared to the blue armour.

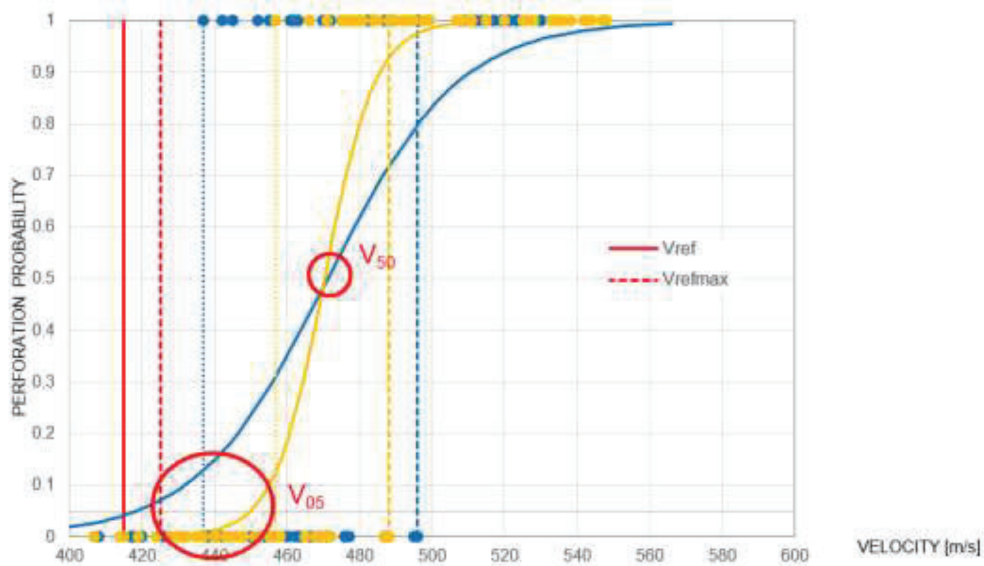

Figure 2. S-curve for two different sets of armour

1.2 Goodness-of-fit test

Standard linear regression minimizes the distance between model predictions and observations and further has the benefit that fit quality is easily visualized. Testing the quality of a logistic regression model is less trivial. Application of logistic regression anyway assumes that the probability of perforation as function of impact velocity is described by a point symmetric S-curve. If the physics of stopping bullets changes for high impact velocity, for instance due to bullet deformation, symmetry of the S-curve may be lost and hence the quality of logistic regression is impaired. In such case one could for example focus on experiments with low to moderate impact velocities only and still use logistic regression. Obviously, such model is then unreliable in predicting probability of perforation for high bullet velocity. Still, the V05 / V50 prediction capability of such a model can be fine. In a general sense, with no prior knowledge on the fit quality of the logistic regression model, the goodness-of-fit of the model can be tested. We apply the Hosmer-Lemeshow test, which was specially developed for this purpose. The expected probability of perforation for each observation is recorded. All observations are grouped in in a finite number of groups with respect to their expected probability of observation. Next, the expected number of observations per group is compared with the actual number of observations. A sum-of-squares test statistic then determines if the distance between 'actual' and 'expected' is small enough in order to accept the fit quality of the model. The logistic regression models in this paper were tested in this way. In all cases the fit quality of the models were found to be acceptable.

2. INFLUENCE OF MECHANICAL STRESS ON BALLISTIC PERFORMANCE OF TWARON® PARA- ARAMID AND UHMWPE

2.1 Tumbler test

Ballistic resistant vests usually are used for a period of 5 – 10 years and in some cases even longer. It is of the utmost importance to the user that the vest, over the course of its wearable lifetime, offers reliable protection in accordance with the performance standard it originally had been designed for and certified to. With the introduction of the NIJ 0101.06 standard [1] in 2008 a tumble test was instituted, with the intention to provide some indication of the armor's ability to maintain ballistic performance after being exposed to conditions of heat, moisture, and mechanical wear. According to this test standard, panels have to be conditioned for 10 days at 65 °C and 80 %RH while being tumbled. The tumbler simulates mechanical stress potentially introduced to ballistic vests during real use. At a tumbling frequency of 0.083 Hz, there are in total 72,000 revolutions during the conditioning period of 10 days. During this

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process the ballistic panel is protected by a heat-sealed pouch and an additional garment stitched around the edges. Figure 3 (right) shows how a panel, removed from its garment, looks like after being tumbled for 10 days. Tumbling typically introduces wrinkles and creases. Those can cause lower velocity perforations during ballistic testing, resulting in a flattening of the S-curve. As a consequence, V_{50} and V_{05} may decrease.

While the NIJ 0101.06 protocol does not predict the service life of the vest nor does it simulate an exact period of time in the field, it is expected that if the sample armor can still meet the requirements after the tumble test, then the production armor *should* withstand normal use wear and tear and still be strong enough to protect the wearer. Forster et al. [2] observed that the retained mechanical properties of yarn material after the NIJ 0101.06 conditioning protocol coincides with the retained mechanical properties of the worst performing fraction of yarn materials collected from field-worn armor. The incentive of this study is to better understand how conditioning affects the ballistic performance of woven fabric and UD made from Twaron® Para Aramid, as well as UDs made from UHMWPE.

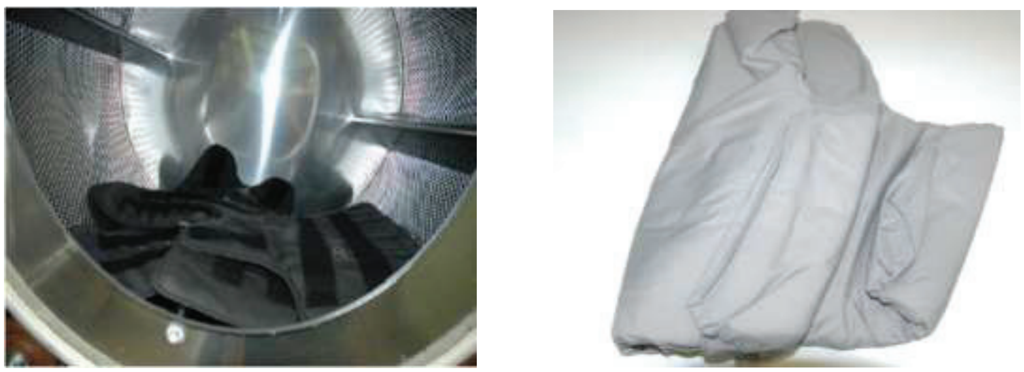

Figure 3. Tumble drum IAW NIJ 0101.06 (left) and tumbled armour panel (right) (reproduced from [3])

2.2 Test program

We tested 4 materials as depicted in the table below. This choice of materials allows a comparison between Twaron and UHMW-PE based UDs as well as a comparison between (Twaron) UD and woven fabrics.

Table 1. Constructions tested

Name	**AD [g/sqm]**	**Material construction**	**Panel construction**	**Test pack AD [kg/sqm]**
Twaron® CT612LS	125	Woven, plain	Quilted	4.5
Twaron® UD	112	2ply UD, no film	Corner tacked	4.2
UHMW-PE UD1*	-	2ply UD, with film	Corner tacked	3.9
UHMW-PE UD2*	-	2ply UD, with film	Corner tacked	3.9

*3rd generation high performance UHMW-PE UDs soured from 2 different manufacturers

2.3 Test procedure

Testing was done using new (as-manufactured) and conditioned ballistic panels. Conditioning was performed in accordance with the NIJ 0101.06 standard, at the Application Competence Center (ACC)

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of Teijin Aramid (Wuppertal, Germany). Ballistic testing was conducted at the ballistic shooting range of ACC, using 9 mm DM41 (steel jacketed round). The shooting pattern and sequence were in accordance with a Teijin Aramid method. At least 10 new and conditioned panels were tested per construction. Each panel was shot 8 times, resulting in at least 80 shots per set of samples. The panel size has been 40 x 40cm and minimum shot-to-shot distance was 90 mm. Analysis was done using logistic regression.

2.4. Test results

The logistic regression analysis provides us with estimates for V_{50} and V_{05} before and after conditioning for each material. See Table 2 and Table 3. As can be seen from Table 2, the V_{50} of Twaron® CT612LS woven fabric is not affected by conditioning. For Twaron UD, a small drop of about 5% in V_{50} was observed, whereas the effect on both UHMW-PE UDs is substantially greater (11 – 14% drop in V_{50}). The effect of tumbling on V_{05} is similar to what was found for V_{50}. While Twaron® CT612LS woven fabric does not show any change, V_{05} is substantially reduced for both UHMW-PE UDs.

Table 2. Effect of tumbling on the V_{50} of different materials

Name	V_{50new} [m/s]	V_{50cond} [m/s]	Δ [m/s]	Δ [%]
Twaron® CT612LS *woven fabric*	470.3	469.2	-1.1	-0.2%
Twaron® UD	514.2	490.8	-23.4	-4.6%
UHMW-PE UD1	566.5	484.8	-81.7	-14.4%
UHMW-PE UD2	567.5	505.6	-61.9	-10.9%

Table 3. Effect of tumbling on the V_{05} of different materials

Name	V_{05new} [m/s]	V_{05cond} [m/s]	Δ [m/s]	Δ [%]
Twaron® CT612LS woven fabric	449.8	450.0	0.2	0.0%
Twaron® UD	480.1	438.0	-42.1	-8.8%
UHMW-PE UD1	516.8	327.1	-189.7	-36.7%
UHMW-PE UD2	507.5	371.8	-135.7	-26.7%

Figure 4 illustrates the S-curves for the new and conditioned materials. Here solid lines are for the new materials and the dashed lines for the conditioned materials.

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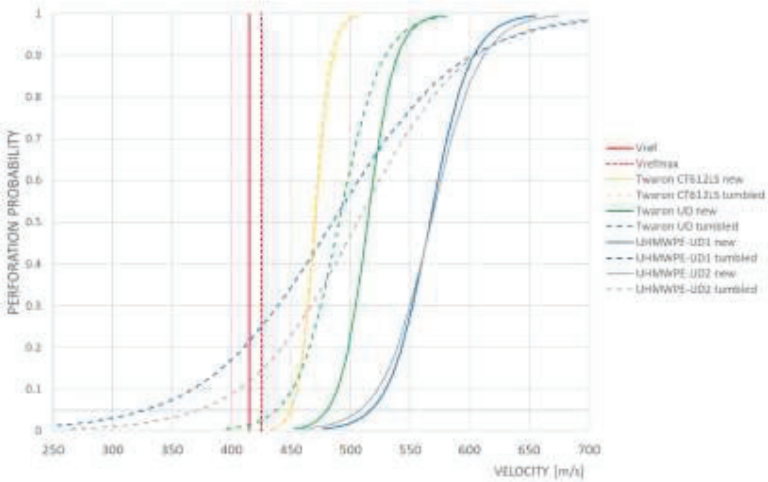

Figure 4. S-curves for Twaron® CT612LS woven fabric, Twaron® UD and UHMW-PE UDs before and after tumbling

The transformation of the S-curves of the tested UHMW-PE UDs after conditioning is eye-catching. Not only do they shift to the left, the flattening is also substantial. This flattening explains that V_{05} is stronger reduced than V_{50}. Twaron® UD also shifts and flattens after conditioning, but these effects are rather mild. Reduction of V_{05} and V_{50} remain below 10 %. It is striking that the S-curve of the Twaron woven material after conditioning is indistinguishable from the S-curve of the new material.

The observed performance change of the UHMW-PE UDs after the NIJ 0101.06 conditioning is statistically significant. Although this inference is already clear from Figure 4, addition of confidence bounds in Figure 5 provides hard evidence. To avoid confusion, we only visualized Twaron® CT612LS and UHMW-PE UD1 with their confidence bounds in Figure 5.

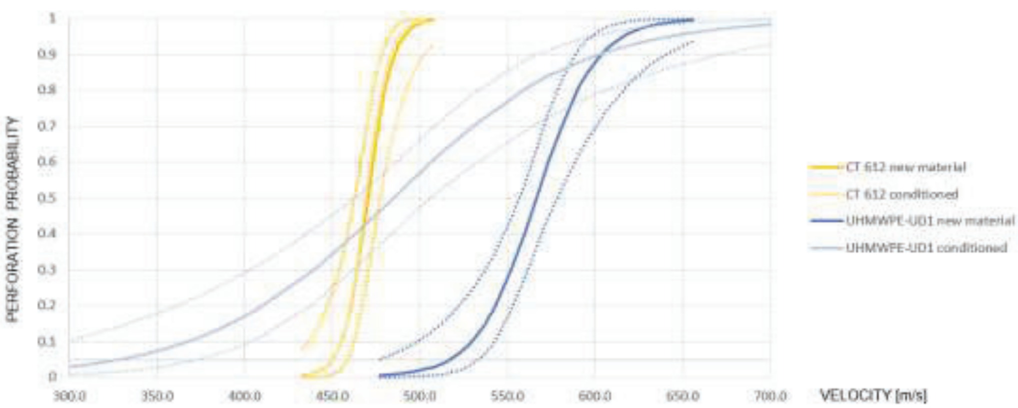

Figure 5. S-curves for Twaron® CT612LS *woven fabric,* and UHMW-PE UD1 before and after tumbling also including confidence boundaries.

3. INFLUENCE OF MECHANICAL STRESS ON BALLISTIC PERFORMANCE OF HYBRIDS MADE FROM TWARON® WOVEN FABRIC AND UHMWPE UD

Both para-aramid woven fabric and UD, as well as UHMWPE UDs, have their pros and cons. While UHMW-PE UD often exhibits higher V_{50} against bullets compared to woven Aramids, the S-curve of woven Aramid is steeper and less affected by mechanical stress/tumbling. The intention of the hybrid testing was to learn whether hybridizing woven Twaron® with UHMW-PE UD could result in constructions having high ballistic performance, combined with good resistance against mechanical stress.

3.1 Test program

We constructed 3 different hybrids (Table 5) from 2 materials (Table 4). All three hybrids have the same weight per meter squared.

Table 4. Materials used for hybrid testing

Name	**AD [g/sqm]**	**Material construction**	**Panel construction**	**Proportion [kg/sqm]**
Twaron® CT612LS	125	Woven, plain	Quilted	2.25
UHMW-PE UD2	-	2ply UD, with film	Corner tacked	2.02

Table 5. Constructions used for hybrid testing
Conditioning and testing in accordance with paragraph 2.3.

Component 1	**Component 2**	**Component 3**	**Test pack AD [kg/sqm]**
strike face	***back face (body side)***		
UHMW-PE-UD2	Twaron® CT612LS		4.27
Twaron® CT612LS	UHMW-PE-UD2	Twaron® CT612LS	4.27
Twaron® CT612LS	UHMW-PE-UD2		4.27

3.2 Test results for hybrid constructions

The results in Figure 6 show that the order of Twaron® and UHMW-PE UD in hybrids seems to have a substantial impact on their resistance against mechanical stress. The construction using Twaron® CT612LS woven fabric at the strike face and UHMW-PE UD at the back face resulted in the highest V_{50}, steepest S-curve and highest V_{05}, both before and after tumbling. The results suggest that by a smart combination of Aramid and UHMW-PE UD materials, ballistic constructions can be well optimized.

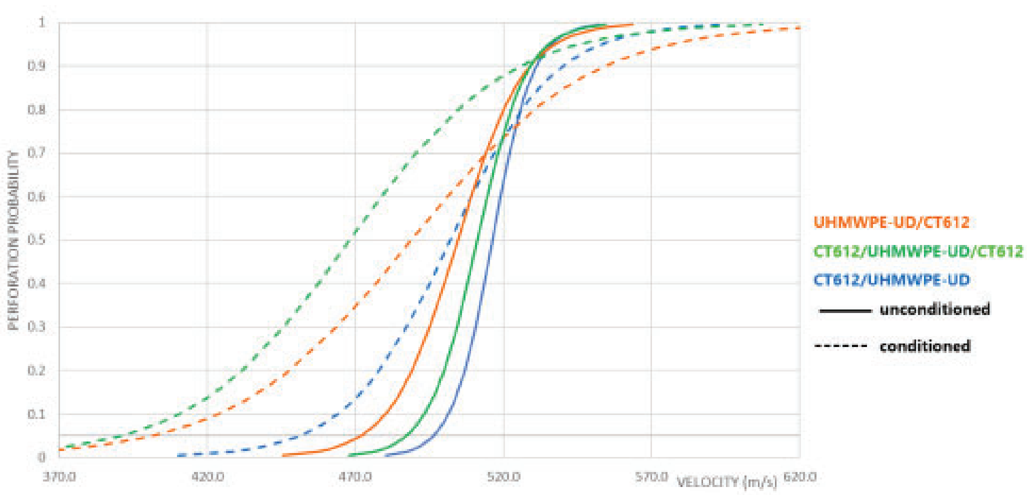

Figure 6. S-curves for various Twaron® CT612LS/UHMW-PE UD hybrids before and after tumbling

4. CONCLUSIONS

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We showed that the tested woven fabric and UD made from Twaron® offer high resistance against tumbling/mechanical stress. On the contrary, the tested UHMWPE UDs are significantly affected after tumbling. Smart hybridizing of woven Twaron® fabric with UHMWPE UD enhances ballistic performance and improves resistance against tumbling. The improvement heavily depends on the construction and the way the materials are combined with each other.

References

[1] Ballistic Resistance of Body Armor, NIJ Standard-0101.06, NCJ 223054, July 2008

[2] Forster A.L., Leber D.D., Engelbrecht-Wiggans A., Landais V.,Chang A., Guigues E., Messin G., Riley M.A., J Res Natl Inst Stan, 2020, 125:125026

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