

Ballistic Response of Hard and Soft Panels Including Innegra™ S Fibers

ABSTRACT: Innegra S high modulus polypropylene (HMPP) fibers were spun, twisted, and woven into fabric appropriate for armor. Hard panels were constructed using 100% Innegra S fabrics and aramid fabrics. Panels were also constructed of hybrid panels containing approximately 25, 50, 75% Innegra S and aramid. These panels were tested for ballistic V_{50} performance against 0.44 caliber semi-wadcutter projectiles. Hard panels were constructed using 100% Innegra S fabrics, aramid fabrics and also of hybrids containing various percentages of aramid and Innegra S fabrics. All panels utilized a polyolefin film as a binder matrix. In the hard panels, all versions of hybrids performed identically to the 100% aramid panel within the measurement accuracy.

Soft panels were constructed using 100% Innegra S fabrics, ballistic nylon fabrics, and aramid fabrics. Hybrid panels were also constructed containing approximately 50% Innegra S/50% aramid fabrics. All panels were tested for ballistic performance against 9mm full metal jacket projectiles measuring V_{50} . The lowest performing fabric was ballistic nylon. The aramid was the highest performing panel. The V_{50} of the hybrid panels of Innegra S and aramid were 97% of the V_{50} of the aramid panels at approximately the same panel areal weight.

Introduction

With the introduction of Kevlar® came the advent of soft armor to protect soldiers and law enforcement officials.¹ Soft armor has saved thousands of lives, and with the rise of global uncertainty, the use of soft and hard armor is increasing. With this increase, the cost of this armor to government and private entities has also increased. The total consumption of fibers in armor has risen to over \$1 billion/year.²

Hard Armor

Methods

To test performance in hard armor, Innegra S fiber was made using 2800 denier and 225 filaments. The yarn was twisted at approximately 1 twist/inch and woven into plain weave fabric of 15 picks per inch and ~12.5 ounces/square yard. The fabric was then compiled into panels by layering with a polyolefin film (0.003") and then compressed at 100 psi and 140° Celsius for 30 minutes, resulting in panels with approximately 12% resin content. Additionally, aramid panels made from Kevlar 29 yarn of 3000 denier in style 745, with 17 picks per inch weighing 13 ounces/square yard, and hybrid panels were made, similarly, by combining layers of Innegra fabric with layers of aramid fabric.³

¹ *High Performance Fibers*, JEW Hearle, Woodhead Publishing Limited, Cambridge, 2001

² *Global Composites Market 2004-2010: Materials, Market and Technologies*, E-Composites, Inc., 2005.

³ The hybrid panels were made from Sealed Air VP306K film (0.003")

Results

The results from testing (using 0.44 magnum SWC projectiles) of hard panels are shown in Table 1 and Figure 1, below.

Material	# layers	Construction	Areal Density (lbs/sq ft)	V50 (ft/sec)
Aramid	14	Layered	1.5	1469
Aramid– Innegra hybrid-75%	11/4	Aramid behind Innegra	1.5	1477
Aramid – Innegra hybrid-50%	8/7	Aramid behind Innegra	1.5	1469
Aramid – Innegra hybrid-25%	4/11	Aramid behind Innegra	1.5	1498
Innegra	15	Layered	1.5	1258 ⁴

Table 1. V₅₀ ballistics results for a 0.44 magnum SWC projectile on aramid and Innegra hard panels.

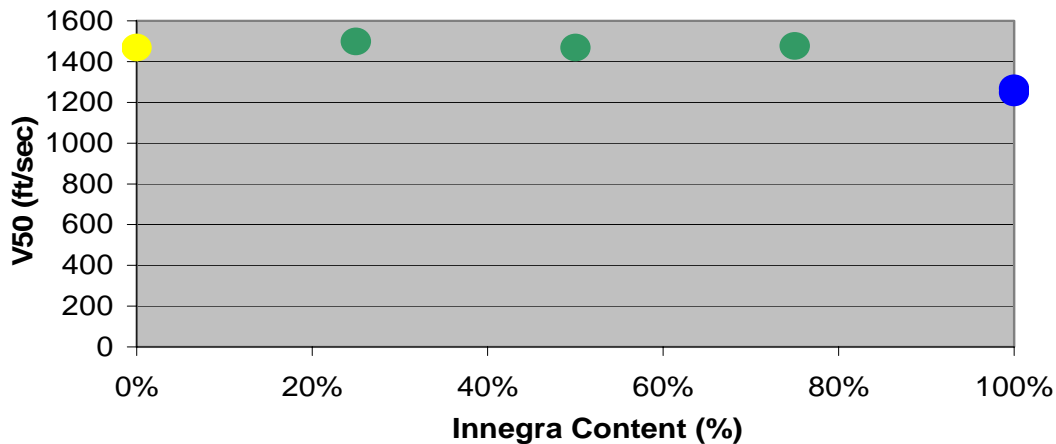


Figure 1. Aramid – Innegra ballistic performance of hard panels as a function of the % of Innegra included in the panel.

Soft Armor

Methods

To test performance of Innegra fiber in soft armor applications, we utilized 625 denier Innegra S yarn, which has 50 filaments each of 12.5 denier per filament. These fibers were twisted at ~1 twist/inch and woven in a plain weave at 26 picks per inch, leaving a fabric which is 4.4 ounces/square yard. The average denier, tenacity, elongation and initial modulus of the yarns, before and after weaving, are shown below.

⁴ Average of two samples with V₅₀ of 1247 and 1268.

Property	Units	Fiber	Warp	Weft
Denier	denier	634		
Tenacity	grams/denier	7.44	8.02	7.70
Elongation	%	6.97	8.94	7.24
Modulus	grams/denier	151	128	149

Table 2. Properties of Innegra fiber before weaving, and after twisting and weaving.

Property	Units	Kevlar KM2 ⁵	Kevlar KM2 ⁶	Ballistic Nylon ⁵	Ballistic Nylon ⁶
Denier	denier	600	617/618		2225
Tenacity	grams/denier	26	16.2/18.8	9	7.5/8.3
Elongation	%	4	5.4/5.0	18	24/23
Modulus	grams/denier	600	608/580	60	57/65

Table 3. Properties of aramid and ballistic nylon fiber and properties of yarn removed from fabrics.

The fabrics were then compiled into soft ballistic panels by layering, edge-sewing and then sewing in an “x” pattern from corner to corner. For comparison and for hybrid panels, two other fabrics were used. One is style JPS Composite Materials style 706 made with 600 denier Kevlar KM2 yarn (34 ends/inch, 34 picks/inch). The other fabric was style 1056 ballistic nylon (19 ounces/yd²). The properties of Kevlar KM2 and ballistic nylon are shown above in Table 3, along with the fiber properties of fibers removed from the woven fabric. The panels were tested for V₅₀ ballistic limit against a full metal jacket 9mm projectile by United States Test Laboratory⁷ according to Mil-Std-662F.

Results

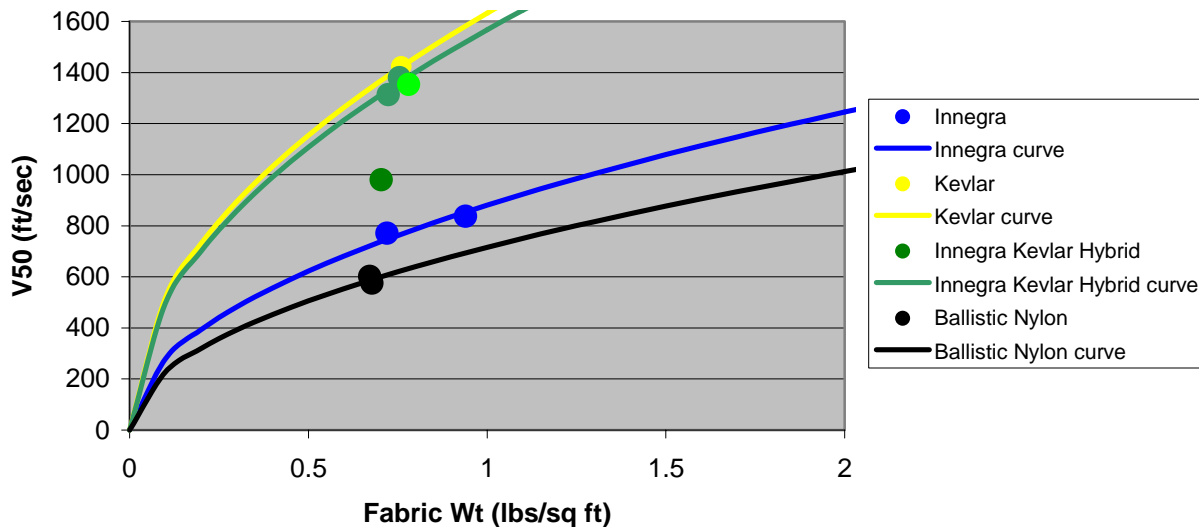


Figure 2. V₅₀ ballistics results for a 9mm FMJ projectile on various aramid, nylon and Innegra panels.

⁵ *Lightweight Ballistic Composites: Military and Law-Enforcement Applications*, A. Bhatnagar, Woodhead Publishing Limited, Cambridge, 2006, pp 338.

⁶ Fibers removed from tested fabrics; results reported warp “/” weft.

⁷ United States Testing Laboratory, 7447 W 33rd St N, Wichita, KS 67205, (316) 832-1600.

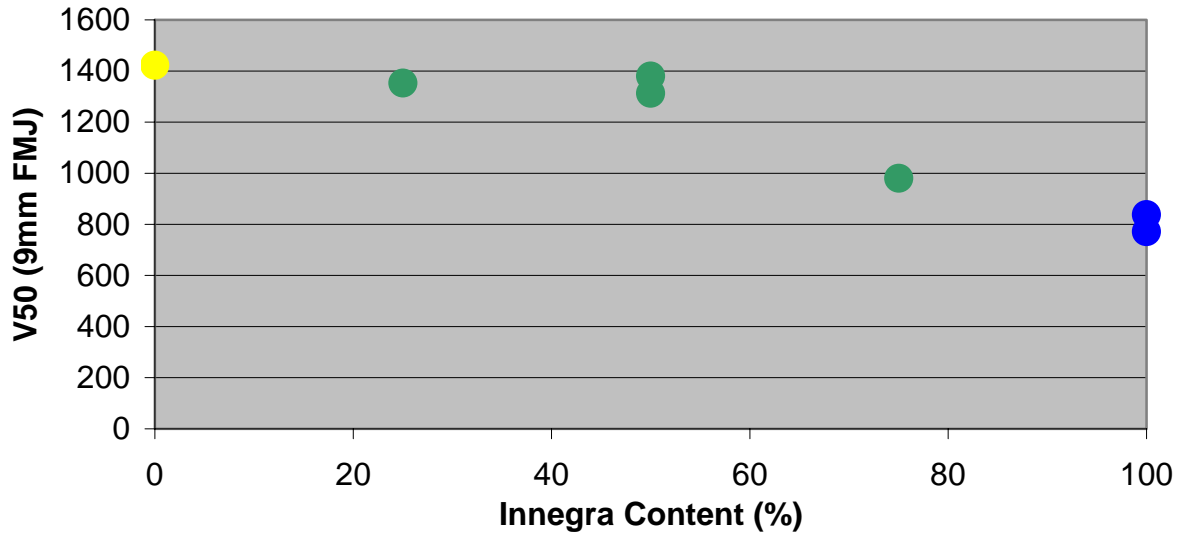


Figure 3. Ballistic limit V_{50} versus 9mm projectiles for four panels.

Analysis

The simplest model of ballistic performance relates the energy absorbed as proportional to the panel weight. Since the energy absorbed $E = m V^2$, the V_{50} which is the ballistic limit is proportional to the square root of the fabric wt. The curves plotted in Figure 2 reflect this estimation. Other models predict different exponents.⁸ Experiments also provide for different exponents which can depend on fabric construction and material response curves.⁹

Discussion

Hard Panels: Innegra S fabrics, alone, provide 86% of the V_{50} performance of similarly constructed aramid fabrics. In hybrid panels, the performance is statistically indistinguishable from the 100% aramid panels with up to 75% Innegra S in the panels, providing a significant cost savings. Again, these initial results have not been optimized for fabric construction, twist level, resin content or type, or other variables. With Innegra costing between 1/4 and 1/3 of the cost of aramid fibers, all of these configurations represent significant cost savings.

Soft Panels: Innegra S fabrics provide significant ballistic protection on their own, comparing favorably to ballistic nylon. However, in hybrid panels with aramid fabrics, they provide the opportunity for significant cost savings and fabric design opportunities over panels made with 100% aramid. Further research will test this performance at different weights and different ratios of Innegra S to aramid. It is also possible that this result is not limited to aramid fabrics, but could be repeated with ultra-high-molecular-weight polyethylene (UHMWPE), such as Dyneema® or Spectra®.

⁸ *Lightweight Ballistic Composites: Military and Law-Enforcement Applications*, A. Bhatnagar, Woodhead Publishing Limited, Cambridge, 2006, pp 229-35.

⁹ *Ibid*, pp 210-29.