Ballistic Response of Soft Panels Including Innegra™ S Fibers

ABSTRACT: Innegra S high modulus polypropylene (HMPP) fibers were spun, twisted, and woven into fabric appropriate for soft armor. Soft panels were constructed of 100% Innegra S fabrics, of ballistic nylon fabrics, and of Kevlar KM fabrics. Panels were also constructed of hybrid panels containing approximately 50% Innegra S and 50% Kevlar KM. All panels were tested for ballistic performance against 9mm full metal jacket projectiles, measuring V50. The lowest performing fabric was ballistic nylon. The Kevlar KM was the highest performing panel. The V50 of the hybrid panels of Innegra S and Kevlar were 97% of the V50 of the Kevlar KM 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]

Methods

To test performance of Innegra fiber in soft armor applications, we spun 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.

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 1. Properties of Innegra fiber before weaving, and after twisting and weaving.

Property	**Units**	**Kevlar KM2[3]**	**Kevlar KM2[4]**	**Ballistic Nylon[3]**	**Ballistic Nylon***
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 2. Properties of Kevlar KM2 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/yd^2). The properties of Kevlar KM2 and ballistic nylon are shown below in Table 2, 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 Laboratory[5] according to Mil-Std-662F. The panels constructed were:

[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] *Lightweight Ballistic Composites: Military and Law-Enforcement Applications*, A. Bhatnagar, Woodhead Publishing Limited, Cambridge, 2006, pp 338.
[4] Fibers removed from tested fabrics; results reported warp "/" weft.
[5] United States Testing Laboratory, 7447 W 33rd St N, Wichita, KS 67205, (316) 832-1600.

Material	# layers	Construction	Areal Density (lbs/sq ft)	V50 (ft/sec)
Kevlar	20	Layered	0.76	1423
Nylon	8	Layered	0.68	575
Innegra	23	Layered	0.72	771
Innegra	30	Layered	0.94	837
Kevlar – Innegra hybrid	22	Kevlar behind Innegra	0.76	1380
Kevlar – Innegra hybrid	22	Alternating layers	0.74	1313

Results

The results of ballistic testing are shown in Figure 1, below.

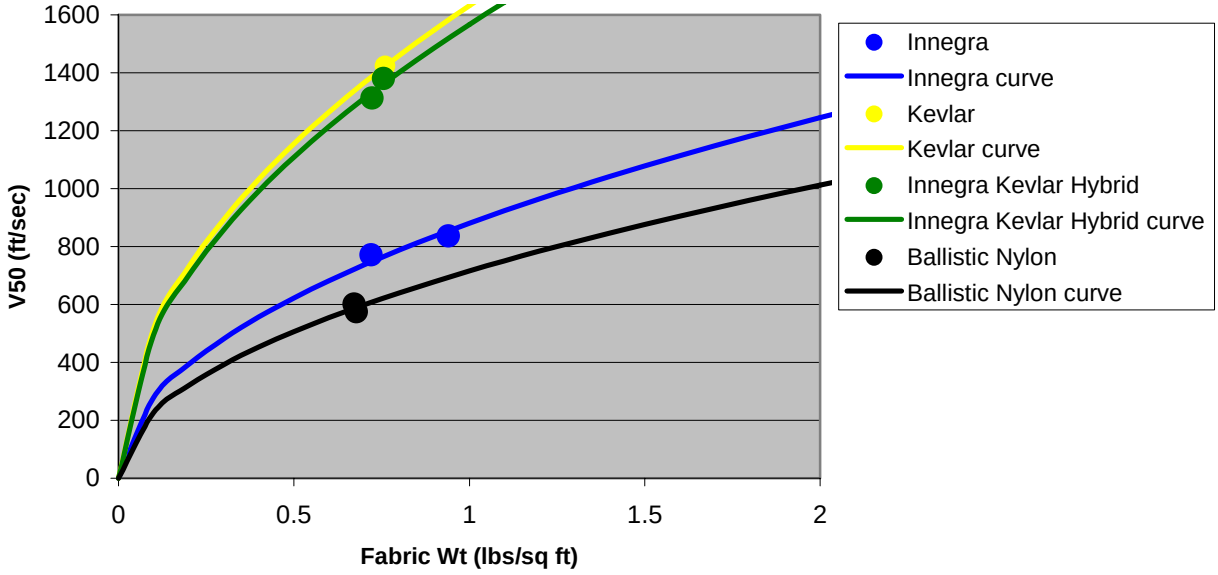

Figure 1. Ballistic limit V50 versus 9mm projectiles for four panels.

Analysis

The most simple model of ballistic performance relates the energy absorbed as proportional to the panel weight. Since the energy absorbed $E = m V^2$, the V50 which is the ballistic limit is proportional to the square root of the fabric wt. The curves plotted in Figure 1 reflect this estimation. Other models predict different exponents.[6] Experiments also provide for different exponents which can depend on fabric construction and material response curves.[7]

Discussion

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. Additionally, similar results may be obtainable with hard panels made from aramid, UHMWPE, or S-glass.

[6] *Lightweight Ballistic Composites: Military and Law-Enforcement Applications*, A. Bhatnagar, Woodhead Publishing Limited, Cambridge, 2006, pp 229-35.
[7] Ibid, pp 210-29.