Journal of Macromolecular Science, Part A
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597274

Construction and Properties of Fabrics of High-Modulus Organic Fibers Useful for Composite Reinforcing

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To cite this Article Lilyquist, M. R. , Debrunner, R. E. and Fincke, J. K.(1973) 'Construction and Properties of Fabrics of High-Modulus Organic Fibers Useful for Composite Reinforcing', Journal of Macromolecular Science, Part A, 7: 1, 203 — 227

To link to this Article: DOI: 10.1080/00222337308061139

URL: http://dx.doi.org/10.1080/00222337308061139

J. MACROMOL. SCI.—CHEM., A7(1), pp. 203-227 (1973)

Construction and Properties of Fabrics of High-Modulus Organic Fibers Useful for Composite Reinforcing

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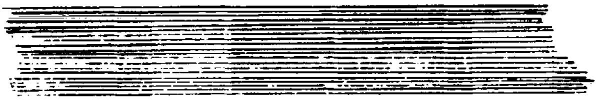
ABSTRACT

Various fabric constructions for composite reinforcement were made from one particular fiber of the X-500 class of high-modulus organic fibers. This particular X-500 fiber (PABH-T) was a polyamide-hydrazide based on p-aminobenzhydrazide and terephthaloyl chloride. Three types of fiber yarns spanning a wide range of achievable tensile properties of the PABH-T X-500 fiber subclass were prepared: Type I, $T/E/M_i$ = 12 (g/den)/2.5 (%)/650 (g/den); Type II, $T/E/M_i$ = 8/6/350; Type III, $T/E/M_i$ = 6/15/250. The effects of yarn denier, twist, sizing, and scouring on the tensile properties of the yarn were evaluated. Selected yarns were woven into fabrics using conventional textile looms. Fabric constructions were designed to provide fiber volumes equivalent to those of nylon and glass fabrics commonly used in reinforced composites. Physical properties of the woven fabrics compared favorably with those of the conventional reinforcing fabrics prepared from nylon 66 and glass. Fabric/resin composite test specimen were prepared and their mechanical properties evaluated. A comparison was made with the mechanical properties of glass fabric/resin composite laminates. The low specific gravity of X-500 fibers (1.45 g/cm^2 in this instance) in comparison to glass fiber (2.55) makes it possible to achieve high strength and high modulus composite structures of very light weight using X-500 type fabric reinforcing.

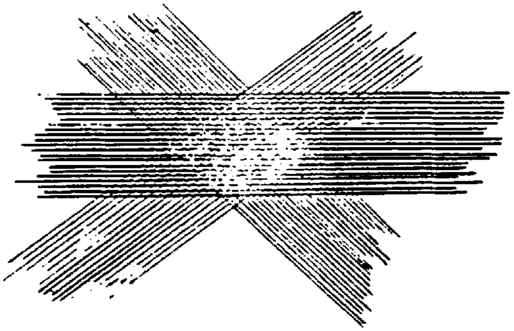
INTRODUCTION

Fiber and fabric reinforced composite structures utilizing high-modulus reinforcing fibers have become commonplace. They developed as a natural extension of technologies of fiber glass production and improved synthetic resins. Demands for higher performance materials are coming from almost every industry supplying materials to meet industrial, military, and consumer needs. High-performance composite materials are being evaluated in end-use applications ranging from aerospace vehicles to automobile tires and golf clubs. Each end-use demands a particular combination of performance related properties and a particular mode of reinforcing. Figure 1 illustrates a few of the more widely used modes of reinforcing with fiber yarns and fabrics. Filament yarns can be formed into unidirectional tapes and broad goods which can be layered to give either unidirectionally reinforced composite laminates or multidirectional reinforcement. Filament yarns can also be woven into fabrics to give bidirectional reinforcing within a single ply.

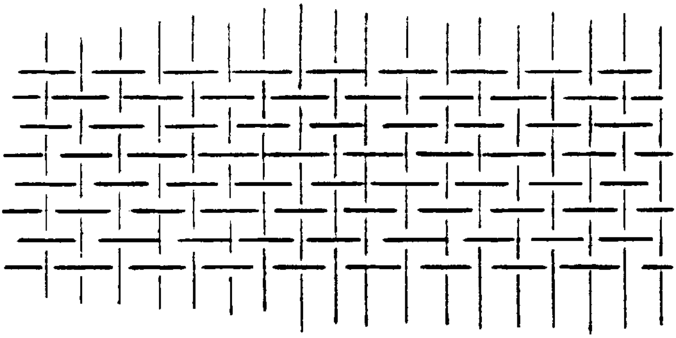
Recently, workers at Monsanto Co's Chemstrand Research Center discovered a class of organic fibers that can be made with specific tensile moduli more than twice that of E-glass [1-3]. Within Monsanto, such fibers are referred to generically as the X-500 class of fibers. The unique wide range of achievable tensile properties of the X-500 class of high-modulus organic fibers makes them attractive candidates to bridge the performance gap between the high-modulus, high-strength properties of glass and the inorganic high-performance fibers on the one hand, and the toughness and impact resistance of nylon and polyester fibers on the other hand. One subclass of the X-500 class of fibers, those



Unidirectional Reinforcing by Tapes or Filament Winding



Multidirectional Reinforcing by Cross-Plies



Bidirectional Reinforcing by Woven Fabric

FIG. 1. Modes of fiber reinforcing.

based on p-aminobenzhydrazide (PABH) and terephthalic acid (TA) were evaluated rather extensively. Those X-500 class polyamide-hydrazide fibers derived from PABH and TA were coded PABH-T fibers. Figure 2 shows the specific strength-specific modulus relationship (properties normalized for weight) of a low elongation

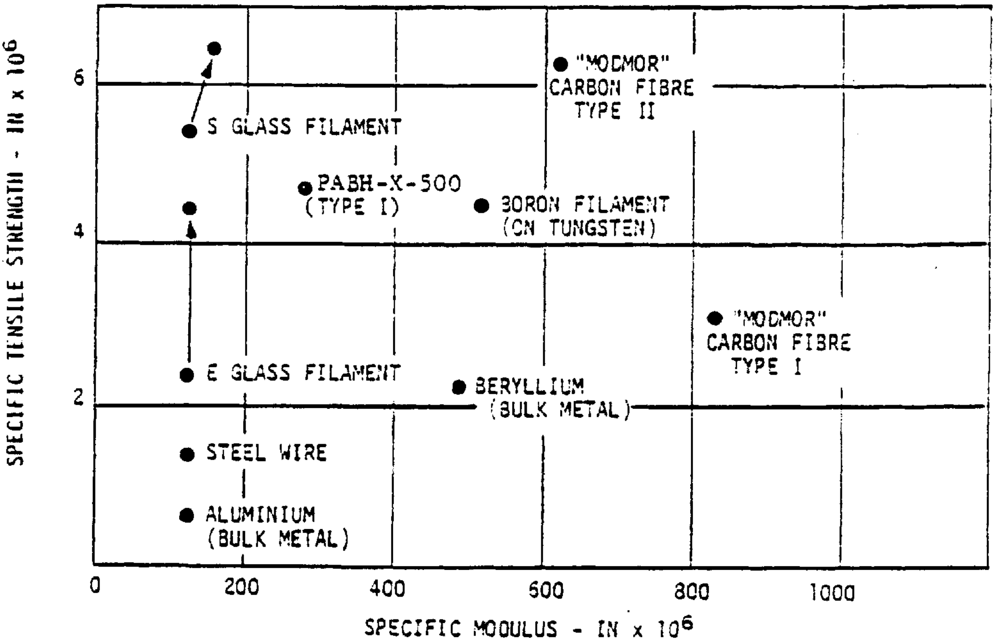


FIG. 2. Specific properties of filament materials.

variant of PABH-T fiber and a number of the high-modulus inorganic materials [4]. It is notable that the organic PABH-T X-500 fiber ranks among the inorganics in specific strength and is exceeded in specific modulus only by graphite carbon fibers, boron, and beryllium metals. The latter two do not form continuous fibers in their own right. Comparative tensile properties of the fibers shown in Fig. 2 are given in Table 1 [4]. The low densities of the PABH-T and carbon fibers, in comparison to those of glass and the other inorganic materials, contribute to their high ranking. This also makes it possible to produce more rigid composites at the same fiber loading or permits lower fiber loading to produce a composite of the same rigidity of glass. It is also of interest to compare the modulus-to-strength ratios for three types of PABH-T X-500 fibers with values of other frequently used reinforcing fibers including textile materials such as nylon and polyester. These data are given in Table 2. The very high ratios shown for the PABH-T subclass of X-500 fibers in comparison to those of textile-type organic fibers, and even

TABLE 1. Typical Properties of Filamentary Materials[a]

Material	Specific modulus[b] (in. × 10^6)	Specific tensile strength (in. × 10^6)	Filament diameter (in. × 10^3)	Filament diameter (μ)	Density (lb/in.^{3})	Young's modulus [lb/(in.^{2} × 10^6)]	Ultimate tensile strength [lb/(in.^{2} × 10^3)]
MODMOR Type I High Modulus	760-900	2.8-4.1	0.3	7.5	0.072	55-65	200-300
MODMOR Type II High Strength	560-710	5.6-7.1	0.3	7.5	0.063	35-45	350-450
PABH-T X-500	263	4.8	1.0	25	0.053	15	250-300
Steel (drawn wire)	104	1.4-2.1	3.0	75	0.280	30	400-600
E-Glass	104	2.7-4.5	0.2-0.4	5-10	0.092	10	250-450
S-Glass	104-140	5.5	0.2-0.4	5-10	0.092	10	500-650
Boron	530	5.3	4.0	100	0.095	50	500
Aluminum[c]	102	0.72	-	-	0.097	10	70
Beryllium[c]	470	2.3	-	-	0.066	45	150

[a] Morganite Research and Development Ltd.

[b] Specific modulus is defined as Young's modulus/density.

[c] Aluminum and beryllium figures are for bulk material.

TABLE 2. Stiffness-to-Strength Ratios of Reinforcing Fibers

	Modulus (gpd)	Tenacity (gpd)	Ratio
Type I PABH-T X-500 (2.5% elongation)	630	11.5	55
Type II PABH-T X-500 (5% elongation)	320	7.6	42
Type III PABH-T X-500 (20% elongation)	180	5.0	36
Nylon	50	9.0	5.5
Polyester	100	8.0	12.5
Glass	~350	~15	~23

to that of glass, are important to the engineer designing rigid reinforced structures. A few of the more important advantages of the X-500 class fibers for composite reinforcing are summarized in Table 3 [5]. The remainder of this paper deals with the construction and evaluation of the PABH-T subclass of X-500 class yarns and fabrics for composite reinforcing.

TABLE 3. Advantages of Organic (X-500 Class) High Modulus Fibers for Reinforcing

1. Generally high abrasion resistance.
2. Low moisture sensitivity.
3. Compatibility with organic polymer resins.
4. Similar thermal expansion.
5. Low density, high strength and stiffness-to-weight ratios.
6. Generally good electrical properties for nonconducting uses.

DISCUSSION OF RESULTS

Yarn Preparation

The continuous filament PABH-T X-500 yarns were intentionally prepared to span the range of tensile properties from glass to the industrial textile materials. However, the modulus values of all the types of PABH-T fiber were substantially above those of the textile-type materials [5]. Thus a limited evaluation of yarn twist level was undertaken for each type of PABH-T fiber in order to achieve the maximum in fabric properties. Yarn twist is highly desirable for the preparation of woven fabrics. It aids in handling of yarns during the weaving process without excessive damage. It also affords a means of holding the individual continuous filaments together in the yarn bundles, so that each filament makes its maximum contribution to the properties of the bundle. Thus twisted yarns generally have higher tensile strengths than do untwisted yarn. However, excessive twist can create shear strains within the yarn filaments so as to reduce the yarn strength and elongation. Excessive twist also increases the filament-to-filament friction within the yarn bundle and can result in damage by abrasive action.

Fabrics used as reinforcement in resin composites are generally rigidized by the resin, so that little movement of filaments or yarn bundles can occur once the composite is fabricated. For such uses, only a minimal twist is given to the weaving yarns; and in some cases, untwisted roving is used. The low twist assures more uniform and complete penetration of the resin into the fabric structure and reduces the formation of voids within the composite structure. Thus only low twist levels were considered in our study. Tensile property data as a function of twist level for the three types of PABH-T X-500 class yarns studied are given in Table 4. These yarns are nominal 1050 den having 100-200 filaments/yarn. The filaments ranged in denier from 5 to 10 and in diameter from 0.7 to 1.5 mils. The maximum twist applied was 4 tpi (turns per inch). At this low level of twist, only small differences in tensile properties are seen. Type I yarn at 1.0 tpi, Type II yarn at 2.0 tpi, and Type III yarn at 4.0 tpi were used to evaluate PABH-T fibers in comparison with glass and nylon for antiballistic components. The 1050 yarn denier corresponds to that used in the preparation of standard nylon ballistic fabric [6]. A sizing coating is generally applied to warp yarns to protect them from abrasive action during the weaving process. A standard

TABLE 4. Effect of Twist on Tensile Properties of PABH-T X-500[a,b,c]

	Tenacity (gpd)	Elongation (%)	Modulus (gpd)
Type I Yarns[d]			
0 twist	8.9	2.0	646
0.8 tpi	11.7	2.4	634
1.0 tpi	10.4	1.9	665
Type II Yarns[e]			
0 twist	7.6	4.4	343
2 tpi	7.7	4.5	335
3 tpi	7.5	4.4	314
4 tpi	7.4	4.5	303
Type III Yarns[f]			
0 twist	6.2	14.5	213
4 tpi	6.2	15.5	208

[a] All yarns are nominal 1050 total denier, 5-10 dpf.
[b] All twists are in Z direction.
[c] Instron tester, average of 20 breaks, 10 in. gauge length.
[d] Strain rate: 5% extension/min.
[e] Strain rate: 10% extension/min.
[f] Strain rate: 20% extension/min.

textile size of polyacrylic acid was added to the 1050 den yarns of Types I, II, and III. This sizing was removable by either neutral detergent in hot water (Scour A) or by TSPP (tetrasodium pyrophosphate) in hot water (Scour B). Very little loss in fiber tensile properties was noted after scouring with either formulation. The data are given in Table 5.

Fabric Weaving

The choice of fabric weave for reinforced composite laminates depends to a large extent on the requirements of the particular

TABLE 5. Physical Properties of Sized and Scoured PABH-T X-500 Warp Yarns

Property	Yarn type I	Yarn type II	Yarn type III
Twist (tpi)	1.0	2.0	3.8
Denier (original yarn)	1050	1050	1050
Sized Yarns[a]			
Tenacity (gpd)	11.2	7.3	5.2
Elongation (%)	3.0	5.0	16
Modulus (gpd)	532	308	161
Scour A[b]			
Tenacity (gpd)	10.5	6.7	5.0
Elongation (%)	3.0	5.0	14
Modulus (gpd)	550	257	157
Scour B[c]			
Tenacity (gpd)	10.9	6.8	4.8
Elongation (%)	3.0	5.0	15
Modulus (gpd)	591	240	142

[a] Sizing formulation: 5 gal orthocryl (polyacrylic acid), 25% solids, 25 gal water, overwax with Syncote A-30.

[b] Scour A formulation: 1 g/liter Triton X-100, 180°F for 20 min in lab ware, dry at 225-250°F.

[c] Scour B formulation: 2 g/liter TSPP (tetrasodium pyrophosphate), 1/2 g/liter Triton X-100, neutralize to pH 9.5, 180°F for 20 min in lab ware, rinse to pH 7, dry at 225-250°F.

end-use application. The satin weaves have been used extensively in the reinforced plastics field because they are pliable and conform readily to contoured planes. The 8 Harness Satin weave (Fig. 3) is among the most pliable of the satins and it can be woven with more threads per inch to achieve a high density of fiber packing. It is used in many aircraft and missile applications. J. P. Stevens' fiber glass fabric Style 7581, an improved modification of the widely used Style 181, was selected as one standard of comparison

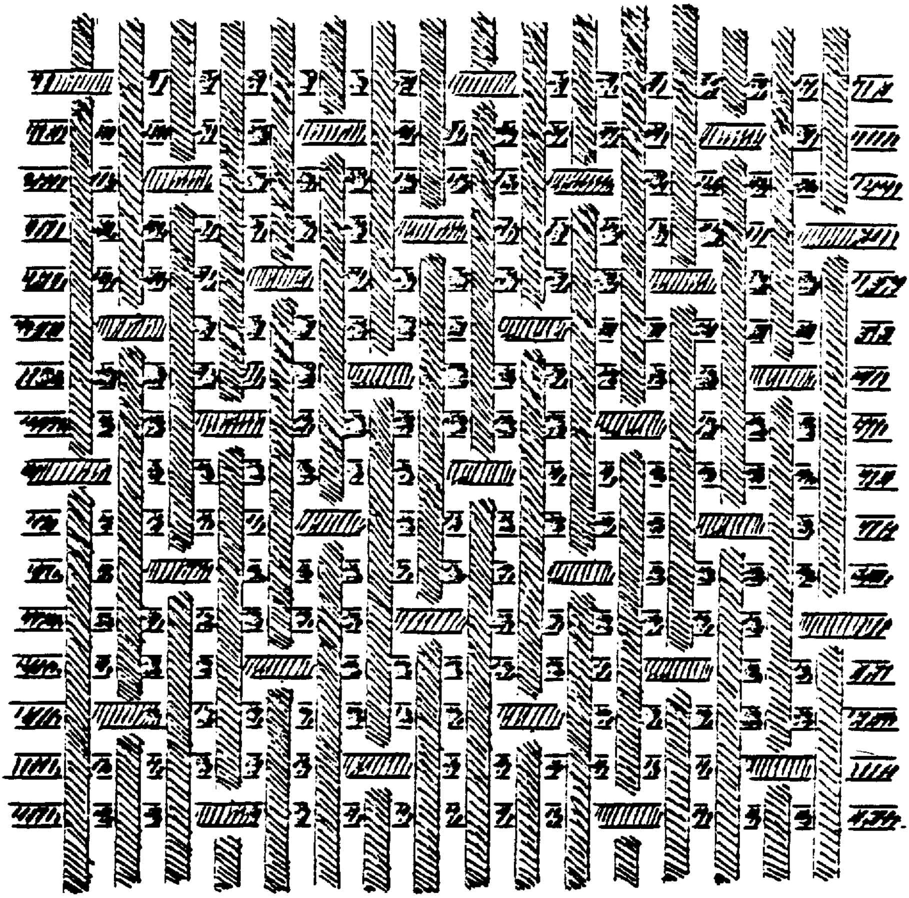


FIG. 3. 8 Harness satin weave pattern.

for PABH-T X-500 fabrics. The fabric geometry and fiber volumes were duplicated as closely as possible with the PABH-T, X-500 Type I, 360 den yarn.

Comparative yarn constructions of the PABH-T X-500 and E-glass fibers are given in Table 6. Since the filament diameter of the PABH-T fiber was four times that of the fiber glass, only 1/16 as many PABH-T filaments (51) would be required to give a yarn of cross-sectional area approximately that of the glass yarn. The closest PABH-T yarn available contained 60 filaments. This resulted in a slightly more bulky fabric than the Style 7581 glass

TABLE 6. Yarn Construction for Reinforcing Fabrics

Yarn property	PABH-T X-500 Type I	E-Glass Style 7581
Fiber diameter (mils)	1.0	0.25
Fiber density (g/cc)	1.41	2.55
No. filaments/yarn end	60	816
Approx yarn cross-section (in.^{2})	4.7×10^{-5}	4.0×10^{-5}
Yarn weight (yd/lb)	11,300	7,500
Yarn twist (tpi)	0.7Z	0.5Z

fabric. This is seen by increases in yarn cross-section and in fabric thickness (Table 7). A small reduction in threads per inch both in the warp and fill reduced the overall fiber volume of the PABH-T fabric somewhat and more closely approximated that of the glass fabric.

The physical properties of the two fabrics were measured and are compared in Table 7. It is interesting to note the closeness of the breaking strength and breaking elongation values of these fabrics. The breaking tenacity and initial modulus values, which are normalized for weight, are about double for the PABH-T X-500 as would be expected from the lower weight of this fabric.

One usually expects the strength and elongation in the warp direction to be somewhat greater than those of the fill direction, especially when more threads per inch are placed in the warp. This was the case with the glass fabric, but the reverse was noted with the PABH-T fabric. This leads one to suspect that the warp yarns were damaged during weaving. Yarns were extracted from the woven PABH-T fabric and tested for tensile properties. Table 8 shows the data obtained from the extracted yarns in comparison to the original twisted yarn. It is quite obvious that the warp yarns especially were badly damaged during the weaving. Substantial loss in all tensile properties occurred. The fill yarns retained much higher percentages of their original

TABLE 7. Reinforcing Fabrics Construction and Properties[a]

Fabric property	PABH-T X-500 Type I	E-Glass Style 7581
Weave pattern	8 H-Satin	8 H-Satin
Threads/in.		
Warp	54	56
Fill	52	54
Fabric weight (oz/yd^2)	5.30	8.65
Fabric thickness (mils)	10	8.9
Breaking strength (strip) (lb/in.)		
Warp	432	433
Fill	512	354
Breaking tenacity (lb/in./oz/yd^2)		
Warp	81	50
Fill	97	41
Breaking Elongation (strip) (%)		
Warp	3.1	3.7
Fill	3.7	3.3
Initial modulus (strip) (lb/in./oz/yd^2)		
Warp	2834	1354
Fill	2737	1199

[a] Data are averages of 5 Instron tests, 5 in. gauge, 100% extension/min.

properties than did the warp, as was indicated by the fabric properties. Several possible causes of damage could be projected: inadequate size, too tight weave pattern, and excessive loom tensions, to name a few.

One relative weakness of glass fiber has been resistance to hot water. The boiling water resistance of the two fabrics is compared using tensile measurements of fibers extracted from the fabrics

TABLE 8. Property Retention of Yarns from Satin Weave Fabric[a]

Yarn source	Denier	Tenacity (gpd)	Elongation (%)	Initial modulus (gpd)
Original yarn twisted 0.7 tpi and sized	372	11.5	2.5	685
Warp yarn from fabric	364	5.6	1.4	296
% Retained		49	56	44
Fill yarn from fabric	373	8.9	2.0	622
% Retained		77	80	91

[a] PABH-T X-500, Type I, greige goods fabric. Values are averages of 10 Instron breaks, 10 in. gauge, 5% extension/min.

after exposure to boiling water for a period of 24 hr. The data shown in Table 9 clearly points to the superior performance of the organic PABH-T X-500.

TABLE 9. Boiling Water Resistance of Reinforcing Fabrics[a]

	% Retention after 24 hr boiling water		
	Tenacity	Elongation	Modulus
PABH-T X-500, Type I	94	98	94
S-Glass	73	72	90
E-Glass	41	56	74

[a] Measured from single filaments extracted from 8-H Satin fabrics.

In addition to evaluating PABH-T X-500 fabrics against glass in rigid reinforced laminates, we wanted to determine whether the properties peculiar to this class of fibers would be advantageous to antiballistic armor. In cooperation and with the support of the U.S. Army Natick Laboratories, we undertook the preparation of woven fabrics and fabric-resin laminates for antiballistic testing. To evaluate the full range of physical properties achievable with this PABH-T X-500 fiber, ballistic fabrics were woven from all three of the PABH-T yarn types. The standard of comparison was a 2 × 2 plain basket-weave fabric woven from 1050 den, multifilament, high-tenacity nylon described by Military Specification MIL-C-12369D(GL) [6]. In this weave pattern (Fig. 4) two ends weave as one in both warp and fill directions to form an alternating over and under pattern. This weave imparts a high level of stability and firmness to the fabric. It also allows minimal yarn slippage within the woven structure. These are desirable features for antiballistic fabrics in that they provide maximum resistance to an entering projectile by prohibiting yarn movement and fabric distortion. This fabric pattern was used as a guide for weaving the three types of PABH-T fiber yarn.

To avoid the extensive damage shown by the warp yarns during weaving of the satin fabric, a change in sizing composition was made to provide more lubrication to the yarn surface. In addition

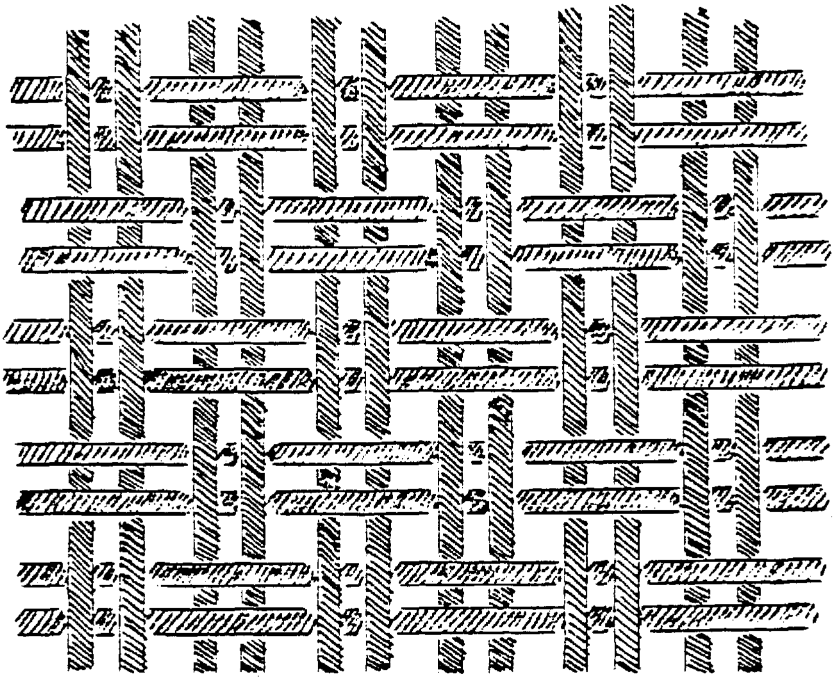


FIG. 4. 2 × 2 Basket plain weave pattern.

to the polyacrylic acid size commonly used on continuous filament nylon warp yarns, an overcoating of a lubricating wax was also applied during the slashing operation. The filling yarns were not sized, but were given a light wax coating during quilling. Table 10 compares the tensile properties of yarns extracted from the woven fabrics with those of the original yarns prior to weaving. Only the yarns from the Type I fabrics showed indication of damage during the weaving operations. The strength loss of about 26% for the warp yarns was much less than the 50% loss experienced with the satin fabric. The tensile values of yarns extracted from the ballistic nylon fabric are shown for comparison.

Fabrics of the three PABH-T yarns were woven on a conventional Draper X-3 textile loom. The fabric construction was intended to match that of the Military Specification for the nylon ballistic cloth (Table 11). A sample of this fabric was found to have 49 yarns/in. in the warp direction and 43 in the filling.

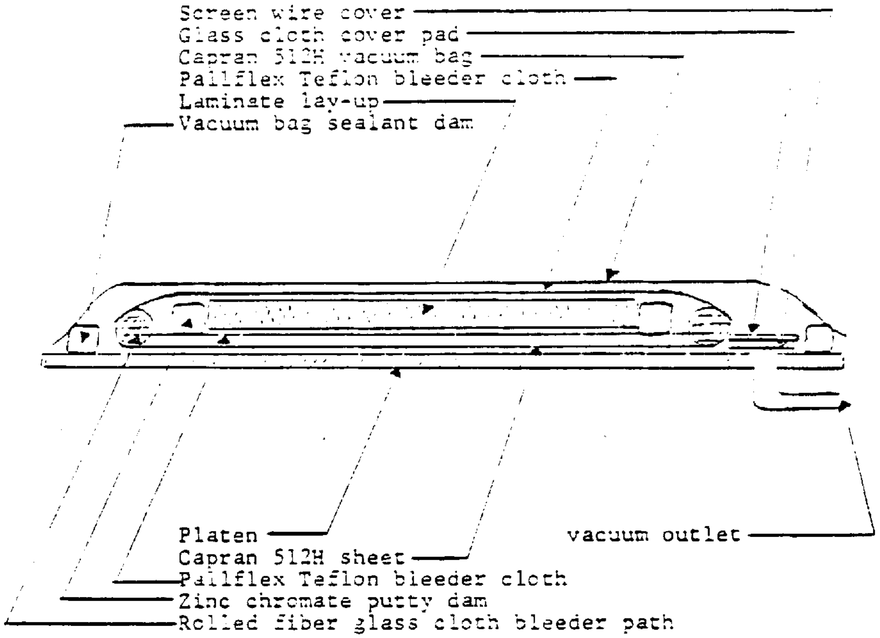


FIG. 6. Vacuum bag assembly.

all laminates prepared. A large cylindrical autoclave was used to cure the laminates. The desired curing temperature and pressure were preset and controlled automatically. The autoclave was preheated to near the desired temperature prior to loading.

The vacuum bag assembly was placed inside the clave and attached to the vacuum line. The assembly was evacuated to 25 inches of mercury and observed for leaks prior to sealing the clave. The vacuum on the bag was reduced as the clave was pressurized and was maintained at 5 in. Hg during the curing cycle. This prevented formation of bubbles in the laminate during curing.

An unsaturated polyester resin catalyzed with benzoyl peroxide (Rohm and Haas P-43) was used in the preparation of most of the ballistic test laminates. The resin was modified with styrene monomer, usually 10 pph resin, to impart better wetting of the fabric. The cure cycle used for the polyester resin laminates was 30 min at 250°F and 40 psi pressure. No postcure was used with this resin.

TABLE 11. Physical Properties of 2 × 2 Basket Weave Fabrics[a]

Property	PABH-T X-500 yarn type			Nylon ballistic fabric control
	I	II	III	
Overall width (in.)	44	39.5	42.5	48
Weight/yd^2 (oz)	10.9	11.8	12.4	14.2
Yarns/in.				
Warp	45	45	45	49
Filling	31	39	40	43
Break strength (lb/in.)				
Warp	876	741	533	944
Filling	675	681	521	827
Break tenacity (lb/in./oz/yd^2)				
Warp	80.0	62.7	42.9	66.6
Filling	61.6	57.6	42.0	58.5
Ultimate elongation (%)				
Warp	7.6	13.1	28.3	46.7
Filling	2.9	8.6	22.6	39.7
Shrinkage in boiling water[b] (%)				
Warp	nil	nil	nil	3.8
Filling	nil	nil	nil	1.56

[a] Test methods described in MIL-C-12369D(GL) unless otherwise noted.

[b] Measured from a single specimen 10 × 10 in. marked to 8 × 8 in.

The PABH-T warp was entered using a straight draw-in on four harness to give the desired 2 × 2 basket pattern with two ends weaving as one and two picks weaving as one. Drag rolls were required for all three warps to maintain the tensions necessary to achieve the desired pick level. The fabric shrinkage off the loom was less than expected and the finished fabric count was 45 × 40. The very low elongation of the Type I yarn resulted in extensive yarn damage during beat-back and necessitated a reduction of picks to 30/in. At this pick level, stable weaving was achieved with minimal damage to the yarn.

Since negligible loss in tensile properties of the sized yarns had been noticed after scouring with either a neutral detergent or TSPP, a portion of each fabric was scoured with the TSPP formulation. Tensile properties were measured on both the off-loom and finished fabrics. The finished fabrics showed slightly higher tensile strength values than did the off-loom greige goods. Table 11 compares the properties of the PABH-T scoured fabrics with those of the nylon ballistic fabric standard. Although none of the PABH-T X-500 fabrics achieved the breaking strength of the nylon ballistic fabric, due in part to fewer yarns per inch of fabric, the breaking tenacity values (the breaking strength normalized for fabric weight) of the Type I and Type II fabrics were greater or equal to that of the nylon ballistic fabric. Elongation values, as expected, were substantially lower than those of the nylon fabric. The PABH-T fabrics showed no shrinkage in boiling water, emphasizing the unusual dimensional stability of the high-modulus organic materials.

Composites Preparation and Characterization

Composite laminates were prepared from Style 7581, E-Glass fabric with A-1100 finish, and the corresponding Type I PABH-T X-500 fabric having no finish. A schematic of the preparation method is shown by Fig. 5. Epon-828/MPD (m-phenylene diamine catalyzed epoxy resin) at 80% solids in acetone was used with both fabrics. The fabrics were saturated with resin by drawing through a dip tank. The excess solution was removed by scraper bars set with a gap just slightly greater than the fabric thickness. The resin saturated fabric was cut into sheets for B-staging in a forced air oven. The sheets were rotated in a revolving oven for 60 min at 165°F. The prepreg sheets were layered between perforated Teflon release sheets. Two thicknesses of glass bleeder cloth were placed above and below the lay-up to absorb

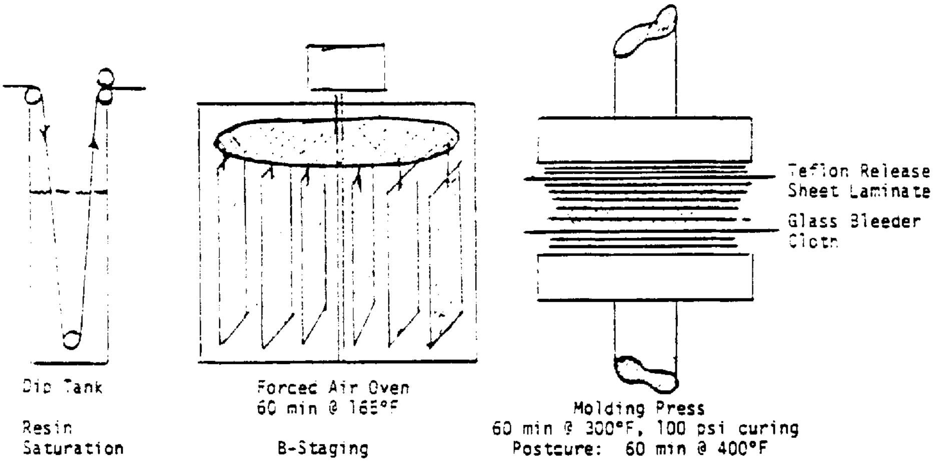


FIG. 5. Preparation of fabric-resin laminates.

excess resin. The fabric laminates were cured for 1 hr at 300°F and 100 psi followed by a postcure of 1 hr at 400°F. Although the evaluation of PABH-T X-500 reinforced composites is discussed in detail by Zaukelies and Daniels in the following paper [7], some of the typical mechanical properties are summarized in Table 12. In the tensile test mode, the PABH-T X-500 composites compare very favorably with the glass composite. The poorer performance of the PABH-T laminates in the flexural and compression modes undoubtedly reflects the anisotropic nature of the PABH-T fiber compared to the almost isotropic glass fiber. The difference in interlaminar shear values probably reflects the influence of fiber finish on the glass composite.

The ballastic fabrics were formed into laminate composites using the vacuum bag technique illustrated by Fig. 6. The PABH-T fabrics were precut into squares. The weight of fabric required for each laminate was calculated from the desired areal density and fabric loading values. The weight of resin required for each laminate was calculated from the actual fabric weight and the desired fabric loading. Each layer of fabric was coated with the proportionate amount of the total resin weight. The resin impregnated fabric swatches were layered on the vacuum bag platen as shown by Fig. 6. No effort was made to orient the warp or fill direction of the fabric in the lay-up; random lay-up was used for

TABLE 12. Mechanical Properties of Fabric Laminates

Property	PABH-T X-500/ Epoxy	E-Glass/ Epoxy
Fiber volume (%)	60.0	55.0
Density (lb/in.^{3})	0.047	0.065
Flexural strength (10^3 psi)		
At room temperature	52	82
At 250°F	20.4	64.3
Flexural modulus (10^6 psi)		
At room temperature	3.7	3.4
At 250°F	2.2	3.0
Specific modulus at room temperature (in. × 10^6)	61.7	52.3
Tensile strength (10^3 psi)		
At room temperature	51	56
At 250°F	19	41
Tensile modulus (10^6 psi)		
At room temperature	4.0	3.2
At 250°F	1.0	1.1
Specific modulus at room temperature (in. × 10^6)	85.1	49.2
Compressive strength (10^3 psi)		
At room temperature	20	63
At 250°F	13	27
Compressive modulus (10^6 psi)		
At room temperature	2.7	3.5
At 250°F	2.5	3.1
Specific modulus at room temperature (in. × 10^6)	57.4	53.8
Interlaminar shear strength (10^3 psi)	3.0	4.3

in the preparation of most of the ballistic test laminates. The resin was modified with styrene monomer, usually 10 pph resin, to impart better wetting of the fabric. The cure cycle used for the polyester resin laminates was 30 min at 250'F and 40 **psi** pressure. No postcure was used with this resin.

Laminated ballistic test panels were prepared using all three types of the PABH-T X-500 fabric with polyester resins. However, ballistic tests using only multiple layers of fabric showed the Type III material to give the best results. Evaluation of the laminated test panels also showed the Type III fabric having the lowest tenacity but highest elongation and work-to-break to perform best. There was no significant difference between Type I and Type II fabrics despite the trade-off that occurred between tenacity and modulus on the one hand and elongation on the other. The V_{50} test data obtained from the P-43 resin laminates of Type III fabric showed values comparable to those of the fabric alone. Table 13 shows the V_{50} values at differing levels of fabric loading. The ballistic evaluation of these laminates is the subject of a following paper by Laible, Figucia, and Ferguson [8].

TABLE 13. Ballistic Results for Type III PABH-T X-500 Fabric Laminates

% Fabric loading	No. fabric plies	Areal density (oz/sq ft)	V_{50} (ft/sec)
40	12	34.0	1043
60	15	39.3	1185
80	22	40.1	1373

[a] P-43 Polyester resin.

CONCLUSIONS

The aromatic polyamide-hydrazide (PABH-T) fibers of the X-500 class of high-modulus materials show exceptionally high strength and modulus values for organic fibers. Continuous filament yarns covering a broad range of physical properties can be readily woven into a variety of weave patterns using conventional textile equipment. However, the relatively poor performance of the fabric reinforced resin laminates, especially in interlaminar shear, points to the need for further research on fabric design to assure maximum utilization of the desirable fiber properties. One such fabric design developed by J. P. Stevens & Co. is the High-Modulus Weave pattern shown by

Fig. 7. This weave uses fine binder yarns to eliminate the interlacing of structural yarns, thereby reducing crimp and shear factors. It should provide improved reinforcing where high-impact resistance combined with high strength and modulus are required and where high shear forces are likely to occur.

Probably an even greater contributor to the poor laminate performance is the highly anisotropic characteristic of the PABH-T fiber. This was particularly noticeable in the low values obtained from the laminates tested under flexural and compression stresses.

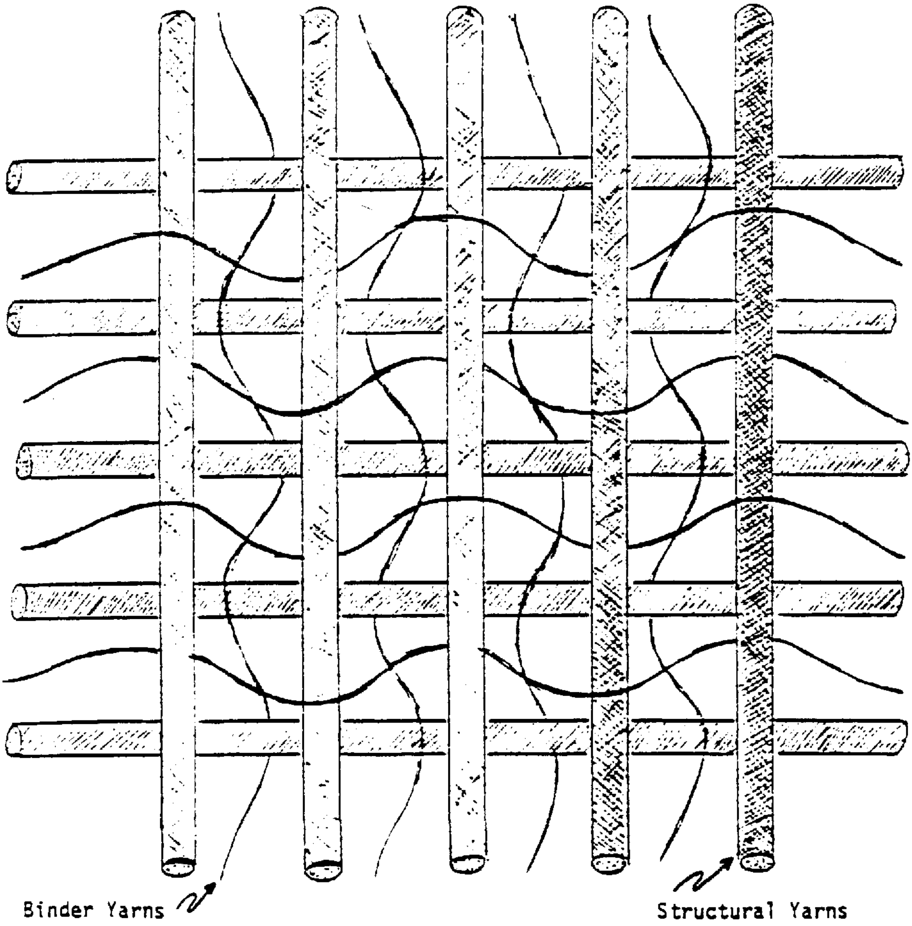


FIG. 7. High-modulus weave, J. P. Stevens and Co.

The unidirectional orientation of the polymer molecules coupled with the rather low intermolecular cohesive forces allow molecular flexing and distortion under these stresses.

The initial ballistic evaluation of the PABH-T fabrics resin laminates [8, 9] indicated that a substantial level of fiber elongation was needed to provide the energy absorbing impact resistance to the laminate. Thus the Type III PABH-T fabrics performed best in this evaluation. In an independent study, Askins and Schwartz [10] showed that PABH-T X-500 fiber of low elongation and high tensile strength (Type I), when formed into a fabric, polyester resin laminate, showed greater promise for surpassing the performance of E-glass polyester resin composites than did graphite/epoxy composites. Indeed, the PABH-T X-500 polyester resin composite was the only one of the several composites tested which showed energy absorption characteristics similar to those of the standard glass/resin composite.

ACKNOWLEDGMENTS

The authors acknowledge with appreciation the contributions to fabric weaving of Mr. N. L. Thurnauer, Monsanto Textiles Co., of Mr. H. S. Morgan and Mr. R. T. Mayes, Chemstrand Research Center, Inc. for fiber preparation and physical testing; and to Mr. G. A. Jenkins, Monsanto Research Corp., in the preparation and testing of laminates. We also express appreciation to the U.S. Army Natick Laboratories for cooperation and support of the antiballistic evaluation work.

REFERENCES

[1] J. Preston, W. B. Black, and W. L. Hofferbert, Jr., J. Macromol. Sci.—Chem., A7(1), 45 (1973).
[2] J. Preston, W. B. Black, and W. L. Hofferbert, Jr., J. Macromol. Sci.—Chem., A7(1), 67 (1973).
[3] W. B. Black, J. Preston, H. S. Morgan, G. Raumann, and M. R. Lilyquist, J. Macromol. Sci.—Chem., A7(1), 137 (1973).
[4] Morganite Research and Development Ltd., New Products Data Sheet, "Modmor, High Modulus Carbon Fibers."
[5] W. B. Black, J. Macromol. Sci.—Chem., A7(1), 3 (1973).
[6] "Military Specification for Nylon Ballistic Cloth," MIL-C-12369D(GL), September 8, 1964.

[7] D. A. Zaukelies and B. K. Daniels, J. Macromol. Sci.—Chem., A7(1), 229 (1973).
[8] R. C. Laible, F. Figucia, and W. J. Ferguson, J. Macromol. Sci.—Chem., A7(1), 295 (1973).
[9] M. R. Lilyquist, U.S. Army Natick Laboratories, Technical Report 71-47-CE (1972).
[10] D. R. Askins and H. S. Schwartz, U.S. Air Force Materials Laboratory, Technical Report AFML-TR-71-283 (1972).