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(54) 3-D RESIN TRANSFER MEDIUM AND METHOD OF USE

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(57) ABSTRACT

A resin distribution system and method for use in resin transfer molding including a 3-D orthogonal fiber structure having capillary channels therein for permitting a fluid to flow through the structure, wherein the 3-D orthogonal fiber structure further includes X-, Y-, and Z-direction fiber systems, each of having substantially no crimp within a body of the structure, thereby providing a system for distributing the fluid uniformly through the structure.

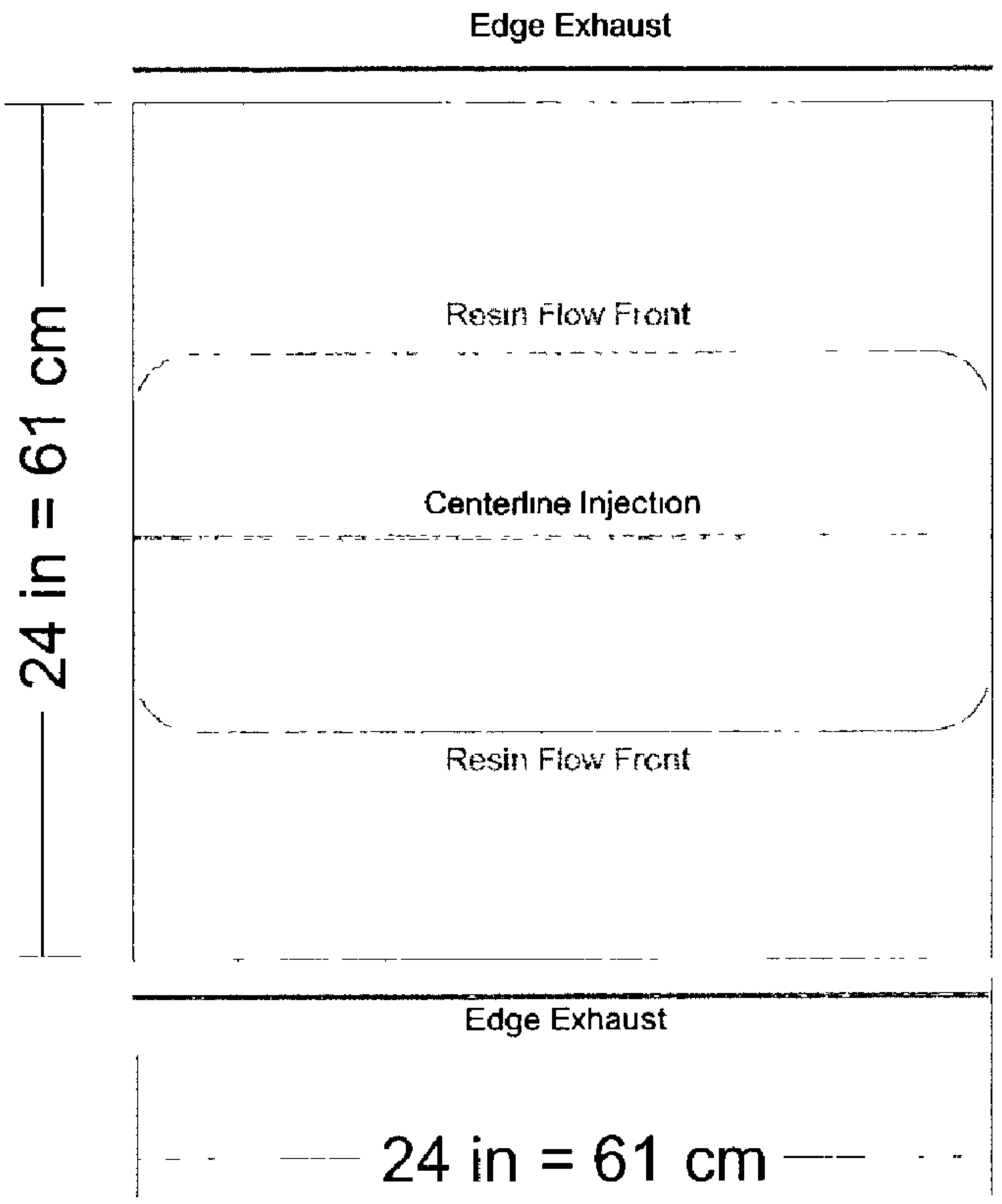


Figure 1: resin injection scheme used in permeability test.

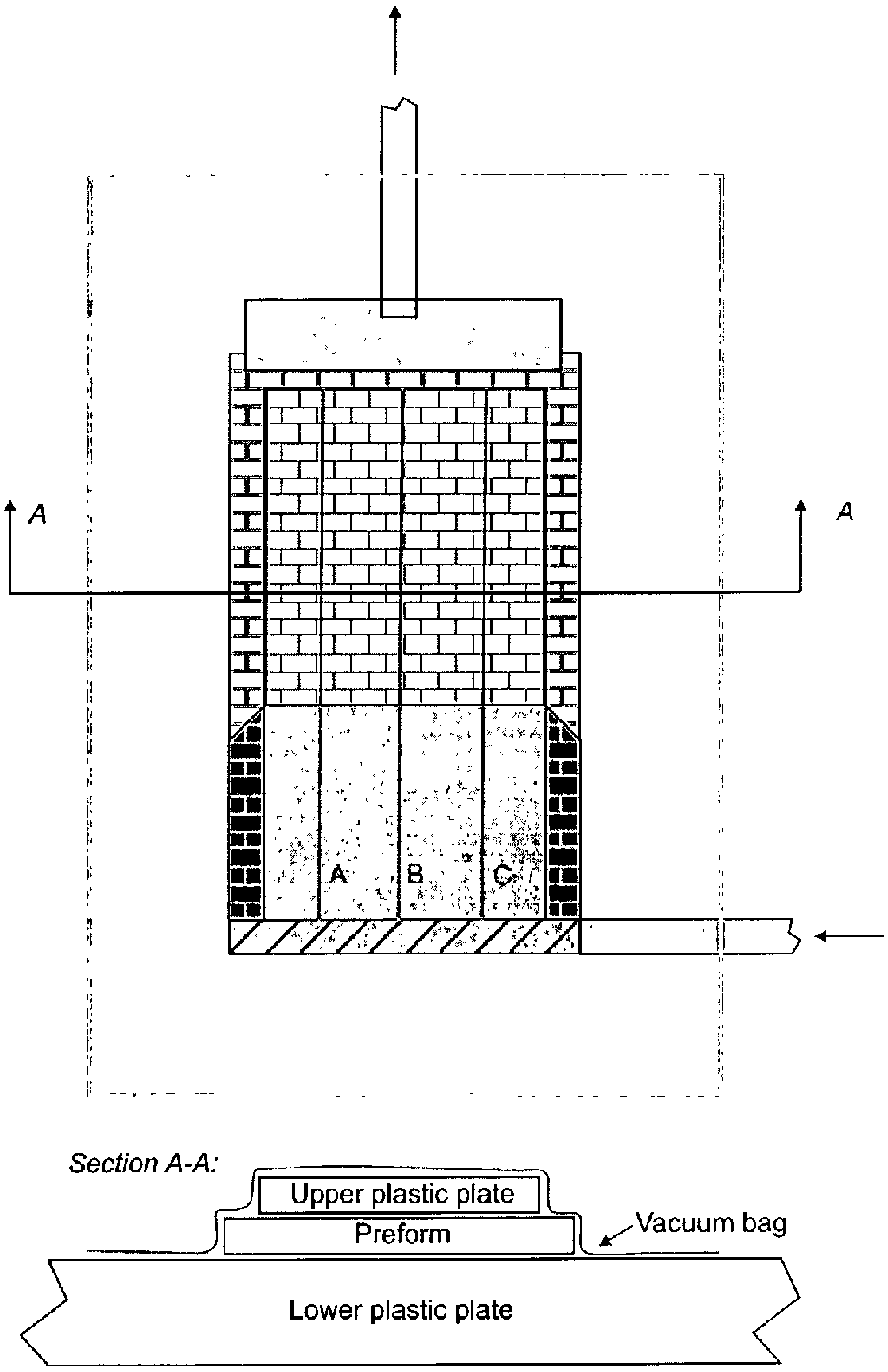


Figure 2: Permeability study set up, to simulate 1-D flow during VARTM, showing advancing resin front. In one set of experiments, the upper plastic plate was removed, allowing the vacuum bag to conform to the preform upper surface.

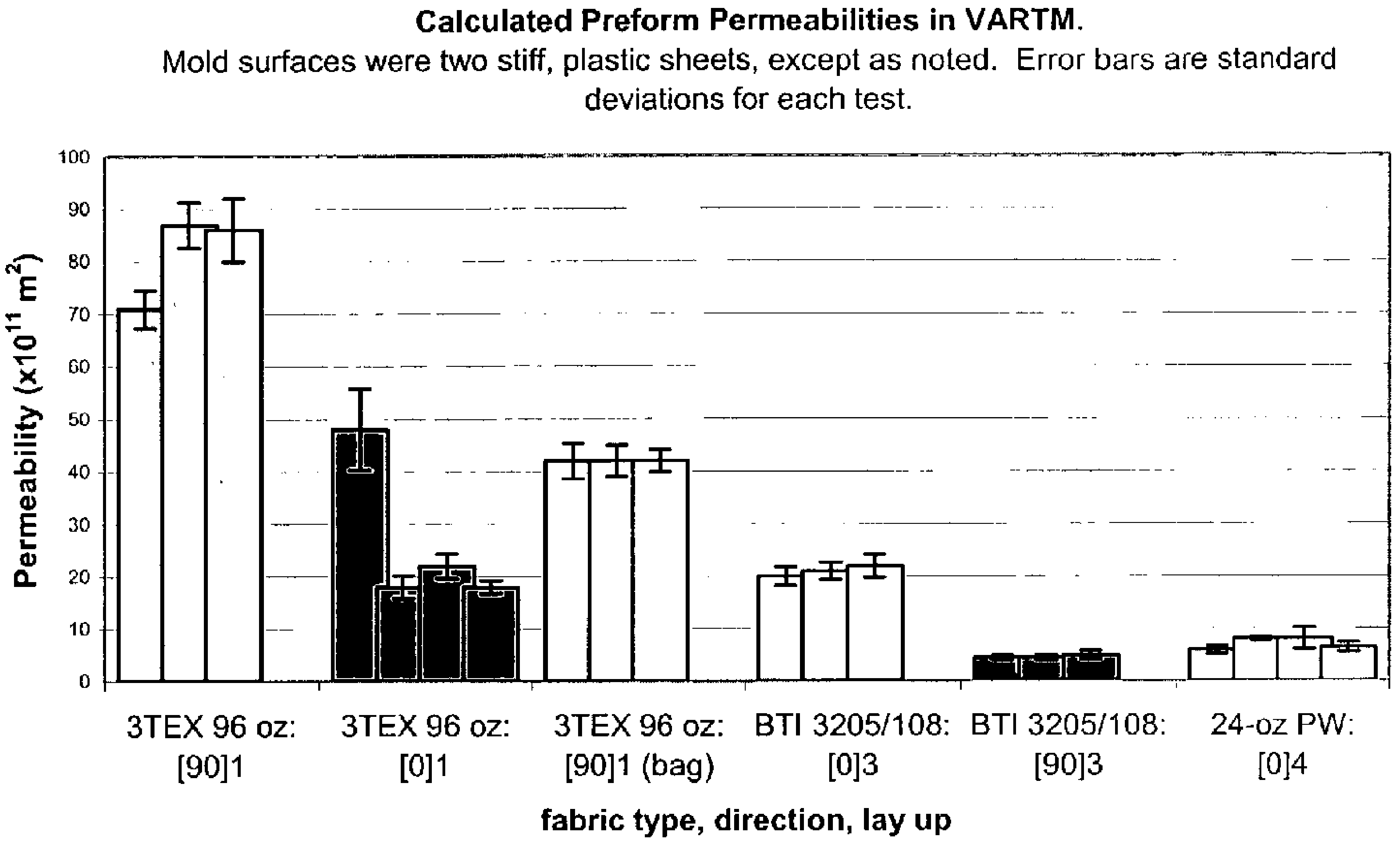
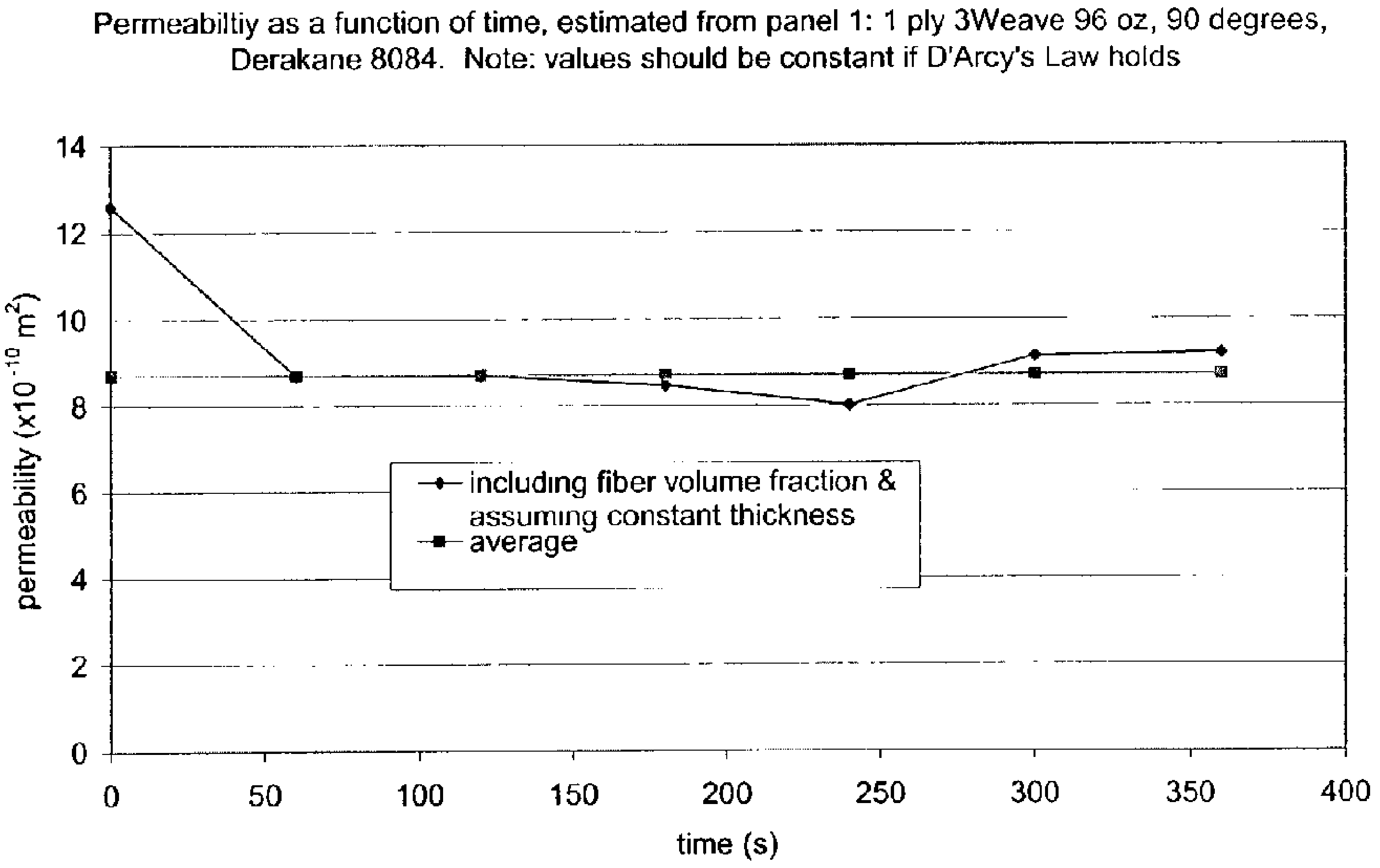


Figure 3: Plotted interim results of permeability study.

Figure 4: Permeability for panel E96X1V120701-2, as determined by D'Arcy's law, using the assumptions described in the Analysis section. The blue line with diamonds indicates permeability, k, determined for each time interval of the test. The pink line with squares indicates average k, after ignoring first data point (see Analysis).



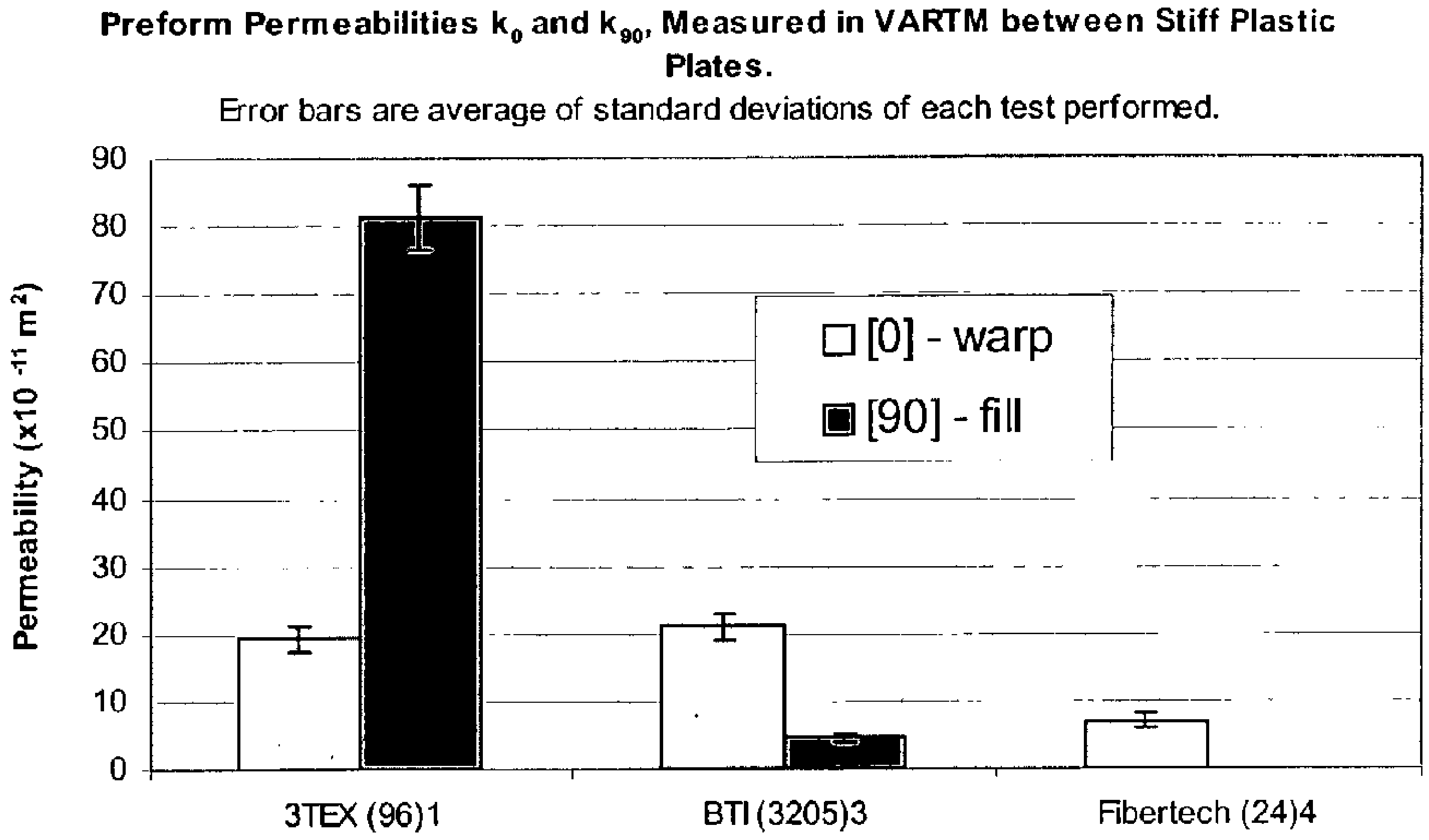


Figure 5: Average measured permeabilities k_0 and k_{90} of three preforms, infused in VATM between two stiff plates.

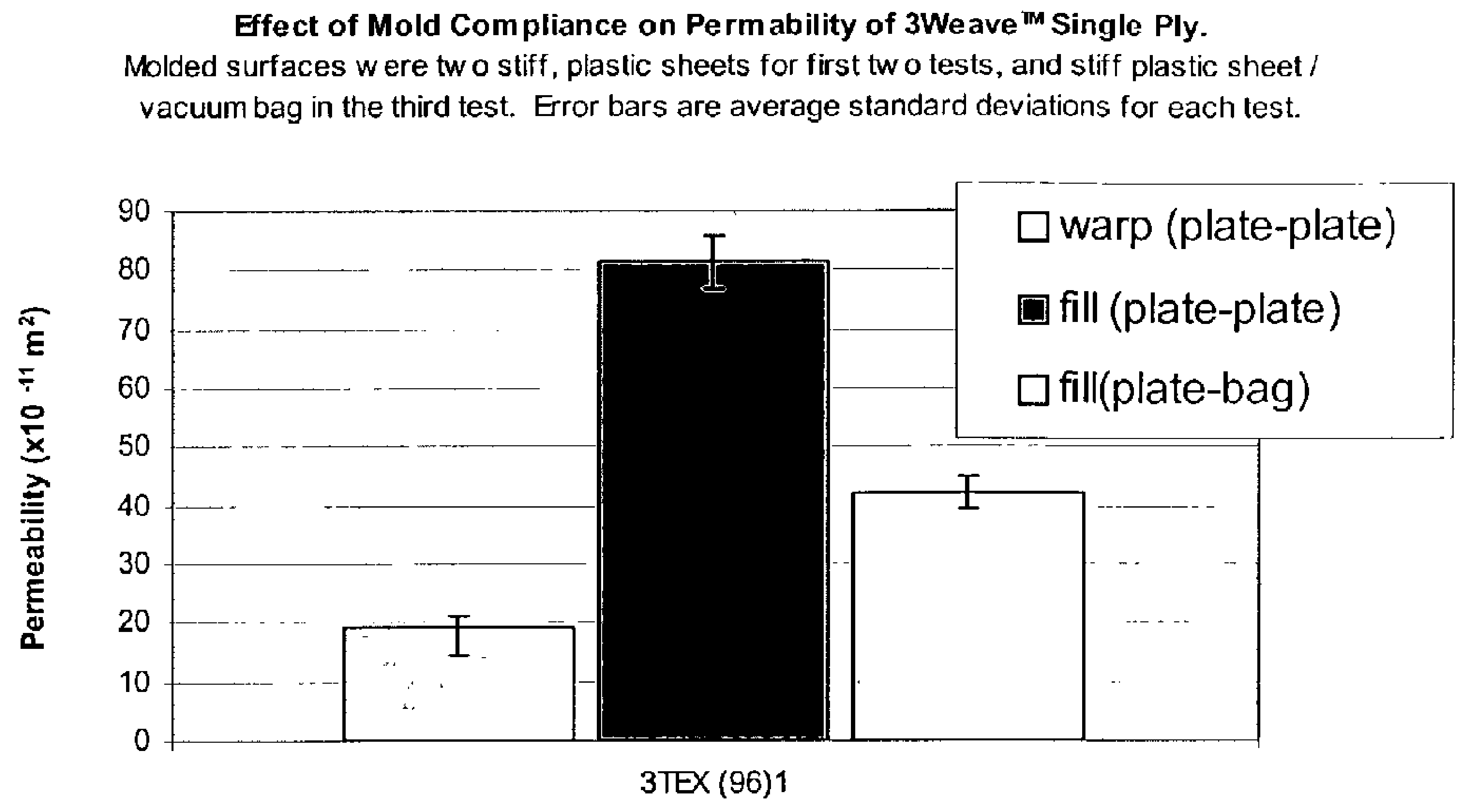


Figure 6: Effect of mold compliance on 3Weave™ preform permeability. Permeability of one ply of P3W-GE0001 between two stiff plates (representative of infusion in a mold with two hard faces) is compared to permeability between a stiff plate and a vacuum bag (representative of VARTM of large parts).

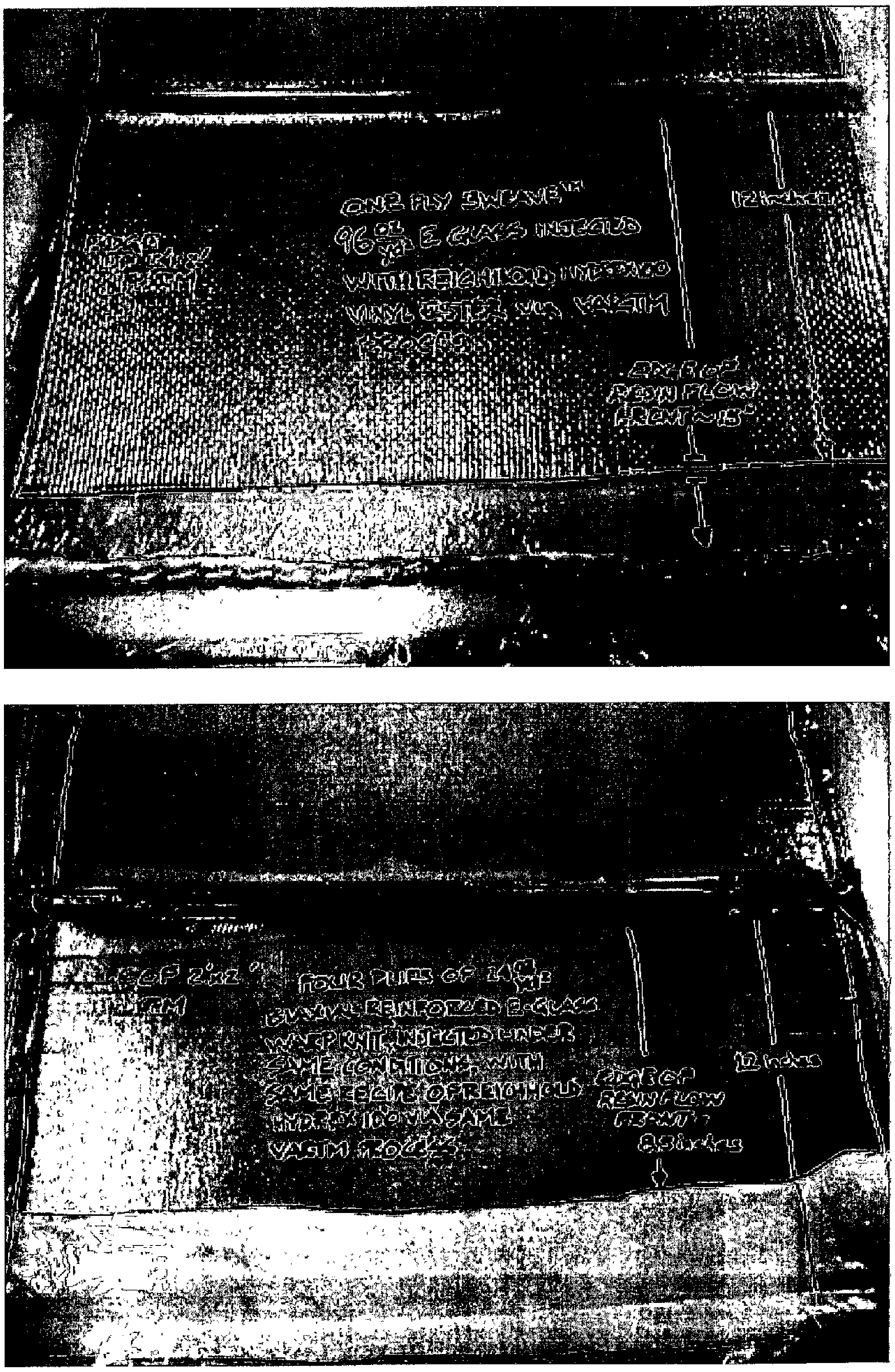


Figure 7:Equal size and area weight VARTM E glass / vinyl ester panels, processed under same conditions, from 3Weave™ and biaxial reinforced warp knits. Each panel 24 in x 24 in (61 cm x 61 cm), with 96 oz/yd2/ 3.2 kg/m^2 of cloth. Flow direction parallel to warp. Both composites were balanced and symmetric.

3-D ORTHOGONAL WEAVE

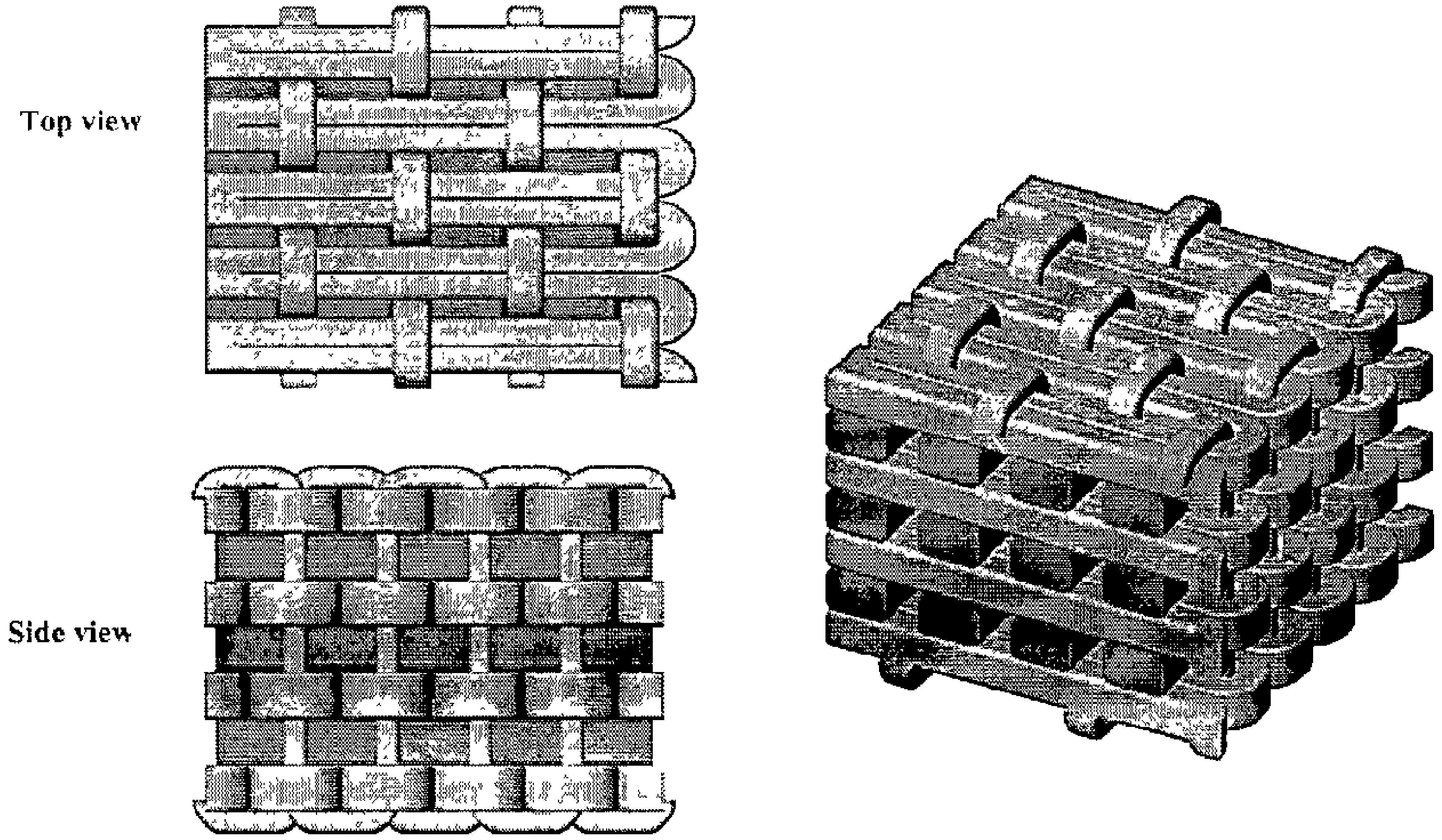


Figure 8

3-D RESIN TRANSFER MEDIUM AND METHOD OF USE

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This nonprovisional utility patent application claims the benefit of provisional application serial No. 60/334,287, which is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

[0002] This invention generally relates to textiles, and more specifically, to resin transfer molding and distribution systems, materials, and methods.

BACKGROUND OF THE INVENTION

[0003] The present invention relates to the improved resin distribution systems and methods for the production of fiber reinforced structures. In particular, it relates to improvements in the apparatus and methods for the production of fiber reinforced structures, especially to improve resin infiltration and impregnation times, resin distribution consistency, and reinforced fiber quality for such purpose.

[0004] Fiber reinforced plastic structures have been commercially produced for some years, the processes for producing these structures requiring the incorporation of a reinforcing fiber, generally in the form of one or more layers of a woven or felted fiberglass, within a resin, or other fluent plastic material. Generally, resin transfer molding (RTM) and vacuum assisted resin transfer molding (VARTM) are known in the prior art for making fiber reinforced plastic structures. Used in combination with the RTM and VARTM, additional external devices are currently commercially available that enhance the resin distribution through the internal in-plane preform, by improving the strength and uniform distribution of resin through the internal in-plane preform.

[0005] British Pat. No. 944,955 to Philip Richard Green, published Dec. 18, 1963, describes a vacuum bag technique for the production of a fiber reinforced plastic structure. The patentee suggests, "In the case of some resin material of high viscosity, it may be necessary to assist the flow of resin through the mold space by applying a suitable squeegee or roller to the outside of the bag." Such a method as provided by the Patentee has the potentials of inconsistent and uneven resin distribution, requiring more time, additional operating labor, and opportunity for human error.

[0006] U.S. Pat. No. 4,312,829, which issued to Fredric J. Fourcher, utilizes the vacuum technique but introduces a perforated core material that is placed within the chamber to which resin is introduced, and on which resin is set for formation of a resin core structure.

[0007] U.S. Pat. No. 2,913,036, issued on Nov. 17, 1959 to George H. Smith, describes a vacuum bag method wherein a rigid network of veins or arteries extend upwardly from the base of the mold. The purpose of the veins or arteries is to flow the plastic, or resin, upwardly through the mold surface, by applying at a multiplicity of points a fluid plastic, or resin, which may then seep from the points to every part of the mold space. After the casting is hardened, the artery structure can be broken away from the finished fiber plastic structure and discarded. The necessity of having to incorporate the network of veins and arteries in the fiber plastic structure can lessen or even destroy the value of many products. Having to break the veins and arteries free of the finished fiber plastic is extremely burdensome, and can injure the surface characteristics of the product.

[0008] U.S. Pat. No. 4,132,755 which issued on Jan. 02, 1979 to Jay Johnson there is disclosed a "bag within a bag" vacuum bag technique for obtaining better and more uniform distribution of the resin. In accordance therefore with a perforated flexible sheet is placed over the dry fiber lay up within the inner chamber is a single cavity mold, and the inner chamber is connected to a vacuum source. An impervious flexible sheet is placed over the perforated flexible sheet to provide an outer chamber between the two sheets, the outer chamber is connected to a resin source, and the edges of both sheets are sealed upon the mold surface. In accordance with this method better distribution of the resin throughout the mold space is obtained than with that of Smith because, in the words of the Patentee, "the resin, instead of flowing longitudinally through the glass fibers and giving a 'washing' effect which orients these fibers is evenly distributed through many pinhole-like apertures in the perforated sheet. In this manner each drop of resin reaches every comer of the laminate without flowing lengthwise through the glass reinforcement. While the Patentee's technique may provide more uniform distribution of resin, this technique is not without its limitations which appear to severely restrict its use. It has been found that the paths of the distribution of the resin across the upper surface of the impervious flexible sheet within the outer chamber results in considerable channeling, is considerably lacking in establishing a uniform network of flow paths, and flow through many pin-hole like apertures is far from uniform.

[0009] In U.S. Pat. No. 4,902,215 issued on Feb. 20, 1990 to William H. Seemann, III teaches both a method and apparatus for producing fiber reinforced plastics via an improved resin impregnation apparatus and resin distribution medium operating within a VARTM-based system. The claimed subject matter for the Seemann Composite Resin Infusion Manufacturing Process, SCRIMP, patents includes an apparatus for the production of fiber reinforced plastic structures via a vacuum assisted technique. More particularly, the apparatus includes a fluid impervious outer sheet or bag with a resin inlet, a vacuum outlet, a chamber for a fiber or fabric lay up, and a resin distribution medium located on one side of the fiber lay up. Resin flows through the resin distribution medium, located between the fabric lay up and the outer sheet or bag. The resin distribution medium has an open array of separated raised segments on its surface that are separate and distinct from the fabric lay up and the outer sheet or bag. The resin distribution medium claimed forms a fabric knitted or woven from a non-swelling, non-resin absorptive monofilament. The resin distribution medium is made of spaced-apart strands running crisscross one with another, and an open array of separated raised segments providing vertically oriented spaced-apart props or pillars, and spaced apart lateral openings between said props or pillars. Finally, there may be a primary and a secondary resin distribution media positioned on the top face and bottom face of the fiber structure.

[0010] Other Seemann patents, hereinafter referred to as "SCRIMP patents" are also considered relevant prior art to the applicant. Generally, resin transfer molding (RTM) and vacuum assisted resin transfer molding (VARTM) are known in the prior art for making fiber reinforced plastic structures. For consideration of the SCRIMP patents in comparison to 3TEX's methods and products, the relevant field of inventions includes enclosed methods for infusing fibrous preforms with a thermosetting polyermic resin for making fiber reinforced polymeric composite structures. Clearly, the SCRIMP patents are positioned in the field of resin transfer molding for the fabrication of fiber reinforced plastic structures. More particularly, the SCRIMP patents relate to both a method and apparatus for producing fiber reinforced plastics via an improved resin impregnation apparatus and resin distribution medium operating within a VARTM-based system.

[0011] Furthermore, the claimed subject matter for each of the SCRIMP patents includes an apparatus for the production of fiber reinforced plastic structures via a vacuum assisted technique. More particularly, the apparatus includes a fluid impervious outer sheet or bag with a resin inlet, a vacuum outlet, a chamber for a fiber or fabric lay up, and a resin distribution medium located on one side of the fiber lay up. Resin flows through the resin distribution medium, located between the fabric lay up and the outer sheet or bag. Note that the resin distribution medium has an open array of separated raised segments on its surface that are separate and distinct from the fabric lay up and the outer sheet or bag. Also, note that the resin distribution medium is claimed to be formed of a fabric knitted or woven from a non-swelling, non-resin absorptive monofilament. The resin distribution medium is made of spaced-apart strands running crisscross one with another, and an open array of separated raised segments providing vertically oriented spaced-apart props or pillars, and spaced apart lateral openings between said props or pillars. Finally, note that there may be a primary and a secondary resin distribution media.

[0012] Also, the claimed subject matter for each of the SCRIMP patents includes an apparatus for the production of fiber reinforced plastic structures via a vacuum assisted technique. More particularly, the apparatus includes a fluid impervious outer sheet or bag with a resin inlet, a vacuum outlet, a chamber for a fiber or fabric lay up, and a resin distribution medium located on one side of the fiber lay up. Resin flows through the resin distribution medium, located between the fabric lay up and the outer sheet or bag. Note that the resin distribution medium has an open array of separated raised segments on its surface that are separate and distinct from the fabric lay up and the outer sheet or bag. Also, note that the resin distribution medium is claimed to be formed of a fabric knitted or woven from a non-swelling, non-resin absorptive monofilament. The resin distribution medium is made of spaced-apart strands running crisscross one with another, and an open array of separated raised segments providing vertically oriented spaced-apart props or pillars, and spaced apart lateral openings between said props or pillars. Finally, note that there may be a primary and a secondary resin distribution media.

[0013] In U.S. Pat. No. 4,902,215 issued Feb. 20, 1990 to Seemann, III for Plastic Transfer Molding Techniques for the Production of Fiber Reinforced Plastics Structures, there is disclosed (1) a fluid impervious outer sheet, suitably rigid but preferably a fluid impervious flexible or semi-flexible outer sheet, (2) an inlet in said fluid impervious outer sheet through which a resin, generally a catalyzed resin can be introduced, (3) a mold surface upon which one or more layers of woven or felted fiber, or fabric can be laid, and over which said fluid impervious outer sheet can be and its marginal edges sealed to form a chamber within which said layer or layers of woven of felted fiber, or fabric is enclosed, and (4) a vacuum outlet to said chamber for drawing a vacuum upon said chamber to provide a driving force to assist flow of the resin, and collapse said fluid impervious outer sheet upon the mold surface and press said layer or layers of fiber, or fabric, while resin is introduced via said resin inlet to said chamber. The apparatus of the Seemann invention, in addition to the combination of features (1), (2), (3), and (4), further includes (5) a resin distribution medium, constituted of spaced-apart strands, or lines, running crisscross one with another, and an open array of separated raised segments providing vertically oriented spaced apart props, or pillars, and spaced lateral openings between said props, or pillars, which provides a vast array of locations which support the fluid impervious outer sheet and, at these locations, prevent direct contact (or closure) between said outer sheet and the outer surface of said layers or fabric, while the resin introduced in the chamber flows through the lateral openings of the distribution medium to the outer edges thereof for distribution upon or to the outer face of said layer or layers of fabric which become readily uniformly impregnated with the resin when a vacuum is applied, and resin is introduced via the resin inlet to the chamber.

[0014] For consideration of the SCRIMP patents in comparison to the methods and products of the present invention, the relevant field of inventions includes enclosed methods for infusing fibrous preforms with a thermosetting polymeric resin for making fiber reinforced polymeric composite structures. The SCRIMP patents are positioned in the field of resin transfer molding for the fabrication of fiber reinforced plastic structures. More particularly, the SCRIMP patents relate to both a method and an apparatus for producing fiber reinforced plastics via an improved resin impregnation apparatus and resin distribution medium operating with a VARTM-based system.

- **[0015]** U.S. Pat. No. 4,902,215 issued Feb. 20, 1990 to Seemann, III for PLASTIC TRANSFER MOLDING TECHNIQUES FOR THE PRODUCTION OF FIBER REINFORCED PLASTIC STRUCTURES
  - **[0016]** resin distribution medium
    - **[0017]** (a) 1st set of spaced-apart parallely aligned monofilaments
    - **[0018]** (b) 2d set of spaced-apart parallely aligned monofilaments laid to intersect at generally right angles
    - **[0019]** (c) bead, post, pillar-like member adhered to the lower face of the crossed monofilaments (a) & (b)
    - **[0020]** (d) peel ply=resin pervious member
- **[0021]** U.S. Pat. No. 5,052,906 issued Oct. 1, 1991 to Seemann for PLASTIC TRANSFER MOLDING TECHNIQUES FOR THE PRODUCTION OF FIBER REINFORCED PLASTIC STRUCTURES

[0022] primary resin distribution medium

[0023] (a) 1st set of spaced-apart parallely aligned monofilaments

[0024] (b) 2d set of spaced-apart parallely aligned monofilaments laid to intersect at generally right angles

[0025] (c) bead, post, pillar-like member adhered to the lower face of the crossed monofilaments (a) & (b)

[0026] (d) peel ply=resin pervious member secondary resin distribution system (same as primary).

[0027] K. van Harten, "Chapter 4: Production by Resin Transfer Molding". In R. A. Shenoi and J. F. Wellicome, *Composite Materials in Maritime Structure, Volume* 1: *Fundamental Aspects*. Cambridge Ocean Technology Series. Cambridge University Press, Cambridge, UK, 1993.

[0028] Vacuum assisted, or vacuum bag techniques have been used in the past to form fiber reinforced plastic structures. In a vacuum bag technique, a flexible sheet, liner, or bag is used to cover a single cavity mold that contains a dry or wet fiber lay up. In accordance with the former, the edges of the flexible sheet are clamped against the mold to form an envelope and seal the member, a catalyzed liquid or plastic resin is generally introduced into the envelope, or bag interior, to wet the fiber and a vacuum is applied to the bag interior via a vacuum line to collapse the flexible sheet against the fiber surface of the mold, while the plastic wetted fiber is pressed and cured to form the fiber reinforced plastic structure. Resin fumes from the process are prevented from escaping into the work space. (see the VARTM description from Seemann, 4,902,215)

[0029] Fiber reinforced plastic structures have been commercially produced for some years, the processes for producing these structures requiring the incorporation of a reinforcing fiber, generally in the form of one or more layers of a woven or felted fiberglass, within a resin, or other fluent plastic material. Generally, resin transfer molding (RTM) and vacuum assisted resin transfer molding (VARTM) are known in the prior art for making fiber reinforced plastic structures. See, e.g., relevant prior art patents:

[0030] Seemann 4,902,215

[0031] Green 944,955

[0032] Fourcher 4,312,829

[0033] Smith 2,913,036

[0034] Johnson 4,132,755

[0035] Thus, there remains a need for a product and method that resolves issues in prior art, as set forth in the foregoing. The present invention product and method provides the following advantages and improvements over the prior art:

[0036] streamlines the process and eliminates an intermediate step that is not necessary.

[0037] alleviates the need for a conventional resin distribution system (RDS), because it constructs a preform that is capable of functioning as the primary RDS itself, and

[0038] there is no for any addition external devices of mediums to ensure consistent and efficient transfer of resin throughout the internal in-plane of the fiber reinforced plastic structure.

[0039] Used in combination with the RTM and VARTM, three dimensional fiber reinforced plastic structures, i.e. those with fibers oriented in an organized fashion in three dimensional space, such as with the present invention, have the improvements for mechanical performance, particularly resin distribution infiltration times, consistency in fiber reinforcement, increased fiber reinforcement quality, and cost effect advantages.

[0040] Furthermore, the use of preform reinforcements with cost effective composite fabrication such as RTM, VARTM, and other resin distribution technologies offer a combination of both improved performance and lower cost.

[0041] Thus, there remains a need for a resin distribution system and method that provides improvements in: 1) resin infiltration and impregnation times; 2) consistency in fiber reinforcement; 3) increased fiber reinforcement quality, by minimizing delamination; and 4) economic advantages in consolidation, particularly in resin infiltration and impregnation times, the elimination for the need of external resin distribution devices, and the ability of the applicants resin distribution system to function with any vacuum assisted resin transfer method (VARTM).

SUMMARY OF THE INVENTION

[0042] The present invention is directed to systems and methods for fluid transfer, specifically resin transfer, through a structure, in particular for applications of resin transfer molding for making composite materials.

[0043] The present invention is further directed to a resin transfer medium having a three-dimensional engineered fiber structure having an X-direction fiber system, a Y-direction fiber system, and a Z-direction fiber system wherein the X-, Y-, and Z-direction fiber systems are selectively, alternatingly distributed with respect to each other forming three substantially orthogonal fiber systems within the structure, and wherein the X-, Y-, and Z-direction fiber systems form a series of spaced-apart, substantially parallel channels for distributing a fluid through the channels in each of the X-, Y-, and Z-directions, thereby providing a structure for uniform distribution of the fluid through the medium. The present invention is also further directed to a method of using such a medium.

[0044] Accordingly, one aspect of the present invention is to provide a three-dimensional engineered fiber structure having an X-direction fiber system, a Y-direction fiber system, and a Z-direction fiber system wherein the X-, Y-, and Z-direction fiber systems are selectively, alternatingly distributed with respect to each other forming three substantially orthogonal fiber systems within the structure, and wherein the X-, Y-, and Z-direction fiber systems form a series of spaced-apart, substantially parallel channels for distributing a fluid through the channels in each of the X-, Y-, and Z-directions, thereby providing a structure for uniform distribution of the fluid through the medium.

[0045] Another aspect of the present invention is to provide a method for resin distribution comprising the steps of: providing a resin transfer medium having three-dimensional engineered fiber structure having an X-direction fiber system, a Y-direction fiber system, and a Z-direction fiber system wherein the X-, Y-, and Z-direction fiber systems are selectively, alternatingly distributed with respect to each other forming three substantially orthogonal fiber systems within the structure, and wherein the X-, Y-, and Z-direction fiber systems form a series of spaced-apart, substantially parallel channels for distributing a fluid through the channels in each of the X-, Y-, and Z-directions; and introducing a fluid into the medium, wherein the fluid is transferred throughout the structure, thereby providing uniform distribution of the fluid through the medium.

[**0046**] Thus, the present invention provides for an improved system and method for resin distribution. These and other aspects of the present invention will become apparent to those skilled in the art after a reading of the following description of the preferred embodiment when considered with the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[**0047**] **FIG. 1** is a schematic diagram illustrating a resin injection scheme used for testing the permeability and resin flow of the present invention.

[**0048**] **FIG. 2** is a diagram illustrating a resin injection set-up using a vacuum assisted resin transfer molding arrangement.

[**0049**] **FIG. 3** is a chart showing plotted results of an experimental study of an embodiment of the present invention.

[**0050**] **FIG. 4** is a diagram showing estimated values of permeability for an embodiment of the present invention.

[**0051**] **FIG. 5** is a chart showing results of an experimental study of permeability comparing an embodiment of the present invention with other structures.

[**0052**] **FIG. 6** is a chart showing results of an experimental study of the effect of mold compliance for an embodiment of the present invention.

[**0053**] **FIG. 7** is an image showing direct comparison of resin flow through the structure of an embodiment of the present invention (3WEAVE structure) compared with another structure (warp knit fabric).

[**0054**] **FIG. 8** is a perspective, top and side view illustrating a 3-D engineered structure of one embodiment of the present invention.

DETAILED DESCRIPTION

[**0055**] In the following description, like reference characters designate like or corresponding parts throughout the several views. Also in the following description, it is to be understood that such terms as “forward,”“rearward,”“front,” “back,”“right,”“left,”“upwardly,”“downwardly,” and the like are words of convenience and are not to be construed as limiting terms.

[**0056**] Referring now to the drawings in general, the illustrations are for the purpose of describing a preferred embodiment of the invention and are not intended to limit the invention thereto. Referring now to FIGS. **1-7**, experimental results are shown for testing one embodiment of the present invention, specifically including a 3-D woven fiberglas structure, hereinafter referred to as 3WEAVE type fabric as shown in **FIG. 8**, having a resin transfer medium including a three-dimensional engineered fiber structure having an X-direction fiber system, a Y-direction fiber system, and a Z-direction fiber system wherein the X-, Y-, and Z-direction fiber systems are selectively, alternatingly distributed with respect to each other forming three substantially orthogonal fiber systems within the structure, and wherein the X-, Y-, and Z-direction fiber systems form a series of spaced-apart, substantially parallel channels for distributing a fluid through the channels in each of the X-, Y-, and Z-directions, thereby providing a structure for uniform distribution of the fluid through the medium; the fluid is preferably a resin, where the medium is used for resin transfer distribution for composite materials production. The medium further provides that the X-, Y-, and Z-direction fiber systems are continuous within the structure. The fluid may be introduced to the structure by vacuum and/or using vacuum assisted resin transfer molding processes. The permeability of the structure is at least two times higher than conventional fabrics used for resin transfer molding, such as with the 3WEAVE type fabric used for the experimental testing and results as set forth hereinbelow.

[**0057**] The present invention also provides for a resin distribution system for use in resin transfer molding including a 3-D orthogonal fiber architecture having capillary channels therein for permitting a fluid to flow through the architecture, wherein the 3-D orthogonal fiber architecture further comprises X-, Y-, and Z-direction fiber systems, each of these fiber systems having substantially no crimp therein within a body of the architecture, thereby providing a system for distributing the fluid uniformly through the architecture. The X- and Y-direction fiber systems do not interlace with each other, thereby providing an internal in-plane openness of the architecture in the X- and Y-directions and no crimping of these fiber systems throughout the internal plane of the 3-D fiber architecture. Significantly, the architecture does not require any external resin distribution system for introducing the resin into a preform that is to be formed into a composite structure.

[**0058**] The present invention also includes a method for resin distribution including the steps of providing a resin transfer medium having three-dimensional engineered fiber structure having an X-direction fiber system, a Y-direction fiber system, and a Z-direction fiber system wherein the X-, Y-, and Z-direction fiber systems are selectively, alternatingly distributed with respect to each other forming three substantially orthogonal fiber systems within the structure, and wherein the X-, Y-, and Z-direction fiber systems form a series of spaced-apart, substantially parallel channels for distributing a fluid through the channels in each of the X-, Y-, and Z-directions; introducing a fluid into the medium, wherein the fluid is transferred throughout the structure, thereby providing uniform distribution of the fluid through the medium. The method may further including the step of providing a vacuum for assisting the fluid flow through the medium.

[**0059**] The present invention provides a system and a medium for improved resin distribution systems and methods for using the same for the production of fiber reinforced structures. In particular, it relates to improvements in the apparatus and methods for the production of fiber reinforced structures, especially to improve resin infiltration and impregnation times, resin distribution consistency, and reinforced fiber quality for such purpose.

[0060] Furthermore, one embodiment of the present invention system, medium, and method provides the following advantages and improvements over the prior art:

[0061] streamlines the process and eliminates an intermediate step that is not necessary.

[0062] alleviates the need for a conventional resin distribution system (RDS), because it constructs a preform that is capable of functioning as the primary RDS itself, and

[0063] there is no for any addition external devices of mediums to ensure consistent and efficient transfer of resin throughout the internal in-plane of the fiber reinforced plastic structure.

[0064] Fiber reinforced plastic structures have been commercially produced for some years, the processes for producing these structures requiring the incorporation of a reinforcing fiber, generally in the form of one or more layers of a woven or felted fiberglass, within a resin, or other fluent plastic material. Generally, resin transfer molding (RTM) and vacuum assisted resin transfer molding (VARTM) are known in the prior art for making fiber reinforced plastic structures.

[0065] Vacuum assisted, or vacuum bag techniques have been used in the past to form fiber reinforced plastic structures. In a vacuum bag technique, a flexible sheet, liner, or bag is used to cover a single cavity mold that contains the dry or wet fiber lay up. In accordance with the former, the edges of the flexible sheet are clamped against the mold to form an envelope and seal the member, a catalyzed liquid plastic or resin is generally introduced into the envelope, or bag interior, to wet the fiber, and vacuum is applied to the bag interior via a vacuum line to collapse the flexible sheet against the fiber and surface of the mold, while the plastic wetted fiber is pressed and cured to form the fiber reinforced plastic structure. Resin fumes from the process are prevented from escaping into the ambient work space.

[0066] One embodiment of the present invention systems, media, and methods for providing resin transfer and vacuum resin transfer via 3-D woven and/or 3-D engineered fiber structures of the medium or fabric itself (hereinafter referred to as "3TEX fabric"), as set forth in U.S. Pat. Nos. 5,465,760 and 5,085,252, entitled MULTI-LAYER 3-D FABRIC AND METHOD FOR PRODUCING and issued Nov. 14, 1995 to Mohamed et al. and METHOD OF FORMING VARIABLE CROSS-SECTIONAL SHAPED 3-D FABRICS issued Feb. 04, 1992 to Mohamed et al., which are incorporated herein by reference in their entirety, provides a uniform network of flow paths without requiring any distribution medium as taught in conventional resin transfer systems, including those patents and prior art references set forth in the foregoing, such as the SCRIMP patents. Even where 3TEX fabric may be used as a distribution medium itself to promote uniform resin transfer within a mold, the 3-D engineered structures, which include non-interlacing orthogonal yarn systems, or non-crossing X- and Y-fiber systems with vertical crossing Z-fiber systems, do not incorporate the same or similar components taught and claimed in the SCRIMP patents or prior art set forth in the foregoing, namely spaced-apart strands running crisscross one with another, and an open array of separated raised segments providing vertically oriented spaced-apart props or pillars, and spaced apart lateral openings between said props or pillars.

[0067] Vacuum assisted, or vacuum bag techniques have been used in the past to form fiber reinforced plastic structures. In a vacuum bag technique, a flexible sheet, liner, or bag is used to cover a single cavity mold that contains the dry or wet fiber lay up. In accordance with the former, the edges of the flexible sheet are clamped against the mold to form an envelope and seal the member, a catalyzed liquid plastic or resin is generally introduced into the envelope, or bag interior, to wet the fiber, and vacuum is applied to the bag interior via a vacuum line to collapse the flexible sheet against the fiber and surface of the mold, while the plastic wetted fiber is pressed and cured to form the fiber reinforced plastic structure. Resin fumes from the process are prevented from escaping into the ambient work space.

[0068] Whereas all the prior art deals with an external resin distribution device, there remains a pressing need for an apparatus and method for adequately and uniformly distributing resin throughout the internal in-plane of the reinforced fiber, and still requiring minimum labor but is still cost and time efficient, without the use of any external devices. The present invention streamlines the process and eliminates the need for an intermediate step, particularly the external resin distribution medium that is not necessary in the present invention. It completely eliminates the need for a resin distribution medium by manufacturing a 3-D orthogonal fiber architecture that actually serves as the primary resin distribution system, and there is no for any addition external devices of mediums to ensure consistent and efficient transfer of resin throughout the internal in-plane of the fiber reinforced plastic structure. Replacing an external resin distribution device with the present invention that provides an internal resin distribution device within the fiber reinforced 3-D architecture rectifies problems with inconsistent or uneven resin distribution and destroying or altering the value of the fiber reinforced plastics by the external device, while providing increased resin infiltration times, minimal operating labor, increase consistency and quality of the fiber reinforced structures.

[0069] Used in combination with the RTM and VARTM, 3-D fiber reinforced plastic structures, i.e. those with fibers oriented in an organized fashion in three dimensional space, have the greatest potential for improving mechanical performance, particularly resin distribution infiltration times, consistency in fiber reinforcement, increased fiber reinforcement quality, and cost effect advantages. A new generation of 3-D orthogonal fiber architectures, 3-D preforms, has recently become commercially available, enabling textile composites to achieve their potential across all sectors of advance composites market. The use of preform reinforcements with cost effective composite fabrication such as RTM, VARTM, and other resin distribution technologies offer a combination of both improved performance and lower cost.

[0070] The method according to one embodiment of the present invention for providing resin transfer and vacuum resin transfer via the a 3-D woven and/or 3-D engineered fiber structures of the fabric itself provides a uniform network of flow paths or channels within the body of the structure, since there is no fiber interlacing and therefore no crimp within the body of the structure, in particular in the X- and Y-direction fiber system planes, without requiring any distribution medium as taught and claimed in the prior art set forth in the foregoing background. Even where a 3-D engineered fiber structure, architecture, medium or fabric may be used as a distribution medium itself to promote uniform resin transfer within a mold, the 3-D engineered structures, which include non-interlacing orthogonal yarn systems, or non-crossing X- and Y-direction fiber systems with vertical crossing Z-direction fiber systems, do not incorporate the same or similar components taught and claimed in the prior art, namely spaced-apart strands running crisscross one with another, and an open array of separated raised segments providing vertically oriented spaced-apart props or pillars, and spaced apart lateral openings between said props or pillars.

[0071] The present invention provides a 3-D orthogonal fiber architecture formed from a three (3) fiber system, having fiber systems in each of the X, Y, and Z directions to provide an enhanced resin distribution system that works with all VARTMs and does not require an external resin distribution medium, which does not impede the flow of resin through the preform so as to improve resin infiltration and impregnation times, increases fiber reinforcement consistency, and fiber reinforcement quality, especially with the Z fibers serving as capillary channels, in-plane openness (with no in-plane jamming or buckling), the absence of interlacing between the warp and weft fibers (resulting in no crimping), the ability to manufacture composites with complex shape patterns. This invention eliminates the need for an external or additional resin distribution medium by developing a preform that in itself is the resin distribution system, formed by the 3-D orthogonal fiber architecture. This unique design according to the present invention facilitates the flow of resin throughout the preform resulting in a quicker and more even distribution of resin infiltration and impregnation.

[0072] One embodiment of the present invention provides a resin distribution system (RDS) and method for facilitating resin flow through fiber reinforced structures or preforms having a 3-D orthogonal fiber architecture. In a preferred embodiment of the present invention a 3-D orthogonal fiber architecture is used to increase resin infiltration and impregnation times, resin distribution consistency, and fiber reinforcement quality. Preferably a 3-D orthogonal fiber architecture is formed using three (3) yarn systems that are combined in a non-interlacing substantially orthogonal structure such as described in U.S. Pat. No. 5,085,252, which is incorporated by reference herein in its entirety, with enhanced in-plane shear strength when compared to previously known 3-D fibers as described in U.S. Pat. No. 5,465,760. A plurality of warp thread layers (X-direction fibers) arranged in parallel with a longitudinal direction of the fabric and defining a plurality of rows. A plurality of weft or filling thread layers (Y-direction fibers) arranged in parallel with a longitudinal direction of the fabric and defining a plurality of columns. A plurality of vertical thread layers (Z-direction fibers) arranged in parallel with a longitudinal direction of the fabric and defining a plurality of three dimensional columns. The fiber system comprising the warp and weft fibers run adjacent to one another and do not adhere, intersect, or crimp, which for the X and Y planes of the fabric architecture of the 3-D orthogonal fiber resin distribution system. The vertical thread layers (Z-direction yarn) also runs adjacent to the warp and weft (X and Y) fiber system and does not adhere, intersect, nor crimp within the in-plane of the fiber system. The vertical Z-direction fiber system crimps only at the ends of each face, but there is no crimping or interlacing within the in-plane of the 3-D orthogonal fiber architecture. Preferably at least one high performance fiber array is used such as S-2 and E-glass, various carbon fibers, various Kevlar, Spectra, metal wires, and optical fibers with sensors are successful for manufacturing 3-D fabric preforms. This design allows for integration of differing fiber types that may not adhere to the same resin in a composite. Where necessary to reduce through-thickness density, fibers of higher density are used. In a preferred embodiment, a less dense in-plane thickness is preferred so as not to impede the flow of resin. This particular 3-D orthogonal architecture is unique in its in-plane internal openness. The vertical fibers, Z-direction fiber system, provide the capillary channels for resin distribution throughout the internal in-plane of the preform, without the assistance of an external resin distribution medium. Additionally the X and Y direction fiber systems provide channels for resin distribution throughout the internal in-plane of the preform in their respective directions.

[0073] Thus, the present invention provides improvements in: 1) resin infiltration and impregnation times; 2) consistency in fiber reinforcement; 3) increased fiber reinforcement quality, by minimizing delamination; and 4) economic advantages in consolidation—particularly in resin infiltration and impregnation times, the elimination for the need of external resin distribution devices, and the ability of the applicants resin distribution system to function with any vacuum assisted resin transfer method (VARTM).

> **[0074]** Z fibers serve as capillary channels which serve as distributors for the resin throughout the preform
>
> **[0075]** Resin flow consistency is established—flow control , VARTM, anti-gravity, etc.
>
> **[0076]** The improved combination of 3TEX's resin distribution system (RDS) technology with the VARTM makes for the desired results of this invention—providing improvements in: 1) resin infiltration and impregnation times; 2) consistency in fiber reinforcement; 3) increased fiber reinforcement quality, by minimizing delamination; and 4) economic advantages in consolidation—particularly in resin infiltration and impregnation times, the elimination for the need of external resin distribution devices, and the ability of the applicants resin distribution system to function with any vacuum assisted resin transfer method (VARTM).

[0077] Benefits of the present invention using the 3TEX RDS include the following:

> **[0078]** 1. No additional external material is required for the resin distribution system (RDS) of the present invention to function; the 3-D, 3TEX fabric provides the RDS itself.
>
> **[0079]** 2. 3TEX's fiber system, because there is no interlacing and crimping, except for the ends of the z fibers, allows the use of inflexible fibers in the x and y planes.
>
> **[0080]** 3. Resin flow—it works with any VARTM, only the vacuum bag, an inlet for the introduction of the resin and an outlet for the vacuum are needed. The types of resin that can be used are not limited to epoxy or polyetheretherketone (PEEK).

[0081] 4. The vertical fiber layer (z-direction) can be at any desired angle depending on the desired shape. Also a five (5) fiber system, could be used as a RDS—but only those made by 3TEX, because it is significant that although the five (5) fiber system is not the best mode, as compared to the three (3) fiber system, that the internal in-plane architecture of all 3TEX's preforms are non-interlacing and exhibit no crimping. This particular unique characteristic minimizes the internal in-plane obstructions and does not impede the flow of resin when making a composite.

EXPERIMENTAL RESULTS

[0082] The unique, 3-D orthogonal structure of the present invention, including but not limited to the experimental trial using 3Weave™ fabrics, with results shown in FIGS. **1-7**, allows fast resin uptake during consolidation. Fast resin uptake can provide lower tooling costs, speed injection times, reduced wastage from short shots when using resin transfer molding. As a demonstration, we injected two preforms of nominally identical fiber, sizing, dimensions, areal weight, and resin type and recipe, using vacuum assisted resin transfer molding (VARTM). Preform **1** was a single ply of 3Weave™ 96 oz/yd^2 (3.2 kg/m^2) E glass, with an approximate preform areal weight distribution of 49%/49%/2% in warp/fill/z. Preform **2** was a laminate of four 24 oz/yd^2 (0.80 kg/m^2) plies of biaxial reinforced warp knits (for a total areal weight of 96 oz/yd^2/3.2 kg/m^2). Each ply of warp knit had a balance of areal weight between warp and fill. Both preforms were balanced and symmetric in the laminate sense. Both preforms were conditioned identically prior to injection. Both preforms were 24 inx24 in (61 cmx61 cm), and were stacked in identical layups of release ply and bleeder cloth. Both preforms were injected along a centerline, with resin removed from the edges parallel to the centerline injection, as shown in **FIG. 1**.

[0083] Both preforms were plumbed with the same lengths and diameters of hoses. Both preforms were injected with the same Reichhold Hydrex® 100 vinyl ester, which had been specially formulated for VARTM, using the same recipes of promotor and initator. Both preforms were injected at the same room temperature and relative humidity. **FIG. 2** shows one side of the resulting 3WEAVE and reinforced knit panels. Both are still in vacuum bags. Both panels wetted out essentially symmetrically about the centerline injection, as expected. The 3WEAVE panel wetted out completely, with the resin gelling in the exhaust lines as desired. The biaxial reinforced warp knit did not wet out completely. The resin gelled in about the same time, but could only wet out about two-thirds of the preform before gelling. The fact that the 3WEAVE preform, which provided one embodiment of the present invention medium for the purposes of experimental results, was successful in wetting out, i.e., in permitting fluid flow or resin distribution through the channels of the structure, when a conventional material, namely a biaxial reinforced weft knit, could not wet out or effectively transfer resin throughout the structure in nominally identical test conditions, demonstrates the permeability of the 3WEAVE architecture and the usefulness of 3WEAVE in resin transfer molding. The permeability of 3WEAVE and competing 0/90 glass reinforcements in VARTM, per project R000024 is shown in **FIGS. 5 and 7**. The need to quantify the flow characteristics of 3WEAVE fabrics was established in PDS 01020505. The following explains the methods used, the materials examined, and resulting permeabilities. One dimensional flow was simulated in thin E glass preforms, of about 96 oz/yd^2, infused with vinyl ester resin. Incremental flow speeds and resin viscosity were measured across the flow fronts. The resulting data was used to determine permeability, k, in the 0 (warp) and 90 (fill) directions in the preforms. The effect of mold surface compliance on preform permeability was also examined.

[0084] Preforms of one ply of 3TEX P3W-GE0001 (96 oz/yd^2 E glass rovings) have a permeability about four times that of three plies of BTI style 3205/108, a 0/90/mat reinforced warp knit, and about two to eight times that of four plies of 24 oz/yd^2 plain woven rovings. Both the 3TEX and the BTI fabrics were substantially more permeable in one direction than in the other. P3W-GE0001 is about four times as permeable in the fill direction than in the warp, when infused between two stiff surfaces. When infused between a stiff surface and a vacuum bag (a more typical method used in fabricating large parts), the fill direction permeability of P3w-GE0001 drops by about a factor of two. This agrees with experimental observation that the 3Weave™ structure permeability is dominated by flow in channels parallel to the fill direction, on the fabric surfaces. The report concludes by speculating on how this dominant flow mechanism may affect the permeability of other 3Weave™ preforms.

EXAMPLE 1

[0085] Test Matrix

[0086] Permeability has been determined so far for the following preforms and flow directions:

[0087] 1. 1 ply 3Weave™ style P3W-GE0001 (96 oz/yd^2 E glass), 0 direction.

[0088] 2. 1 ply 3Weave™ style P3W-GE0001, 90 direction.

[0089] 3. 4 plies Fibertech 24 oz/yd^2 plain woven E glass rovings, 0 direction.

[0090] 4. 3 plies BTI style 3205/108 0/90/mat reinforced warp knit, 0 direction.

[0091] We intend to take three data points for each preform and direction, to assess the confidence of the results. We will continue to test other materials and expand this database as interim results and future needs lead. Additional future tests already planned for the future is discussed below.

[0092] Experimental Set Up

[0093] The experimental set up is shown schematically in **FIG. 2**. 1-D flow was simulated by using a line inlet and a line outlet across a long strip of fabric of constant width, and allowing flow parallel to one of the orthotropic axes of the reinforcement. The preform was constrained between two pieces of plastic sheeting, with no bleeder, peel ply or distribution media to affect the flow. All preforms were cut to 13"±⅛"x26"±⅛". Cut lines were adhered with a thin line of 3M Spray 77 tackifier before cutting. Preforms were placed on a stiff, flat plastic bottom plate (the VARTM surface typically used in our shop) much larger than the preform, and a 12"x24" plastic upper plate was centered atop the preform. Care was taken to ensure that the preform was not sheared, so that the fiber directions in plane were parallel to the plastic top plate edges throughout the part. A line inlet for the resin to reach the preform was laid across the fabric exposed on one of the narrower edges. We used Fastenal 3/8" OD spiral wrap polyethylene pipe for consistency in all trials. Peel ply was draped over the exposed fabric on the opposite, narrower side, to form a line outlet for exhaust, and was connected to the vacuum pump via a 3/8' OD polyethylene tube.

[0094] The upper plate was marked with three lines, parallel to the flow direction, 2", 6", and 10" from the left edge (as viewed from the resin inlet side). These lines were denoted A, B, and C, respectively.

[0095] The entire assembly was bagged and evacuated and checked for leaks. A careful effort was made when bagging each preform, to ensure that the bag fit tightly to the edges of the upper plate. This proved sufficient to prevent race-tracking of the resin around the sides of the preform, and ensured a nearly uniform flow front.

[0096] When a vacuum seal was ensured, Dow Derakane 8084 was mixed with 0.3% by weight of 6% solution cobalt napthanate promotor and 1.5% by weight Akzo Nobel Trigonox 239A cumyl hydroperoxide initiator. This is a common recipe used in our shop, with a typical working life of 1.5 hours. For consistency, all chemicals were from the same batches. The mixed resin was then degassed for 5-10 minutes. Resin viscosity, □ was then determined with a Brookfield LVT analog viscometer (serial number 200642), bought for this project. Spindle speed was set at 6, and spindle size **1** was used in all measurements. The manufacturer's stated nominal viscosity for Derakane 8084 is 350 cP at 75F. We measured 310-335 cP at 78-80F during this initial study. We attribute the difference between nominal and measured values to typical styrene content variation noted in the resin's specifications, and to the slight change in measured temperature. Vacuum pressure was recorded from a Bourdon-type pressure gage (grade B: nominally accurate to ±2% of full vacuum). The liquid ring seal pump used gave vacuum pressures of 25-27 in Hg, depending on the temperature of the cooling water used in the pump. This pressure range is within the pump's specifications. Initial data showed vacuum pressure varied negligibly during each test, therefore, vacuum pressure was only recorded once for each test. Ambient temperature was also recorded at the start of each test. After measuring resin viscosity, the resin pot was coupled to the inlet line, and placed in a holder at a consistent height, about one foot lower than the preform. Infusion was started by releasing a clamp on the inlet line. A wall clock with a second hand was used to note the time at which the resin had filled the inlet pipe completely and was just beginning to infuse into the fabric. The leading edge of the flow front (i.e., the farthest advance of resin, where resin is flowing mainly between yarns instead of inside them) was marked on the vacuum bag with a permanent ink pen, across lines A, B and C at one minute intervals. The trailing edge of the flow front, where the part is fully translucent and essentially fully wetted out, tended to trail the leading edge by a constant distance throughout each test.

[0097] Initial study with a thermometer and viscometer demonstrated that resin viscosity (and temperature—another indicator of resin gelation) differed negligibly for the recipe used for at least one hour after mix. Therefore, to be conservative, the technician recorded data for less than 45 minutes after mixing the resin, typically stopping after about 20 minutes of flow. If the panels had not filled by that time, they were allowed to continue filling until either gelation or complete infusion.

[0098] After green cure, panel thickness underneath the upper plastic plate was measured in the corners, at mid edges, and at four points in the interior, using a deep throat caliper precise to 0.001", torqued to the clutch torque of the caliper. All twelve thicknesses recorded. All panels were labeled and archived for possible later use.

[0099] Theory

[0100] D'Arcy's law describes the flow of liquids through porous solids. It states that volumetric flow rate, Q, is proportional to the pressure gradient of the liquid, and is thus similar in form to Fick's law of diffusion and Fourier's law of thermal conduction. In D'Arcy's law, the proportionality constant is a function of geometry, liquid dynamic viscosity, μ, and the permeability of the solid medium, k. In the simplifying case where the flow is parallel to one dimension and perpendicular to gravity, D'Arcy's law may be written simply as:

$$Q=dP/dx*A\ k/\mu \tag{1}$$

[0101] where P is pressure, x is the flow direction, and A is the cross sectional area of flow. If the differential is approximated by a finite difference, equation (1) can be solved readily for k by data easily obtainable in the laboratory:

$$k=Q\mu\Delta x/(A\ \Delta P) \tag{2}$$

[0102] Note that permeability is actually a tensorial quantity in the general expression of D'Arcy's law. In general, k is highest along the three orthotropic axes of weaves, because resin generally flows faster parallel to fibers than perpendicular to them. The set up used can determine k in plane, but not through the thickness.

[0103] Permeability has been found experimentally to be sensitive to not only the viscosity but also somewhat sensitive to the chemistry of the flowing liquid. This is because the surface finish of reinforcement fabrics is generally intentionally reactive with infiltrating resins. For this reason, we measured permeability to actual resin, instead of silicone oils or other test liquids as have been used in some previous studies in the literature. Also note that k as determined in (2) depends on preform compaction. We used VARTM to give compactions relevant to the closed molding of large parts from 3TEX glass fabrics.

[0104] Analysis

[0105] The following assumptions were made for Example 1:

> **[0106]** 1. Panel thickness is constant in time and throughout the preform, and is the average of the twelve thickness measurements, t_{avg}. Flow area A for equation (2) was determined from t_{avg}. We believe that this is the most significant source of uncertainty in our calculations of permeability.
>
> **[0107]** 2. Resin volumetric flow rate is measured by the volume of resin needed to fill the entire void space between the measured flow front leading edge in successive minute intervals. While absolute resin volume would be inaccurate using this method, as the panel is not completely filled at the leading edge

of the flow front, volume flow rate is insensitive to this error, as long as the leading and trailing edges move at roughly equal speeds. This was observed to be the case.

[0108] 3. Resin viscosity μ is constant in time and equal to the initially measured value. This proved reasonable in practice (see above).

[0109] 4. Pressure drop due to viscous drag in the inlet line is negligible relative to the pressure drop due to the permeability of the fabric, i.e., the resin passing out of the inlet line and contacting the preform is at atmospheric pressure.

[0110] 5. Pressure difference ΔP is assumed constant and equal to the initially measured value. This proved reasonable in practice (see above).

[0111] 6. The pressure head loss of drawing the resin up about 12" into the preform is neglected. Given the resin's nominal density, this results in about a 3% error in ΔP. Since the accuracy of the pressure gage is ±2%, we believe this a reasonable expedient, and could be corrected for in later analyses of the test data.

[0112] 7. The first minute of data is discarded, because in the first minute, the resin leaving this inlet line and entering the fabric fills both forwards, towards the outlet, and backwards, to wet out the tail of the preform (see **FIG. 3**).

[0113] 8. The average length of resin flow, Δx, is calculated by $\Delta x = \text{average}(\Delta x_A, \Delta x_B, \Delta x_c)$, where Δx_i is the distance measured at a given time interval along line i.

[0114] The constant k was calculated for each one minute time interval during the test, using equation (2) and the above assumptions.

[0115] For the experiment, it was initially tried to place the resin bucket on a scale, and record resin mass flow directly at minute intervals from the scale. However, the mass of the stiff resin inlet line, and the resin it contains when full, is large relative to the modest amounts of resin needed to fill these small panels. As a result, motion in the inlet line as it deformed viscously under its own filled weight tended to significantly affect scale readings throughout the experiment. Therefore, we concluded that these mass measurements were not useful, and stopped recording incremental resin mass flow after initial trials.

[0116] Experimental Results

[0117] Table 1 shown below lists the permeabilities determined so far. They are plotted in **FIG. 3**. **FIG. 4** shows typical results from a single test. Values of $10^{-11}<k<10^{-9}$ m^2 have been reported in the literature for glass weaves and mats in closed molds, over a wide range of fiber volume fractions, therefore, this data is at least reasonable [1]. The coefficient of variation (COV) of each test fit is the COV of k determined for each time step. 5-20 time steps were recorded for each test, with slower flow through less permeable fabrics allowing more time steps. Results suggest significant differences in preform permeability, as seen in **FIG. 1**. In particular, the 3Weave™ architecture examined appears to have a significantly higher permeability than the woven roving laminate or the 0/90/mat stitched fabric laminate.

[0118] Large deviations in k (i.e., a coefficient of variation greater than 10%) correlated with technician's notes about unusual flow behavior. The most common example was racetracking around the edges of the preform. Permeability appeared to increase dramatically when the technician's notes indicated racetracking started, as expected. This could also be seen by large variations between □X_A, □X_B, and □x_c for a given time interval, caused by racetracking around one side of the preform. These results were ignored. The first test on k_0 for the 3TEX fabric was ruled erroneous by Chauvenet's criterion, and discarded in average permeabilities, plotted in **FIG. 5**. Table 1: Interim results from permeability study. Note that the stitched fabric contains both roving (denoted r) and mat (m).

		ply areal		preform	flow	permeability			Mold
fabric producer	fabric style	weight (oz/yd^2)	# plies	areal weight (oz/yd^2)	direction (deg)	k ($\times 10^{11}$m^2)	COV (%)	panel number	surfaces used
3TEX	GE0001	96	1	96	90	71	5%	E96x1V110701-2	plate-plate
3TEX	GE0001	96	1	96	90	87	5%	E96X1V120701-2	plate-plate
3TEX	GE0001	96	1	96	90	86	7%	E96x1V110701-1	plate-plate
3TEX	GE0001	96	1	96	0	48	16%	E96X1V120701-2	plate-plate
3TEX	GE0001	96	1	96	0	18	12%	E96X1V250701-2	plate-plate
3TEX	GE000l	96	1	96	0	22	11%	E96X1V250701-2	plate-plate
3TEX	GE0001	96	1	96	0	18	7%	E96X1V310701	plate-plate
3TEX	GE000l	96	1	96	90	42	8%	E96X1V020801	plate-bag
3TEX	GE0001	96	1	96	90	42	7%	E96X1V020801-2	plate-bag
3TEX	GE0001	96	1	96	90	42	5%	E96X1V020801-2	plate-bag
BTI	3205/108	36.5	3	96 r + 13.5 m	0	20	9%	CM32X3V240701-3	plate-plate
BTI	3205/108	36.5	3	96 r + 13.5 m	0	21	8%	CM32X3V240701-2	plate-plate
BTI	3205/108	36.5	3	96 r + 13.5 m	0	22	10%	CM32X3V240701	plate-plate
BTI	3205/108	36.5	3	96 r + 13.5 m	90	4.4	11%	CM32X3V010801	plate-plate
BTI	3205/108	36.5	3	96 r + 13.5 m	90	4.4	13%	CM32X3V010801-2	plate-plate
BTI	3205/108	36.5	3	96 r + 13.5 m	90	4.9	17%	CM32X3V010801-3	plate-plate
Fibertech	plain weave	24	4	96	0	5.9	13%	WR24X4V130701	plate-plate
Fibertech	plain weave	24	4	96	0	8.1	5%	WR24X4V180701	plate-plate

-continued

fabric producer	fabric style	ply areal weight (oz/yd^2)	# plies	preform areal weight (oz/yd^2)	flow direction (deg)	permeability k ($\times 10^{11}$m^2)	permeability COV (%)	panel number	Mold surfaces used
Fibertech	plain weave	24	4	96	0	8.1	25%	WR24X4V170101	plate-plate
Fibertech	plain weave	24	4	96	0	6.4	14%	WR24X4V170701	plate-plate

[0119] The effect of mold compliance on preform permeability is shown in **FIG. 6**, which plots permeability results for a single ply of P3W-GE0001 infused both between two stiff plates and between a stiff plate and a 0.003" thick nylon vacuum bag. A vacuum bag top may better simulate infusion of large parts than between two flat plates. The more compliant bag was able to pull into the ridges between outer fill yarns. The resulting composite panels thus had a (relatively) smooth bottom and rough top. Using a vacumm bag as the top mold surface reduced fill permeability by about a factor of two, apparently by disallowing flow in channels in the fabric surface. The value k_0 was not measured between a stiff plate and a vacuum bag.

[0120] Referring now to **FIG. 4** the permeability for panel E96X1V120701-2, is shown, as determined by D'Arcy's law, using the assumptions described in the Analysis section. The blue line with diamonds indicates permeability, k, determined for each time interval of the test. The pink line with squares indicates average k, after ignoring first data point (see Analysis).

[0121] Referring now to **FIG. 5** the average measured permeabilities k_0 and k_{90} of three preforms, infused in VATM between two stiff plates is shown.

[0122] Referring now to **FIG. 6** the effect of mold compliance on 3WEAVE preform permeability is shown. Permeability of one ply of P3W-GE0001 between two stiff plates (representative of infusion in a mold with two hard faces) is compared to permeability between a stiff plate and a vacuum bag (representative of VARTM of large parts).

[0123] Permeability of Preforms Examined

[0124] The one ply P3W-GE0001 preform was about four times as permeable as the comparable areal weight, three ply style 3205 warp knit preform, when infused between two stiff plates, and about twice as permeable as three plies of style 3205 when infused between a stiff plate and a vacuum bag. This is despite the fact that the warp knit contained mat on one surface of every ply, whose permeability is high relative to woven rovings, and is therefore used to enhance laminate wet out [1]. Both these materials were much more permeable in the direction of rovings on the fabric surface (90 for the 3Weaver™ and 0 for the warp knit) than perpendicular to the direction of rovings on the fabric surface. In both cases, this appears to be because resin racetracks along interstices between outer fill yarns, hence, 3Weave™ in-plane permeability appears dominated by surface roughness, with permeability increasing with increasing surface roughness. As a result, 3Weave™ permeability decreases when used between a flat surface and a vacuum bag, as the bag reduces the size of the bag-side channels. Our casual experience with unbalanced 3Weave™ fabrics is that they are generally more permeable in the high fiber fraction direction, as would be expected. The balanced, symmetric plain woven rovings should have nearly equal permeabilities in both 0 and 90 directions, but did not measure k_{90}). A third permeability, which we cannot measure, is permeability through the fabric thickness, k_z. This may be critical in thick parts, where areal wetting will be provided by a highly permeable layer, such as transfer media used in SCRIMP, but through-thickness wetting must come from the inherent permeability of the fabric architecture. Additional, unquantified experience suggests that k_z for 3-D weaves is greater than for laminates of 2-D reinforcements with similar in-plane yams.

[0125] Implications for Tailoring Preform Permeability

[0126] Results of this study suggest that, when high permeability is needed in fabrics similar to the balanced, symmetric P3W-GE0001, flow should be parallel to the fill direction. At this time, no data is available for the permeabilities of highly imbalanced 3WEAVE type preforms. It has been observed that highly imbalanced 3-D structure preforms, with much more warp weight than fill, are more permeable in the warp direction. If the 3-D structure permeability is dominated by surface roughness, then z yarn size and tension, which control the crimp in the outermost fill layer, could be used to tailor permeability. In general, increasing crimp in the outermost fill yams, when the preform is compacted in a mold, should decrease k_{90} and may increase k_0.

[0127] Photomicrographs of laminates of 3Weave™ have repeatedly shown that the fabric nests readily when laid up warps parallel. This would probably result in higher fiber volume fraction and interlaminar strengths. In light of the effect that eliminating ply surface channels has on fill permeability (**FIG. 6**), the in-plane permeabilities of 3WEAVE type 3-D structure laminates will probably be less likely than those of single plies. In contrast, laying 3WEAVE up as a cross ply (i.e., $[0/90]_n$) should tend to create resin rich interfaces, with lower interlaminar strengths, and a lower overall fiber volume fraction, but with a higher preform permeability.

[0128] If 3WEAVE type 3-D structure in-plane permeability is dominated by surface roughness, then high permeability will conflict with the need to reduce resin print-through by using smoother fabrics. In hard surface molds, one way to compromise between these two needs would be asymmetric fabrics, such as P3W-GS0002 (90 oz/yd^2 S-2 glass), with one coarser and one smoother side. The coarser side would assist flow parallel to the fill, and the smoother side could be placed towards the part outer surface. Results from this study suggest that asymmetric fabrics would make a less effective compromise between aesthetics and permeability in more typical VARTM molding, between a tool surface and a vacuum bag, however.

[0129] Ultimately, materials other than tows or rovings could be included at discrete locations into a 3Weave™ design, to serve as a resin distribution network. Materials such as springs, which had high permeability and hoop strength (to prevent collapse during compaction), could be substituted for selected tows during draw in. This would probably reduce composite stiffness, fiber volume fraction, and density, but could dramatically improve preform permeability, perhaps even to the point of obviating the need for complex plumbing for VARTM infusion of medium-sized parts.

[0130] The through-thickness permeability, k_z, was not measured in this experiment; it is expected to be estimated as higher than planar-reinforced fabrics of prior art, which would correspond to a wet out of thick preforms, especially those wet out by through-thickness permeability dependent infusion processes like SCRIMP-type prior art.

[0131] Experimental Method

[0132] It was found that bagging technique can eliminate race tracking, giving lower coefficients of variation in k determined for each time interval in a test. Improving bag technique correlated with standard deviation in experimental k values, which decreased as the test matrix developed, indicating that results became more repeatable with experience in testing. Because this test is dependent on manual technique, one technician performed all tests, to minimize variation due to multiple technicians. Race tracking appeared to be less of a concern with higher permeability fabrics, which impede normal flow less. This tendency may explain the high COVs in the lower permeability plain weaves and warp knits. An examination of test uncertainty suggests that most uncertainty in this test method comes from assuming that the panel is of constant thickess, t_{avg}, and thus that the flow area is constant. It is well known that VARTM parts are thicker near the resin inlet than the resin outlet. For a given preform, increasing thickness decreases fiber volume fraction, allowing greater space for resin passage, and thus increases permeability. To circumvent the uncertainty in measured part thickness, many other studies have used closed molds (which precisely define thickness, but result in more arbitrary preform compactions and fiber volume fractions). Others, performed at CCM, have used overhead laser distance finders to raster across the bag during testing to record bag swelling that accompanies the resin flow front. The first method is objectionable, because results may not correlate with typical production fiber volume fractions. I believe the second method is prohibitively expensive for 3TEX to set up. We can contract the use of such a more accurate (and more expensive) set up to CCM.

[0133] Because it is estimated that $Q=w\ t_{avg}\ \Delta x/\Delta t$, and the flow cross sectional area is $A=w\ t_{avg}$, systematic errors in using the average consolidated thickness should tend to cancel out of the denominator and numerator of equation (2). Alternately, we could measure volumetric flow rate directly by driving the resin with a calibrated, positive displacement pump, such as the peristaltic pump in our shop. For the assumption of a (n essentially) constant volumetric flow rate with a resin metering pump, the pressure head would change over time according to equation (2). Therefore, an additional pressure gage between the pump outlet and the vacuum bag would need to be installed. The gage would be exposed to liquid resin, and would need to be removed and cleaned before green cure with every test. Recording this additional data would also add difficulty to the technician's job. Additionally, previous experience with a positive displacement pump shows it could easily produce sufficient pressure head near the end of the experiment (when the entire preform length resists flow) to 'float' the bag, pumping resin between the vacuum bag and the plastic top plate. When the resin is thus forced through passages other than the preform, the apparent permeability measured is no longer only that of the preform, but that of the entire assemblage, and therefore loses meaning.

[0134] Conclusions

[0135] A method was developed for determining in-plane preform permeability in VARTM, using mostly stock equipment in the RTM shop in Cary. 3WEAVE fabric, 0/90/mat-reinfored warp knits, and plain weaves of E glass rovings, all plied to preform areal weights of about 96 oz/yd^2, were infiltrated with a vinyl ester resin typical of those used in VARTM, using two stiff plastic sheets as a mold. Resin flow appeared to be dominated by resin travel between surface tows, and thus to increase with increasing surface roughness. The 3WEAVE type fabrics and warp knit fabrics both had about four times higher permeabilities in the direction of surface tows (90 direction for 3WEAVE, and 0 direction for the warp knit) than in the perpendicular direction. The 3WEAVE permeabilities were about four times higher than the warp knit laminate permeabilities. The 3WEAVE was two to eight times more permeable than the plain weave laminate, depending on direction. When the one mold surface was replaced by a vacuum bag (to simulate more typical VARTM conditions), resin channels on the fabric surface were blocked, and the (faster) fill direction permeability of the 3WEAVE dropped by about a factor of two.

[0136] References

[0137] [1] K. van Harten, "Chapter 4: Production by Resin Transfer Molding". In R. A. Shenoi and J. F. Wellicome, *Composite Materials in Maritime Structure, Volume* 1: *Fundamental Aspects*. Cambridge Ocean Technology Series. Cambridge University Press, Cambridge, UK, 1993.

[0138] **FIG. 7**: Equal size and areal weight VARTM E glass/vinyl ester panels, processed under same conditions, from 3Weave™ and biaxial reinforced warp knits. Each panel 24 in×24 in (61 cm×61 cm), with 96 oz/yd2/3.2 kg/m^2 of cloth. Flow direction parallel to warp. Both composites were balanced and symmstric. Top: one ply of 3Weave™. Bottom: Four plies of 24 oz/yd^2 (0.80 kg/m^2) E-glass biaxial reinforced warp knit.

[0139] Certain modifications and improvements will occur to those skilled in the art upon a reading of the foregoing description. By way of example,

[0140] All modifications and improvements have been deleted herein for the sake of conciseness and readability but are properly within the scope of the following claims.

What is claimed is:

1. A resin transfer medium comprising:

a three-dimensional engineered fiber structure having an X-direction fiber system, a Y-direction fiber system, and a Z-direction fiber system wherein the X-, Y-, and Z-direction fiber systems are selectively, alternatingly distributed with respect to each other forming three substantially orthogonal fiber systems within the structure, and wherein the X-, Y-, and Z-direction fiber systems form a series of spaced-apart, substantially parallel channels for distributing a fluid through the channels in each of the X-, Y-, and Z-directions, thereby providing a structure for uniform distribution of the fluid through the medium.

2. The resin transfer medium according to claim 1, wherein the X-, Y-, and Z-direction fiber systems are continuous within the structure.

3. The resin transfer medium according to claim 1, wherein the fluid is a resin.

4. The resin transfer medium according to claim 1, wherein the fluid is introduced to the structure by vacuum.

5. The resin transfer medium according to claim 1, wherein the fluid is introduced to the structure using vacuum assisted resin transfer molding processes.

6. The resin transfer medium according to claim 1, wherein the permeability of the structure is at least two times higher than conventional fabrics used for resin transfer molding.

7. A resin distribution system for use in resin transfer molding comprising a 3-D orthogonal fiber architecture having capillary channels therein for permitting a fluid to flow through the architecture, wherein the 3-D orthogonal fiber architecture further comprises X-, Y-, and Z-direction fiber systems, each of these fiber systems having substantially no crimp therein within a body of the architecture, thereby providing a system for distributing the fluid uniformly through the architecture.

8. The system according to claim 7, wherein the X- and Y-direction fiber systems do not interlace with each other, thereby providing an internal in-plane openness of the architecture in the X- and Y-directions and no crimping of these fiber systems throughout the internal plane of the 3-D fiber architecture.

9. The system according to claim 7, wherein the architecture is does not require any external resin distribution system for introducing the resin into a preform that is to be formed into a composite structure.

10. A method for resin distribution comprising the steps of:

providing a resin transfer medium having three-dimensional engineered fiber structure having an X-direction fiber system, a Y-direction fiber system, and a Z-direction fiber system wherein the X-, Y-, and Z-direction fiber systems are selectively, alternatingly distributed with respect to each other forming three substantially orthogonal fiber systems within the structure, and wherein the X-, Y-, and Z-direction fiber systems form a series of spaced-apart, substantially parallel channels for distributing a fluid through the channels in each of the X-, Y-, and Z-directions;

introducing a fluid into the medium, wherein the fluid is transferred throughout the structure;

thereby providing uniform distribution of the fluid through the medium.

11. The method according to claim 10, further including the step of:

providing a vacuum for assisting the fluid flow through the medium.

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