

# **NOVEL THERMOPLASTIC FOAM STRUCTURAL CORE MATERIAL WITH ENHANCED THERMOFORMABILITY, FATIGUE ENDURANCE AND ELEVATED TEMPERATURE PROPERTIES**

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## **Abstract**

Recent advances in thermoplastic resin chemistry have enabled the development of a thermoplastic polyester foam core material with excellent thermoformability, elevated temperature and chemical resistance, and superior fatigue endurance. Possessing high strength and rigidity, this foam product fulfills the demanding requirements for structural core materials used in sandwich composites, though it can be successfully used without facings for many applications. Presented will be the physical properties, including at elevated temperatures, in comparison with rigid polyurethane foams and other core materials. The results of an extensive sandwich flexural fatigue study will also be reviewed and discussed. Finally, examples of complex thermoformed shapes will be shown, both of the foam, alone, and in combination with GMT facings to form contoured structural sandwiches all at once.

## **Introduction**

Sandwich composite designs, wherein a lower-density core has been laminated between two relatively thin but high tensile strength facings or “skins,” are successfully employed in a wide variety of applications that require lightweight, yet structurally strong and stiff constructions. To name but a few, structural sandwich composites are used in marine, aerospace, transportation, industrial applications. Structural sandwich composites are useful because the inclusion of a low-density core provides substantial enhancement in strength and stiffness versus using just the skin material alone, but adds only a small amount of weight per unit area (1).

The comparative properties of a structural core material are especially important. Desirable properties include high strength and rigidity, low density, high chemical and heat resistance, and low cost. How well a core material functions in a structural sandwich in real-world applications can be predicted from laboratory test measurements of its respective compressive, tensile and shear strengths and moduli. As for other market applications, automotive sandwich construction must be cost-effective in comparison to steel-forming or glass-mat technology (GMT) consolidation, which translates to the requirement for the capability to thermoform the core during the forming, curing or bonding of the skins that are employed. The most common core materials used in all sandwich applications include wood, honeycomb structures, and foams comprised of both thermoplastic and thermosetting compositions.

Wood core materials suffer from variations in properties and are susceptible to water uptake and possibly fungal decay, especially when used in applications where moisture is present. Honeycomb cores have an open-celled structure, i.e., they are comprised of contiguous, connected, and/or interlocked cells, and typically are constructed from rigid materials, such as thermoplastics, fiberglass, aluminum, and stainless steel. While honeycomb core materials provide for strong, high-performance composites, their open-celled geometry is a particular disadvantage. The connective nature of the cells precludes composite manufacture by vacuum-mediated resin-infusion techniques such as vacuum-assisted resin transfer molding (VARTM)

because the applied vacuum draws resin into the individual cells. Furthermore, honeycomb cores cannot be cold- or thermo- formed and must be pre-crushed in order to render them sufficiently contourable. Lastly, honeycomb cores are not recommended for applications where moisture is present because of the tendency of their cells to fill with water.

Closed-cell thermoplastic or thermosetting foams avoid many of these problems. Those finding a growing utilization in automotive sandwich applications are comprised of polyurethane as well as polyolefin compositions such as polypropylene and polyethylene, although the latter are typically used for relatively non-structural applications. Both amorphous as well as semi-crystalline thermoplastic resins may be expanded into foam, although amorphous resins are generally more thermally or chemically sensitive than semi-crystalline resins. Certain solvent-containing adhesives or resins used for bonding or creating composite skins can significantly degrade them and, during lamination, the temperatures required for curing thermosetting adhesives can often exceed their practical thermal limits.

Foams based on thermoplastic polyester resins are a relatively recent development, due in the past to a lack of availability of suitable foaming grades. Advances in resin modification, primarily through reaction treatments to create polymer chain "branching," have opened opportunities for this thermoplastic foam. The branching agents, which have multiple chemical-reaction sites, function by chemically condensing two or more polyester chains. Polyester foams prepared from branched polyesters, especially polyethylene terephthalate (PET), have been referenced often in the literature (2-6). When melt-extruded with a suitable physical or inert gas blowing agent, these branched thermoplastic polyester resins yield closed-cell foams with the potential for a low density, good mechanical properties, and high chemical and thermal resistance (7).

Unfortunately, due to the process used for their manufacture, such foams are often inferior core materials because of wide cell-size distribution and oversized cells, which leads to poor mechanical properties. In the references mentioned above, thermoplastic polyesters are generally foamed by extruding a pressurized mixture of a branched-polyester melt and a volatile, organic expanding or "blowing agent," or a dissolved inert gas, through an annular or slot die. Upon entering ambient pressure, the blowing agent expands the polyester resin resulting in a foamed structure. This process suffers in that if the die opening surpasses a critical limiting cross-sectional area, the required "back pressure" necessary to prevent foaming within the extruder cannot be maintained. Furthermore, as the extruded material's thickness is increased (i.e., larger die opening) to that which is in general use for core materials, blowing-agent evaporation throughout the material becomes non-uniform leading to erratic cell-size distribution, oversized cells, and an irregular surface.

Coalesced-strand thermoplastic foams are more suitable as core materials because they can be produced in greater thickness, exhibit a smaller cell-size, and a more even cell-size distribution (8-9). Generally, coalesced-strand thermoplastic foams are prepared by melting a thermoplastic resin, injecting a volatile organic or inert gas expanding agent, mixing the expanding agent with the melt, and extruding the resulting gel through a multi-orifice die. The orifices are arranged such that some contact between adjacent strands occurs during the subsequent foaming, and they adhere to one another resulting in a coalesced-strand structure. Previously cited coalesced-strand foams, however, were comprised of tenacious but low rigidity thermoplastic resins, such as polypropylene or polyethylene, which may have been advantageous in producing articles for certain applications such as automotive shock absorbers (10). Coalesced-strand foams based on these polyolefin resins were not developed or promoted for use as a structural core material since they exhibited poor performance in the metrics essential for structural cores.

## **Preparation of Foam Samples**

In this work, a foamable grade of semi-crystalline polyethylene terephthalate (PET) was processed into coalesced-strand foam planks over a broad range of densities, from 80 to 400 kg/m<sup>3</sup>, with a large cross-section of up to 60 mm x 400 mm, by use of a two-stage, single-screw extruder as well as twin-/single- and single-/single-screw tandem extruders fitted with multiple-orifice die technology. Intra-strand voids were eliminated by using a specially designed shaper resulting in a core material with a unitary cross-section. In the following sections, the physical, chemical, thermo-mechanical properties of coalesced-strand PET foam are discussed, and potential “near-net shape” processing such as thermoforming is illustrated with multiple examples.

## **Characterization of PET Coalesced-Strand Foam**

The performance of a core material in a structural sandwich can be predicted from knowledge of its compressive, tensile and shear strength and modulus. Additional properties of importance for core materials include chemical, heat and water resistance.

The density of the coalesced-strand foam was determined according to ASTM D 1622-98 “Standard Test Method for Apparent Density of Rigid Cellular Plastics” (11). The open-cell content of this experimental foam was characterized according to ASTM D 2856-98 “Standard Test Method for Open-Cell Content of Rigid Cellular Plastics by the Air Pycnometer” using a sample size of 15 cm x 15 cm x 3 cm (12).

The compressive properties the PET coalesced-strand foam boards were measured according to the procedure described in ASTM C 365-00 “Standard Test Method for Flatwise Compressive Properties of Sandwich Cores,” in a direction both parallel and perpendicular to the strand direction (13). The sample size used for this testing was 5.08 cm x 5.08 cm x 1.27 cm.

The tensile strengths and moduli, in a direction perpendicular to the plane of the core material, were measured according to ASTM Test Method C 297-94 “Standard Test Method for Flatwise Tensile Strength of Sandwich Constructions” (14). This test consists of subjecting a sample to tensile loads by withdrawing steel fixturing blocks bonded directly to the foam samples, which in turn were of dimensions 5.08 cm x 5.08 cm x 1.27 cm. Testing was performed in a direction both parallel and perpendicular to the strand direction.

Foremost among the various stresses imposed on a structural sandwich core material is “in-plane” shear, or shearing due to the facings displacing with respect to each other. As with an I-beam, structural sandwich beams that are simply-supported at their ends will transmit loads applied to their top “compression” skin, down to their bottom “tension” skin, through the core in shear. The shear strengths and moduli were measured according to the procedures set forth in ASTM C 273-00 “Standard Test Method for Shear Properties of Sandwich Core Materials” (15). This standard describes the determination of the shear strength, modulus and ultimate shear elongation in a direction parallel to the core material’s plane. This test was conducted on foam samples having dimensions of 5.72 cm x 15.24 cm x 1.27 cm, bonded directly to steel loading plates, and shear properties were individually determined in directions perpendicular to, transverse to, and parallel with the strand direction.

The shear strength of a structural core material may also be determined by performing flexural testing of sandwich beam specimens containing the core material in question, but employing over-designed (thick) facings, so that failures occur exclusively within the core. The methods described in ASTM C 393-00 were used to characterize the core’s static shear

strength in bending (16). Thus, 20 mm thick cores, in the range of densities of 300 to 450 kg./cu.m., were laminated on both sides with three plies of a 2408 knitted E-glass fabric using vinylester resin, then 75 mm x 460 mm sandwich beam specimens were cut from the laminated panels. Static flexural testing was performed in three-point bending on a support span of 425 mm and, utilizing the calculations from ASTM C 393-00, core shear strength and sandwich flexural stiffness were thus determined.

Following static testing, and as part of a comprehensive study to investigate core material suitability for application in marine sandwich transoms, additional specimens were evaluated for fatigue endurance by employing load-controlled, cyclical flexural testing at +/- 75%, +/- 50% and, for some of core material variants, +/- 25% of their respective average static failure load (17). Fully-reversing ( $R = -1$ ), that is equal load applied in both directions, load-control was employed to minimize the chance for progressive shear creep, a phenomenon that can occur for "plastic-elastic" core compositions that are loaded in one direction only. In addition to the novel coalesced-strand PET foam core of this work, core materials for this particular study, all of which were in the density range of 320 to 480 kg./cu.m., included two glass-reinforced and one un-reinforced polyurethane cores all obtained from the field.

For structural core materials used in applications exposed to water, resistance toward water absorption is very important. Water absorption testing of PET coalesced-strand foam was conducted according to the ISO 2896-87 method, involving immersion of test samples in artificial sea water (DIN 50905) maintained at 40 °C for 7 days (18, 19). Samples were cut with dimensions of 5.08 cm x 5.08 cm x 1.80 cm and weighed. After immersion, the samples were removed, blotted off with a dry paper towel, then re-weighed. The individual sample's weight gain was divided by the sample's surface area and reported in units of kg./sq.m.

Unsaturated polyester and vinylester thermosetting resins are frequently used in the production of sandwich components for automotive applications. Typically accomplished by using "closed-mold" processing, the required reinforcements (usually E-glass) are placed on both sides of the intended core material and this assembly is placed into a heated, matched-metal tool, then the resin is injected to saturate and fill out the skin around the part. Thus, resistance toward warm polyester resin can be a critical requirement for such core materials since the contained styrene monomer, an aggressive aromatic hydrocarbon solvent, can shrink and even dissolve certain core material compositions. The warm polyester shrinkage tests were conducted as follows: samples of the PET coalesced-strand foam were cut with dimensions of 3.81 cm x 3.81 cm x 1.27 cm, weighed, then immersed for 30 minutes into an uncatalyzed general purpose (GP) ortho-phthalic unsaturated polyester resin maintained at 71 °C. Upon removal, specimens were allowed to cool, blotted-off, then dimensioned and re-weighed. The resulting percentage change in specimen volume (negative if shrinkage) and percentage weight gain due to absorbed resin were used as indications of the degree of styrene attack and invasion into the foam structures.

## Results and Discussion

### Mechanical and Physical Properties

As mentioned above, generally coalesced-strand thermoplastic foams are prepared by melting a thermoplastic resin, injecting a suitable blowing agent into the melt, mixing, and extruding the resulting gel through a multi-orifice die. The expanded strands are forced or pulled through a suitable shaping device where they are compressed together, thereby removing the intra-strand voids. The PET coalesced-strand foam boards of this study appeared to be unitary, as illustrated in Figure 1, photos of the foam planks, bonded in this case into a block, and the foam cell configuration within and around an individual strand. This result is suggestive of a “foam-filled, foamed honeycomb” structure wherein the honeycomb cell walls are of higher density foam, while the interiors are of a lower density.

The absence of inter- and intra-strand voids is largely confirmed by test results of the open-cell content, which are reported in Table I. This table shows that the PET coalesced-strand foams of this study exhibited an open-cell content of only 15% to 20%. Further confirmation of the absence of voids may be seen from the ISO 2896-87 water absorption test results presented in Table II, suggesting a high resistance toward water ingress. Absorption of water by PET thermoplastic resin is negligible, as demonstrated by its wide utilization in blow-molded beverage containers. The ISO 2896-87 water absorption test is specified by Det Norske Veritas (DNV), a major shipbuilding and material “type-approval” classification agency, and the response of the PET coalesced-strand foams of this study was well below the 1.5 kg./sq.m. requirements of DNV (20).

Prior to a discussion of physical properties, a brief glossary is necessary. For purposes of this work, “strand direction” means along the strand’s length direction that the core material was extruded during production. If core panels are cut such that the strand direction goes through the thickness of the panel, this is referred to as the “end-strand” orientation. For panels cut wherein the strands lie in the plane of the core panel, shear testing may be accomplished in two, distinct directions. If the strands are oriented in the direction of the shear testing forces, this is referred to as the “longitudinal direction.” Appropriately, if the strands are 90° to the shearing direction, it is called “transverse” direction. For flatwise tensile testing, there is no distinction between longitudinal or transverse in the case that the strands lie in the plane of the core material, so to avoid confusion that orientation will be called “transverse.”

These coalesced-strand PET foams are significantly anisotropic in nature, since they exhibit different physical properties depending upon the direction, with respect to the strands, that the property is measured. Referring to Figures 2 through 8, the PET coalesced-strand foams of this study exhibited different shear, tensile, and compressive properties depending upon the direction along which that property was measured. Although the strand character of the core materials may have not been visible for some of the higher density variants, the anisotropic character is readily apparent in the results of the mechanical property testing.

Thus, ASTM C 273 shear testing was conducted on specimens cut from end-strand, transverse, and longitudinal core panels. The results are presented in Figures 2, 3 and 4, for shear strength, shear modulus, and ultimate shear elongation, respectively. The differences in shear strength with orientation ranged from about 60% greater in the end-strand versus transverse direction at the lower densities to about 130% greater at the higher densities. The substantial increase in shear strength in the end-strand direction, and similarity for transverse or

longitudinal results, is supportive of this “foam-filled, foamed honeycomb” product concept described earlier. Honeycomb core materials comprised of aramid fiber paper (i.e. NOMEX™ - Dupont Co.), or of aluminum foil, elicit a similar response. Usually honeycomb cores are cut so that their cells are oriented through the thickness of the core panel. Similar enhancements in shear modulus and ultimate elongation for the end-strand orientation, as opposed to the transverse or longitudinal, were obtained for the coalesced-strand PET foams of this study, as illustrated in Figures 3 and 4.

As well, ASTM C 297 flatwise tensile testing was conducted in both the end-strand and the transverse directions. The results are presented in Figures 5 and 6 for tensile strength and tensile modulus, respectively, showing that the tensile properties also depended upon the direction of the applied forces in relation to the strand direction. Roughly, the tensile strength in the end-strand direction was nine times greater than in the transverse direction over this density range. More dramatically, the tensile modulus in the end-strand direction was as much as eleven times greater than in the transverse direction.

Similarly, ASTM C 365 compression testing was conducted in the end-strand direction and the transverse direction. Those results are shown in Figures 7 and 8, for compressive strength and modulus, respectively. Consistent with the previous trend for shear and flatwise tensile testing, a substantial enhancement in compressive strength and modulus was observed in the end-strand orientation. End-strand compressive strength was up to about 4 times greater, and compressive modulus was up to about two times greater, than in the transverse direction over this range of densities.

To summarize, the resulting properties for shear, tensile and compression testing revealed that the core materials of the work are significantly anisotropic in character. Furthermore, the optimal orientation for each physical property was in every case the same – with strands oriented through the thickness of the core’s plane – leaving no performance compromises in the three primary stresses that a structural core material experiences in actual application. This behavior demonstrates the unique advantage toward coalesced-strand foams as structural core materials, as compared to foam boards produced by extruding the same resin through a conventional rectangular slot die, resulting in a relatively anisotropic cell configuration.

In Figures 9 through 14, the shear, flatwise tensile and compressive properties of the coalesced-strand PET foams of this work are compared to the data sheet values for a commercially available, general-purpose polyurethane (GP-PUR) foam composition (21). Also utilized in automotive structures are foams based on polypropylene, although comparative data were not readily available from any manufacturer and only one density of polypropylene foam had been characterized in the laboratory of these authors. Thus, a commercially available polypropylene honeycomb’s data sheet properties were instead included (22). As mentioned before, the honeycomb geometry is the optimal configuration for any composition used as a structural core material, thus an anisotropic foam based on polypropylene would be expected to exhibit properties no better than the included honeycomb core.

Briefly reviewing the comparative properties, coalesced-strand (CS) PET foams of this work exhibited superior shear strengths, and especially shear moduli, in comparison to the GP-PUR or polypropylene honeycomb (PP-HC) cores of comparison, as evidenced in Figures 9 and 10. Shear properties for the one density of polypropylene foam that had been tested by this lab are also included in these figures, and appear to be consistent with the density-property trends of the polypropylene honeycomb.

With reference to Figure 11, the flatwise tensile strength for CS-PET and GP-PUR foams were comparable at the lower densities, favoring the polyurethane foam at the higher densities.

As for shear modulus, Figure 12 illustrates the superior flatwise tensile moduli that accompany the CS-PET foamed structure. Flatwise tensile data for the PP-HC core was not available.

Figures 13 and 14, for flatwise compressive strength and modulus, respectively, reveal roughly equivalent results for the CS-PET foams of this work and the GP-PUR foam at lower densities. However, by exclusively orienting a core's composition through the thickness in a honeycomb pattern, optimal compressive properties would be expected, as illustrated by the polypropylene honeycomb's superior compressive response in Figures 13 and 14.

### **Static Shear Strength and Fatigue Endurance in Flexure**

To reiterate, cores for the static and flexural fatigue testing were laminated with over-designed facings to ensure that failures in flexural testing occurred exclusively within the core. Included were both a 320 kg./cu.m (PET-CS 20) and a 400 kg./cu.m. density (PET-CS 25) coalesced-strand PET foam of this work. Both of these coalesced-strand PET foam variants had strands oriented in the plane of the core specimen, since this is the preferred orientation for this product at these an elevated density. A general purpose polyurethane foam without glass-reinforcement, PUR-U, also at a density of 400 kg./cu.m., was included in this fatigue study (23). As well, two different glass reinforced polyurethane foams were included. PUR-G1 was a polyurethane composition wherein continuous glass strand mat was dispersed more or less uniformly throughout its thickness, with an average density of 385 kg./cu.m. (24). The other glass-reinforced polyurethane foam, PUR-G2, had woven glass roving plies close to the surface of each outer face, as well as a continuous glass strand mat more or less uniformly dispersed between the two woven plies, and exhibited an average density of 320 kg./cu.m. (25).

The average core shear stress at failure for static flexural testing is summarized in Figure 15. Curiously, of the three polyurethane foams investigated, the un-reinforced PUR-U exhibited the greatest shear strength in sandwich bending tests, even though one of the glass-reinforced polyurethanes, PUR-G1, was of a similar density. Intuitively, in order to arrive at a similar density, the addition of glass reinforcement must be accompanied by a reduction in the density of the polyurethane foam component, which appears to be detrimental toward the shear strength of these glass-reinforced polyurethane cores. PUR-G2, which had both continuous glass mat and woven roving, exhibited a lower shear strength than the PUR-G1 which was reinforced with only continuous glass mat.

The comparative flexural stiffness results from this static testing are illustrated in Figure 16. More or less, all materials except PUR-G2 showed similar stiffness results in this laminate flexural testing.

As described above, three-point flexural fatigue was performed using the same support span as for static testing, by applying a "fully-reversing" load at a level of +/- 75% of the average failure load in static testing, and also at +/- 50%. The intent was to identify the number of cycles until core failure occurred under each of those conditions. By definition, static testing is one cycle. The resulting data, presented as core shear stress versus number of cycles until failure, is shown in Figure 17.

While exhibiting superior static strength, the un-reinforced polyurethane core PUR-U suffered a rapid loss in useful shear strength for periodic loading beyond about 1000 cycles. In fact, all three polyurethane cores shared this trend. The two coalesced-strand PET foam cores, PET-CS 20 and PET-CS 25, appeared to offer the greatest fatigue endurance, even though their static strengths were considerably below the un-reinforced polyurethane. In particular, only one specimen of PET-CS 25 was tested at +/- 50% static load, and at the time it was removed from the fatigue apparatus, it had surpassed 1.5 million cycles without failing.

A valid way with which to compare various core materials with differing densities and static strengths is to present the fatigue data using a normalized stress, where the cyclically applied stress is divided by the static strength. Such a comparison is illustrated in Figure 18 for the core materials of this fatigue study. The reason for selecting +/- 75% and +/- 50% of static ultimate strength should now become apparent, as one can quickly compare the fatigue life of the various core materials according to how many cycles they endured at say 50% of static ultimate loads:

(best) PET-CS 25 > PET-CS 20 > PUR-U > PUR-G2 > PUR-G1 (worst)

Thus, although inferior in static strength to some or all of the polyurethane cores evaluated, the two coalesced-strand PET foam cores showed the greatest longevity at a cyclically-applied stress level equal to half of their static strength.

### **Thermal, Chemical and Electrical Resistance**

Foamable PET resins used in this work have crystallinities of from about 5% to about 45% depending upon the cooling rate from the melt to the solidified state. Relatively low cooling rates accompany foams, due to their lowered thermal conductivity, thus the crystallinity of coalesced-strand PET foams of this work are about 28% to 39%. These semi-crystalline foams exhibit excellent chemical and thermal resistance that translates to high performance as structural core materials for use in sandwich applications.

The retention of room-temperature compressive strength and modulus of coalesced-strand PET foam, over a range of temperatures, is illustrated in Figures 19 and 20, respectively. Included are data sheet values for a general purpose polyurethane (21) at a density of 240 kg./cu.m., and PEI foam (26) over a density range of 60 to 80 kg./cu.m. In compression, coalesced-strand PET foam showed 50% strength retention at about 100 °C - similar to the polyurethane foam – though the latter had about a 20 °C advantage for the temperature at which there was 50% retention in modulus. As will be seen below, the reduced compressive modulus of coalesced-strand PET foam at elevated temperatures will prove to be highly advantageous toward simultaneously consolidating GMT, thermoforming coalesced-strand PET foam while laminating it between GMT facings to form a structural sandwich part in a single event. Polyetherimide, having a bulk resin glass transition temperature of about 204 °C, not surprisingly outperformed both coalesced-strand PET and PUR foams in retention of compressive properties.

ASTM C 273 shear characterizations of coalesced-strand PET foam were also performed at 80 °C, with results presented in comparison to PEI foam in Figures 21 and 22, for shear strength and modulus retentions, respectively. Curiously, with reference to Figure 21, the shear strength of coalesced-strand PET foam at 80 °C was even higher than at room temperature. This result has been confirmed over a range of coalesced-strand PET foam densities, and there may be an element of “strain-hardening” to explain this phenomenon. As shown in Figure 22, the shear modulus retentions for both coalesced-strand PET as well as PEI foams at 80 °C were roughly the same as for their compressive modulus retentions at the same temperature. Figure 23 presents the five- and even six-fold increase in ultimate shear elongation for various density coalesced-strand PET foams at 80 °C, a condition that is slightly above the approximately 63 °C glass transition temperature for PET resin, thus rendering it amenable toward “work-toughening.”

A practical example of the thermal resistance of coalesced-strand PET foam in compression was created while attempting to simulate an actual aerospace processing application involving cyanate-ester pre-preg lamination of a PEI foam sandwich in an autoclave under a vacuum-bag



with full vacuum. For this study, a compression-creep test of PET coalesced-strand foam was conducted using an Instron controlled-temperature chamber fitted with an ASTM C 365 compression fixture, all maintained at 182 °C. An MTS servo-hydraulic test machine was used to apply a constant 173 kPa compressive stress, which was equal to the combined force from the autoclave and vacuum-bag, to specimens of “end-strand” coalesced-strand PET foam of different densities for a duration of over two hours. The “compressive-creep” results are exhibited in Figure 24 for coalesced-strand PET foam densities of 160, 210 and 224 kg./cu.m. The results show about a 4% compressive strain for the 160 kg./cu.m. specimen and less than a 2% strain for the 224 kg./cu.m. sample, a remarkable outcome considering that the 182 °C condition was more than 100 °C above the glass transition temperature for PET resin. Considerable “spring-back” of the specimens was observed upon removal of the applied force.

In a related test, meant to simulate a vacuum-bagging lamination at 200 °C under full vacuum, a compressive stress of 103 kPa was applied to a sample of coalesced-strand PET foam having a density of 143 kg./cu.m. for one hour. The resulting dimensional and weight changes are summarized in Table III. The permanent change in thickness under these conditions was only about 8.9%.

The foaming grade of PET resin used in this work starts melting at about 210 °C, based on Differential Scanning Calorimeter (DSC) testing. The temperature at the melting peak is about 250 °C and has completely melted by 270 °C. Based on the various thermal resistance tests of this work, most if not all laminating processes could be conducted on coalesced-strand PET foam up to about 200 °C without substantial changes in core dimensions.

The semi-crystalline PET used in this work also exhibits excellent chemical resistance at room or modest temperatures. Very little property changes are incurred with semi-crystalline PET as a result of contact with most of the aromatic and aliphatic organic solvents. Unsaturated polyester and vinylester resins are commonly used for sandwich lamination. A “warm” styrene resistance test was conducted by immersing coalesced-strand PET foam specimens into a general-purpose (GP), unsaturated ortho-polyester resin at 71 °C for 30 minutes. The shrinkage and weight change results are reported in Table IV, confirming negligible effects of the approximately 35 weight % styrene monomer in this GP resin. For comparative purposes, also included are results for a commercially available cross-linked PVC product (26) at several densities as well as end-grain balsa core material. The resin weight gain results are more a consequence of resin absorbing into the outer cut-cell surface for foam cores, and into the end-grain surface of the balsa variant, than actual cell wall attack.

An elevated-temperature epoxy lamination trial was conducted using a 12.5 mm thick coalesced-strand PET foam (“flat-strand”) plank with a density of 160 kg./cu.m. as a core. Two plies of 7781 E-glass cloth were laminated to each side of the core in a heated-platen press, using a high-temperature curing epoxy resin system. The curing process utilized a platen temperature of 182 °C and an actual part profile pressure of 172 kPa for a total of two hours. A photo of the edge of the laminated sandwich panel, shown in Figure 25, demonstrates an excellent skin/core interface appearance without any cell collapse.

Dielectric properties are of great importance in certain applications where the attenuation of radio-frequencies must be minimized. Dissipation factor (DF) is a measure of how much a material attenuates radio-frequency waves. “Radomes” are quite simply covers that protect high-power, high-frequency transmitter/receiver units and are quite often constructed of sandwich laminates using PEI core material due to its low dissipation factor (27). In the world of measurement, the trend in sensor design is increasing toward wireless (microwave), which has taken a \$500 million share of the \$40 billion per year sensor market (28). In the automotive

industry, wireless tire pressure sensors are the preferred design, but sensor power requirements are limiting their adoption. A multitude of automotive wireless sensors are possible if the attenuation of the signal from the sensor to the receiver/controller can be minimized, reducing the power requirements of the sensor, and that translates to the need for low dissipation factors and dielectric constants for the construction of the vehicle.

Figures 26 and 27 present the dissipation factor (DF) and dielectric constant (K), respectively, of two densities of coalesced-strand PET foam and two densities of PEI foam (27). While exhibiting somewhat greater dielectric constants than the PEI foams tested, the coalesced-strand PET foam results followed the trend of increasing dielectric constant with density. The resulting dissipation factors for the coalesced-strand PET foams were very attractive and should stimulate great interest in various low-attenuation sandwich applications for automotive as well as other markets.

## **Processing Examples**

The various advantages, such as high temperature and chemical resistance, and thermoplastic behavior, should position semi-crystalline PET foam well as a structural core material in the sandwich composites industry. This type of foam can be used as a general core material for sandwich applications involving fiberglass construction with polyester, vinylester or epoxy resin systems laminated at room temperature. It can also be used as a high performance core material where elevated processing or continuous-use temperatures, extreme chemical hazards, and low dielectric requirements dominate. As well, it can be processed using special techniques, such as thermoforming, simultaneous thermoforming/lamination, vacuum-infusion lamination, autoclave/vacuum-bagging lamination, and lamination with low melt temperature thermoplastic composites skins. In the following sections, some of these special applications are explored.

### **Thermomolding**

Coalesced-strand PET foam can be molded into any shape or contour, and replicate the intimate details of the tooling, by heating the foam sheet to about 180 °C then pressing it within, or against, a tool or mold. Figure 28 shows the result of an experiment where various objects (key, allen wrenches, washers, etc.) were pressed into a pre-heated sheet of coalesced-strand PET foam using light pressure in a hydraulic press. The registration of the “tooling” detail was quite impressive.

### **Thermoforming**

Coalesced-strand PET foam can be thermoformed by warming the foam sheet as mentioned above (180 °C for about 10 minutes), then using conventional vacuum- or pressure-forming methods with a suitable tool to make the required shapes. Figure 29 shows some examples of thermoformed coalesced-strand PET foam core sheets. The cell structure and foam configuration was fully retained after the thermoforming process.

### **Simultaneous Thermoforming/Lamination - “One Shot GMT Sandwich Processing”**

Typical automotive processing of GMT (i.e. AZDEL™) “glass-mat-technology,” comprised of a glass reinforcement and polypropylene resin, was performed on a sandwich lamination using two GMT facings around a coalesced-strand PET foam core within a matched aluminum mold. Thermoforming and laminating the coalesced-strand PET foam core within the GMT facings was accomplished in a simultaneous or “one-shot” process providing a structural sandwich product with a complicated shape, as illustrated by the resulting profile in Figure 30. This trial

demonstrated a special application for coalesced-strand PET foam where GMT may already be employed, and the advantages of greater strength and stiffness can be realized by adding a coalesced-strand PET foam core within GMT sheets, to result in a structural sandwich design.

The processing was conducted according the following procedure:

- 1). Pre-loft two pieces of GMT facings in an oven at about 210 °C for about 20 minutes.
- 2). Pre-heat coalesced-strand PET foam core and the matched metal mold in a press at about 160 °C for about 20 minutes.
- 3). Assemble facings around the core quickly, place into the press with platens at 160 °C under 140 – 200 kPa actual profile pressure, holding them for about 1 minutes.
- 4). Turn off the heat, cool under pressure to a temperature of less than 65 °C.
- 5). Remove laminated product from mold and trim edges.

As shown in Figure 30, the shape of the coalesced-strand PET foam core adopted the shape of the mold during lamination. The GMT facings showed good surface quality and excellent bond strength to the coalesced-strand PET foam core.

### **“One-Resin” Thermoplastic Composite Sandwich Structure**

Generally, non-metallic composite sandwich structures are comprised of a core material and reinforced facings that in turn use a resin composition (thermoplastic or thermosetting) that is different from that of the core. This type of sandwich usually cannot be thermoformed because the core material and facing resin system have different softening temperatures and capabilities to stretch or compress to the contour of the tooling during thermoforming process. However, by laminating coalesced-strand PET foam core material with (dry) pre-heated reinforcements such as glass fabrics, a one-component thermoplastic composite sandwich structure can be successfully fabricated. In this process, the glass fabric melts into the PET foam core, creating a glass-reinforced PET facing and, by using the same resin for the facing as for the core material, results in a new “one-resin,” thermoformable sandwich article.

An example of this type of “one-resin” sandwich panel was made using the following process:

- 1). Pre-heat two pieces of product no. 7781 glass cloth (areal weight of 300 g/sq.m.) at 265 °C for about 5 minutes.
- 2). Assemble the pre-heated glass cloth and coalesced-strand PET foam core in a heated-platen press at 265 °C and 100 kPa actual part profile pressure for about 2 minutes.
- 3). Cool the assembly to about 65 °C, or move the assembly from the heated press to a cold press, and maintain a holding pressure of 100 kPa for about 5 minutes.

A sample cut from the product made by the above procedure is shown in the center photo of Figure 31.

This type of sandwich panel can also be made by a continuous process using infrared heaters or heated rollers to heat the glass fabric, then a combination of heated and cooled rollers to laminate the glass fabric over the core. The glass fabric can be made to partially or totally melt into the PET foam core by adjusting the processing conditions. Certain applications may require that the outer surface of the glass fabric be “dry” for subsequent lamination with a

different type of resin than thermoplastic PET.

The sandwich panel made by this process can be thermoformed by heating to about 180 °C, press-forming it in a matched metal mold for about 2 minutes then cooling it to near room temperature. Two thermoformed samples of this “one-resin” thermoformed sandwich are also illustrated in Figure 31, demonstrating good replication of the tooling and good condition of the sandwich laminate after thermoforming.

## CONCLUSIONS

Coalesced-strand PET foam core materials, produced by continuous extrusion processing, were characterized against a broad range of metrics for suitability as structural core materials in automotive applications. Key among the unique attributes for this novel foam material include:

- Produced using a thermoplastic resin thus totally recyclable
- Capabilities for available densities in the range of 60 through 400 kg./cu.m.
- Low open-cell content, low water absorption
- Significant anisotropy for mechanical properties, which are mutually optimal in the “end-strand” orientation
- Mechanical strength properties that are comparable to, and mechanical stiffness properties that are greater than, polyurethane foams at the same density
- Outstanding fatigue endurance in shear
- Good retention of physical properties at elevated temperatures, improvement in shear strength and elongation at 80 °C
- Excellent chemical resistance, good compatibility with a broad range of resins and adhesives even at elevated temperatures
- Capabilities for processing at temperatures up to about 200 °C without cell collapse or substantial dimensional changes
- Dielectric properties that rival PEI foams
- Excellent thermoformability, capabilities for GMT/PET foam-cored sandwich lamination/thermoforming in a one-step process, and for the fabrication of glass-reinforced PET/PET foam-cored thermoplastic composite sandwich in one step

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## REFERENCES

1. Marshall, A. C., "Composites Basics," 5th Ed, 3-1, Marshall Consulting, CA, 1998.
2. Xanthos, M. and S. K. Dey, "Foam Extrusion Principles and Practice", Lee, S. T. Ed., Technomic Publishing Company, Inc., Lancaster, PA, pp 307-338, (2000).
3. Champagne, M. F., Gendron, R. and M. A. Huneault, "Branched Polyethylene Terephthalate Foaming Using HFC-134a: On-Line Process Monitoring," Society of Plastics Engineers ANTEC, 2003.
4. Xanthos M., Dhavalikar, R., Tan, V. and U. Yilmazer, "Properties and Applications of Sandwich Panels Based on PET Foams," Society of Plastics Engineers ANTEC, 2000.
5. Japon, S., Leterrier, Y. and J. E. Manson, "Recycling of Poly(Ethylene Terephthalate) Into Closed-Cell Foams," Polymer Engineering and Science, Aug. 2000.
6. Park, C. P., Garcia, G. A. and R. G. Watson, "Expandable Foam From Amorphous Polyester Resin," Society of Plastics Engineers ANTEC, 2002.
7. Khemani, K. C. "Polymeric Foams Science and Technology," Khemani, K. C. Ed., American Chemical Society, Washington, DC, pp 54-80, (1997).
8. Park, C. P. and G. A. Garcia, "Development of Polypropylene Plank Foam Products", Society of Plastics Engineers ANTEC, 2000.
9. Grinshpun, S., "Development of Hollow Strand Plastic Foam," Society of Plastics Engineers ANTEC, 2001.
10. U.S. Patent No. 6,213,540 (issued April 10, 2001).
11. "Standard Test Method for Apparent Density of Rigid Cellular Plastics," American Society for Testing and Materials, Standard No. D 1622-98, 1998.
12. "Standard Test Method for Open-Cell Content of Rigid Cellular Plastics by the Air Pycnometer," American Society for Testing and Materials, Standard No. D 2856-98, 1998.
13. "Standard Test Method for Flatwise Compressive Properties of Sandwich Cores," American Society for Testing and Materials, Standard No. C 365-00, 2000.
14. "Standard Test Method for Flatwise Tensile Strength of Sandwich Constructions," American Society for Testing and Materials, Standard No. C 297-94, 1994 (renewed 2000).
15. "Standard Test Method for Shear Properties of Sandwich Core Materials," American Society for Testing and Materials, Standard No. C 273-00, 2000.
16. "Standard Test Method for Flexural Properties of Sandwich Constructions," American Society for Testing and Materials, Standard No. C 393-00, 2000.
17. Feichtinger, K. A., Ma, W. and T. Touzot, "Classification of Core Materials Used for Structural Sandwich Marine Transoms," pp 37-48, Society for the Advancement of Material and Process Engineering (SAMPE) Journal, Nov/Dec Ed., 2003.

18. "Determination of Water Absorption of Rigid Cellular Plastics," International Standards Organization, Standard No. ISO 2896-87, 1987.
19. "Preparation of Artificial Sea Water," Deutsches Institut für Normung, Standard No. DIN 50905.
20. "Sandwich Core Materials," Det Norske Veritas, Type Approval Programme No. 1-501.10, Jan.1999.
21. "LAST-A-FOAM® FR-6700" Core Material, General Plastics Manufacturing Company, Tacoma, Washington.
22. "PP Tubus Core," Tubus-Bauer AG, Data Sheet "e-si-pp.pdf," [http://www.tubus-bauer.com/uk/data\\_sheets.htm](http://www.tubus-bauer.com/uk/data_sheets.htm)
23. "LAST-A-FOAM® FR-7125" Core Material, General Plastics Manufacturing Company, Tacoma, Washington.
24. "EXTREME 2000" Core Material, Penske Composites, Mt. Juliet, Tennessee.
25. "BLUEWATER 20" Core Material, Coosa Composites, LLC, Pelham, Alabama.
26. "C 70" Core Material, Alcan Airex AG, Sins, Switzerland.
27. "R 82" Core Material, Alcan Airex AG, Sins, Switzerland.
28. Allan, R., "The Future of Sensors," Electronic Design, pp. 52-54, July 5, 2004.

**Table I. Open-Cell Content Results for PET Coalesced-Strand Foam**

Length cm	Width cm	Thickness cm	Weight g	Density kg/m <sup>3</sup>	Open-Cell Content, %
15.223	15.202	3.216	75.990	102.151	19.5
15.223	15.204	3.207	75.551	102.426	21.7
15.295	15.300	3.185	94.018	126.174	18.6
15.303	15.311	3.141	103.574	141.304	16.2
15.227	15.210	3.148	124.291	170.330	19.2
15.214	15.222	3.087	122.951	172.028	15.6
15.292	15.294	3.223	133.431	176.393	18.0

**Table II. ISO 2896-87 Water Absorption Test Results For Pet Coalesced-Strand Foams**

Density (kg/m <sup>3</sup> )	Weight, (g)	Surface Area, (m <sup>2</sup> )	Weight After Testing, (g)	Weight Gain, (g)	Weight Gain (kg/m <sup>2</sup> )
99.60	4.523	0.00869	6.621	2.098	0.242
98.89	4.635	0.00883	6.749	2.114	0.239
99.44	4.614	0.00880	6.672	2.058	0.234
Mean: 99.31	4.591	0.00877	6.681	2.090	0.238
St.Dev: 0.372	0.060	0.00008	0.064	0.029	0.004
131.30	6.164	0.00885	8.483	2.319	0.262
131.66	6.122	0.00878	8.501	2.379	0.271
132.16	6.036	0.00869	8.251	2.215	0.255
Mean: 131.71	6.107	0.00877	8.412	2.304	0.263
St.Dev: 0.432	0.065	0.00008	0.139	0.083	0.008
165.24	7.769	0.00886	9.673	1.904	0.215
164.22	7.728	0.00886	9.734	2.006	0.226
166.71	7.671	0.00875	9.650	1.979	0.226
Mean: 165.39	7.723	0.00882	9.686	1.963	0.223
St.Dev: 1.252	0.049	0.00006	0.043	0.053	0.007

**Table III: Test Results of Compression-Creep at 200 °C and Full Vacuum**

	Before tested	After tested	Change, %
<b>Weight, (g)</b>	235.7	235.2	-0.21
<b>Thickness, (mm)</b>	11.4	10.4	-8.89
<b>Width, (mm)</b>	377.8	376.2	-0.42
<b>Length, (mm)</b>	381.0	379.4	-0.42
<b>Density, (kg/m<sup>3</sup>)</b>	143	158	+10.52

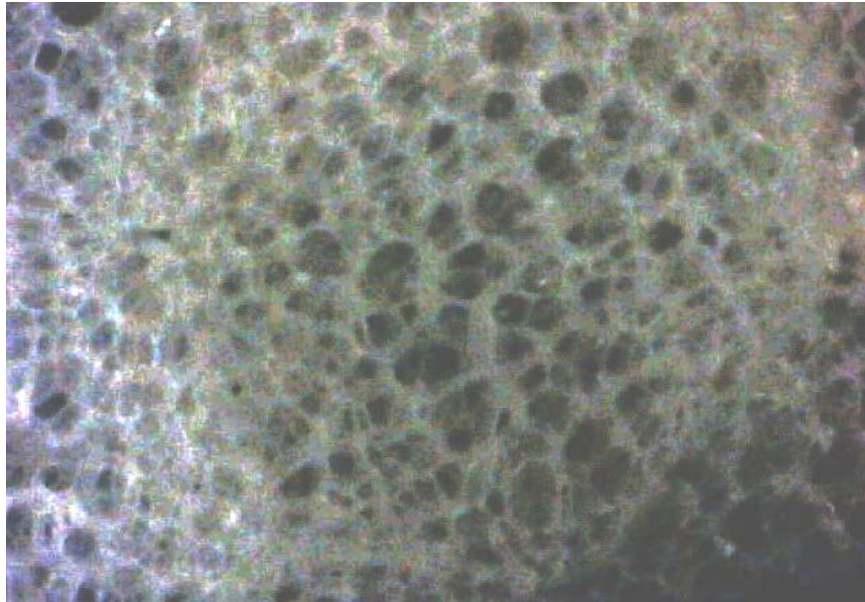
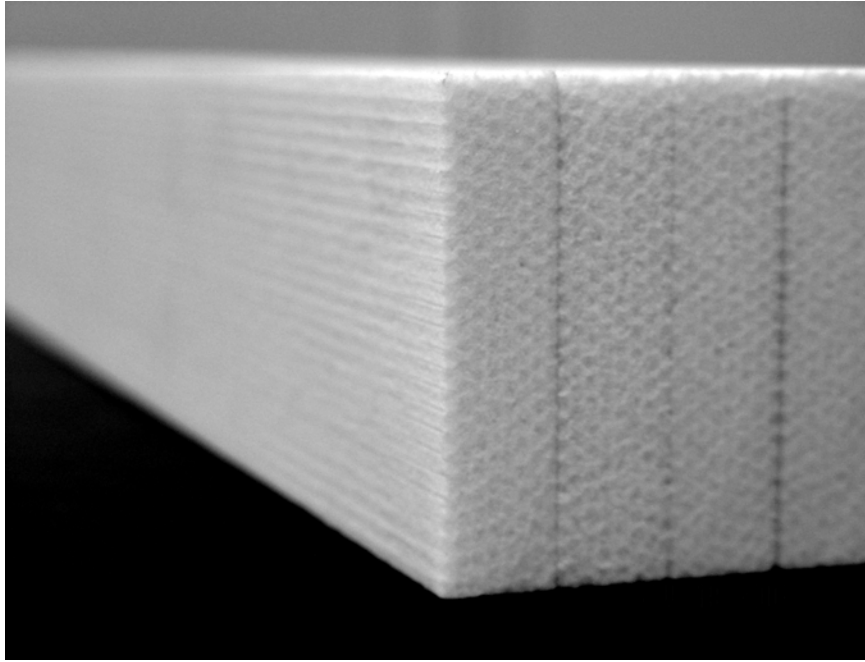
**Table IV. Warm Styrene Shrinkage Test Results:**  
 (Immersion in General-Purpose Unsaturated Polyester Resin at 71 °C for 30 min.)

<b>CS-PET Foam Density, (kg/m<sup>3</sup>)</b>	<b>Resin gain, (g/m<sup>2</sup>)</b>	<b>Volume Change, (%)</b>
96	333.3	-0.236
130	328.6	0.067
160	262.0	-0.339

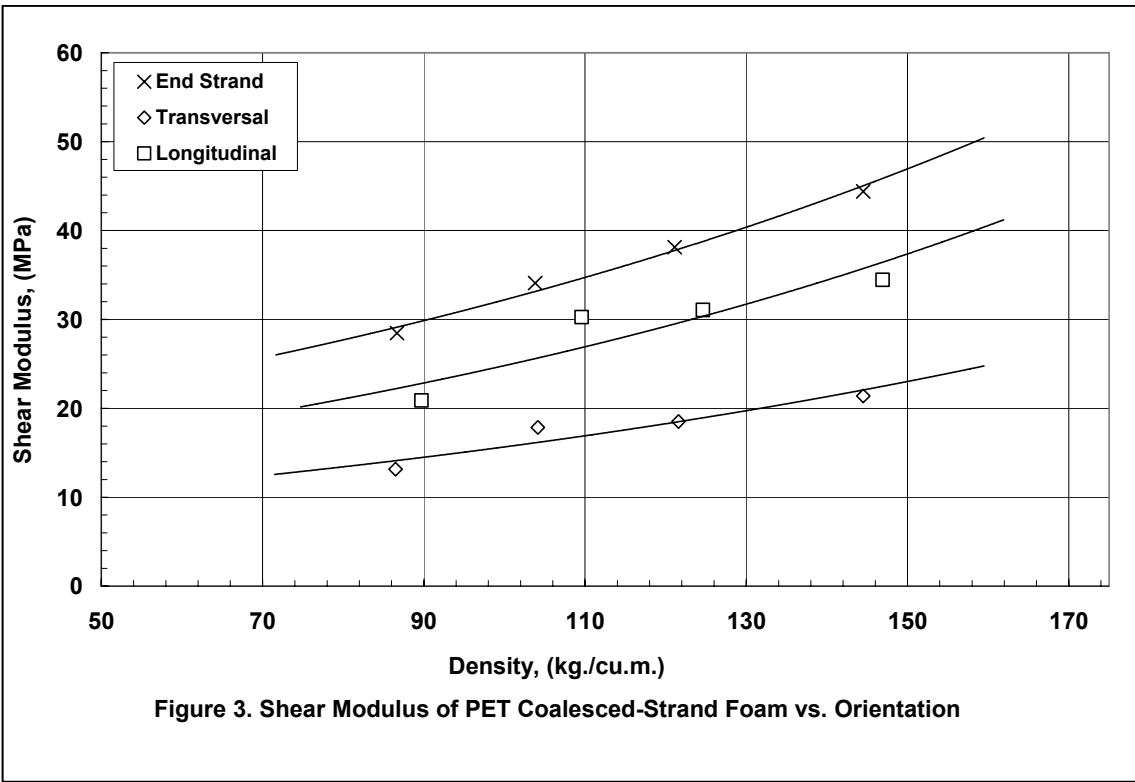
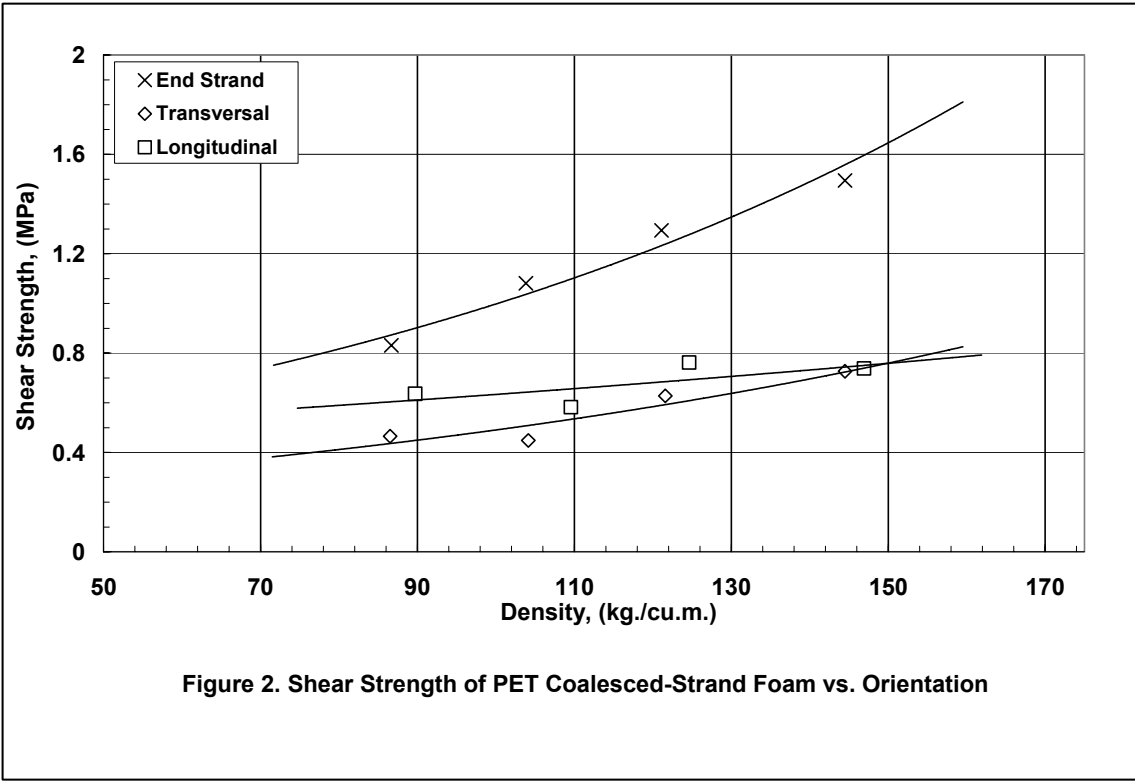
<b>XLinked PVC Foam Density, (kg/m<sup>3</sup>)</b>	<b>Resin gain, (g/m<sup>2</sup>)</b>	<b>Volume Change, (%)</b>
104	188.1	-1.740
134	178.3	0.985
178	142.3	2.137

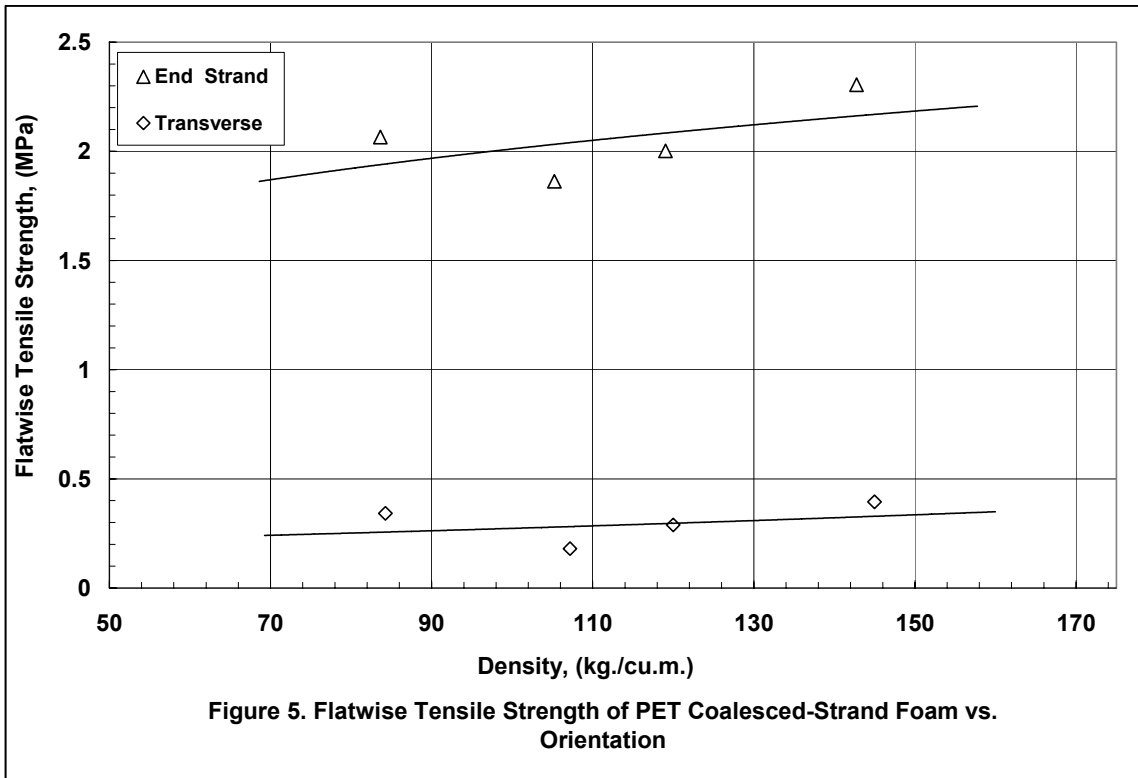
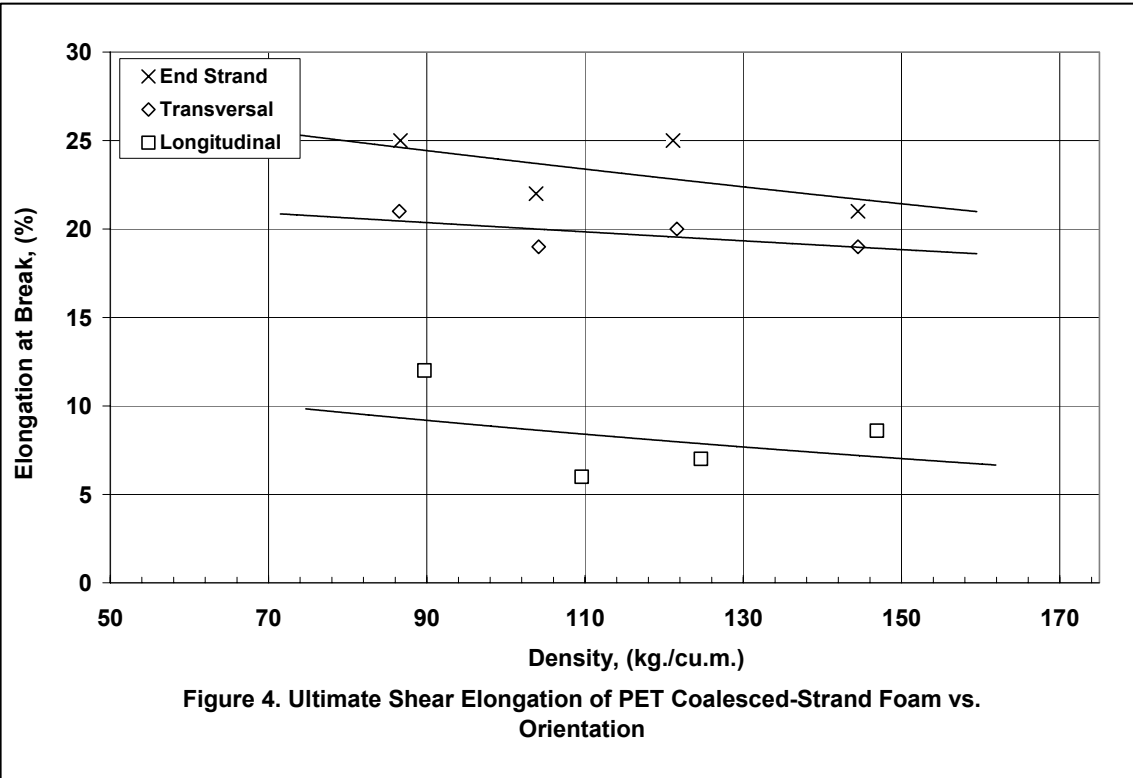
<b>End-Grain Balsa Density, (kg/m<sup>3</sup>)</b>	<b>Resin gain, (g/m<sup>2</sup>)</b>	<b>Volume Change, (%)</b>
152	580	-0.070

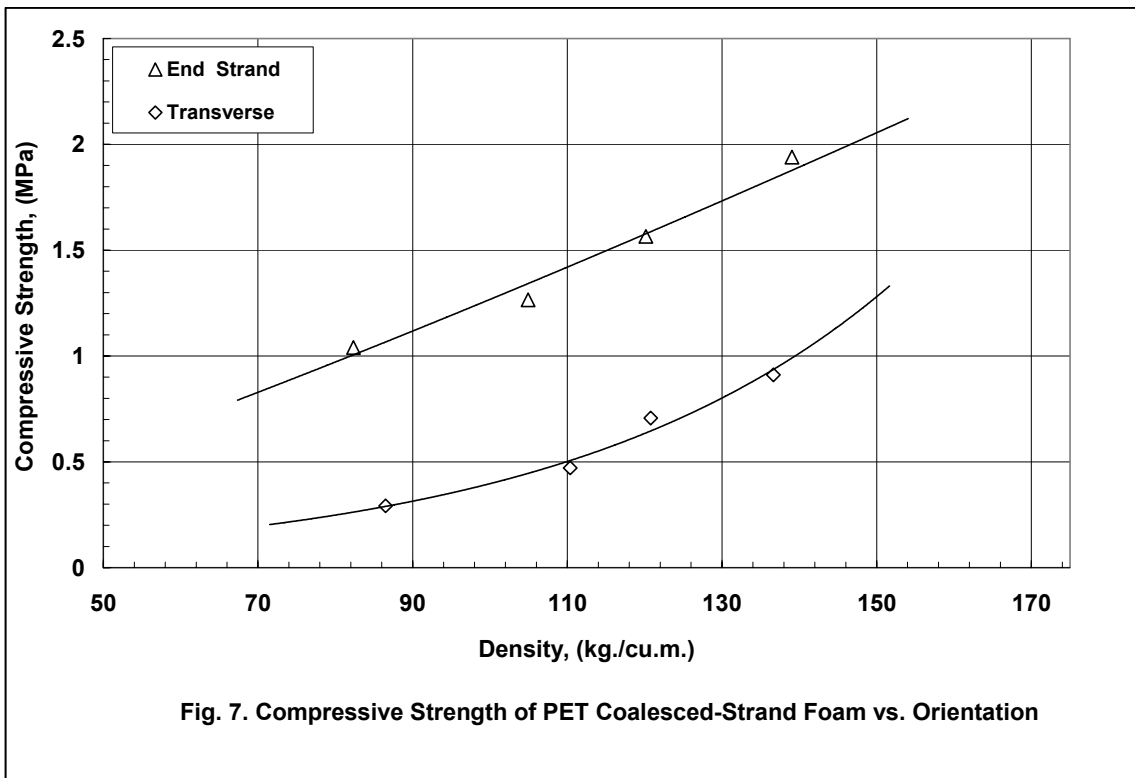
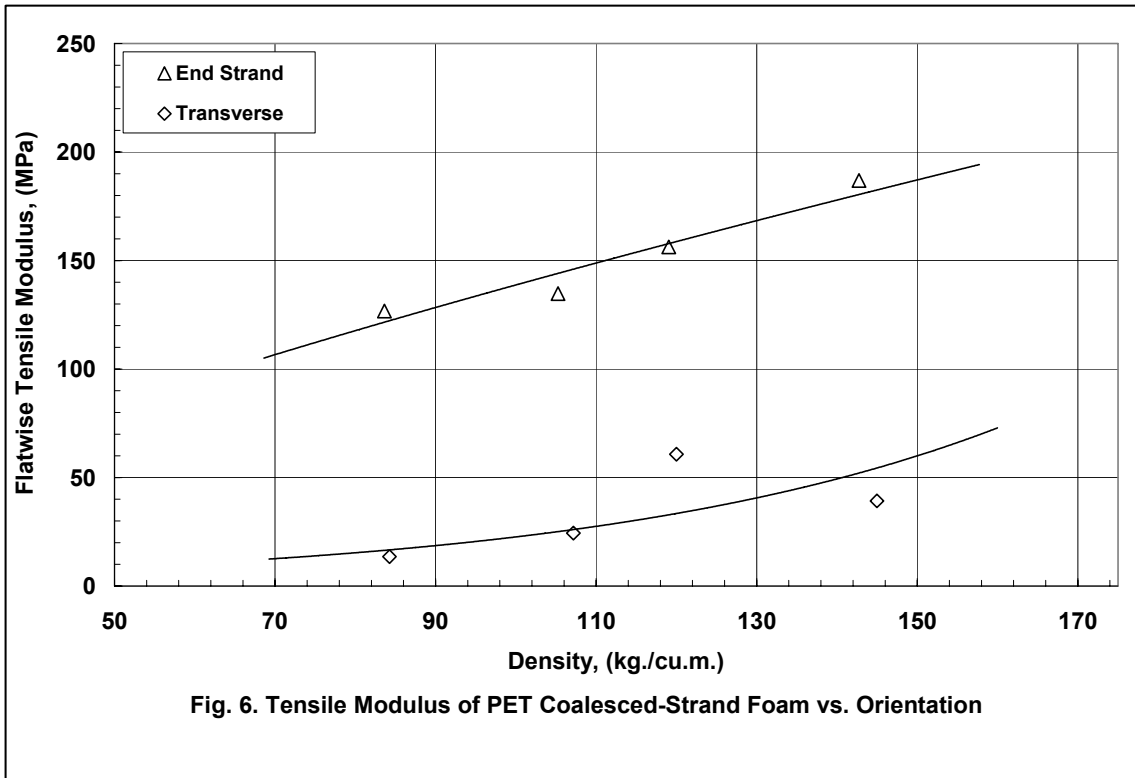


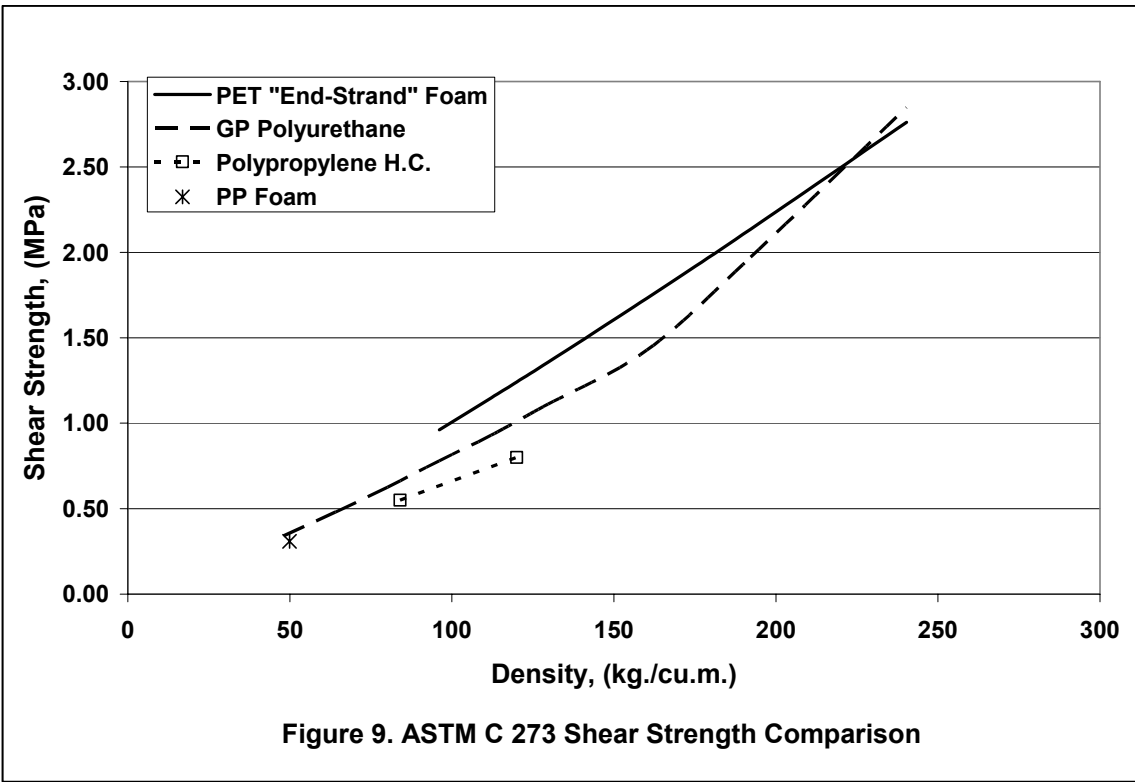
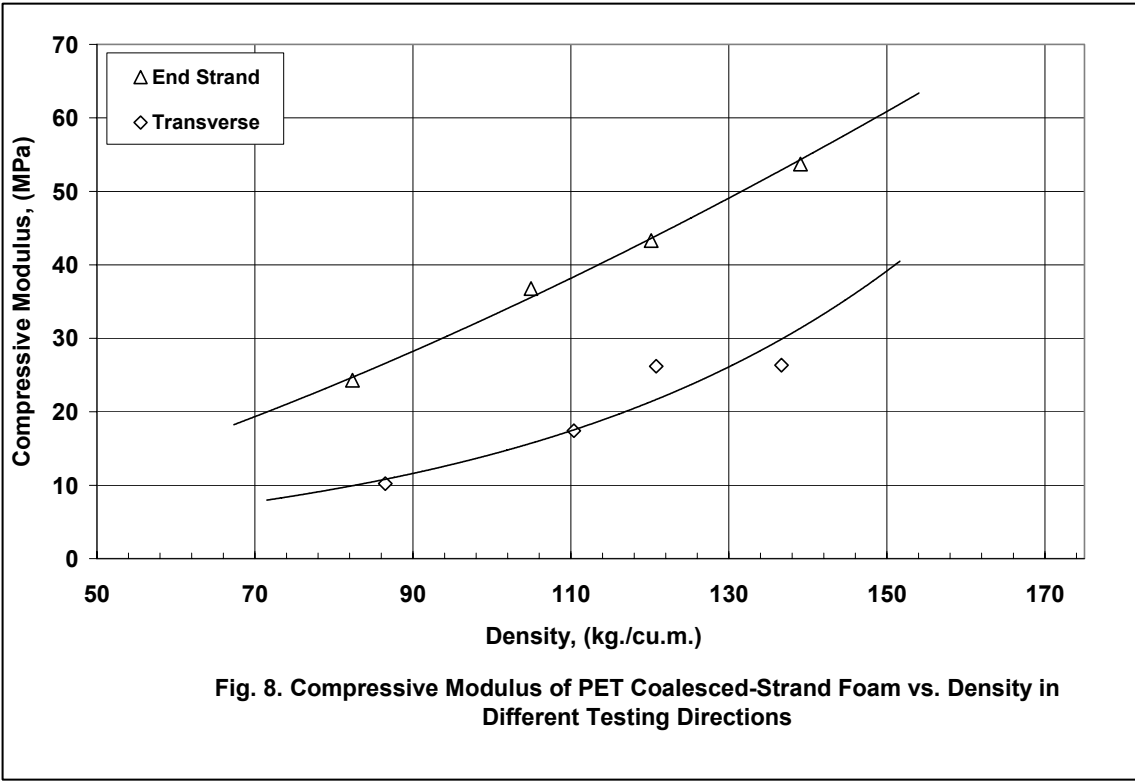


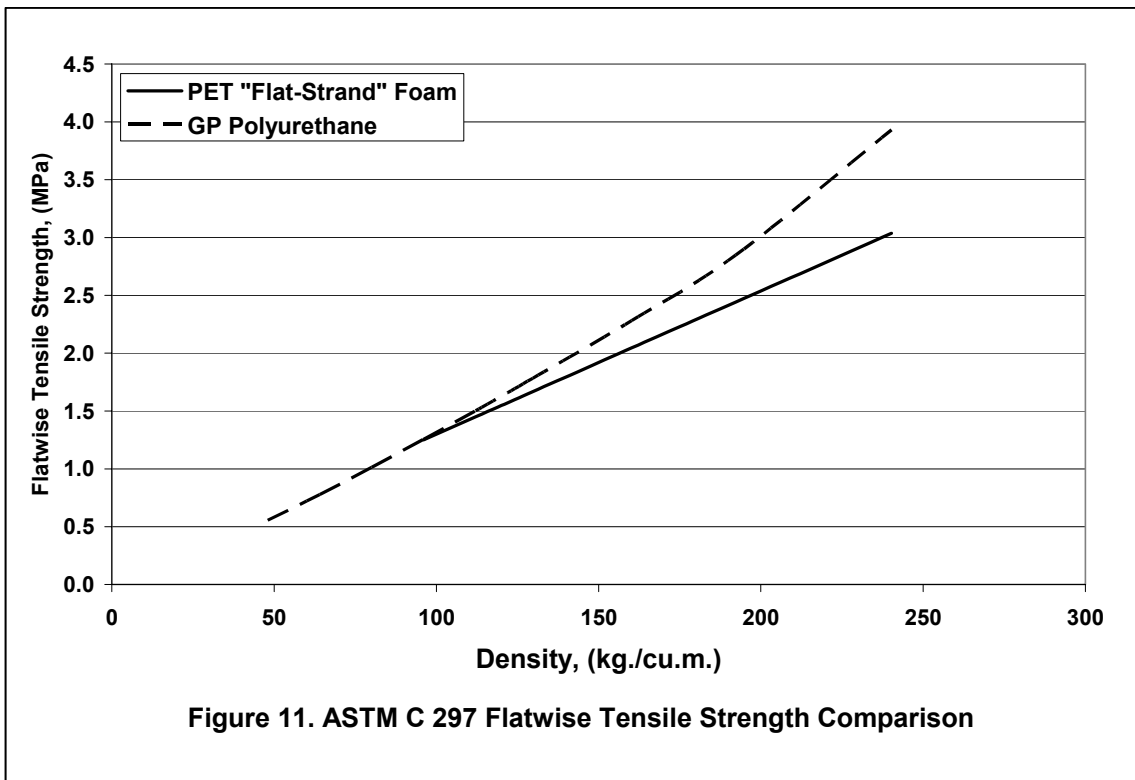
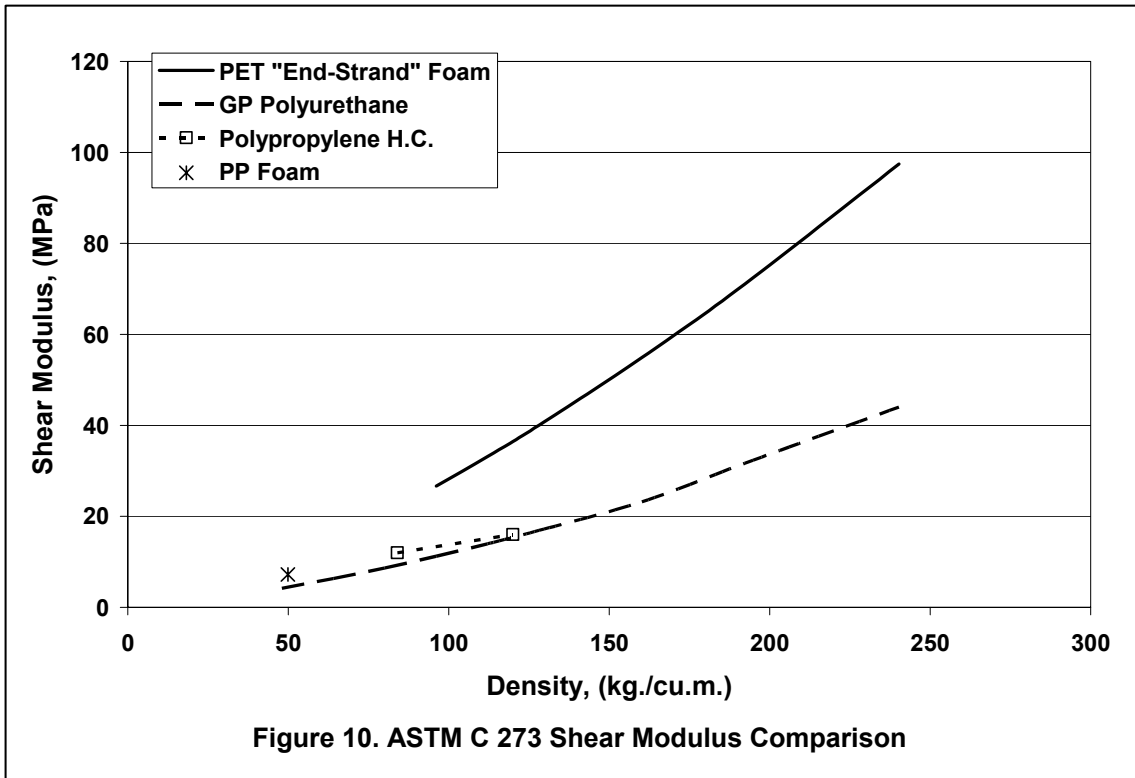
**Figure 1. Cell Structure, Configuration of PET Coalesced-Strand Foam**

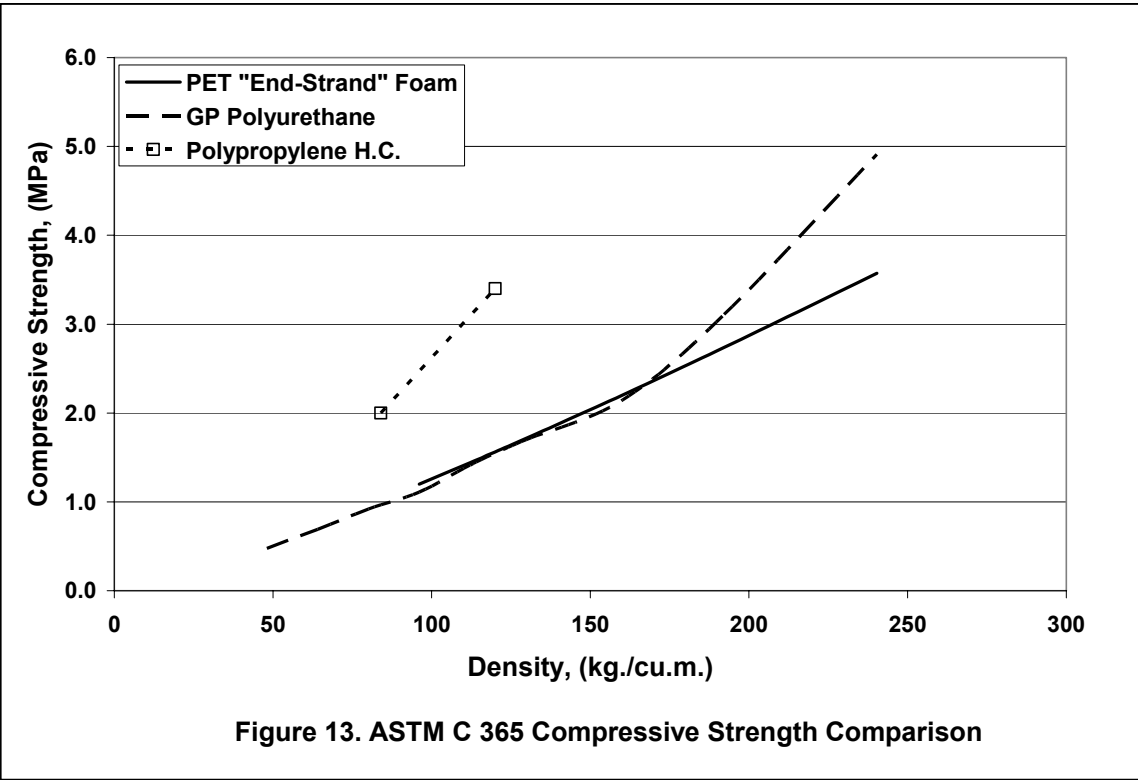
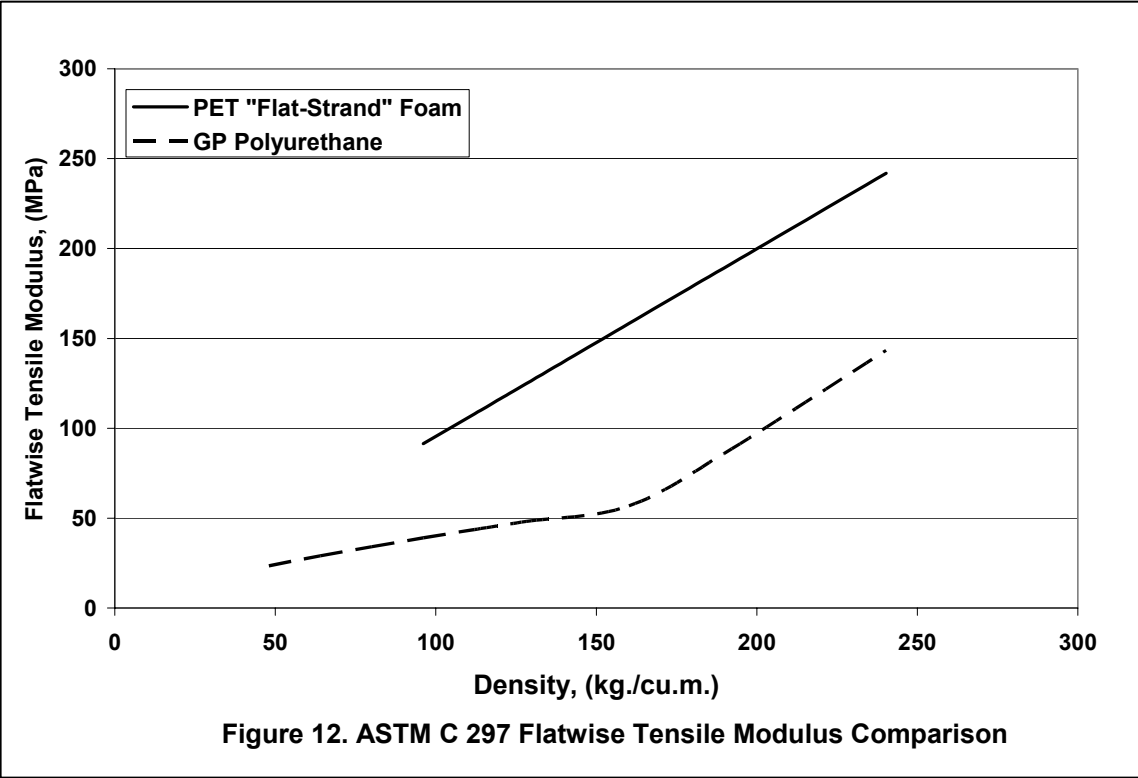


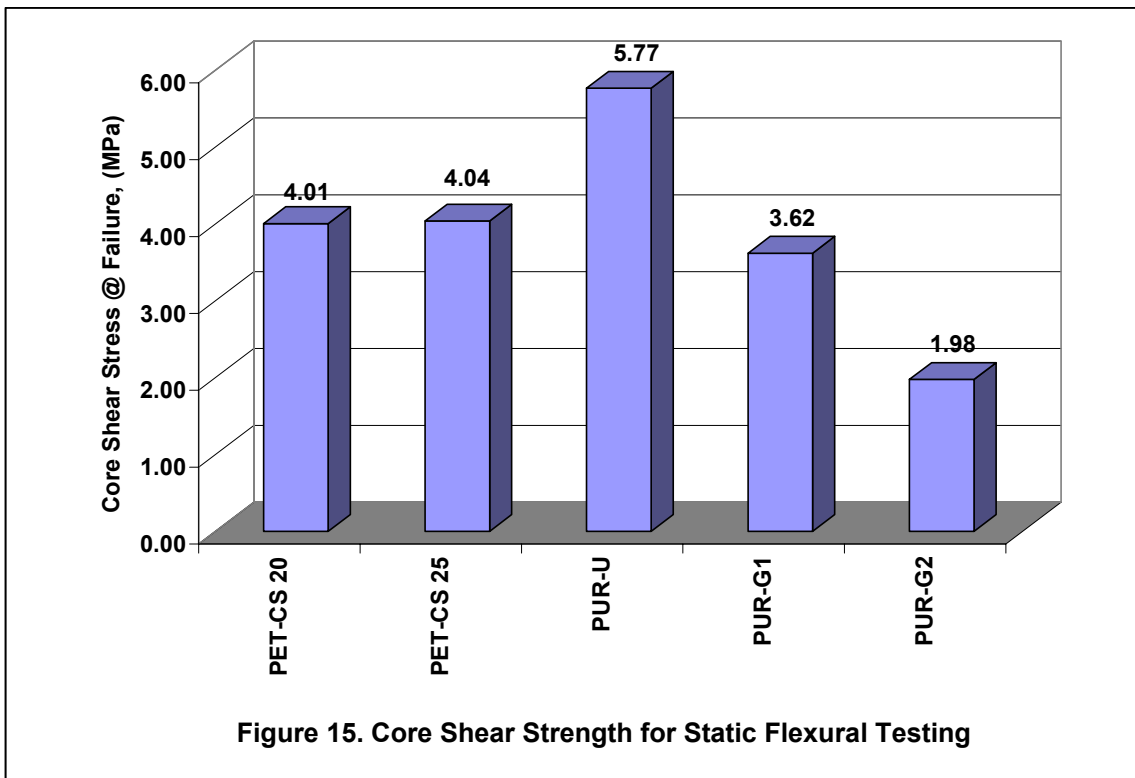
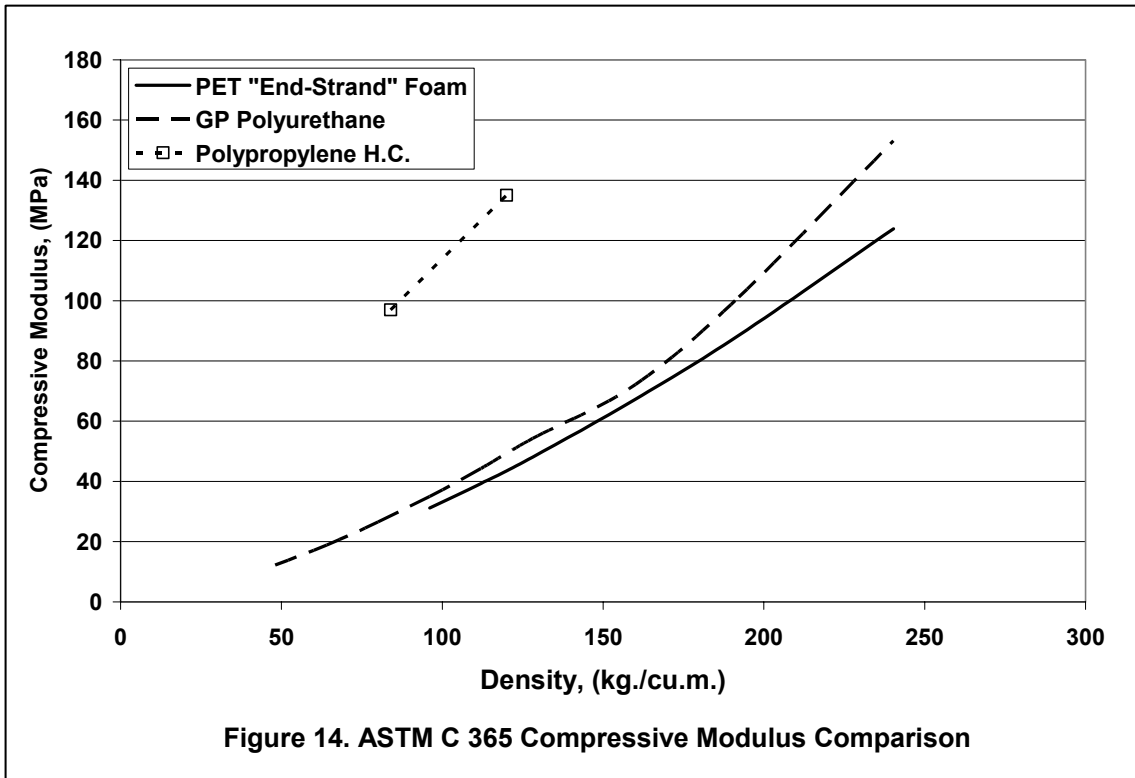














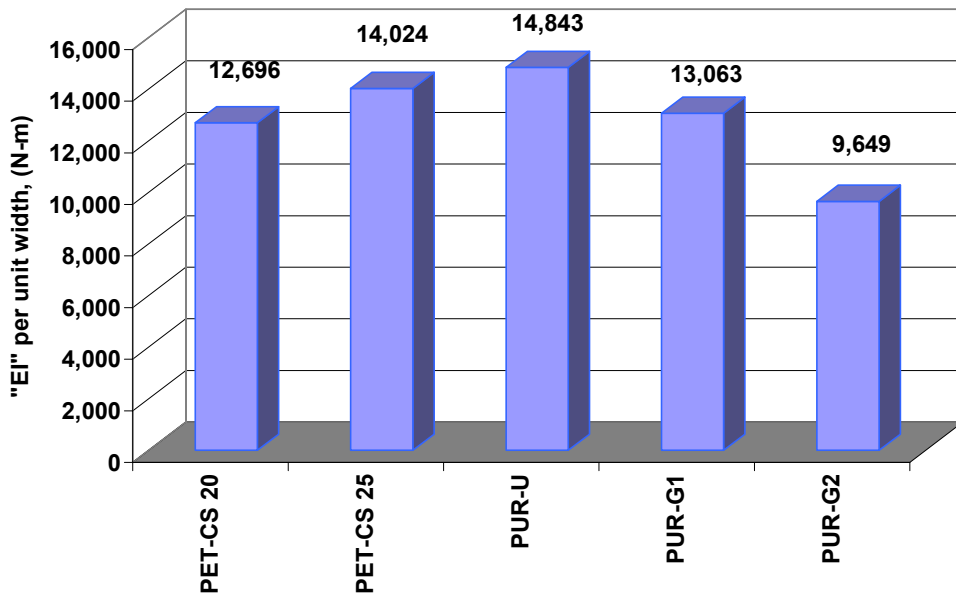


Figure 16. Sandwich Flexural Stiffness for Static Testing

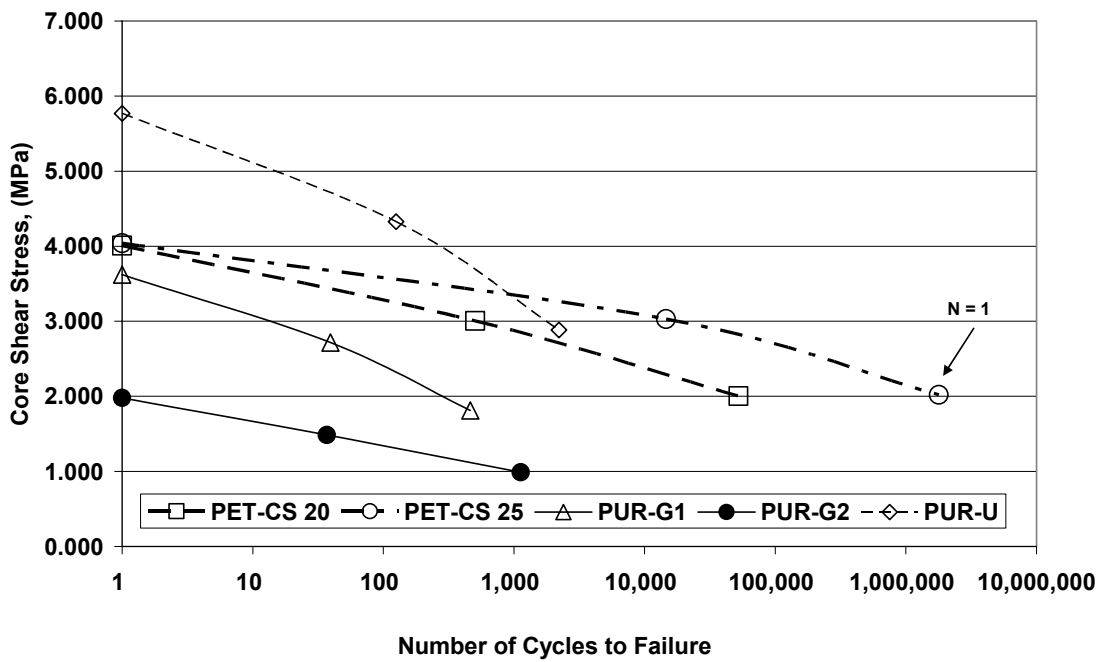
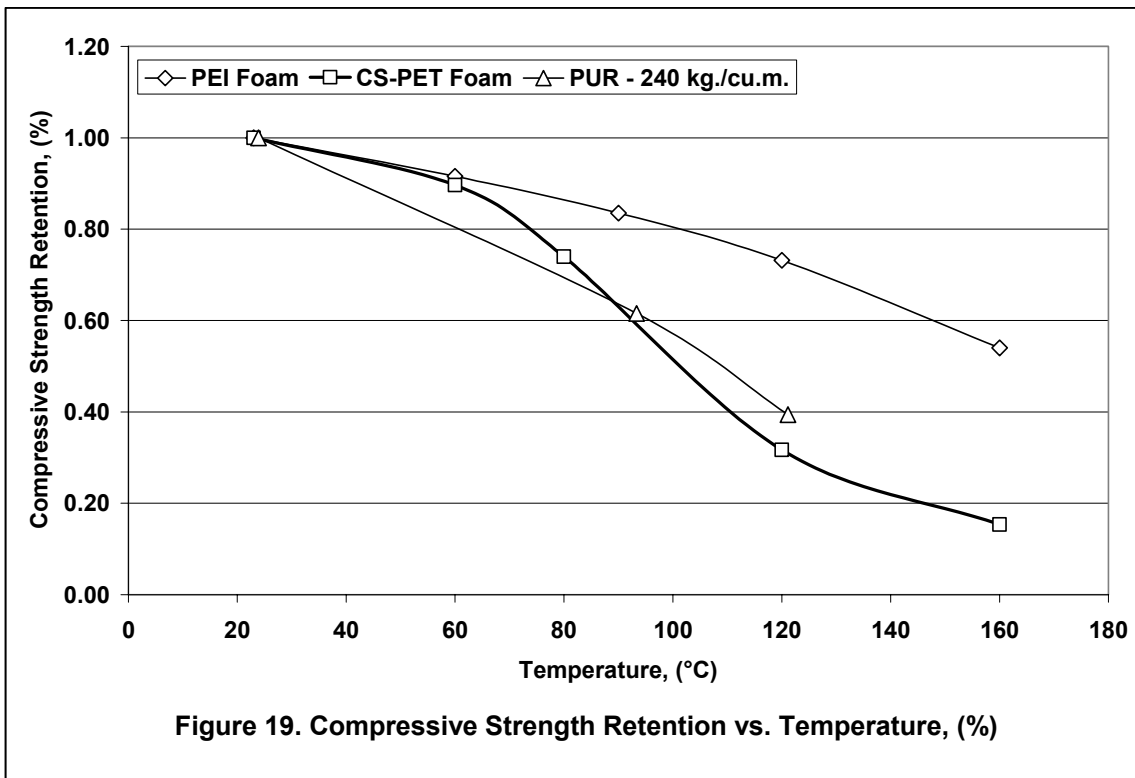
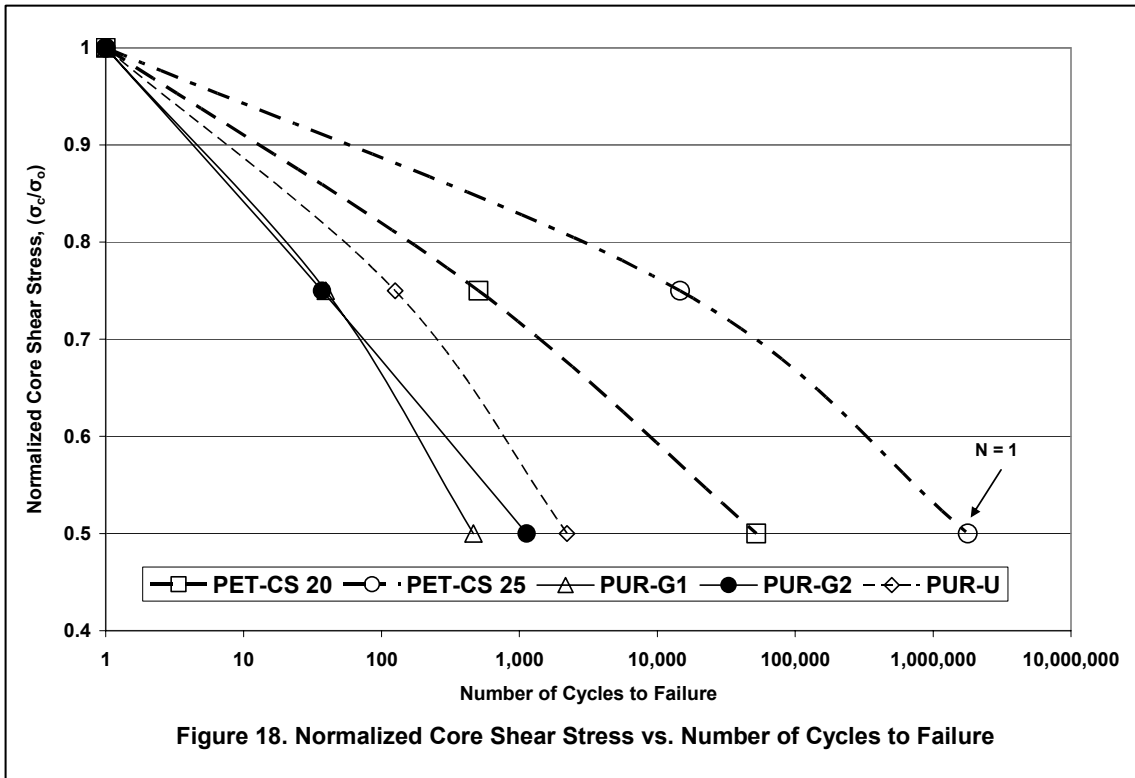
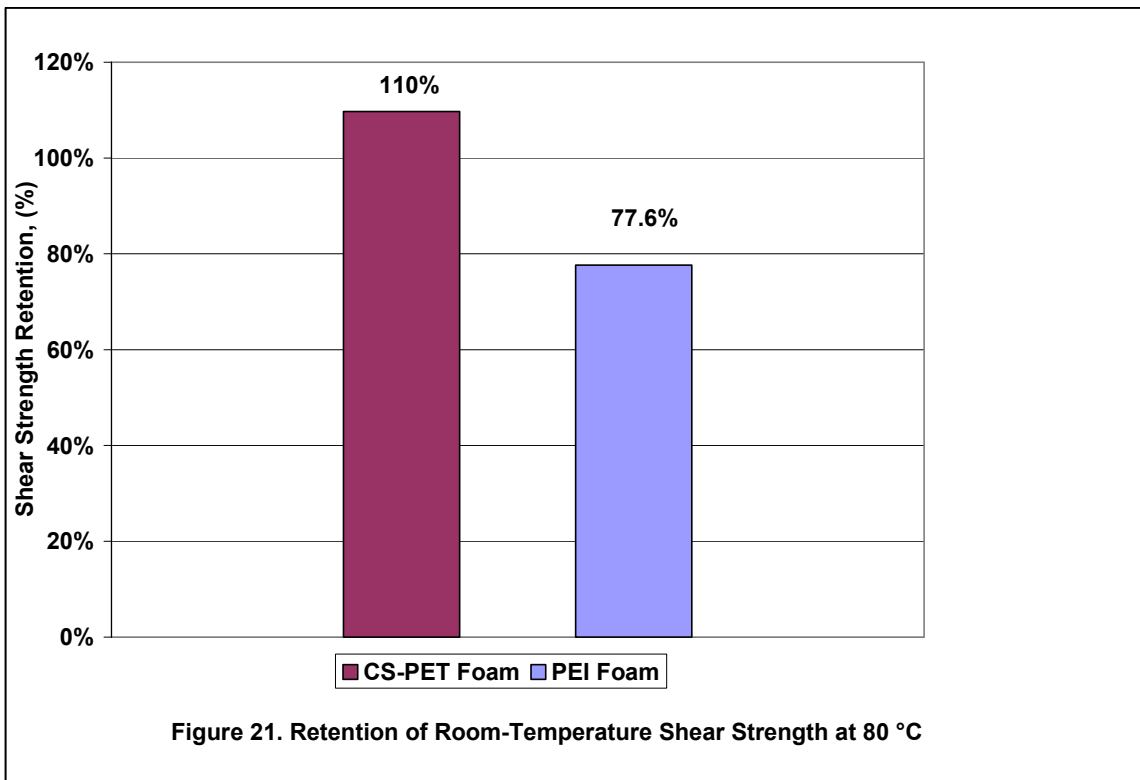
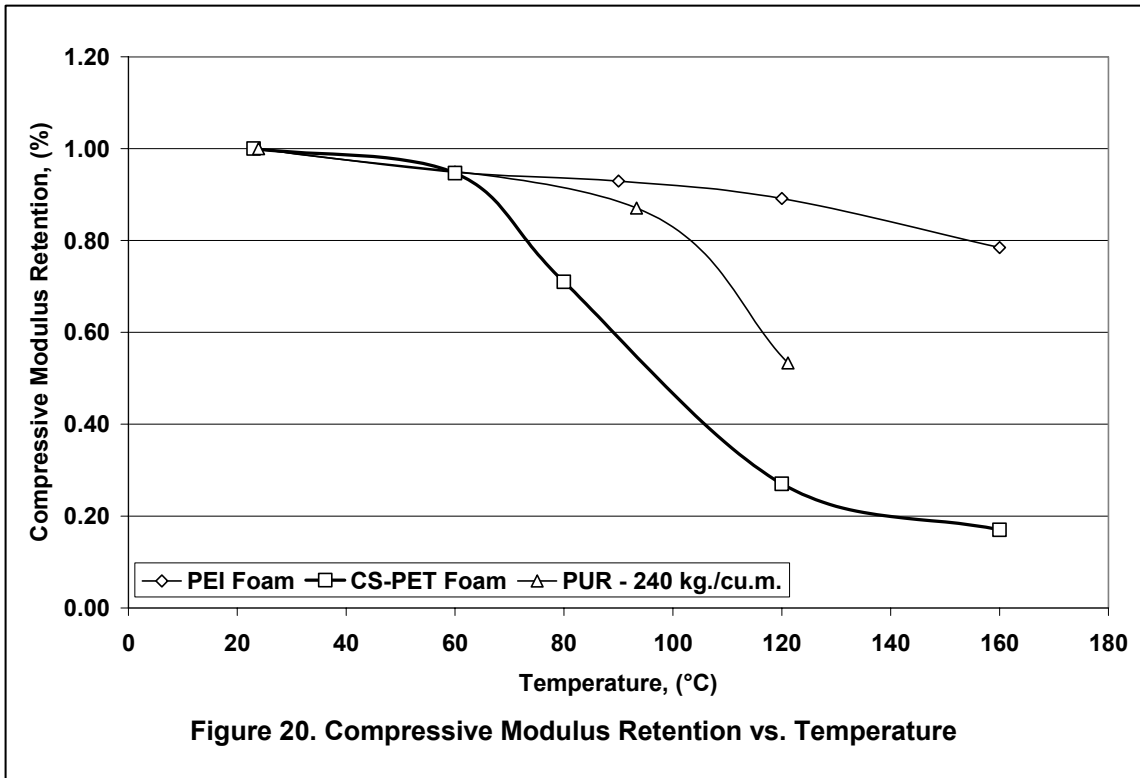


Figure 17. Core Shear Stress vs. Number of Cycles to Failure





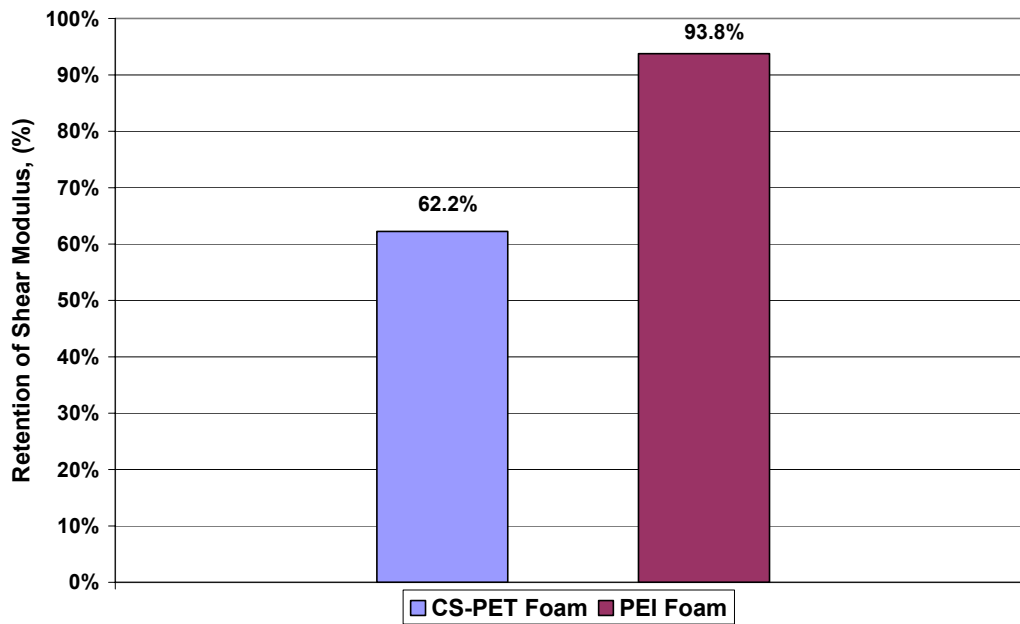


Figure 22. Retention of Room-Temperature Shear Modulus at 80 °C

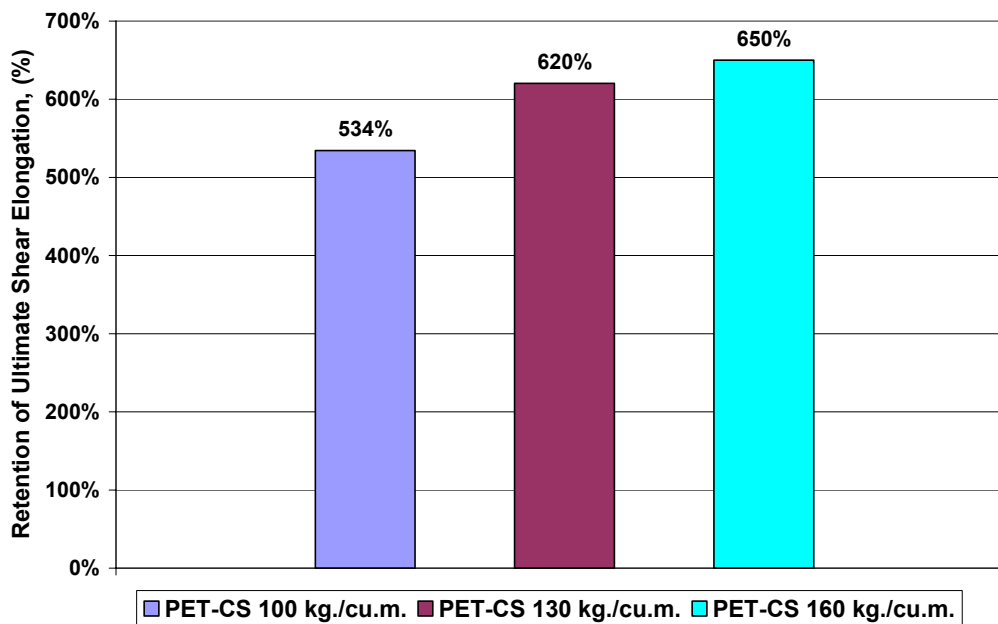


Figure 23. Retention of Room-Temperature Ultimate Shear Elongation at 80 °C

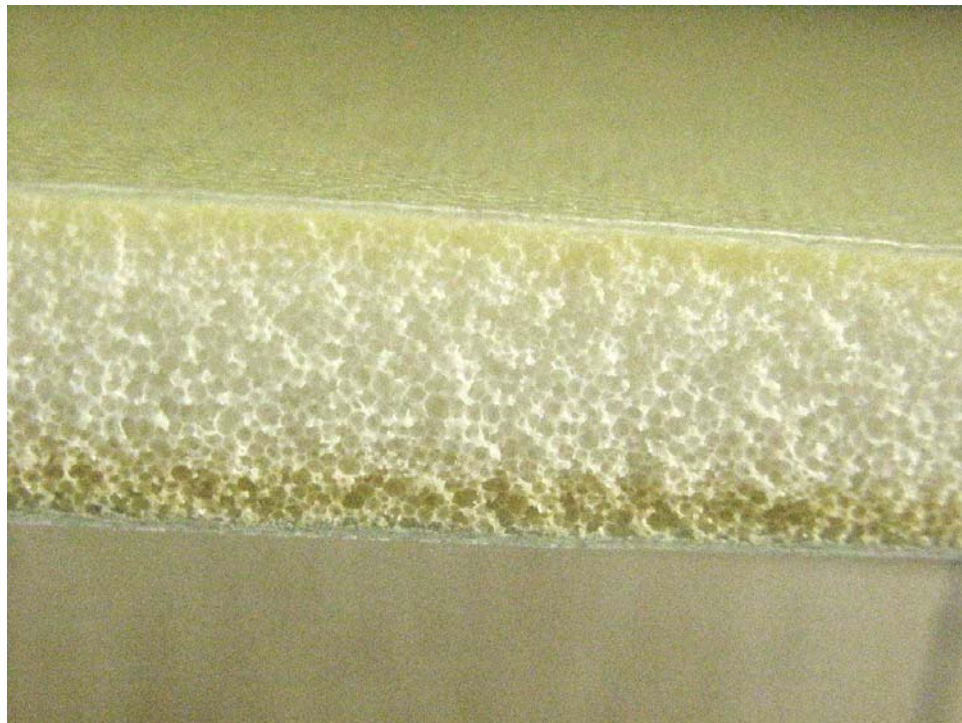
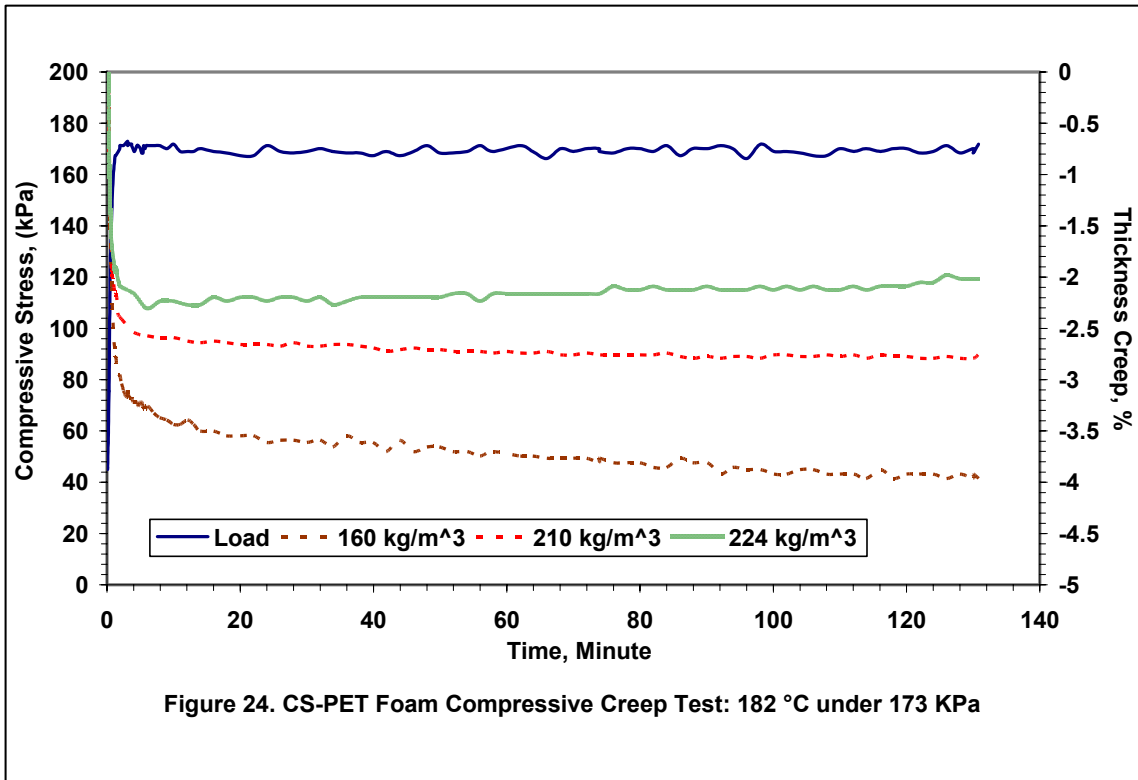
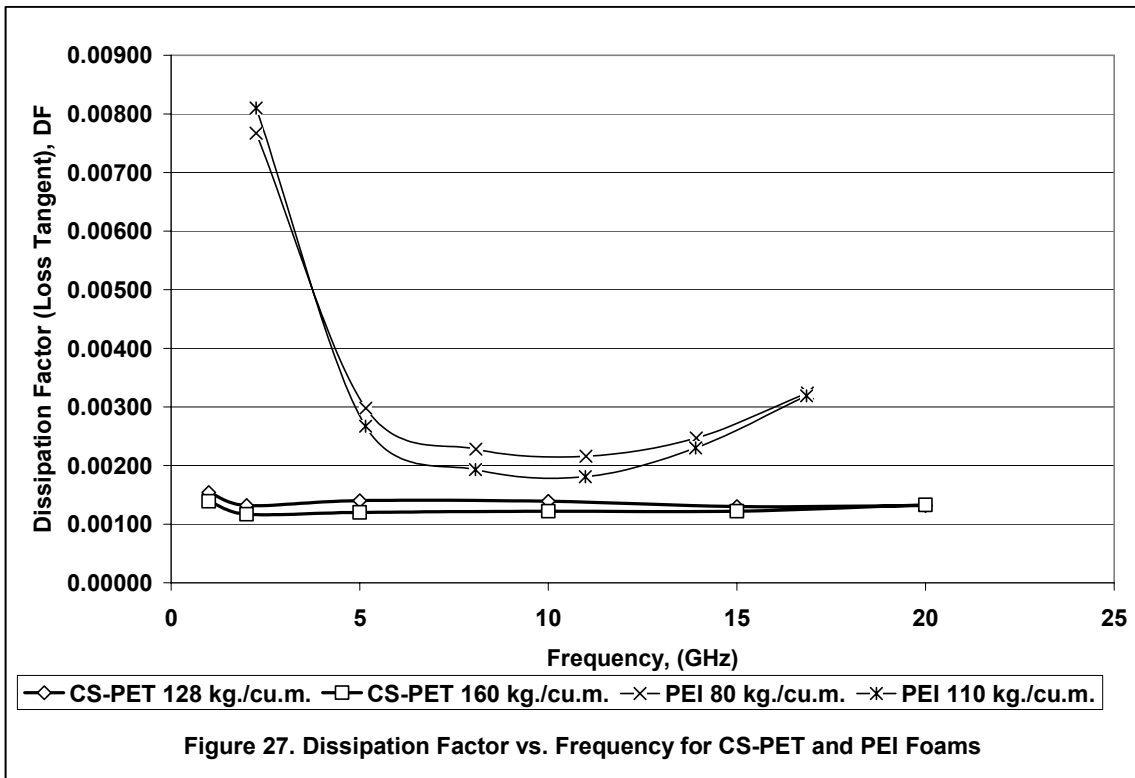
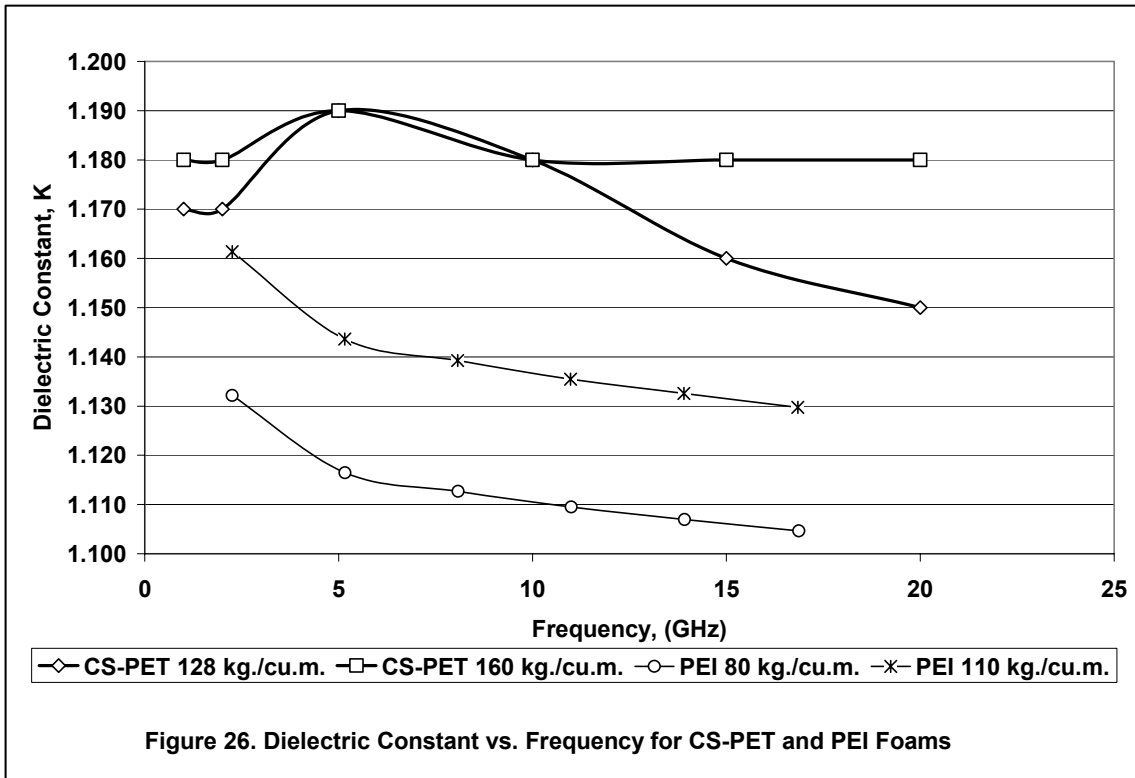
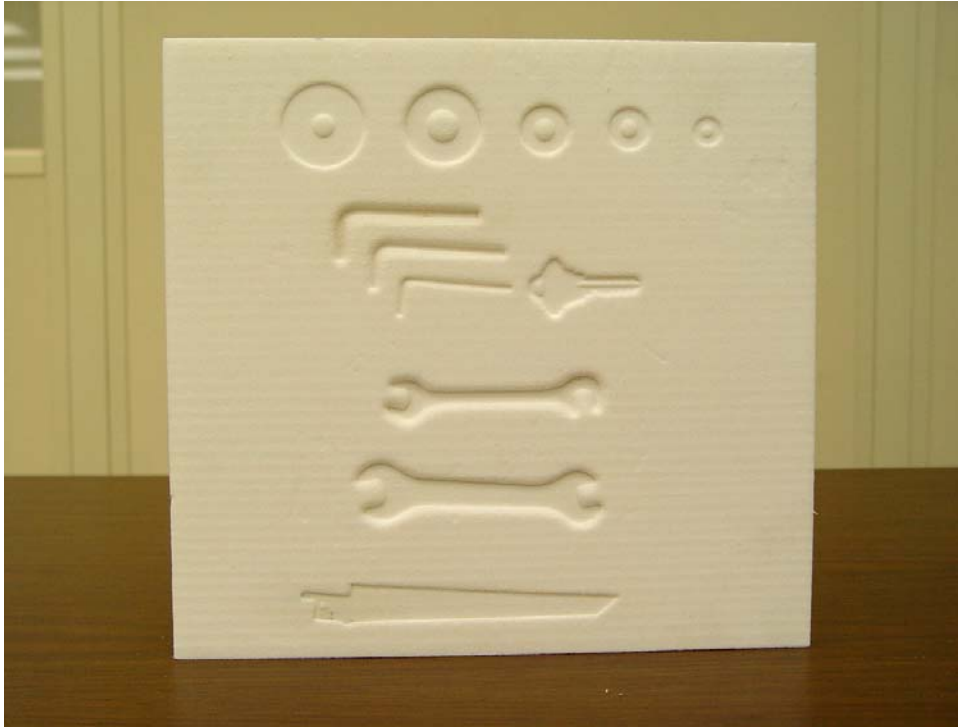
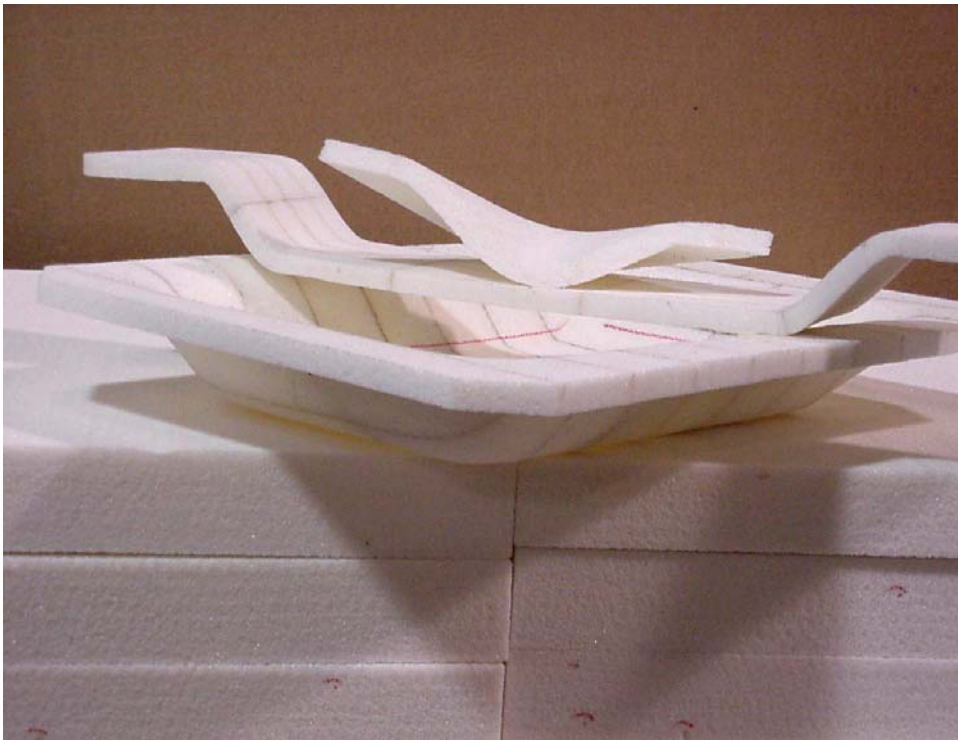


Figure 25. Sandwich Panel of CS-PET Foam Core & Glass-Fiber/Epoxy Composite Skin

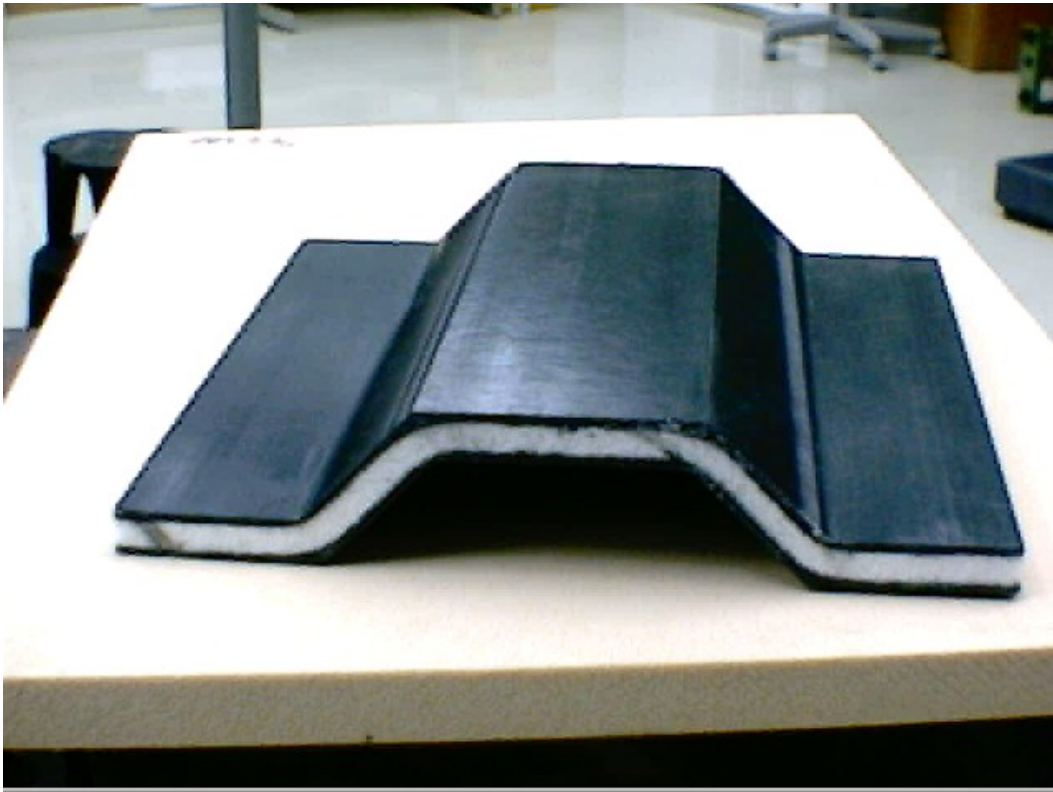




**Figure 28. CS-PET Foam Core after Heating and Pressing Various Items Into It**



**Figure 29. Thermoformed CS-PET Foam Sheet**



**Figure 30. Structural Sandwich Product of CS-PET Foam-Cored GMT**



**Figure 31. Thermoplastic Composite Sandwich of E-Glass/ PET Facings & CS-PET Foam Core, Before and After Thermoforming**