ArmaFORM® PET:
Technical Information

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1) Introduction

PET foam core has in the past 10 years established a position as the preferred choice for applications such as wind energy blades. However, compared with most other core materials available such as PVC foam, SAN foam or Balsa wood, it is still a very young material. This also means that the rate of development for PET foam core has been rapid and its full potential has not yet been reached by far.

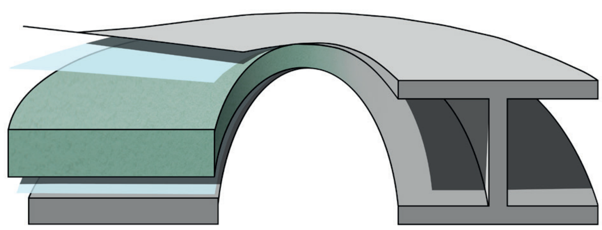
The success to date of PET foam core in wind energy blade applications has been due to a combination of its excellent fatigue properties, very good temperature stability compared with most other foam cores, as well as excellent compatibility with all resins and manufacturing methods. Owing to the extrusion process utilized in producing PET foam core compared with the batch process of most other structural foam cores, variations in density and other properties are markedly less and quality control procedures are easy to implement.

The basic thermoplastic properties of PET foam core enable wider processing possibilities with both thermoset and thermoplastic resins. This enables a higher curing or post-curing temperature resulting in quicker cycle times as well as better mechanical properties in the laminates. It also means that thermoforming and thermomoulding is possible which opens up a wider range of applications. Being thermoplastic also means that recycling into the same or similar products is possible. The latest ArmaFORM PET grade, PET GR, is based entirely on recycled PET mainly from reused drinking bottles. The bottles are cleaned of impurities and then ground to flakes, used as the raw material basis for ArmaFORM production with the necessary consistent properties.

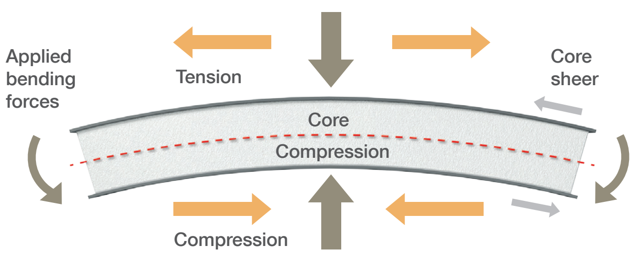
Another development within recent years has been an increased use of high density PET foam core in different applications. One use is for traditional inserts where high screw retention properties are of great use. Another is as a replacement for end-grain balsa where it has been proven that PET foam core can provide better shear strength at a lower weight due to lower resin uptake when using the infusion process. This has enabled blade producers to avoid using moisture sensitive Balsa wood in critical locations.

2) Sandwich theory

Sandwich composites are a special group of laminated composites widely used in engineering applications such as aircraft, aerospace, vehicles, buildings, etc. A good way to visualize the structure of a 'sandwich core panel' is to use the analogy of an "I" beam. It consists of a thick and lightweight core with a strong and relatively thin skin.



Caption: "I" beam analogy for composites



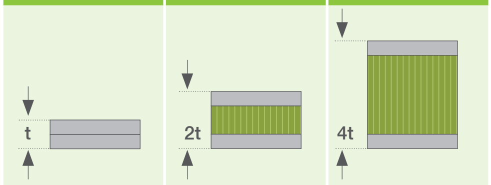
Caption: Stress in sandwich panels

The bending resistance for a rectangular cross-sectional beam or plate is proportional to the cube of the thickness. Increasing the thickness by adding a core increases resistance with only a negligible increase in weight. The maximum normal stresses occur at the bottom and top surface so it makes sense to use thin high strength/rigidity skins with a thick lightweight core material in the middle. The advantages in weight and bending stiffness make sandwich composites attractive in many applications such as wind energy, marine, transportation, B&C and many other "niche" applications.

Benefit of using composites and sandwich structures:

- > High strength to weight ratio
- > Very high stiffness to weight ratio
- > Freedom of design
- > Long service life, low maintenance
- > Easy to repair

Armacell provides high end core foams compatible with all reinforcement or resin systems and suitable for most manufacturing processes.

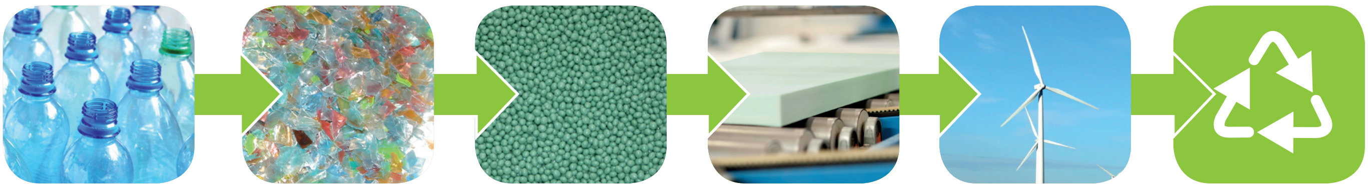


	Solid material	Core thickness t	Core thickness 3t
Stiffness	1.0	7.0	37.0
Flexural Strength	1.0	3,5	9.2

Caption: Strength to weight ratio

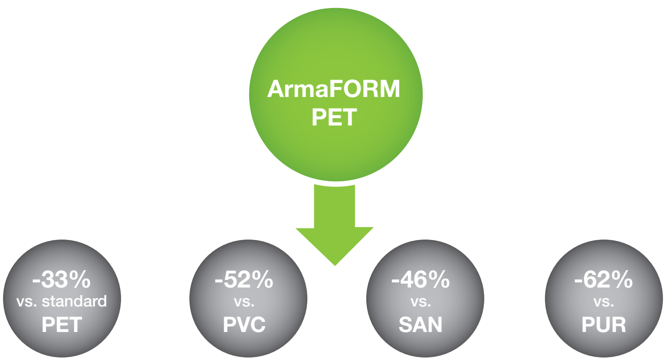
3) Life Cycle Assesment

Polyethylene Terephthalate (PET) is considered an engineering plastic due to its excellent mechanical and thermal properties. However, because of its large demand in the textile, bottle and packaging industries, it has become a commodity plastic in terms of price and availability. Furthermore, thanks to the bottle industry, it is also the most recycled plastic material in the world.
In this analysis, the environmental impact of ArmaFORM PET has been evaluated using the Life Cycle Assessment (LCA) method. The results prove that the environmental benefits of ArmaFORM PET GR, which is 100% made of post-consumer PET material, outperform any other foam core currently available on the composite market.
All ArmaFORM PET foam cores are manufactured in an energy and resource-optimized production process: 100% re-use of material loss and no use of ozone-depleting HFH or CFC blowing agents. In addition, the products are fully recyclable at life cycle's end and thus are considered to be an environmentally sensitive solution in the composite industry. But Armacell did not stop there and has again made a significant contribution to sustainable growth in the composite industry. Scientists from the global R&D Team have spent several years in the development of a technology that enables the production of PET foam boards with consistent, reliable qualities 100% made of post-consumer PET materials, called ArmaFORM PET GR. The life cycle of ArmaFORM PET GR is presented below.



PET material collection — *Sorting, crushing,... to flakes* — *PET granulation process* — *Extrusion foaming process* — *Use in a variety of applications* — *ArmaFORM can be 100% recycled*

Caption: Life-Cycle ArmaFORM PET



Caption: CO_2 emission of ArmaFORM PET GR vs. other foam core materials

In 2016, Armacell turned no less than 80,000,000 PET bottles into efficient and sustainable foams: For us, running a profitable business goes hand in hand with environmental and social responsibility. We are committed to continue with growth while protecting our environment through innovative products and technology. ArmaFORM PET meets not only stringent technical requirements but also provides sustainable development, following the guidelines of circular economy and helping in preservation and enhancement of the human environment.

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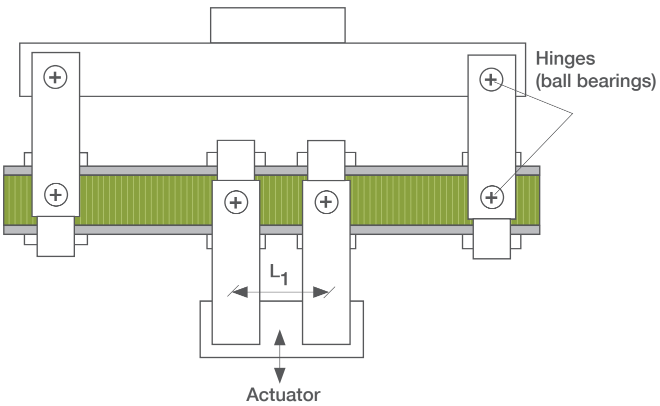
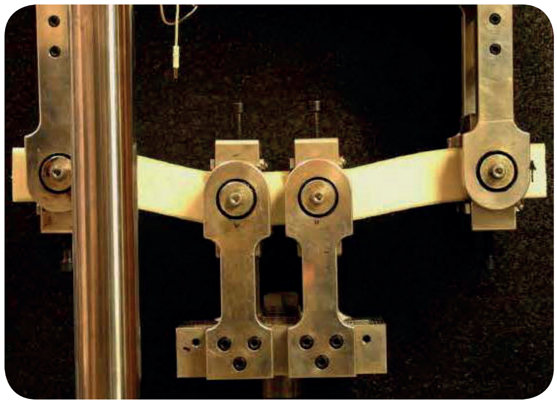
4) Dynamic loading / fatigue

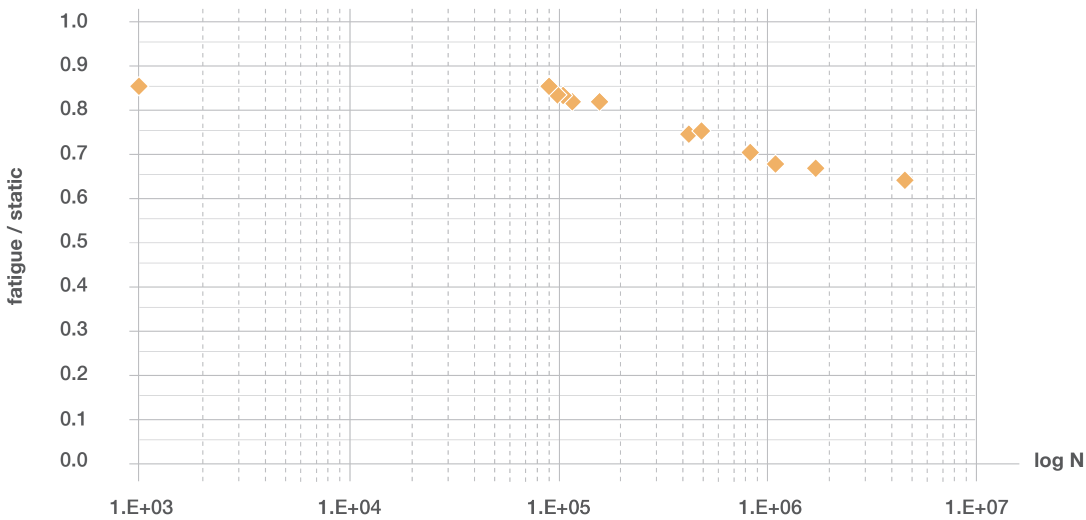
Mechanical structures have to withstand static loads at a foreseen maximum deflection without collapsing. Structures are actually subjected not once but thousands or even millions of times to these loads which become cyclic, leading designers to predict a fatigue life.
Fatigue testing can be thought of as simply applying cyclic loading to a test specimen to understand how it will perform under similar conditions in actual use. The load application can either be a spectrum load or a fixed load. The load application may be repeated millions of times and up to several hundred times per second.
The most common way of determining time to failure are S-N tests and curves (or Wöhler curves) where specimens are subjected to cyclic loading at different levels of stress, S, and the number of cycles to failure, N, is measured at each level. Fatigue tests on sandwich structures are normally performed with bending loads, as they are known to be the most demanding. The four-point bend test method provides an almost pure shear stress in the core, between the inner and outer supports, and is hence suitable for the purpose. The ASTM test standard C393-00 “Standard Test Method for Flexural Properties of Sandwich Constructions” describes the test set-up and requirements but is only designated for static and not fatigue testing. However, the same basic set-up can be used for the fatigue testing.





Caption: Four-point bending set up

Armacell organised fatigue testing for its ArmaFORM PET foam cores at the KTH (Department of Aeronautical and Vehicle Engineering) in Stockholm. Sandwich panels used for the test were manufactured using the infusion technique by KTH with four layers of glass-reinforced polyester on each side of the panel.

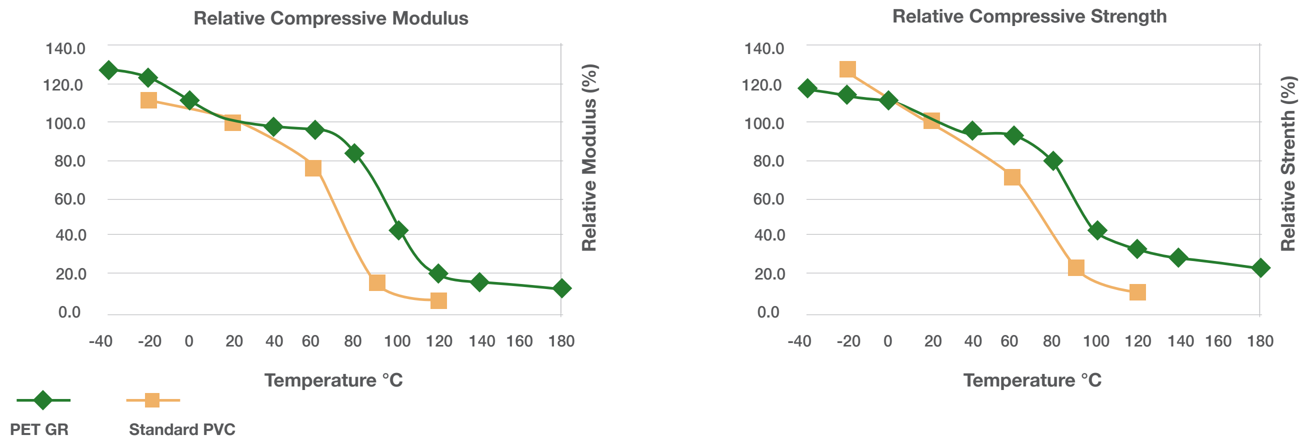


Caption: Normalized S/N diagram for GR115

The fatigue performance of ArmaFORM in relation to the static strength of the materials tested is excellent. One can observe that all qualities tested here can sustain well over millions of cycles at load levels corresponding to 60–70% of the shear strength while this level is normally at 30–35% for other core foams such as PVC.

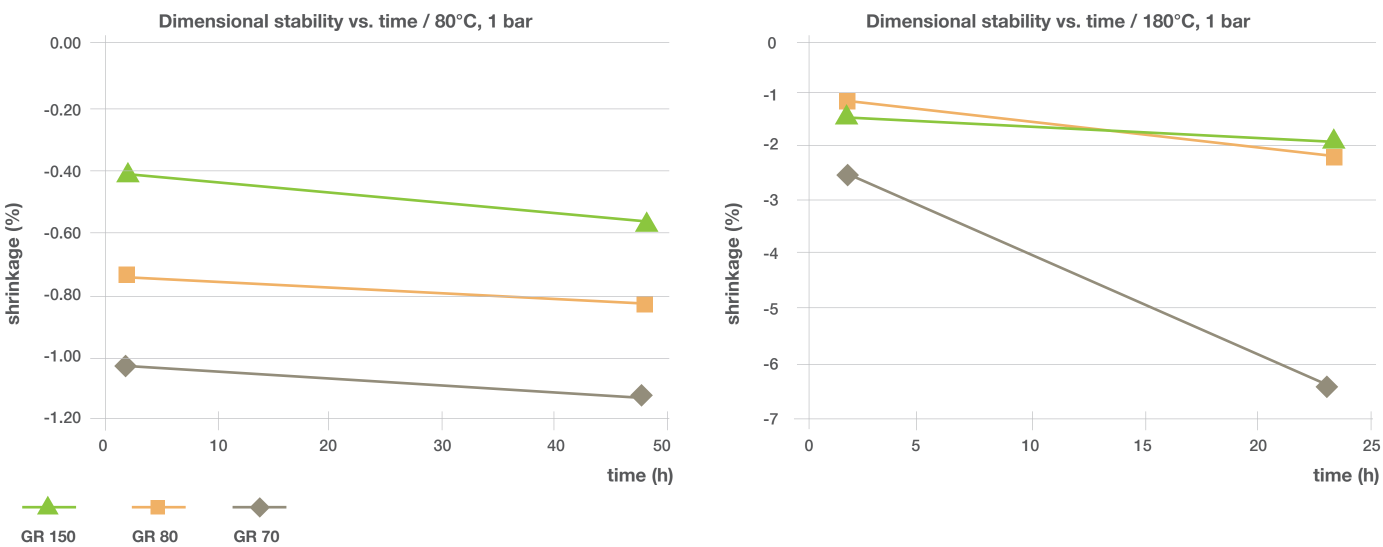
5) Thermal stability

ArmaFORM PET core materials exhibit a glass transition temperature (Tg) close to +75°C, and normally foam cores cannot be used at much higher temperatures than their Tg. However, crystallization in PET foam cores produces a crystalline structure that will act as a static, non-movable system until melting begins in the crystalline phase at about +240° to 250°C (melting point Tm). It takes hours to melt all crystalline structures at temperatures of +180°C while melting is rapid at +240°C. This allows for a wide range of processing temperatures for PET cores. At a temperature of e.g. +150°C, a process time of days is possible; a temperature of +180°C allows only short process cycles of a couple of hours.
As in all other foam cores, the softness, strength and stiffness of ArmaFORM PET cores decrease when heated, but more slowly due to its crystalline structure allowing a wider operating and processing window than most other cores. In the same way, ArmaFORM PET cores stiffen and get stronger when temperatures decrease but also lose some of their ductility. This is in line with other polymer materials.



Caption: Mechanical properties vs. temperature

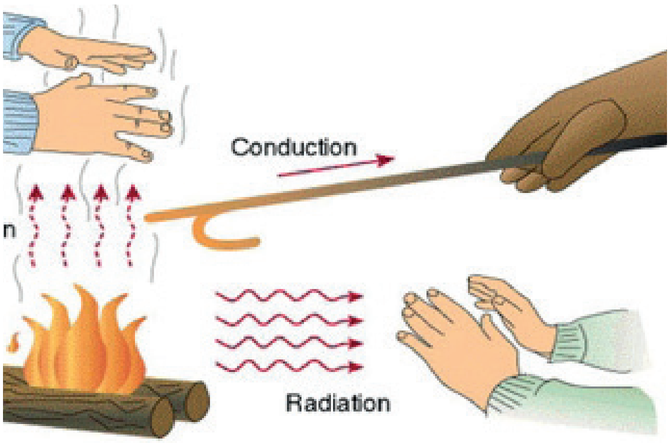
When processing foam cores at elevated temperatures (close to or above their Tg), the combination of time, temperature and pressure together with the density (compression strength) of the core, has to be taken into account to reach a good result. Generally, the core will shrink slightly in thickness but the values in the following table can be taken as worst case as these samples have been allowed to move unrestrictedly. Normally this is not the case and preventing in-plane expansion will also minimize thickness shrinkage.



Caption: Maximum shrinkage rate depending on temperature and duration

6) Thermal insulation

Heat is a form of energy associated with the random motion of molecules, atoms or smaller structural units of matter. Thermodynamic laws say that heat transfers always flow from higher to lower temperatures. Depending on the situation, insulation is required to prevent heat loss or heat ingress.
Currently, due to eco-friendly mindsets and an awareness of the earth's limited resources, thermal insulation is gaining increasingly more interest to improve the comfort and energy efficiency of buildings and systems. A material's insulation properties describe the ability of heat flux to go through the material. Armacell ArmaFORM PET foams exhibit outstanding insulation properties even for high densities thanks to their closed cell structure and high gas ratio within the material. Indeed, unlike fibrous insulating materials, water or liquid ingress is prevented by the closed cell structure which ensures stable thermal properties over time. Heat flows can occur according to three phenomena: conduction, convection and radiation. Their principles are shown in the following illustration:



Conduction is the critical criterion regarding thermal insulation in the B&C sector. The thermal resistance of a multilayer wall can be calculated as such:

$$R_{wall} = \sum_i \frac{e_i}{\lambda_i}$$

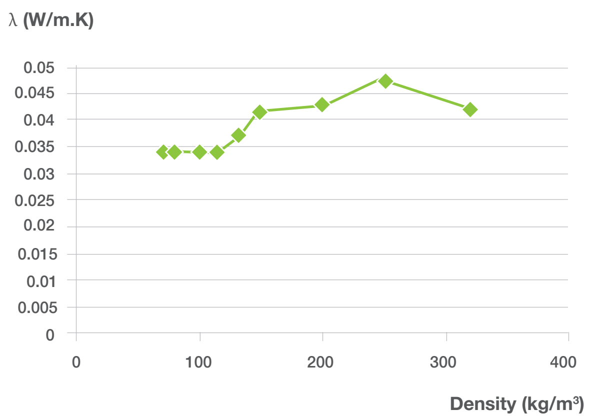
Where:
R is the total thermal resistance of the wall **($m^2.K.W^{-1}$)**

e is the thickness of each component **(m)**

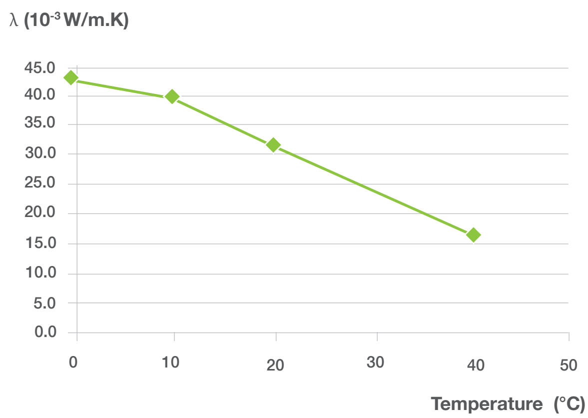
λ is the thermal conductivity of each component **($W.m^{-1}.K^{-1}$)**

Sometimes a **U**-value **($W.m^{-2}.K^{-1}$)** is used instead of **R**-value.
It represents the overall heat transfer coefficient and is defined as **$U = {}^{1}/_{R}$**

ArmaFORM PET foam core can be used for the construction of roofs, ceilings, facades, domes, bridges etc. The use of PET foam in sandwich composites provides thermal formability giving architects and engineers benefits such as flexibility in design and installation, as well as low thermal conductivity. This gives building structures an attractive surface with no deterioration, and minimum maintenance and repair costs.



Caption: Evolution of thermal conductivity of PET GR in relation to density



Caption: Evolution of thermal conductivity of PET GR70 in relation to temperature

Its performance and advantageous properties, such as a high strength-to-weight ratio, reduced weight, and good thermal insulation characteristics, are driving the market. ArmaFORM PET, when used in construction, results in easy installation, higher energy efficiency, low maintenance and repair costs, and lower life cycle costs as compared with other outdated/traditional building materials used in the construction industry such as steel, concrete, and other foam core or fibrous materials.

7) Acoustic insulation

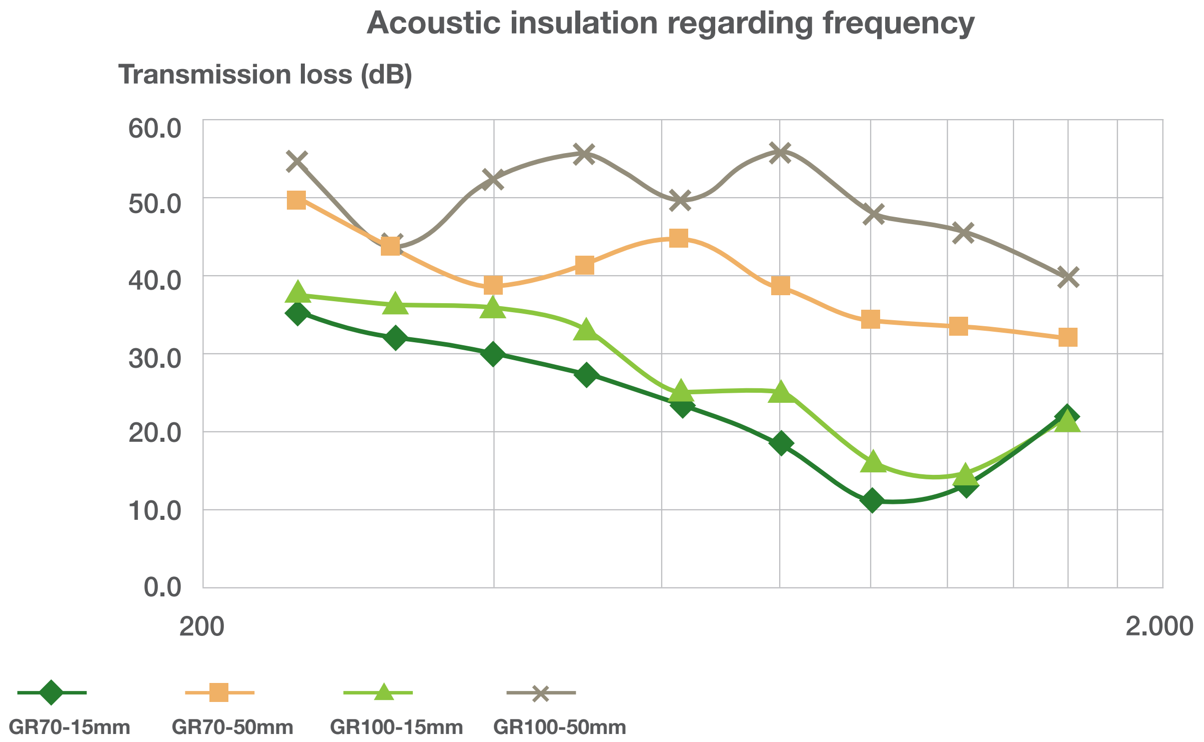
In acoustic and noise control engineering, the main goal is to reduce or eliminate noise power, whether outdoors or indoors. Armacell tested sound attenuation properties of its ArmaFORM PET products in the 250Hz–1600Hz range which covers most situations of domestic and industrial noise. If specific needs are required for other frequencies, special frequencies can be tested on request.

Sound barriers are differentiated according to two types:

1) The barrier is made with a single homogeneous material. Here, the main parameter is mass: the heavier the barrier, the better the insulation. Mass can be increased by using a thicker wall in the same material or using a more dense material. There is a relationship between sound transmission loss and the weight of the barrier called the mass law. The mass law states that for every doubling of the weight of material, a 6 dB increase in transmission loss can be expected.

2) The barrier is made with multilayer panels (analogous to mass/spring/mass). This kind of structure is more effective but it is more difficult to forecast results because, depending on the combination of skins and core, bonding etc., each situation will require testing to determine the best set-up and fit to specification.

Below are acoustical insulation graphics for different thicknesses and densities of ArmaFORM PET:



Caption: Acoustic insulation regarding frequency

So ArmaFORM PET shows very good results in terms of sound insulation properties taken alone or in combination with skins to produce multilayer insulators.

8) Processing

ArmaFORM PET core will work with almost all kinds of resin and adhesive systems. The only main exception is with 1-component moisture curing adhesives (such as white PUR wood glue) as ArmaFORM PET core is closed cell and very diffusion resistant so moisture cannot diffuse in or out of the adhesive thereby preventing proper curing.

In general it is therefore best to start with the resin or adhesive system that works well with the skins or laminates to be used in the production process and that the manufacturer is familiar and comfortable with. In almost all cases, the resin or adhesive will then work sufficiently to bond or laminate ArmaFORM PET core.
PET core material exhibits a glass transition temperature (Tg) close to +75°C crystalline structure will act as a static, non-movable system until melting begins in the crystalline phase, at about +240° to 250°C (melting point Tm).

It takes hours to melt all crystalline structures at temperatures of +180°C while melting is rapid at +240°C. This allows for a wide range of processing temperatures for PET foam cores. At a temperature of e.g. +150°C, a process time of days is possible; a temperature of +180°C allows only short process cycles of a couple of hours under full vacuum. When a higher pressure is used, the combination of time and temperature has to be verified to avoid creep affects in the core.

The high processing temperature of the ArmaFORM PET means that it can readily accept high peak exothermic reaction from, for example, thick laminates which would affect or destroy other foam cores.

It has been noted in a few case that degrading of the PET foam core can happen leading to increased brittleness when using a wet high temperature curing epoxy system, mostly mould-building high Tg systems. It has been identified that a few epoxy hardeners, when not mixed well with the epoxy resins, can create degradation of PET foam. This effect is much more pronounced if the curing is done at once at a high elevated temperature. If the resin base and hardener are mixed well, this effect will most probably not occur, and with a suitable cure cycle, all systems tested have been compatible.

Version: September 2017

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