



Fig. 2 Example of reinforced fiber orientation [5].

2D random orientation of fibers occurs in composites made by the method of pressing thin-walled components or in composites from mats. 3D random fiber orientation occurs in composites produced by injection molding or extrusion. In a composite material with randomly oriented fibers, we can speak of isotropy, so its properties are independent of the orientation of the fibers. The disadvantage is that one-way orientation of the fibers can occur, making the material anisotropic. [5]

According to the reinforcement material we know:

- metals,
- non-metals: - inorganic: - ceramic material,
 - glass,
 - Ad basalt,
- organic: - polymers,
 - polyamide fibers, kevlar,
 - nylon. [4]

The fibers can be man-made, natural (glass, carbon, aramid, basalt and others) or other reinforcing materials. The role of the fibers is to provide the matrix with the required strength and stiffness, thus helping it to resist cracks and fissures. [1]

3. Properties of polymer composites with long fibers

The current trend in the automotive sector is to reduce weight, which directly contributes to reducing fuel consumption and thus to reducing the emissions that cars produce. From this point of view, polymer matrix composites are the most promising material due to their mechanical properties and low weight. However, their disadvantage is the high price, which is higher than the price of conventionally used materials.

Each of the polymer composites has properties that make the composites more attractive for use in automotive manufacturing than conventionally used materials. These features include at least one of the following:

- high strength, • corrosion resistance,
- high rigidity, • high strength to weight ratio,
- high ductility, • low maintenance,
- thermal properties, • resistance to weather conditions,
- low weight, • good resistance to cracking,
- chemical resistance, • versatile use. [1]

Today, there are a large number of polymer-based composites. These materials are based on the combination of reinforcement and macromolecular material in order to improve mechanical properties. Many of the properties of composite materials depend on the appropriate combination of matrix type, reinforcement used, and manufacturing process.

The basic component of the composite matrix is a polymer that binds the filler of organic or inorganic origin. The matrix is divided into thermosetting and thermoplastic in polymer composites.

According to the most important manufacturers, the most commonly used thermoset and thermoplastic matrix types include the following:

THERMOSETS

- unsaturated polyester (UP),
- vinyl ester (VE),
- unsaturated epoxide (EP),
- polyamide (PA),

THERMOPLASTICS

- polypropylene (PP),
- polyamide (PA),
- polycarbonate (PC). [1, 6]

The properties of the most commonly used thermoplastic and thermosetting matrices can be seen in the following table.

Table 1: Overview of matrix properties [6]

Matrix type	Density [g/cm ³]	Young's modulus [GPa]	Tensile strength [MPa]
Thermosets	1.1 - 1.67	1.3 - 6.0	20 - 190
Polyesters	1.1 - 1.5	1.3 - 4.5	45 - 85
Epoxies	1.1 - 1.4	2.1 - 6.0	35 - 90
Vinyl esters	1.05 - 1.2	70 - 90	3.5 - 4.5
Polyamides	1.2 - 1.9	3.0 - 3.1	80 - 190
Thermoplastics	0.9 - 1.45	1.0 - 4.0	20 - 250
Polypropylene	0.9	1.1 - 1.5	28 - 41
Polyamide	1.42	2.8 - 3.4	76 - 83
Polycarbonate	1.21	2.1 - 2.8	62 - 76

Polyester matrix composites

Polyester resins are the most widely used resin systems in the shipbuilding industry. They are also used in the construction industry and for the production of common structural composite parts. The basic types of unsaturated polyester resins are:

- orthophthalic - lowest price. average properties.
- isophthalic - better than orthophthalic. better chemical and thermal resistance.
- fumaric - good chemical and thermal resistance.
- chlorophthalic - is non-flammable. but mechanical properties are worse than other species.
- vinyl ester - very good chemical and thermal resistance.

Unmodified and unsaturated polyester resins have a high shrinkage during curing, which is in the range of 7 to 8%. They are fragile and easily create microcracks, which are an undesirable element. The electrical properties are very good, as is the resistance to ultraviolet radiation. The resins saturate the fibers well, but the bond strength of the matrix and the glass fiber is lower. [7]

For processing, it is necessary for the resin to contain still other substances, such as catalyst, accelerator, additives, and chemical refractories. In order to achieve the best material properties, it is necessary to add the accelerator and the catalyst in well-measured amounts according to the ratios given for the individual resins. An excess of catalyst causes a shortening of the gelation, while its lack causes insufficient curing. Fillers are added in amounts up to 50% by weight of the resin, but some additives can affect the flexural and tensile strengths of the laminates. The description and suitability of the selected polyester resins can be seen in Table 2 below. [7]

Table 2: Selected polyester resins from HAVEL COMPOSITES CZ s.r.o.

Polyester resin	List
HAVEL pol. 1	Basic orthophthalic resin, which is pre-accelerated.
HAVEL pol. 2	Standard orthophthalic, pre-accelerated, low-emission and thixotropic resins.
HAVEL pol. 4	Clear, UV stable and non-accelerated resin.
HAVEL pol. 5	Non-accelerated resin suitable for the production of more demanding parts.
HAVEL pol. 6	Standard orthophthalic pre-accelerated resin with a lower price. It is suitable for the production of structural parts of ordinary fiberglass, where price is the main criterion.
HAVEL pol. H 834	It is a moderately reactive thixotropic resin that is pre-accelerated with low shrinkage. It is designed for the production of ships and other composite parts. It is suitable for production by spraying or manual laying. It has a high heat stability up to 95 °C

Vinyl ester matrix composites

Vinyl ester resins have a molecular structure similar to polyester, but primarily differ in the position of their reactive sites, which are located at the ends of the molecular chains. They are easy to handle, especially at room temperature, while providing mechanical properties comparable to epoxy resins.

Compared to cheaper polyester resins, they have better chemical resistance, including hydrolytic stability, which contributes to easier control of curing time. Polyester resins have poorer resistance to water and other chemicals, corrosion resistance and lower heat resistance. However, their price is lower compared to vinyl ester resins and they cure faster. They are used in the production of gas pipelines, cooling towers, shipbuilding and rotor presses.

In general, vinyl ester resins, which are unsaturated thermoset resins, combine the best properties of polyester and epoxy resins. [6, 7]

Epoxy matrix composites

Epoxy resins outperform most other types of resins due to their mechanical properties and resistance to degradation, which is why they are used in the aerospace industry. Another application of epoxy resins is in the shipbuilding industry, thanks to increased adhesion properties and resistance to water degradation. In this area, they are used as a primary construction material, a secondary application for hull shells or as a replacement for polyester composites and gelcoats. They can also be used as adhesives and sealants, varnishes, paints, but also as laminar resins for a wide range of applications.

They can be easily and quickly cured at any temperature in the range of 5 to 150 °C, depending on the type of accelerator used. One of the most advantageous properties is low shrinkage during curing, which makes it possible to minimize internal stresses. They have high adhesive strength, good chemical resistance and high electrical insulation capacity.

They differ from polyesters in the method of curing, where they are cured with a hardener instead of a catalyst. Curing can be accelerated by the application of heat, which means that the higher the temperature, the sooner the curing of the resin is achieved. In other circumstances, curing may take several hours. [7]

An overview of hardeners, their mixing ratios with epoxy resins and the curing time of epoxies can be seen in Table 3.

Table 3: Hardeners overview of company HAVEL COMPOSITES CZ s.r.o.

Resin	Mixing ratio		Pot-life
	Parts by weight	Parts by volume	
			100g at 20 °C [min]
133 MGS	100:35	100:40	10 - 15
135 MGS	100:35	100:40	25 - 30
136 MGS	100:35	100:40	60 - 120
500 MGS	100:40	100:50	10 - 15
H 285	100:40		50
H 505	100:27		15 - 30
			100g at 25 °C [min]
H 10	100:45	100:50	15 - 25
			100g at 25 °C [min]
C	100:60		50
L	100:40		40
			100g at 20/45 °C [min]
386 MGS	100:35	100:40	300 - 360 / 80 - 120

Table 4: Overview of epoxy resins HAVEL COMPOSITES CZ s.r.o.

Epoxy resin	List of resins
LH 145	Resin with very low viscosity and resistance to crystallization. Suitable for the production of sporting goods, boats and car parts.
LH 160	Laminating resin with low viscosity, high hardness and chemical resistance. It is used for the production of boats and boat accessories, sports equipment, models and molds. It is more prone to crystallization at low temperatures.
LH 260	It is a clear resin that is resistant to crystallization with a higher viscosity compared to LH 160. Available in three variants - with UV stabilizing substances, with a defoamer for faster removal of microbubbles and with limited flammability.
LH 289	It creates a smooth and shiny surface, and is most often used as a glaze for artificial stone. It is characterized by a lower price.
LH 288	Special epoxy resin with extremely low viscosity, which is suitable for infusion technologies. Products made with this resin are characterized by high hardness.
LH 300	Resin with higher viscosity and high heat resistance up to 150 °C. It is very important to follow the technological procedure in the production of composites.
L 20	It has good adhesion to wood, steel materials, plastics, ceramics and other similar materials.
C	Chemically very resistant epoxy resin. It is used in the construction of stops, tanks and pipelines.
L 285 MGS	High quality resin that is certified for the aerospace industry and model production. In combination with the hardener, it forms a very viscous mixture, thanks to which the fibers are supersaturated faster.

4. Evaluation of the properties of polymer resins and composites

The similarity of epoxides to vinyl esters is in the long chain molecular structure and in the reactive sites located at the end of the chain. The difference is that in epoxy resins, these sites are formed by an epoxy group instead of an ester group. As a result, they have extremely good resistance to the aquatic environment.

Compared to polyesters and vinyl esters, epoxies have very good fatigue resistance, which is also one of the many reasons why they are used in the aerospace industry. The main disadvantages include high cost, critical mixing ratios and corrosivity.

Reinforcement of matrices with different fiber content, as well as different orientation and type of reinforcement affects the mechanical properties of the resulting composite material. Therefore, it is important to pay attention to the appropriate choice of matrix and reinforcement and other additives, as well as to the selection of a suitable production technology.

Table 5: Properties of selected materials with composites

Material	Density [g/cm ³]	Young's modulus [GPa]	Tensile strength [MPa]
Steel SAE 1010 (cold processed)	7.87	207.0	365.0
Steel AISI 4340 hardened and tempered	7.87	207.0	1722.0
Aluminum alloy 6061-T6	2.70	68.9	310.0
Titanium alloy Ti-6Al-4V	4.43	110.0	1171.0
Stainless steel 17-7 PH	7.87	196.0	1619.0
High-strength epoxy matrix with carbon fibers (non-oriented)	1.55	137.8	1550.0
High-tensile epoxy matrix with carbon fibers (non-oriented)	1.63	215.0	1240.0
Epoxy matrix with E-glass (non-oriented)	1.82	39.3	965.0
Epoxy matrix with Kevlar (49%) (non-oriented)	1.38	75.8	1378.0
Epoxy matrix with carbon fibers (quasi-isotropic)	1.55	45.5	579.0
SMC pressed composite (isotropic)	1.87	15.8	164.0
Vinyl ester matrix with glass fibers (67%) (randomly oriented)	1.84	19.3	269.0
Vinyl ester matrix with glass fibers (50%) (randomly oriented)	1.80	15.8	166.0

5. Conclusion

In the production of composites, it is important to pay attention to the processing time of the resin, the so-called Gel time. Gel time is the time during which the viscosity of the resin changes, after which it is no longer possible to work with the resin or the individual layers of the resin and the reinforcement are not sufficiently connected. If this time is not observed, cavities may form after curing or the individual layers may separate from each other, resulting in reduced mechanical properties or deterioration of

the composite. Each resin has a gel time specified by the manufacturer, which can be influenced by the type of resin used or by changing the hardener used. Ambient temperature also affects the rate of transition of the resin to the gel state.

Curing at a controlled temperature changes the viscosity of the resin, which increases with increasing temperature until the resin is completely cured. By increasing the curing temperature to a certain limit, it is possible to improve the mechanical and thermal properties of composites. As the temperature rises, the curing time of the resin decreases.

The type of reinforcement used in the composite has a significant effect on the mechanical properties of the composites. Carbon composites had the highest strength-to-weight ratio compared to other composites, but their ability to absorb energy was low due to the brittleness of the material. Glass fiber reinforced composites had significantly higher energy absorption after post-curing at elevated temperatures compared to carbon composites, approximately 3.6 times. By combining the reinforcement fibers, a balance of the mechanical properties of the composite can be achieved. However, the post-curing of the already cured composite does not have such a significant impact on the mechanical properties of the composites compared to the initial curing of the composites at elevated temperature.

At the same time, however, by additional curing of the already cured composite at room temperature, the mechanical properties can be further increased to a certain temperature, regardless of the reinforcement used. The process of post-curing in the furnace at elevated temperature results in an average of 10% increase in the impact resistance of the material and a 9% increase in tensile strength, which does not represent such a significant improvement in mechanical properties as in the initial curing. Finally, it is important to note that it is necessary to examine specific types of composite materials in this way. Such an examination would determine the temperatures at which the material needs to be cured in order to fully exploit its potential and achieve maximum mechanical properties.

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