Flowing towards Efficiency:
LCM-compliant Matrices for Composites

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Structural parts from fibre reinforced plastics can be manufactured economically with methods of injection and infusion. Large scale production on the one hand, maximum operation temperatures on the other: a growing portfolio of liquid processable materials allows for the multiple requirements. This paper gives a survey.

1. The Motivation

The trends in application of fibre reinforced plastics are:

- Large parts in small series: Hand-lay-up and similar methods are being substituted by closed-mold techniques, motivated by ecological and toxicological considerations
- High-performance sector such as space and aerospace: Manufacturing turns away from prepregging and autoclaves towards automated and cheaper processes
- Automotive: Methods suitable for mass production are supposed to be harmonized with the lightweight construction potential of continuously fibre reinforced composites
- Industrial applications in general: The demands for structural components concerning temperature limits and flammability are rising dramatically.

Injection and infusion of resins, comprising impregnation of reinforcements under pressure and / or in vacuum, are called „Liquid Composite Molding“ (LCM), Figure 1. They can be integrated in automated production lines, being accompanied by appropriate process control, from cutting and performing of the reinforcement, its placement in the mold, resin supply and curing process, up to demolding and postprocessing.

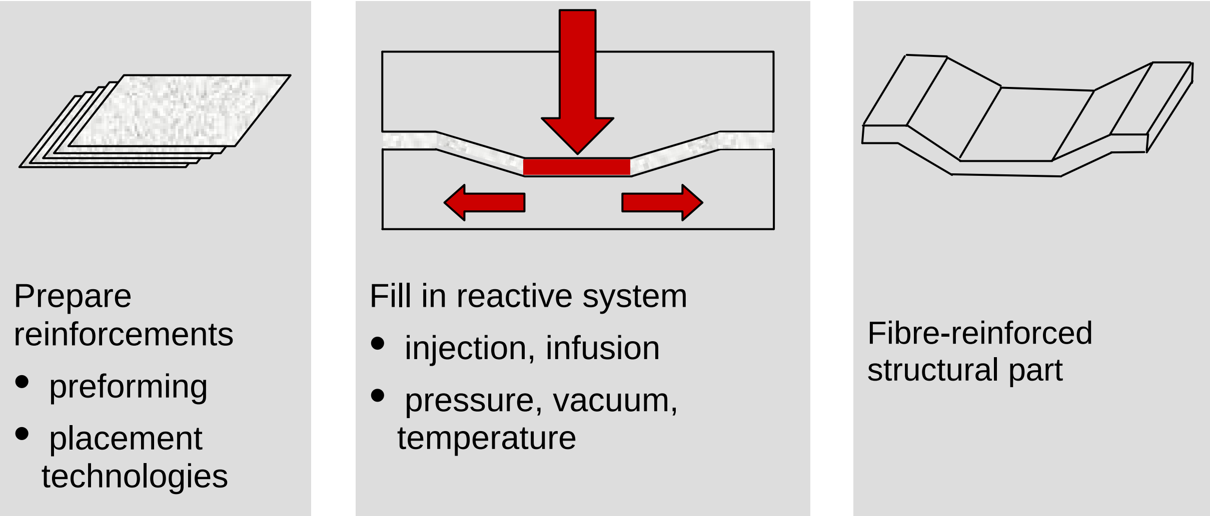


Figure 1: Principle of Liquid Composite Molding LCM

Appropriate material for LCM technologies are thermoset reaction resins and, limited, condensation resins, as far as they are capable of flowing and impregnating. Newer developments cover prepolymers of thermoplastic resins.

2. Viscosity versus Thermal Limit?

In general, a LCM-resin should show a viscosity of clearly less than 1.000 mPa*s and not exceed this value considerably during fibre impregnation. When the resin starts curing, the flowability decreases. That means, the quicker the curing reaction – which is a definitely wanted effect in order to reduce cycle times – the shorter the pot life of the thermoset. This is especially important for large structural parts.

It is not easy to cope with this problem. Polyester resins` reactivity and viscosity is quite easily controlled by additives; for other resin systems a lot of research is going on in this field. Modern epoxy resins with delayed viscosity rise, combined with quick cure, benefit from the wind power boom which enabled new developments.

The application of fibre reinforced plastics increasingly takes place also in areas with high temperature load. For components in aerospace, showing long-term limits of over 200 °C, polyimides are being used which are expensive in respect to material and prepreg-autoclave manufacturing. Moreover, the classical reaction resins are only stable up to a maximum of about 180 °C. As temperature limits rise even in industrial applications, economical solutions have to be found.

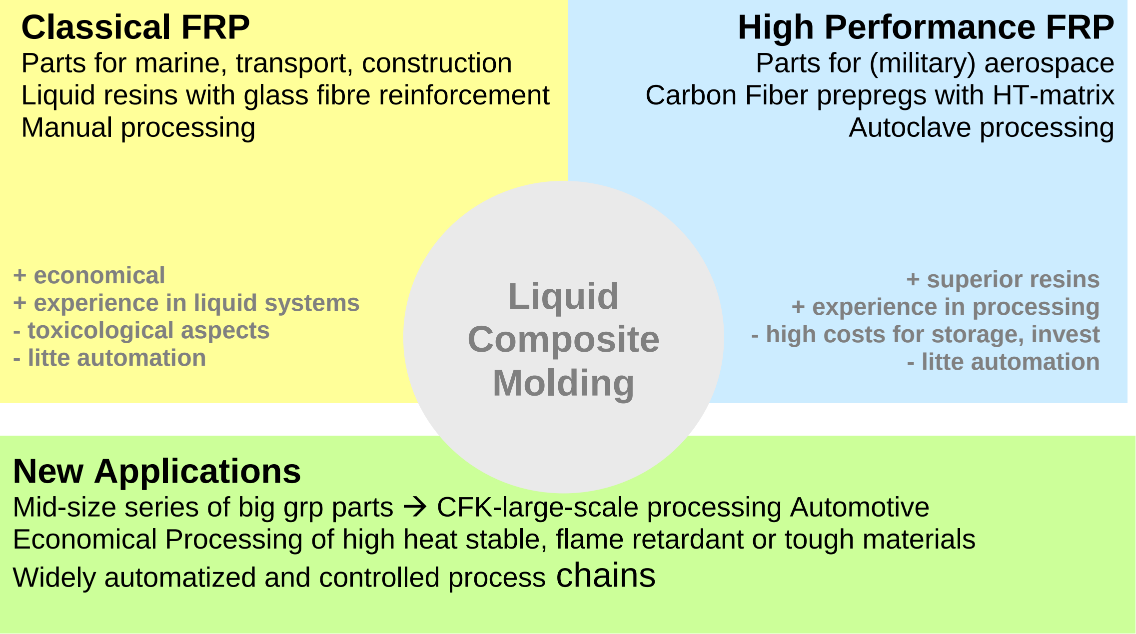
High heat resistance of thermosets means bulky and polar chemical groups in the molecular chain that limit the molecular mobility and / or many functional, i.e. reactive groups that form a close meshed network through curing. Fulfilment of these conditions normally means high viscosity of the liquid resin. Modification of resins by structural variation of the source material, copolymerisation or other methods have to be found in order to solve the balancing act between viscosity and temperature demands. Concerning LCM of high-performance resins, this procedure is just at its beginning.

3. Materials for Liquid Composite Molding

In all areas of application there have been efforts to optimize liquid processable matrices for LCM processes, Figure 2. Traditional frp manufacturing and high-performance sector have been mutually beneficial in this respect. The progress will be demonstrated for three groups of resins:

- The „Classics“
- The „High Performers“
- The „Newcomers“.

The technical data of the materials to be discussed are listed in tables at the end of this document. Nonetheless, dividing the resins in these groups may seem arbitrary and subjective but has been done in order to reflect the general trend in a structural manner.



Classical FRP
Parts for marine, transport, construction
Liquid resins with glass fibre reinforcement
Manual processing

+ economical
+ experience in liquid systems
- toxicological aspects
- litte automation

High Performance FRP
Parts for (military) aerospace
Carbon Fiber prepregs with HT-matrix
Autoclave processing

+ superior resins
+ experience in processing
- high costs for storage, invest
- litte automation

Liquid Composite Molding

New Applications
Mid-size series of big grp parts → CFK-large-scale processing Automotive
Economical Processing of high heat stable, flame retardant or tough materials
Widely automatized and controlled process chains

Figure 2: Classical manufacturing and high-performance sector yield new matrix systems

3.1 The „Classics“

- **Unsaturated Polyester and Vinylester resins (UP, VE)**
  - economical, “simple” LCM-prozcsses
- **Epoxy Resins (EP)**
  - variable through choice of hardener
  - wind energy is driving force
  - HT-Systems proven in aerospace
- **Phenolic resins (PF)**
  - Matrix of choice for flame retardant frp in public transport

Tradition in liquid processing for very long time

Infusion methods take hold for big structural parts

RTM for high performance reinforced plastics

Figure 3: The „Classics“: Thermosets with long tradition, being manufactured with rather simple processing techniques

3.1.1 Unsaturated Polyester Resins

The economical allrounders, mostly used as glass-fibre reinforced plastics (grp) dominate applications in plant engineering, construction and transport, Figure 4 (www.dsm.com, www.reichhold.com, www.ashland.com). Low viscosity and easy-to-handle radical curing reaction by hardeners, accelerators and inhibitors as well as short curing times belong to the advantageous profile of the unsaturated polyesters (UP). They are, however, not appropriate for higher thermal and mechanical demands which is the field of epoxies or other resins.

Vinylester resins (VE) also belong to the UP family; they produce cured material with higher touhgness and chemical resistance. VE-urethane-resins lead to excellent laminate quality due to good fibre impregnation.

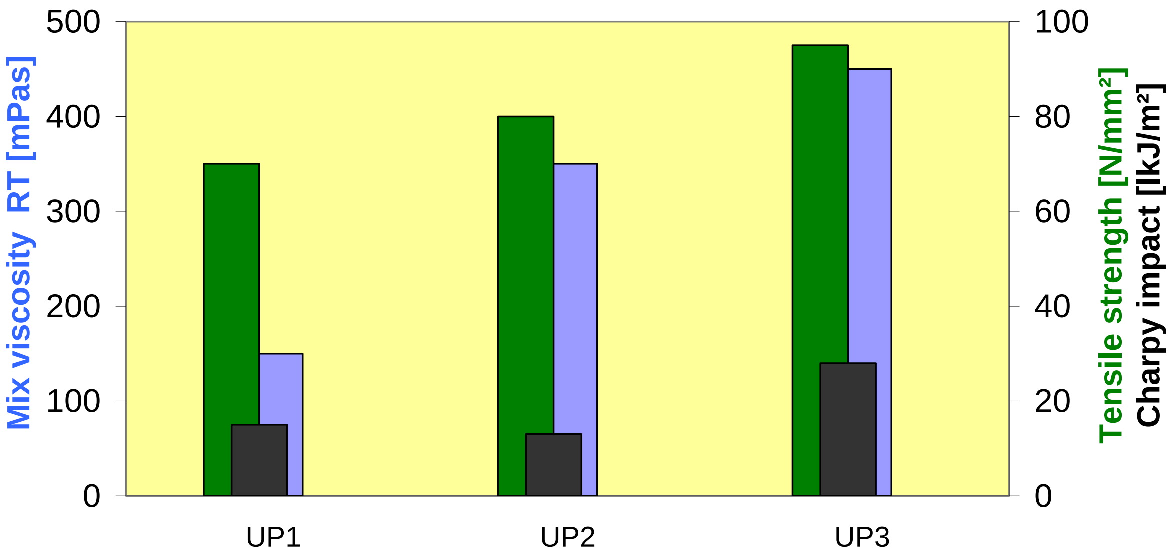


Fig. 4: Mix viscosity and mechanical data of three typical unsaturated polyester resins

UP1: based on dicyclopentadiene, low shrink, typical application: marine

UP2: heat-stabilized standard UP resin based on orthophthalic acid

UP3: vinyl ester resin,typical application: chemical engineering, wind rotors

Up to 150 mm thick VE laminates can be cured in a controlled vacuum infusion process thanks to a new catalysator system. Combining a traditional peroxide initator with a nitroxide leads to a chemical compound that is inactive at room temperature but reacts at about 40 °C. Using temperature-governed moulds, the exotherm can be controlled in a way that the maximum temperature inside the laminate does not exceed 100 °C (www.arkema.com), Figure 5 [1].

Unsaturated Polyester Resins:

- intrinsic low viscosities
- processing mostly at room temperature, followed by postcuring
- pot life and cure behaviour controllable by peroxides, accelerators and inhibitors

New catalysators and adjusted temperature profiles enable gentle curing of thick Vinyl ester laminates

Hatch cover for Flue Gas Desulphurization

Thickness 135 mm

source: Arkema

Figure 5: Technology and innovation regarding unsaturated polyester resins

UP and VE resins are basis for newly developed matrix systems combining the chemistry of polyester and polyurethane resins, as will be shown in the following.

3.1.2 Phenolic resins

Phenolic resins are material of choice for structural parts in public transport and when flame retardancy is of importance. Curing a phenolic resole with acid hardener leads to thermosetting material with high fire proof. Pot life and curing time can be controlled by the amount of hardener. Regarding the mechanical niveau, phenolic resins do not reach the values of UP or EP resins, but they show high dimensional and oxidative stability at high temperatures. Processing phenolic resins means handling with non-corrosive reinforcements and tools; moreover the curing reaction can be so exotherm that the application of heat for the reaction start may have to be followed by a cooling process. At temperatures below 100 °C the water occurring from the condensation reaction remains in the cured part (www.cytec.com, www.hexion.com).

3.1.3 Epoxy resins

Among the „classics“, epoxy resins are the thermosets with the most variable properties, and they will remain of importance in the future. They are the standard matrix for carbon reinforced components with long-term temperature limits of up to 150 °C, e.g. for aerospace, racing and sport goods. They are often being processed using an appropriate temperature profile, Figure 6.

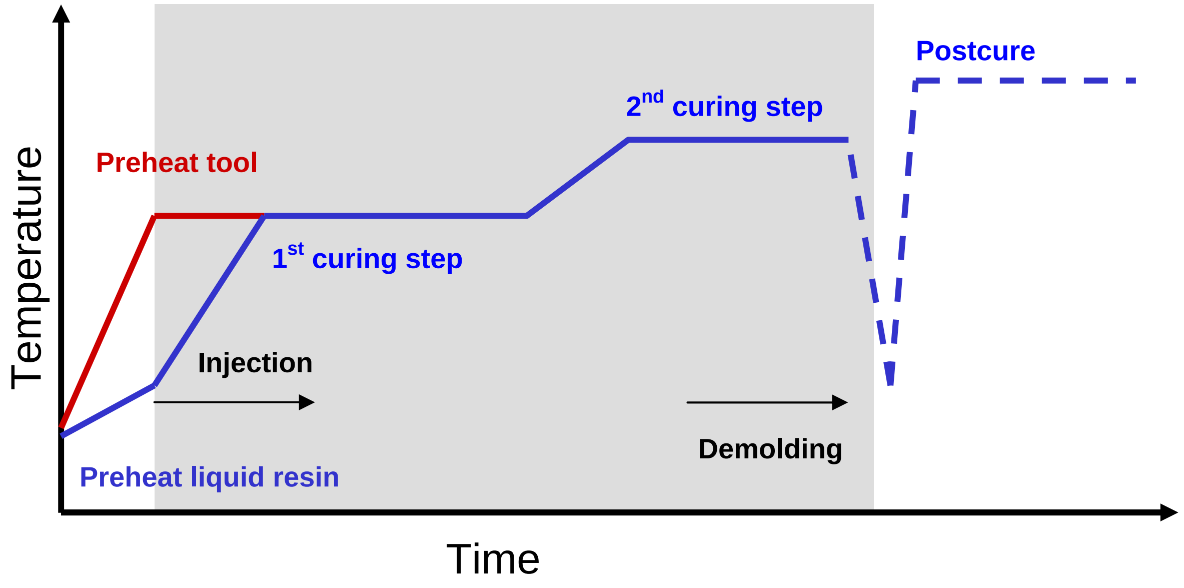


Figure 6: Principle of a step curing for high-grade resin systems via LCM

There are lots of low-viscous LCM-epoxies for mechanically highly strained large structural parts such as wind rotors, Figure 7 (www.hexion.com, www.huntsman.com). Special resin systems that are able to cure within minutes when processed at moderate temperatures, are gaining interest for large-scale production of carbon reinforced exterior automotive parts.

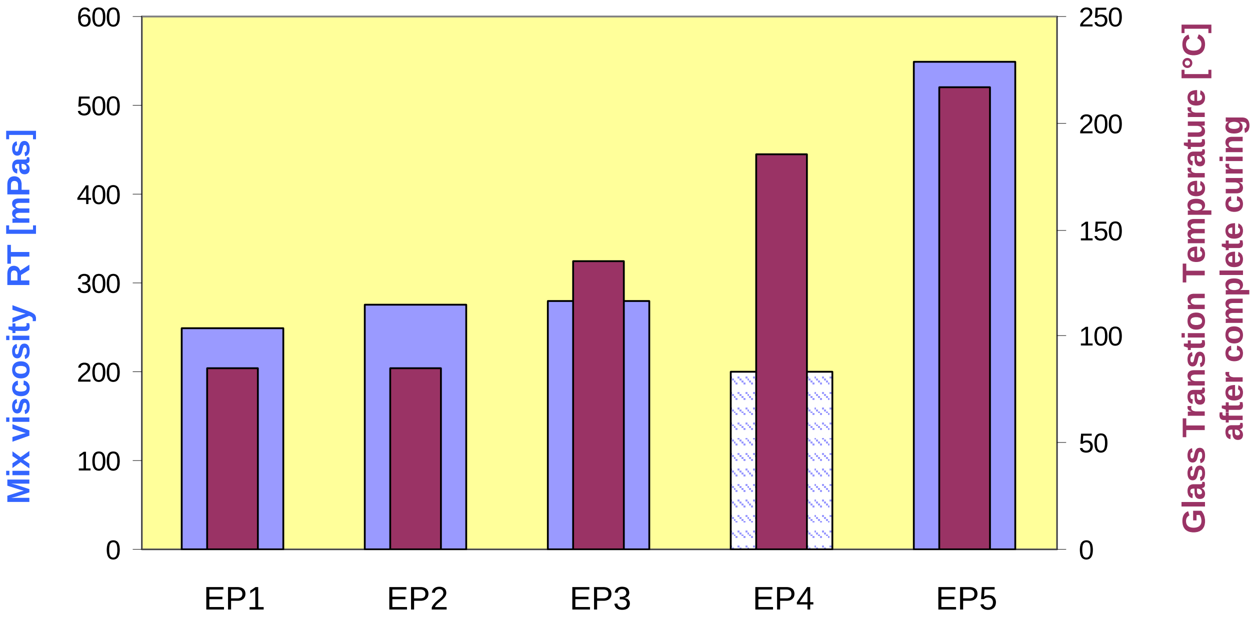


Figure 7: Mix viscosity and glass transition temperature of typical epoxy systems for the LCM process

EP1:	*Resin system with good flowability for wind rotor blades („building blocks“)*
EP2:	*Resin system with good flowability for wind rotor blades (latent cure)*
EP3:	*Heat-stable resin system for exterior automotive parts; curing at elevated temperatures leads to short cycle times*
EP4:	*Hot curing resin system for aerospace. Viscosity shown refers to 80 °C*
EP5:	*resin system with good flow combined with highest temperature limits, application tooling*

RTM-epoxies for aerospace have been available for many years. A one-component system that had to be stored at very low temperatures has now been substituted resp. complemented by a 2K-option (www.hexcel.com). Resins of this kind require warm processing and long curing times at high temperatures. Anyway, low viscosities of HT-systems in terms of a simple LCM manufacture can be achieved with special developments, e.g. for tooling (www.huntsman.com). Nevertheless, all resins with high glass transition temperatures have to be postcured with appropriate heat supply.

There are different approaches towards quick impregnating and curing of laminates, Figure 8: The same epoxy resin, combined with hardeners that show different reactivities, creates a variety of pot life and cure times which also influences the heat release in the laminate ("building blocks"). Even more advantageous seem newly developed latent curing systems. The cure reaction is started only by addition of heat (e.g. 75 °C). Fibre impregnation can thus be performed without marked viscosity rise at room temperatures or slightly (e.g. 30°C) [2].

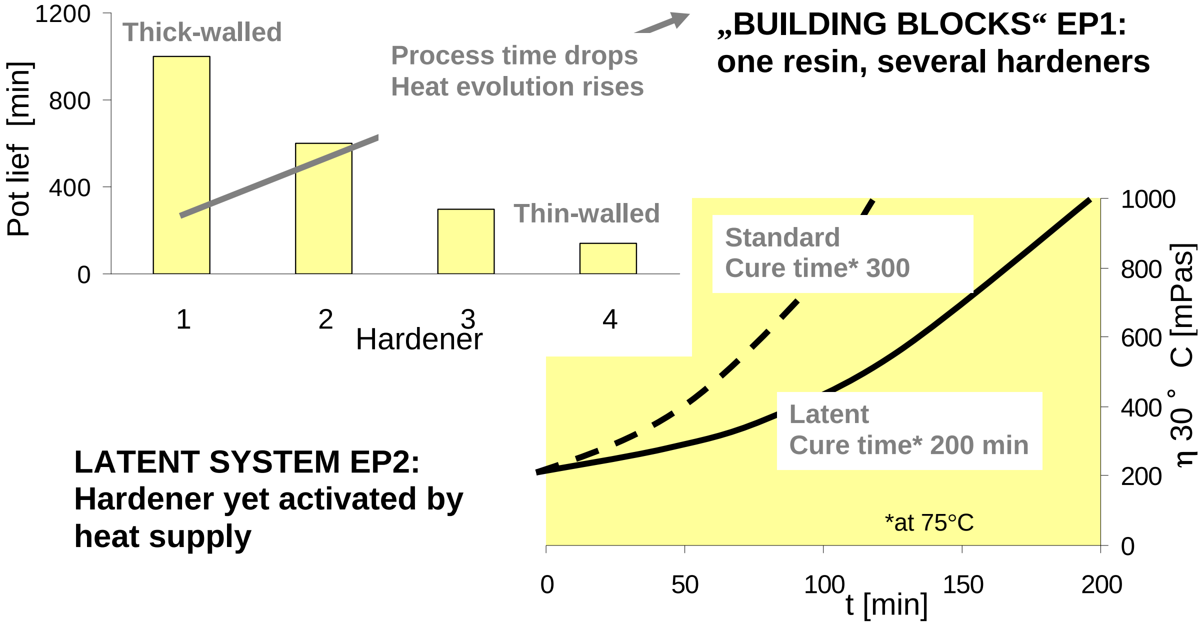
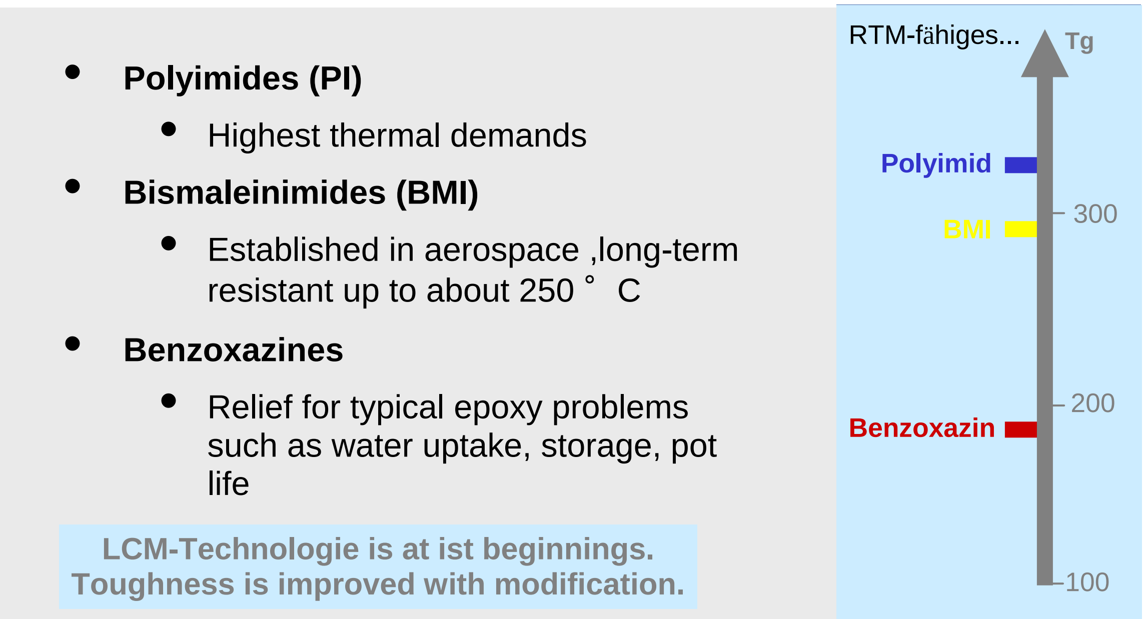


Figure 8: Comparison of the mode of action of „building blocks" and latent epoxy systems

3.2 The „High Performers"

High temperature resins have been established in aerospace for decades, Figure 9 [3,4]. The high cost for those structural parts results from raw material price and form the little automated and extensive prepreg-autoclave process. After first LCM-compatible and thus more efficient HT-systems have been adapted, even the general industry seems to profit from these developments. Besides the high thermal limit, flame retardancy is an important motivation. Aims of development are a high processing window, good flowability, low porosity and good hot-wet-behaviour. An appropriate "tailoring" of these materials that exist in a broad chemical variety is starting to become successful.



- **Polyimides (PI)**
  - Highest thermal demands
- **Bismaleinimides (BMI)**
  - Established in aerospace ,long-term resistant up to about 250 ° C
- **Benzoxazines**
  - Relief for typical epoxy problems such as water uptake, storage, pot life

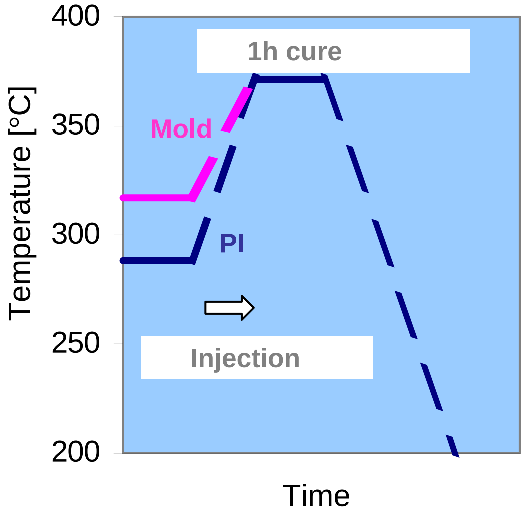
**LCM-Technologie is at ist beginnings.
Toughness is improved with modification.**

Fig. 9: The „High Performers“: Thermoset resins for high temperature, e.g. in aerospace

3.2.1 Polyimides

Exhibiting glass transition temperatures of more than 300 °C, these stable resins are indispensable for highest demands in space and aerospace. The classical PMR resins („in-situ polymerization of monomer reactants“) as well as their less toxic successors such as PR-46 are being processed in solvents, moreover they cure in a condensation reaction. Therefore, they have by now been applied more or less only in prepregging technology.

A phenylethynyl-terminated polyimide attains a stability of more than 1000 h at 288 °C. It cures by polyaddition. It can be used to produce parts for aircraft turbine engines within short cycles by HT-VARTM (vacuum assisted high-temperature RTM), figure 10 (www.ube.com). The cure temperature of the polyimide which appears as powder at RT amounts to 370 °C and thus demands a great deal of the RTM equipment.



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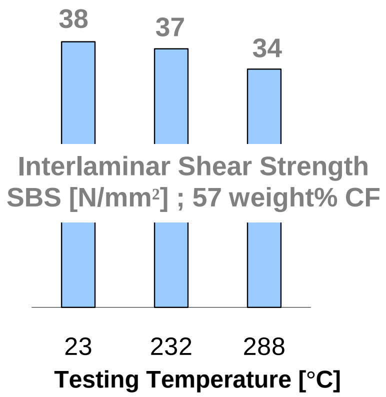


- LCM-compatible PI with short cycle times
- Viscosity at injection <1.000 mPas
- Values keep constant up >280 ° C
- Application in aerospace structures for engines

Figure 10: RTM-compatible polyimide: Cure cycle for HT-RTM process (left) and mechanical properties (right above)

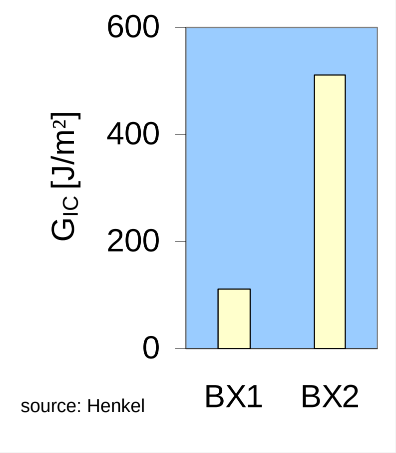
3.2.2 Bismaleinimide

Technically spoken, bismaleinimides also belong to the polyimides, but they are comparably reactive and cure at 150-250 °C in an addition reaction. The raw material price is located between the one of epoxies and polyimides. Military aerospace has used these resins for a long time, e.g. for wing and stabilizer spars, fuselage stiffeners and engine components. They keep their excellent properties up to about 250 °C, exhibit high chemical resistance and good fire properties (www.evonik.de, www.cytec.com, www.hexcel.com). Most of the BMI formulations are based on copolymers in order to reduce brittleness or to tailor special properties. Comonomers for these modifications are allylphenoles, allylphenyethers and others; further reactive monomers or fractions of other resins (epoxy, cyanate ester, vinyl ester etc.) can be added. Normally, the systems are one-component and have to be stored refrigerated.

3.2.3 Benzoxazine

Being related to the chemistry of phenolic resins, the benzoxazines offer excellent flame retardancy and very little shrinkage. In contrast to phenolic resins, they cure without elimination of volatiles and show by far better properties of the cured material, Figure 11.

Compared to the high amount of structural variations that are being applied as prepreg systems, even for automotive applications (www.huntsman.com), the use of benzoxazines in LCM manufacturing has not yet established well.



source: Henkel

Two-phase-modfication for toughening

- Basis Phenol, but compared to phenolic resins:
    - no volatile components
    - higher mechanical level
    - numerous molecular structures
- long storage of 1K-systems for RTM
- long pot life at injection temperature (110 °C)
- Glass transition temperatures > 180°C
- relatively low moisture uptake
- parts are highly flame retardant

Fig. 11: Benzoxazines for RTM: properties and aspects of modification

From the working aspect, the long latent time is advantageous; this means that the ready-to-use formulations can be stored for months at room temperature. Even at incjection temperatures of more than 100 °C the slow viscosity rise offers a large process window, e.g. for the impregnation of large reinforcements.

The benzoxazines' decline in mechanical values due to moisture is less pronounced in comparison to the bismaleinimides. New efforts in order to make the resins tougher by two-phase modification have shown noticeable success (www.henkel.com) [5].

3.3 The „Newcomers“

From the different fields of thermoset resin application new materials have arisen, Figure 12, that are supposed to eliminate disadvantages of existing LCM-systems, such as:

- too slow curing (epoxies)
- too high viscosity respectively too high temperature necessary (HT resins)
- inadequate mechanical and thermal performance (polyester resins)
- problematic hot-wet- behaviour (bismaleinimides, epoxies)
- high brittleness (almost all thermoset matrices).

- **Systems based on urethanes**
  - Quick-curing UP/V urethane systems
  - HT-resin polycyanurate
- **Cyanate esters**
  - High performance, combined with good processability
- **Thermoplastic material**
  - Melt processing of liquid oligomers
  - Short cycle times
  - High toughness of the composites

Low viscosity

Moderater process temperatures

High thermal limits
or
high toughness

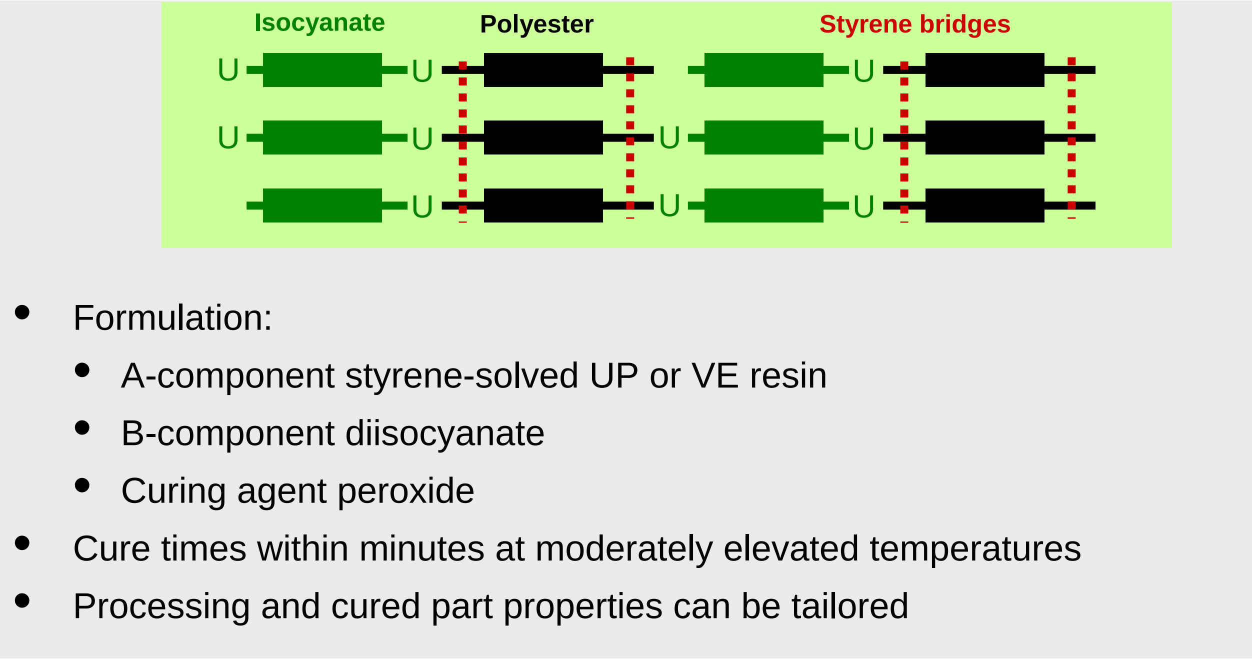
All resin variations are specially optimized for LCM methods

Figure 12: The „Newcomers“: survey of material types that have been developed or optimized specially for LCM

3.3.1 Systems based on urethanes

The polyurethanes possess properties which are lacked by polyester and epoxy resins: They are less brittle and polymerize quickly. Besides typical PUR manufacturing methods such as RIM and fibre spray there are basic approaches towards LCM processing of polyurethane systems that exhibit “long” pot lifes of more than 5 minutes (www.bayer.de).

The UP and VE resin suppliers, in addition, have become aware of the potential of the crosslinking via isocyanates and use it in combined systems that are largely called “hybrid resins”. In the backbone of the UP- or VE-molecules there are OH groups that can react with a second hardener component, an isocyanate that is being added to the resin-peroxide mixture which cures via double bonds with styrene, Figure 13 [6,7]. LCM processing can be easily controlled and leads to a wide variety of cured material with either high toughness or Tgs of over 200 °C (www.dsm.com, www.cytec.com). Die highly crosslinked variations are an interesting option for producing continuously reinforced composites, i.e. for automotive applications. They cure quickly at moderately elevated temperatures and reach properties that are at least comparable with the ones of epoxies, Figure 14.

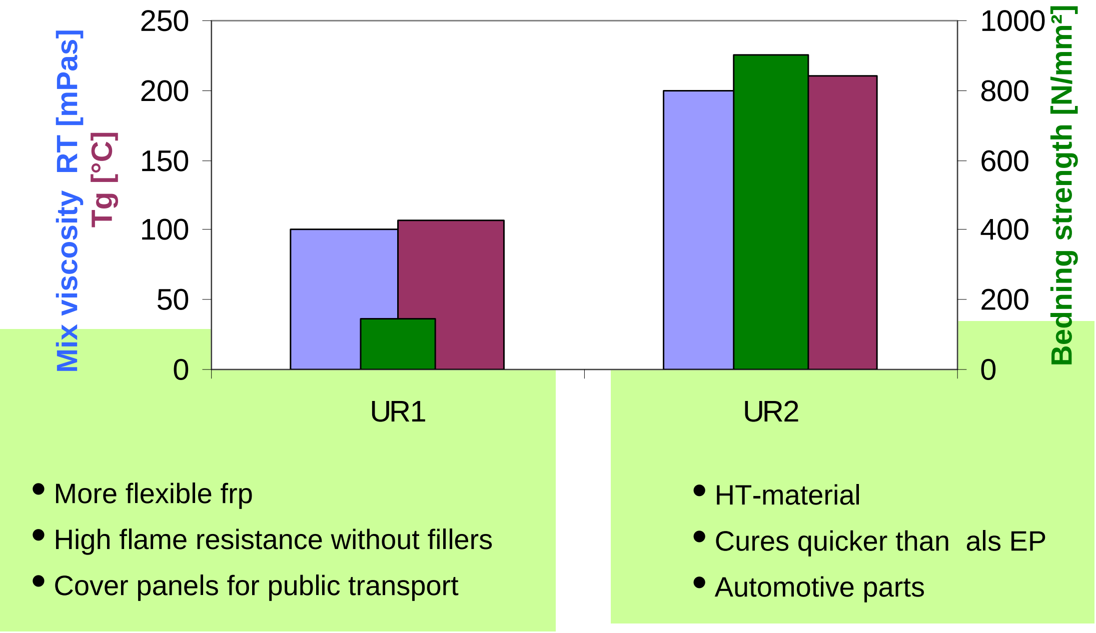


- Formulation:
    - A-component styrene-solved UP or VE resin
    - B-component diisocyanate
    - Curing agent peroxide
- Cure times within minutes at moderately elevated temperatures
- Processing and cured part properties can be tailored

Bild 13: Basic configuration of resin systems based on unsaturated polyesters and isocyanates (urethane-„hybrid“ systems)

Even aerospace is beginning to make a claim on these new urethane resins.

Compared to polyester resins, the high flame resistance, enabled by the urethane component, is of advantage. For operation areas that are critical in respect to fire, UP resins have been a problem because of the high viscosity due to the ATH fillers. LCM is getting possible by means of these halogen-free, easily flowing thermosets, i.e. for train cover panels.



- More flexible frp
- High flame resistance without fillers
- Cover panels for public transport

- HT-material
- Cures quicker than als EP
- Automotive parts

Bild 14: Examples for urethane-„hybrid" systems based on UP (left) and VE (right

A relative of the epoxies is at the vanguard of the urethane-based thermosets. The so called polyisocyanurate is a „building blocks" system with a broad range of viscosities and reactivities. Though curing slowly and by steps, it reaches a long-term durability of more than 200 °C (www.bayer.de).

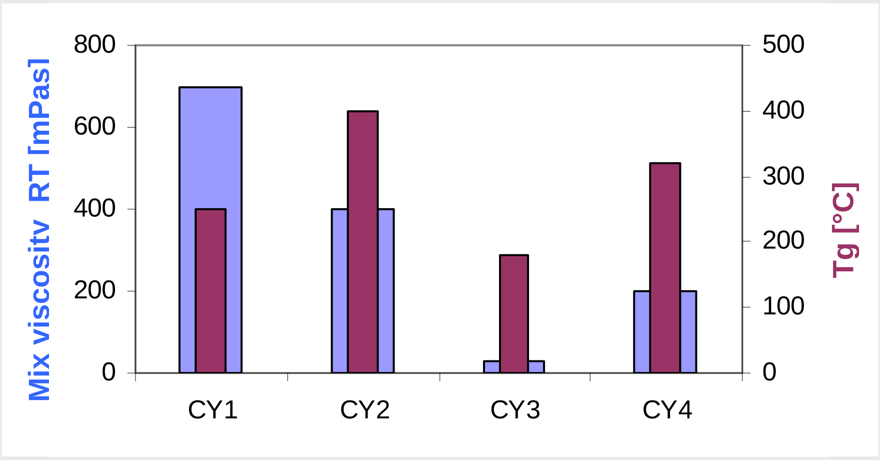
3.3.2 Cyanate esters

Proven in mars vehicles, satellite antennae and military aerospace components, cyanate esters (CE) are about to find their way into industrial application, Figure 15. They are also favoured because of their low moisture uptake and good dielectrical properties (www.lonza.com, www.tencate.com).

- Processing similar to epoxy resins
- Liquid processible at 80 ° C
- T_g up to 400 ° C
- Flow behaviour and cured properties controllable with cyanate ester monomers
- Very good dielectrical properties
- Low water uptake
- High flame-retardancy achievable
- Cyanate esters can be used as hardener component for epoxy resins

Figure 15: Characteristical features of cyanate esters

Thanks to new syntheses they can today be processed by infusion and injection, in a similar way like epoxies, but they show much higher temperature limits. Cyanate ester molecules react with each other, at high temperatures spontaneously, building up an aromatic ring structure. At cure temperatures below 150 °C, when temperature-critical components or moulds have to be considered, appropriate catalysators have to be added.



EP:CY	Tg [°C]
0:100	120
20:80	205
30:70	215
50:50	250
100:0	400

„tailor“ properties with epoxy resins

Bild 16: Mix viscosities and glass transition temperatures of cyanate ester systems

The pot lives are at several hours at 80 °C; even at 200 °C they can reach more than 20 min, depending on the formulation.

Mixtures of monomer and oligomer CE types as well as copolymerisation with toughening agents enable a broad variety of viscosities and cured properties. Mixed systems with epoxies that are polymerized in the network are also possible. By that, flame-retardant composites with Tgs up to 400 °C can be put into practice, Figure 16.

3.3.3 Liquid Composite Molding with Thermosets

Among composites the thermoplastic materials are still of minor weight, but they offer a couple of advantages which already account for the growth of organic sheet, for instance. Thermoplastics are tough, weldable and easily recycled. The application of the mentioned semifinished parts demands a separate process step before molding and thus high tool invest; moreover, part size and design variety are limited.

For some years there have been commercially available precursors that can provide thermoplastic composites via RTM thanks to the water-like consistency of their melts – they show viscosities of 10-50 mPa*s, Figure 17. The duration of the polymerization step can be influenced markedly by dosage of catalysator, and there are hardly any problems with exothermal reaction.

The most advanced version is based on a cylclic butylene terephthalate oligomer which polymerizes at temperatures between 170 and 220 °C, leading to a material with a molecular weight above standard PBT (www.cyclics.de). Process times from few minutes up to more than one hour can be realized by process parameters and catalysator dosage.

Alternatively, LCM can also be applied to the anionic polymerization of polyamide [8]. The economical precursor A-PA6 is being processed at 150-170 °C via RTM. Due to the low polymerization temperature – to be controlled during manufacturing -, a fine crystalline structure is built up, leading to good mechanical properties. All in all, the use of the butylene terephthalate system seems more sophisticated for the time being.

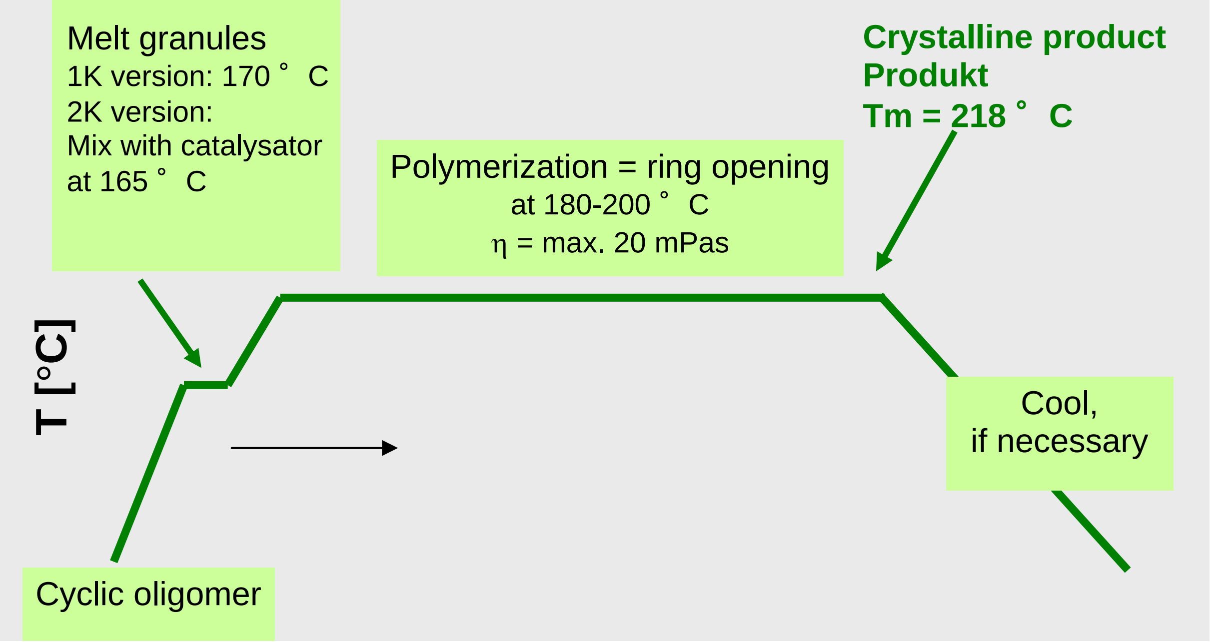


Bild 17: Temperature cycle for LCM processing of the thermoplastic oligomer C-PBT (cyclic butyleneterephtalate)

4. Conclusion

Traditional thermoset applications and high performance technologies have lead to a broad range of new liquid processable resins. Combined with the latter, methods of Liquid Composite Molding (LCM) allow for manufacturing high-capacity structural parts from fibre reinforced plastics. In detail, high temperature limits, enhanced toughness of the laminate and many more material properties can be obtained. Developing reliable large-scale production with the aid of these new materials is offering high potential.

5. Acknowledgements

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Annotations concerning the following tables:

The presented matrix systems only represent a part of the commercially available portfolio; there is no claim for completeness. The shown material data may have been determined due to differing testing standards which are, as far as possible, mentioned in the tables. Informations exceeding the given data are supposed to be obtained fromt the raw material suppliers.

System		**supplier**	**Pot life / gel time**	**Cure cycle for complete curing**	**Testing methods for results in diagrams:** TSS = tensile shear strength, I = impact V = Viskosity, Tg
UP1	Synolite 1967-G-6	DSM	45 min (TM2625, 2g Butanox M-50 in 100g resin)	cure 24h RT postcure 24h 70 °C	TSS: ISO 527-2 I: ISO 179 unnotched V: TM2013, 23°C
UP2	Palatal P80-02	DSM	15 min (TM2625, 1g Trigonox 44B, 0.5g NL49P in 100g resin)	cure 24h RT postcure 24h 100 °C	TSS: ISO 527-2 I: ISO 179 unnotched V: TM2013, 23°C
UP3	Atlac 430	DSM	15 min (TM2625, 2g Butanox LPT, 1g NL49P in 100g resin)	cure 24h RT postcure 24h 120 °C	TSS: ISO 527-2 I: ISO 179 unnotched V: TM2013, 23°C
PF1	Phenodur VPW9340 Additol VXK1310	Cytec	e.g. excession of 1000 mPas after 3h (7% hardener, 20°C)	Cure several h h 70°C Postcure several h 80 °C	
PF2	Cellobond J2027L Härter P382	Hexion	ca. 60min (probably RT)	n.s. (not specified)	
EP1	Araldit® LY 1564 Hardener XB 3485	Huntsman	16-18h 100g, 23°C	Infusion/ Injection RT-40 °C; cure 8h 80 °C	V: ISO 12058-1B Tg: DSC IEC 1006
EP1	Araldit® LY 1564 Hardener Aradur® 3486	Huntsman	9-10h 100g, 23°C	Infusion/ Injection RT-40 °C cure 8h 80 °C	V: ISO 12058-1B Tg: DSC IEC 1006
EP1	Araldit® LY 1564 Hardener XB 3416	Huntsman	5-6h 100g, 23°C	Infusion/ Injection RT-40 °C cure 8h 80 °C	V: ISO 12058-1B Tg: DSC IEC 1006
EP1	Araldit® LY 1564 Hardener Aradur 3487	Huntsman	2-2½ h 100g, 23°C	Infusion/ Injection RT-40 °C cure 8h 80 °C	V: ISO 12058-1B Tg: DSC IEC 1006
EP2	Baxxores ER 5300 Hardener Baxxodur EC 5310	BASF	10 (100g, 23 °C) 4 (1000g, 23 °C)	Infusion/ Injection RT-40 °C cure 6h 70 °C	V: plate-plate, d25mm, fissure 1mm, 100s^{-1} Tg: torsional pendulum onset
EP3	MGS RIM 935 Hardener RIMH 936	Hexion	2 (100 g, 30 °C)	cure several h RT post cure 5h 160 °C	V: k.A: Tg: DMA onset
EP3	MGS RIM 935 Hardener RIMH 937	Hexion	3,5 (100 g, 30 °C)	cure several h RT post cure 5h 160 °C	V: k.A: Tg: DMA onset
EP4	Hexcel RTM 6-2	Hexcel	>4 (at 120 °C) (at RT: storage for 15 days)	injection 80°C cure 75 min 160 °C post cure 120 min 180 °C	V: k.a. Tg: DMA onset
EP5	Araldit® LY 8615 Hardener Aradur® 8615	Huntsman	20 at 25°C ASTM D 2471	24h RT 6h 120 °C 6h 200 °C	V: ASTM D 2393 Tg: DMA onset, ASTM D-4065

Table 1: The „Classics“ – Data for processing behaviour and cured material properties from Technical Datasheets

System		**supplier**	**Mix viscosity and pot life**	**Cure cycle for complete curing**	**Tg**
PI1	Polyimide PETI-330	UBE	viscosity 500 mPas at 280 °C	prewarming 280 °C, injection 320 °C, cure 1h 370 °C	330 °C
BMI1	Bismaleinimide Compimide 353RTM-ST	Evonik	Pot life 160 °C: > 90 min, DIN 16945 viscosity 100 °C 400 mPas, DIN 16945	prewarming 100 °C; injection 150 °C, cure 4h 200 °C, postcure 4h 250 °C	285 °C
BMI2	Bismaleinimide Compimide 353RTM-HT	Evonik	Pot life 160 °C: > 50 min, DIN 16945 viscosity 100 °C 550 mPas, DIN 16945	prewarming 100 °C; injection 150 °C, cure 4h 200 °C, postcure 4h 250 °C	285 °C
BMI3	Bismaleinimide Cycom 5250-4 RTM	Cytec	Pot life 177 °C: 35 min viscosity : ca. 1000 mPas at 120 °C, RDSII dyn.	cure 4h 191 °C, postcure 6h 243 °C	293°C
BMI4	Bismaleinimide Hexflow RTM651	Hexcel	Gel time hot plate 150 °C: 98 min viscosity 110°C: ca. 100 mPas	prewarming 110 °C; injection 150 °C, cure 4h 191 °C, postcure 7h 245 °C	285 °C DMA E*peak
BX1	Benzoxazine Epsilon 99110	Henkel	viscosity 100 mPas bei 110 °C; no excession of 200 mPas within several hours	prewarming 70 °C, injection 90-120 °C, cure 90 min 180 °C	191 °C
BX2	Benzoxazine Epsilon 99120	Henkel	viscosity 100 mPas bei 110 °C; no excession of 200 mPas within several hours	prewarming 70 °C, injection 90-120 °C, cure 90 min 180 °C	180 °C

Table 2: The „High Performers““ – Data for processing behaviour and cured material properties from Technical Datasheets

System		**supplier**	**Mix viscosity and pot life**	**Cure cycle for complete curing** (T-RTM: Polymerisation cycle)	**Tg** (T-RTM: differing)
UR1	UP-Urethane resin Viapal VUP 4812B/60 Additol VXT 6225/1	Cytec	viscosity 100 mPas at 23 °C; DIN EN ISO 3219 gel time 20 °C: 60 min; DIN 16945 (18g Additol, 2g Dibenzoylperoxid for 100 g resin)	cure RT, postcure 80 °C	107 °C DIN 53445
UR2	VE-Urethane resin Turane Daron 45 Lupranate M20R	DSM	gel time 25 °C: 20 min, TM 2625 (2% NL64-10P+2%Perkadox CH50L for 100g resin) viscosity 23 °C 200 mPas, DIN TM 2013 (Z2, $100s^{-1}$)	cure 24h RT, postcure 4h 200 °C	200 °C
UR3	UP-Urethane resin Daron 41/B1	DSM	gel time 25 °C: 8-16 min , TM 2625 (2% NL64-10P+2%Perkadox CH50L for 100g resin) viscosity 23 °C 250 mPas, TM 2013 (Z2, $100s^{-1}$)	cure 24h RT, postcure 4h 120 °C	130 °C
UR4	Polyisocyanurate Blendur VP.90IK28	Bayer	viscosity 1K-System 40 mPas, 25 °C gel time 160 °C: ca. 160s	cure 3h 80 °C + 3h 120 °C + h 160 °C + 3h 200 °C	ca. 200 °C
CY1	Primaset BA-200	Lonza	gel time 200 °C > 20 min viscosity 80 °C 700 mPas	prewarming 80 °C, cure e.g. 1h 150 °C, 3h 200 °C, 3h 270 °C	250 °C DMA tan δ
CY2	Primaset PT-30	Lonza	gel time 200 °C > 30 min viscosity 80 °C 400 mPas	prewarming 80 °C, cure e.g.1h 150 °C, 3h 200 °C, 3h 270 °C	400°C DMA tan δ
CY3	EX1545	Tencate	Pot life 24h 25 °C viscosity 80 °C 35 mPas	prewarming , Injection e.g. 50 °C cure 2h 177 °C	173 °C
CY4	EX-1551-1	Tencate	Pot life 8h 50 °C viscosity 80 °C 200 mPas	prewarming , Injection e.g. 50 °C, cure 2h 260 °C	330 °C
TP1	CBT (div. types)	Cyclics	viscosity 180 °C 20 mPas pot life depends on catalysator	Prewarming / mixing 165-170 °C, Polymerisation 180-200 °C	HDT 150 °C
TP2	anionic polyamide	*In project state*			Tm 218 °C

Table 3: The "Newcomers" – Data for processing behaviour and cured material properties from Technical Datasheets