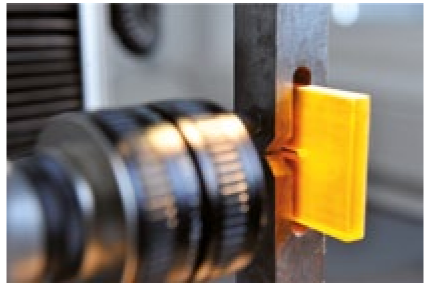
The well-balanced formulation shows a fracture toughness around 0.8 and a glass transition temperature around 105 °C. Depending on the required T_g also a higher fracture toughness at a decreased T_g is possible. The moderate T_g limits the broad applicability to applications which require only low thermal stability, e.g. for Central European climate conditions.

Optical Crack Tracing (OCT) has been developed by Fraunhofer PYCO and LaVision GmbH, Göttingen (Germany) in the last decade to optimize the commonly used method for determination of fracture toughness.
By using OCT the validity of the measurement is increased. The disparity between both methods is that OCT measures the complete crack-curve and not the single value for crack initiation.



***5:** Optical Crack Tracing with digital video camera*

Market Benefits

The most important benefit is the quick curing and the low infusion time during processing and therefore the major decrease in production costs. Also the costs for the resin will be lower than for comparable resins based on epoxy or polyurethane chemistry.

Therefore the total costs of part production will be much lower for all parts and especially for large parts like wind mill rotor blades.
All financial benefits are combined with excellent material properties.

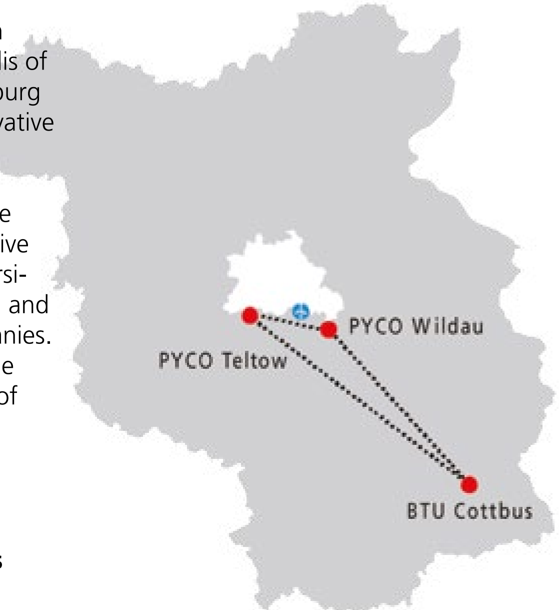
Technical Readiness Level (TRL)

The chemical principle and the technology has been patented. Licensing is possible but further research work is necessary for technical implementation and market launch.

First formulation samples can be provided up to 20 kg for processing and handling tests with costs covered by the customer. To ensure the right formulation for the appointed processing technology and component properties joined research projects are recommended.

Location Berlin-Brandenburg

New solutions require new approaches:
The locations of the research institute in Teltow and Wildau, where the metropolis of Berlin and the federal state of Brandenburg meet, offer optimal conditions for innovative scientific research.
Here, the products of tomorrow emerge from ideas and visions. Therefore, the institute's scientists have formed a creative research network with renowned universities, well-known large-scale enterprises, and various innovative medium-sized companies. Additionally, new synergy arises from the integration in the third largest location of aerospace industry in Germany.



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Fraunhofer
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FRAUNHOFER RESEARCH INSTITUTION FOR POLYMERIC MATERIALS AND COMPOSITES PYCO

Unsaturated Polyester Resins with Very High Fracture Toughnesses

UNSATURATED POLYESTER RESINS WITH VERY HIGH FRACTURE TOUGHNESSES

Motivation

One of the most important disadvantages of unsaturated polyesters is the high brittleness of cured parts.
This brittleness can be decreased to a certain level with fillers and other additives but unfortunately not to a level that ensures the use in high dynamic loaded and impact loaded parts like wind mill rotor blades or chassis parts for automotive applications.
A higher toughness can be achieved with epoxy resins which dominate the market for these applications. In terms of processing and handling unsaturated polyesters often show much better properties especially for infusion and Resin Transfer Molding (RTM) techniques.

***1:** 20 kg condensation plant*

Here the very low viscosity of unsaturated polyesters and the short curing time reduce the cycle time of the process and therefore also the production costs for cured parts. Especially for very large parts like off-shore wind mill rotor blades (up to 100 m) infusion time and curing time are major aspects.
Due to the radical curing mechanism unsaturated polyesters can be cured much quicker than epoxy resins.
A second major aspect is the price of the resin. Unsaturated polyesters are one of the least expensive resin systems (only formaldehyde-based resins, e.g. phenolic, melamine and urea resins are cheaper).
For this reason scientists at Fraunhofer PYCO have been investigating the mechanisms of curing and formation of the 3-dimensional network and transferred the results to a special chemical formulation.

Possible Applications at a Glance

- Wind mill rotor blades
- Automotive applications
  - o Wind deflectors for trucks
  - o Spoilers for automobiles
  - o Underbody skidplates
  - o Body parts for racing cars
- Sport equipment
  - o Hockey sticks
  - o Skis and snow boards
- Leisure applications

Resin Properties at a Glance

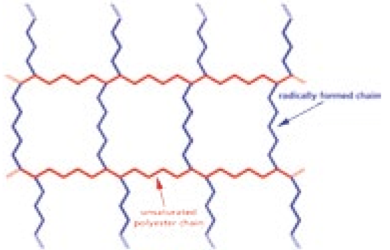
- Low viscosity (below 1 Pas at 25 °C)
- Fast curing at variable temperatures
- Highly increased toughness
- Satisfying thermal stability
- Low resin costs
- Low styrene content (approx. 30% or less)

Formation of 3-dimensional Network

The very high increase of toughness can be achieved by optimizing the 3-dimensional network of the unsaturated polyester. Therefore, a new and special composition of raw materials for the unsaturated polyester and a special combination of reactive diluents has been studied.
High toughness needs a homogeneous network (figure 2) with well-defined chain lengths between the crosslinking bondings. Transferred to unsaturated polyesters there are two challenges.
The first one is the unsaturated polyester backbone. The modification of this could be easily reached by variation of raw materials in a condensation process. Much harder is the optimization of the radical forming network. Due to the curing mechanism the network will be formed statistically which leads to a broad variation in chain lengths. It was only possible to optimize the formation by modifying the reactive diluent.

Processing of the Resin

The process is optimized for RTM. Due to the low viscosity of the resin short infusion times and a low temperature infusion will be possible. Depending on the type and amount of radical initiator the pot life, curing time and curing temperature can be adjusted to a partly optimized production.

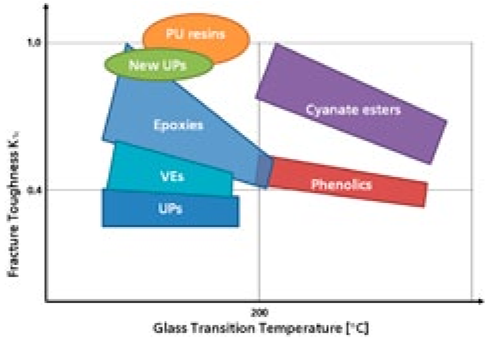


***2:** Idealized schematic structure of a homogeneous 3-dimensional network*

SMC as well as BMC-formulations are possible (Sheet Molding Compound / Bulk Molding Compound). These semi-finished components are favorable for automotive applications because of adjustable short cycle times and good surface qualities (class A).
Hand lay-up and spray lay-up processing is also possible, especially for prototypes and small product series.
Furthermore, all other processing techniques are possible as well, e.g. filament winding and RIM.
For all processing techniques state of the art curing is possible from room temperature (post cure is recommended) up to high temperatures (> 200 °C) for press processing.

Fracture Toughness

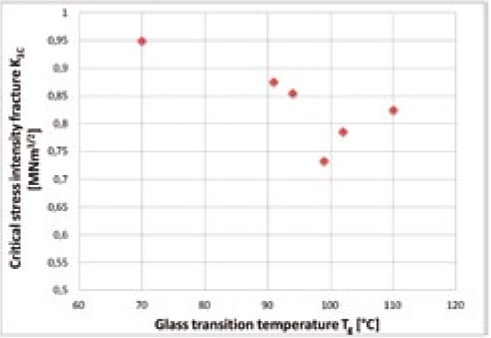
Fracture toughness is one of the key properties of thermosetting resins and describes the damage tolerance. Using linear fracture mechanics the critical stress intensity fracture K_{1C} and the critical strain energy release rate G_{1C} can be used to predict the damage tolerance and other parameters.
Due to the optimized resin and network structure the new unsaturated polyesters show very high fracture toughness compared to standard UP-types. In comparison to other unmodified thermosetting resins these new UPs perform like tough epoxy resins at more or less identical glass transition temperatures (T_g).
Figure 3 shows a qualitative schematic overview of the most important thermosetting resins together with the new development (green ellipse).



***3:** Schematic comparison of different classes of unmodified thermosetting resins for fracture toughness and glass transition temperature*

The new class of polyurethane-based thermosetting resins (more or less an assumption, orange ellipse) and the well-known epoxy resins (light blue box) surrounds the new development in terms of K_{1C} and T_g.
Typical values of the new unsaturated polyester resins are between 0.7 and 0.95 $MNm^{3/2}$ at glass transition temperatures around 100 °C measured with Optical Crack Tracing (OCT) (K_{1C}) and dynamic mechanical analysis (T_g).

Figure 4 shows the relationship between fracture toughness and glass transition temperature of different UP-formulations. The unsaturated polyester formulations differ in adjusted chain lengths at the unsaturated polyester back bone.



***4:** Relationship between fracture toughness and glass transition temperature for different new UP formulations*