

EMAC 276 Polymer Properties and Design

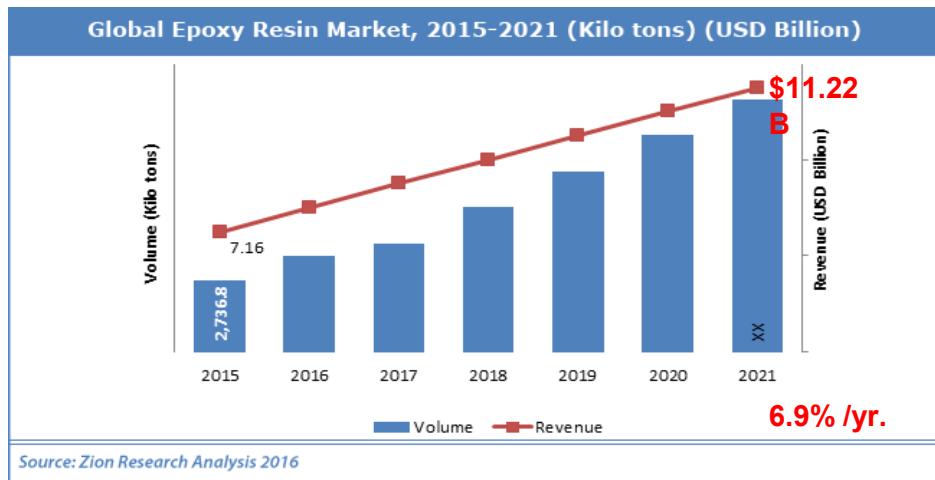
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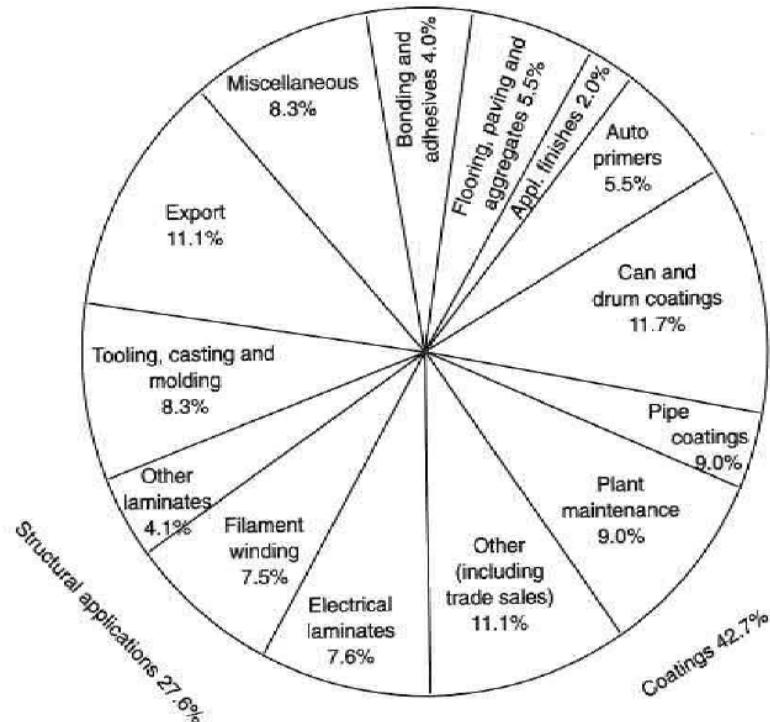
**MWF 10:35-11:25 pm
Spring 2025**

Epoxy Polymers



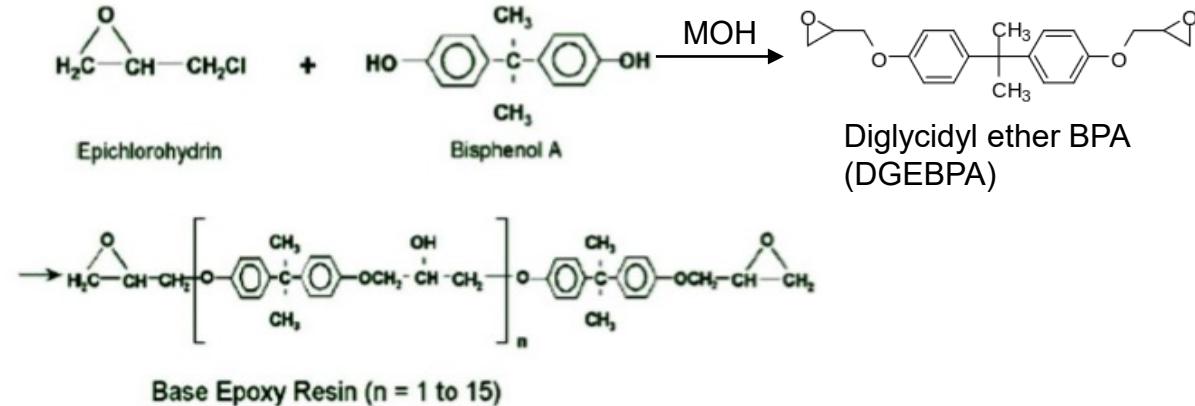
<https://www.zionmarketresearch.com/news/global-epoxy-resin-market>

Epoxy end use by applications



Feldman, D, Barbalata, A. (1996). Synthetic Polymers: Technology, Properties, Applications. Chapman & Hall.

EPOXY CHEMISTRY



Greek prefixes:

epi – upon

oxy – sharp and acidic

Epoxy History

- 1890s-1930: Russia chemist Prileschajev – epoxide from olefin/vinyl compounds + peroxides
German chemist P. Schlack made polyamine from epoxide in mid-1930's
- Patented formulations, 1930s: Dr. Pierre Castan, Switzerland, licensed to Siba, Inc. 1934, Dr. S.O. Greenlee, USA, → Devoe-Reynolds (later Shell Chemical, and now Momentive Specialty Chemicals).
- Commercialization during 1950s-1970s: Aerospace applications
- After 1970s: Varnish compositions, epoxy resin compositions, stable aqueous epoxy dispersions. Now: windmill blades

Intro for Epoxy Resins

- The second largest thermoset polymer resin – after thermoset polyesters
 - (unsaturated & saturated)
 - ~50% for non-reinforced forms – coatings and adhesives
 - Reinforced laminates. Recently, reinforced structural parts – windmill blades
 - Electronic applications – circuit boards (laminated). Now, 5G boards are in high demand.
 - General Properties:
 - Excellent mechanical properties: high strength and large cohesive force
 - Good adhesion: polar functional groups
 - Excellent stability
 - Flexibility and diversity in formulations and material designs



Adhesives



Coatings



Structures

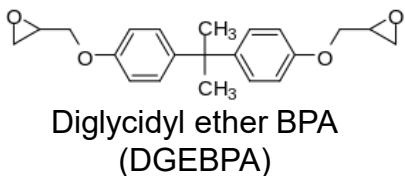
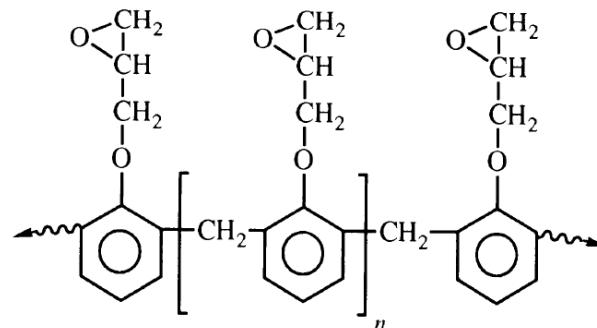
Electronics

Epoxy Components

1. Epoxides from Epichlorohydrin

i) Phenols

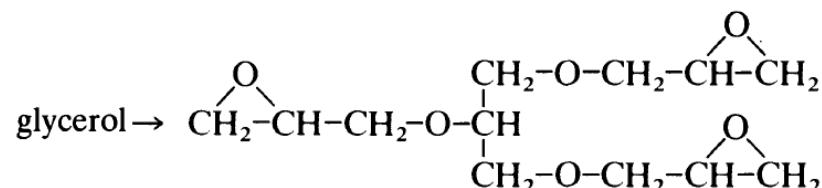
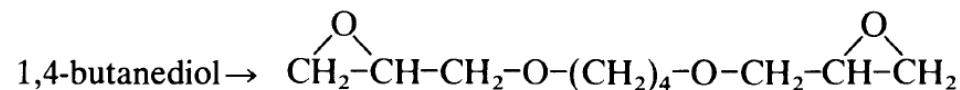
- a. Many difunctional phenols, e.g., BPA
- b. Phenolic novolac (see below)
- c. Monofunctional phenols: modifiers for epoxy resins
- d. Halogen-substituted phenols



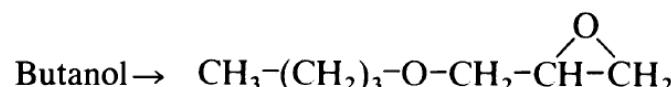
Diglycidyl ether BPA
(DGEBA)

ii) Alcohols

a. Multifunctional

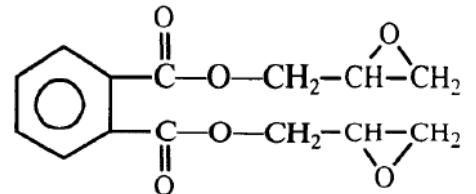


b. Monofunctional: Resin modifier

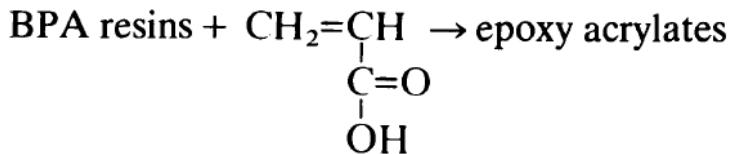


iii) Carboxylic and fatty acids

- a. Phthalic acid → glycidyl esters



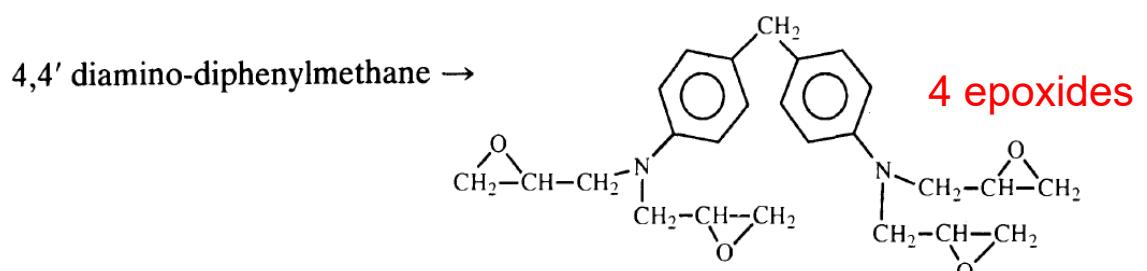
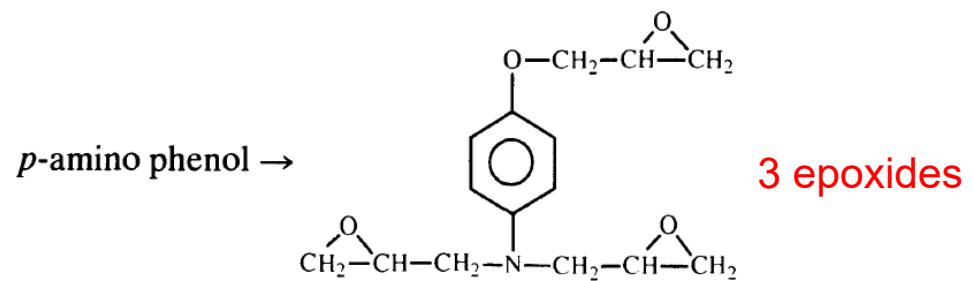
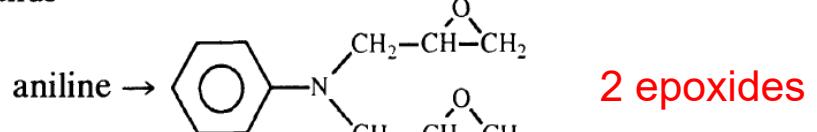
- b. Long-chain acids → epoxy resin esters
- c. Acrylic acid



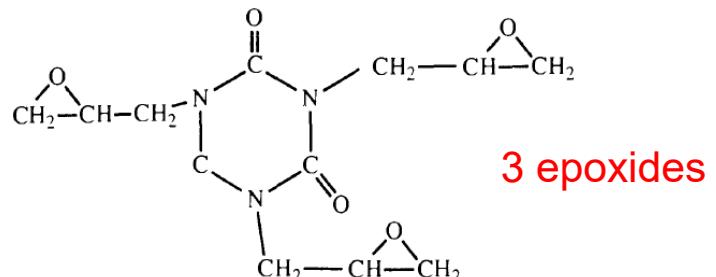
Epoxy Components

1. Epoxides from Epichlorohydrin

iv) Nitrogen compounds
a. Amines

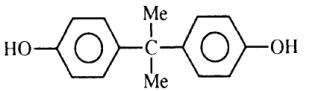


b. Cyanuric acid

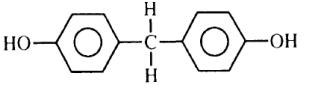


2. Phenols

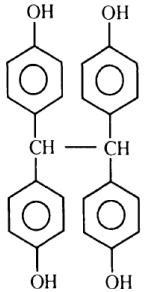
1. Bisphenol A (BPA)



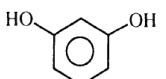
2. Bisphenol F



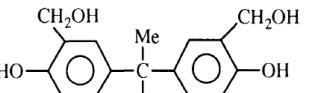
3. Tetrakis phenylolethane



4. Resorcinol

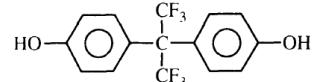
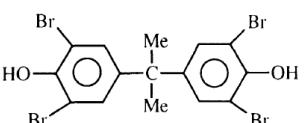


5. Methylolated phenol

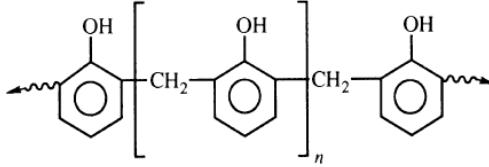


→ diglycidylether the -OH groups accelerate amine cure

6. Brominated and fluorinated phenols

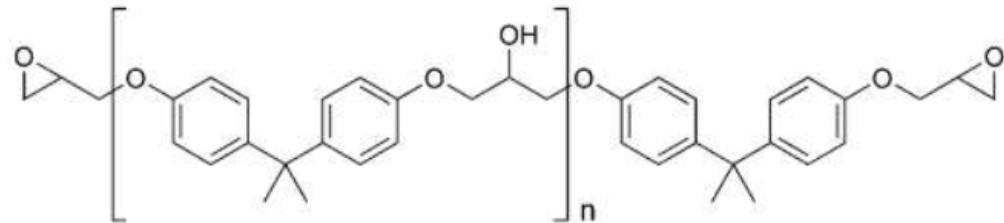


7. Phenolic novolac



Epoxy Prepolymers from Epoxides and Phenols

1. Bisphenol A Epoxy



n	Heat distortion temp (°C)	Physical state
2	40	semi-solid
4	70	solid
9	130	solid
12	150	solid

i) Taffy method

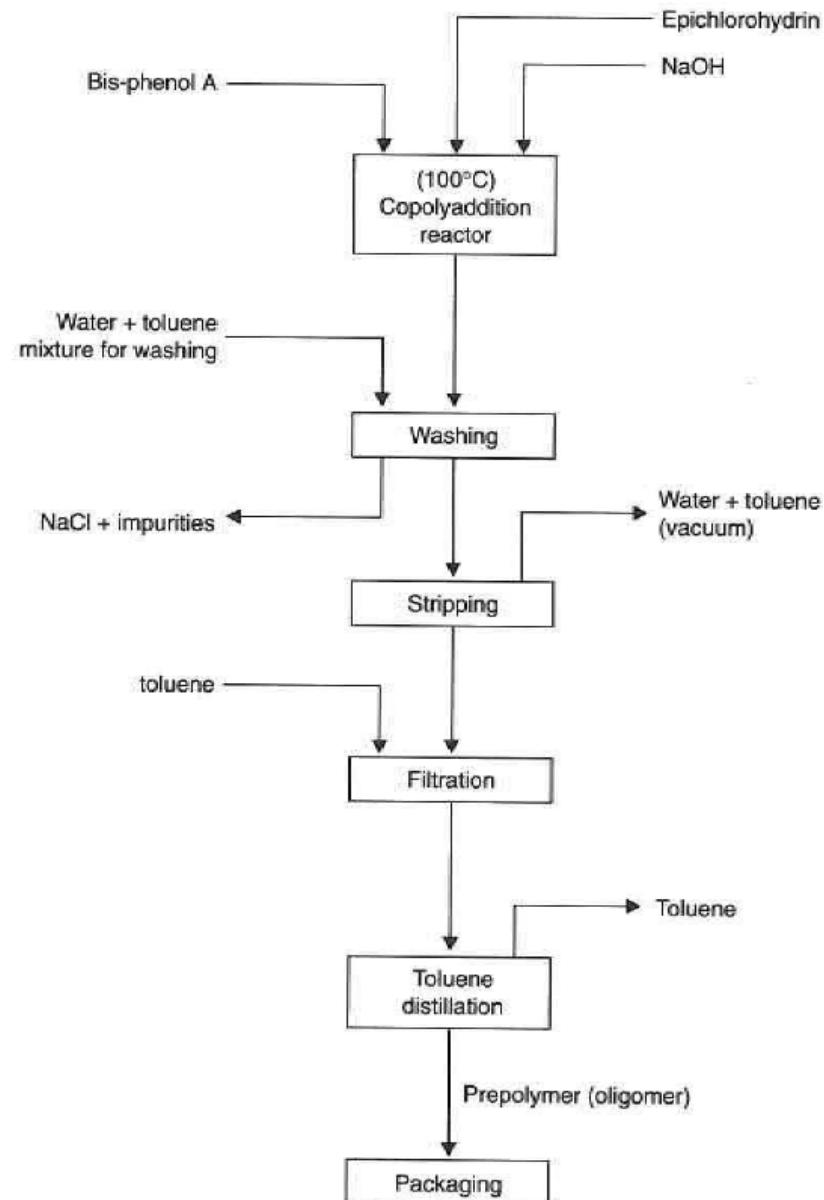
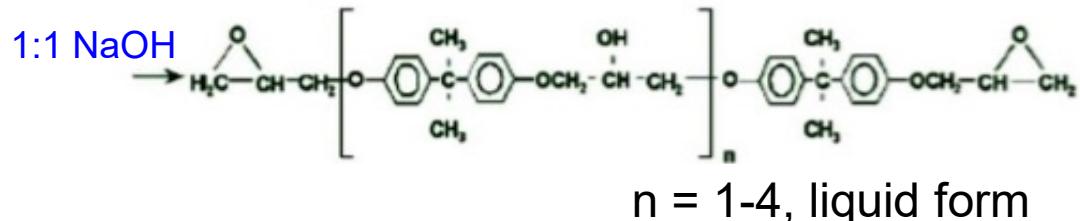
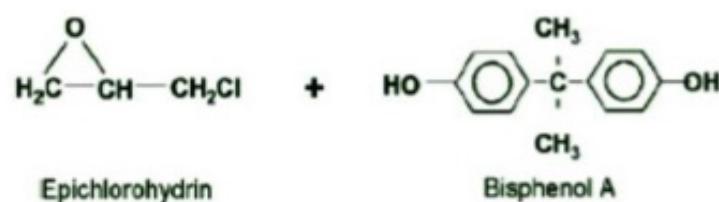
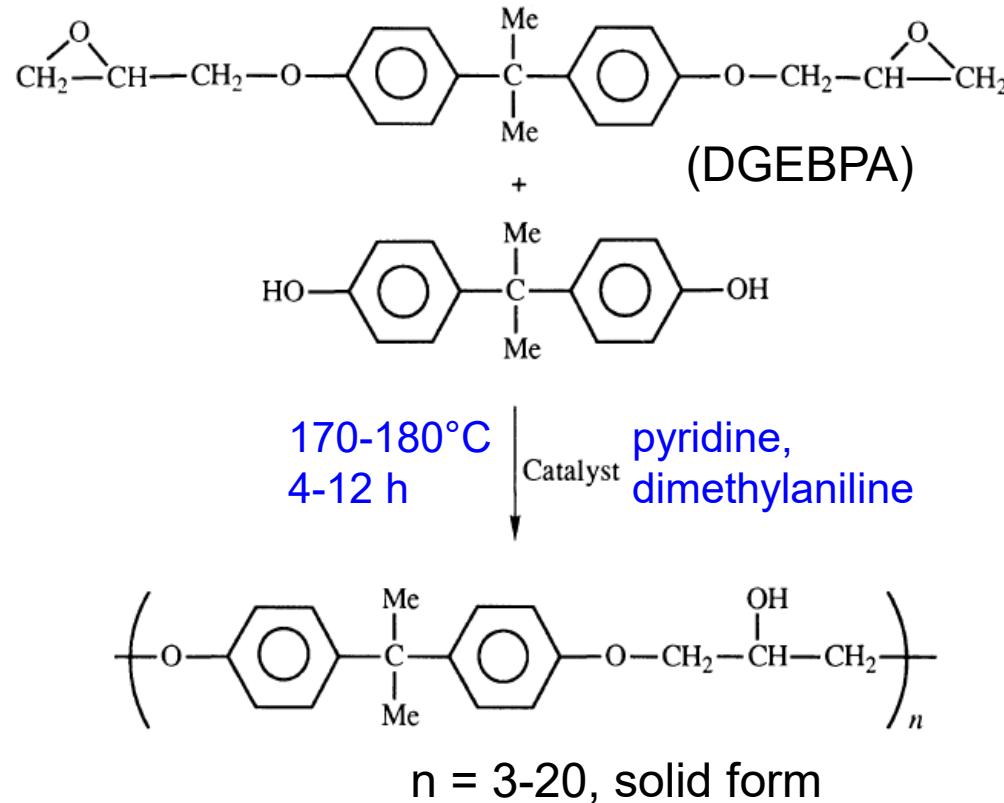


Figure 8.2 Taffy process for epoxy prepolymer synthesis.

Epoxy Prepolymers from Epoxides and Phenols

ii) Fusion or advancement method



iii) Important Properties of Epoxy Prepolymers

- a) Softening point;
- b) Viscosity

Note to the fusion reaction:

1. To obtain high molecular weight (i.e., large n), the stoichiometry should be strictly controlled.
2. The fusion reaction is very sensitive to the type and concentration of catalysts used. These should also be strictly controlled to ensure reproducibility. If not well-controlled, chain branching and gelation can happen by reaction of secondary hydroxyl groups with epoxy groups.

Phenoxy Resins (the high MW form)

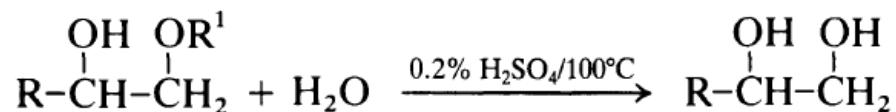
High molecular weight epoxy polymer with $n \sim 100$ and $M_n \sim 30-45$ kDa. Direct solid polymer. Can react with other reactants (e.g., isocyanate) to form coating. Granular resins can be used for extrusion and injection molding.



Basic Epoxy Reactions

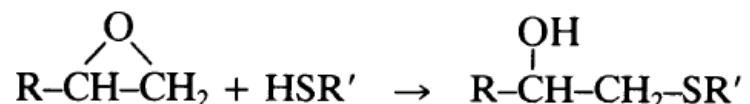
1. Addition reactions by nucleophilic substitution

a. Hydroxylic nucleophiles



R' = alkyl, alcohol; R^1 = aryl, phenol

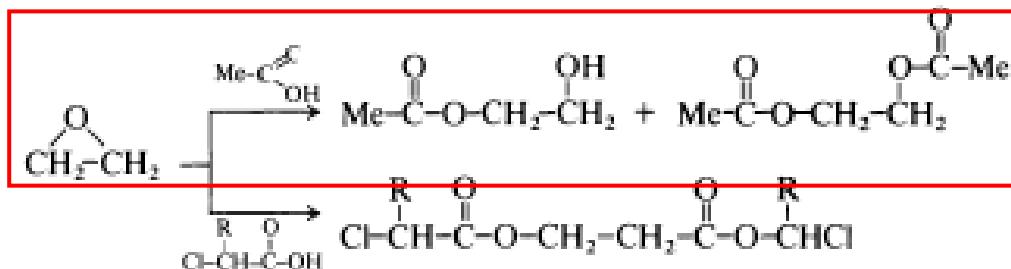
b. Thiol nucleophiles



Reactions in red boxes are responsible for crosslinking!

c. Acids

ii. Carboxylic acids



iii. Ammonia and amines



$\text{R}^1, \text{R}^2 \equiv \text{H}$: ammonia
 $\text{R}^1 \equiv \text{H}; \text{R}^2 \equiv \text{alkyl, aryl}$: primary amine
 $\text{R}^1, \text{R}^2 \equiv \text{alkyl, aryl}$: secondary amine

2. Electrophilic additions

a. Alkyl halides



$\text{X} \equiv \text{Br}; \text{R} \equiv \text{Et}$
 $\text{X} \equiv \text{I}; \text{R} \equiv \text{Me, Et, Pr}$

b. Isocyanates



Curing Agents or Hardeners

i) Amines – the most versatile, fast reaction

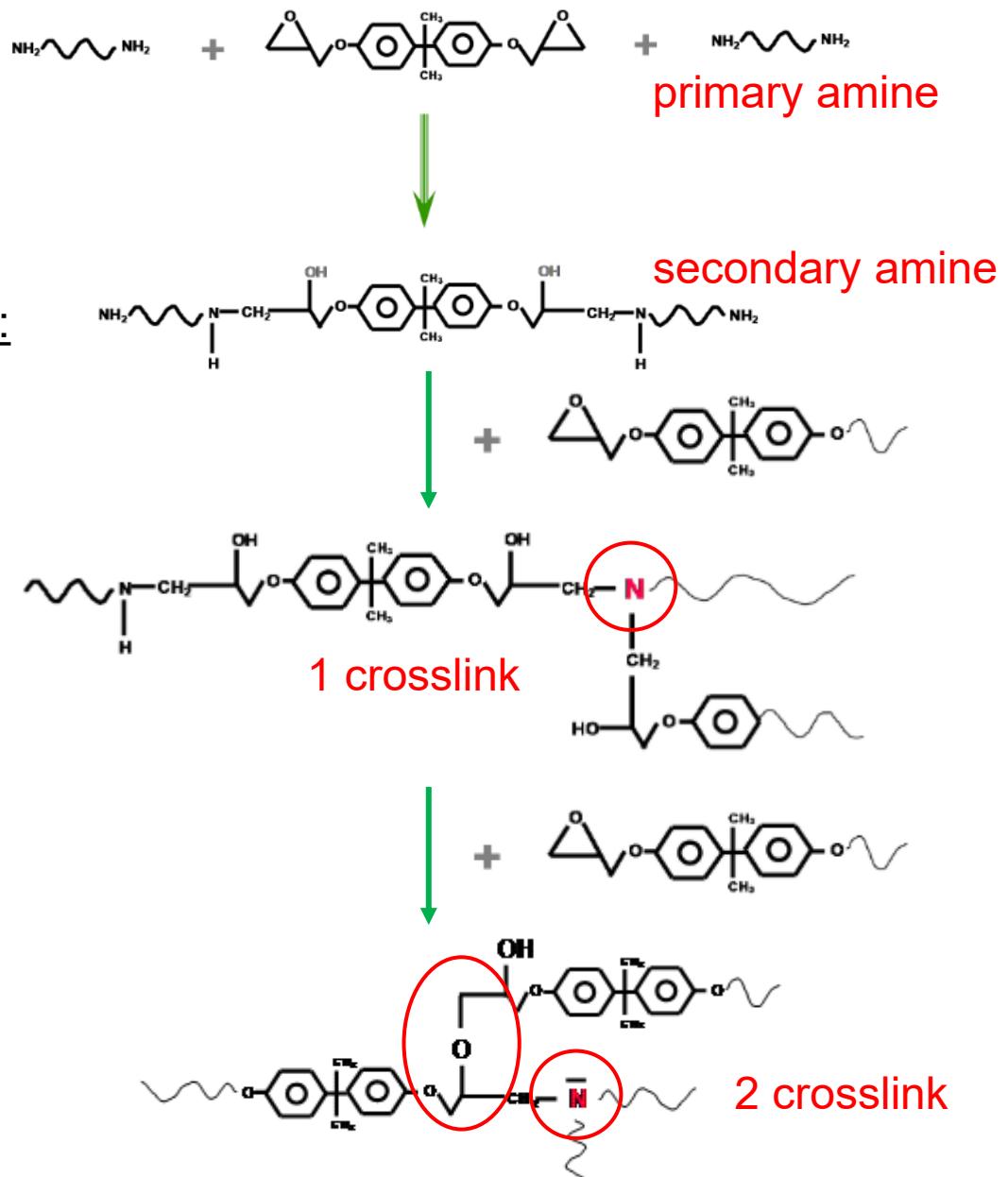
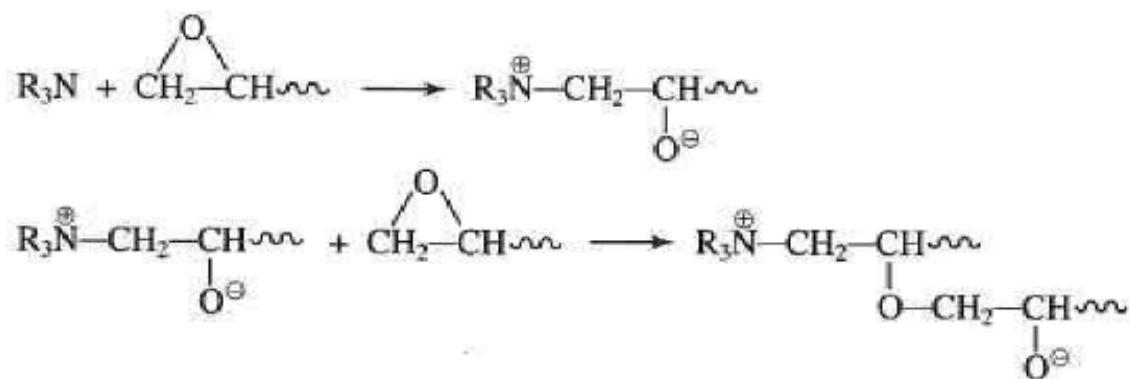
Primary and secondary amines (see the right)

Tertiary amines can also catalyze the crosslinking of epoxy prepolymers via anionic ring-opening polymerization:

Example tertiary amines:

- triethylamine (TEA);
 - benzylidimethylamine (BOA);
 - dimethylaminoethylphenol (DMAMP);
 - tri(dimethylaminomethyl)phenol (TDMAMP);
 - tri-2-ethylhexoate salt of TDMAMP.

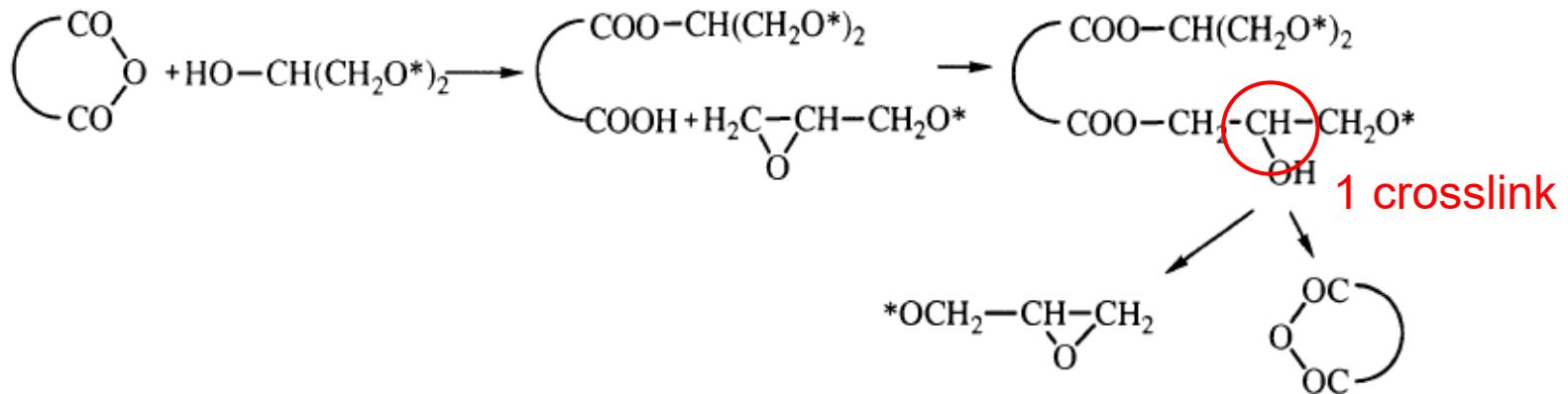
Reaction mechanism (optional):



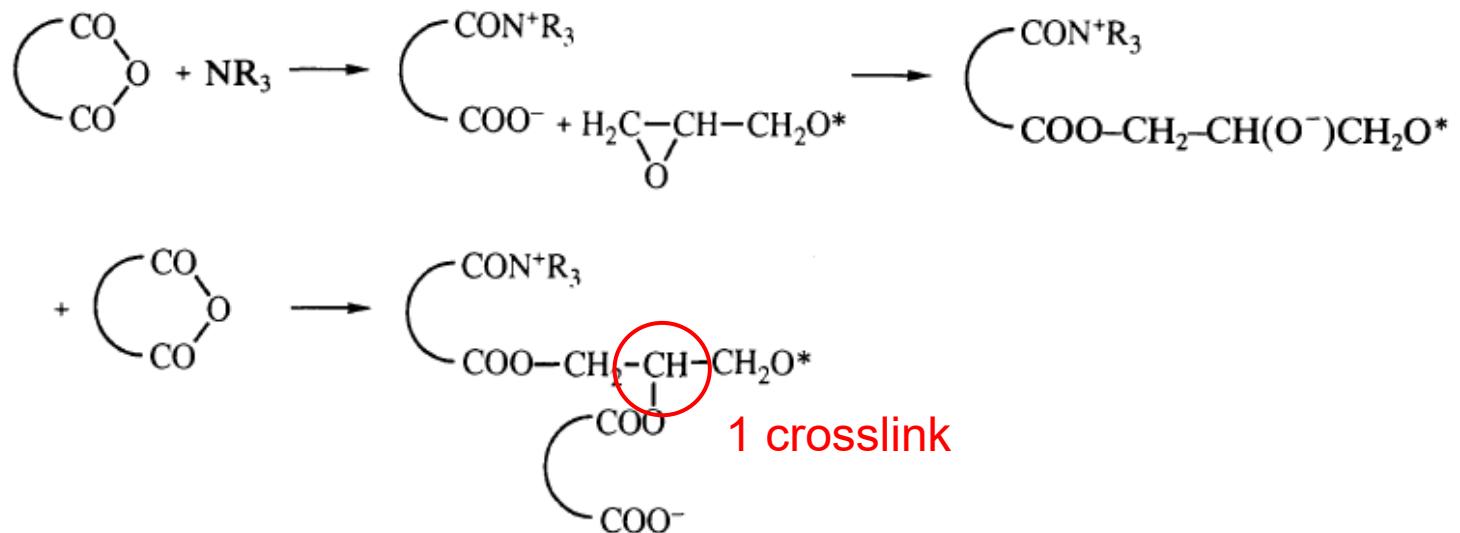
Curing Agents or Hardeners

ii) Diacids or anhydrides

(a) Uncatalyzed crosslinking



(b) Lewis base-catalyzed crosslinking (tertiary amines)



Effects of Various Hardeners

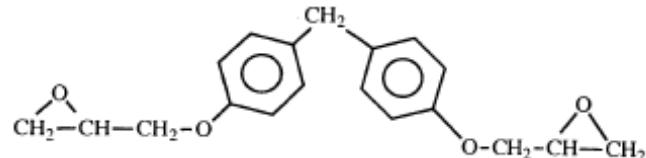
Hardeners	Advantages	Disadvantages
Aliphatic amines	Convenient, low cost, RT cure, low viscosity	Skin irritant and blushes
Aromatic amines	Moderate heat resistance, chemical resistance	Solids at RT, long and elevated cures
Polyamides	RT cure, flexibility, toughness, low toxicity	High cost, high viscosity, low heat distortion temp. (HDT)
Anhydrides	Heat and chemical resistance	Long, elevated cures
Polysulfides	Moisture insensitive, quick set	Odor, poor HDT
Catalysts (e.g., imidazoles, Lewis acids/bases)	Long pot life, high HDT	Long, elevated cures, poor moisture resistance
Phenol/formaldehyde	High HDT, chemical resistance, hardness	Solid, weatherability

Summary of Epoxy Resins

Table 9.1 Summary of commercially available epoxy resins^a

epoxide equivalent weight: MW/no. of epoxide groups

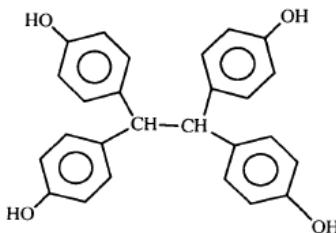
	E.e.w.	Viscosity (250°C) cp	Applications
1. Bisphenol A-epichlorohydrin resins			
a. Liquid resins			
i. Wide ranging characteristics	95–450	5000–30 000	Table 9.3
ii. Chain extension	185–200	2000–7000	Contain specific catalysts for conversion of these resins
iii. Lower viscosity resins			Contain reactive diluents, e.g. glycidyl ethers of <i>iso</i> -octanol or butane-1,4-diol
b. Solid resins			
i. So. pt. 60–180°C	500–6000		Coatings, especially powder coatings Manufacture of epoxy resin esters for coatings With amino- or phenolic-resins; high chemical resistance for tube coating primers and stoving enamels
ii. Mixtures and solutions			Castings Prepregs Solvents include butoxy(ethoxy)ethanol, xylene, acetone, methyl isobutyl ketone and combinations
2. Epoxy-novolacs			
Derived from bisphenol A-epichlorohydrin resins			
i. Phenol, <i>liquid</i>	170–190	30 000–90 000	Coatings, encapsulators, laminating, moulding, adhesives
ii. Phenol, <i>solid</i> (So. pt. 90–100) (So. pt. 90–95)	190–220		Moulding powder
iii. Cresol, <i>solid</i> (So. pt. 35–90)	275–330		Adhesives, coatings
	200–240		Adhesives, coatings, mouldings
3. Polyhydric phenols			
i. Bisphenol F			
Diglycidyl ether of bisphenol F	158–175	5000–7000	Additive for BPA resins in coating and flooring, e.g. Araldite G7 281
	CH ₂		



Summary of Epoxy Resins, cont'd

ii. Others include:

Tetraphenol ethane derivatives

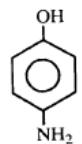
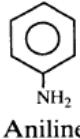
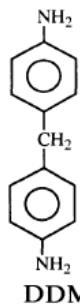


Powder coating

Polyglycidyl ether of tetraphenol ethane: Shell 1031

4. Amines

Reaction products of epichlorohydrin with amines such as:



Triglycidyl *p*-amino phenol

Union Carbide ERL-0500

5. Halogen-containing epoxides

Flame retardancy applications: general purpose laminating, moulding

6. Cyclo-aliphatic resins

Range of resins lower viscosities than BPA resins

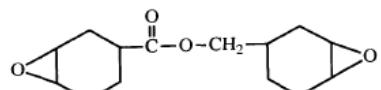
3,4-epoxycyclohexylmethyl 3,4-epoxy-cyclohexane carboxylate

131–143

350–450

Good UV light stability, electrical properties: general purpose casting resin, filament winding. Acid scavenger, plasticizer

Union Carbide ERL-4221



So. pt. = softening point, °C. ^a For a fuller list see Tanaka (1988).

Summary of Hardeners for DGEBPA Epoxy

Table 9.3 Some typical curing agents and applications for BADGE-type resins

Hardener ¹	Physical state at ambient	Concentration (phr) ²	Typical cure schedule	Approximate heat distortion temperature (°C)	Suggested applications ³
1. Aliphatic amine Triethylene tetramine	Liquid	13	a. 25°C, 7 days b. 25°C, 1 day plus post-cure at elevated T	a. – b. Up to 120	General purpose Co, A, Ca, M, F, S and FW
	Liquid	55	110–120°C, 30 min	~30	Flexible resin Co, A, Ca, F and S
2. Aromatic amine DDM	Solid	27	1 h at 150°C + 3 h at 180°C	Up to 150	Glass cloth laminate
	Solid	25	5 h at 125°C + 1 h at 200°C	Up to 175	A, Ca, M, E, S and FW
3. Polyamides	Liquid	Depends on type	a. Ambient temperature 7 days b. 1 h at 100°C	Up to 100 Up to 100	a. Co, A, Ca, F, M and S b. Ca and A
	Liquid	80	2 h at 20°C + 2 h at 150°C	130	Liquid hardener processing A, Ca, M, S and FW
4. Anhydrides Methyltetrahydro-phthalic anhydride (MTHPA)	Solid	35	1 h at 120°C + 2 h at 150°C	250	High heat distortion temperature A, Ca, M, S and FW
	Solid	35	1 h at 180°C + 2 h at 150°C	150	A, Ca, M, E, S and FW
5. Miscellaneous Dicyandiamide (DICY)	Solid	4	1 h at 180°C	170	A, Ca, M, E, S and FW
	Solid	3	1 h at 120°C + 2 h at 170°C	150	A, Ca, M, E, S and FW

¹ See chapter 2 for fuller details. Many hardeners are mixtures and/or derivatives and are not included in this list. Many other hardeners may be used. Shell list 30 curing agents for Epon 828. This table is only illustrative.

² phr = parts per hundred of resin by weight.

³ Code: Co = coatings; A = adhesives; Ca = castings; E = electrical laminates; F = flooring; M = mouldings, S = structural laminates; FW = filament winding.

Comparison with Polyesters

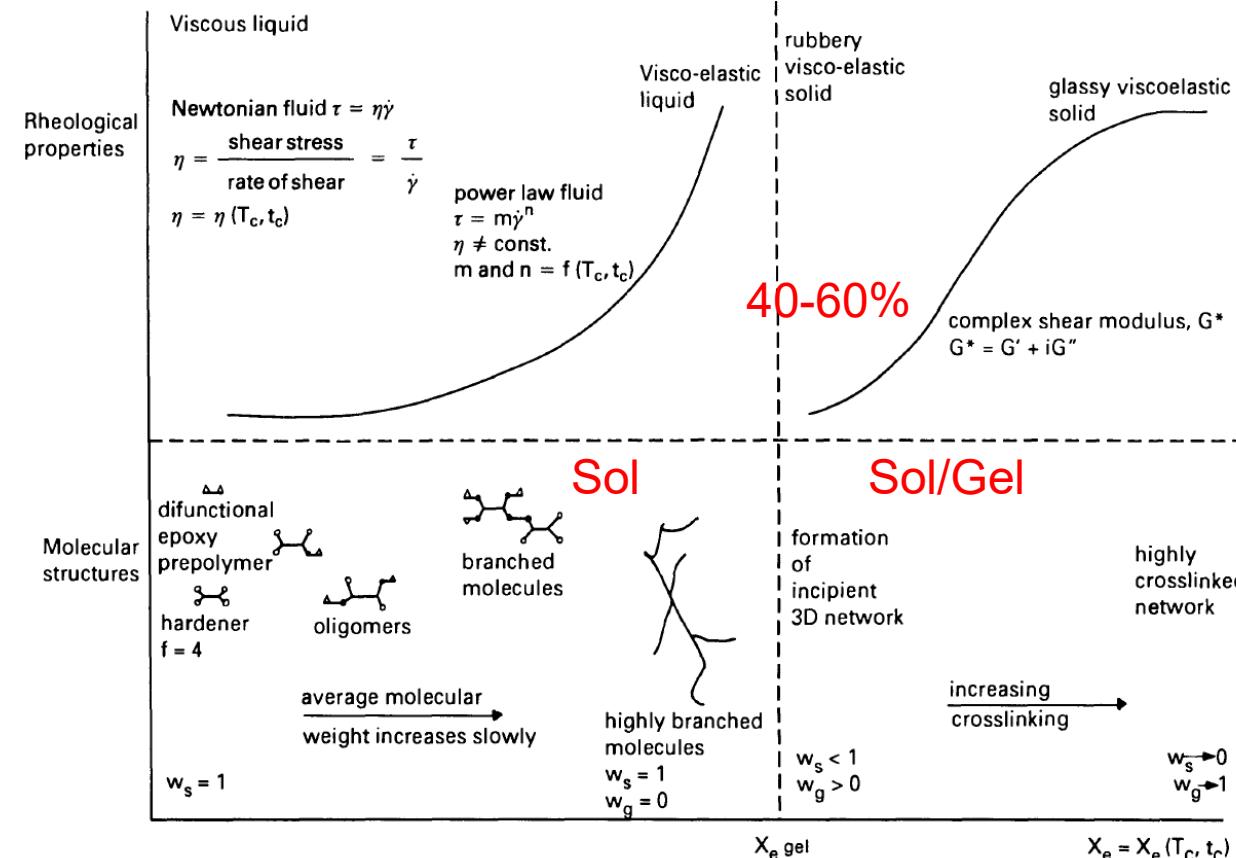
	Polyester	Epoxy
Active site	C=C	epoxide
Crosslinking reaction	Addition/free radical	Ring-opening
Crosslinking agent	Initiator (e.g., peroxide)	Hardener (diamine or dianhydride)
Amount of xlink agent	1-2% of resin	1:1 with resin
Solvent/viscosity	Styrene/low	Infrequent/high
Volatiles	High	Low
Inhibitors, accelerators	Frequent	Infrequent
Reactant toxicity	Low	Moderate
Cure conditions	RT or heated	Heated or sometimes RT
Shrinkage	High	Low
Post cure	Rare	Common

Comparison with Polyesters - Properties

	Polyester	Epoxy
Adhesion	Good	Excellent
Shear strength	Good	Excellent
Fatigue resistance	Moderate	Excellent
Strength/stiffness	Good	Excellent
Creep resistance	Moderate	Moderate to good
Toughness	Poor	Poor to good
Thermal stability	Moderate	Good
Electrical resistance	Moderate	Excellent
Water resistance	Poor to moderate	Moderate
Solvent resistance	Poor to moderate	Good
UV resistance	Poor to moderate	Poor to moderate
Flame retardancy	Poor to moderate	Poor to moderate
Smoke	Moderately dense	Moderately dense
Cost	Low	Moderate

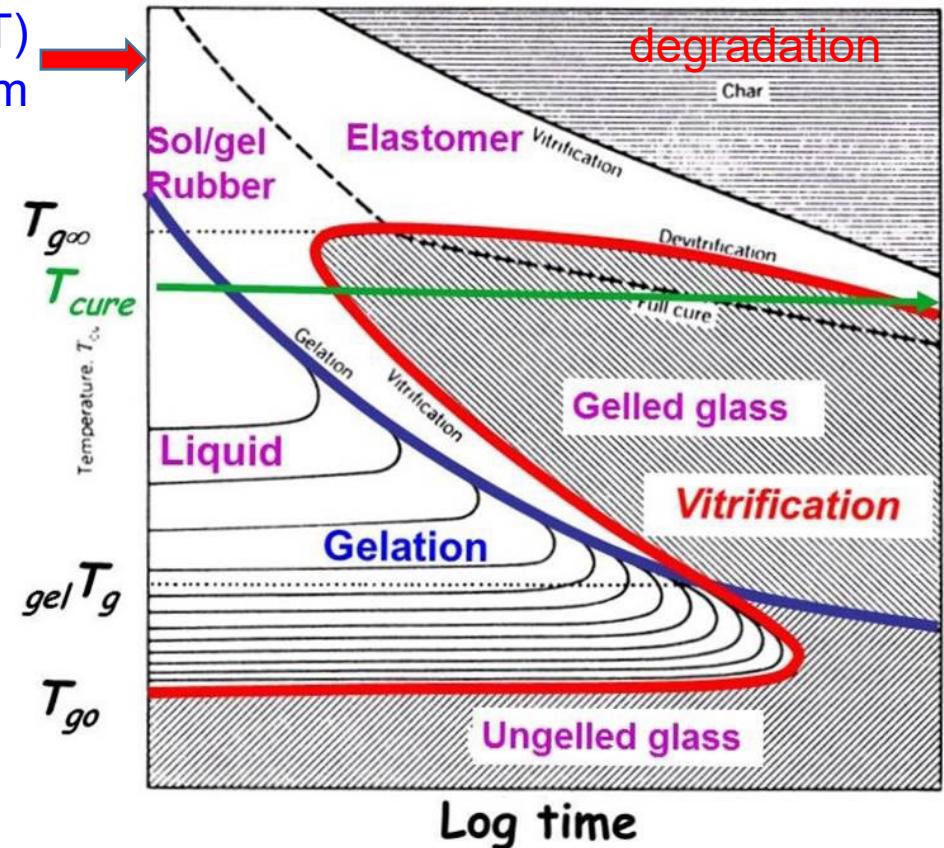
Curing of Epoxy Resins

Time-temperature-transformation (TTT) cure diagram for the neat epoxy system



Schematic of crosslinking reaction and viscosity increase.
(from *Chemistry and Technology of Epoxy Resins*; Ellis, B., Eds. Springer, 1993)

w_s – sol. content; w_g – gel content; X_e – extent of reaction



Aronhime M.T., Gillham J.K. (1986) Adv. Polym. Sci., 78, 84-113.

$T_{g,o} - T_g$ of the uncured epoxy prepolymer;
 $gel\ T_g$ – the temperature where gelation meets vitrification;
 T_{cure} – curing temperature;
 $T_{g\infty}$ - the maximum T_g for the system.
Note: $T_{g,o}$ increases as the MW of the sol increases.
So, if T_{cure} is too low, vitrification of sol will stop curing of the epoxy resin. You need to increase temp. to further cure it.

Structure-Property Relationship

The most important characteristic of a thermoset network is unquestionably its degree of crosslinking. It is related to M_c – the molecular weight between crosslinking points. For highly crosslinked polymers it is generally agreed that $M_c < 1000$ g/mol. Typical commercial epoxy thermosets have networks with M_c values in the range of 200-400 g/mol.

$$E_c = 3\rho RT/M_c$$

E_c is Young's modulus, ρ is density at absolute temperature T , and R the gas constant. Therefore, M_c can be determined by measuring the E_c of the crosslinking epoxy.

Also, T_g is a function of ρ or M_c :

$$T_g = 3.9 \times 10^4 / M_c + T_{g0},$$

T_{g0} is the T_g of the uncrosslinked prepolymer.

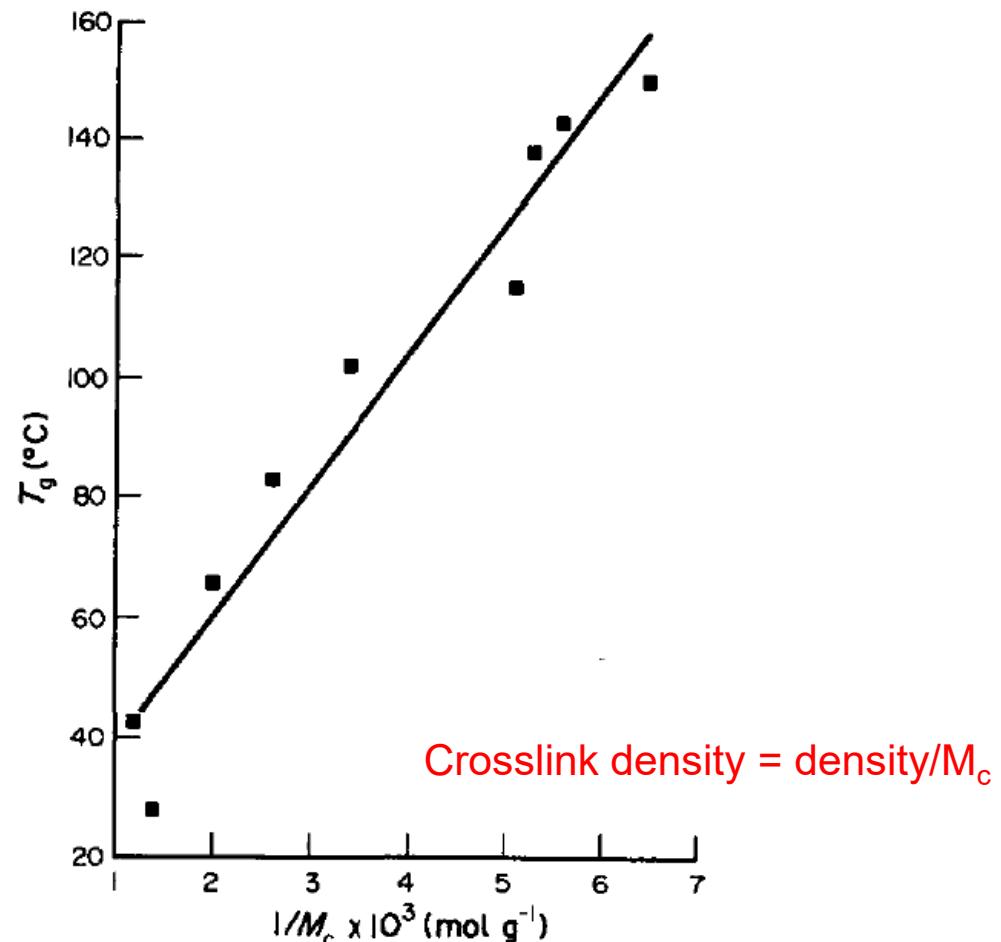


FIG. 10. Glass transition temperature vs crosslink density.¹⁵⁷

Effect of Curing Agents on T_g

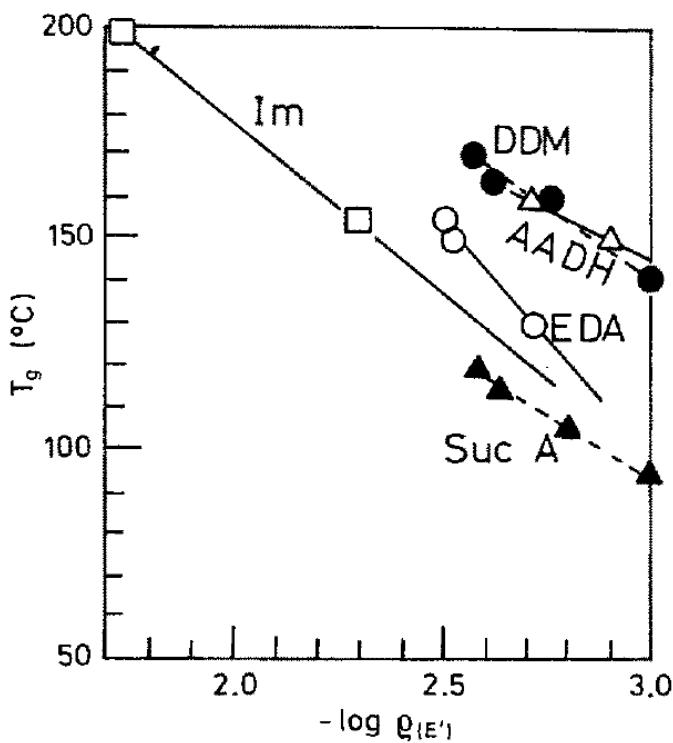
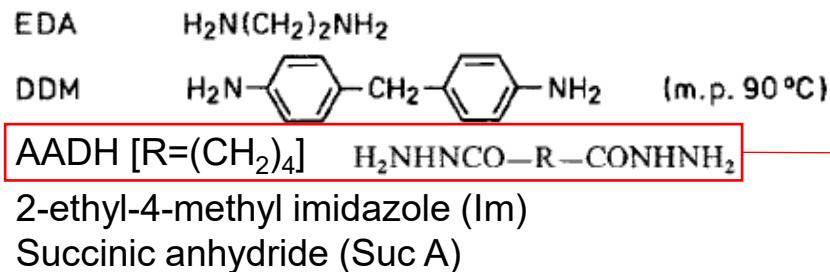


Fig. 4. Glass transition temperature (T_g) vs. crosslinking density ($Q_{(E')}$) for resins cured with various curing agents

Table 4. Structure and melting point of dihydrazides

Code	$\text{H}_2\text{NNCO}-\text{R}-\text{CONHNH}_2$	m. p. (°C)
SuADH	$\text{---CH}_2\text{---}_3$	163
AADH	$\text{---CH}_2\text{---}_4$	180
SeADH	$\text{---CH}_2\text{---}_8$	184~5
DDADH	$\text{---CH}_2\text{---}_{10}$	184~5
SL-16DH	$\text{---CH}_2\text{---}_{14}$	174
IPADH		212
N-PDPDH	$-\text{CH}_2\text{CH}_2-\text{N}(\text{C}_6\text{H}_5)-\text{CH}_2\text{CH}_2-$	141~5

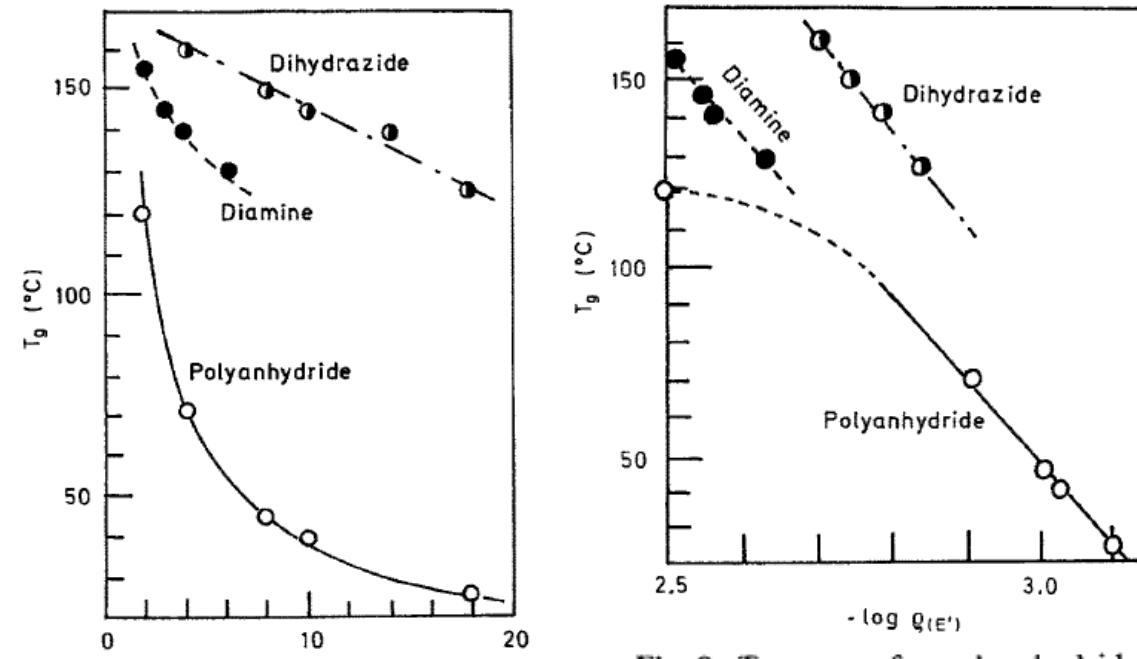


Fig. 8. Effect of the number of methylene group (n) in diamine, dihydrazide and polyanhydride for cured epoxy resins on T_g ⁴¹⁾

Fig. 9. T_g vs. $Q_{(E')}$ for polyanhydride, Diamine and dihydrazide cured epoxy resins⁴¹⁾
 crosslink density = density/M_c

Additives

1. Diluents

To reduce viscosity and increase wettability and dispersion of fillers such as glass fibers.

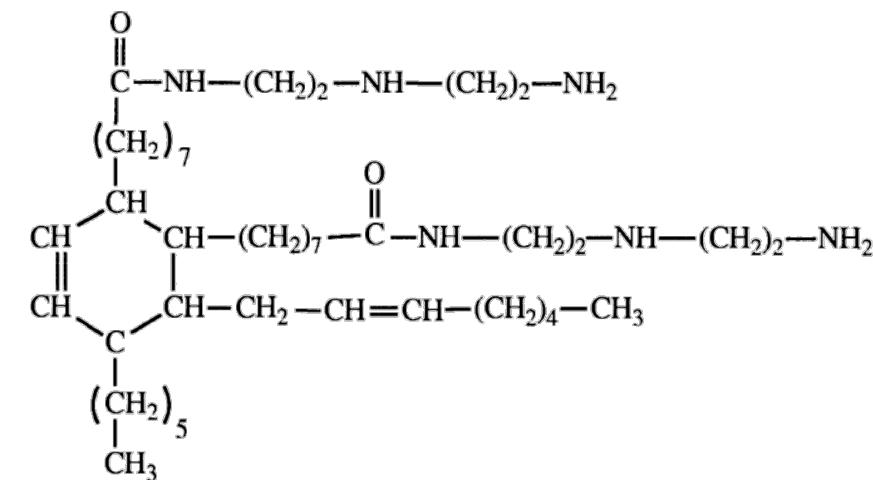
i) Non-reactive: organic solvents such as xylene or toluene at around 10% by weight.

ii) Reactive: low MW mono- or di-epoxide compounds, or triphenyl phosphite are preferred, because they become bound into the system and do not cause problems through volatilization.

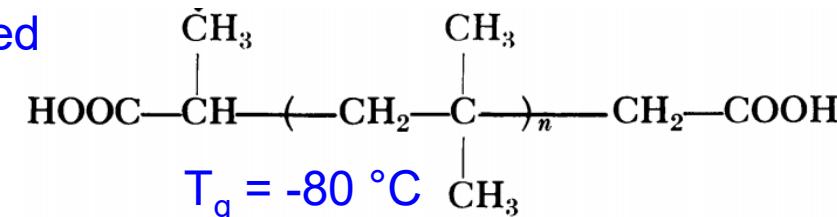
2. Flexibilizers

- Different from nonreactive plasticizers, flexibilizers are **reactive and can be incorporated** into the epoxy network.
- The main purpose is to reduce brittleness, increase flexibility, and improve adhesion for epoxies.
- **Disadvantage**: reduced modulus and strength.

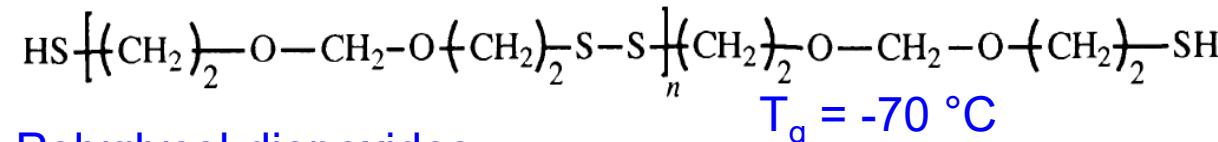
Amides



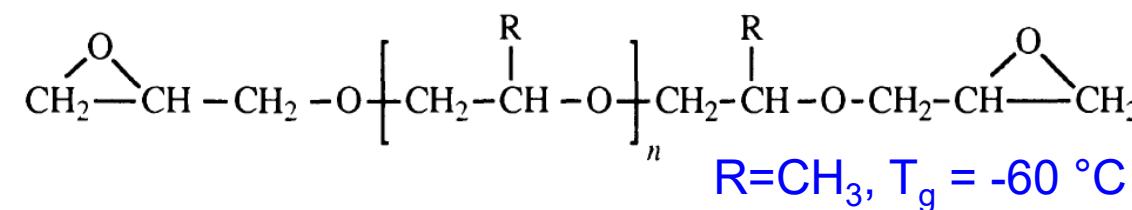
COOH-terminated polyisobutylene



Polysulfides



Polyglycol diepoxides



Inorganic Fillers

- The most common additives.
- Primarily to reduce shrinkage and cost.
- Reduce the coefficient of thermal expansion, increase thermal stability and thermal conductivity.
- Examples are aluminum oxide, aluminum powder, iron powder, copper powder, silica, talc and CaCO_3 .
- The influence of a filler is generally related to the amount incorporated rather than to the type.
- Mechanical properties can be affected by the nature and amount of the filler.

Table 4.1 Advantages and disadvantages of filler incorporation

Advantages	Disadvantages
Reduced formulation cost	Increased weight
Reduced shrinkage	Increased viscosity
Improved toughness	Machining difficulties
Improved abrasion resistance	Increased dielectric constant
Reduced water absorption	
Increased heat deflection temperature	
Decreased exotherm	
Increased thermal conductivity	
Reduced thermal expansion coefficient	

Table 8.1 Effect of fillers and epoxy resin properties [38]. (Reprinted with permission of Elsevier Science Publishers, from *Polymers in Microelectronics* by D.S. Soane and Z. Martynenko, 1989)

Filler or extender	Property improved
Silica; calcium carbonate	Cost
Glass microballoons	Density
Fibrous glass, chopped nylon	Impact strength
	Tensile strength
	Flexural strength
Aluminum powder, calcium carbonate	Machinability
Carbon black asbestos	Heat resistance
Silica; metal powders	Dimensional stability
	Thermal conductivity
Lithium aluminum silicate	Thermal expansion coefficient
Inorganic fillers	Fire retardance
Asbestos; powdered coal	Moisture resistance
Mica; silica; asbestos	Electrical insulation
Silver or aluminum powder; carbon; graphite	Electrical conductivity
Graphite; mica; molybdenum disulfide	Lubricity

Toughening of Epoxy

Progress in Materials Science 130 (2022) 100977



Contents lists available at [ScienceDirect](#)

Progress in Materials Science

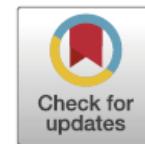
journal homepage: www.elsevier.com/locate/pmatsci



Toughness and its mechanisms in epoxy resins

Xiaoqian Mi, Nuo Liang, Haifeng Xu, Juan Wu, Yu Jiang ^{*}, Bei Nie, Daohong Zhang ^{*}

Key Laboratory of Catalysis and Energy Materials Chemistry of Ministry of Education & Hubei Key Laboratory of Catalysis and Materials Science, Hubei R&D Center of Hyperbranched Polymers Synthesis and Applications, South-Central Minzu University, Wuhan 430074, China



A good literature review of epoxy toughening and mechanism.

Toughening of Epoxy

Research goal:

To increase the energy density, i.e., to increase strength and elongation at break, without sacrificing other mechanical properties.

1. Resinous additives

PC and aliphatic polyamides or nylon

- Good toughness improvement;
- Nylons are hygroscopic – absorb moisture and mechanical property decreased

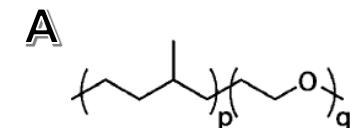
2. Elastomers (similar to HIPS)

- Reactive butadiene-acrylonitrile rubbers (successful and commercialized);
- Polysiloxanes;
- Fluoroelastomers;
- Acrylate elastomers.

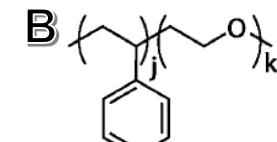
Reason of toughening:
Rubbery microdomain cavitation
- absorb a large amount of energy!

An effective but expensive approach

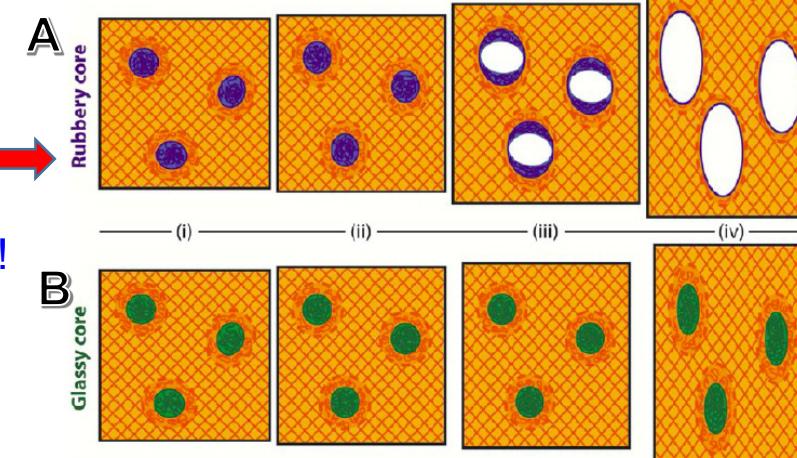
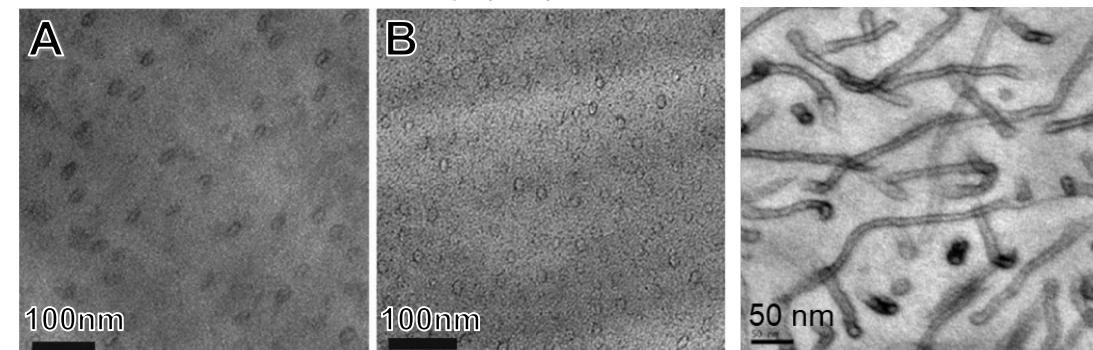
Block Copolymer Modifiers



Poly(ethylene-*alt*-propylene)-
b-poly(ethylene oxide)



Polystyrene-*b*-
poly(ethylene oxide)



Toughening by Modified Rubbers

Advancing Adhesives: High-Performance Epoxy Paste for Aircraft Applications

A new structural adhesive for metal and composite aircraft parts reduces cure time and costs.

F-14 Tomcat



Produced: 1969-1991

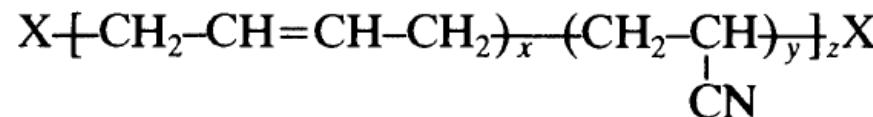
https://en.wikipedia.org/wiki/Grumman_F-14_Tomcat



<https://www.adhesivesmag.com/articles/92776-advancing-adhesives-high-performance-epoxy-paste-for-aircraft-applications>

Toughening by Modified Rubbers

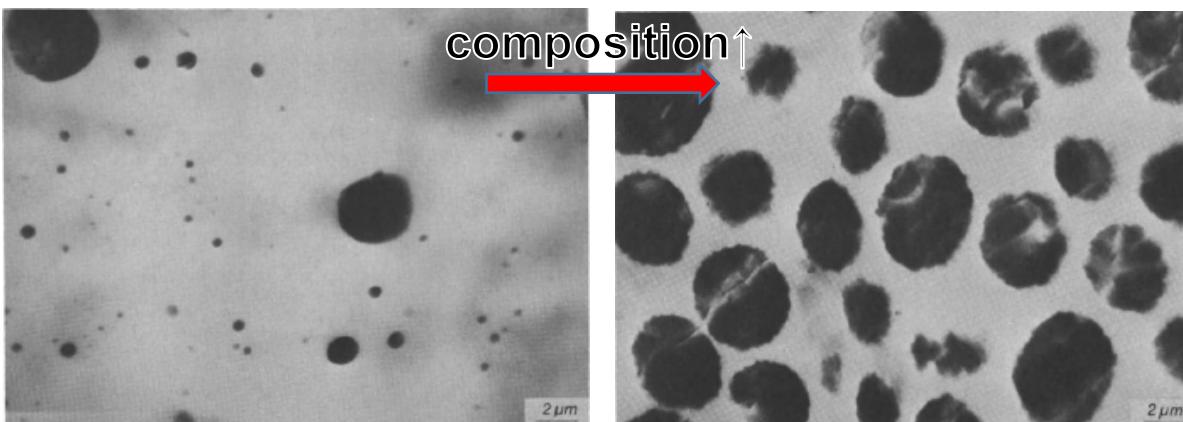
End-functionalize BAN



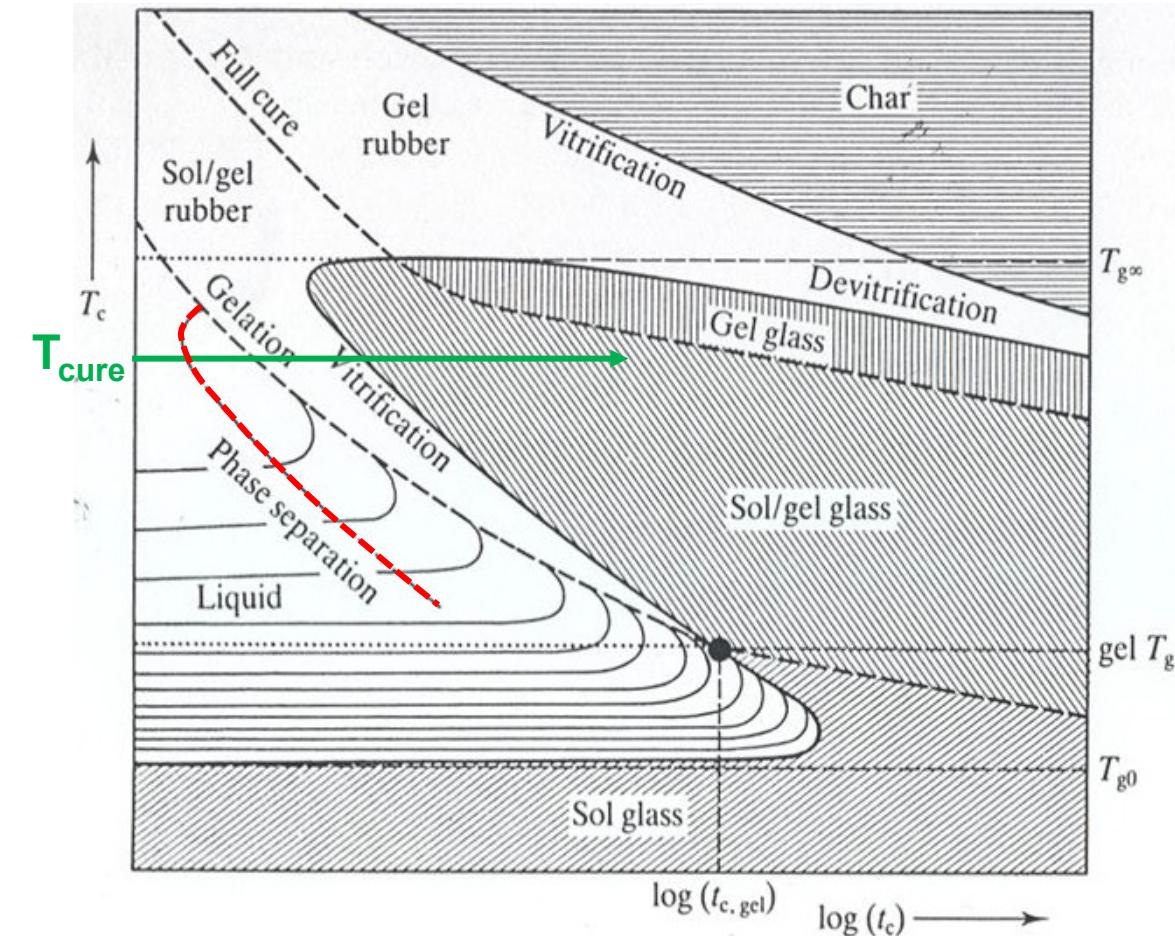
$X = -COOH$, epoxide, hydroxyl, phenol, mercaptan, vinyl, and amine.

Extensive research has been performed:

- i) Composition of AN – to increase polarity to be compatible with epoxy resin matrix.
- ii) Molecular weight
- iii) End functional groups – **COOH is the most successful.**
- iv) Rubber composition (<20 wt.%)



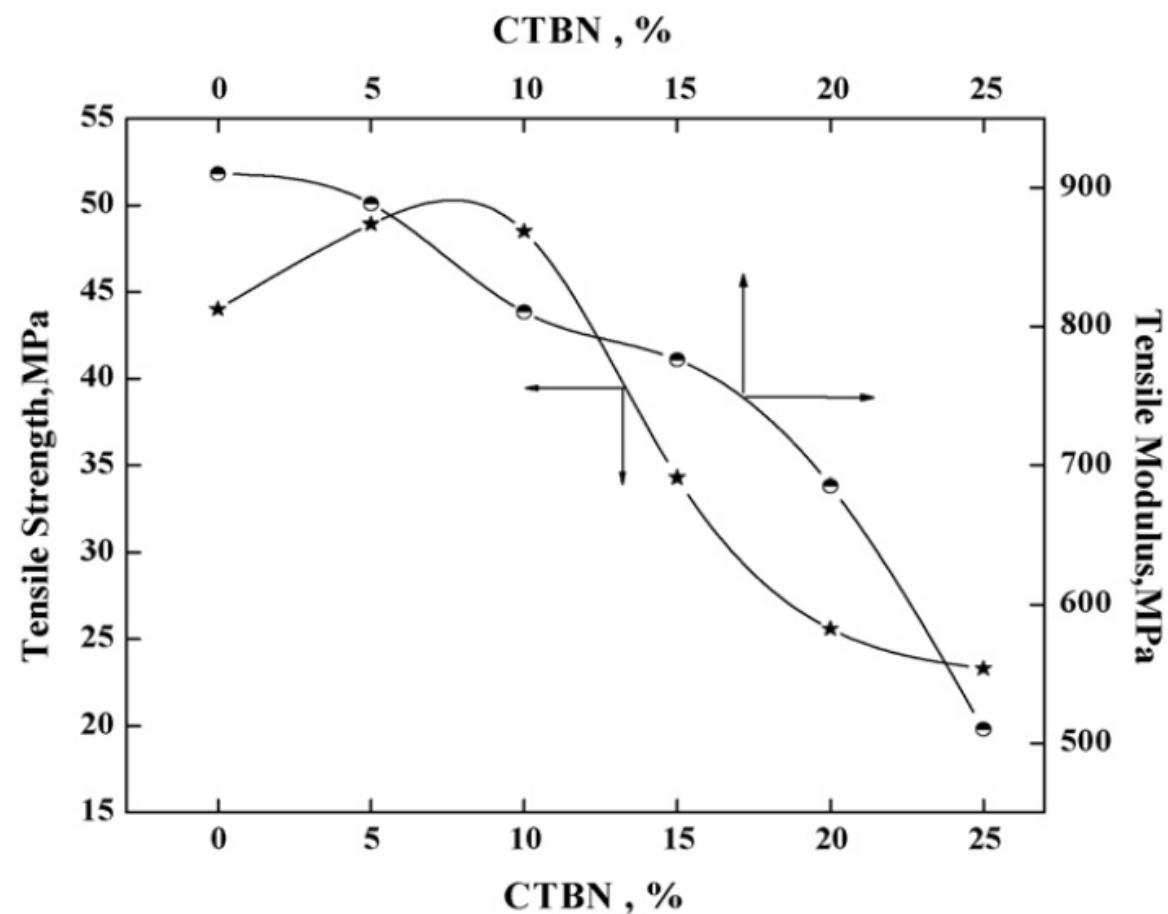
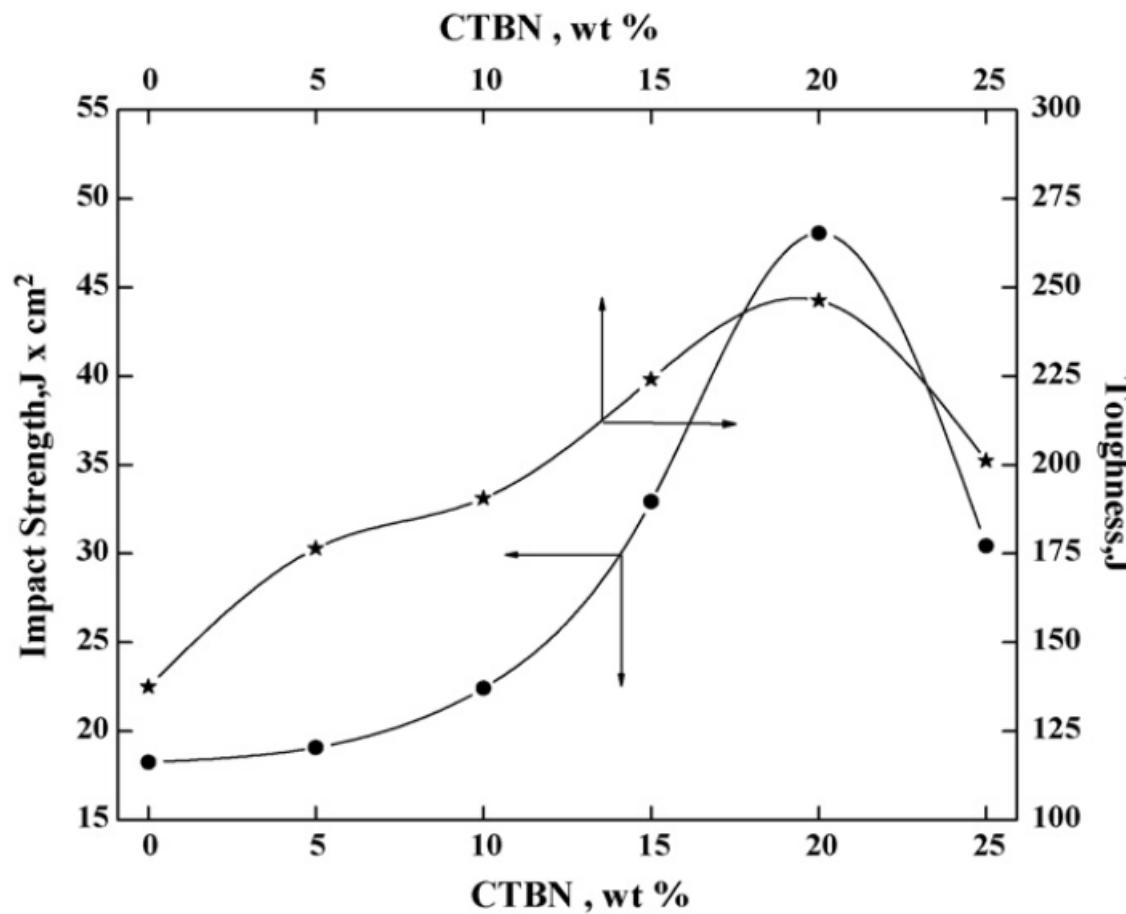
Black domains are rubber microdomains stained by OsO₄.



Time-temperature-transformation (TTT) cure diagram for rubber-modified epoxy system.

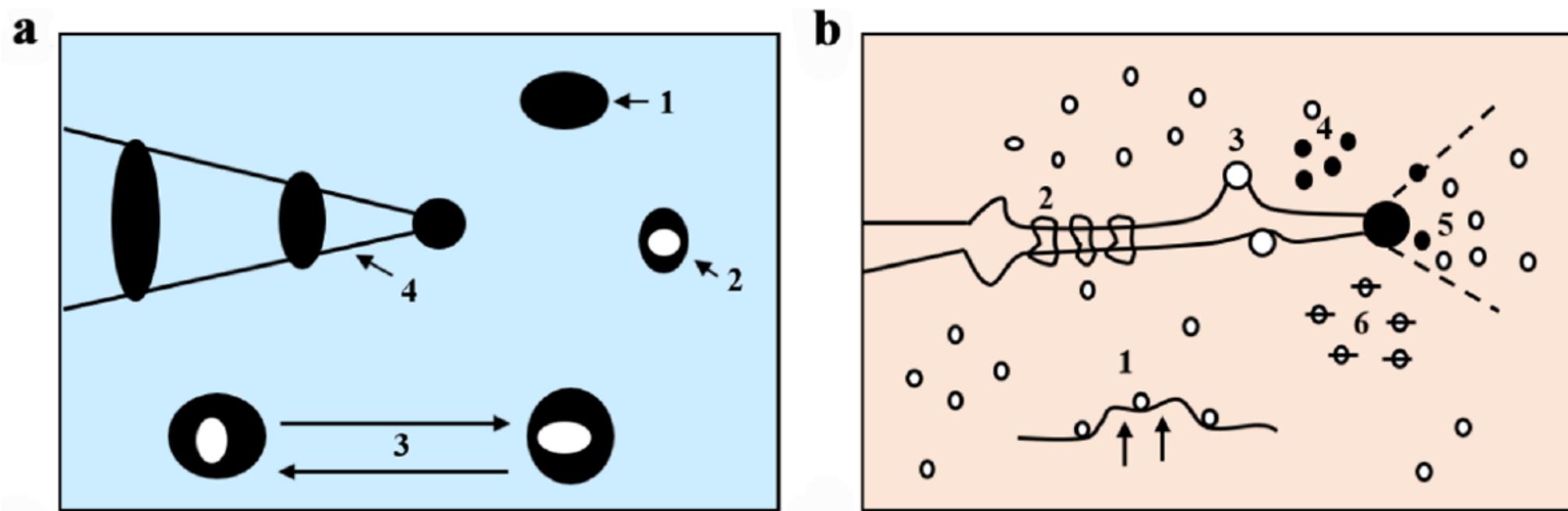
Note the phase separation line! It is just before the gelation line. Therefore, microphase separation is possible to have similar morphology as those in ABS and HIPS.

Toughening by Modified Rubbers - Deficiency



>20 wt% CTBN will cause decreased modulus and tensile strength

Toughening Mechanisms



Toughening mechanisms in toughening agents modified epoxies

(a) Rubber elastomers: 1. particles, 2. cavity, 3. shear yielding, 4. crazing.

(b) Thermoplastics: 1. crack pinning, 2. particle bridging, 3. crack path deflection, 4. particle yielding, 5. particle-yielding-induced shear banding, 6. microcrack.

Mechanical Properties of Reinforcing Fibers

Table 8.1 Typical mechanical properties of reinforcing fibres

	Relative density	Young's modulus (GPa)	Tensile strength (GPa)	Failure strain (%)	Fibre diameter (μm)
E glass	2.55	72	1.5–3.0	1.8–3.2	10–16
S glass	2.5	87	3.5	4.0	12
S-2 glass	2.49	86	4.0	5.4	10
Carbon-mesophase pitch	2.02	380	2.0–2.4	0.5	10
Carbon-PAN					
Type A high strength	1.8	220–240	3.0–3.3	1.3–1.4	7
Type A high performance	1.8	220–240	3.3–3.6	1.4–1.5	7
Type A high strain	1.8	220–240	3.7	1.5–1.7	7
Type II high strength	1.8	250	2.7	1.0	7
Type I high modulus	2.0	330–350	2.3–2.6	0.7	7
Intermediate modulus	1.9	280–300	2.9–3.2	1.0	7
SiCO-continuous	2.5	200	3.0	1.5	10–15
SiC-whisker	3.2	480	7.0	—	1–50
SiCTiCO continuous	2.35	200	2.8	1.4	8–10
Boron	2.6	410	3.4	0.8	100
α-alumina (FP)	3.9	380	1.7	0.4	20
β-alumina (Saffil)	3.3	300	2.0	0.5	3
δ/θ-alumina (Safimax)	3.3	250	2.0	—	3.1
η alumina (Safimax LD)	2.0	200	2.0	—	3.2
Fe ₈₀ B ₂₀ metallic glass	—	100	3.6	—	—
H.C. steel	7.8	210	2.8	—	250
Polyphenylene terephthalamide					
Aramid – high modulus	1.47	180	3.45	1.9	12
Aramid – intermediate modulus	1.46	128	2.65	2.4	12
Aramid – low modulus	1.44	60	2.65	4.0	12
Aramid – staple fibre (polymetaphenylene-isophthalamide)	1.4	17.3	0.7	22.0	12
Polybenzothiazole (PBT)	1.5	250	2.4	1.5	20
Polyamide 66	1.44	5.0	0.9	13.5	≈10
Polyethene (theory)	—	200	—	—	—
Solution spun	1.0	100–150	—	—	—
Drawn	≈1	6–80	—	—	—

Specific Properties for Fiber Reinforcements

Specific strength = $\sigma/(\rho g)$ with unit of m

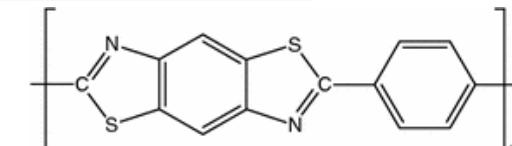
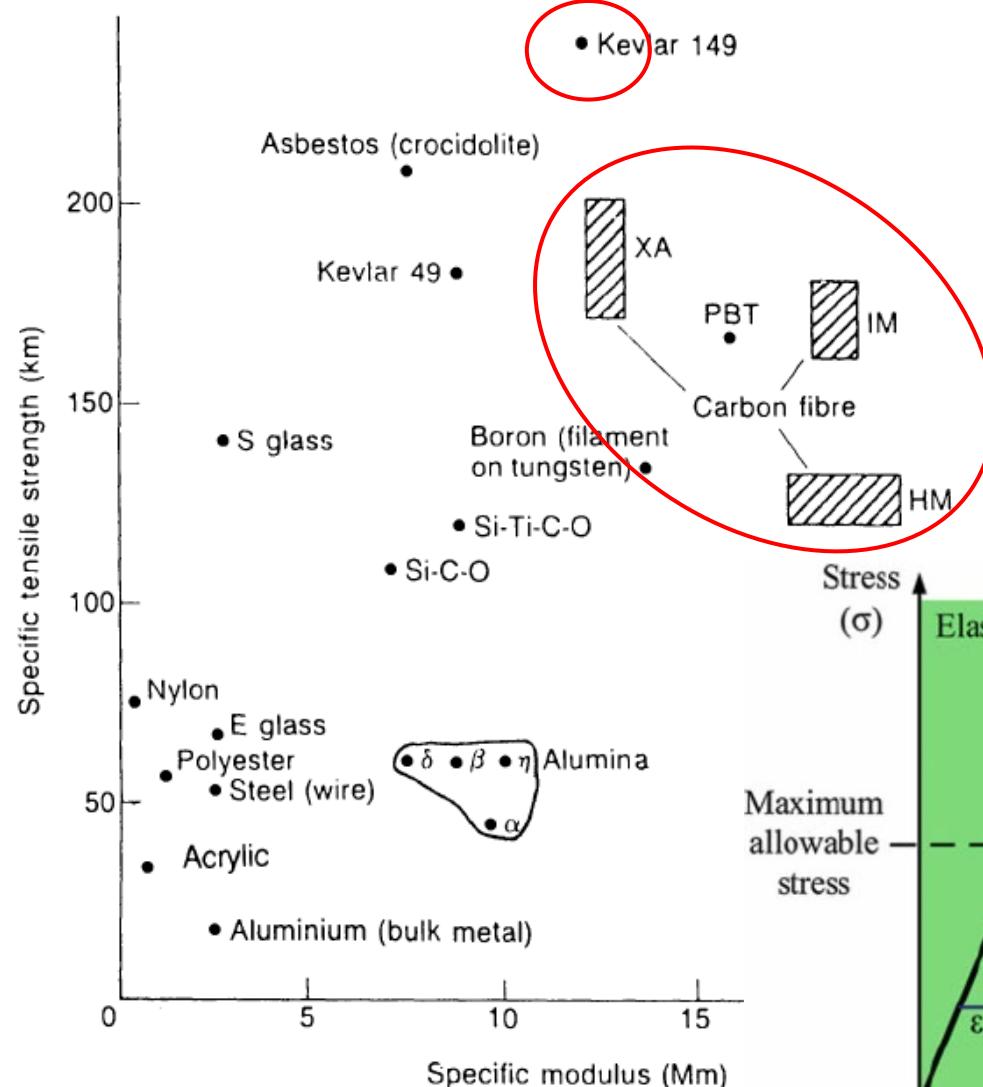
Specific modulus = $E/(\rho g)$ with unit of m

σ – strength

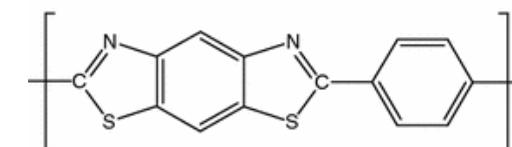
E – Young's modulus

ρ – density

g - gravitational acceleration



trans-polybenzothiazole



cis-polybenzothiazole

PBT: polybenzothiazole
Only at sample level

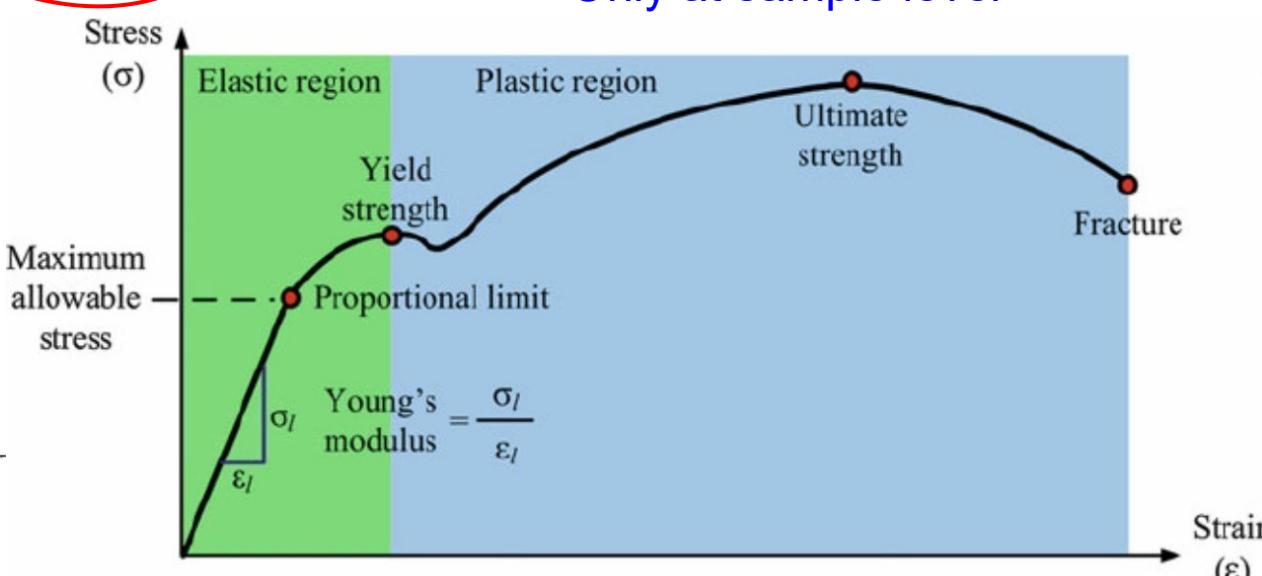
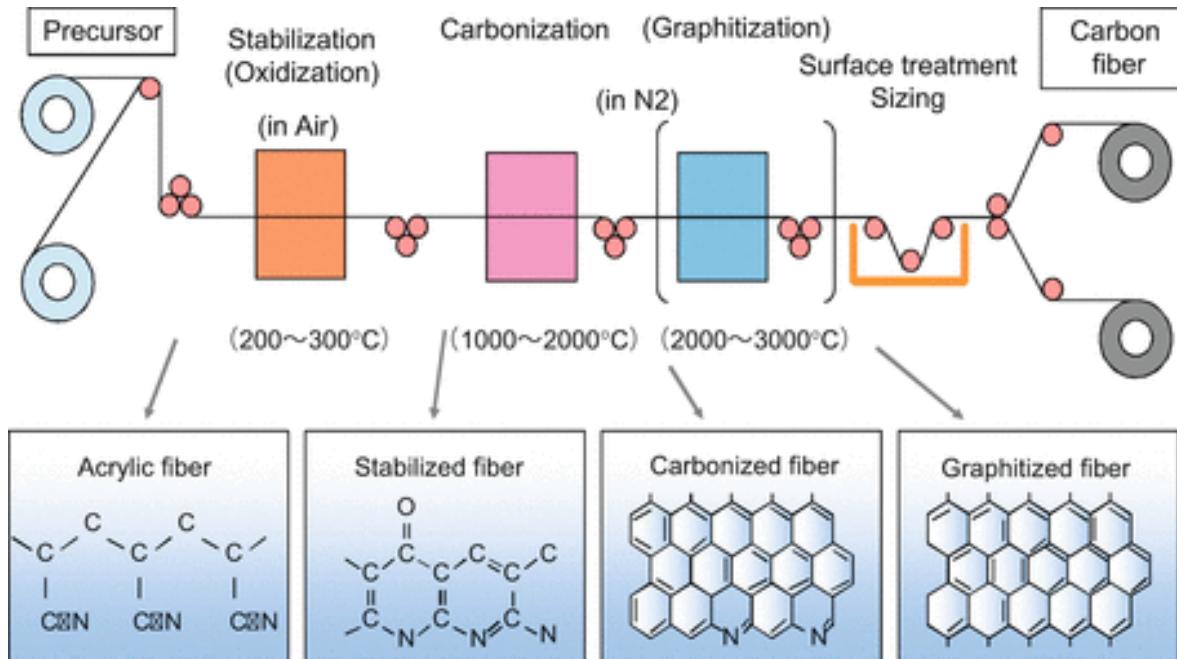


Figure 8.1 Specific properties of fibre reinforcements. XA, 1M, HM, refer to differing grades of carbon fibre. For other definitions see Table 8.1.

Carbon Fibers and Prepregs



Endo M. (2016) Carbon Fiber. In: The Society of Fiber Science and Techno J. (eds) *High-Performance and Specialty Fibers*. Springer, Tokyo

Manufacturing of Carbon Fiber Prepregs at SGL/BMW

<https://www.youtube.com/watch?v=kaoq8Mc4xxw>

A **prepreg** often refers to woven cloth pre-impregnated with an epoxy resin (or other thermosets or thermoplastics) modified with a thermoplastic polymer, together with a latent hardener (i.e., only reactive at high temperatures).

History about Carbon Fibers

- Carbon fiber/filaments for light bulbs.
- In 1958, Roger Bacon made carbon fibers at the Union Carbide, Parma, Ohio – from rayon fibers followed by carbonization.
- In the early 1960s, polyacrylonitrile (PAN) was used as the precursor material - Dr. Akio Shindo at Agency of Industrial Science and Technology of Japan – 50% carbon.
- High strength carbon fiber was realized in 1963 by W. Watt, L. N. Phillips, and W. Johnson at the Royal Aircraft Establishment at Farnborough, Hampshire.
- In the late 1960s, Japan took the lead in manufacturing PAN-based carbon fibers.

Mechanical Properties

Type	Manufacturer	Product name	Tensile strength (GPa)	Young's modulus (GPa)	Strain to failure (%)
PAN	Toray	<i>T300</i>	3.53	230	1.5
		<i>T1000</i>	7.06	294	2.0
		<i>M55J</i>	3.92	540	0.7
	Hercules	<i>IM7</i>	5.30	276	1.8
GP-Pitch	Kureha	<i>KCF200</i>	0.85	42	2.1
HP-Pitch	BP-Amoco	<i>Thornel P25</i>	1.40	140	1.0
		<i>Thornel P75</i>	2.00	500	0.4
		<i>Thornel P120</i>	2.20	820	0.2

Carbon Fiber Composites for Electric Vehicles

Carbon fiber reinforced plastics (CFRP) was started in luxury sports cars. E.g., McLaren 570S uses CFRP structural panels and body frame:

562 horsepower V8 engine gives a 0-to-60-mph acceleration at 3 seconds and a max speed of 204 mph, but only weighs 3,150 lbs. But, \$200k!



2020 McLaren 570S / 570GT

Koenigsegg CFRP Regera (\$2M):

https://www.youtube.com/watch?v=504I_hJDFck

Electric car market is the major driver for CFRP to be light weight and strong. E.g., BMW i8, Tesla Model 3, BMW i3, and Volkswagen eGolf.



BMW i8 electric supercar uses a fully carbon fiber chassis.

BMW electric cars use CFRPs.

https://www.youtube.com/watch?v=LEjQL_scUaM

Epoxy Laminates for Wind Turbine Blades

- The new application for epoxy resins – 27% of the market
- Epoxy/fiber glass or carbon fiber laminates
- Aerodynamic design to be energy efficient
- Polyurethane coating to be UV resistant and durable
- Avoid damages from lightning hits

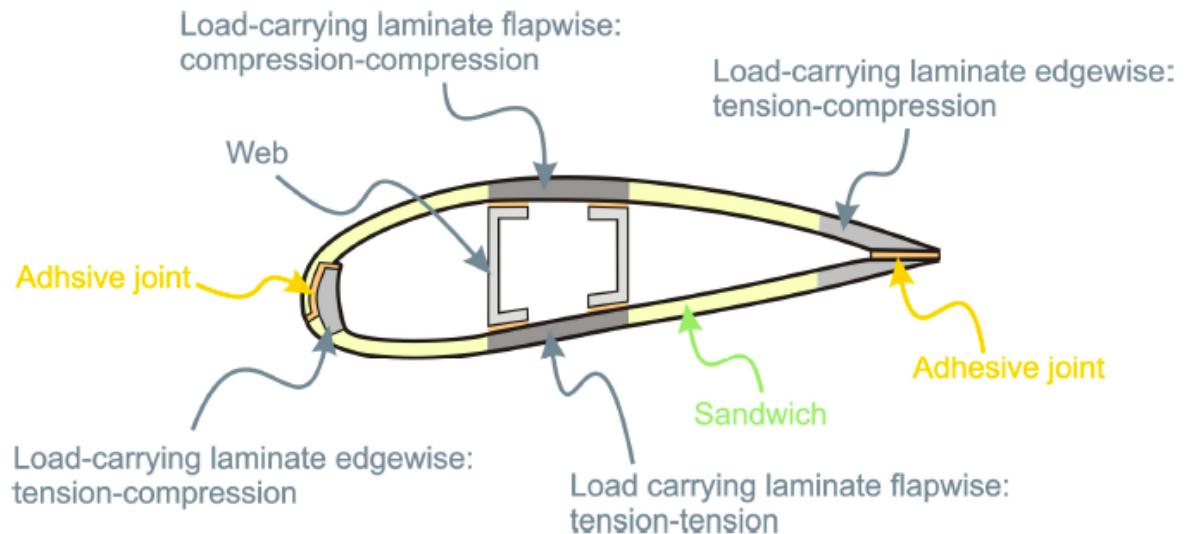
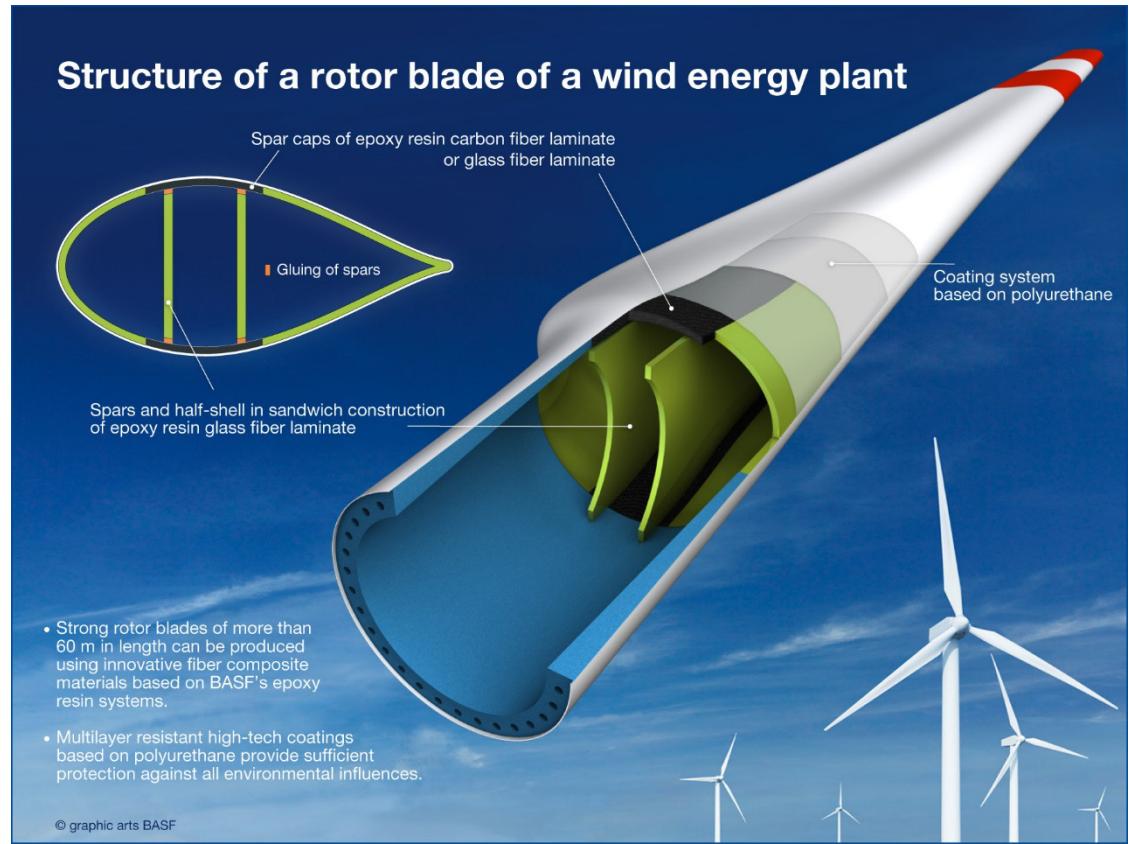


Figure 2. Schema of the section of the blade.

Mishnaevsky L, Branner K, Petersen HN, Beauson J, McGugan M, Sørensen BF. Materials for Wind Turbine Blades: An Overview. Materials. 2017;10(11):1285.



A short video introducing the manufacturing of the longest wind turbine blades (88.4 m) at LM Wind Power, Denmark:
<https://www.youtube.com/watch?v=gl8xoWLtCps>

Fabrication Processes of Epoxy Composites

Table 8.4 Fabrication processes for composites from epoxy resins

Processes	Reinforcement	Vol. (%)	Method	Typical application
1. Spray-up	Chopped rovings (G)	15–30	Direct application of chopped rovings and resin	Pipe linings
2. Autoclave	Continuous (G, C, A)	60	Forming of stacked prepreg in vacuum bag	Aerospace components
3. Filament winding	Continuous rovings, occasionally particulate fillers included (e.g. sand) (G, C)	~50	Wet resin carried by fibres onto mandrel at predetermined angles. Variants: prepeg tape, woven tape, dry preform manufacture	Pipes and containers, geodesic shapes
4. Pultrusion	Continuous fibres, occasional CSM and fillers (G, C)	60–80	Wet resin-impregnated roving or cloth formed through a heated die	I-beam or rods
5. Compression moulding	Chopped or continuous fibres or preforms and fillers (G, A, C)	10–60	Prepeg or wet resin/preform pressed to shape in a closed mould between matched dies	Medium-sized complex mouldings
6. Resin injection, resin (RTM) transfer	Continuous or discontinuous fibre plus preform polymer foam inserts (G, C, A)	25–30	Wet resin injected into woven, knitted or CSM preform within a closed mould	Panels
7. Reinforced reaction injection moulding (RRIM)	Short-milled glass fibre or fibre preform (G)	5 20	Fibre-resin dispersion and hardener mixed at rapid mixing head and injected into mould. Chemistry controlled to give rapid reaction	Large complex parts (e.g. auto parts for impact resistance but with low stiffness)
8. Structural RIM	Continuous fibre preform (G, A, C)	30–50	Similar to 6 with the more rapid RIM chemistry	Large structural parts. Rapid production possible

Fibres: G = glass; C = carbon; A = aramid. CMS = chopped strand mat.

Epoxy Coatings

Table 9.4 Film forming materials for coatings

Application	Epoxy resins	Epoxy resin mixtures						Other thermosetting resins ^c			
		Acrylic	Alkyd	Polyester	P/F ^a	A/F ^b	Coal tar modified	Alkyd	Polyester	A/F	P/F ^a
Can and drum coatings	✓	✓		✓	✓	✓		✓		✓	✓
Heavy duty plant maintenance coatings	✓	✓	✓	✓				✓	✓	✓	✓
Automotive – primers, topcoats and respray	✓	✓	✓	✓				✓		✓	✓
Pipe coatings	✓				✓		✓				
Appliance finishes	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Marine coatings, primers and top coats	✓				✓	✓	✓	✓	✓	✓	✓
Coil coatings	✓						✓				✓
Metals, general primers and top coats	✓	✓	✓	✓			✓				✓

^a P/F is a phenol-formaldehyde resin; ^b A/F includes urea and melamine formaldehyde resins; ^c Non-convertible coatings include drying oils and cellulose ethers and esters.

Advantages of Epoxy Coatings

- Corrosion resistant (powder coating for metals)
- Excellent adhesion to various substrates (primer)
- Excellent water, heat and chemical resistance
- Versatile (formulations can be tailor-made to the needs) and easy to apply
- No release of volatiles during curing
- Film thickness adjustable

- Can combine with other coatings (i.e., hybrid coating, see above table)
- Environmentally friendly for water dispersion formulations

Here is a video compare floor coating using polyurethane and epoxy:
https://www.youtube.com/watch?time_continue=496&v=oD2Cio0m3TM&feature=emb_logo

Different Methods of Epoxy Coatings

1. Surface preparation and primers

- A primer can improve the 'wettability' of the surface and protect the cleaned surface before the final application of the coating.

2. Solution coating

- Adjust rheological properties
- Control film thickness
- Selection of epoxy/solvent systems

3. Dip coating

- Avoid evaporation of solvent from dip tank
- A good control of dipping and withdrawal speeds

4. Water dispersions

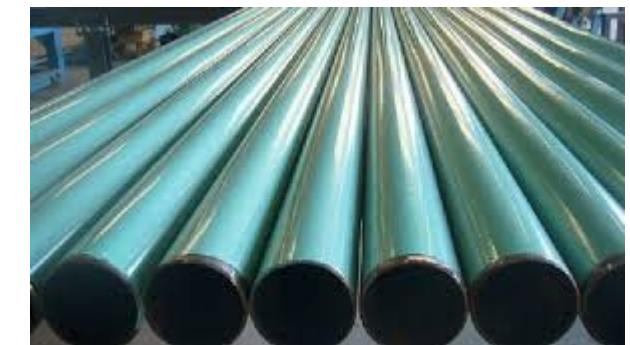
- Strong mechanical shearing to reduce particle size
- Amphiphilic surfactants to stabilize the emulsion
- Difficult to achieve uniform dispersions, but it is okay for coatings
- Can be used for dip coating and spray coating

5. Powder coating

- 100% solid, no solvent or water
- Application methods: fluidized-bed, electrostatic spray, flock spray, and electrostatic fluidized-bed
- Excellent electrical resistance and thermal stability
- Resistance to corrosion: coating for underground/water pipes and marine applications
- Curing at 200-250 °C for 10 min (oven, IR or laser)



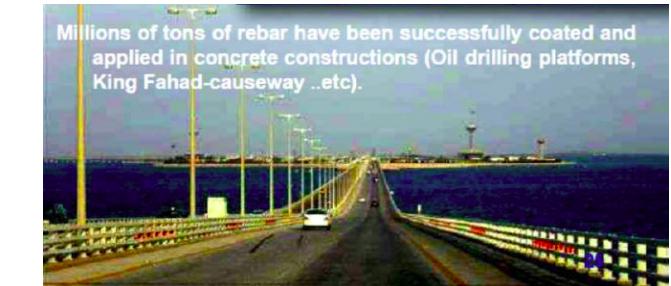
Spray gun



Fusion bonded pipes



Construction steels



<https://www.youtube.com/watch?v=sdls8bt1UFA>

Industrial Applications of Epoxy Coatings



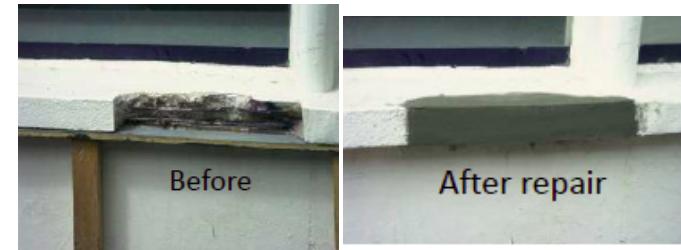
Industrial flooring



Waterproofing roof



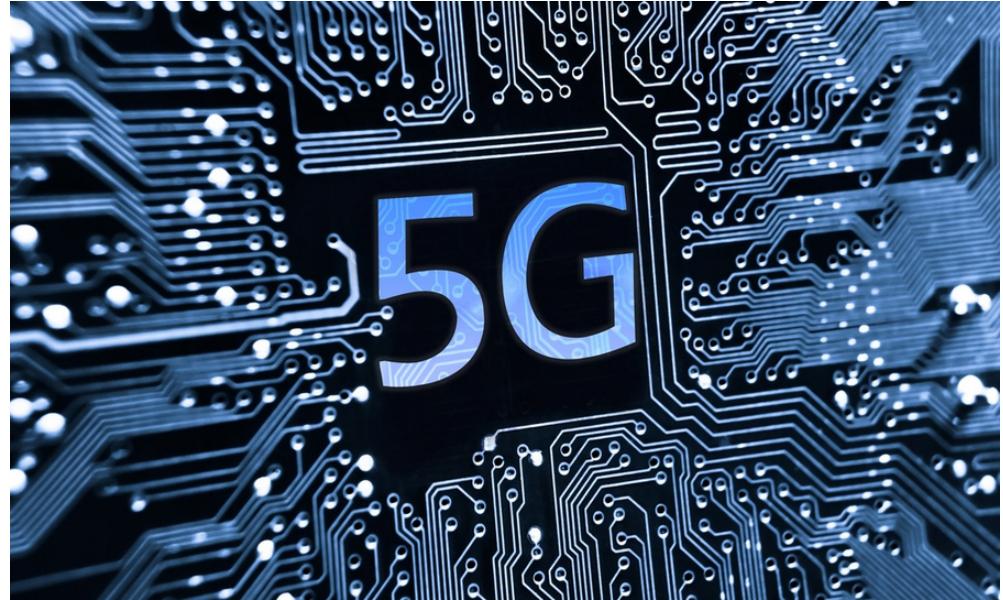
Non-slip flooring in stadiums, gyms



Concrete repairing

Epoxy Laminates for Printed Circuit Boards (PCBs)

- Laminates are made from epoxy with fiber glass prepgs.
- The selection of woven fiber glass fabrics is important for both mechanical and electrical properties of PCBs:
https://www.youtube.com/watch?v=JJWD4_giIXM
- PCBs are made in a continuous fabrication way:
<https://www.youtube.com/watch?v=DM4ubbGWWGU>
- Afterwards the PCBs are finished in a series of processes:
<https://www.youtube.com/watch?v=59Io2Moz8G4>
- For 5G-ready PCB design, this webinar is helpful:
https://www.youtube.com/watch?time_continue=43&v=kkpTDAOWUJg&feature=emb_logo



Next Generation PCBs – 5G Technology

- 10-20x faster data rates (up to 1 Gbps), about 1000x more traffic compared to 4G.
- The channel bandwidth in 4G is 20 MHz, while it is 100 MHz below 6 GHz carrier frequencies and 400 MHz above 6 GHz carrier frequency.
- Materials with lower dielectric constant (around 3) and low dielectric loss at 5G frequencies.
- High thermal conductivity to dissipate the heat generated.