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Physical Properties of UV Curable Composites

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Composites - Definition

- Two or more materials with markedly different physical or chemical properties – categorized as “matrix” and “reinforcement” – combined in a way to act in concert, yet remain separate and distinct because they don’t fully merge or dissolve into one another.

- While other materials are technically composites, this term has come to refer to a combination of resin and fiber reinforcement, sometimes called “fiber-reinforced polymers” or FRP composites.

Benefits and boundaries of UV curing technologies

Thermally-Cured system	UV-Cured system
Fiber Type	
- All fiber types	- Glass fiber
Curing Equipment	
- Heating chamber (typically high investment and requiring big floor space)	- UV lamps more cost effective and having small floor space requirements
- 70-180 minutes @ - Heating chamber - Once components - Temp / %RH condi	cation
Emissions (Styrene)	
- Impact on ecological footprint - Regulatory risks - Incineration (Installation)	- Very low to no VOCs
Cleaning of Processing Equipment	
- 0.5-1h / production shift	- Virtually unlimited open time (no pot life) Resin stays liquid and can easily be removed
Resin Waste	
- Excess in resin bath has to be removed - Waste disposal / processing cost	- Excess in resin bath can be re-used

Typical Reasons to Implement UV Curing

- Fast Curing : High Throughput with Low Investment
- Single Component System with “No” Potlife – Cure on Demand
- Reduce Energy Consumption and Ecological Footprint

Composites - Reinforcement

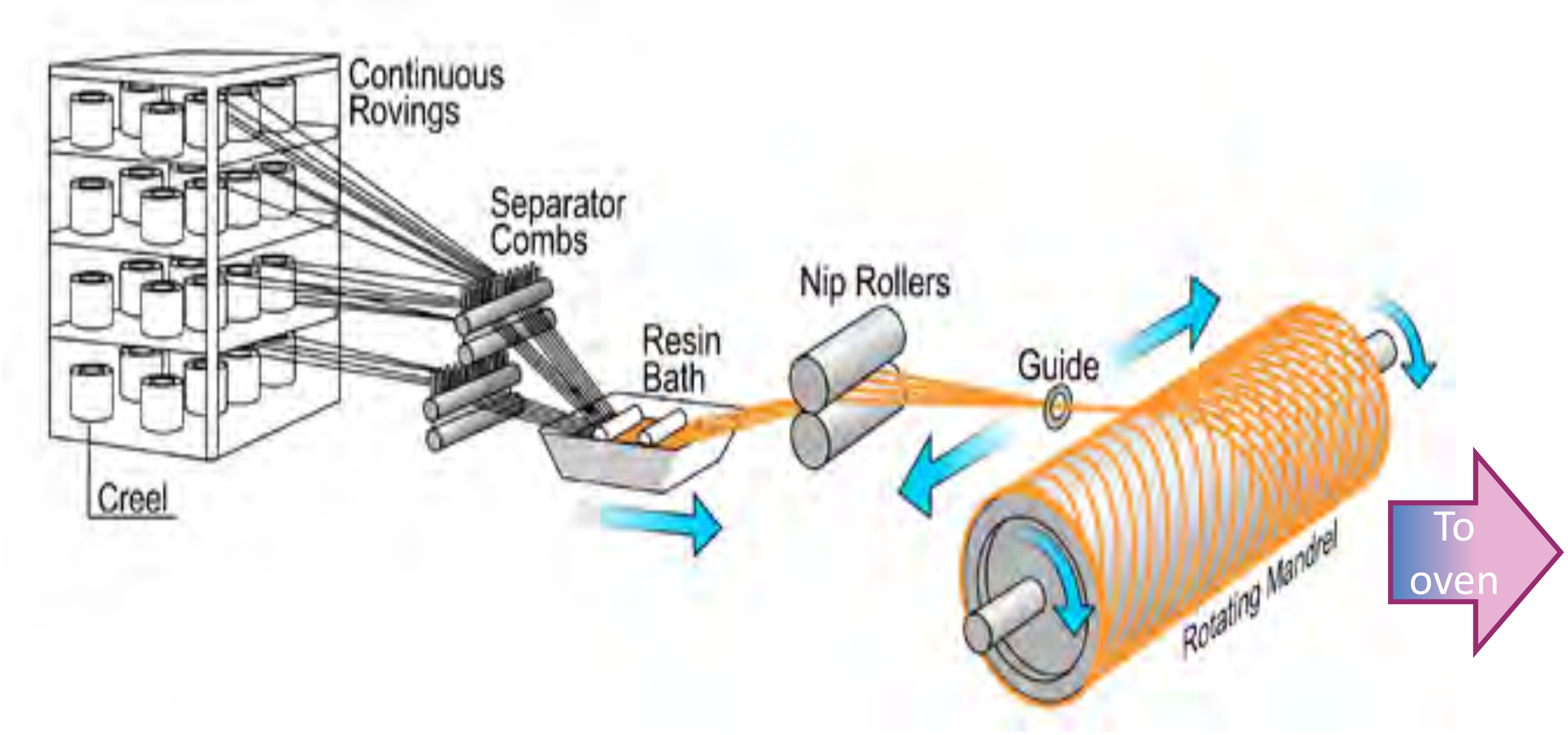
- The reinforcement provides the strength or “carries the load” in a composite
  - Tensile strength of glass – 500-725,000 psi, tensile strength of resin ~10,000 psi
- Types of reinforcement
  - Glass: good mechanical properties, inexpensive, transparent to RF and UV (90% of reinforcements)
  - Carbon: great strength to weight ratio, can be brittle
  - Basalt: fire resistance
  - Aramid: good mechanical properties , low density, good toughness
  - Thermoplastics: formable composites
  - Natural fibers: bio-based composites
- We will focus on glass reinforced composites

Composites Manufacturing Methods

- Open mold vs. Closed mold
  - For UV, open mold techniques offer easiest implementation
  - EB can be used for closed mold processes, but is far less common

- Manufacturing Methods
  - Filament winding
    - Printing rollers, pressure vessels , tent poles
  - Pultrusion
    - Strength elements in FOC, wind blades
  - Resin Transfer Molding (RTM) and Vacuum Assisted RTM (VaRTM)
  - Cured in Place Pipe (CIPP)

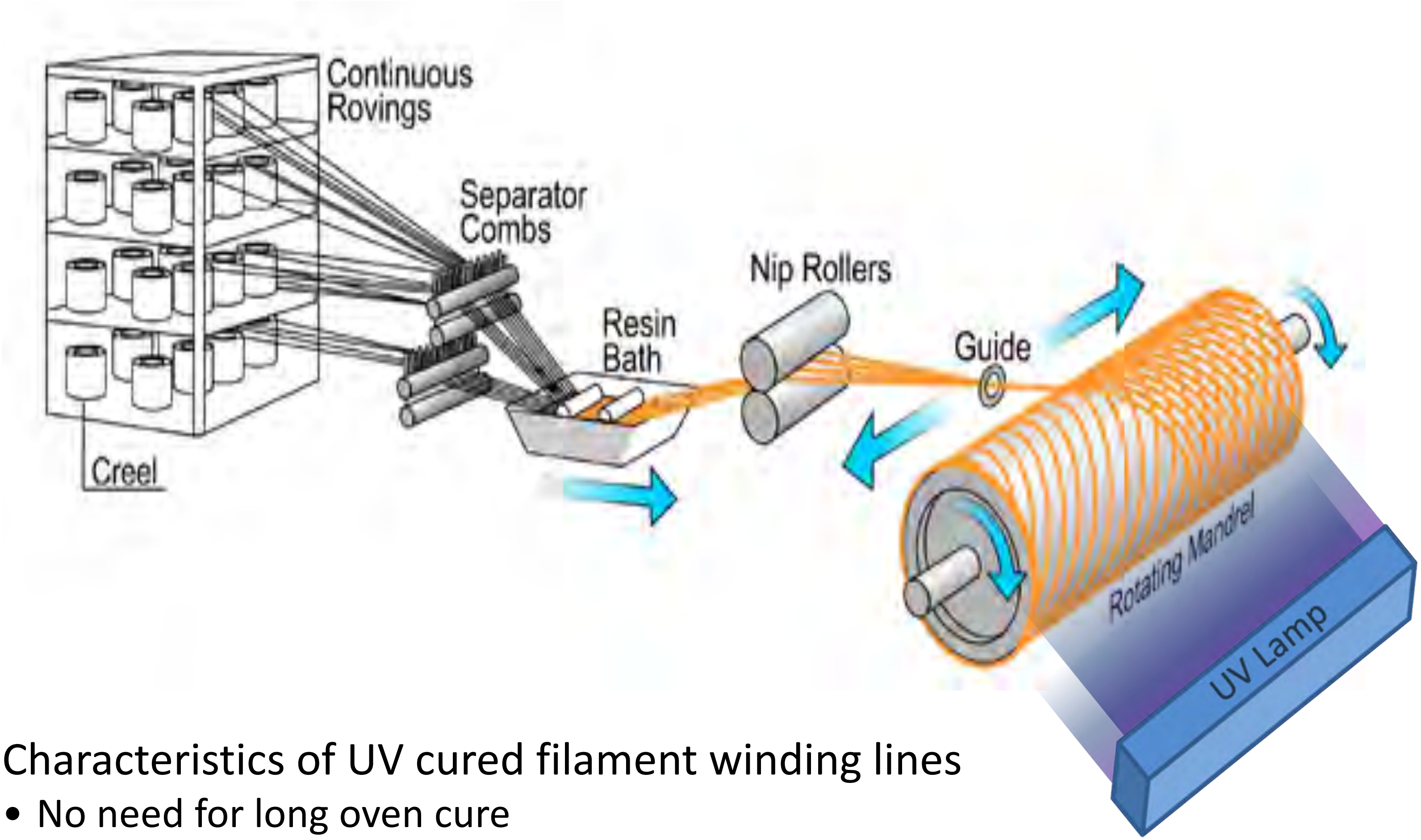
Composites Manufacture – Filament Winding



Challenges of thermally cured filament winding lines

- Two component resin system leads to pot life concerns and waste
- Continuous part rotation necessary during heating
- Mandrel turnover may be slow – increased capital needed

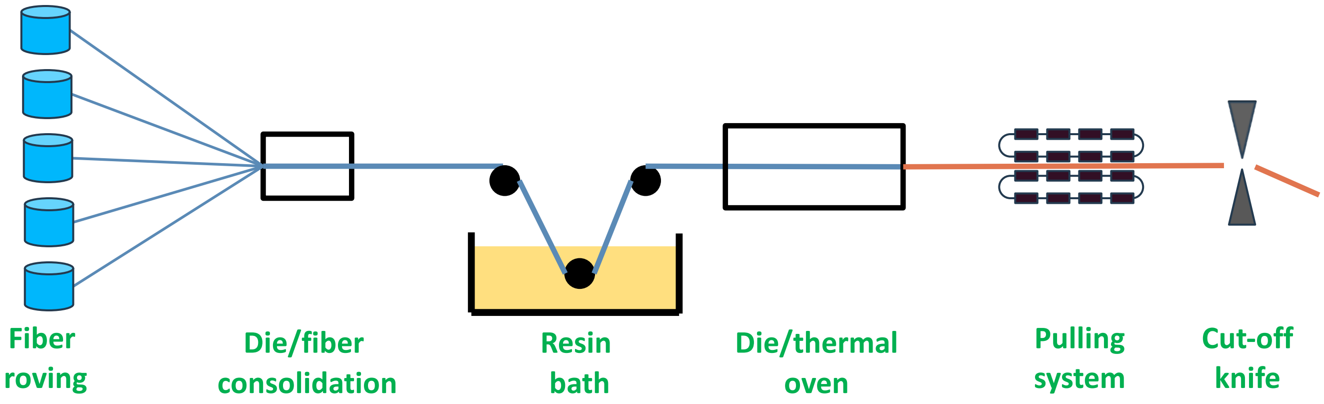
Composites Manufacture – Filament Winding



Characteristics of UV cured filament winding lines

- No need for long oven cure
- Faster mandrel turnaround
- Extremely long pot life – “cure on demand”
- Cure process depends on UV intensity, NOT ambient temperature

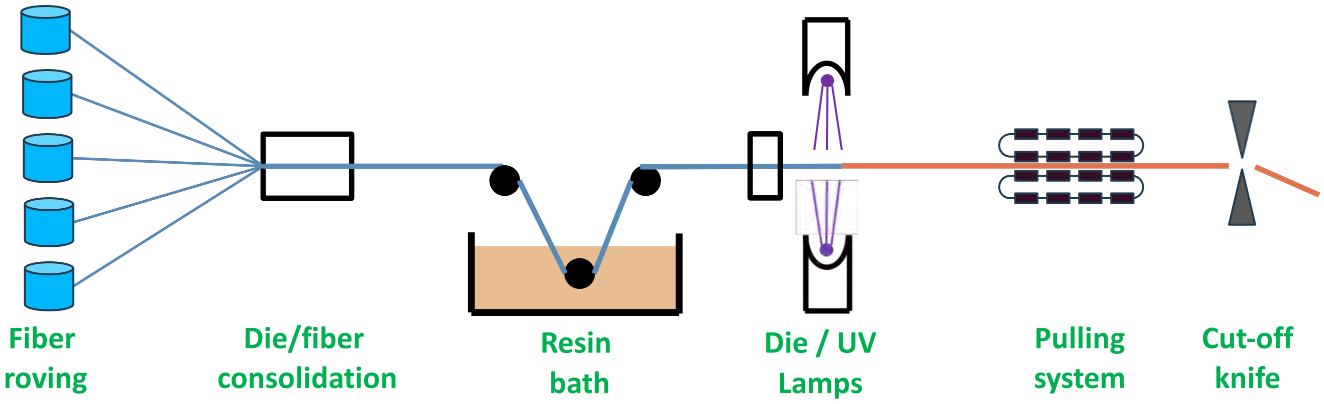
Composites Manufacture – Pultrusion



Challenges of thermally cured pultrusion lines

- Line speed dependent on oven size, heat transfer rate, reaction kinetics
- Two component resin system leads to pot life concerns and waste

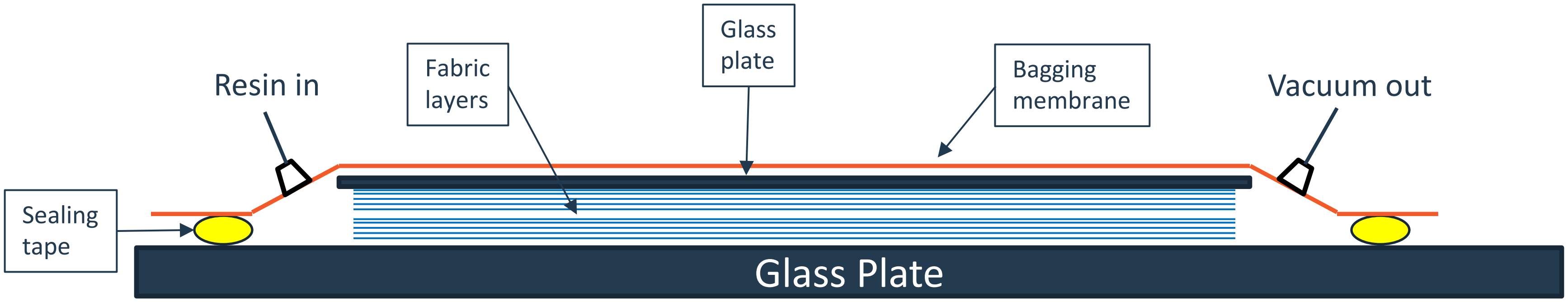
Composites Manufacture - Pultrusion



Benefits of UV cured pultrusion lines

- Fast line speeds due to rapid UV cure process
- On demand cure means very long pot life and less waste
- Lamp installation without major line reconfiguration
- Cure process depends on UV intensity, NOT ambient temperature

Composites Manufacture – VaRTM (Vacuum Bagging)



Benefits of UV cured vacuum bagging

- Fast line speeds due to rapid UV cure process
- On demand cure means very long pot life and less waste
- Lamp installation without major line reconfiguration
- Cure process depends on UV intensity, NOT ambient temperature
- Easy process produces flat test pieces

Composites Manufacture – Cure Depth

- There are a number of advantages to using UV vs. thermal energy to cure composites: increased throughput, very long pot lives, reduced waste, and a wide breadth of properties.

- A challenge for UV energy is depth of cure. Energy is attenuated with increasing composite thickness. A property gradient can occur across the thickness of the part.

- Determine maximum thickness that can be cure, then try to augment with second reaction.

Formulations – Cure Depth

Raw Material	27C2 (parts)
Bis-A Epoxy acrylate	12
Cyclic aliphatic diacrylate	87
Phenyl bis(2,4,6-trimethylbenzoyl)phosphine oxide	0.5

Vacuum bag processed 55 layer fabric composite, Two thin quartz plates were inserted to separate 6 layers from top and bottom. The thin composite samples (~ 1.3 mm) were removed for DMA testing
Lamp: Autoshot UVA400 lamp
Cure time: 1 hr
Energy density: 1115 J/cm^2
Thickness of composite : ~ 12 mm

Formulations – Cure Depth

	% Double bond conversion	Tg by tan δ, °C	Tg by E”, °C
Top	90	193	173
Bottom	79	153	130

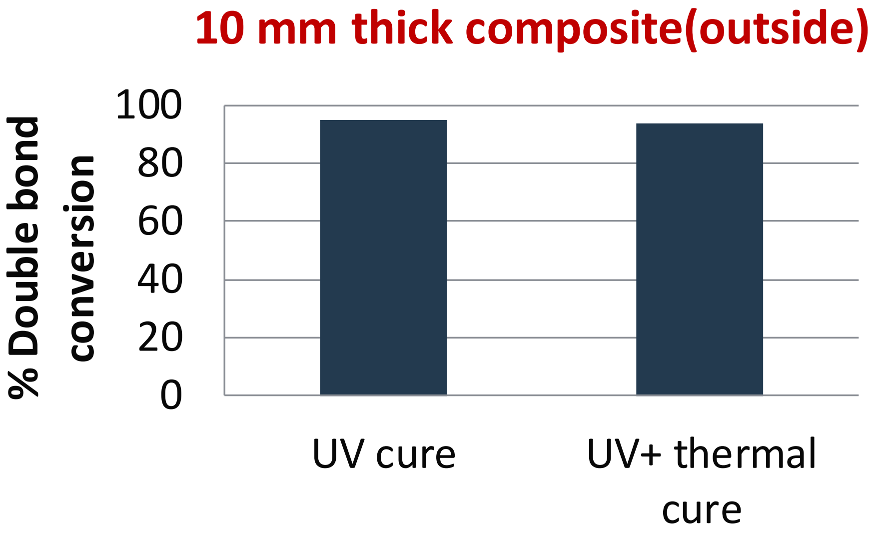
Need to address the property gradient with secondary reaction that is not dependent on UV energy.

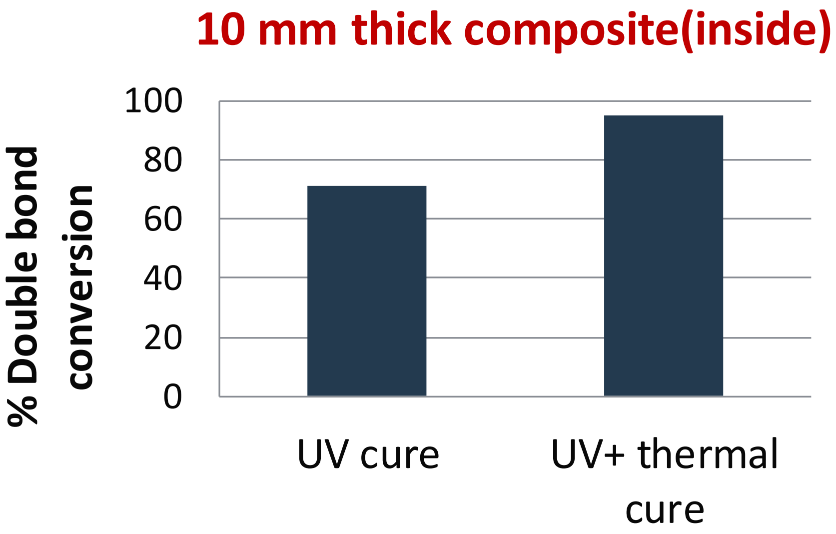
Formulations – Cure Depth in Filament Winding

Raw Material	**142A1 (parts)**	**142A1P (parts)**
	UV	UV+ Thermal
Bis-A Epoxy acrylate	55	55
Hexanediol diacrylate	45	45
Deaerator	1	1
2-Hydroxy-2-methyl-1-phenyl propanone	2	1
Phenyl bis(2,4,6-trimethylbenzoyl)phosphine oxide	0.5	0.5
Peroxide (thermal initiator)	--	5

Cure conditions: Hg lamp @ 2" distance, 5 minute cure time while mandrel still rotating (total energy density ~ 250 J/cm^2)

Formulations – Cure Depth in Filament Winding





High degree of double bond conversion at surface of composite with and without addition of peroxide

Addition of peroxide increases cure at inner surface of filament wound cylinder

Conclusions – Cure Depth

- Increased cure depth with inclusion of 2nd cure
- Heat from Hg lamp + heat from cure may generate discoloration
- Future work will involve LED curing to reduce heat from lamp

Composites Manufacture – Composite Properties

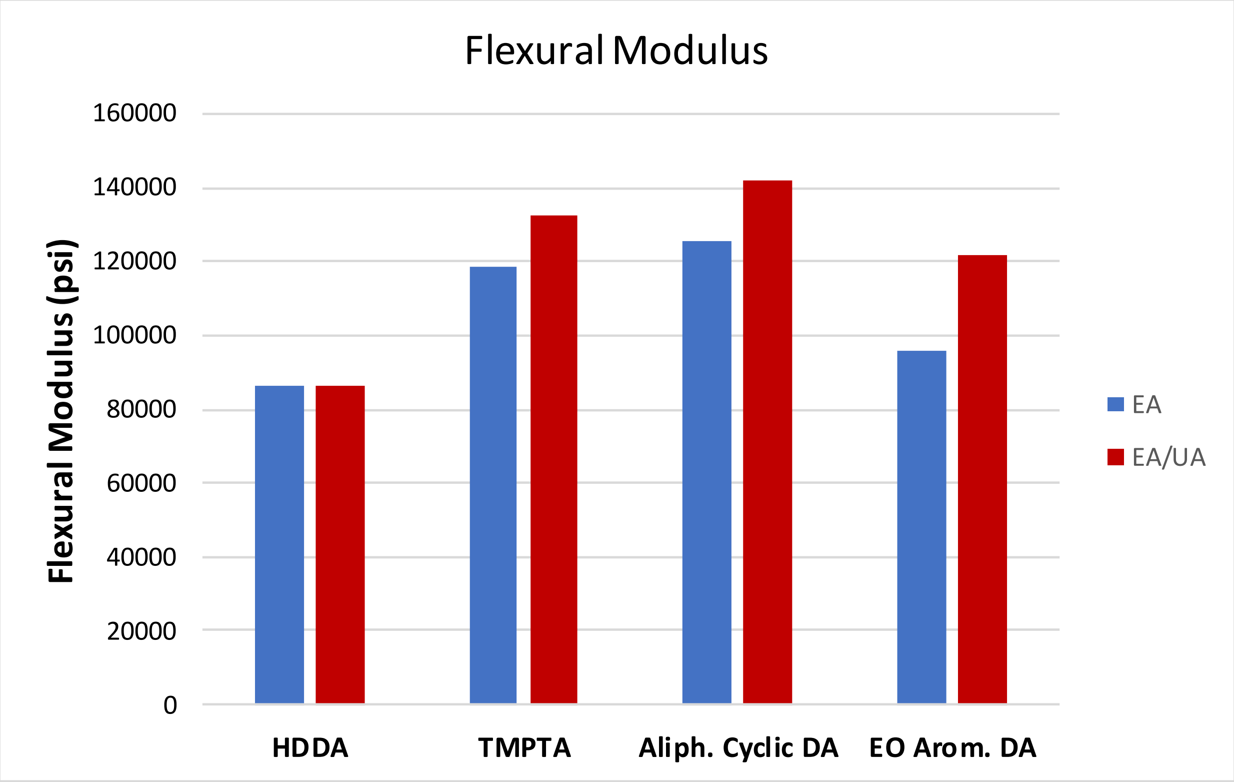
- Measure the effect of diluent and oligomer on liquid, free film, and final composite properties.

Formulations – Composite Properties

Raw Material	143 A0	143 C	143 D	143 E	143 B0	143 F	143 G	143 H
Bis-A Epoxy acrylate	55.0	20.0	12.0	38.0	30.0	12.5	10.0	15.0
Aliphatic urethane diacrylate					30.0	12.5	10.0	15.0
Hexanediol diacrylate	45.0			38.0	40.0			30.0
Trimethylolpropane triacrylate		80.0				75.0		
Cyclic aliphatic diacrylate			88.0				80.0	
Ethoxylated aromatic diacrylate				24.0				40.0
2-Hydroxy-2-methyl-1-phenyl propanone	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Phenyl bis(2,4,6-trimethylbenzoyl)phosphine oxide	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Viscosity @ 25ºC	356	330	338	283	400	440	457	329

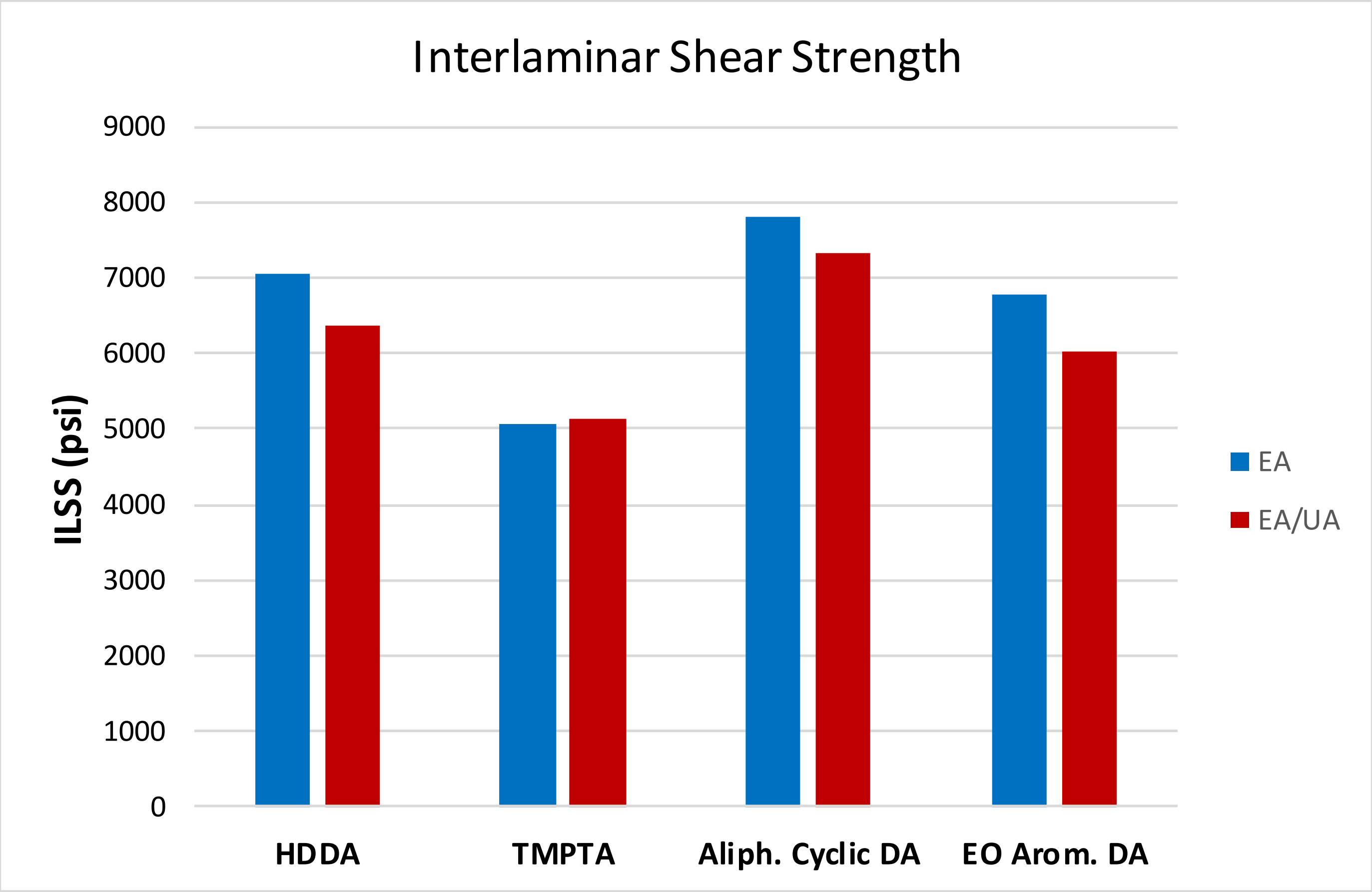
Formulations – Composite Properties

3 Point Bend (2 layers, 5 min cure @ 2")	**143 A0**	**143 C**	**143 D**	**143 E**	**143 B0**	**143 F**	**143 G**	**143 H**
Fiber content (wt. %)	65	59	63	66	66	68	68	66
Flexural strength (psi)	86411	118862	125342	95801	86234	132702	142031	122012
Maximum strain (%)	3.4	4.0	4.0	3.1	2.8	3.8	3.8	3.5



Formulations – Composite Properties

Interlaminar Shear Strength, ILSS (8 layers, 5 min cure @ 2")	143 A0	143 C	143 D	143 E	143 B0	143 F	143 G	143 H
ILSS (psi)	7043	5058	7816	6787	6371	5151	7331	6021



Conclusions – Composite Properties

- Flexural strength increases with higher XLD, or inclusion of cyclic diluents
- Flexural strength increases with inclusion of ALUA (toughener?)
- ILSS increases with higher Tg monomers but not with increased XLD
- ILSS decreases with inclusion of ALUA

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Thank you

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