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Effect of Curing Regime on the Tensile, Flexural and Impact Behaviour of Hand Lay-Up Glass Fibre / Orthophthalic Polyester Laminates

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Abstract— The mechanical performance of a hand lay-up glass fibre reinforced polymer depends as much on how the matrix is cured as on the constituents themselves, yet the curing step is frequently left to ambient conditions in small-scale fabrication. This paper reports a destructive characterisation of three laminates produced from identical materials — E-glass fabric reinforcement in an orthophthalic unsaturated polyester matrix catalysed with 1.5 % MEKP — and differing only in the curing regime applied: ambient curing for 24 h, post-curing in a hot-air oven at 90 °C, and microwave-assisted oven curing. Five specimens from each laminate were tested in uniaxial tension, five in three-point flexure and five in Charpy impact to ISO 179. The ambient-cured laminate gave a mean tensile strength of 141.95 MPa, a mean flexural strength of 203.77 MPa and a mean impact strength of 249.92 kJ/m². Post-curing at 90 °C did not improve these values; tensile and flexural strengths fell by 9.51 % and 11.02 % and the scatter in flexural strength more than doubled, consistent with thermal stress introduced during an uncontrolled heating cycle. Microwave-assisted curing raised tensile strength to 181.99 MPa (+28.21 %), flexural strength to 262.67 MPa (+28.91 %) and impact strength to 278.01 kJ/m² (+11.24 %), while reducing elongation at break from 2.29 % to 1.61 %. The results indicate that volumetric heating produces a more completely crosslinked and more uniform matrix than surface-driven oven post-curing, and that the strength gain is obtained at the cost of ductility.
Keywords— *Glass fibre reinforced polymer; orthophthalic polyester; hand lay-up; curing regime; tensile strength; flexural strength; Charpy impact*

1. INTRODUCTION

A composite material is a combination of two or more constituents with distinct chemical and physical properties, assembled so that the resulting material outperforms any of its constituents used alone. In the fibre-reinforced form that dominates engineering practice, flexible high-tensile fibres are embedded in a matrix that binds them into a rigid body: the fibres carry tensile load, the matrix carries compression and transfers load between fibres, and the pair together resist bending far better than either could separately. The two essential constituents are therefore the *matrix phase*, the continuous body that gives the composite its bulk form and may be polymeric, metallic or ceramic, and the *dispersed phase*, the structural constituent that determines the internal architecture and may take the form of fibres, particulates, flakes or whiskers.

Classified by matrix, three families are in common use. Ceramic matrix composites offer extreme temperature and corrosion resistance and excellent wear properties, and are used for gas turbine blades, rocket components and heat exchangers, but they remain costly and comparatively brittle. Metal matrix composites, typically an aluminium or magnesium matrix reinforced with carbon fibre or silicon carbide particles, give increased strength and stiffness, better elevated-temperature capability, improved wear resistance and a reduced coefficient of thermal expansion, at the price of difficult processing. Polymer matrix composites are by far the most widely used: hand lay-up of glass or carbon fabric in epoxy, polyester or vinyl ester resin gives high specific stiffness and strength together with good thermal, chemical and abrasion resistance, and it does so with tooling costs low enough for small workshops. The penalty is a strong dependence on operator skill and on process control, particularly control of the cure.

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That dependence is the subject of this paper. In hand lay-up practice the laminate is very often simply left to cure at room temperature, because ambient curing needs no equipment. Resin manufacturers, however, specify an elevated-temperature post-cure to drive the crosslinking reaction towards completion, and a partially cured matrix will under-perform in every mechanical property that depends on matrix integrity — most obviously flexural strength and interlaminar behaviour, but tensile and impact response as well. What is less clear is whether the *manner* in which the heat is delivered matters. Conventional oven post-curing heats the laminate from its surfaces inward by convection and radiation, so a through-thickness temperature gradient exists for as long as the cycle lasts, and residual thermal stress can be locked into the part. Microwave-assisted curing deposits energy volumetrically in the polar matrix, so the gradient is far smaller.

The objective of this work is therefore to quantify, on laminates that are identical in every other respect, how ambient curing, conventional oven post-curing and microwave-assisted curing affect tensile strength, elongation at break, flexural strength and Charpy impact strength — and to establish whether the differences are large enough to justify the additional process step in routine fabrication.

2. LITERATURE BACKGROUND

Testing and standardisation are what allow composites to be compared against conventional engineering materials on a defensible basis, and the international standards maintained by ASTM, ISO and CEN define the mechanical and physical test methods — tension, compression, flexure, shear, impact, fatigue, density, void content and water absorption — on which that comparison rests. Because composites are anisotropic and inhomogeneous, the fixturing used is generally test-specific, and results are only meaningful when the specimen geometry and conditioning are reported with them.

A recurring theme in the literature is the sensitivity of measured strength to specimen size. Reviews of unnotched strength in continuous fibre reinforced composites show a consistent tendency for strength to fall as specimen volume rises, across fibre-direction tension, fibre-direction compression and matrix-dominated transverse tension and shear, with the magnitude of the effect corresponding to Weibull moduli in the range 13–29 for unidirectional carbon and glass/epoxy materials. Higher strengths are routinely recorded in bending than in tension on nominally identical material, and lower compressive strengths are found in large components than in small coupons, the difference being attributed to defects. The practical consequence, and the reason the present study reports five specimens per condition with standard deviations, is that data taken from small coupons must be applied to large structures with care.

The behaviour of polymer matrix composites under impact has been characterised both by small-specimen methods based on the split Hopkinson pressure bar and by small-scale structural tests on plates and beams, with analytical and numerical models developed to link the two. Work on numerical stress concentration in brittle matrix composites, on micromechanical modelling coupled to reliability approaches for damage evolution, and on residual stress profiles measured in carbon fibre embedded in polypropylene by micro-Raman spectroscopy, all point the same way: matrix state and residual stress, not fibre properties alone, control the damage tolerance of the laminate. Since the matrix state is exactly what the curing regime determines, a direct experimental comparison of curing regimes is warranted.

3. MATERIALS AND METHODS

3.1 Constituent materials

The matrix was an orthophthalic unsaturated polyester resin, the standard general-purpose resin for contact moulding. The reinforcement was E-glass fibre in fabric form, produced by extruding silica-based glass into fine filaments suitable for textile processing. The catalyst was methyl ethyl ketone peroxide (MEKP), an organic peroxide supplied blended with inert compounds and the most widely

used initiator for room-temperature cure of polyester and vinyl ester resins. MEKP was added at 1.5 % by mass of resin, that is 15 g per kilogram of resin, and mixed immediately before lay-up.

3.2 Laminate fabrication

All three laminates were produced by the same hand lay-up route. A mould of the required plan dimensions was prepared and treated with release agent. The glass fabric was cut to size and laid into the mould in successive plies, up to five layers, with the catalysed resin applied between plies and worked through the fabric to ensure complete wet-out. Alternating ply orientations were used to balance in-plane properties. Compression was then applied to expel entrapped air and to distribute the resin uniformly, minimising void content in the cured part. After cure the laminates were de-moulded, trimmed and cut into test coupons.

3.3 Curing regimes

Three laminates were produced, identical in constituents, ply count and lay-up sequence, and differing only in cure:

- **Laminate A — ambient curing.** The wet laminate was left in the mould at room temperature for 24 h with no applied heat.
- **Laminate B — oven post-curing.** The laminate was allowed to gel and was then transferred to a hot-air oven and held at 90 °C.
- **Laminate C — microwave-assisted curing.** The laminate was cured in a microwave oven, so that energy was deposited volumetrically in the matrix rather than conducted inward from the surfaces.

3.4 Test methods

Five specimens were taken from each laminate for each test. Uniaxial tensile tests were performed to failure on a universal testing machine, giving ultimate tensile strength and elongation at break directly, and stress–strain records from which tensile modulus was obtained. Flexural strength was measured in three-point bending; the specimen is loaded in tension on the lower face and compression on the upper, with the span-to-thickness ratio chosen wide enough to keep in-plane shear stress small. Charpy impact tests were carried out to ISO 179 on notched specimens struck by a pendulum hammer on the face opposite the notch, the absorbed energy being read from the pendulum swing and converted to impact resistance in J/m and impact strength in kJ/m² using the measured specimen width and thickness.

4. RESULTS AND DISCUSSION

4.1 Tensile behaviour

Table 1 gives the individual tensile results. The ambient-cured laminate A reached a mean ultimate tensile strength of 141.95 MPa with a standard deviation of 14.80 MPa, the largest scatter of the three conditions. Oven post-curing (laminate B) did not improve on this: the mean fell to 128.45 MPa, a reduction of 9.51 %, although the scatter halved to 7.87 MPa. Microwave-assisted curing (laminate C) gave a mean of 181.99 MPa, an increase of 28.21 % over the ambient-cured laminate and 41.68 % over the oven post-cured laminate, with the lowest scatter of all three at 6.59 MPa.

Table 1. Tensile strength (MPa) and elongation at break (%) for the three curing regimes.

Specimen	**A — ambient cure**		**B — oven post-cure**		**C — microwave cure**	
	Strength	**Elong.**	**Strength**	**Elong.**	**Strength**	**Elong.**
1	142.85	2.41	132.37	2.07	193.54	1.55
2	129.99	2.01	127.50	2.36	177.33	1.59
3	125.72	2.18	138.38	2.54	180.72	1.73
4	162.54	2.34	117.02	1.69	178.43	1.68
5	148.65	2.53	127.00	2.45	179.92	1.51
Mean	**141.95**	**2.29**	**128.45**	**2.22**	**181.99**	**1.61**

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Specimen	A — ambient cure		B — oven post-cure		C — microwave cure	
	Strength	Elong.	Strength	Elong.	Strength	Elong.
Std. dev.	14.80	0.20	7.87	0.35	6.59	0.09

Elongation at break moves in the opposite direction. Laminate A extended 2.29 % on average and laminate B 2.22 %, while laminate C reached only 1.61 %, a reduction of 29.73 % relative to ambient curing. This is the classical signature of increased crosslink density: as the polyester network becomes more fully reacted the matrix stiffens, the composite carries more load before failure, and it does so with less deformation. The reduction in scatter for laminate C reinforces the interpretation — a more completely and more uniformly cured matrix produces coupons that behave more alike.

4.2 Flexural behaviour

The flexural results in Table 2 follow the same ranking but with larger margins, which is expected because three-point bending loads the matrix-dominated outer plies most severely and is therefore the more sensitive probe of matrix state.

Table 2. Flexural strength (MPa) in three-point bending.

Specimen	A — ambient cure	B — oven post-cure	C — microwave cure
1	202.05	196.95	273.42
2	220.37	132.13	275.83
3	210.64	194.69	259.35
4	190.74	196.27	251.17
5	195.05	186.49	253.60
Mean	**203.77**	**181.31**	**262.67**
Std. deviation	11.95	27.81	11.34
Change vs. laminate A	—	−11.02 %	+28.91 %

Laminate B is the informative case. Its mean flexural strength of 181.31 MPa is 11.02 % below the ambient-cured laminate, and its standard deviation of 27.81 MPa is more than twice that of either other condition — driven by a single specimen that failed at 132.13 MPa while its four companions all lay between 186 and 197 MPa. A population that is tight apart from one low outlier is characteristic of a localised defect rather than a uniform degradation of properties, and the most probable source is the thermal gradient imposed by convective heating. Heating a gelled but incompletely cured polyester laminate from its surfaces produces differential shrinkage through the thickness; the resulting residual stress can initiate matrix microcracking that a flexural test, which places the outer ply in maximum tension, is well placed to find. Laminate C, cured volumetrically, shows no such outlier and reaches 262.67 MPa, 28.91 % above laminate A and 44.88 % above laminate B.

4.3 Impact behaviour

Charpy results to ISO 179 are given in Table 3 as means over five specimens.

Table 3. Charpy impact results (ISO 179), mean of five specimens.

Quantity	A — ambient cure	B — oven post-cure	C — microwave cure
Specimen width (mm)	8.51	8.52	8.48
Specimen thickness (mm)	3.48	3.54	2.91
Absorbed energy (J)	7.40	7.37	6.86

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Quantity	A — ambient cure	B — oven post-cure	C — microwave cure
Impact resistance (J/m)	2126.83	2082.50	2359.09
Impact strength (kJ/m²)	**249.92**	**244.36**	**278.01**
Change vs. laminate A	—	−2.22 %	+11.24 %

Impact strength is the property least affected by the curing regime: laminate B is 2.22 % below laminate A, a difference comparable with the specimen-to-specimen scatter, and laminate C is 11.24 % above it. The modest size of the gain, set against the 28–29 % gains in tensile and flexural strength, is consistent with the mechanics of the test. Fracture energy under impact is absorbed largely by fibre pull-out, fibre fracture and delamination, processes governed by the fibre and by the fibre–matrix interface, whereas quasi-static tensile and flexural strength depend more directly on the stiffness and integrity of the matrix itself. Improving the cure improves the matrix, so it improves the quasi-static properties strongly and the impact property only modestly.

The absorbed energy figures require one note of caution. Laminate C absorbed less total energy (6.86 J) than laminate A (7.40 J), yet records the higher impact strength, because its specimens were thinner — 2.91 mm against 3.48 mm — and impact strength is energy normalised by the fractured cross-sectional area. The normalised comparison is the correct one, but the thickness difference between the laminates is itself a reminder that hand lay-up does not deliver tight dimensional control, and that comparisons of this kind should be made on normalised quantities throughout.

4.4 Overall assessment

Taken together the three test series give a consistent picture. Ambient curing produces a serviceable laminate but one with the widest tensile scatter, indicating variable degrees of cure across the panel. Conventional oven post-curing at 90 °C, applied without a controlled ramp, is not merely ineffective but mildly counter-productive: it tightens the tensile distribution while lowering its mean, and it introduces the flexural outlier that signals thermally induced damage. Microwave-assisted curing improves every mean value measured and narrows every distribution, at the cost of a 30 % reduction in elongation at break. For applications governed by strength and stiffness this is a favourable trade; for applications requiring damage tolerance and energy absorption the loss of ductility should be weighed against the 11 % gain in impact strength.

5. CONCLUSIONS

- Three glass fibre / orthophthalic polyester laminates of identical constituents and lay-up were tested in tension, flexure and Charpy impact after ambient curing, oven post-curing at 90 °C and microwave-assisted curing.
- Microwave-assisted curing gave the best performance in every property measured: tensile strength 181.99 MPa (+28.21 % over ambient cure), flexural strength 262.67 MPa (+28.91 %) and impact strength 278.01 kJ/m² (+11.24 %).
- Conventional oven post-curing at 90 °C reduced tensile strength by 9.51 % and flexural strength by 11.02 % relative to ambient curing, and produced the largest flexural scatter of the three conditions, consistent with residual thermal stress from surface-driven heating.
- The strength gains under microwave curing were accompanied by a fall in elongation at break from 2.29 % to 1.61 %, a 29.73 % reduction, reflecting the higher crosslink density of the more completely cured matrix.
- Curing regime is therefore a first-order design variable in hand lay-up practice, not a process detail. Where an elevated-temperature cure is adopted, volumetric heating is preferable to convective post-curing, and any convective cycle should use a controlled ramp and dwell to avoid the through-thickness gradient identified here.

Further work should quantify degree of cure directly by differential scanning calorimetry, measure void content and fibre volume fraction on each panel so that the strength differences can be

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normalised against them, and extend the comparison to a controlled-ramp oven cycle to separate the effect of heating mode from the effect of heating rate.

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