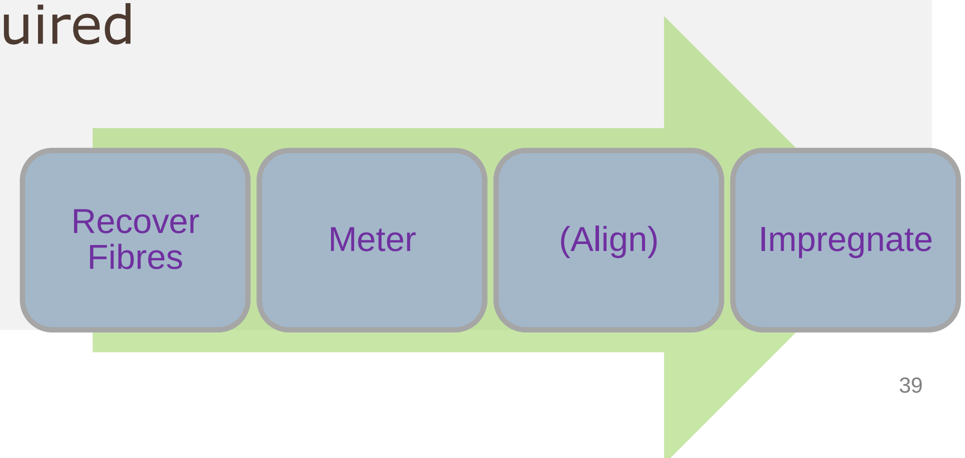
Potential product forms

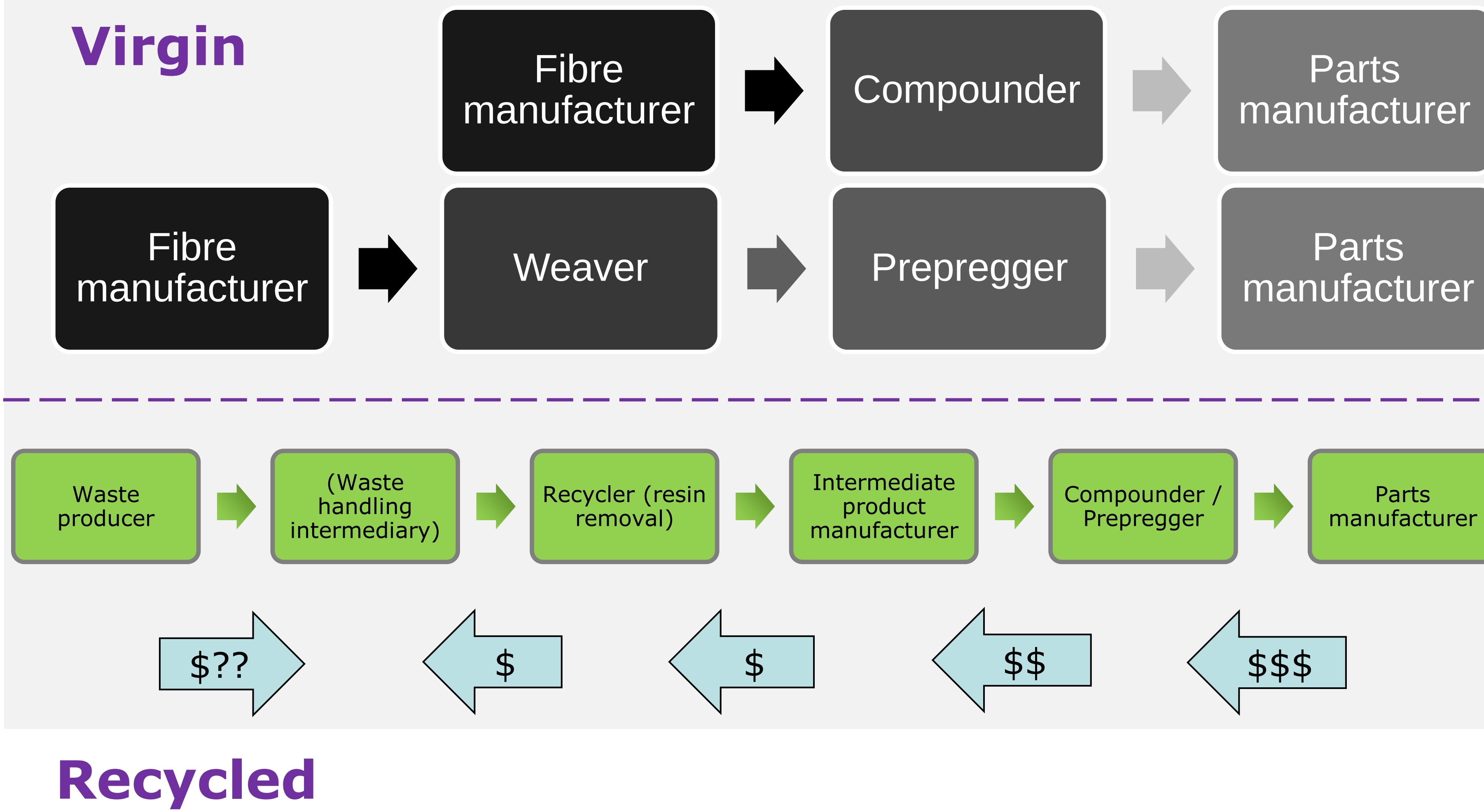
- Recycling process influences
  - Fibre discontinuity at some level inevitable
  - Fibre length short and variable
  - Cost of recovery potentially significant
  - Optimisation challenges – e.g. part thickness in pyrolysis

- Market influences
  - Target mechanical properties required to justify re-use
  - Fibre volume fraction required
  - Cost

- Some common factors…



Value chain – virgin vs. recycled



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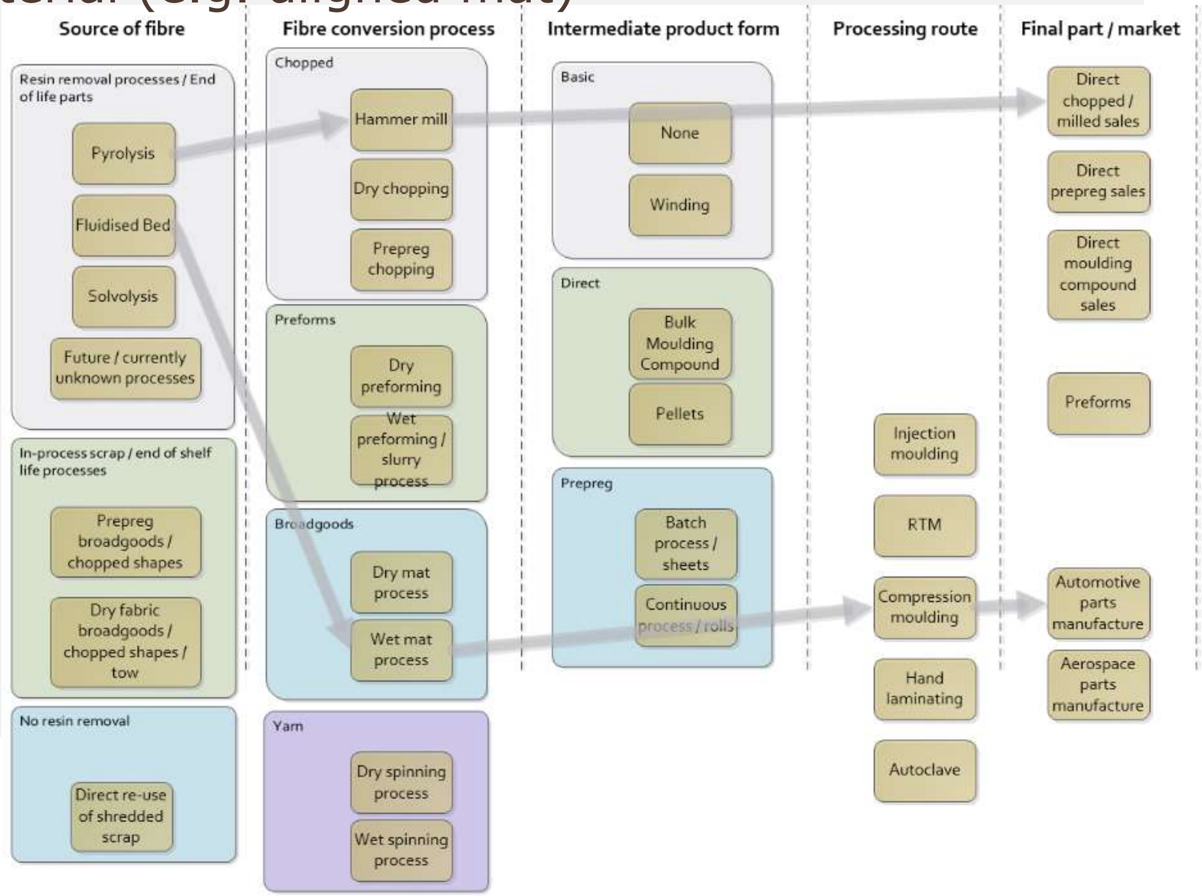
Re-use options

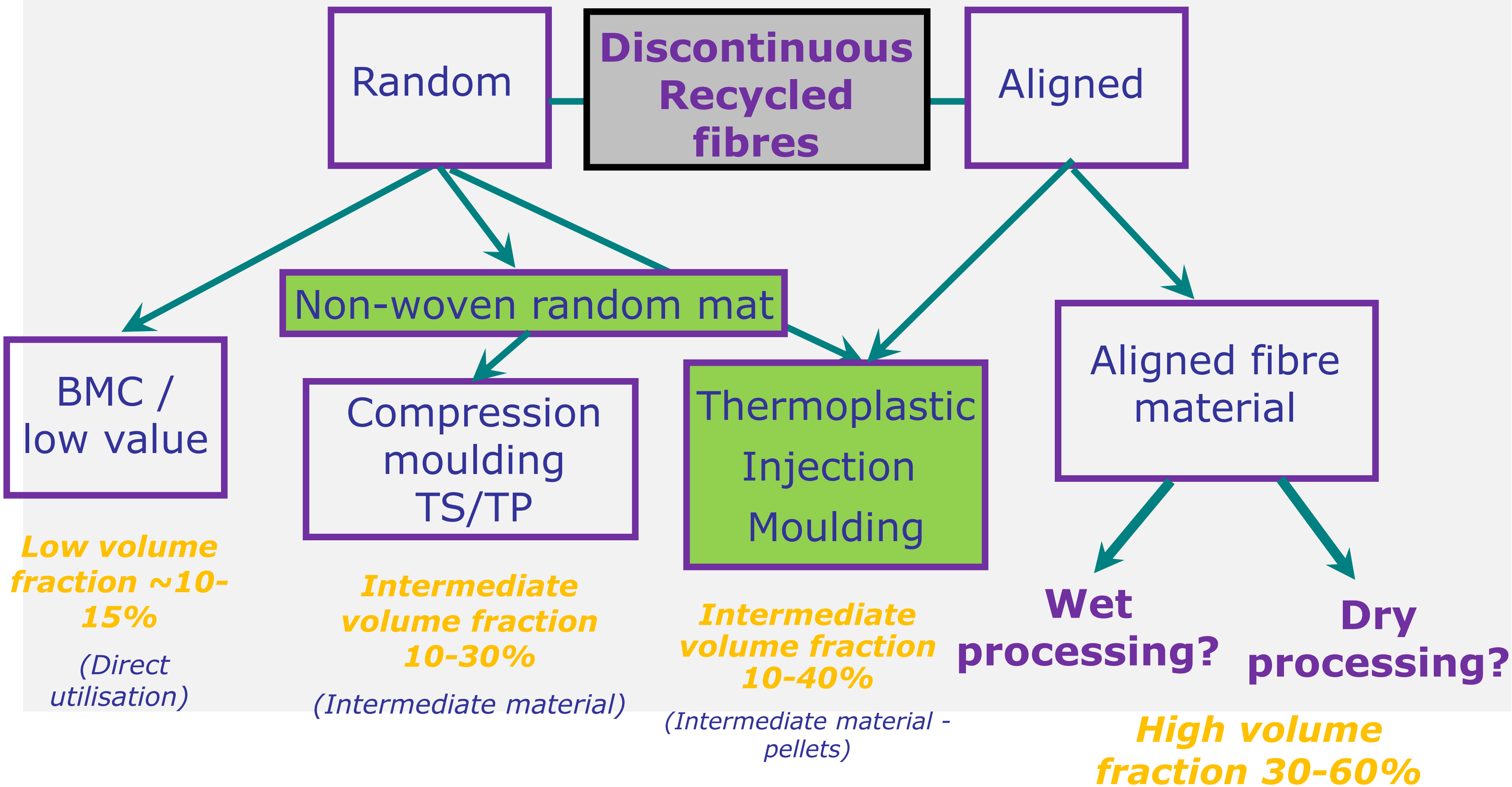
- Direct re-use of cured shredded scrap composite
- Direct re-use of uncured scrap prepreg or dry fabric scrap
- On-line at end of recovery process (e.g. milled fibre)
- Via an intermediate material (e.g. aligned mat)



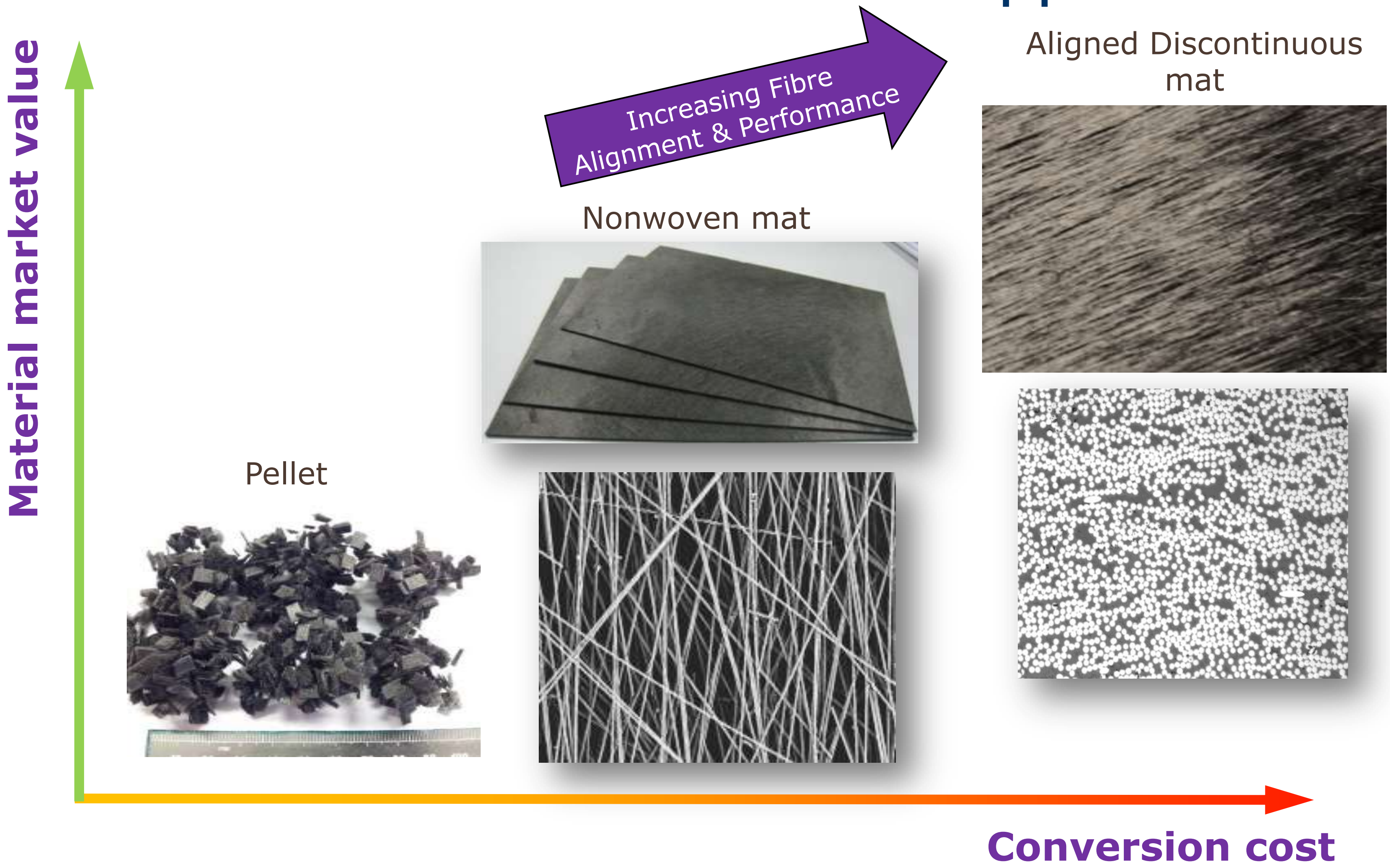
Fibres for non-structural use

- One current commercial process route
- Easy to produce from fluffy (non bundled) recycled fibre
- Can be sold into existing markets
  - conducting fillers for polymers (anti-static)
  - high stiffness, low density filler for polymers
- Is the size of the market sufficient?
- Cost typically comparable with virgin fibre at present

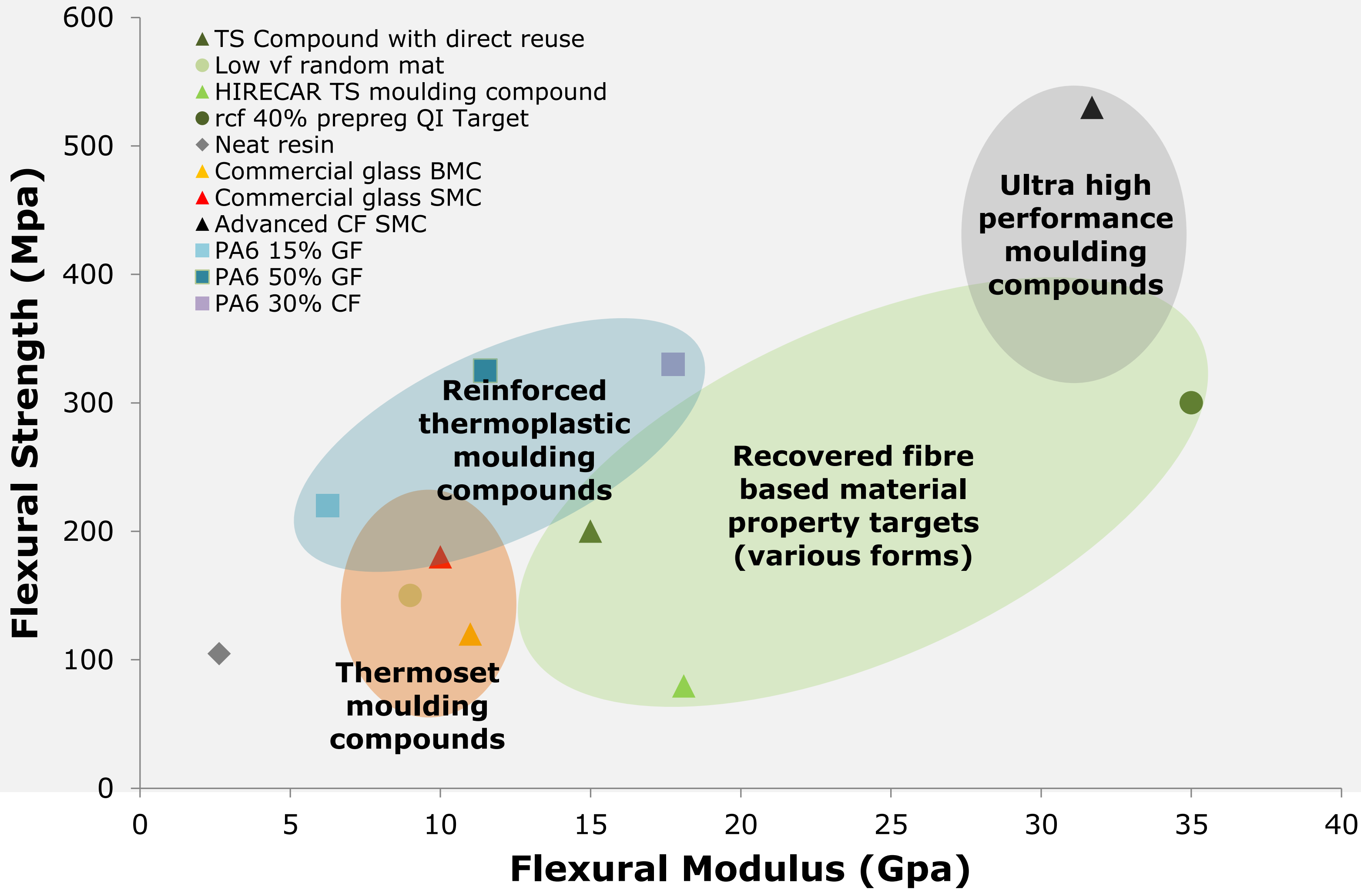
Structural Reinforcement - Processing Routes



Recovered Carbon Fibre reuse - Applications



Potential structural end uses for rCF



Direct reuse of cured scrap & shredding

- Size reduction is often required…
  - Relatively low rates
  - Very high size reduction ratio…
- Excellent results obtained with 2 stage process
  - Twin screw shredder
  - Hammer mill
- Low capital and running cost

Shredding technology review

- Central issue is the requirement to process large pieces at low rate but at low cost
- 2 stage appears to offer best compromise
    - Initial primary stage – Twin shaft shredder
    - Secondary stage – Hammer mill

Shredding technology review

- Energy use rates are very low compared to resin removal
- Order of magnitude jumps in cost as size goes down
- Preparatory operations should be added to cot breakdown for and process requiring preparation of materials

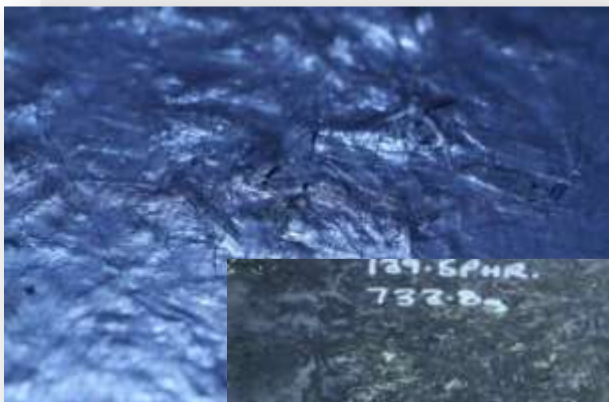
- Primary size reduction (to 20mm) –Shredder
  - 11kW @ ~400kg / hr
  - 0.004 $/kg energy cost
  - Machine cost ~$30,000
  - Blade change every two years at ~$4500 cost

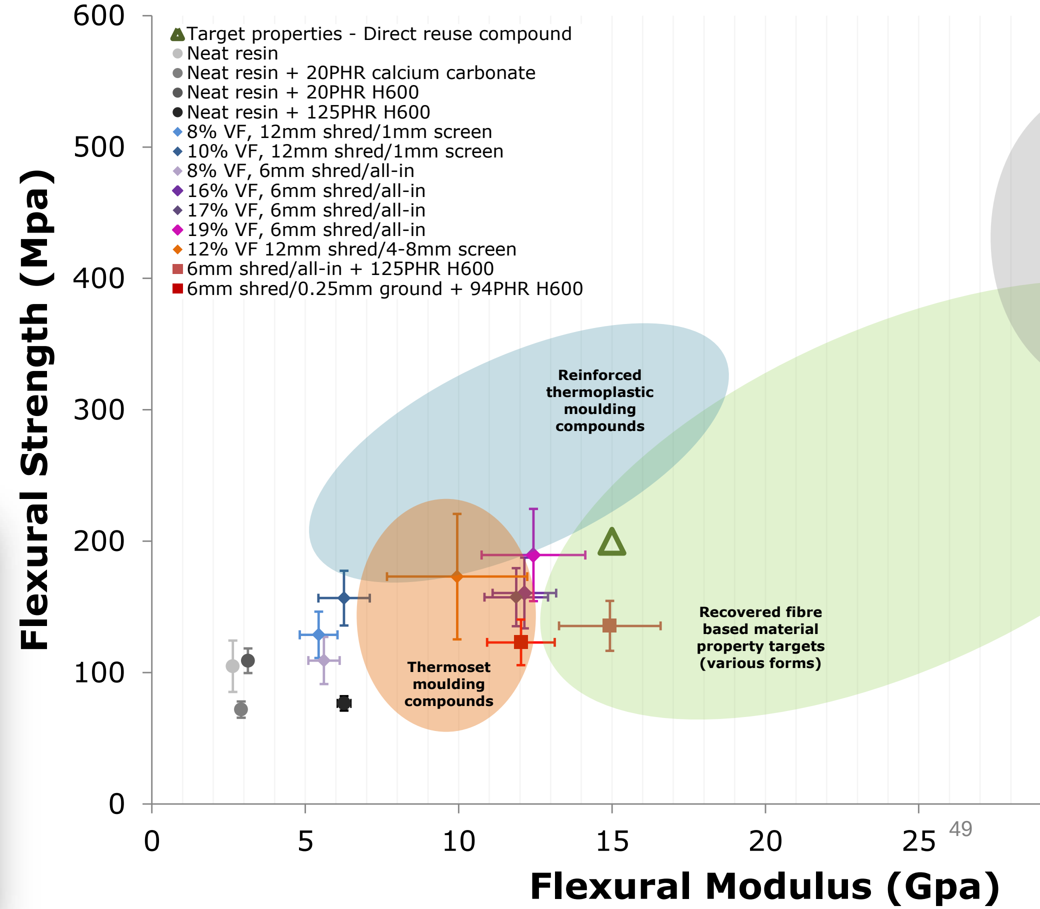
- Secondary size reduction (to 1mm) – Hammer Mill
  - 7.5kW @ ~30kg / hr
  - 0.038 $/kg energy cost
  - Machine cost ~$20,000

- Optional tertiary size reduction (to 0.25mm) – Centrifugal Mill
  - <1kW @ ~40g/hour (based on our lab mill)
  - 0.287 $/kg energy cost

Direct re-use - Compound development

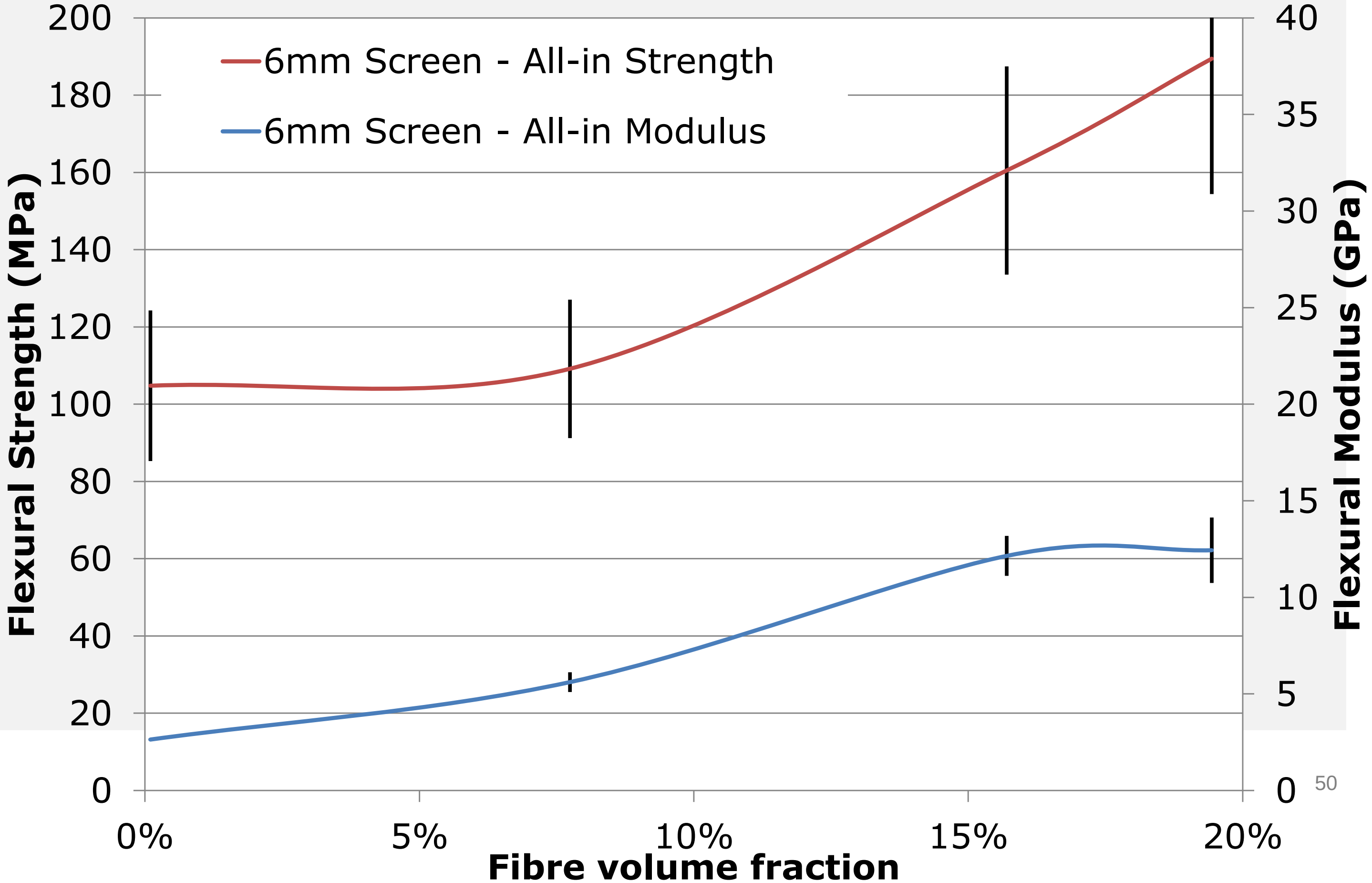
- Early efforts concentrated on filled resin benchmarking and then hand mixing of low addition levels (with considerable effort in process development)
- Mechanical mixing greatly improved addition levels
- 12mm screen + sieve vs 6mm screen all-in – which is better??
- Peak addition levels – how high can we go?
- Further optimisation required – increased resin viscosity & tooling





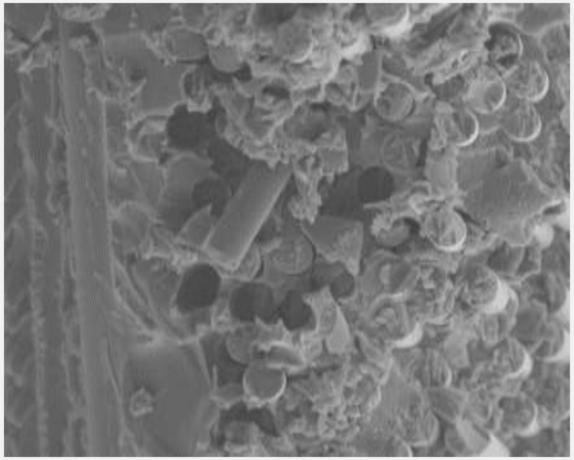
Direct re-use - Compound development

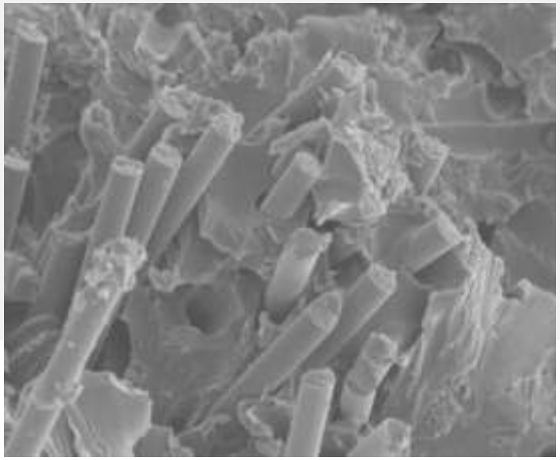
- Current addition levels result in a very dry mix – not a paste
- Air entrapment a major issue at high addition levels
- Good improvement in strength with increasing fibre level

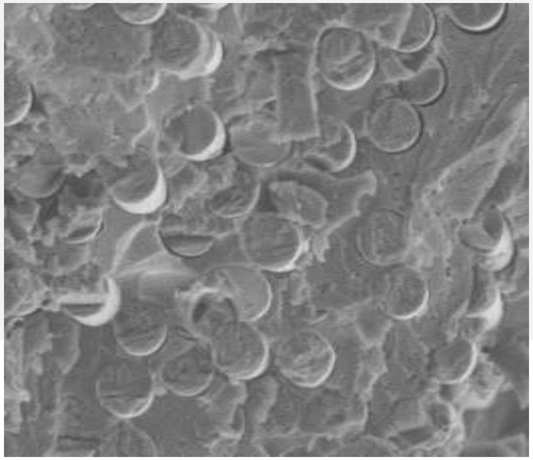


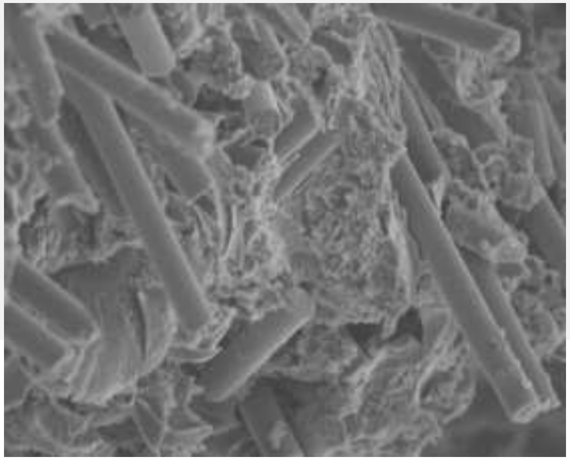
Direct re-use - Fibre / Matrix Adhesion

- Unable to identify the two different matrices
- Mixed results on adhesion – some evidence of pull-out









Intermediate Compound development

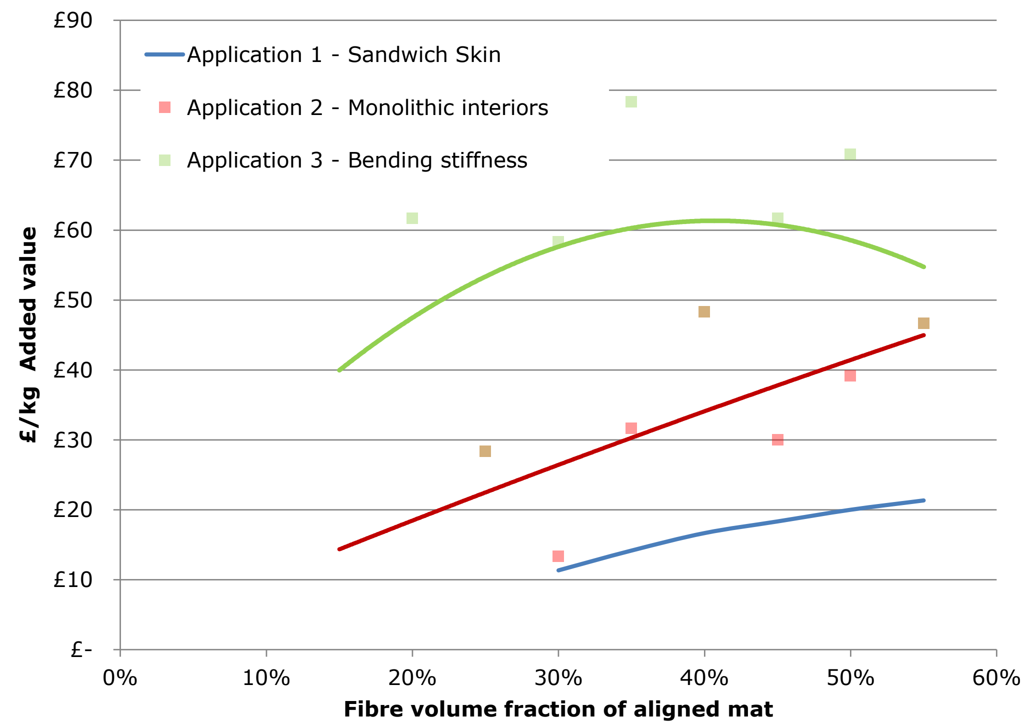
- Many methods for compound manufacture have been demonstrated;
  - Direct mixing of recovered fibre filaments in viscous resin
  - Conversion of dry fabrics to chips for injection moulding and SMC
  - Chipping of partially cured prepreg for ASMC
- Pros
  - Potentially a high volume solution
  - Low added cost in intermediates development
- Cons
  - Wide range of mechanical properties obtained
  - Problems with matrix viscosity and in-tool flow

Intermediate mat development

- Easy to use at low addition levels in thermoset moulding compounds
- Papermaking, wet lay processes suitable for recovered fibres
- Random preforms give limited fibre volume fraction (~35%)
- Higher volume fractions require alignment / additional processing
- Significant potential for use in thermoplastic moulding compounds

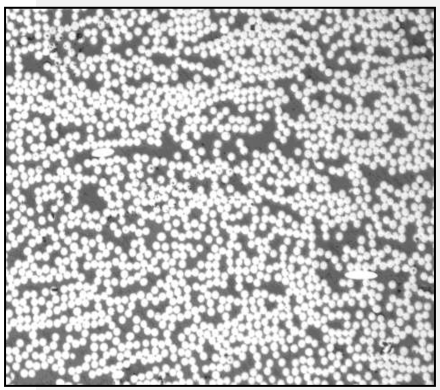
Cost benefits of high VF

- This analysis emphasises fabric cost (no prepregging or laminating)
- Interiors are highly optimised already – very challenging for discontinuous (strength limited)
- Virgin carbon offers ~65% weight save over glass but for 5x materials cost
- Recycled fibres need to be at least 30% v.f. to compete with glass for demanding applications
- Low vf materials offer *weight penalty* against glass in some applications
- **Added value cost for recycled materials can exceed 12$/lb (8$/m² cost at 300gsm)**

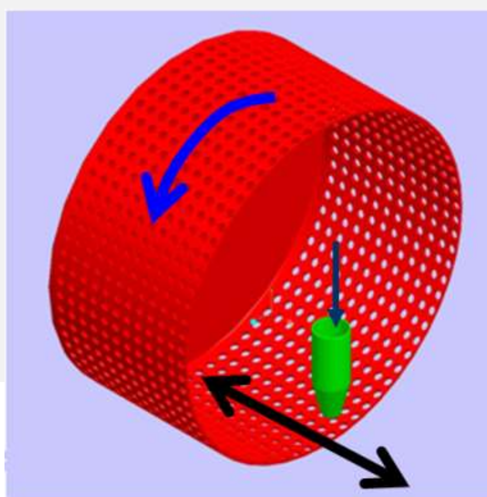


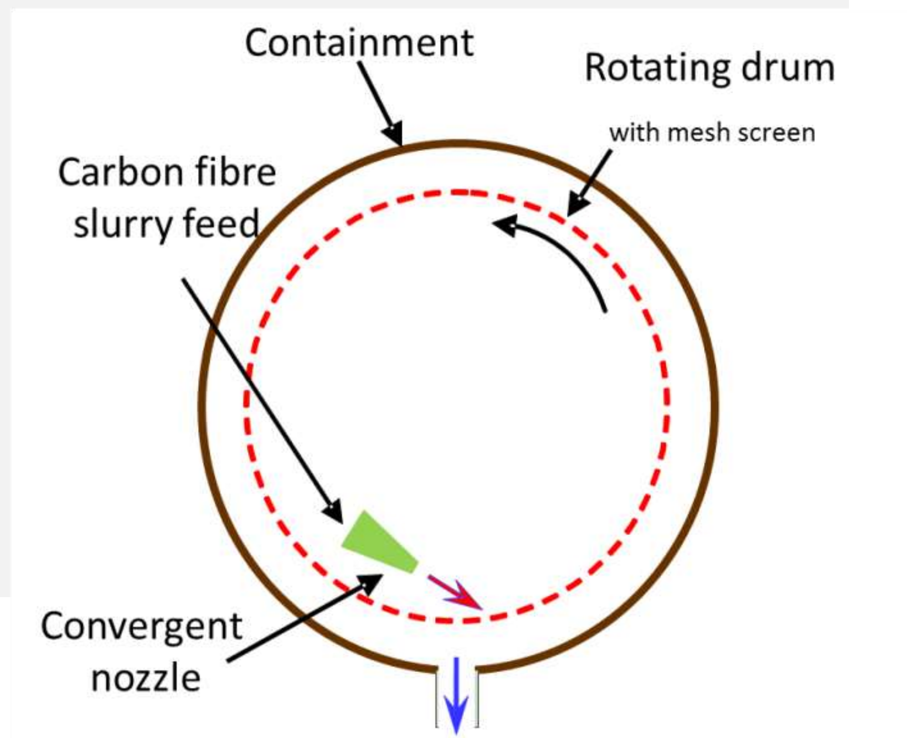
Manufacture of Aligned Broadgoods

- High level of fibre alignment needed
- Wet lay with convergent flow
- 60% fibre volume fraction composites can be achieved
- Commercial scale costs still to be determined



60% fibre volume fraction achieved with compression moulding





Manufacture of Aligned Broadgoods

- Several processes have been investigated
- Some excellent alignment results have been achieved
- Dewatering behaviour is now the main emphasis – this is the main cost driver

- Current goals
  - Lab work / hardware development
    - Batch rig development for improved performance and rate
    - Investigating commercial scale issues
    - Manufacture of materials for composites testing

  - Analysis of suspension flow behaviour
    - Understand nozzle performance
    - Permeability of aligned mats (affects dewatering behaviour)
    - Development of analytical and CFD models to understand behaviour

Alignment technical findings so far (1)

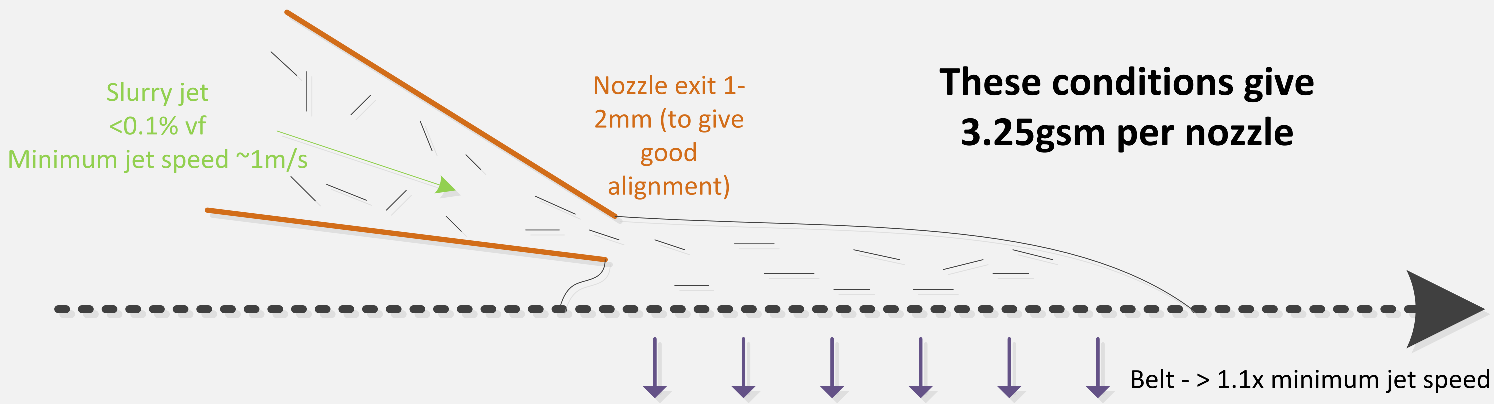
- Nozzles are better than submerged flows
    - Higher performance alignment
    - Much easier to control
- Static nozzles are better than moving ones
    - Oscillation causes misalignment
    - Rotation causes splashing problems
    - Air leakage can *dramatically* effect efficiency
- Steady state conditions are difficult to achieve

- Unknowns
    - Alignment quality
    - Energy use

- Technical challenges
    - Nozzle blockage
    - Splashing & misalignment
    - Mat de-lamination

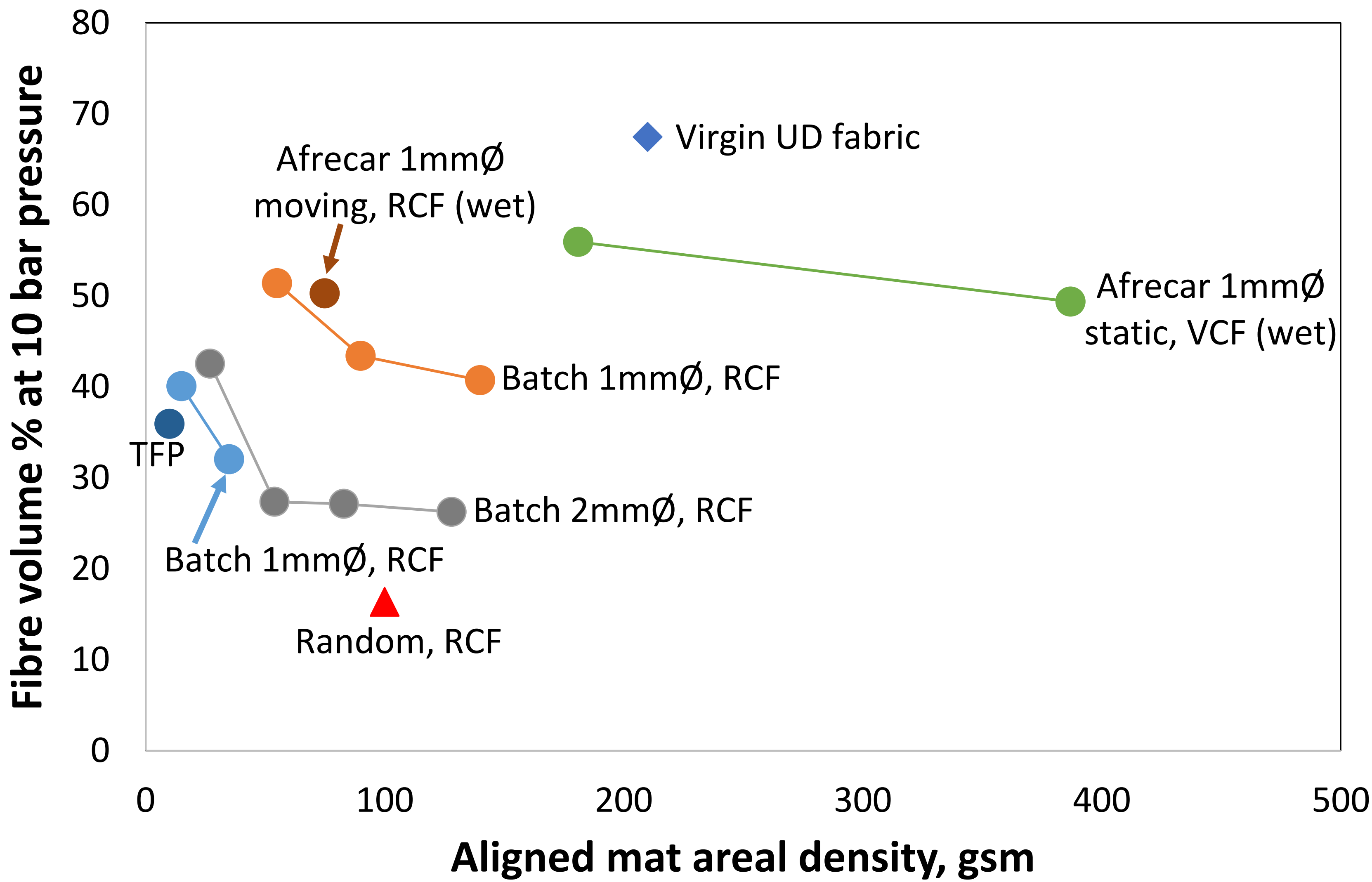
Alignment technical findings so far (2)

- The big problem with nozzles…



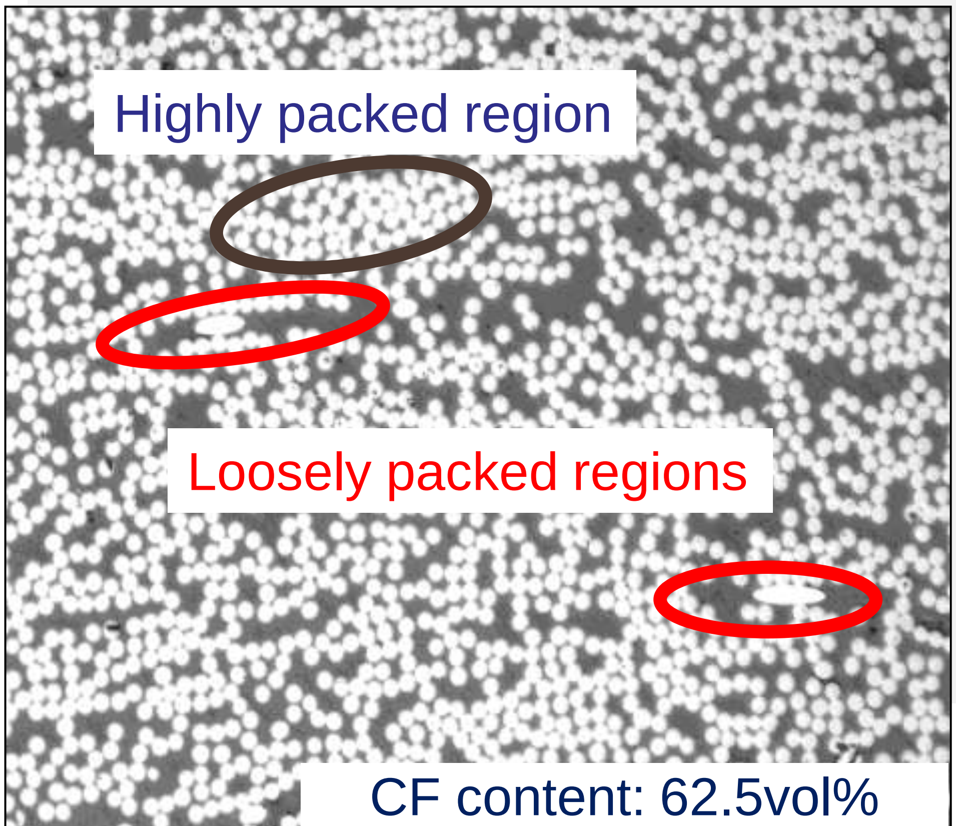
- … so we need a way of having multiple nozzle passes
    1. Few nozzles lots of times (several configurations tested)
    2. Lots of nozzles (several options of how to do this)

Aligned mat compaction (10 bar)

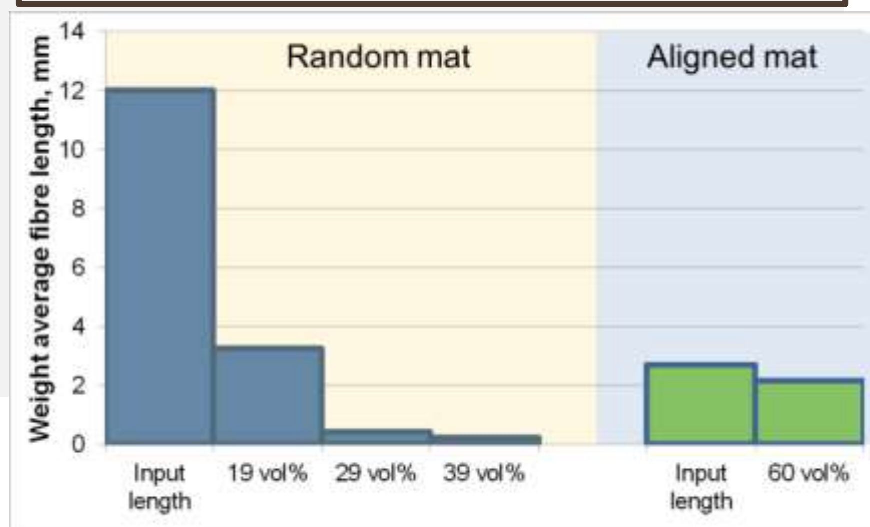


Composite properties

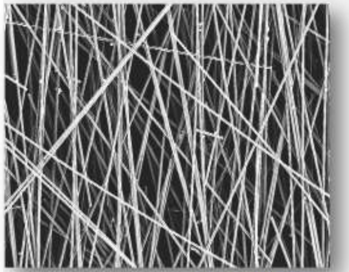
Flexural property	Aligned direction, 0°	Transverse direction, 90°
Strength	1248 ± 68.5 Mpa	107 ± 2.1 MPa
Stiffness	81.8 ± 5.0 Gpa	7.2 ± 0.2 GPa



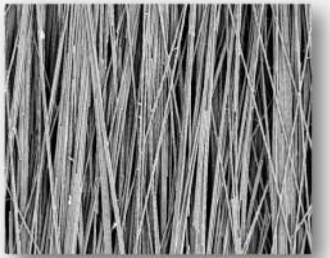
- High volume fraction (62%) aligned fibre composite manufactured.
- Excellent mechanical properties.
- Aligned fibre results in low fibre breakage at high moulding pressure



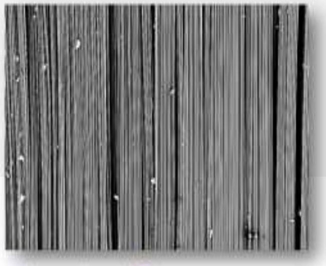
High volume fractions achieved through fibre alignment –*processes under development*



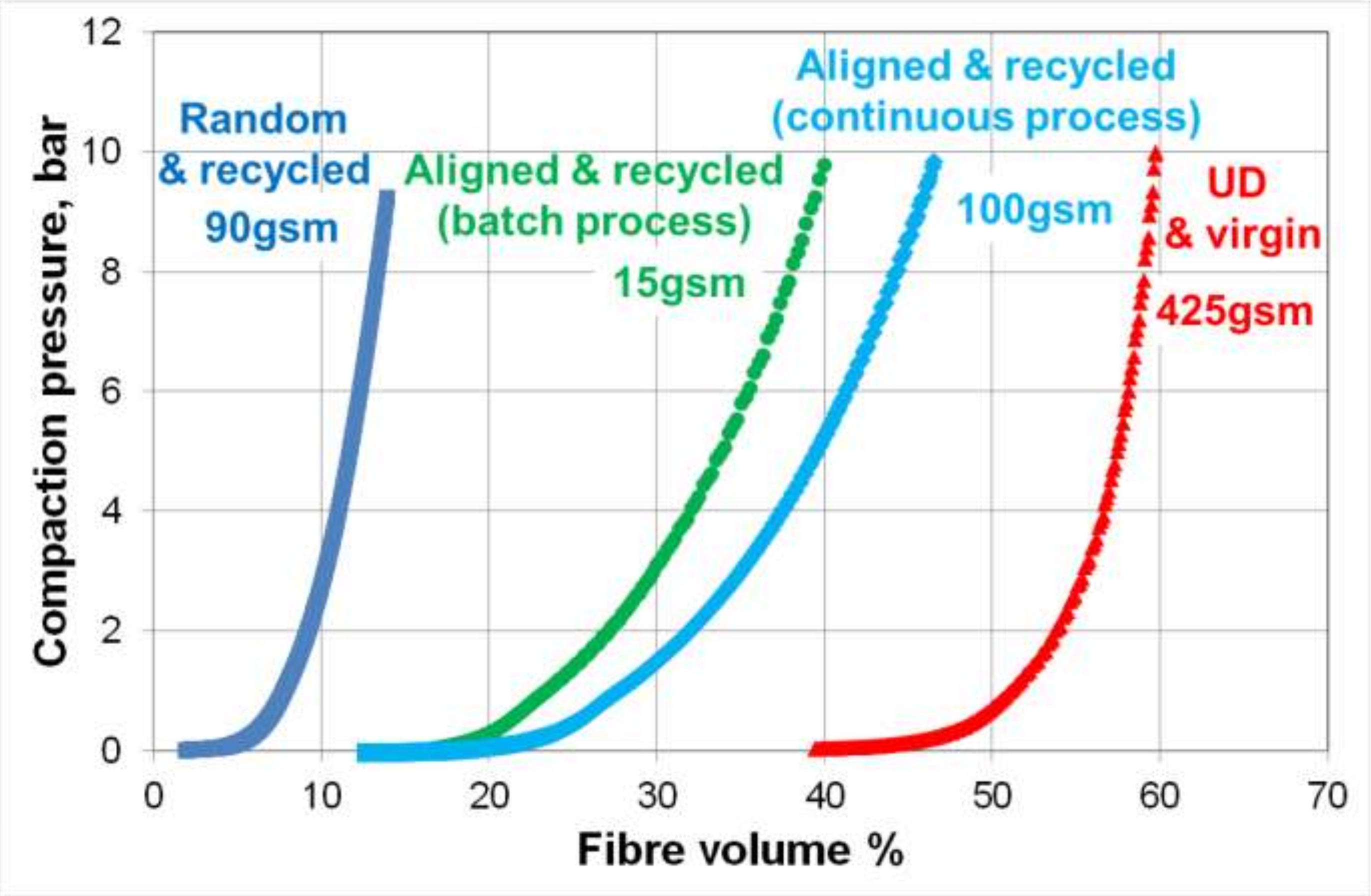
2-D random



Aligned short fibre (30gsm)



Non-crimp UD



Commercialisation route plan

- Proposed plan similar to Fluidised Bed commercialisation
- No wet process is ready for commercial scale
- Design at Phase 3 to give cost targets & business case
- Build at Phase 2 to give commercial confidence in technical areas

Phase 1 (current lab scale)

- TRL3
- Grams per hour
- Identification of technical challenges and possibilities

Phase 2 (large lab scale)

- TRL5
- Scale to sell process (1-2kg/hr. ?)
- Solving majority of technical challenges

Phase 3 (commercial at partner)

- 100T per annum (20kg/hr.)
- Located at 3rd party?

- 100T per annum = 1% of projected 2020 UK demand for CF broadgoods

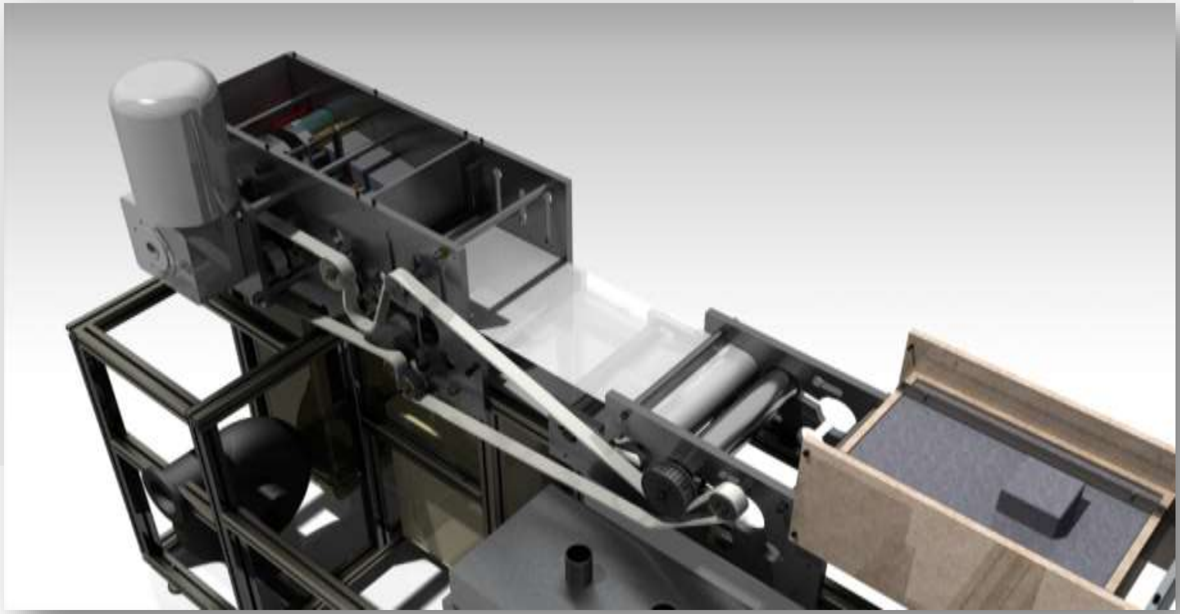
Batch rig scale-up

- Requirements
  - Higher rate of material production – bigger mats, faster performance
  - Easier visibility of what is happening at the nozzle
  - Facility for vacuum & pressure dewatering as well as centrifugal
  - Integrated heating, washing & binder application – more representative
  - Not ignoring commercial aspects!

Conversion of dry fabrics into chips

- Lab testing identified an approach allowing us to process dry fabric waste material with an epoxy binder to facilitate slitting and chopping into 6mm chips

- A machine was constructed to;
  - Allow production of material for trials at suppliers
  - Generate knowledge for scale-up – hardware and operation



Dry fibre conversion

- Multi-stage process – cutting, binder application, curing, slitting, chopping

Dry fabric conversion – current status

- We can produce good quality material – high bundle integrity, free flowing chips
- There are several challenges to solve to achieve stable operation at high rate
- Competing processes?

Section:03

Questions?

Key LCA research initiatives

- Quantification of resource and environment implications of fluidised bed recycling process
- Matching rCF mechanical properties and existing/novel manufacturing techniques to component requirements
- Quantify financial/environmental trade-offs of automotive component material selection, leading toward optimisation
- Assess potential scale of rCF uptake in automotive sector; indirect effects (e.g., enabling low carbon drivetrains)

Future R&D directions

- Markets to aim for? – low fibre volume fraction/low value or high volume fraction/high value?
- Market volume? High - automotive / low - aerospace
- Economics? – processing cost / value of product
- rCF processing for application in existing markets (e.g. thermoplastic compounding)
- Dry fibres & more in-process waste materials
- Prepreg recycling / end of life recycling

Conclusions

- Range of fibre recovery processes available – costs / recovered products / suitability for various scrap feeds.
- Variety of methods available for fibre re-use
- Not necessarily seek to re-manufacture virgin type materials
- Niche value-added products possible but small markets given level of scrap available *(e.g. milled fibre / speciality non-woven products)*
- Large markets *(e.g. injection moulded thermoplastics)* dominated by large players – small profit margins
- R&D necessary, but who pays?

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Questions?