COMPOSITES RECYCLING:

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Where are we now?

Composites UK Trade Association

UNIVERSITY OF BIRMINGHAM

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

MANCHESTER 1824
The University of Manchester

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AUTHORS

Stella Job
Supply Chain and Environment Manager at Composites UK, trade association.

Dr Gary Leeke
Head of Bioenergy and Resource Management, Cranfield University (Previously Reader in Low Carbon Technologies, the University of Birmingham)

Prof Paul Tarisai Mativenga
Chair in Multiscale and Sustainable Manufacturing, University of Manchester

Dr Geraldine Oliveux
Research Fellow, University of Birmingham

Prof Steve Pickering
Hives Professor of Mechanical Engineering, University of Nottingham

Norshah Aizat Shuaib
Researcher & PhD student, University of Manchester

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CONTENTS

1. Executive summary

The use of composites is growing and the global market for composite products is expected to reach $95bn globally by 2020, an increase of 40% from 2014. The benefits of lighter weight and durability are increasingly recognised and so market penetration is growing in established sectors while new sectors are adopting composites. Inevitably this results in more waste from manufacturing, and an increasing challenge to develop economically sustainable recycling routes for end-of-life.

Composites are by nature strong, durable and non-homogeneous, which makes them inherently difficult to recycle and commercialisation of recycling routes has been challenging. A supply chain for recycling carbon fibre reinforced polymers (CFRP) using a pyrolysis process is now becoming established, led by ELG Carbon Fibre in the UK. Intermediate products with recycled carbon fibre have been developed for milled and chopped applications in thermoplastic and thermoset compounds and coatings, non-woven textiles and 3D preforms. The next challenge is for increased take up of these intermediates in high volume applications.

Glass reinforced polymers (GRP) are more challenging economically and the most promising route for end-of-life applications is to co-process with refuse derived fuel in cement kilns. This process is available in Germany, and cement kiln co-processing and energy from waste solutions are starting to become available in UK. Regrind from manufacturing waste can be incorporated in various processes including spray-up, casting and moulding, providing some reinforcement value from short fibres or flakes. Some companies operate this in-house, though grinding to fine filler is not commercially viable because of the very low cost of virgin fillers.

Alternative processes are the subject of much research, particularly chemical processes which can recover value from the resin chemicals. Also variants of pyrolysis, e.g. within a fluidised bed or using microwave energy, have potential to provide cleaner fibres or use less energy.

Environmental impact of different recycling processes shows that energy demand for chemical processes is typically higher than others, though may be offset by the potential to gain value from the resin chemicals as well as fibres. Pyrolysis is in the intermediate range, but only around 10% of the energy input required to produce virgin carbon fibre. Mechanical grinding uses very little energy in comparison, but produces a lower value product.

Thermoplastic composites can be shredded and recycled by melting, though the existing supply chain is limited. Epoxy resins which are easier to recycle have been developed, where the composite can be degraded in low temperature chemical processes to release fibres and downgraded resins suitable for use as thermoplastics or adhesives.

Dry fibre waste has been frequently overlooked, but adds up to around 15,000t in UK, from manufacture of raw fibres and intermediates to offcuts in ply cutting. Some textile products from dry carbon fibre waste are commercially available and small but increasing amounts of glass fibre waste are used in infrastructure/timber replacement products.

Trends in legislation tend to increase producer responsibility, increase recycling rates and reduce availability of landfill. The European Union (EU) Circular Economy Package and proposed changes to the Waste Framework Directive will limit municipal waste to landfill to 10% by 2030 but it is not clear yet how this will affect industrially derived and construction waste other than packaging (75% must be recycled by 2030).

For carbon fibre, further development is needed to improve properties by scaling up of processes to achieve better fibre alignment in textiles. Development of chemical processing routes may allow for higher value to be obtained from resin chemicals, though commercial viability has not yet been demonstrated. There is scope to introduce variants of pyrolysis processing to optimise fibre surface properties and reduce processing energy. For GRP, product specific development is needed to incorporate regrind as a reinforcing filler, e.g. in infrastructure products. The main need is to develop appropriate business models, integrating with existing waste management supply chains and with associated capital investment, to enable commercialisation of what is technically proven. There is also a need to develop the supply chain in UK for co-processing GRP waste in cement kilns.

2. Introduction

2.1 Scope

This report is concerned with the recycling of long fibre reinforced polymer (FRP) composites where the polymer matrix is thermoset, with a brief comment on thermoplastic composites.

2.2 Background to this report

A 2010 Knowledge Transfer Network (KTN) report summarised UK research since 2000 and was followed by two workshops in 2011 looking at developing glass and carbon fibre composite recycling respectively[1]. Following these, Composites UK took the initiative to seek funding from the Waste & Resources Action Programme (WRAP) to develop a Resource Efficiency Action Plan (REAP)[2]. This was done in 2013-14 with stakeholders from across industry and focussed mainly on GRP recycling as the biggest challenge. Responsibility for delivering the actions specified in the REAP lies with the Composites Leadership Forum Sustainability Working Group, chaired by Composites UK. This report is one result of this activity.

A significant amount of research on composites recycling has been done in the UK, notably by the University of Nottingham. A current project, EXHUME[3], is a partnership between the universities of Birmingham, Cranfield, Exeter and Manchester, funded by the Engineering and Physical Sciences Research Council (EPSRC). Running from 2013 to 2016, this has developed new and resource efficient composite recycling and re-manufacturing processes in collaboration with industry, as well as investigating life cycle impact and business models for recycling. This report draws heavily on the work of EXHUME, in particular a recently published, very thorough academic review by University of Birmingham[4]. The environmental impact section draws on the work of University of Manchester in EXHUME.

2.3 Market size and waste volumes

The use of composites is growing and the global market for composite products is expected to reach $95bn globally by 2020, an increase of 40% from 2014 (see Fig 1). The benefits of lighter weight and durability are increasingly recognised and so market penetration is growing in established sectors while new sectors are adopting composites.

Inevitably this results in more waste. End-of-life waste for CFRP is still small, though production waste can be 30 to 50% of production volumes where prepreg processes are used, resulting in an estimated 2000 to 3000t p.a. CFRP waste in the UK. GRP manufacturing waste has been estimated at about 15kT p.a. in UK (approx. 10% of manufactured parts, estimated to be 150kT in 2014 for UK & Ireland[5]). GRP end-of-life waste is likely to be around 50-60kT p.a. but waste classification does not distinguish between FRP and other material so no accurate figure is available.

2. Introduction (cont...)

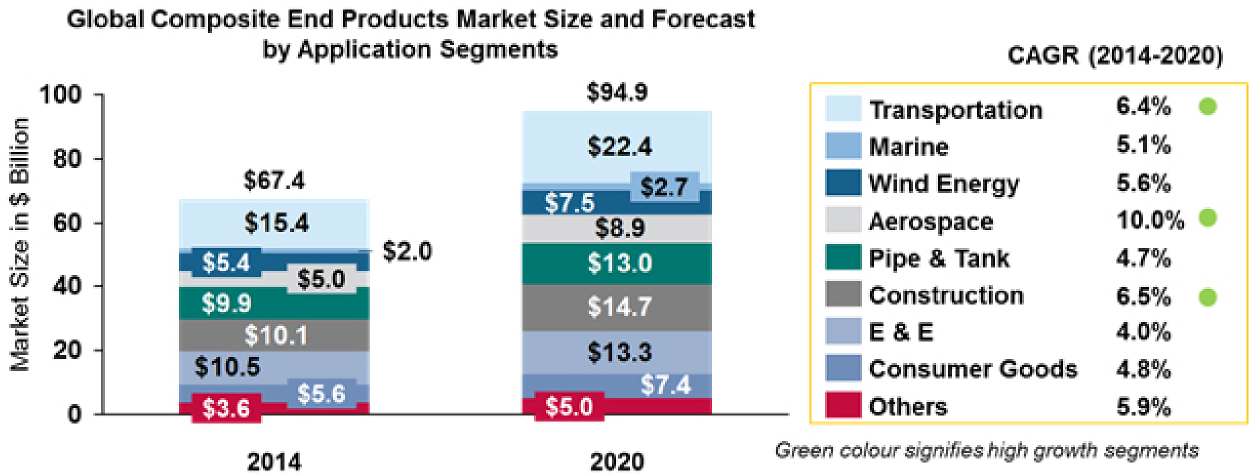


Fig 1. Global Composite End Products Market Size and Forecast by Application Segments. Courtesy of Lucintel LLC.

2.4 Challenges to commercialisation

Many research projects in recycling FRP have been undertaken in the UK and overseas. Most have demonstrated technically viable methods for reclaiming fibres and re-using them in products. However, the challenges in bringing such processes and products to market have been hard to overcome.

There is the need to undertake expensive tests and create or change standards for products to be accepted with recycled content. Questions about waste volumes, provenance, how to maintain a consistent supply of waste and whether companies will pay for that waste to be recycled are unclear. Additionally, waste management licences need to be acquired. Understanding health and safety requirements for new processes can be time consuming. There then is the usual challenge of finding the investment required for what may be a low profit margin product.

The economic downturn since 2009 shifted the focus of manufacturers away from sustainability issues to simply surviving, but now that manufacturing, particularly in composites, has moved back into a growth phase, interest is being rekindled.

Commercial recycling of CFRP has progressed further since it is an order of magnitude more valuable than glass fibre, and some large aerospace primes have supported carbon fibre recycling initiatives where equivalent support for GRP has been lacking. Carbon fibre recycling using pyrolysis processes was first established in UK by Milled Carbon in the West Midlands, now known as ELG Carbon Fibre since it was purchased by ELG Haniel in 2011. Now pyrolysis based carbon fibre recycling is active in USA, Germany, Italy and Japan.

GRP recycling in the UK currently remains limited to small volumes of in-house activity.

2.5 What is commercially active now?

While many processes have been developed and several companies have been started to exploit these technologies, only a few are currently commercially active in taking waste from others, processing it and selling recyclate on to new markets. There are also in-house and private business to business recycling activities, not listed here.

Several companies now exist globally to recycle CFRP and carbon fibre prepreg waste using variations of pyrolysis processes. These include:

- ELG Carbon Fibre, UK
- CFK Valley Stade Recycling, Germany
- Carbon Conversions (formerly MIT-RCF), South Carolina, USA
- Karborek, Italy
- Carbon Fiber Recycle Industry Co Ltd, Japan (may be still at pilot scale)

GRP waste can be sent to Neocomp in Germany to be co-processed with refuse derived fuel in cement kilns. (This was formerly operated as Compocycle by Zajons.) It is hoped that this route will soon be available in UK, and some UK companies are now sending GRP waste to energy from waste (EfW) plants.

Some companies supply equipment for incorporating recycled materials (e.g. GRP regrind) into a resin mix for spray up or casting. These include Eco-Wolf, based in Florida, USA and ADM Isobloc in Germany.

In summary, CFRP recycling is under way, though needs more applications to match waste supply as there is currently an oversupply. There is demand for a GRP recycling solution in the UK. Further comment can be found in the article *Recycling Composites Commercially*[6].

3. Recovery process

3.1 Mechanical

After suitable size reduction, the material is ground in a hammer mill or similar and graded into different fractions. These can be separated by sieving into powders (from the ground resin and any fillers) and fibres of various lengths that are still partially embedded in resin. Flakes of materials may also be present in the recyclates. This technique has been more applied to GRP, in particular SMC and BMC (sheet and bulk moulding compounds), but limited work on CFRP also exists.

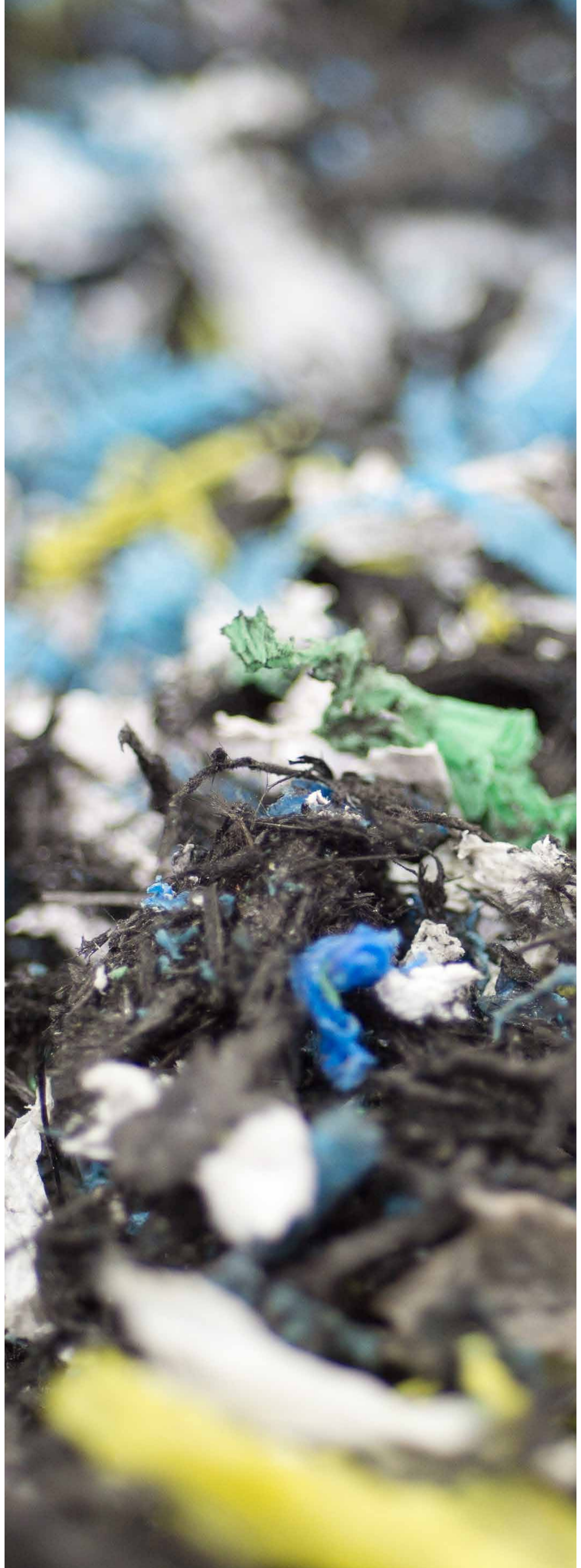
The use of ground composite materials can have two purposes: filler or reinforcement. The powdered products recovered after sorting can be used as filler but this is not considered commercially viable because of the very low cost of virgin fillers such as calcium carbonate or silica. The incorporation of filler material in new materials is limited to typically less than 10wt% because of the deterioration in mechanical properties and increased processing problems at higher contents as a result of higher viscosity of the compound. As an alternative they have been used as an energy source as they are rich in organic resin components.

Industrial applications of this technique actually exist among GRP manufacturers. There is no known grinding process exploited commercially to treat CFRP other than for destroying material provenance prior to pyrolysis.

3.2 Thermal: Pyrolysis variants

Pyrolysis processes typically operate between 450°C and 600°C depending on the resin and the atmosphere. The lower temperatures for polyester resins, and higher temperatures for epoxies or high performance thermoplastics (e.g. PEEK). The resin matrix is degraded thermally resulting in an oil, gases and solid products (fibres, fillers if present, and char). A small amount of oxygen is generally required to minimise char formation.

These techniques allow the recovery of fibres, fillers and inserts. The resin is broken into lower-weight molecules and produces mainly gases and an oil fraction which technically could be recovered as chemicals, but in practice are typically burnt, in some cases with energy recovery.



The resulting mechanical properties of the fibres are dependent on the process conditions. The tensile strength of carbon fibres can be reduced between 4 and 85% whereas glass fibres are between 52 and 64%. and reflects the effect of the selected temperature on the resulting fibre properties. A pyrolysis temperature from 500-550°C appears to be the upper limit of the process in order to maintain an acceptable fibre strength and is typically used commercially for carbon fibre. Any thermal or chemical process strips the sizing off the fibres. In the case of glass fibre, this results in dramatic loss of strength and handling /processability. Thus thermal and chemical treatments are not suitable for GRP unless the fibres are post-treated. A post-treatment to recover glass fibre properties after thermal treatment has been proposed by University of Strathclyde[7]. If this can be scaled up to produce glass fibres that can compete with virgin glass fibres, then use in applications for chopped glass fibres such as automotive thermoplastic composites would be substantial. To achieve this economically may be challenging, given the relatively low value of glass fibre.

3.2.1 Chain conveyor pyrolysis

Commercial pyrolysis (as operated by the companies listed in 2.5) is typically undertaken in a chain conveyor which moves the composite material through a furnace with controlled temperature and atmosphere. With skilled control, carbon fibre mechanical properties can be maintained at 90% or virgin properties.

3.2.2 Fluidised bed pyrolysis

A fluidised-bed process has been developed to pilot scale which involves passing the size-reduced recyclate through a bed of sand, fluidised by a stream of hot air. This enables a rapid heating of the materials and releases the fibres by attrition and thermal degradation of the resin. This process is interesting in that it can treat mixed and contaminated materials, with painted surfaces, foam cores or metal inserts. It is therefore particularly suitable for end-of-life waste, though as yet it has not been commercialised. However, carbon fibres seem to be more damaged than with pyrolysis, with the strength of fibres typically reduced by about 25%, though stiffness is retained. In addition to the high temperature, attrition by the fluidised sand might also damage the fibres.

3.2.3 Microwave assisted pyrolysis

For microwave assisted pyrolysis the material is heated in its core so that thermal transfer is very fast, potentially enabling energy savings. This has been trialled by several universities and companies but thus far has not been successfully commercialised.

3.3 Chemical/Thermochemical: Solvolysis

Solvolysis uses a heated solvent or solvent mixture to break the resin into lower molecular weight chemicals. Carbon fibres are not dissolved and are released from the resin. Glass fibres suffer degradation from the process due to removal of the sizing and other factors, so these processes are more suited to carbon fibre.

Solvolysis offers a large number of possibilities thanks to a wide range of solvents, temperature, pressure and catalysts. Among all the tested solvents, water appears as the most used. Alternative solvents with lower critical temperature and pressure have been considered, mainly ethanol, methanol, propanol and acetone, as well as their mixtures with water. Additives or catalysts can be added to water in order to moderate the operating conditions. However, using a catalyst can be very detrimental to the fibre mechanical properties, and also to the environment and worker health. Catalyst molecules also remain on the fibre surface after treatment which gives poor resin to fibre adhesion in future applications.

Advantages compared to pyrolysis include:

- Lower temperatures (<500°C, c.350°C) are generally necessary to degrade the polymers.
- Potential to reclaim chemical value from the resin is higher
- Can lead to cleaner fibres, with no char formation

Disadvantages include:

- If supercritical water is used reactors are expensive as nickel-rich stainless steel alloys must be used to avoid corrosion from the solvent and resin breakdown products at the elevated conditions (>374°C and >221 bar).
- Solvents and catalysts have negative environmental impact, with associated disposal costs, as well as potential health risks.

Solvolysis has been more intensively researched to recycle CFRP due to the high value of the carbon fibres. In many cases the mechanical properties of carbon fibres from solvolysis are retained above 90% or virgin properties. When applied to GRP, only the resin degradation was studied in most cases. The glass fibres themselves were almost never considered because of their low commercial value and their degradation when exposed to thermal, acidic or alkaline conditions.

The work is generally at lab-scale with only a few examples reaching industrial or semi-industrial scale. Adherent Technologies Inc. (USA) and more recently Innoveox (France) have proposed to sell or licence their solvolysis technology. Panasonic Electric Works (Japan) have built a pilot plant for their hydrolysis process to recycle 200 tons of GRP manufacturing wastes annually.

3.4 Cement Kiln

The European Composites Industry Association (EuCIA) recommends that GRP waste is recycled by co-processing in cement kilns[8]. Composite parts are size-reduced and mixed with other solid recovered fuel (SRF) to feed into the kilns.

GRP typically contains E-glass, which is usually alumino-borosilicate, along with an organic resin and sometimes calcium carbonate filler. When fed into a cement kiln the organic resin burns providing energy and the mineral constituents provide feedstock for the cement clinker. The clinker is ground to form cement. Any calcium carbonate calcines (releasing carbon dioxide) to calcium oxide, the primary component of Portland cement. Alumina and silica also have cementitious properties in an alkaline environment and are typically present in Portland cement at about 25%, and in much higher proportions in cement alternatives from fly-ash and slag. Boron, which is found in most E-glass, can cause a reduction in early strength during the setting of cement, but as long as proportions are kept low it is not considered a problem. E-glass from European manufacturers now contains much less boron due to emissions regulations at manufacturing plants, though quantities are still significant in E-glass from China.

This is preferable to incineration in EfW facilities for two reasons:

- The high calorific value of composite resins (and the carbon in CFRP) is not desirable in EfW because the capacity is limited by energy release, rather than by tonnage burnt, and the tonnage burnt is more significant in terms of revenue.
- The mineral content of the GRP (glass and fillers) is recycled into the cement clinker, whereas in incinerators it falls as ash. (Though in some cases the ash is recycled into aggregates or construction products.)

4. Re-use and application

4.1 Products from the Resin

Products from resins can be recovered from fibre/matrix separation processes such as solvolysis and pyrolysis.

Solvolysis of GRP has been largely considered for the recovery of organic products from polyester resin. The glass fibres are significantly damaged by the treatment. The few studies released to date have shown significant potential in the reuse of products recovered from the degraded resin in the form of monomers or additives.

When CFRP is solvolysed the focus has been on the recovery of the carbon fibres due to their high value and resin recovery has in most cases been neglected. The degradation of thermosets is variable and it is difficult to predict the chemical degradation products. The only solution considered has been energy recovery.

In pyrolysis the resin is volatilised into lower-weight molecules and produces mainly gases (carbon dioxide, hydrogen and methane for example) and an oil fraction. The oil fraction recovered from pyrolysis has mainly been studied for energy recovery and would have a gross calorific value (GCV) sufficient to heat the process.

The recovery of resin products whether for energy or product recovery is not straightforward and requires separation and purification steps. Further research is necessary to propose suitable solutions which can be commercialised.

4.2 Applications of mechanically recycled composite

The fibrous fractions of ground thermoset materials can be reused as reinforcement. This represents a higher value route compared to grinding to fine filler because fine filler replaces very low value materials such as calcium carbonate or silica; more energy is needed to grind to fine filler; the reinforcing value of the fibres is at least partially retained.

When incorporating regrind, careful attention needs to paid to mixing in order to achieve full wet-out of fibres. Mechanical properties may be significantly impaired compared to virgin fibres due to fibre damage and poor bonding between the recyclates and the new resin. Separation processes will inevitably leave some resin particles attached to the fibres. However there have been successful demonstrations using glass fibres separated from regrind in BMC or SMC and in a recycled thermoplastic matrix. In some cases, the full regrind has been incorporated with resin in a casting or cold press process, though these may also include dry glass fibre waste.

This approach has not been developed beyond early research for CFRP because the fibre value is high enough to justify thermal or chemical processes which result in cleaner fibres.

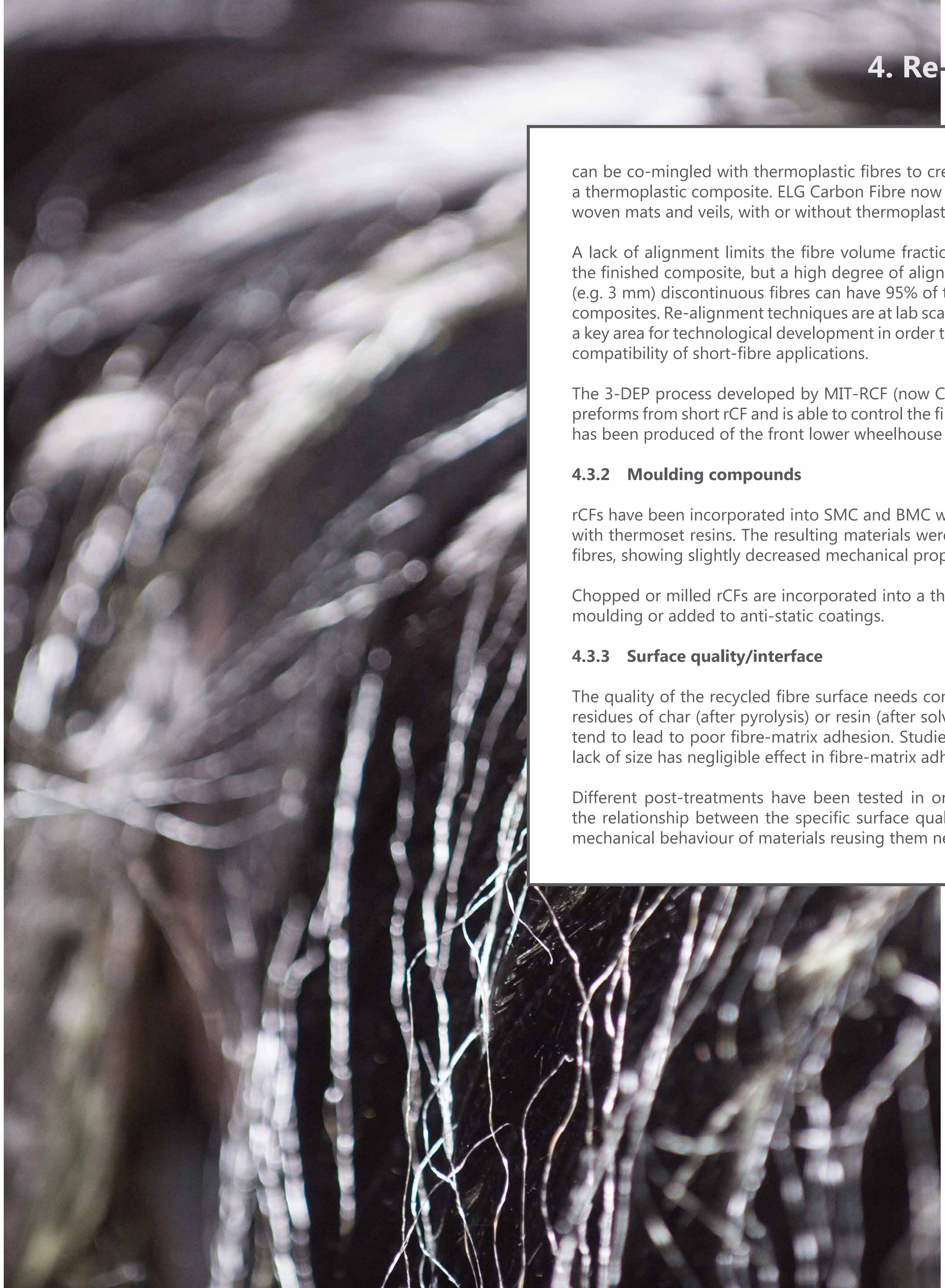
4.3 Applications of fibres reclaimed from thermal/chemical processes

As mentioned previously, glass fibres recovered by thermal or chemical processes are significantly damaged, so applications are not discussed here. The key to increasing demand for recycled carbon fibres is to develop intermediate products that fit easily into manufacturing processes (e.g. stampable reinforced polymer sheets, SMC, pelletised injection moulding compounds).

4.3.1 Textiles and preforms

In some demonstrators, pieces of woven carbon fibre (CF) fabrics have been reclaimed from cured parts or prepreg scrap and re-used with new resin, retaining the weave and alignment, which maximises the properties of the CF fabric. These include composite tooling, part of the WorldFirst F3 car and a 6.5m racing kayak. Retaining the fabric structure in this way may enable higher value recycling of whole rolls of out of date prepreg. However it is not easily scaled up for cured parts and offcuts as variable shapes will be recovered which cannot be used directly, so a short fibre intermediate is needed.

Non-woven textiles have been manufactured from short recycled fibres by a wet papermaking process (Technical Fibre Products' Optiveil and Optimat ranges[9]), by dispersing fibres by blowing with compressed air, by needlepunching and by carding to create slivers which are stitched into a partially aligned veil. The recycled carbon fibre (rCF) can be co-mingled with thermoplastic fibres to create a semi-finished material for processing as a thermoplastic composite. ELG Carbon Fibre now has industrial scale capability to produce non-woven mats and veils, with or without thermoplastics from thermally reclaimed fibres.



A lack of alignment limits the fibre volume fraction and therefore the mechanical properties of the finished composite, but a high degree of alignment is difficult to achieve. Well aligned, short (e.g. 3 mm) discontinuous fibres can have 95% of the properties of continuous fibre carbon fibre composites. Re-alignment techniques are at lab scale in Nottingham and Bristol Universities. This is a key area for technological development in order to improve the performance and manufacturing compatibility of short-fibre applications.

The 3-DEP process developed by MIT-RCF (now Carbon Conversions) creates three-dimensional preforms from short rCF and is able to control the fibre placement and orientation. A demonstrator has been produced of the front lower wheelhouse support for the Corvette.

4.3.2 Moulding compounds

rCFs have been incorporated into SMC and BMC which are random discontinuous fibre materials with thermoset resins. The resulting materials were equivalent to compounds with virgin carbon fibres, showing slightly decreased mechanical properties.

Chopped or milled rCFs are incorporated into a thermoplastic matrix, e.g. pelletised for injection moulding or added to anti-static coatings.

4.3.3 Surface quality/interface

The quality of the recycled fibre surface needs consideration as it will lack sizing and potentially residues of char (after pyrolysis) or resin (after solvolysis) may be left on the fibres. Residues will tend to lead to poor fibre-matrix adhesion. Studies have shown that, where fibres are clean, the lack of size has negligible effect in fibre-matrix adhesion with epoxies.

Different post-treatments have been tested in order to improve the fibre surface quality, but the relationship between the specific surface quality of recycled carbon fibres and the induced mechanical behaviour of materials reusing them needs further investigation.

5. Environmental impact of composites recycling methods

The environmental impact of materials processing is dominated by energy demand. For most manufacturing and recycling processes electricity energy usage is the main source of power and dominates the energy footprint of the process. Reducing energy demand is important for improving sustainability or for reducing the collateral damage caused by excessive energy input. Figure 2 shows a summary of specific energy demand for composite recycling processes. It is clear that recycling processes are not equal in terms of energy demand.

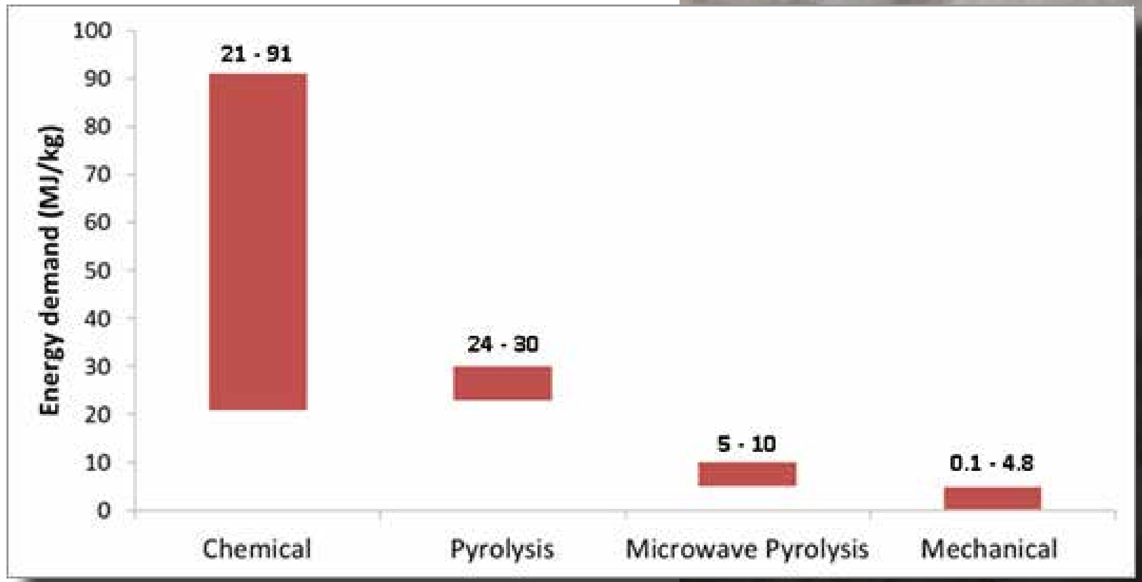


Fig 2: Energy demand in composite recycling methods

For example, in a mechanical recycling process, the energy demand is used for powering the motor of the granulator or hammer mill machine. The value varies according to the machine type. Studies in the EXHUME project reported the energy demand to be around 0.17-0.27MJ/kg for Wittmann ML2201 granulator at maximum capacity of 150kg/hour and around 0.35MJ/kg for Wittmann MAS1 granulator (at 30kg/hour). Eco-Wolf grinder Model GM-2411-50 and IIT Ltd M300 machine has energy demand of 0.14MJ/kg (800kg/hour) and 4.75MJ/kg (around 29kg/hour) respectively. Pre and post recycling stages such as shredding and sieving is not as energy intensive as the actual recycling processes. The specific energy demand of the mechanical recycling process is dependent on the process throughput and has the lowest value when operating at maximum machine capacity. At this processing scale, the basic power requirement of the machine drive motors can be utilised therefore the specific energy demand can be reduced.

It should be noted that some recycling processes can also generate usable energy and materials. For example, glass fibre composite waste is incinerated in a cement kiln for energy recovery. The incombustible parts (glass fibre, filler) can be used as raw material for cement production.

Pyrolysis and chemical processes are commercial scale processes available for recycling carbon fibre composites. For a conventional pyrolysis process, average energy demand was reported in literature to be within the range of 23-30MJ/kg but no information on processing scale is included. Microwave pyrolysis is reported as more energy efficient compared to the conventional pyrolysis due to fast and selective heating – with estimated energy demand about 5-10MJ/kg. Also, organic by-products can be retrieved for energy or chemical feedstock from these processes. However, synthesis and refining steps may escalate the process energy demand even further. Hitachi Chemical (Japan), developed a chemical recycling process for epoxy based tennis racquet with energy demand between 63-91MJ/kg and maximum processing capacity of 17,000 rackets per month. The solvent dissolution and water distillation steps dominated the process energy footprint. A pilot scale chemical recycling process at the University of Birmingham, used a mixture of acetone and water to recycle 300 gram of RTM6 CFRP plate. The process took around 3.5 hours (0.085 kg/hour) and had an electricity energy demand (for heating) around 21MJ/kg. Optimisation and upscaling the process will enable higher processing rate and lower specific energy demand.

The recycling energy demand is relatively lower (10 to 20 times lower) compared to embodied energy of production for virgin glass (13-32MJ/kg) and carbon (183-286MJ/kg) fibres, as illustrated in Figure 3. Environmental credits from avoidance of virgin material can be realised through cross sector applications of the recyclate. For example, usage of glass fibre thermoset waste in railway products can avoid production of virgin or new concrete material. By avoiding production of high embodied energy material (such as fibres or polymer based material), major environmental benefits can be successfully gained.

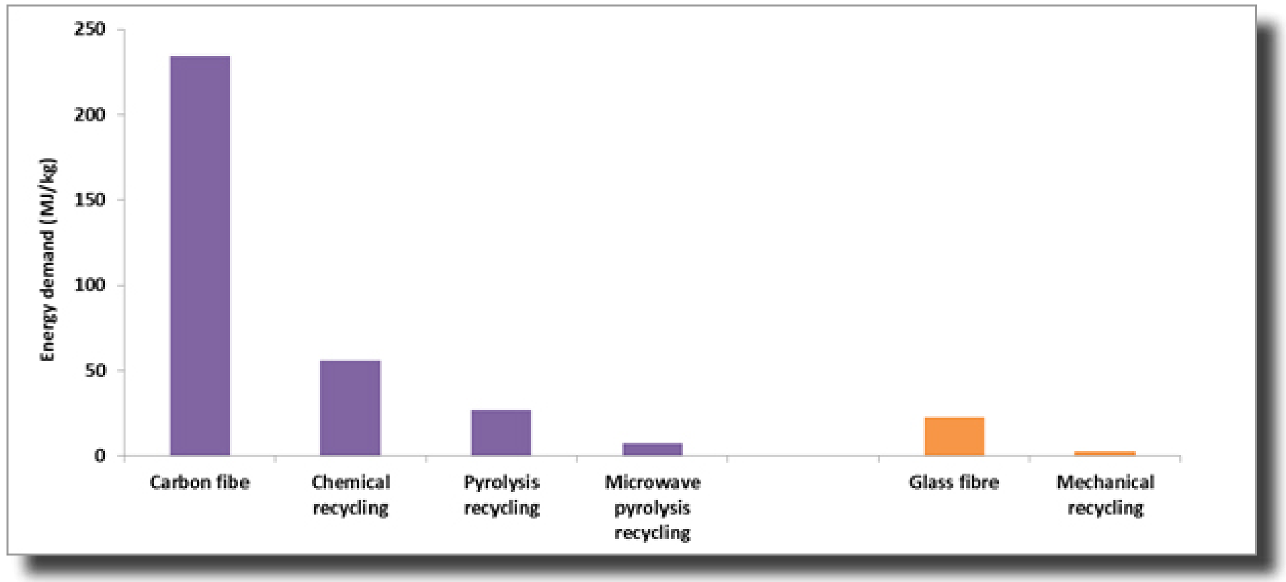


Fig 3: Comparison between embodied energy of fibre production and potential recycling processes (average)

6. Fibre reinforced thermoplastics and recyclable resins

Little work has been done on long or continuous fibre reinforced thermoplastics, as they are currently a minor sector in the composite market. Contrary to thermoset resins, thermoplastic resins can re-melted and reprocessed[10]. Glass fibre filled thermoplastics from automotive waste are already recycled into new compounds in some cases. Alternatively, thermochemical processes would degrade the resins, as for thermosets, enabling the recovery of low molecular weight organics.

Carbon fibre reinforced PEEK has been ground and successfully incorporated into a virgin PEEK resin and moulded by injection or press up to 50wt%, leading to materials with mechanical properties comparable (even better) than the same virgin material. A direct reforming process without grinding was also successfully performed. This was not applied to end-of-life materials but it may be appropriate for production waste.

While thermoplastics can replace thermosets in some cases, thermoset resins provide excellent mechanical and high temperature properties as well as durability. Thermoset epoxy resins which are easier to recycle have been developed by Connora Technologies and Adesso, where the composite can be degraded in low temperature chemical processes to release fibres and downgraded resins suitable for use as thermoplastics or adhesives.

7. Applications for dry fibres

In addition to cured composite waste and prepreg, there is a large amount of dry fibre waste, from offcuts, from converters making fabrics and veils, and from the fibre manufacturers themselves. In the UK this could be around 15,000 tonnes, mostly glass fibre.

Dry carbon, aramid and other fibre wastes (not glass) can be taken and processed into various forms by several companies including Aptec Products and Davy Textiles in UK and Procotex in Belgium and France.

Several projects have developed commercial intermediate products from dry carbon fibre waste streams, such as:

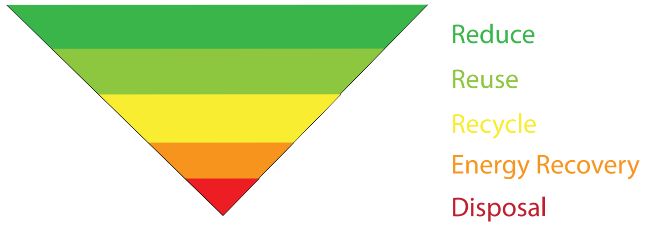
- Reclaimed fibre is incorporated by SGL Group into stitched non-woven materials used in the BMW i3's rear seat structure and roof sections for both the i3 and i8, and it is understood that this fibre is reclaimed dry fibres from process waste at this stage[11].
- Sigmatex produce uni/bi-axial fabrics marketed as sigmaRF, based on recovered carbon fibre co-mingled with PET to make a thermoplastic composite when hot pressed. Working in the Fibrecycle project, they also created co-mingled yarns which were woven into fabrics, but the aligned non-wovens were found to be more cost-effective[12].

Dry glass fibres from waste have found limited use commercially as chopped fibre reinforcement in infrastructure/timber replacement products in recycled thermoplastics or with a thermoset resin matrix and other fillers. Volumes are limited at present, but several companies may be on the verge of using these materials in large quantities.

8. Legislation

Landfill tax now stands at £84.40/tonne (2016-2017 rate), making the cost of landfill, including gate fees and transport, typically £120 to £130 per tonne. While sharp increases in landfill tax are not expected, Germany and several European countries have already largely banned landfill. The European Commission's Circular Economy Package[13] seeks to increase recycling rates and reduce the amount of municipal waste that can go to landfill to 10% by 2030. It is not yet clear how this will affect industrially derived and construction waste other than packaging (75% must be recycled by 2030).

The European Waste Framework Directive (2008/98/EC) sets the basic concepts and definitions related to waste management and develops a "polluter pays" principle known as extended producer responsibility. It requires EU Member States to apply the waste management hierarchy: Prevention, Re-use, Recycling, Recovery, Disposal.



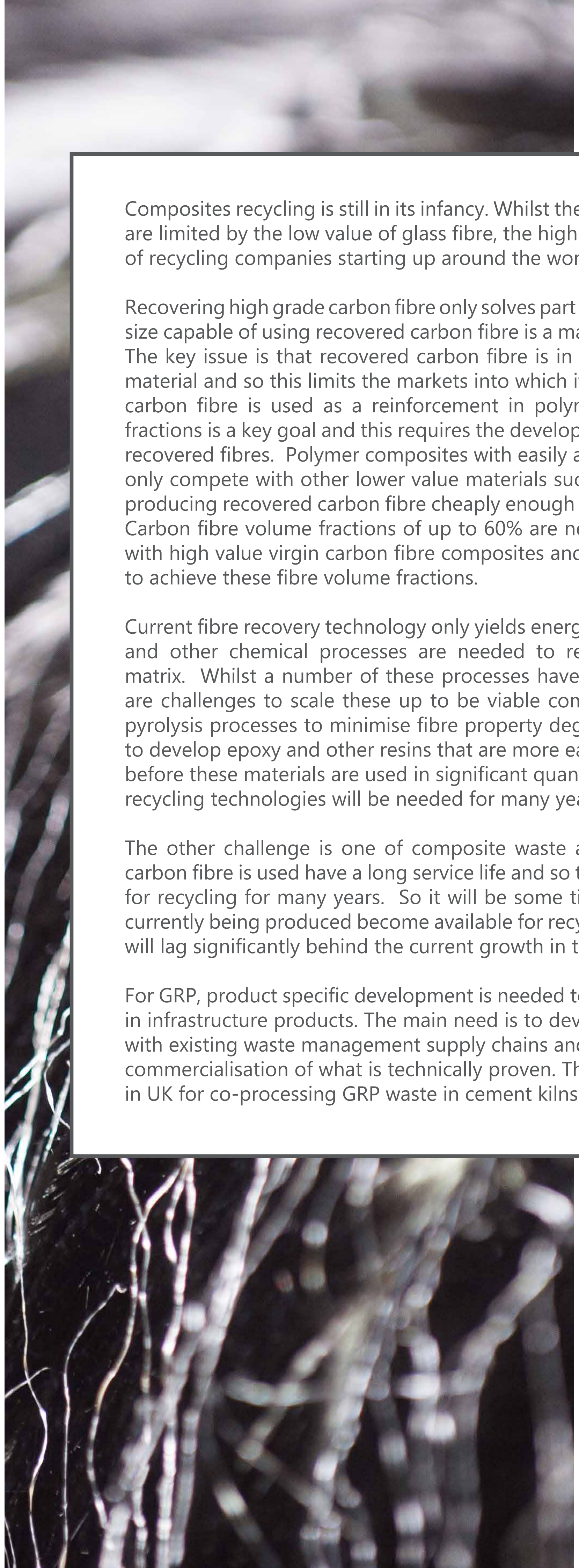
EuCIA considers composites to be recyclable according to the Waste Framework Directive by the cement kiln route, although European capacity to recycle composites still meets only a fraction of demand.

The emissions target for passenger cars[14] imposes a limit of 95 g CO_2/km for emissions, averaged across a manufacturer's fleet by 2020. This target is unlikely to be achieved solely by powertrain and aerodynamic improvements thus it will be essential to reduce vehicle weight, encouraging the use of composites. But the End-of Life Vehicle Directive[15] (ELV) requires 85% by weight of vehicles to be reused or recycled, and 95% to be reused, recycled or recovered. ('Recovered' here means burnt for energy recovery). CFRP composites offer the highest weight reduction potential but their current cost[16] and lack of a viable recycling route are barriers to CFRP uptake[17].

Similarly the Waste Electrical and Electronic Equipment Directive (WEEE, 2012/19/EU) sets collection, recycling and recovery targets for electrical goods.

Construction waste is governed by article 11.2 of the Waste Framework Directive which stipulates that "by 2020 a minimum of 70% (by weight) of non-hazardous construction and demolition waste…shall be prepared for re-use, recycled or undergo other material recovery" (including backfilling operations using waste to substitute other materials).

Therefore, with potential limits on landfill in view and the strong drive for more composites in automotive, it is essential that we build a resilient composite recycling supply chain.



9. Forward Look

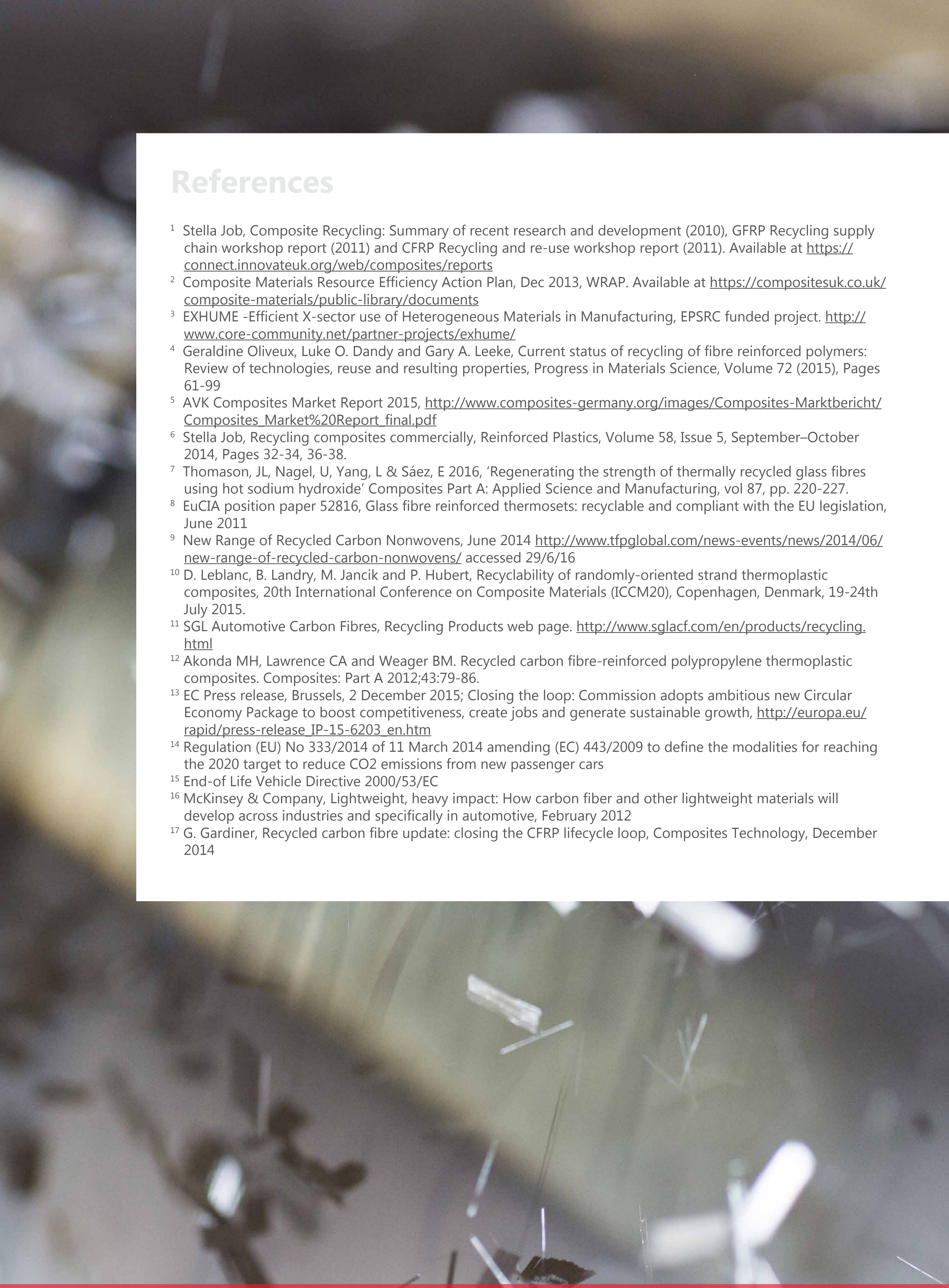
Composites recycling is still in its infancy. Whilst the options for recycling of glass fibre composites are limited by the low value of glass fibre, the high value of carbon fibre has resulted in a number of recycling companies starting up around the world.

Recovering high grade carbon fibre only solves part of the problem and finding markets of sufficient size capable of using recovered carbon fibre is a major challenge where research is being focused. The key issue is that recovered carbon fibre is in a physical form unlike any virgin carbon fibre material and so this limits the markets into which it can be sold. In applications where recovered carbon fibre is used as a reinforcement in polymer composites, achieving high fibre volume fractions is a key goal and this requires the development of viable techniques for alignment of the recovered fibres. Polymer composites with easily achievable fibre volume fractions of about 30% only compete with other lower value materials such as glass fibre composites or aluminium and producing recovered carbon fibre cheaply enough to compete with these materials is a challenge. Carbon fibre volume fractions of up to 60% are needed to make composites that compete only with high value virgin carbon fibre composites and near unidirectional fibre alignment is needed to achieve these fibre volume fractions.

Current fibre recovery technology only yields energy from the polymer and in the future solvolysis and other chemical processes are needed to recover valuable chemicals from the polymer matrix. Whilst a number of these processes have been demonstrated at laboratory scale there are challenges to scale these up to be viable commercially. There is also scope for improving pyrolysis processes to minimise fibre property degradation. Some research is being undertaken to develop epoxy and other resins that are more easily recyclable. However, it will be many years before these materials are used in significant quantities and enter the recycling chain. So current recycling technologies will be needed for many years to come.

The other challenge is one of composite waste availability. Most of the products into which carbon fibre is used have a long service life and so the end of life components will not be available for recycling for many years. So it will be some time before the larger volumes of carbon fibre currently being produced become available for recycling and so the growth of the recycling sector will lag significantly behind the current growth in the carbon fibre manufacturing.

For GRP, product specific development is needed to incorporate regrind as a reinforcing filler, e.g. in infrastructure products. The main need is to develop appropriate business models, integrating with existing waste management supply chains and with associated capital investment, to enable commercialisation of what is technically proven. There is also a need to develop the supply chain in UK for co-processing GRP waste in cement kilns.



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