End of Life Options for Composite Waste
Recycle, Reuse or Dispose?

National Composites Network Best Practice Guide

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END OF LIFE OPTIONS - COMPOSITE WASTE – RECYCLE, REUSE OR DISPOSE?

1. INTRODUCTION

Whilst by no means a new concept, recycling has over the past couple of decades become part of everyday life. It is now common practice to recycle or reuse newspapers, glass, plastic bottles, aluminum cans and clothes. The concept of recycling polymer based products gained momentum towards the end of the 1970's fueled by the oil crises in 1974 and 1978-9, which resulted in significant increase in raw material costs. Recycling of polymer composites is an even more recent occurrence with significant work generally not starting until the latter half of the 1980's. However, with the increase in use of composite products, particularly in the automotive industry which consumes up to a quarter of all composites manufactured, the issue of composite recycling is becoming ever more important. Successful composite recycling requires incentives, infrastructure, recycling techniques and market commitment.

1.2 Composite waste management practice – waste hierarchy

Landfill and incineration have always been the simplest and preferred methods of disposal accounting for 98% of composites waste, while alternative routes such as re-use and mechanical recycling account for the remaining 2% [1].

New European waste directives on landfill and incineration will put mounting pressure on these traditional disposal routes. Landfill of composite waste has been banned by the end of 2004 by most EU Member States and incineration has limits imposed on the level of energy content [1]. Other directives on construction and demolition waste, end-of-life vehicles, electrical and electronic equipment, and UK government policy such as the Waste Strategy 2000, the landfill tax and local government policy, also influence the UK composites industry. Such waste legislation focuses on dealing with waste through the waste hierarchy (Fig 1) and will therefore put more pressure on solving composites waste management through recycling and re-use. In order to comply with such legislation, manufacturers of composite products will need to have products for which real recycling solutions exist.

Most Desirable

Reduction
↓
Reuse
↓
Recovery
↓
Disposal

Least desirable

Figure 1: The waste hierarchy

Environmental factors are seen to be one of the most critical elements affecting the composites industry, with the issue of recycling having the greatest impact. This is due to the lack of clear, developed recycling routes (logistics, infrastructure and recycling technologies) relative to other materials industries, and the lack of clear end products for recycled composite materials. Legislation on recycling will have a major effect on the use of composites, and in some cases may suppress their use in favour of more easily recyclable materials [2].

In Europe, the trend in transportation was, up until very recently, towards thermoplastics, almost to the exclusion of thermosets [2]. The end-of-life vehicle directive places strong emphasis on recyclability (even at the expense of through-life environmental impact), and it seemed that this would significantly affect the use of thermoset composite components in vehicles. However, there has been a significant increase in the number of companies using glass mat thermoplastic (GMT) materials as opposed to sheet moulding compound (SMC) and bulk/dough moulding compound (BMC/DMC). This reflects the emergence of recycling as an issue for the automotive industry, the major customer for these high-volume processes.

Volumes of waste produced by the total composite market were estimated to be 156 000 tonnes in 2000, with around 70% of this coming from end-of-life waste and the remainder from production waste. It is thought that these figures could almost double to a total of 304 000 tonnes in 2015, with over 80% of this arising from end-of-life waste [3]. Other figures of at least 500 000 tonnes of composite being scrapped in Europe have also been estimated. The amount of waste produced by composite manufacturers is dependent on the type of material and the manufacturing process [4]. Currently the total amount of collected composite waste in Europe is around 400 tonnes per year, of which 300 tonnes is used in BMC/SMC for non-visible automotive applications, and 100 tonnes is used as an additive in concrete to avoid crack formation during the drying process [3].

2. LEGISLATION

There are many regulations and directives relating to waste management which could impact on the composites industry. It is estimated that there are 2.8 million tonnes of various types of plastics waste generated in the UK annually, of which a small proportion is composite material [5]. The increasing volumes of all types of waste are leading to concern over methods of waste disposal and ways in which waste can be prevented. This has resulted in the creation of directives and regulations at European and UK government levels which relate to the efficient management of waste. Waste management legislation places a focus on dealing with waste through the waste hierarchy of preventing (reducing), re-using, recycling, and recovering energy from waste before disposing of it in landfill as a last resort. Such waste legislation will put more pressure on solving waste management of composite material through recycling and re-use. Pressures from European directives are likely to increase further in the future.

2.1 EU waste management legislation

This Directive provides the overarching legislative framework for the collection, transport, recovery and disposal of waste, and includes a common definition of waste [6]. The Directive requires all Member States to take the necessary measures to ensure that waste is recovered or disposed of without endangering human health or causing harm to the environment and includes permitting, registration and inspection requirements. The Directive also requires Member States to take appropriate measures to encourage firstly the prevention or reduction of waste production and its harmfulness, and secondly the recovery of waste by means of recycling, re-use or reclamation or any other process with a view to extracting secondary raw materials, or the use of waste as a source of energy. The Directive's overarching requirements are supplemented by other Directives for specific waste streams.

On 27 May 2003 the Commission adopted a Communication "*Towards a Thematic Strategy on the Prevention and Recycling of Waste.*" [7]. In the document, the Commission sets out a wide range of suggestions and ideas for the possible future development of policy on waste in the EC. The Communication aims at developing a comprehensive strategy which includes prevention targets and measures needed to achieve them. For waste recycling, this Communication investigates ways to promote recycling where potential exists for additional environmental benefits and analyses options to achieve recycling objectives in the most cost-effective way possible

2.2 UK government policy - Waste Implementation Plan

The Waste Implementation Programme (WIP) responds to the package of strategic measures recommended by the Strategy Unit (SU) report "Waste Not Want Not" published in November 2002 [8], and the Government's Official Response [9]. The remit of the Strategy Unit was to consider action to be taken to help the UK to meet the legally binding targets under Article Five of the EU Landfill Directive.
Taking account of the derogations available to the UK, the targets are:

- By 2010 to reduce biodegradable municipal waste landfilled to 75% of that produced in 1995
- By 2013 to reduce biodegradable municipal waste landfilled to 50% of that produced in 1995
- By 2020 to reduce biodegradable municipal waste landfilled to 35% of that produced in 1995

2.3 Landfill directive

The aim of the landfill directive is to prevent or reduce negative effects on the environment and human health from the landfilling of waste, during the whole life cycle of a landfill [10]. The directive states that the price charged for disposing of waste in landfill should cover the costs of setting up and operating the site as well as the estimated cost of closure and after-care of the site.

The landfill directive places strict regulatory controls on the operation, monitoring and after-care of landfill sites. It will require some significant changes to current landfill practice in the UK [11]. Landfill sites will be classified as one of three types depending on the waste they accept: hazardous, non-hazardous or inert. The current UK practice of co-disposing hazardous and non-hazardous waste in the same landfill will end. The directive requires all waste to undergo treatment to cut its volume or hazardous nature, or to aid recovery. Certain wastes are banned from being sent to landfill, for example liquid wastes, tyres and certain hazardous wastes. The volume of biodegradable waste going to landfill is also being targeted. Composite waste is currently classed as non-hazardous under the banner heading of ‘Biodegradable wastes and other non-special waste which can give rise to organic or other contamination’ according to the UK Waste Classification Scheme [12]. As a landfill material, composite waste is relatively inert compared with other waste (such as food waste), producing no leachate or methane gas.

The landfill directive is likely to have some influence on the composites industry as the cost of disposing of waste in this manner will increase in the near future. The directive focuses on diverting as much waste as possible away from landfill, which means that the re-use, recycling and recovery of composite waste will be encouraged over landfill. As engineered products the value of the composite component is far greater than the value of the raw materials. Production processes already focus on waste minimisation, although certain processes may create considerable waste or rejects at the beginning and end of the production sequences. Generally, around 10% of the total weight of raw material processed is believed to end up as waste.

2.3.1 Landfill tax

The landfill tax credit scheme (LTCS) [13] was introduced with the landfill tax in 1996 and applies to waste disposed of in licensed landfills. The LTCS was designed to help mitigate the effects of landfill upon local communities. It encourages partnerships between landfill operators, their local communities and the voluntary and public sectors. The aim of landfill tax is to ensure that the price of landfill fully reflects the impact that the landfilling of waste has upon the environment. It provides an incentive to reduce the quantity of waste sent to landfill and increase the amount of waste managed by processes higher up the waste hierarchy. The money raised from the landfill tax is used to encourage the use of more sustainable waste management practices and technologies. There are two rates of tax: a standard rate of £18 per tonne and a lower rate of £2 per tonne [14]. The Government has stated that the standard rate of tax will rise by £3 per tonne per annum to a rate of £35 per tonne in 2010. Even though composite waste tends to be lightweight, these increasing costs will have some impact on the composites industry if it continues to rely on landfill as a disposal route for composites waste.

The typical charge made by a waste disposal firm for skip hire is around £320 + VAT for a 40 cubic yard (31 m^3) container, which is the largest available [15]. No distinction is usually made by the operator on the nature and weight of the contents, provided that they are non-hazardous. Landfill tax is applied to the skip operator and not the waste producer, although this is of course reflected in the fees and passed on to the ‘consumer’.

2.4 Incineration of waste directive

The aim of this directive is to prevent or limit the negative effect on the environment and resulting risks to human health, from the incineration and co-incineration of waste [16]. Limits are set concerning levels of emissions to air, water and soil. Residues from the incineration process will be minimised in their amount and harmfulness and recycled where appropriate.

All incineration processes should comply with the incineration of waste directive [17]. An operator dealing with composites would have to ensure that the material was burnt properly without exceeding any of the set pollution limits. Should GRP (glass-reinforced polymer) be sent to a municipal waste incinerator it would probably need to be well mixed with other waste to ensure operation within the combustion envelope of the incinerator and to prevent emissions that may swamp the pollution abatement system.

At present, the apparent environmental benefits of energy recovery by burning plastics such as GRP in a waste incinerator are likely to be outweighed by significant drawbacks. Burning plastics waste limits the amount of biodegradable household waste such as paper and cardboard which can be processed. This means that more biodegradable waste goes to landfill, where it breaks down to form methane and carbon dioxide. Although much of the methane can be collected and used as fuel, some may escape into the atmosphere. Methane is known to be about 25 times more potent as a greenhouse gas than carbon dioxide. Unless plastics waste is burnt as a direct replacement for oil or gas, the environmental effects are negative.

2.4.1 Typical costs
London Waste incinerate municipal waste to generate electricity. They will accept ground GRP waste, but actually make a higher charge for its disposal than they do for ordinary waste because the high calorific content of the waste and limited capacity of the boiler cause them to burn less domestic waste material – of which there is a practically unlimited supply – which must then be sent to landfill. The estimated charge for GRP incineration is £120 to £150 per tonne, whereas ordinary waste can be incinerated for around £30 per tonne. This firm is not able to process any piece of GRP material larger than 1 square metre, and will send it to landfill. The bottom ash, which in the case of GRP incineration will contain the glass content, is capable of use in road construction.

2.5 End-of-life vehicle directive

Around 2 million end-of-life vehicles (ELVs) arise in the UK each year [18]. There are two categories of end-of-life vehicles: relatively new cars resulting from accident 'writeoffs' (premature ELVs), and cars which have reached the end of their life naturally. The average life of a car is about 14 years. Around 85% (by weight) of vehicles are presently recycled or recovered. The ferrous and non-ferrous metals account for around 76 per cent of its overall weight and are routinely recovered, reused and recycled to high levels for the economic value that they represent [19] . The more difficult challenge is to recover, recycle or reuse the non metallic parts which together with the metallics will be required to be recovered up to 95 per cent by weight within 15 years. Recycling these materials is more difficult for technical and economic reasons; therefore the majority of these currently end up in landfill. It is estimated that on average plastics make up 9% of the weight of a car, and this is increasing as car manufacturers continue to lighten vehicles to improve fuel efficiency [19]. Vehicle component engineers are increasingly specifying plastics parts with a recycled content, which helps to stimulate the market for recycled plastics and therefore recycling rates for ELVs.

The end-of-life vehicles directive came into force in October 2000, and was due to be transposed into national law in all Member States by 21 April 2002. This was delayed since, as in most other Member States, the UK is currently in the process of introducing the remaining provisions relating to producer responsibility - Articles of the ELV Directive (5 and 7) - and these will be transposed through the End-of-Life Vehicles (Producer Responsibility) Regulations 2005. The directive aims to prevent waste from vehicles and promote the re-use, recycling and other forms of recovery of end-of-life vehicles and their components so as to reduce the disposal of waste [20]. Waste prevention is the priority objective of the directive. Articles 5 and 7 require that: -

- Owners must be able to have their complete ELVs accepted by collection systems free of charge, even when they have a negative value, from 1 January 2007 at the latest;
- Producers (vehicle manufacturers or professional importers) must pay 'all or a significant part' of the costs of take back and treatment for complete ELVs;
- Rising targets for re-use, recycling and recovery must be achieved by economic operators by January 2006 and 2015

Specifically, the ELV directive's main requirements are for member states to ensure that:

- Producers limit the use of hazardous substances and increase the quantity of recycled material used in the manufacture of their vehicles; and that producers design vehicles for easy recycling
- As of 2007, producers pay all or a significant part of the costs of free take-back of no or negative value vehicles to a treatment facility;
- Producers meet certain recovery and recycling targets by 1 January 2006 and 1 January 2015; and
- Treatment facilities have permits if they want to deal with ELVs and should operate to higher environmental standards.

New vehicles should be designed and produced to facilitate the dismantling, re-use, recovery and especially the recycling of ELVs and their components and materials. The amount of recycled material used in vehicle manufacture should be increased in order to develop the markets for recycled materials. The waste hierarchy must be applied wherever possible, encouraging the re-use of components which are suitable for re-use, and recovering components which cannot be re-used giving preference to recycling when environmentally viable. The directive sets a re-use and recycling rate of a minimum of 80% within a re-use and recovery rate of 85% (by an average weight per vehicle and year) to be reached by 2006. The targets will be increased to 85% re-use and recycling within a 95% re-use and recovery rate to be achieved by 2015.

Automotive composite suppliers could lose their market share to metal industries if they cannot ensure that their composite components can be re-used or recycled at the end of their lives. The main composite competitors in the car industry are aluminium and iron/steel industries who can easily meet the re-use and recycling targets. Cars being sold in the future will have to comply with these targets. These cars are in the design stages now, meaning that component suppliers will soon be asked to deliver items meeting these re-use and recycling specifications. The perception that composites are not recyclable could prove damaging to the use of thermoset based composites in the automotive industry, which is ironic since the use of composites is designed to reduce fuel consumption and increase performance. In the case of bodywork, the aim of the use of composites is to prolong the life of the vehicle by utilising a corrosion-proof material. Although composite bodywork has been used on caravans, van roofs and threewheel cars, it is also used on high-value cars such as Lotuses and TVRs which, unless written off, are not actually scrapped.

The end-of-life vehicles directive takes no account of the re-use of plastics waste as fuel. This has a direct bearing on the composites industry, since energy recovery is widely considered to be the best practicable environmental option for this material. Polymers in composites are derived from crude oil in the first instance and 95% of the world's production of crude oil goes to energy production.

On Monday 3 November 2003 the End-of-Life Vehicles Regulations 2003 came into effect. The guidance notes [21, 22] explain how the Regulations apply to sites used for the storage and treatment of end-of-life vehicles (ELVs). The Regulations require operators to hold a site licence if accepting vehicles which have not been depolluted and set new minimum technical standards for all sites that store or treat ELVs.

2.5 Electrical and electronic equipment directives

Nearly one million tonnes of waste electrical and electronic equipment (WEEE) are discarded every year in the UK. Owing to their hazardous material content, electrical and electronic equipment cause environmental problems during the waste management phase if not properly pre-treated. Because of the complex nature of WEEE, recycling can be difficult [23]. Scrap electrical and electronic equipment was chosen as an EC priority waste stream in 1991. Current data on the recycling of WEEE suggest that about 49% by weight of all WEEE is sent to a recycling process [24]. On average 22% of this are plastics although the composition varies widely from item to item.

There are three EU directives in preparation concerning the management of electrical and electronic equipment. They could affect the use of composites in electrical equipment if the subject of re-use and recycling of composites is not tackled. The directives' focus and emphasis on recycling of components could pose a threat to the use of composites in electrical and electronic equipment.

2.5.1 Waste electrical and electronic equipment (WEEE) directive

This directive focuses on the management of waste electrical and electronic equipment and sets out measures for collecting end-of-life electrical and electronic equipment for recovery, recycling and re-use [25]. The objectives of the WEEE directive are the prevention of WEEE and increasing the reuse, recycling and other forms of recovery of WEEE in order to reduce the disposal of waste and encourage resource efficiency. It also aims to improve the environmental performance of all operators involved in the life cycle of electrical and electronic equipment, particularly those involved in the treatment of WEEE. The directive proposes separate collection of WEEE and a target to collect a minimum of 4 kg per year of WEEE per household by the year 2006. The directive also proposes recovery targets of between 70 and 80% by an average weight per appliance, and re-use and recycling targets of 50 to 75% depending on the category of the WEEE. The targets are due to be reviewed five years after the directive comes into force.

On 15 December 2005 the Department for Trade and Industry announced that there will be a review of current proposals for the implementation of the WEEE Directive. This decision reflects the continuing concerns expressed by businesses and stakeholders. It also reflects the Government's commitment to implementing the Directive in the UK in a way that maximises the environmental benefits associated with the Directive and minimises the costs to business [26].

2.5.2 Restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS) directive

This was originally intended to form part of the WEEE directive but has now been made into a separate directive. The UK RoHS Regulations have now been made and were laid before Parliament on 7 October 2005. The main objectives are to protect soil, water and air from pollution caused by the current management of WEEE, and to reduce the harmfulness of WEEE [27]. The environmental risks associated with the waste stream are not properly dealt with by current waste management practice. Currently more than 90% of WEEE is landfilled, incinerated or recovered without any pre-treatment, which leads to a considerable input of hazardous materials into the disposal or recovery routes. The separate collection and treatment of WEEE (as suggested by the WEEE directive) will contribute to a cleaner municipal waste stream and therefore reduce the emissions caused by the incineration or smelting of WEEE containing heavy metals and halogenated substances. The most effective way of ensuring the significant reduction of risks to health and the environment related to heavy metals and flame retardants used in electrical and electronic equipment is to substitute these with safe or safer materials. The directive states that by 1 January 2008 new electrical and electronic equipment put on the market must not contain lead, mercury, cadmium, hexavalent chromium, or brominated flame-retardants. This directive may influence the composites industry as the materials sometimes incorporate brominated flame-retardants. One of the main difficulties in recycling plastics containing brominated flame-retardants is the risk of dioxin release during the plastics recycling process.

Envirowise [28] offers UK businesses free practical help on the WEEE and RoHS Directives, as well as other environmental issues free of charge.

2.6 Proposed recommendations for construction and demolition waste

In 2001 the Office of the Deputy Prime Minister carried out a survey into the arisings and use of Construction and Demolition wastes [29]. This followed an initial survey in conjunction with the Environment Agency in 1999/2000. Total construction and demolition waste for England and Wales was estimated at 93.91 million tonnes up from an estimated 72.5 million tonnes in 1999. 48 per cent was recycled and a further 48 per cent was beneficially re-used, mainly for layering or topping at landfill sites and backfilling quarries. The remaining 4 per cent was sent to landfill as waste.
The European Commission wishes to introduce a recommendation (a non-binding measure) for construction and demolition (C&D) waste with the aim of improving the management of the C&D waste stream by following the waste hierarchy, giving preference to prevention over re-use, material recycling, energy extraction and lastly disposal. It will aim to reduce the impact of C&D waste on the environment whilst better utilising natural resources.

The recommendation will also encourage the substitution of hazardous substances in new buildings and make sure that waste from construction (bricks, glass, wood, etc) is sorted at the point of generation. It would also include proposals for recycling targets set initially at 50% and an increase in landfill charges. It is thought that the European Parliament would prefer binding legislation rather than just a recommendation. So far progress has been very slow. If adopted, this recommendation/legislation will have a significant impact on the composites industry which supplies the construction sector.

2.8 Life cycle assessment and cost implications of recycling or disposal

Life Cycle Assessment (LCA) is a method of assessing and quantifying the environmental impact of products taking into account the methods and materials used for manufacture. It also considers the impact on the environment during use of the product and its disposal, whether through recycling, incineration or dumping in a landfill site. Much of the necessary data for performing an LCA can be found in various software packages available commercially. However, there is some debate as to the accuracy of this information as the technique is still in its relative infancy. The main use of LCA is to provide a comparison between the use of different materials or manufacturing processes for a given product to determine the benefits or disadvantages or adopting a specific design strategy. It is, however, very difficult to assess the impact caused by a single product without a comparison, since the impact scores obtained in the analysis cannot be taken as absolute. This is because no way exists to quantify an exact damage to the environment from a particular process or emission. Hence, the best way to interpret the data is to compare with a similar product or design. There is also the potential problem that the impact factors calculated for the same product in different commercial packages may be different as the parameter and data used in the analysis are unique to that package. A point which is increasingly important is the issue of cost and no package yet includes any method of inputting cost into the equation.

The main potential problem with LCAs is the lack of international standards. The ISO14000 [30] series of standards are currently being created to deal with these areas but until that process is complete, there will be no definitive answer to many of the problems faced by users of the LCA software. There is no standard method of applying the weightings to the different environmental effects that occur to take into account the seriousness and potential for environmental damage. Each package has its own weightings and, without years of research, these cannot be either discounted or recommended. There is also the issue of whether to include the internal environment of the manufacturing facility within the LCA.

The main emphasis of LCA is also in question as different reports have suggested different ways of looking at the environmental impacts. These can be either defined as the risk to human health or the potential damage to the earth's ecosystem, there are convincing arguments for both ideas. As with any method, the data used are of critical importance, particularly in respect of the disposal of the products at the end of their use.

The main problem facing designers when working with composites will be deciding on how to input the material into the LCA. This could be done either by calculating and measuring a new set of data for each material, or by calculating the data from the constituents of the material summed together. This second method has a number of potential flaws in that the processes used during manufacture may be completely different, or because by adding materials together certain benefits or disadvantages could be gained in terms of environmental impact. Equally, the disposal of the composite product after use could result in significantly different data for assessing the environmental impact. Also, the processes that can be used to dispose or recycle the components may be significantly different from those used for single materials. In the short term the way forward for using LCA tools with composites is to concentrate on comparing the impact of the composite material with the impact of the equivalent single material. This will allow designers to see how they can use composites to benefit the 'greenness' of their products. The main aim should therefore be to produce a set of guidelines that designers can utilise to help them design with composites by using LCA tools. Hopefully, this will show designers how to reduce the environmental impact damage of their products whilst letting them explore the possibilities of composites. The long term aim would be to incorporate comprehensive data for a range of composites in the software LCA tools that are available so that designers have to think less about how to use and interpret the data.

Various life cycle assessment tools are available:

Green Guide to Composites: This guide has been created to allow the composites industry to understand the environmental and social impacts of different composite materials and manufacturing processes.
The life-cycle impacts of each material and process choice from the cradle to the factory gate are presented in simple A to E comparative rankings, for the first time allowing informed decisions to be made on the environmental and social effects of composite materials and process choices. http://www.netcomposites.com/composites-green-guide.asp

SimaPro 4 (PRé Consultants BV) SimaPro is a full-featured LCA software tool. Complex products with complex life cycles can be compared and analysed. The process databases and the impact assessment databases can be edited and expanded without limitation. The ability to trace the origin of any result has been implemented in a very flexible and powerful way. Special features are: multiple impact assessment methods, multiple process databases, automatic unit conversion. Furthermore, there are powerful tools to analyse take-back and disassembly of products, as well as complex waste treatment and recycling scenarios.
http://www.pre.nl/simapro/

ECO-it: (PRé Consultants BV) Eco-Indicator Tool for environmentally friendly design. ECO-it allows you to describe a complex product and its life cycle. By entering the materials and processes that are used. ECO-it immediately calculates the environmental load, and shows you which parts of the product contribute most. Based on this information you can design to reduce the environmental load of the product.
http://www.pre.nl/eco-it/default.htm

Useful links:
De Vegt OM and Haije WJ, Comparative Environmental Life Cycle Assessment of Composite Materials, ECN-I--97-050, December 1997. Downloadable pdf file:
http://www.ecn.nl/docs/library/report/1997/i97050.pdf

3. WASTE MINIMISATION

Waste minimisation is about preventing and reducing waste at source through the efficient use of raw materials, energy and water [31,32]. This is achieved by understanding and changing processes to reduce and prevent waste. This is also known as process or resource efficiency. Waste minimisation includes the substitution of less environmentally harmful materials in production processes and the design of products that have less environmental impact during their manufacture and use. Waste minimisation can provide competitive advantage to business in four ways:

- Cost savings
    - Production costs can be reduced through improved resource efficiency.

- Compliance
  - A proactive approach ensures that the company minimises the possibility of litigation.
- Risk reduction
  - Control and reduction of risks and liabilities not only reduce the likelihood of fines and bad publicity but can also boost investor confidence.
- Market positioning
  - Eco-friendly products can give supply chain confidence and improve customer relations.

Waste minimisation is a basic management philosophy and approach to achieve a more profitable business [33]. There are waste minimization tools available [34]. The key tools in waste minimization are the 'waste tracking model' and the 'cause and effect diagram'. These help to find both 'fast starts' and to develop a systematic approach for long-term savings.

Envirowise [28] offers UK businesses free practical help on waste minimisation issues, as well as other environmental issues free of charge. The Waste Minimisation Faraday [35] can also offer guidance,

4. RE-USE OF COMPOSITE MATERIALS

Re-grading and re-certification of materials is important if a component and/or material from post-manufacture or from demolition is to be re-used in another project. Thus it is necessary to consider whether re-use of composite material is appropriate [15].

Re-use is high in the waste hierarchy, but may not provide the most practical option for many composite applications. The way in which a material is used, its applications and how it is secured to other components must be considered with a view to deconstruction and re-use at the end of that application's life. The manufacturing process must be examined to identify any possible modifications to enable design for future re-use or recycling.

4.1 Issues associated with material re-use

4.1.1 Properties of composite components

Although composite manufacturers today have largely solved the problem of ultraviolet stability and colour fading of their products, composite materials used in external applications may have suffered surface degradation.

Many items made from composites are bespoke in nature, being especially designed for a particular application. This means that it is very unlikely that such products will to be able to be re-used for another, different, application. Some downgrading of product use may be possible (e.g. to agriculture). Some unusual or novel re-use of bespoke composite features may occur. Re-use already takes place of items like cabins and gatehouses in the construction sector, pallets in the packaging sector.

Structural items may be difficult to re-use because it is difficult to re-calculate their load-carrying properties as recovered items. Without reference to the original manufacturer, it will be impossible to derive the strength characteristics (such as shear and bending) of a composite section. Composites tend to be produced to meet a particular set of circumstances and conditions so will often not be transferable to a different use. The designer of a structure has a duty of care to make sure that it is sound, and a recycled material cannot be used if its strength properties are unknown or in doubt. Similarly, a composite material may not be able to be re-used for certain applications if its fire-resisting properties are unknown.

4.1.2 Re-certification

Re-certification of composites products is unlikely to be cost effective if testing is involved. For example, the cost of testing a trussed rafter is around £1500 for a product which costs around £30 to manufacture. Re-certification by the original manufacturer may not be in their financial interests.

4.1.3 Dismantling for re-use

Dismantling a composite structure for re-use can prove difficult as there are often problems associated with removing any fixings and then removing the item undamaged. Additionally, there may be hazards to deconstruction staff such as exposure to dust if the composite has to be cut up. Within the construction sector, the demolition firm at such sites is unlikely to consider the careful recovery of items and deconstruction lengthens the process of site development. Development of modular and prefabricated systems using composites may allow re-use if this aspect is considered in design, especially with respect to the type of site-applied sealing and gluing of joints [15].

After use, composite materials may be dirty and require careful cleaning, which is a costly, labour-intensive task. They may also be contaminated (e.g. with sewage or chemicals). The reclaimed materials will require storage and composite materials tend to be quite bulky.

There is presently little or no market for used composite components. For re-use to be successful there must be an established supply chain.

4.2 Certification of recycled composites construction products

Schemes are being developed to make it easier to approve construction products on performance rather than on materials specification. However, current procedures do limit the incorporation of recycled product in many instances.

Oxford Brookes University supported by AEA Technology, Mouchel Consulting and Tony Gee & Partners are addressing the development of a performance-based classification scheme to enable engineering designers to select materials systems on the basis of performance requirements [36]. Procedures are being developed for the assessment of materials systems on site, involving the development of manufacturing techniques for on-site fabrication of reliable and consistent test pieces. This activity is linked with development of in-service health monitoring techniques that employ both destructive and non-destructive testing. Generic design guidance is being compiled that utilises the performance classification scheme and is informed by experience. Case histories are being used to reinforce the guidance further. The major outputs from this project include the performance classification scheme, test protocols, design guidance and practical application guidance.

5. RECOVERY OF COMPOSITES WASTE

To make recycling procedures as easy and cost effective as possible, composite waste needs to be recovered in as clean and pure a condition as is feasible. This can be difficult to achieve since the materials are often used in association with other materials, often being joined together by adhesive or mechanical means. Materials need to be clearly labelled for rapid and accurate identification of component contents. Thus deconstruction of structures and components in order to recover composite waste is a key step in the recycling process. After use, composite materials may be dirty and require careful cleaning, which is a costly, labour-intensive task. They may also be contaminated (e.g. with sewage or chemicals). The reclaimed materials will require storage and composite materials tend to be quite bulky.

5.1 Sorting and cleaning of mixed composite waste

Usually, in order to obtain good properties of recyclates, even mechanical recycling of mixed polymer-based waste will require some preliminary sorting. Methods to sort polymeric materials should be as easy and economical as possible for the resulting recyclates to be competitive. Currently, most sorting of this waste is still done by hand, a time consuming and expensive process, that on the other hand needs little equipment. Technology to sort polymers automatically is being developed and introduced [37, 38].

Before sorting, polymer-based waste is usually reduced to smaller and uniform particle sizes. In a first step, shredders or hammer mills are used to break up the waste objects. With a grinder or granulator, they can then be reduced to smaller particle sizes. Furthermore, to improve efficiency of following sorting steps, the waste needs to be cleaned from dirt particles and contaminants (e.g. friction washer) and subsequently dried (e.g. fluid bed dryer) [37, 39].

With magnetic separators, ferromagnetic particles are removed from the waste (e.g. top belt magnets, drum magnets). Non-ferrous but paramagnetic metals such as aluminium, copper, lead etc. can be removed with eddy current separators by deflecting the non-ferrous metals from the main particle stream [39].

Density characteristics are exploited in various ways to separate materials. For example, separation can simply be achieved by subjecting a material mix to an air stream or with hydrocyclones and centrifuging, where size and shape of the polymer particles will also play a role. Only if the difference in density is sufficiently high can polymers be separated from each other by these techniques [39]. In a sink-float separator, particles with higher density than the separation medium will sink and the other particles will float on the surface. Similar processes use a surfactant that makes thermoplastic materials hydrophobic so that aeration causes the particles to float. This works rather because of surface properties than density characteristics [39, 40].

Electrostatic separation as a means of charging the materials has long been used for the separation of polymeric materials and metals. Nowadays, a variant of this technique can also be used to separate different polymer types. Polymer flakes are given a slightly positive or negative charge allowing, for example, separation of polyethylene and polypropylene. This is effective for a simple two-material separation, but for separation of mixtures with more than two resins it may require more than one pass or a combination with other methods [40].

Helped by an organic solvent, two or more polymer types can be separated from each other in a process called selective dissolution. In this process, the polymers are first dissolved, then filtered, isolated, re-solidified and dried. The solvent can be recovered after filtration. However, environmental impact of the solvent itself and solvent remaining in the separated polymers can not be neglected [39, 41].

A new process developed by Oekutec (Germany) is able to separate thermoplastic materials from thermoset materials as well as a specific thermoplastic polymer from a mixed stream of various thermoplastics. A polymer stream is heated with a specific IR-spectrum that softens only the target material (e.g. polypropylene). The softened material is then picked up by a roller, while all the other materials pass by and can be separated in following steps helped by another IR-spectrum [42].

There are also many different types of automated sorting systems on the market that employ some kind of detection signal and sensor to detect and analyse chemical or physical characteristics of different polymers. Some technologies can sort a large number of different resin types by type and colour, while others can only identify one item and separate it from a waste stream. [43-45].

5.2 Material Labeling

Several schemes exist to label polymer products to facilitate separation of waste and promote easier recycling. The SPI system was developed in 1988 in the USA to provide a consistent national system to facilitate the recycling of polymer products. It has been universally accepted by the packaging industry, but covers only 6 main resin types, all others being categorised under a seventh named ‘other’. Each plastic component is stamped according to its resin type [46]:

The SPI categories are:
Type-1 Plastics – PET (polyterephthalate)
Type-2 Plastics – HDPE (high density polyethylene)
Type-3 Plastics – V (PolyVinylChloride)
Type-4 Plastics – LDPE (low density polyethylene)
Type-5 Plastics – PP (polypropylene)
Type-6 Plastics – PS (polystyrene)
Type-7 Plastics – other (which commonly includes: Polycarbonate, ABS, Nylon, Acrylic or a composite of 2 or more resins)

In addition, the Publicly Available Specification 103 (PAS 103) [47,48] will help to reduce the amount of plastics packaging waste sent to landfill in the UK by enabling more material to be recycled. PAS 103 is a classification and grading system for the quality of collected waste plastics packaging intended for recycling. Through this system the value of the materials being bought and sold will increase, markets for the waste will expand and the trading process will be simplified through the adoption of a common language.

5.3 The Universal Recycling Symbol

The universal recycling symbol was invented by Gary Anderson in 1970 as part of a contest sponsored by a paper company. The design is based on a Mobius strip, i.e. an endless loop that has only one surface. It is used to indicate that a material is recyclable. For more on the history of this symbol and the paper recycling symbols that were derived from it, see http://www.afandpa.org/recycling/anders.pdf

6. RECYCLING TECHNOLOGIES

There are essentially four classes of recycling technique which apply to composite waste in general:

- Primary recycling – conversion of waste into material having properties equivalent to those of the original material
- Secondary recycling – conversion of waste into material having properties inferior to those of the original material
- Tertiary recycling – conversion of waste into chemicals and fuel
- Quaternary recycling – conversion of waste into energy.

Most tried techniques for primary and secondary recycling essentially involve mixing of some waste material with virgin raw material, which is then processed as if it were all virgin material. Whether the proper designation for the procedure is primary or secondary recycling is a matter of how successful it is. Tertiary recycling refers to chemical decomposition of the polymer, i.e. depolymerisation, into useful chemical substances and fuel, while quaternary recycling is synonymous with incineration with utilisation of the energy released. The technique of incineration without energy utilisation is not really recycling at all, merely a means of reducing waste volume.

From the point of view of material utilisation it is generally preferable to succeed with the highest possible level of recycling, e.g. secondary rather than quaternary recycling. However, from economical and overall resource utilisation perspectives this need not necessarily be the case, since for example secondary recycling may require excessive amounts of energy and other resources (facilities, man power, chemical additives etc.), while quaternary recycling is straightforward and does not require energy or specialised resources.

6.1 Primary and Secondary Recycling

The most attractive recycling option is to recycle waste into material with properties equivalent or at least comparable to those of the original material (as common with metals and glass) since it implies a possibility for an infinite number of recycling circuits. The division between primary and secondary is relative and a question of what extent of property degeneration that one is able to allow while still saying that the properties are equivalent. Common alternative names for primary and secondary recycling are material recovery or mechanical recycling.

6.1.1 Recycling thermoset composites

Although it may be conceptually less straightforward to recycle thermoset composites than thermoplastics, the common misconception that thermoset composites cannot be recycled, due to the presence of crosslinks, is a myth. Proven technologies for material recovery are based on shredded then ground or milled composites used as a filler or possibly as replacement for some of the reinforcement in composites that generally end up having properties inferior to those in the original material.

To enable material recovery of thermoset composites, the component to be recycled must first be reduced in size. With a large component the first step is generally to saw or break it into manageable pieces that can then be fed into a shredder to further reduce their size to the order of tens of centimetres. Prior to shredding all metal inserts and fastners must be removed. The shredded material is then ground to small pieces or milled to a powder, the final particle size may be anywhere between several millimetres to fractions of a millimetre. This regrind is separated by size using gradually courser meshes. In coarse regrind the reinforcement remains partially intact and thus the regrind may be used for reinforcing purposes, while the fine powder may only be used as a filler.

Ground composite waste can be recycled as secondary raw materials for SMC (sheet moulding compound) and BMC (bulk moulding compound), and also as filler or reinforcement. Only good quality composite waste with guaranteed formulation and no contamination is suitable for this, for example manufacturing waste. Using ground composite recyclate in SMC and BMC does not have a detrimental effect on the mechanical properties of the product as long as the recyclate is used under certain ratios (no more than 20% for SMC and 30% for BMC). However, the low-value use of recyclate in this way means that it is difficult to recover the cost of the recycling process [49, 50].

An example of the cost implication has been demonstrated in a study using recyclate in the form of granulates from SMC used parts and production scrap to manufacture sandwich structures. Recycled contents of between 10 and 20% of total laminate weight were obtained, using the recyclate as a substitute core material. The overall cost increase for using recyclate was under 10%, but this did not take into account reduction of disposal costs and future costs for recycling after product life, which will have increasing importance in years to come [51].

There is concern that more complex composite products such as sandwich panels may be more difficult to recycle with separation of the components necessary. The outside skins must be easily separated from the core to enable recycling. A study in Spain [52] has shown that sandwich panels produced using unsaturated polyester composite resin transfer moulded (RTM) skins and PET foamed cores can be recycled. The sandwich panels were milled resulting in separation of the skins and cores. Water flotation was used to sort the foam from the skin, since the foam floats to the top because of its low density. The separated parts were dried and further milled. The resulting powder from laminate skins was used in BMC trials and other processes as a filler, and the PET powder was recycled [52].

In the UK, the **RRECOM** project (1994-97) focused on strategies and technology for the re-use of suitably comminuted (ground) thermoset recyclate as a functional filler for polymers leading to products with added value [53]. An integrated continuous compounding process was developed which included comminution, drying and volatile extraction, combination of reinforcement with the matrix, optimum mixing, and die forming of the material. The recyclate was combined with the polymer matrix ensuring that effective dispersion and wet-out occurred. A range of polymer compositions were created containing fibre reinforced polyester and phenolic recyclate derived from industrial scrap. The thermoset recyclate fillers were successfully incorporated into polypropylene and an enhancement in mechanical properties relative to the unfilled polymer were achieved. Reinforced phenolic recyclate was successfully incorporated into polyester resin and improvements in fire performance (reduction of smoke emission) relative to unfilled polyester resin were obtained. The study suggested that integrated compounding technology provides a cost-effective route for realising value from reinforcing thermoset recyclate fillers.

6.1.1.1 Issues to consider for use of ground recyclate

The major factor shaping the future of thermoset composite recycling is economics. One way to improve the economics of recycling is to use the recyclate in applications that create a higher value. The economics of recycling thermoset composites for use as replacement filler is a breakeven situation for the consumer [50].

The inclusion of composite waste into new material may change the properties, colour and fire resistance. Addition of the recyclate to a resin may result in increased stiffness, possible decrease in strength, and increase in density and damping. The importance of these changes will depend on the application of the new material. Recycling is feasible but not necessarily cost-saving. Environmental benefits must be offset against the costs of the recycling process. Political and environmental pressures may force manufacturers to consider recycling composite materials more in the coming years [15].

There are several issues associated with use of ground thermoset composite [15]. These will determine whether this is an economically viable option for disposal.

- Common filler materials (sand, calcium carbonate, glass) are inexpensive and so this may not be an economical option.
- The grinding machines themselves represent a considerable investment and are subject to heavy wear because of the abrasive nature of the material. Grinding plants also require energy to operate. Utilisation of ground composite merely as a non-structural filler thus represents a waste of a commodity with reasonably high energy value (around 36 MJ/kg), as well as a loss of the reinforcement properties of the glass fibres.
- Transport of composite waste to a distant recycling plant rather than a local landfill will add to traffic pollution and road congestion.
- Composite material may itself be combined with other materials to make a ‘composite’ from which it is difficult or impossible to recover the polymer composite element
- Waste material has to be sorted and stored.
- Fragmented composite material can constitute some hazard due to the glass fibre content.

6.1.2 Recycling thermoplastic composites

Since thermoplastics can in theory be melted and cooled to solidify an infinite number of times, recycling of thermoplastic composites through material recovery should be easier than for thermosets. While this is generally the case, studies have shown that repeated recycling processes often induce degradation of polymeric materials in the form of chain scission (shortening) and narrowing of molecular weight distribution. This affects viscosity and mechanical properties. This is mainly due to mechanical shear and grinding, although it seems that incorrect processing parameters (e.g. temperature too high) cause more damage than repeated processing at suitable temperatures. However, these studies show that in a lot of cases recycling is possible without having to accept significant loss in properties. Characteristics of recyclates will always depend on the specific input material as well as on contamination and processing history. Properties can be improved by addition of compatibilisers or blending with virgin material [37, 38, 54-56].

Several studies have proven the feasibility of using GMT (glass-mat thermoplastic) materials by grinding and use, possibly with virgin material, in injection moulding [57]. An intermediate alternative is to extrude GMT scrap, with or without virgin material, and use the extrudate in compression moulding. This process is economically viable and many compression moulders manage to sell their GMT scrap to injection moulders.

Thermoplastic composites also offer the opportunity of reshaping one component into another. For example, a scrapped component of moderate curvature may be used as a blank in a compression moulding operation (possibly with intermediate reconsolidation into a flat blank). This amounts to true primary recycling without any property degeneration; properties may indeed be improved due to enhanced impregnation resulting from repeated melting and consolidation [58, 59].

SMC (Sheet Moulding Compound) from automotive applications is already successfully recycled nowadays. For example Southfield (US) reprocesses SMC into composite filler, used to substitute calcium carbonate, as well as into milled and chopped-strand glass fibre, used in injection moulding, BMC and other applications. Using the composite filler weight of a SMC component could be reduced up to 10% [60].

Materials such as natural fibre reinforced composites (NFRC) or self-reinforced PP (sePP) can be a significant advantage in terms of recycling. The main advantage of NFRCs is that if incinerated they don't form residues [61]. The benefits of srPP are based on the single material composition, making it easier to reprocess the material and allowing combination with other PP waste streams for mechanical recycling [62].

Ground thermoplastic composite material could be used, for example, to reinforce resin systems such as additives for sealants and adhesives, that presently don't use reinforced fibres [63]. Theoretically, inert particles from finely ground composite materials can also substitute fillers such as silica or calcium carbonate. However, in this case the recyclate cannot compete with the low cost virgin material because of added cost due to grinding of the composite material [61, 63]. In another case it has been shown that when using ground composite material to reinforce rigid polyurethane foam or for compression moulding compounds based on epoxy resin, strength of the resin systems can be significantly improved, even if only relatively small fractions of the recyclate are added. In this application there appears to be some market potential due to high cost of the substituted virgin material. These results also indicate potential for other resin systems, both from a technological as well as economical point of view [63].

6.2 Conversion of waste into chemicals and fuel – tertiary recycling

6.2.1 Pyrolysis

Pyrolysis is the heating of waste in the absence of air (oxygen) and is used to separate composite material into its original constituents. The process breaks composites down into gas, oil, fibre and a small amount of carbon. The oil and fibre obtained can both be reprocessed into composites. Again, the operating temperature must be tailored to the type of composite being processed in order to minimise thermal degradation of the fibres recovered.

Many people view pyrolysis as a means of recycling composite waste and many trials have been successfully conducted. However, the European Commission does not consider pyrolysis to be a recycling process [15].

The evolving technology of pyrolysis is thought to offer a route for the recovery and re-use of both the hydrocarbon and inorganic content of composites, producing recovered streams in the optimum condition for re-use. In particular, the process temperature and subsequent separation stage can be tailored to liberate the component materials whilst minimising thermal degradation. It is expected that the pyrolysis-based recycle route will be applicable to all composite wastes. The materials recovered will be optimised and their recycling and re-use fully evaluated to achieve viable and sustainable recycling routes with the potential for commercial uptake. A cost-effective recycling process is an essential step towards sustainable manufacturing. It will be particularly important for the automotive industry as it prepares to meet the requirements of the European end-of-life Vehicle Directive. For plastics manufacturers, the process could have a major impact in overcoming resistance to composites for new applications in an increasing range of advanced, lightweight components

6.2.2 Supercritical water processing

Supercritical water processing can hydrolyse and decompose composites effectively and cleanly without charring. The process involves heating waste composite in steam at 300 to 500 °C resulting in the material being decomposed and partially hydrolysed to phthalic acid, styrene, glass fibre and oil. A supercritical water system for recycling composite waste can be considered if its economics are reasonable. Such a system should also be able to take all types of composite, including those with epoxy or phenolic resins for example [53].

In Japan, a supercritical water processing system has been developed with a generating unit fuelled by mixed waste plastics which are thermally decomposed to generate gas which is in turn used as a fuel to produce supercritical water and electricity [64]. Using this system, it is feasible to recycle both composite waste and general plastics waste without any pre-treatment such as washing and sorting. It is thought that such a process can be economically viable as the system generates electricity which can be sold, creating considerable income, and also handling fees can be charged for the acceptance of waste plastics for thermal treatment. Little residue is produced by the system meaning only a small amount needs to be landfilled [64].

6.2.3 Fluidised-bed processing

A number of studies have looked at the use of fluidised-bed thermal processing techniques for recycling composites resulting in materials and energy recovery.
A fluidised bed is a chamber containing sand which acts like a fluid when suspended in an airstream. The chamber is heated to between 450 and 500 °C, too low and the fibres will not be fully cleaned, any higher and the fibres suffer a reduction in strength. Chopped-up composite material is placed in the bed. The resin is evaporated and the fibre is blown by the airstream to a collection point for recovery [65]. Gas enters a

secondary combustion chamber for heat recovery leading to clean flue gas and recovered energy.

A phase of the RRECOM project focused on the use of fluidised-bed thermal processing techniques to recover energy and fibres from composite waste in a form suitable for recycling into high-value products. In this study, initial investigations were conducted using a typical industrial sheet moulding compound (glass fibre reinforced polyester). The fluidised-bed process effectively cleaned the fibres of the polymer matrix leaving fibres of good quality with little surface contamination. The recovered short fibres had the same stiffness but 50% of the strength of virgin glass fibres.
Two high-value opportunities for re-use of the recovered glass were demonstrated:
- in the production of a glass veil product, and
- as a direct substitute for virgin glass fibre in a thermoset moulding compound.

A key aim of the project was to demonstrate that the fluidised-bed process was capable of recycling end-of-life components especially those of large volumes such as from the automotive industry which may be contaminated and mixed in nature. A painted car boot lid made from a double-skin glass reinforced polyester with a polyurethane foam core and metal inserts was processed in the fluidised bed. The recovered glass fibres were no different in quality from fibres recovered when pure composites were processed [53].

An economic analysis of the fluidised-bed recycling process showed that an operation recycling in excess of 10 000 tonnes of glass fibre composite material per year would be commercially viable. These are quantities that do not exist in the UK at present [53].

Further studies have been conducted by the University of Nottingham regarding the recycling of carbon fibre reinforced composites which are potentially a source of more valuable fibre for re-use. Prepreg offcuts currently provide the greatest source of carbon fibre reinforced polymer scrap. Carbon fibre composites generally do not contain fillers, only fibres and resin. These composites usually require the fluidised bed to be operated at a higher temperature (450 to 550 °C) as the epoxy resins they use are broken down at a higher temperature. Results have shown that the tensile strength of carbon fibres recovered is reduced by 20% at operating temperatures of 450 °C.

Potential applications for the re-use of recycled carbon fibre include thermoplastic moulding compounds, tissue products (non-woven), and lower-grade prepreg. In order to achieve high-value uses, research needs to be concentrated on improving fibre length, developing fibre alignment, high strength and modulus, and producing recyclate in suitable physical form for reprocessing.

A carbon fibre recycling plant has the potential to be viable at much lower annual throughputs than one for glass fibre composites, and may show a more favourable prospect of being viable in the short term. Most existing manufacturing technology has been designed for the use of long strands of fibre, so for the recovered fibres obtained from fluidised-bed processing to be used effectively, new manufacturing processes need to be developed which can use short fibres [65].

6.3 Incineration - quaternary recycling

When composites are combusted with energy recovery, the calorific value will depend on the inorganic content. Although the combustion of composite waste is thought to be cleaner than that of coal, there is still a bulky ash residue. For example, in a typical GRP product 40% is glass, 30% inorganic filler and 30% resin. The glass and the filler do not burn, leaving 70% of the composite as a residue after incineration. It has also been suggested that incinerating composite material with energy recovery results in energy loss (in the region of –400 kJ/kg). Together, these mean that incinerating GRP is not a long-term solution for dealing with this waste stream. Natural-fibre reinforced polymers are thought to be the best type of composites for incineration with energy recovery, as the natural fibres and fillers should burn easily leaving no residue and resulting in no energy losses [66].

Co-incineration of GRP in cement kilns is thought to be a slightly better option as this offers combined material and energy recovery and therefore utilises the material more effectively. The resin is burnt for energy recovery, and the glass fibres and fillers become part of the cement resulting in material recovery [67]. The cement kiln process means that no residue is left at the end. Companies wishing to use composite waste in cement kilns should ensure that their emissions meet the necessary regulations.

One problem with cement companies taking composite for raw material is that it can generate dust including glass fibre. For use in cement kilns, fragments of composite waste must be of a designated size, contain low concentrations of toxic materials and heavy metals, contain no foreign material (such as metal), have a specific calorific value, and must not generate dust such as glass fibres [68].

During trials in Japan, the shredded composite material was found to have a lower than expected calorific value as some of the resin was lost during the shredding process. This meant that the waste had to be mixed with another material to reach the necessary calorific value for use as a fuel by the cement industry [68].

The need for the composite waste to be shredded before use increases overall costs, and the production of a large amount of dust has to be controlled. It has been suggested that the fuel substitution with GRP is limited to around 10% (due to the boron in the E-glass fibres) [69]. There is the question of whether the unburnt filler and glass incorporated into the cement produced, change the specifications of the product. The cement industry charges a fee for using the composite material. It is estimated to cost 1 Euro per kg to send composite material to the cement industry for processing. It has also been suggested that the potential saving of substituting fuel with composite waste is around £20 per tonne of GRP used.

In addition to co-incineration in cement kilns, composite waste can be co-combusted with coal in a fluidised bed. When limestone-filled composites are used in this way, energy is recovered from the polymers, and the limestone filler absorbs oxides of sulphur from the coal, making the process cleaner.

Flame retardants are additives widely used in consumer electronics products to ensure safety. However, some brominated compounds used as flame retardants generate brominated dioxins when incinerated at low temperatures. For this reason, plastics containing such compounds are currently sent to landfill or incinerated at temperatures high enough not to generate brominated dioxins [70].

All incineration processes must comply with the European incineration directive [71] which aims to prevent or limit the negative effect on the environment and human health from the incineration and co-incineration of waste.

There are no specific limits or conditions for the incineration of FRP except for:
● Composites containing more than 1% halogenated organic substances (for example, this may affect fibre reinforced PVC, materials with >1% brominated flame retardants, sandwich structures with CFC foam)
● Composites polluted during use (for example, GRP tanks used for storage of loaded gasoline or PAH-containing products).
These particular types of waste may be classed as hazardous and their incineration would have to comply with operation conditions. With regard to co-incinerating waste in cement kilns, it is thought that this is still possible after the introduction of the directive, but careful attention would have to be paid to Annex II.

Discussions have taken place as to whether a tax on incineration should be implemented in the UK. It was suggested that introducing a tax on incineration would ensure that waste management did not simply shift from being a landfill-dominated system to an incineration-centred one [72]. The incineration tax would be set up similar to the landfill tax, with revenues from both contributing to developing UK waste management systems aiming to encourage re-use and recycling of waste where possible before incineration or landfill. The decision to create an incineration tax has been deferred until after the government publishes its study of the environmental health effects of all waste disposal and management methods [72, 73].

6.4 Use of composite recyclate

Several potential uses for ground composite recyclate exist and much research is being carried out to develop high value end market applications.

Artificial woods have been manufactured using powder from pulverised composite waste. The artificial woods were autoclaved from cementitious compositions with various other contents including carbon fibre. The material can be nailed and sawn like natural wood [74].

Other research has investigated the use of scrap graphite/epoxy prepreg waste as a high-performance reinforcement for recycled HDPE plastics obtained from the municipal solid waste stream [75]. Flexural properties increased dramatically with increasing prepreg content and creep resistance was enhanced. It is thought that the product may find a niche in the plastics lumber market owing to the improved modulus, strength and creep resistance compared with current commercial recycled plastics lumber [75,76].

The UK highway engineering industry shows a willingness to adopt alternative sources of material for use in road construction and thereby promote sustainable development. As road construction consumes vast quantities of natural materials, it has the potential to provide a suitable end-use for composite waste. A joint RMCEF project [77] is aiming to improve the recyclabilty of composite building products by incorporating GRP waste composites into highway materials and conducting tests to ascertain whether they have a detrimental effect on the material performance. Preliminary findings have shown that the addition of shredded GRP off-cuts at 1% has had minimal effect on the performance properties of 20 mm dense bitumen macadam [77]. The research is continuing using higher proportions of shredded composite material. Current research at BRE involves collation of information on types, quantities and location of composite waste-streams and selection of samples for laboratory evaluation [78]. Testing will include determination of aggregate equivalent properties, modification of bitumen properties, optimisation of percentage addition to wearing course and base course bituminous mixtures, determination of mixture properties using gyratory compaction, and determination of stiffness, fatigue, creep and permanent deformation. Road trials will evaluate perfomance of base course and wearing course mixtures following guidelines laid down by HAPAS.

The University of Nottingham is currently undertaking a DTI-funded project HIgh value composite materials from REcycled CARbon fibre (HIRECAR) [79]. This project aims to deliver a low-cost high specific stiffness/strength composite material obtained from recycled carbon fibres. This will offer sustainable manufacture and recycling at all volume levels, particularly in automotive production, and will enable a step-change in design and performance of vehicle structures. Carbon based polymer composites can deliver weight reductions of over 40% when used to replace steel in vehicle structure, but applications are limited by End-of-Life directives. The project brings together industrial partners from the automotive supply chain to deliver a high-grade low-cost recycled carbon composite material. Reclaimed short carbon fibres will be mixed with novel polymer matrices to produce bulk and sheet moulding compounds and preformed parts suitable for exterior body panels, structural components and for co-moulding with carbon fibre textiles - thus, representing all body in white (BIW) technologies. The resulting structure can itself be subsequently recycled. The proposal is viable at existing UK prepreg waste levels. Therefore the project delivers a route for immediate implementation that can be expanded as usage of carbon fibre increases to the proposed steady-state level of over 50% content of recycled carbon fibre in production of vehicle BIW.

In developing end uses for composite recyclate, the products should utilise properties given by the recyclate, particularly where these give added value [11], such as:

- Chemical and physical properties (e.g. phenolic composites for greater fire resistance)
- Where recyclate can give special surface effects and designs
- For noise absorption (wall panels or in roads)
- Use of fluffy material for high thermal insulation or for non-woven materials
- For viscosity modification of polymer mixes
- Use of coarse-grade material as a permeable flow layer in reinforcement for vacuum injection
- Low-cost core material (in boats or in wood substitute products)
- As reinforcement
- Milled fibres
- Asphalt reinforcement
- For concrete repair (concrete is prone to cracking in the first 2 days of drying, use of glass avoids crack formation, there is a few thousand tonne market in Europe for this application)
- In white lines for road markings (abrasive resistance)

The development of new, high-grade markets is a high priority for the development of composites recycling.

6.5 Composite recycling facilities

There are no composites recycling facilities in the UK at present [15]. Trials have been conducted in the UK to assess methods for material and energy recovery from composites, including fluidised-bed processing, pyrolysis, grinding, and incineration/co-incineration. However, there are currently no facilities set up to conduct this on a large scale. There are processes in development that can use mixed polymer waste as raw material. These processes could also utilise composite waste, for example, Plascrete [80] which uses mixed waste polymer as an aggregate in a cementitious composite and can use glass reinforced polymer. This is in trial production in the UK at present.

Facilities exist in other European countries, including Germany (ERCOM), France (MCR) and Norway (Miljotek), which grind composite waste for re-use. However, these facilities are not greatly used and have little output. They also have difficulties in finding markets for their recyclate.

The feasibility of mechanical recycling has been proven on an industrial scale, but low utilisation levels mean that these ventures are currently uneconomical. Therefore, an imbalance remains between the collectable waste and the potential end markets for recyclate. In order to meet these challenges, the key suppliers in the chain together with the European composite trade association, the EuCIA, and associated bodies are introducing the 'European composite recycling concept' [81]. This will help to fund the high investment needed to develop, validate and promote new recycling, re-use and end-of-life solutions for composite waste.

A European composite waste management company is currently being set up via the Green FRP Recycling Label [82] which will co-ordinate the recycling of all European composite waste. This pan-European approach developed by the EuCIA aims to address the waste management problems currently associated with composites by dealing with European waste in the most cost-effective way whilst respecting environmental and other obligations imposed by Europe, national and local legislation. It also aims to develop new, economically viable markets for composite recyclate so that industry can meet the recycling targets imposed by specific European legislation [58].

European waste legislation will force a move away from traditional waste management through landfill and incineration, to re-use and recycling. This is likely to result in significant increases in the cost of waste management for the composites industry. Under the Green FRP Recycling Label, license fees are paid by the industry for the use of the label, which in turn finances the waste management services. Products with the Green FRP Recycling Label are guaranteed to possess a recycling concept according to the latest European waste directives. Recycling is free of charge for products that have the label, whereas a charge will be made for recycling products without the label. It has been suggested that the Green FRP Recycling Label could lead to cost reductions for composites waste management in the region of 40%. The recycling label will promote waste management in order to increase the volume of compsoites waste collected for recycling. It will also finance the development of new technologies and markets for composite recyclate. Two fees make up the licence fee for the Green FRP Recycling Label:

- The recycling fee covers the recycling of parts and is based on the 'producer pays' principle and takes into account the weight of the part, the complexity of recycling (pushing for designing for recycling), and bonuses for using recyclate (to encourage and achieve recycling). The recycling fee should be added to the part price, the amount of which is variable and should be revised annually, but is around 0.06 Euro (£0.05) per kg of end product.

- The system fee finances closing the loop, is paid by all parties involved within the composites industry, and is approximately 30 000 Euro (£22 556) per company per year. The system fee covers the cost of the Green FRP Recycling Label system, waste management services, research and development of new and improved recycling technology, and market development activities.

There are concerns that the EU regulation on the shipment of waste within, into and out of the European Community (259/93/EEC) may have an impact on the transport of composite waste across borders to countries in which a composites recycling plant exists. The GPRMC [81,82] are endeavouring to ensure composite and polymer concrete waste is classified Green in the Green–Amber–Red list of this regulation in order to facilitate the transport of waste to existing composite recycling plants. Composite waste for recycling is not yet listed in the Green–Amber–Red list. Therefore, if composite waste is transported between countries, it must follow the same procedure as for material on the Red list. This means that certain procedures must be followed and there is a need for notification of transport of the material, a sample for analysis before the composite can be ground, and agreement from the origin country and all others it will be travelling through. The GPRMC argue that the individual components of composites are on the Green list, therefore the waste should be on the Green list.

6.5.1 ERCOM recycling facility, Germany

The ERCOM recycling process is based upon the shredding of material. The pilot plant has a capacity of 4000 tonnes per year. The process uses a mobile shredder with a value of around 200 000 Euro (£150 375). This mobile unit is moved from plant to plant eliminating the need for expensive shredding equipment at each small moulding shop. Therefore the material can be efficiently transported to the ERCOM plant [4].
At the plant, a hammer mill is used to pulverise the composite into powdered resin and filler with individual glass pieces throughout. The mill can grind 2 to 3 tonnes of composite per hour. The material obtained is classified into three powder products depending on the size of the granules, and three fibre products depending on the average length of the fibre. The longer the fibre, the better the chance of obtaining additional value from the recyclate product, as a higher price can be asked for fibre recyclate to be used as reinforcements rather than just a filler. There is plenty of input material, but the problem arises with what to do with output material. Recyclate was landfilled for a while when no application was found.

Currently the total amount of collected composite waste is around 400 tonnes per year, of which 300 tonnes is used in BMC/SMC for non-visible automotive applications, and 100 tonnes is used as an additive in concrete to avoid crack formation during the drying of the concrete [4].

Around 5000 tonnes of ERCOM recyclate has been used to date. Some products can utilise 25% recyclate, although this is rare. The use of recyclate in products does, however, change the viscosity because it absorbs styrene. The minimum quantity of recyclate that can be used is ideally 3 to 5%. The bumper used on the BMW 5 series car incorporates 5 to 6% composite recyclate [4].

6.5.2 Mecelec composites recycling facility, France

(Mecelec composites et recyclage, MCR)

The Tournon recycling plant in France was created in 1993. The plant currently operates at 400 to 600 tonnes per year, although it has a theoretical processing capacity of 3000 tonnes per year. MCR believes that waste should be thought of as a material to be upgraded instead of something to be disposed of in the cheapest possible way. The plant recycles MCR's own composite waste stream.

Large parts are shredded into small pieces, which are then put into a hammer mill where the glass fibres are separated from the polymer. Approximately 50% of the output is long fibres (10 mm), with the rest being short fibres (1 mm) and powder. The process is more complicated when the composite material has metal inserts. The production line currently processes about 30 tonnes of product a month [64]. The powder is recyclable as filler, although it is more expensive than traditional fillers such as calcium carbonate. It can also be used in certain types of concrete. The mechanical properties of the glass fibres are slightly degraded. The short fibres can be used in thermoplastics, and the long fibres have a number of possibilities in applications where surface finish or mechanical behaviour is not paramount. The price advantage of recovered long fibres is considerable. The largest potential is in road surfacing applications, where fibre slows down the deterioration of roads by crack formation.

Fibres are also used in concrete slabs for anti-cracking properties. However, it is thought that the use of fibres in this way is still too costly and therefore its use is not widespread [64].

6.5.3 Transportation implications of recycling composite waste

Distance from source of the waste to recycling facilities should always be considered. The cost of transporting composite waste will depend on the distance involved as well as the form of the composite. Products tend to be bulky, so unless they are reduced in size before transportation, volume rather than weight will be transported owing to the amount of void space (air). Size reduction of the material before transportation will improve the efficiency of journey. This process would, however, add cost before the material starts its journey to recycling facilities.

Machinery is available in the UK to shred and grind composite parts. The machinery is relatively expensive and so on a small scale the process is not economic. However, if it is possible to set up a shredding service within a particular region this may be cost effective.

There are other problems associated with shredding waste such as:

- Dust created from the process
- Wear and tear on equipment (due to the tough and abrasive nature of the composite)
- Storage of material (to ensure large enough quantities for transportation)
- Process scrap must be fully cured before it can be shredded (otherwise it will jam the machinery)
- Fire risk (due to storage of material and possible residual catalyst and reactivity)

Transportation any type of waste to European composite recycling facilities will have an environmental impact. Impacts will include:

- Use of fossil fuels
- Traffic congestion on roads
- Air pollution
- Cost of transporting material these distances

There are concerns that the EU regulation on the shipment of waste within, into and out of the European Community (259/93/EEC) may have an impact on the transport of waste across borders to countries in which a composites recycling plant exists.

Clearly, the treatment and disposal of waste as near to the source as possible depends on the quantities and types of waste arising on a regional and local level, and on the location of the facilities. Therefore, the application of the principle will vary according to the waste concerned, the volume and the potential environmental impact of the method of waste disposal and the mode of transport. There also has to be a balance between the proximity principle and economies of scale. In some cases, economies of scale may mean that some specialist recovery or disposal operations may be located far from the point where the waste arises.

6.5.4 Logistical implications of recycling composite waste

Manufacturers all over the UK generate small amounts of composite waste during production. Many manufacturers have problems relating to storage of waste on their sites including space restrictions, health and safety implications, and hazards such as fire. Therefore, centralised collection for composite waste facilities may be beneficial. This would enable larger volumes of material and economies of scale for sorting and transportation to European recycling plants.

Another consideration is whether there are enough end markets for recyclate from all the UK waste composite material if it were to be recycled. There is no point in developing an infrastructure for collection of the waste for recycling by European facilities if there were not enough uses for the recyclate produced. This is where the European composite waste management company suggested by GPRMC could be of benefit if they invest in developing further end markets for recyclate in order to promote and encourage composite recycling.

7. DISPOSAL

The most common disposal method for composite waste is landfill as this is the easiest and currently the most cost efficient option. However, there is increasing pressure from the EU and UK governments to reduce the landfilling of all types of waste. Space in landfill sites is decreasing and it is thought that there are many other better uses for much of the waste that is currently sent to landfill. Legislation has been introduced to encourage diversion of waste from landfill, including the EU landfill directive [10] and the UK landfill tax [11].

The European landfill directive means that the cost of disposing of waste in landfill will increase in the near future. The directive focuses on diverting as much waste as possible away from landfill which means that the re-use, recycling and recovery of composite waste will be encouraged over landfill.

Under the directive, certain wastes are banned from being sent to landfill. These include liquid wastes, tyres and certain hazardous wastes. The volume of biodegradable waste going to landfill is also to be reduced. Polymers (resins) are ‘organic materials’ as they originate from oil. The interpretation of the legislation in most EU member states has resulted in composites being classed as organic. Therefore, the landfill of composite waste will soon be forbidden in most EU member states. The exception to this is the UK.

The UK landfill tax scheme [14] was introduced in 1996 and applies to all waste disposed of at licensed landfill sites. The aim of the tax is to ensure that the price of landfill fully reflects the impact that the landfilling of waste has upon the environment. It provides an incentive to reduce the quantity of waste sent to landfill and increase the amount of waste managed by processes higher up the waste hierarchy. The money raised from the landfill tax is used to encourage the use of more sustainable waste management practices and technologies. (Refer to section 2.3.1.1 of this guide for rates)

The cost of disposing of waste to landfill is predicted to rise significantly in the future. In addition pre-treatment of waste in order to comply with the landfill directive is likely to become necessary. Even though composite waste tends to be lightweight, these increasing pressures and costs will have some impact on the composites industry if it continues to rely on landfill as a disposal route its waste. Such significant increases in costs will drive the need to find alternative mechanisms of dealing with composite waste.

8. FUTURE AND EMERGING TECHNOLOGIES

8.1 EcoComposites

Ecocomposites are made by combining wood or other natural fibres, such as flax, hemp, jute or kenaf, with natural or synthetic polymers, including polyethylene, polypropylene or polyvinyl chloride [83]. They can be used to produce products for building, automotive, infrastructure and consumer applications. Ecocomposites are equally strong as usual polymeric composites, but are environmentally friendly. Natural fibres are also attractive because they have chemically reactive surfaces which make more complete fibre–matrix bonding possible.

Ecocomposites will become increasingly common as the price of wood continues to climb, environmental problems with plastics disposal increase, and agricultural fibres pose increasingly costly disposal problems. Most ecocomposite materials can be recycled (composted or digested) or burned without the residues that are left with glass and carbon fibre composites [84].

Composites based on natural and wood fibres are one of the fastest growing markets in the plastics industry, expected to achieve double-digit annual growth rates to 2010[83].

8.2 Self-reinforced polymers

In the automotive industry, polymers have made a major inroad in the past decades to make parts such as body panels, underbody structures, dashboards, seating components, front ends and bumpers. At this moment polypropylene (PP) is used for a large number of applications. It is cheap, can be reprocessed several times without significant losses of properties and can be easily modified to achieve specific requirements. In order to be able to compete with standard engineering plastics such as Polyamides in terms of the high demands on stiffness and strength, PP has to be reinforced and glass fibres are the major reinforcing elements used for this purpose. Although both polypropylene and glass are perfectly recyclable, when combined they are not all that easy to recycle.

One of the important rules in 'designing for recycling' is based on selecting the smallest possible number of different constituents in a material system or alternatively in the case of plastics, selecting compatible polymers, which in practise means the use of mono-materials. An obvious reinforcing element for polypropylene would therefore be the use of a high-performance polypropylene fibre [85, 86]. In that case, upon recycling, a polypropylene blend is obtained which can be re-used to make again all-PP composites, or alternatively, be used for other high value PP-based applications.

High-performance polypropylene fibres in combination with polypropylene matrices can lead to a fully recyclable 'all-PP' composite which gives major ecological advantages and is of interest to all industries. Besides recyclability the use of PP fibres has a number of other ecological and technological advantages over glass fibres. PP fibres are non-abrasive to processing equipment, can at the end of their lifetime be thermally recycled for energy recovery (they have a calorific value similar to oil) and have a very low density, which can potentially lead to lightweight parts, which again may lead to lighter vehicles and thus lower fuel consumption and gas emissions. Another advantage of the use of a more flexible and ductile fibre will be its safer crash behaviour. All-PP composites will not splinter, but will fail in a more ductile manner. Such 'soft' crash behaviour is of significant interest for various inner-trim parts as well as for external panels, bumper bars etc. since it will lead to safer cars.

8.3 Design for easier re-use and recycling

Designers need to find out what is happening to the products now to provide directions for the future. Examination of the current methods of disposal can reveal opportunities for increasing the product's recycling potential and decreasing the end-of-life costs. Typical questions are:

- Is the product typically disposed of to landfill? This can give rise to environmental impacts through the production of leachate and landfill gas and will be subject to increased costs in the future.
- Can the product be re-used or recycled instead of being sent to landfill?
- If products with only minor faults are typically discarded, is it possible to salvage some of the parts or components for reuse or remanufacture?
- Is there potential for re-using modules or parts of the product at the end of its useful life?
- Does the product contain materials or components that can be easily recovered and recycled to reduce costs?
- Can various modules or parts be stamped with labels indicating their recycling potential? This is particularly relevant for plastics where standard material designations and labels are available for common materials.
- Can the product and/or its modules be designed for service or maintenance to increase their life span?
- Can a product take-back service be developed to reduce 'producer pays' costs?

Answering these questions will help to identify the existing options for product re-use, recycling or recovery. In the future these will need to be improved to minimise the total cost of the product and avoid end-of-life costs that were not accounted for in the 'first' cost of the product.

8.3.1 Design considerations

Designers need to consider the costs of the end-of-life stage of products now - if this is ignored then the eventual costs will be unduly high if legislation changes. Designers must:

- Make re-use, remanufacturing and recycling easier for all products - re-using, remanufacturing or recycling all or part of the product will significantly reduce the eventual costs by reducing raw material use and diverting material away from limited landfill space.
- Design the product for re-use in its current form (i.e. without processing) - this can extend the useful life of the product. Future product designs need to incorporate the requirements of subsequent uses, e.g. for packaging and containers, this may mean extra durability and the introduction of a re-use system suitable for the market.
- Design for product remanufacture or recycling - this needs increased focus on the physical organisation of the product, i.e. the structure and the way in which components and materials are put together. Reducing the number of fastenings and making fastenings easier to undo will help to make the product easier to disassemble and recycle.
- Design to enable recycling by reducing the number of materials used - single material products are much easier to recycle.
- Design to eliminate materials that can be hazardous during remanufacturing or make recycling difficult.

Cleaner design in the future will not be easy but the alternative high end-of-life costs are even less acceptable.

8.4 Recycled products guide

The Recycled Products Guide [87] is an information resource designed to help to buy recycled. It contains the details of over 1000 companies in the UK who can supply a range of products, from recycled aggregates to kitchenware. Buying recycled products helps 'close the loop', creating a demand for the materials recovered by recycling collection schemes. For recycling to work, there needs to be markets for the products made with recycled materials. Buying recycled helps keep reusable material in the economy, reduces waste needing to be landfilled and conserves resources, particularly energy.

8.5 Pyrolysis

There is considerable interest in pyrolysis as a cost-effective technique for converting composite waste into energy, and a potential solution to the composite waste challenge.

The **RECOMP** project lead by PERA Technology [88] aims to address the problem of composites recycling by developing a process combining pyrolysis to liberate the composite components, and physical separation processes to achieve recyclable materials in their optimum form. The materials produced will be fully assessed for re-use in a range of applications. The overall aim of the research is to develop a recycling process that will give a commercially viable route towards sustainable manufacture of composite products. The RECOMP project and resulting technology aim to raise the profile of composites as fully recyclable materials to enable them to continue to bring performance, cost and environmental benefits to a wide range of applications and products. The final benefit will be a substantial reduction in the quantity of composite waste being disposed of by landfill.

The University of Leeds under the **WMR3 LINK programme ('Waste minimisation through recycling, recovery and re-use in industry'**) has also been investigating the potential of pyrolysis combined with physical separation for the recycling of composites. The new recycling process combines pyrolysis and physical separation. Composites are broken down into gas, oil, a small amount of carbon and fibre. Recycled oil and fibre can both be reprocessed into composite plastics. The research shows that both the oil and the fibre can be processed back into composite plastic or re-used in other ways. Pyrolysis operates at a much lower temperature, around 500C, so recycled fibre retains its size and much of its strength. After cleaning, up to 25% of recycled fibre can be combined with 75% virgin fibre in new composite plastics without any deterioration in product quality. Results show that recycled fibre can be woven into cloth and sprayed with resin to build structures such as boat hulls [89]. Use in fibreboard is also being investigated.

In **Spain**, research has been carried out into the pyrolysis of SMC of unsaturated polyester and glass fibre. The most appropriate temperatures for recycling SMC by pyrolysis were found to be between 400 and 500 °C. The pyrolysis oils obtained were thought to be good liquid fuels as they have high calorific value and no contaminants. The gas obtained was also thought to be an appropriate fuel, providing enough energy to self-sustain the process. The inorganic components of the SMC (glass fibres and calcium carbonate filler) were left almost unaltered as a solid residue. They were recycled both together and individually in BMC of polyester and glass fibre. Recycled pyrolysed calcium carbonate filler replaced raw filler with no deterioration of BMC properties, while recycled pyrolysed glass fibre was deteriorated and worsened the properties of the BMC [90].

In **America**, the University of Missouri has worked on several projects to recover carbon fibre from composites by the application of pressure and heat which have shown that it is technologically possible, but expensive. Commercialisation of the process required carbon fibres to be recovered and sold at about 50% of the cost of virgin carbon fibres. It was also found that as a composite has more fillers the process economics of pyrolysis become worse [91].

In **Denmark**, there is a growing problem relating to disposal of the huge FRP blades on windmills at the end of their life. This equates to 8000 tonnes of composite waste currently going to landfill in Denmark [15]. This has lead to research into whether pyrolysis can be used to recycle the blades. Operating temperatures of up to 600 °C were used in the pyrolysis chamber to help to degrade the epoxy resins as these have a greater resistance to heat than polyester resins do. Glass fibres, fillers and metal components were separated successfully and energy was recovered. There are plans for the construction of the first commercial pyrolysis plant in Denmark with a capacity of 5000 tonnes per year. It is expected that the plant will be able to recycle manufacturing waste as well as the windmill blades.

The aim of the Danish research was to use the glass fibres obtained as a functional filler or to recycle the glass. The metal elements could be recycled by the usual recycling routes. However, the recovered glass is not wanted by the glass industry for recycling as its properties have changed during the pyrolysis process. If the glass was ground to a powder (~20 micrometres) it would be ideal for use as millfibre which is a product specifically made to reinforce materials such as polyurethane. This material has a value of 1 to 1.5 Euros. Uses for larger fibres vary; those in the region of 2–3 mm long are not sought after but fibres of 4–6 mm in length are wanted for their reinforcement properties.

8.6 Recycling Carbon Fibres

In partnership with the French Environment and Energy Management Agency (ADEME), the Rhone-Alpes Materials Agency (ARAMM) and industrialists from the composites sector, Compositec launched the Recycarb project, which focuses on recycling carbon fibres from composite industry waste, at the beginning of October 2005 [92].

Most of the waste generated by the use and manufacture of carbon-based composites is currently disposed of in authorised landfill sites. European regulations now limit such landfilling and require that industrial companies consider recycling solutions. Carbon fibres contained in composites are valuable products that are worth recovering for other uses. Recycling processes have already been identified and tested within the scope of the Recycomp project, which aims at reusing thermosetting composite waste and more specifically fibreglass-based waste.

The Recycarb project intends to continue work initiated as part of the Recycomp project and help implement recycling schemes for carbon fibre produced by the composite sector. The project includes the following stages:

- Evaluation of the tonnage of carbon fibre-based waste produced by the composite industry on both a French and European level,
- State of the art of recycling solutions designed for such waste,
- Continuation of the tests launched during the Recycomp project for carbon fibre recycling processes.

Depending on the conclusions of the Recycarb project, additional work will be launched, in partnership with the industrialists concerned, on specific recycling solutions and outlets for recycled carbon fibres.

9. SUMMARY

Existing composite recycling plants such as ERCOM, MCR and Miljotek have proven that mechanical recycling of FRP is possible, but these plants are in need of profitable markets for the recyclate generated. In order to solve the current waste management problems, research needs to be conducted to develop new applications, write recyclate standards and develop new high-value markets for composite recyclate. Other aspects that need addressing include reducing manufacturing waste, investigating the dismantling and collection of end-of life waste, and the construction of new recycling plants based on better technology.

The issues of recycling and sustainability continue to grow in importance in public and political spheres. Designers using composite materials today should consider the life cycle of the application and the end-of-use properties. The issues of re-use, recycling or safe disposal of materials should be considered at the design stage.

European legislation and its transposition into national legislation pushes industry towards re-use, mechanical or chemical recycling, puts limits on incineration with energy recovery and in many countries already forbids direct landfill of composite waste. Producers of materials which compete directly with composite are very active today in promoting their material as having a functioning recycling concept.

Re-use of composite material is possible, but is dependent on the nature of the materials used, how they are joined and fixed, and their condition. Recycling of composite waste is a viable option, but certification schemes need to be adapted to make it easier to test components containing recycled composite material.

There is currently no market value for waste composite in the UK as a recyclate. Other than a few firms which grind production waste and use it as filler, no recycling of this material takes place. Many manufacturers would like to be able to recycle their waste. However, cost appears to be the major factor determining whether this is viable.

Most production and post-service waste is currently placed in landfill. Waste disposal charges for producers remain low in comparison to the added value and cost–benefits of their products. Also, waste disposal charges are merely transferred to the end users. It appears that at present the environmental benefits of energy recovery by burning composites in a waste incinerator are likely to be outweighed by significant disadvantages. It is thought that opportunities for re-use of composite products will be limited. A number of examples have been found in which waste material has been successfully incorporated into a new product, but little is known about the cost-effectiveness of these recycling practices.

The development of new, high-grade markets for composite recyclate is a high priority for the development of composites recycling. The Green FRP Recycling Label will contribute to the development of viable waste management routes for composites and high-value end uses for the recyclate produced.

To assist in the transition from disposal of composite waste in landfill to recycling, industry needs to consider designing components for easier disassembly, re-use and recycling at the end of the product life.

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