Review

JOURNAL OF
REINFORCED
PLASTICS &
COMPOSITES

Journal of Reinforced Plastics and Composites
2014, Vol 33(11) 1069–1084

DOI: 10.1177/0731684414521087
jrp.sagepub.com
SAGE

Sustainability and human health issues pertinent to fibre reinforced polymer composites usage: A review

Asif uz Zaman[1], Saud A Gutub[1], Mohamed F Soliman[1,2] and Mahmoud A Wafa[1,2]

Abstract
The specific properties of fibre reinforced polymers give them a lot of advantages over traditional materials but the long life of polymeric composites poses serious environmental threats raising sustainability concerns. The other issue of importance concerning the innovators and environmentalists in the mass usage of this material is its health impacts on human beings. This paper thus attempts to highlight and surface out the issues related to fibre reinforced polymers' sustainability and their health impacts on human beings, by reviewing past studies on the subject, to examine critically the extensive body of published data, prior observations and ideas on the subject in order to identify and analyse those features that are intrinsic and unique to fibre reinforced polymers. This would thus serve as a conceptual model for future research on fibre reinforced polymer composites sustainability and health concerns.

Keywords
Fibre reinforced polymer, sustainability, recycling, health impacts, energy recovery

Introduction

Fibre reinforced polymer (FRP) is the generic term for a uniquely versatile family of composites used in everything from chemical plant to luxury powerboats. A variety of industries including electronics, automotive and transportation have contributed significantly to the increasing use of FRPs.[1] Due to its advantageous characteristics, FRP composites are now being increasingly used in construction industries as well.[2] They have been included in new construction and rehabilitation of structures through their use as reinforcement in concrete, bridge decks, modular structures, formwork and external reinforcement for strengthening and seismic upgrade. The composites industry is now producing a wide range of FRP products that include strengthening strips and sheets, reinforcing bars, structural profiles, sandwich panels, moulded planks and pipings, etc.[3] It should be noted that currently the volume use of composites in construction is in the area of upgrading existing structures and in seismic retrofit. Although very few instances of new structures wholly built with FRPS are present to be considered as a possibility for wide acceptability in the future development. To date, these examples are so rare to be regarded as substantial.

FRP structure typically consists of unsaturated polyester resin applied to a mould in combination with reinforcement; most commonly glass fibre, carbon or aramid, to form a part that is rigid, highly durable and low in weight. The resins used in the matrix of FRPs, often combined with fillers and additives, can be classified as thermosetting or thermoplastic, according to the nature of their molecular structure. Thermosetting resins (such as epoxy, polyester and vinylester) suffer irreversible reactions during manufacturing and permanent cross-links are created in their

[1]Department of Civil Engineering, Faculty of Engineering-Rabigh, King Abdulaziz University, Kingdom of Saudi Arabia
[2]Department of Civil Engineering, Faculty of Engineering, Aswan University, Egypt

Corresponding author:
Asif uz Zaman, Department of Civil Engineering, Faculty of Engineering-Rabigh, King Abdulaziz University, P.O. Box 344, Rabigh 21911, Kingdom of Saudi Arabia.
Email: azaman@kau.edu.sa

molecular chains. On the other hand, thermoplastic resins (polyethylene, polyurethane, polypropylene and polyvinyl chloride) do not suffer any remarkable chemical changes during production and can be easily converted back to their original monomer,[4] unless they are contaminated.[5]

Until 2005 thermoplastic FRPs were reported to have a higher growth rate than thermoset composites, at 9 and 3% per year, respectively, but thermoset FRPs account for more than two-thirds of the market. Glass fibre reinforced polymer (GFRP) morphology was reported to constitute the bulk of thermoset FRPs in use during the times, primarily in the form of sheet moulding compound (SMC) and bulk moulding compound (BMC) and hence they make up the largest portion of thermoset composite wastes because of their use in high-volume applications whereas high tech carbon fibre (CF), carbon fibre reinforced polymer (CFRP) and/or thermoset plastic matrix resin morphology is mainly concentrated in the sports and aerospace industry, which contributes much less to the overall waste volume.[1]

For structural applications, FRP composites are typically fabricated using a polymer matrix (thermosetting resins), such as epoxy, vinylester or polyester, and reinforced with various grades of carbon, glass and/or aramid fibres.[2] The tailor-ability and performance attributes of glass, aramid and CF reinforced composites make these materials attractive for use in civil infrastructure applications and provide a challenge for the civil engineering designers. In addition, with the newer materials being introduced into the infrastructure, initial material characterization and the assessment of the durability and damage tolerance over the service life periods, required of civil structures, become of critical importance.[6]

The potential advantages present in the use of FRP composites related to considerations, such as higher strength, high specific stiffness, lighter weight, higher performance, non-corrosive, longer lasting, good electrical insulating properties, possibility of production in any shape, ease of installation and improved durability even in harsh environments, make them suitable for extensive use in the rehabilitation of existing structures and extending their life. Other potential benefits are in seismic upgrades, defence systems unique requirements, space systems and ocean environments.[1,2,7,8] These benefits can be realized from FRPs physical characteristics and their potential in developing structural systems with service lives exceeding traditional materials. The light weight of the composite can result in lower construction costs and increased speed of construction resulting in reduced environmental impacts. FRP composite materials' high strength and stiffness characteristics can require less material to achieve similar performance as traditional materials resulting in minimizing resource use and waste production. In general, the promise of FRP composites is its potential to extend the service life of existing structures and to develop new structures in the future that are far more resistant to the effects of ageing, weathering and degradation in severe environments.[2]

However, validation of the durability of FRP composites in harsh, changing environments is not yet fully established. Quantification of durability of the material and its comparison to conventional materials is critical to provide designers with the knowledge to select the best solution towards achieving a sustainable, built environment. FRPs are facing with the problem of not having wide acceptance in construction industries as well as other industries because of the sustainability and legislative regulations, recycling problems, longevity concerns, initial cost constraints, etc.

Environmental factors are seen to be one of the most critical elements affecting the composites industry the most, 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 definitely have a major effect on the use of composites, and in some cases may suppress their use in favour of more easily recyclable materials.[9] As the industry continues to grow and the volume of FRP used increases, both production scrap and end-of-life (EOL) waste will also increase.[10] In view of the increasing use of FRPs in almost every sector of development, more and more measures are being taken to curb the menace of the waste generation from the composites, which is very critical from the viewpoint of environmental sustainability. One such drive is taken by the UK latest governmental strategy for composites,[11] identifying 'Increasing Sustainability and Recycling' as one of the three major goals for the composites industry.[12] Apart from the UK many other countries have also shared their part in addressing the problem of environmental sustainability with FRPs which will be discussed briefly in the subsequent sections.

Landfill is a relatively cheap disposal route but it is the least preferred waste management option under the European Union's (EU) Waste Framework Directive. Landfill of composite waste is already forbidden in Germany and other EU companies are expected to follow this route. Moreover, the cost for landfill and incineration is also expected to increase over the coming years.[10] Thus, two major factors inhibiting the growth of FRP at present are cost, which should reduce over time, and longevity.[13] Thus, it can be very safely concluded that recycling of waste now becomes the need of composite industries because of the environmental concerns associated with it as well as the restrictions posed on the other disposal routes (landfills, etc.) due to the setting up of strict coercive legislation all over the world. To address the current problems associated with the use of FRPs at large, an attempt has been made through this paper to surface out the issues of sustainability and the impacts of FRPs exposure on human health by reviewing the studies made on the subject. But our main focus is specifically concentrated on the construction sector only but wherever felt necessary other sectors of importance are also discussed but are limited to a few, keeping in view the extent of elaboration possible in a single literature.

Directives and legislations

There are many regulations and directives set up by various countries across the world relating to the waste management, which could have an impact on the composites industry. The increasing volumes of all types of wastes are leading to concerns over methods of waste disposal and ways in which waste can be prevented. This has resulted in the establishment of directives and regulations at European and UK government levels along with many other countries which relate to the efficient management of waste. In general, waste management legislation places a focus on dealing with waste through the waste hierarchy of preventing (reducing), reusing, recycling and recovering energy from waste before disposing of it in landfill as the last resort (Figure 1).[14] Such waste legislation will put more pressure on solving waste management of composite material through recycling and reuse.[15] Many countries have taken stern action in this regard by forming strict directives and legislations. A brief description of the initiatives taken by some of the countries is discussed below. Keeping in view the restrictions on the length of the paper a detailed description is deliberately avoided.

Figure 1. The waste hierarchy.

Before 1970s, many of the current environmental laws and regulations had not yet been fully developed or implemented. Once a product's useful life was complete, the product was typically disposed of in a landfill. That is certainly not the case today. 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.[16] Germany and likes had already taken a lead by making it illegal to landfill composite wastes. The Netherlands had already banned land filling with FRP scrap from late 1997. Moreover, the cost of disposing of waste to landfill is predicted to rise significantly in the future making it absolutely impossible to landfill the waste where it is not illegal yet. In addition, pre-treatment of waste in order to comply with the landfill directives is likely to become necessary. Such directives are bound to make life more difficult and expensive but Europe, with its high population density and limited potential for new landfills has fewer options.[13] Pressures from European directives are likely to increase further in the future[15] making it mandatory for the composite industries to abandon the traditional disposal routes and resort to newer sustainable environmentally benign methods of disposal.

In general, the purpose of introducing landfill directives is to prevent or reduce negative effects on the environment and human health from the land filling of waste, during the whole life cycle of a landfill.[17] The Directive requires all Member States to take 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, reuse or reclamation or any other process with a view to extract secondary raw materials, or the use of waste as a source of energy.[15]

EU directives such as End of Life Vehicles (ELV, 2000/53/EC)[18] require 85% of the ELV will have to be reused or recycled by 1 January 2015 with 10% incinerated with energy recovery and 5% landfill wasted. Other EU directives such as the Waste Electrical and Electronic Equipment, Landfill (1999/31/EC)[19] and Incineration[20] will put similar pressure on fabricators and end-users for sustainable FRP waste management. The EU directives on waste landfill regulate the amount and type of waste that can be dumped in landfills whereas the directives on incineration aim to reduce the environmental effects and risks to human health caused by waste incineration. It is also envisaged that more regulations on construction and demolition waste will be issued soon.[21]

Almost all countries around the world share their concern in this regard. The UK government policies, such as the Waste Strategy 2000, the sustainable construction strategy and the landfill tax, could all influence the FRP industry there. In the United States, approximately 14,000 nationwide landfills have been closed since 1978 due to being full or because of environmental issues. The cost of disposal of the materials will only increase as landfills begin to fill up. The State of Minnesota calculated that 18,750 tonnes of FRPs were being sent to landfills in the state each year at a cost of nearly $20 million. Cost increase can already be seen in Europe; in Germany, landfill transfer costs have increased 300% in recent years. 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 for its waste. Such significant increase in costs will drive the need to find alternative mechanisms of dealing with composite waste.

Producers of materials which compete directly with composites are very active today in promoting their material as having a functioning recycling concept. For the composite industry to remain competitive and more effective, the development of new, high grade markets for composite recyclates is a high priority for the development of composites recycling. To assist in the transition from disposal of composite waste in landfill to recycling, industry needs to consider designing components for easier disassembly, reuse and recycling at the end of the product life.[15] EOL products will increasingly be dismantled so that their constituent materials can be collected, sorted and recycled. Future need under legislation to make majority of vehicles from recyclable materials has obliged the automotive industry to study recycling options. Some environmentalists envisage that, eventually, used vehicles will be returned to their original makers for post-use processing, the costs being covered as part of the original purchase. The European Composites Industry Association, Groupe des Plastiques Renforces et Materiaux Composites believes that recyclability will be a key factor in future FRP development, alongside health and safety. It foresees future bans on dumping post-use material, no matter how finely ground, into landfill, and even on burning it – though the latter has, some argue, merit where usable energy can be derived in the process.[13] On nearly the same account, Japan's Recycling and Treatment Council is so concerned about the environmental effects of unusable composites that it has commissioned a committee to address the technological and social problems regarding recycling thermoset composite wastes. The environmental concerns of FRPs are not only confined to the above-mentioned countries but have rather become an issue of prime importance for almost all the countries dealing with FRPs. They are now looking deeper and wider into the recycling issues of FRPs with more emphasis than ever before.

FRPs sustainability issues

While the mechanical advantages of using FRP composites are widely reported in literature, questions remain concerning the feasibility of FRP composites within the framework of a sustainable environment.[2] Therefore, the issues of recycling and sustainability continue to grow in importance in public and political spheres. Traditional disposal routes such as landfill and incineration are becoming increasingly restricted, and composites companies and their customers are looking for more sustainable solutions.[10] Designers using composite materials today should consider the life cycle of the application and the end of use properties. The issues of reuse, recycling or safe disposal of materials should be considered at the design stage.[15]

The fabrication of constituent materials for FRP composites, namely matrix and fibre, is an area of concern especially when considering that the primary resources from which polymers (excluding biopolymers) are derived are crude oil, natural gas, chlorine and nitrogen.[22] The most commonly used fibre reinforcements in structural applications, glass and CFs, require high temperatures (1400°C for glass; 1200–2400°C for carbon) during production and in some cases require petroleum by-products as precursors. That is to say that the current range of materials cannot be considered environmentally sustainable, despite some claims by the composite industry to the contrary. For example, the production of reinforcing fibres, such as glass, carbon and aramid requires an enormous amount of energy, wherein glass is derived from a non-renewable resource. When considering only energy and material resources it appears, on the surface, the argument for FRP composites in a sustainable, built environment is questionable.[2]

However, on the other hand, resins sometimes are claimed to be more environmentally friendly than materials such as metals despite being derived from the by-products of the petroleum industry which itself is not sustainable. Similarly some filler materials used to provide bulk to some resin systems are derived from the waste of coal-fired power stations; this industry may not be sustainable in the long term due to public awareness of pollution despite vast coal reserves. This is not to say that the effort spent on the development of current fibre composite technology is being wasted rather it is being attempted here to reflect the other dark side of such a versatile material which could be used in wide applications in the near future if it can be turned into a sustainable product. Methods, systems and standards need to be developed which are generally applicable to fibre composite materials in the construction industry[23,24] in particular. Nevertheless, when considering the energy component of FRP composite and the material resources in isolation it would appear that the argument for FRP composites in a sustainable environment is uncertain. However, such a conclusion needs to be evaluated in terms of the potential advantages of FRP composites in terms of[24]

- the in-service and mechanical properties and in particular its long-term durability when compared with more conventional materials;
- its utilization in conjunction with the conventional materials in terms of rehabilitation of structures, seismic retrofitting of columns, the manufacture of bridge decks and the hybrid structures to form cost-effective structures in terms of whole life cost and to provide an economic structural system.

The sustainability approach to design and construction challenges architects and engineers, to weigh environmental factors, energy/resource consumption, social factors, economic considerations and performance criteria appropriately. One approach towards evaluation of material's sustainability involves life cycle assessment that includes the inputs and outputs for the phases of material life: raw materials acquisition, fabrication/processing, construction, maintenance, recycling/disposal. The ideal sustainable structure and material would have a closed life cycle where renewable resources, energy and zero waste, along with minimal impact on environment and society, are considered. Certainly, there are few materials that could qualify as ideal sustainable materials and still satisfy all the performance requirements of structural systems.

When identifying appropriate metrics for sustainability, one is likely to encounter a myriad of proposals and ideas each potentially yielding unique results; however, in general, measures are typically centred on factors that account for the following:

- Minimum resource use;
- Low environmental impact;
- Low human and environmental health risks;
- Sustainable site design strategies;
- Higher performance.

In the case of FRP composites, environmental concerns appear to be a barrier to its feasibility as a sustainable material especially when considering fossil fuel depletion, air pollution, smog and acidification associated with its production. In addition, the ability to recycle FRP composites is limited and, unlike steel and timber, structural components cannot easily be reused to perform a similar function in another structure. On the other hand, FRP composites', potential benefits, as described earlier, may potentially mitigate some environmental impacts.[2]

It is important to note that the best way to minimize use of resources is to not rebuild in the first place. In this regard, the primary benefit of FRP composites will be its role in solutions that seek to extend the service life of existing structures and to develop new structures that achieve superior service life with minimal maintenance. Hence, it can be inferred that for wide usage and acceptability of FRPs no decision can be taken or any conclusion be drawn merely by considering one aspect only. We have to look deeper and wider into all the aspects before dictating the future fate of FRPs. We in no case can be driven either in favour of or against FRPs by looking at a single aspect. We have to carry out a comparative analysis of merits and demerits associated with the usage of FRPs before drawing any conclusion.

Recycling concerns

The growing use of FRPs in the construction and transportation industries implies larger and increasing amounts of FRP wastes, produced at different stages of their life cycle. Although FRPs, in general, are difficult to recycle due to their multiphase nature, typically containing three or more components: fibre reinforcement, resin matrix and fillers (typically calcium carbonate, $CaCO_3$) but the main concern is related to the limited solutions for the waste management of the non-reprocessable thermosetting FRPs.[14,21,25]

Recycling of thermoset FRPs presents an especially difficult challenge because once the thermoset matrix molecules are cross-linked they cannot be melted or reformed[21] whereas thermoplastics, on the other hand, are inherently recyclable. The other problem associated with thermosetting FRPs (which currently are in use far more often than the other forms) is the low value of the material constituents reclaimed from recycling. For instance, the value of the material constituents of glass reinforced polymers (GRP) reclaimed from recycling is low. Hence there is a little business (monetary) incentive to recycle.[1] However, CFs have a higher return value than glass fibre reinforcement but are difficult to recycle. Hence failure to meet the recycling challenge could see this property of composites becoming their major weakness.[13] Despite these drawbacks, thermosetting resins are currently used far more often in FRPs since they allow much faster production (owing to their low viscosity), have better properties of impregnation and adhesion to the fibres and guarantee better mechanical performance.[8]

Thus, it can be said that for recyclers, thermoset composites are the real challenge. With thermoplastic composites, depending on the fibre type and volume fraction, it is often possible to clean up the material intended for reuse and then thermoform it directly into a new product. Thermosets, on the other hand, have either to be reduced to small granules or a powder, or have their fibres separated out if this can be justified economically. That may be so with, for example, CFs which are left with much of their original strength and can help fabricators dilute their costs by cutting down on use of new fibres. Currently, it is rarely worth reclaiming glass fibres, although the higher performance types can be an exception.[13]

The concept of recycling polymer-based products gained momentum towards the end of the 1970s fuelled by the oil crisis in 1974 and 1978–1979, 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 1980s.[15] Landfill and incineration have always been the simplest and preferred methods of disposal accounting for 98% of composite waste, while alternative routes such as reuse and mechanical recycling account for the remaining 2%.[16]

The waste management of FRP materials, in particular those made with thermosetting resins, is a critical issue for the composite industry because these materials cannot be reprocessed as mentioned earlier. Therefore, most thermosetting FRP waste has to be landfilled, in spite of the significant environmental impact caused by disposing of it in this way. Incineration is another common method of disposal of FRP. However, in this process around 50% of the composite waste remains as ash which again has to be land filled. Moreover, incineration is not always possible (where limits are imposed on the energy content of the waste), it is not suitable for large parts and glass fibre residue can cause process stoppages.[10] Although, today newer regulations on waste disposal have been formulated in many countries restricting land filling and incineration to a great extent but even now some countries have not made these illegal yet allowing the liberty to practice these processes.

Despite all the advantages associated with CFRPs, the increasing use also generates an increasing amount of CFRP waste raising an environmental and economic awareness for the need to recycle CFRP wastes. The worldwide demand for CFs had reached approximately 35,000 tonnes in 2008; this number is expected to double by 2014, representing a growth rate of over 12% per year.[26] CFRP is now used in a wide range of applications[27] generating a lot of waste in turn. Common sources of wastes include out-of-date pre-pregs, manufacturing cut-offs, testing materials, production tools and EOL components (Figure 2); manufacturing waste is approximately 40% of all the CFRP waste generated,[21] while woven trimmings contribute with more than 60% to this number.[28] The EOL components are expected to aggravate the

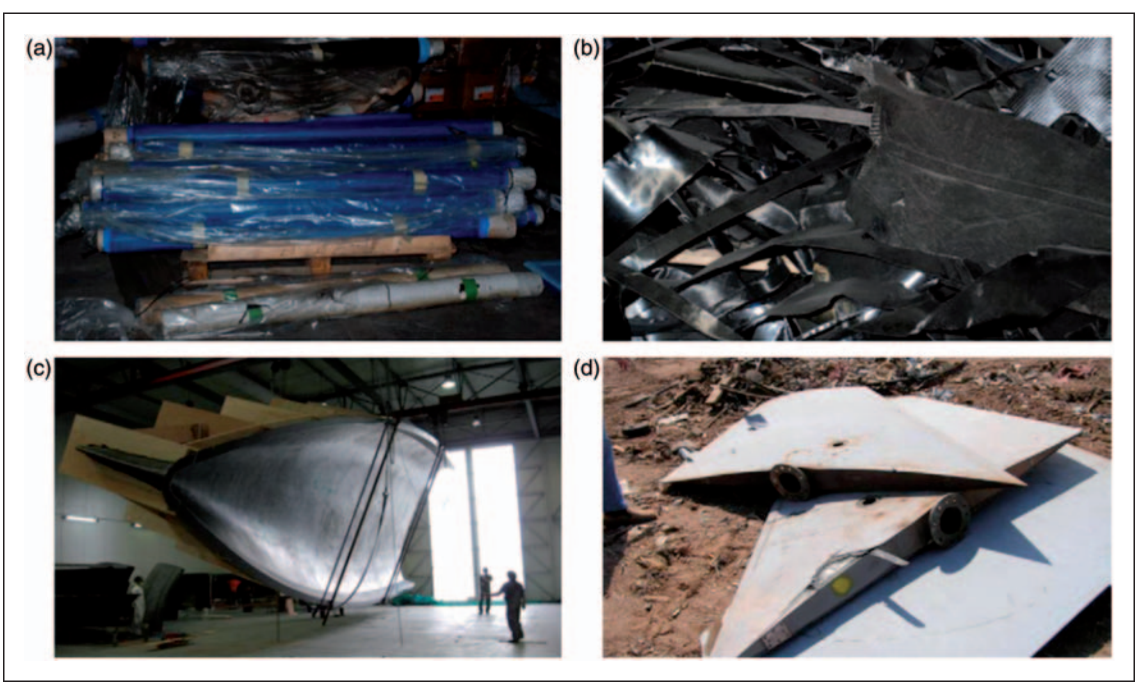

Figure 2. CFRP waste. (a) Out-of-date pre-preg rolls, (b) manufacturing cut-offs, (c) yatch mould, (d) EOL aircraft wings.[36]

problems of environmentalists and policy makers to a much higher level in the coming years. Starting with the aeronautics sector as an example, the first aircraft with structural CFRP components will soon be decommissioned[29]; within 30 years, the same will happen to the new composite-generation aircraft (8500 commercial planes will be retired by 2025,[30] with each vehicle representing more than 20 tonnes of CFRP waste).[31] Within a similar time frame, the wind industry will also turn out to be another great source of CFRP waste.[32]

Presently, most of the CFRP waste is landfilled[21]; the airframe of EOL vehicles is usually disposed in desert graveyards, airports or by landfilling.[30,33] However, these are unsatisfactory solutions in the light of the following reasons:

1. Environmental impact: the increasing amount of CFRP produced raises concerns on waste disposal and consumption of non-renewable resources.
2. Production cost: CFs are expensive products, both in terms of energy consumed during manufacturing and material price.[30]
3. Management of resources: demand of virgin (v-) CFs usually surpasses supply capacity,[31] so recycled (r-) CFs could be reintroduced in the market for non-critical applications.[34]
4. Economic reasons: disposing of CFRP by land filling, where not illegal can be very costly[35]; recycling would convert an expensive waste disposal into a profitable reusable material.

It can be inferred that since more and more waste is being produced throughout the life cycle of FRPs, innovative solutions are needed to manage these.[3] It is clear that in particular, turning CFRP waste into a valuable resource and closing the loop in the CFRP life cycle is vital for the continued use of the material in some applications.[21] The demand of the time is to look for sustainable and beneficial ways of recycling, reclaiming and reusing FRP wastes to the best possible profitable manner presently feasible and also strive to explore innovative and novel ways of mitigating the menace of FRP wastes through continuous and rigorous researches. Some of the well-researched and documented methods of recycling the wastes are briefly discussed in the next section shedding some light on the practices followed till date with an understanding that it may be improved or modified in the coming years for better impact on the outcome.

Recycling methodology

Broadly speaking, the recycling methodologies can be divided into four major classes: energy recovery method, thermal breakdown of the matrix, chemical breakdown of the matrix and size reduction.

Energy recovery method

The potential energy recovered from unreinforced plastics can be substantial. In 1990, it was estimated that the reaction injection moulding production scrap of North America would have been the energy equivalent of 30–35 million litres of crude oil. Incineration is not a favourable method for recycling thermoset composites such as SMCs and BMCs because of their high inorganic contents (up to 70%), which significantly reduces the energy available.

Thermal breakdown of the matrix

The main goal of thermal methods is to separate the fibre reinforcement from the polymer matrix. This allows the former component of the composite to be reused, and it may have a greater recoverable value, particularly if it consists of CFs. Within the thermal methods, there are essentially two techniques: (i) the fluidized bed thermal process, described in detail by Pickering et al.,[37] and (ii) pyrolysis processes,[38,39] which are used to recycle thermoset composites. These techniques, which have been researched and developed for both carbon and glass fibres, basically consist of heating the composite material to a high enough temperature to volatilize the polymeric matrix, thereby making it possible to reclaim the fillers and fibres.[21] The by-products of the composite materials after heating are typically gases and liquids from the resin, which are used as fuels and extenders in other materials. The fuel that is created by the condensation of the gases resulting from polymer volatilization can be used to provide energy for the heating process itself. However, it should be noted that the high temperatures the material is subjected to may damage the fibres. The problem is more with glass fibres where the high temperatures needed for these processes either degrade the properties of the glass fibres or have heating costs that approach or exceed the value of the products extracted.[1]

The method of fluidized bed process has been used by few researchers[40] as the well-known implementation[21] which was developed and implemented at the University of Nottingham. According to Pickering et al.,[37] in the fluidized bed thermal process, heating up to 450 and 650°C causes a reduction in the tensile strength of glass fibres by 50 and 90%, respectively. Yip et al.[41] showed that the performance of CFs suffers less – for a heating temperature of 550°C the tensile strength loss is about 20% and stiffness retains its original value.

Pyrolysis, the thermal decomposition of organic molecules in an inert atmosphere (e.g. N_2), is one of the most widespread recycling processes for CFRP. During pyrolysis, the CFRP is heated up to 450–700°C in the (nearly) absence of oxygen; the polymeric matrix is volatilized into lower weight molecules, while the CFs remain inert and are eventually recovered.[29,42] Pyrolysis is seen as hopeful for use in aerospace, where large amounts of carbon/epoxy scrap emanate from production lines.[13]

Chemical breakdown of the matrix

Three methods for chemically recycling BMCs and SMCs have been discussed in literature: hydrolysis, glycolysis and solvolysis. All the three methods have been successful to some extent but chemical recycling is a mixed blessing because there is often a large amount of chemical waste produced in the process. In order for a process to be environmentally viable, more materials must be recycled than the chemical waste produced. While this appears possible in laboratory conditions, large-scale industrial chemical recycling does not seem to be feasible.[1] Chemical methods for CFRP recycling are based on a reactive medium – e.g. catalytic solutions,[43] benzyl alcohol[44] and supercritical fluids (SCFs)[45–48] – under low temperature (typically <350°C). The polymeric resin is decomposed into relatively large (and therefore high value) oligomers, while the CFs remain inert and are subsequently collected.[49]

Chemical recycling with SCFs is a more recent approach; it is nevertheless already recognized for producing recyclable carbon fibres (rCFs) with virtually no mechanical degradation – especially when using propanol – and for allowing recovery of useful chemicals from the matrix.[49–51]

Mechanical methods of size reduction

Thermoplastic composites are recycled by grinding finished parts into small particles. These particles can be fed into an injection moulding machine together with virgin thermoplastic composite materials. Thermoset composites can also be recycled. Contrary to thermoplastic composites, the resin part of the thermoset composite cannot be reshaped again by heating. Thermoset composites are therefore ground in special equipment where the reinforcing fibres are separated from the resin and filler part. The fibres can be reused as reinforcing material in other applications; the resin and filler part is used again as filler in many other applications.[52] A number of processes which recover the fibre and resin/chemical content of the original composites are also being developed, but these tend to be more complex and expensive.[10]

Mechanical recycling is presently the only process used commercially for thermosetting polymers.[53] It involves a series of operations, including breaking down the composite by shredding, crushing, milling or other similar mechanical process that successively reduce the recycled materials' size. The first processing stage normally referred as shredding consists of using slow speed cutting or crushing mills to break the original material into 50–100 mm sized pieces. Hammer mills may then be used to grind these pieces into particles measuring from 100 mm down to less than 50 mm by a process called granulation. Once processed, the resulting scrap pieces can then be segregated by sieving into powdered products (rich in resin) and fibrous products (rich in fibres).[21,54] Total grinding of residue to a fine particulate is a recycling strategy that has composite recyclate replacing mineral fillers. Normally, fibres are separated out first for subsequent reuse as short-fibre reinforcement. Separation can be accomplished mechanically.[13]

Two technology families have been proposed to recycle CFRPs (Figure 3)[12]: mechanical recycling and fibre reclamation. Most efforts have been focusing on these composites, as their cross-linked matrix cannot be reprocessed simply by re-melting. Fibre reclamation processes are particularly suitable to CFRPs: CFs have high thermal and chemical stability,[21] so usually their excellent mechanical properties are not significantly degraded (especially regarding stiffness). Fibre reclamation consists of recovering the fibres from the CFRP, by employing an aggressive thermal or chemical process to break down the matrix (typically a thermoset); the fibres are released and collected, and either energy or molecules can be recovered from the matrix. Fibre reclamation may be preceded by preliminary operations, e.g. cleaning and mechanical size reduction of the waste.

Generally, the rCFs have a clean surface and mechanical properties comparable to the virgin (v-) precursors; nevertheless, some surface defects (pitting, residual matrix and char) and strength degradation (especially at longer gauge lengths)[55] have also been reported.

Many initiatives have looked at the mechanical recycling of glass fibre composites as well. In this route, the waste composite is broken up and then ground into small particles. The resulting mixture of fibre, polymer and additives is then reused in other products. A range of applications for this waste have been investigated. These include its use as filler in SMCs and BMCs and in asphalt and concrete reinforcement.[10] Size reduction is the only method currently being used commercially to produce useful recyclate from SMC and BMC waste. The grinding processes employed by different recyclers involve individual technologies, but every methodology

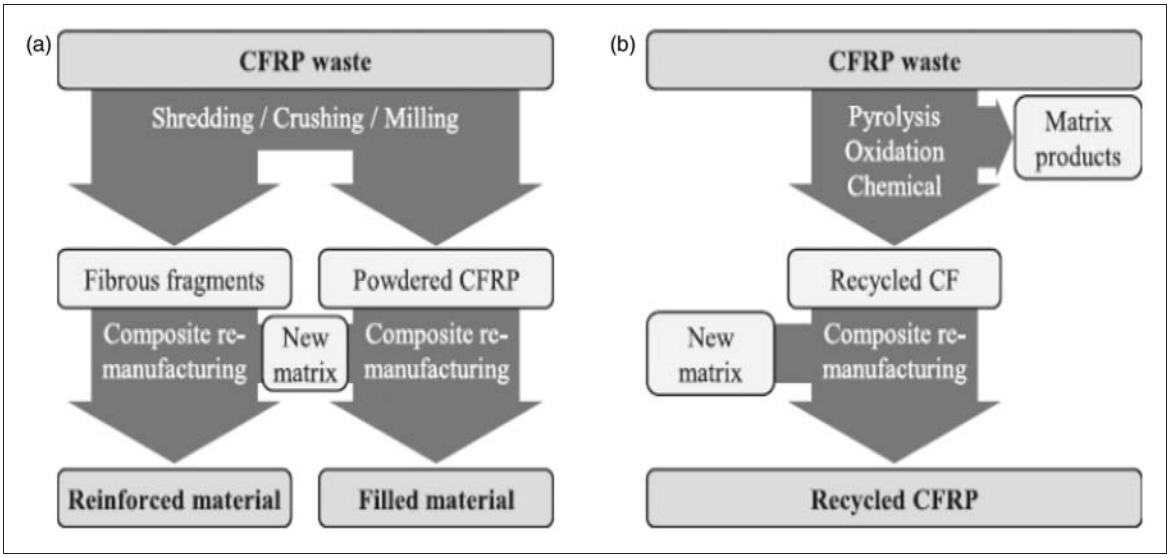

Figure 3. Main technologies for CFRP recycling. (a) Mechanical recycling, (b) fibre reclamation.[12]

involves a series of size reduction and separation steps. The ground recyclate is added to virgin constituents to form a new FRP material. The problem with this material is that it experiences significant reductions in stiffness and strength compared to all virgin constituent FRPs.

The increasing legal pressures, together with general environmental concerns and a perceived need that the composites industry should manufacture more sustainable products are encouraging the development of solutions for the post-utilization of FRP products in the higher levels of the waste hierarchy. Many possible suggestions and procedures in this regard have been proposed and practiced for the two classes (thermoplastic and thermoset) of FRPs. But our main focus here in this subsequent text is emphasized on the post-use solutions for the thermosetting FRPs mainly.

Post-use solutions for FRP wastes

The reuse and recycling of thermosetting FRP wastes is still not a regular practice and landfill remains the most popular solution to manage FRP wastes.[21] However, this disposal procedure is the least sustainable option and does not offer the advantages of the higher levels of the waste hierarchy, i.e. the lower cost of products incorporating recycled or reused waste.[14] Although landfill is still the commonest disposal solution for thermosetting FRP wastes, some alternative and more sustainable methods to manage these types of wastes are now available, the most important of which are described next wherein it is deliberately intended to focus mainly on the thermosetting FRPs with a little discussion carried out on the other form of FRP as and when felt necessary.

Incineration with energy and material recovery

Thermosetting FRPs, like other organic materials, have high calorific power and so can be used as an energy source. According to Pickering and Benson,[56] current thermosetting resins approximately have a calorific value of 30,000 kJ/kg. Some combustion trials have managed to combust composites for energy recovery.[56,57] The main problem here is that the high calorific power of FRPs and their considerable toxic emissions tend to overload incinerating systems. Therefore, incinerators actually charge more for burning post-use FRPs than other types of waste.

Recycling

Recycling of thermosetting polymers can be achieved through two major processes viz. mechanical recycling and thermal methods, already discussed earlier in ‘Recycling methodology’ section.

Reuse

Reuse of FRP wastes is very important from the viewpoint of better sustainability and wide acceptability of the material in the future. Chevrolet’s Corvette became the first vehicle to use FRP recyclate (in interior panels) in 1993.[13]

The construction industry, which consumes about a quarter of all plastics, is seen as a potential outlet for both plastics and FRP recyclates since there are many structures in non-critical applications – like partitions, insulation products, fibreboard, pipes, aggregates and cement, where shredded and ground composite materials could contribute to the required bulk, at costs less than those for virgin materials. However, structural items may be difficult to reuse because it is difficult to recalculate their residual mechanical properties like load-carrying properties and to take into account the effects of both environmental degradation and creep. Without reference to the original manufacturer, it will be impossible to derive the strength characteristics (such as shear and bending) of a composite section. Most thermosetting FRP parts (such as pultruded profiles, moulded gratings, panels and pipes) are produced for a specific purpose and so there is a little practical chance of post-utilization reuse in other applications as they tend to be produced to meet a particular set of circumstances and conditions so will often not be transferable to a different use. Finally, in most cases, at the end of the life cycle of a given FRP part, the fibre/matrix architecture is usually unknown.[14] Hence, 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 reused for certain applications if its fire-resisting properties are unknown.[15]

One possible application of filler-size particles (either yielded by mechanical treatments or collected from the cutting process) is their use as filler in the resin matrix of new FRPs. Some composite manufacturers already use this type of waste, often to replace calcium carbonate, particularly in BMCs and SMCs. According to Pickering,[21] for loading levels up to 10% the loss of mechanical properties is satisfactory. Hedlund-Astrom[53] notes that the incorporation of 20% of recycled filler does not significantly reduce performance when compared with a reference composite, and so represents a reduction of the material's self-weight and final cost. For higher loading, however, although the matrix density may be considerably lower, the mechanical properties also suffer significant reductions; furthermore, processing problems may arise, stemming from the higher resin absorption of the recyclates.[21]

The fibre-size particles recovered from thermal processes can also be used as fillers or reinforcements in new FRPs. Research has shown some success for this alternative.[53] But most research results have concluded that the incorporation of fibre-size particles instead of virgin reinforcing fibres causes a considerable loss of mechanical performance. Several studies have also reported strength reduction when recyclates are used as filler substitute. Petterson and Nilsson[58] replaced the calcium carbonate of new BMC with reground BMC scrap – for a 10% incorporation of BMC waste there was a slight reduction of the flexural modulus and the flexural strength slightly increased, but for higher proportions of incorporation of reground material the flexural strength of the BMC suffered a 52% reduction. In another study, Bledzki et al.[59] partially replaced the virgin fibres of BMCs with 5, 15 and 30% (in weight) of recyclates and obtained reductions in the flexural strength that varied from 7 to 30%. DeRosa et al.[60] studied the influence of incorporating 30% of fibre recyclates on the tensile strength of new BMC composites. The recycled material was obtained by grinding SMC composites and was used to replace virgin fibres of different lengths. The substitution of virgin fibres 19.05, 12.7 and 6.35 mm long caused loss of tensile strength of 40, 38 and 50%, respectively. The authors suggest that these large reductions are due to a significantly weaker connection between the fibre recyclates and the new matrix.

As mentioned earlier some typical applications for mechanically recycled composites include their reincorporation in new composites as filler or reinforcement. In construction industry they can be used as fillers for artificial woods or asphalt, or as mineral sources for cement.[14] However, these products represent low-value applications; mechanical recycling is therefore mostly used for GFRPs, although applications to thermoplastic and thermoset CFRPs can be found as well.[61–64]

Joao et al.[3] assessed the feasibility of incorporating the fine waste generated during the manufacturing of GFRP composites in concrete mixtures. Tests were carried out to evaluate the fresh- and hardened-state properties of concrete mixes in which between 0 and 20% of sand was replaced by GFRP fine waste. Although the incorporation of high proportions of GFRP waste was found to worsen the concrete performance in terms of both the mechanical and durability-related properties, it seems feasible to incorporate low proportions and reuse GFRP fine waste in concrete, particularly in non-structural applications such as architectural or pavement slabs, where good mechanical properties are less important.

Another possibility, as much a disposal concept as reuse, is to burn composite waste as an alternative fuel in heat-intensive processes such as cement manufacture in a kiln. In Europe tyres are utilized in this way and, at first sight, composites might seem to be a promising fuel. However, trends to minimize resin content in favour of inert filler loading, and the fibrous nature of residues where separation has not occurred, mean that the final ash waste could be both substantial and unhealthy. On balance, pyrolysis would seem to be a better option.[13] But nowadays various agencies are advocating the disposal of composite wastes by the cement kiln route as an option available in hand to abate the curse of FRP wastes completely.

The European Composites Industry Association (EuCIA) is calling for the disposal of composite wastes by the cement kiln route to be accepted as 'recycling' in new European legislation. EuCIA has issued a position paper on the revision of the European Commission's Waste Framework Directive for the same.[7] In cement production, incorporation of ground scrap may be complemented by incineration of plastic waste to generate high processing temperatures needed. In time the industry may benefit from recycling its own post-use structures, but as supplies of these are still limited due to the long lives of buildings, there is a scope for bringing in recyclate from other industries.[13]

The manufacturing process of cement requires lot of energy (which is partly provided by the resin fraction of the composite material) and raw materials (partly provided by all other ingredients of the composite material). This energy turns the raw materials (present in the composite waste) into anhydrides which gives cement its binding power. This means the energy is incorporated into the cement and becomes part of it (which is different from pure incineration). When mixed with water, and while recombining with water, the cement uses this energy to bind together the mortar and stones. Some energy recovery will therefore always be an inseparable integral part of the recycling process when composites are recycled via the cement kiln route.[7]

In cement kiln the composite waste is converted into energy and into raw materials for the cement, resulting in 67% material recovery: the mineral part of the composite (silica, calcium carbonate, alumina, etc.) is integrated into the clinker (the product of the cement kiln and the basic raw material for cement); 33% energy recovery: the organic part of the composite (resin) is used as a substitute fuel, enabling savings to be made in the use of other (fossil) fuels. This is a relatively simple and cheap solution, with almost 100% recovery rate, but the composite waste needs to be reduced to a small particle size and formulated to make it suitable for use in the cement kiln.[10] EuCIA believes that without the cement kiln route complete recycling of all FRP composite waste will be impossible. Therefore, the use of glass reinforced polymers (GRP) composites wastes in cement kilns means 70% material recycling and 30% energy recovery = 100% useful application.[7]

Ground GRP has been used in the manufacture of artificial wood products. Reynolds et al.[65] reported that The Building Research Establishment developed and evaluated the performance of GRP/plastic lumber as an alternative to tropical hardwood or treated softwood, and GRP reinforced wood particleboard for domestic flooring. Demura et al.[66] have also used fine FRP waste to manufacture artificial wood products. In addition, they tested the possibility of combining ground recycled GRP/polyester with wood flour to produce high density polyethylene (HDPE) plastic lumber. The results showed a significant increase of the tensile and flexural modulus, though the impact strength decreased. George and Dillman[67] also reported a considerable increase in the flexural properties and creep performance of HDPE plastic incorporating carbon-epoxy prepreg waste. Bolin and Smith[68] recently carried out a cradle-to-grave life cycle assessment of wood deck plastic composite decking.

The other possible sustainable use for recycled FRP wastes may be in road construction since road construction consumes large amounts of natural materials. According to BREWEB,[69] some preliminary research carried out by the Building Research Establishment and the University of Ulster showed that the incorporation of low quantities of GFRP waste (about 1% of total weight) in 20 mm dense bituminous mixtures for road construction had only a marginal effect on material performance.

Ogi et al.[70] investigated the behaviour of concrete mixtures incorporating granulated CFRP waste of three different particle sizes (length $\times$ width): small ($3.4 \times 0.4\,mm^2$), medium ($9.9 \times 2.2\,mm^2$) and large ($21.0 \times 7.7\,mm^2$). Four mixtures were prepared for each particle size with a fixed water/cement (w/c) ratio and by increasing the proportion of CFRP incorporated, corresponding to CFRP/cement mass ratios of 0, 0.05, 0.075 and 0.1. The mixture with the highest incorporation of recycled material had a CFRP volumetric content of 2.6%. The fresh-state results showed that the workability decreases with the incorporation of CFRP particles, regardless of their size. This indicates a worse behaviour of concrete with CFRP particles, as concrete mixtures with similar workability would need more water and, consequently, a higher w/c ratio. Regarding the hardened-state results, it was found that flexural strength increases and compressive strength increases slightly with increasing CFRP content. Compressive and flexural strengths both exhibited a decreasing trend with large-size recycled particles. However, it should be noted that these average trends represented a considerable scatter, most likely caused by the elongated shape of the particles which confer an anisotropic behaviour on concrete. This may be the most important difficulty of using recycled FRPs as coarse aggregate.

If the fibrous nature and elongated shape of fibre-size FRP recycled particles prevent them from being used as coarse aggregates in concrete, there may be some potential for filler-size particles. In fact, recent experiments conducted by Asokan et al.[71] showed that replacing fine aggregate by GFRP waste powder (with substitution rates of 5 and 15%) may lead to considerable improvements in concrete performance for both mechanical (compressive strength, tensile splitting strength) and durability (shrinkage, initial surface absorption and water absorption of concrete) properties. However, a previous study conducted by the same authors[72] found that similar replacement procedures were not so successful. Another recent study reported by Tittarelli and Moriconi[73] showed that the incorporation of GFRP waste powder in both cement mortars (substitution rates of 10, 15 and 20%) and self-compacting concretes (substitution rates of 25 and 50%) caused considerable loss of mechanical performance, although some durability-related properties were improved.

Although whatever technique may be adopted to find ways of prudently reusing and recycling FRPs but the concern about the impact of FRPs' exposure onto humans' health would always be there to haunt the environmentalists for years to come, no matter how much little or pronounced the effect would be. Keeping in mind the severity of the problem in hand associated with the usage of FRPs we in the next section have tried to present forth some of the past findings on the effects of FRPs' exposure onto humans' health.

Health hazards

Thermosetting polymers are extensively used in civil infrastructure owing to their added structural advantages over thermoplastics. They contain styrene monomer and hence are flammable because of this. When these resins burn, toxic gases such as carbon monoxide and halogenated products of combustion may be produced. The major problem with them is that the styrene monomer is a hazardous chemical that has initially been classified as a possible carcinogen to humans by the International Agency for Research on Cancer (IARC). This is partially based on recent mouse studies and it is not known how or if the results are applicable to humans.

Styrene can be absorbed into the body by inhalation and through the skin and eyes. Both airborne and skin overexposure to styrene should be avoided. The health effects of styrene include irritation of the eyes, nose and respiratory system. Additionally, headache, fatigue, dizziness, confusion, malaise, drowsiness, weakness and unsteady gait may result from overexposure to styrene. Skin exposure can lead to the defatting of the skin. Long-term effects of overexposure to this chemical include central nervous system disorders and liver injury. Comprehensive reviews of the developmental and reproductive data indicate that styrene is likely not teratogenic (i.e. causing birth defects) and provides little indication that styrene exposure could lead to any developmental or reproductive toxicity. The data for mutagenicity are mixed and the data are inadequate to classify it as a mutagen.[74]

Occupational exposure to styrene can result in various health effects not only on the central and peripheral nervous system[75–77] especially impairment of colour vision[78,79] and hearing ability[80] but also on the respiratory tract,[81] liver, kidneys[82,83] and skin.[84] Those health defects are reported to occur at a relatively low dose, and the reduction of individual exposure to styrene is essential in those industries making fibreglass reinforced plastics with styrene.[85]

In field installation of FRP duct, there are several activities that could result in exposure to nuisance dust including dust from fibreglass and resin. During the preparation for joining the duct, the installer must handle, cut and sand the duct material including fibreglass strapping. These activities could lead to the generation of airborne particles.

Studies have suggested that glass fibres are possibly carcinogenic to humans,[86,87] but recent reviews are cautious in making conclusions, because there is not enough evidence from human studies, so the conclusions are based mainly on evaluation of animal toxicology and mechanisms.[88–90] There are even fewer studies on potential non-carcinogenic respiratory effects of glass fibres[89,91,92] and these have provided inconsistent results. There is more consistent evidence of occurrence of skin diseases in glass fibre workers.[93,94]

Only a few previous studies have been reported on non-cancer respiratory effects of glass fibres and they have provided inconsistent results. According to reviews there has been insufficient evidence to make any firm conclusions,[89] so more studies on this topic in human subjects are needed.

The IARC has recently concluded its re-evaluation of the carcinogenic risk of airborne man-made vitreous fibres including glass wool and glass filaments. Continuous glass filaments, which are used principally to reinforce plastics, are considered not classifiable as to carcinogenicity to humans which earlier was regarded as carcinogen by the same agency. Review of these fibres in 1988 provides no evidence of increased risks of lung cancer or of mesothelioma (cancer of the lining of the body cavities) from occupational exposures during manufacture of these materials and inadequate evidence of any cancer risk.[74]

Also only a few studies have investigated nonmalignant respiratory effects of glass microfibres and these have provided inconsistent results. Workers exposed to glass microfibres experienced increased risk of cough, wheezing, breathlessness, nasal and skin symptoms and even asthma, the risks of breathlessness and skin symptoms remaining statistically significant after adjustment for confounders.[95]

On a contrary there are a substantial good number of studies on issues of skin and eye exposure to FRPs. Workers are exposed to glass microfibres through direct contact with the skin. Skin symptoms, such as itching, and dermatitis are rather consistently reported in relation to occupational exposure to glass microfibres in case reports, studies of individual factories and registry-based studies.[93,94,96,97] Prolonged or repeated resin skin contact may cause contact dermatitis. Contact dermatitis can develop due to the material being irritating to the skin. It can also be caused by an allergic reaction to something in products used, and many workers develop allergenic contact dermatitis due to exposure to epoxies. Some components of the resins may be absorbed through the skin, into the bloodstream. Once in the body, damage can occur to target organs such as the liver, reproductive system and central nervous system. Also overexposure to the chemicals used in FRP duct installation causes eye irritation, stinging, redness or swelling. Some chemicals, including styrene not only cause irritation, but can be absorbed into the bloodstream through the eyes.[74] But definitely more studies are needed on the subject to know with surety the exact response of FRPs exposure onto humans' body.

Conclusion

The conservative approaches of design are in favour of limiting the use of FRPs in the construction industry by surfacing out the black side of FRPs while some innovators are supporting and advocating the use of FRPs by considering it as an eco-friendly, cost effective and low energy material. They often claim that FRPs have benefits beyond general understanding today, which later will prove out to be acceptable that somehow looks doubtful now. They claim that FRPs are beneficial to a larger extent than presently believed. The claims would be accepted by general public with full confidence only after trusted performance response and through proper legal codes and documentations. The authenticity of their claim should first be ascertained before moving on to accept FRPs as a versatile and invincible material. Nevertheless, the decision of its wide acceptability and applicability lies wholly on the overall response in every aspect of its usage over a substantial period of time.

That is to say that the innovations are needed in costs of production and minimizing environmental impacts. Although the effects of occupational exposure of FRPs on humans health are not very well documented with regard to carcinogenicity and breathlessness but the skin contact effect and eye effects are very well documented which suggests that the exposure to FRPs can have adverse effects on the skin and eye.

In terms of implementation, the development of codes and standards that include considerations for safety, performance and sustainability are needed in transferring technology from laboratory to the market. Equally importantly, education of designers and architects is a paramount component of the use of composites in a built environment. At the end, it can be concluded that FRPs with few issues to resolve can turn out to be a future material bringing high levels of flexibility for many industries including construction. FRPs have the potential to outscore all other materials of construction, provided some severe issues related to them discussed at length in this paper are resolved first.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of interest

The authors declare no conflict of interest.

References

1. Steven JM. Alfred University, Mechanical engineering. *JEC Magazine*, May 2005, p.17.
2. Luke SL and Ravi J. The role of FRP composites in a sustainable world. *Clean Technol Environ Policy* 2009; 2: 247–249.
3. Joao RC, Almeida Nuno M and Figueira Joao R. Recycling of FRP composites: Reusing fine GFRP waste in concrete mixtures. *J Cleaner Prod* 2011; 19: 1745–1753.
4. Correia JR. *GFRP pultruded profiles in civil engineering: Hybrid solutions, bonded connections and fire behavior*. PhD Thesis in Civil Engineering, Instituto Superior Técnico, Technical University of Lisbon, 2008.
5. El Haggar S and El Hatow L. Reinforcement of thermoplastic rejects in the production of manhole covers. *J Cleaner Prod* 2009; 17: 440–446.
6. Hollaway LC and Head PR. The future for the advanced polymer composite in the civil infrastructure. In: *Advanced polymer composites and polymers in the civil infrastructure*, 1st ed., Elsevier Science, 2001, pp.287–292.
7. Jacob A. Recycling threat to Europe's composites industry. *Reinforced Plastics Magazine*, 2006.
8. Bank LC. *Composites for construction: Structural design with FRP materials*. Hoboken, NJ: Wiley, 2006.
9. Sims G and Bishop G. UK polymer composites sector: Foresight study and competitive analysis. Middlesex, UK: NPL; Chesterfield, UK: Net Composites, 2001.
10. Jacob A. Composites can be recycled. *Reinf Plast* 2011; 55: 45–46.
11. BIS. The UK Composites Strategy, Department for Business, Innovation & Skills, http://www.bis.gov.uk/~/media/biscore/corporate/docs/c/composites-strategy.pdf (2009, accessed 1 December 2013).
12. Soraia P and Silvestre TP. Recycling carbon fibre reinforced polymers for structural applications: Technology

review and market outlook. *Waste Manag* 2011; 31: 378–392.
13. Marsh G. Facing up to the recycling challenge. *Reinf Plast* 2001; 45: 22–26.
14. Conroy A, Halliwell S and Reynolds T. Composite recycling in the construction industry. *Compos Part A* 2006; 37: 1216–1222.
15. Halliwell S. National composites network best practice guide, net composites, end of life options for composite waste recycle, reuse, or dispose. http://www.compositesuk.co.uk/LinkClick.aspx?fileticket=f3y8cNT6pIg%3D&tabid=111&mid=550 (2006, accessed 2 December 2013).
16. GPRMC JEC 2003 Press Release 2003-2. *The green FRP label,* http://www.gprmc.be/PressReleases.htm.
17. Electronic version of Council Directive 1999/31/EC/ on the landfill of waste L 182/1-19, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:1999:182:0001:0001:EN:PDF (1999, accessed 28 November 2013).
18. The Council of the European Union, Council directive 2000/53/EC, of 18 September 2000 on end-of-life vehicles. *Off J Eur Commun* 2000; L269: 34–42.
19. The Council of the European Union, Council directive 1999/31/EC, of 26 April 1999 on the landfill of waste. *Off J Eur Commun* 1999; L182: 1–19.
20. The Council of the European Union, Council directive 2000/76/EEC, of 4 December 2000 on the incineration of waste. *Off J Eur Commun* 2000; L332: 91–111.
21. Pickering SJ. Recycling technologies for thermo-set composite materials – current status. *Compos Part A* 2006; 37: 1206–1215.
22. Gerdeen JC, Lord HW and Rorrer RAL. *Engineering design with polymers and composites*. Boca Raton, FL: CRC Press, 2006.
23. Humphreys MF. The use of polymer composites in construction. In: *International conference on smart and sustainable built environment,* Brisbane, Australia, November 2003.
24. Hollaway LC. A review of the present and future utilization of FRP composites in the civil infrastructure with reference to their important in service properties. *Constr Building Mater* 2010; 24: 2419–2445.
25. Scheirs J. *Polymer recycling: Science, technology and applications*. London, UK: Wiley, 1998.
26. Roberts A. The carbon fibre industry worldwide 2008–2014. England, UK: Materials Technologies Publications, 2009.
27. Sloan J. Carbon fibre 2007 looks forward with optimism. In: *High performance composites carbon fibre 2007 conference coverage,* Composites World, Washington, DC, USA, 5–7 December 2007.
28. Hunter T. A recycler's perspective on recycling carbon fibre pre-preg production scrap. In: *Carbon fibre recycling and reuse conference*, IntertechPira, Hamburg, Germany, 2009.
29. Marsh G. Reclaiming value from post-use carbon composite. *Reinf Plast* 2008; 52: 36–39.
30. Carberry W. Airplane recycling efforts benefit Boeing operators. *Boeing AERO Magazine QRT* 2008; 4: 6–13.
31. Roberts A. Rapid growth forecast for carbon fibre market. *Reinf Plast* 2007; 51: 10–13.
32. Wood K. Carbon fibre reclamation: Going commercial. *High Perform Compos* 2010; 3: 1–2.
33. Pamela. Process for advanced management of end of life of aircraft, *LIFE05ENV/F/000059*, http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=2859&docType=pdf (2005, accessed 2 December 2013).
34. Carberry W. Aerospace's role in the development of the recycled carbon fibre supply chain. In: *Carbon fibre recycling and reuse 2009 conference*, IntertechPira, Hamburg, Germany, 2009.
35. Meyer LO, Schulte K and Grove-Nielsen E. Optimisation of a pyrolysis process for recycling of CFRP's. In: *ICCM-16, Japan society for composite materials,* Kyoto, Japan, 2007.
36. Panesar S. Converting composite waste into high quality reusable carbon fibre. In*: JEC composites show*. *JEC composites,* Paris, France, 2009.
37. Pickering SJ, Kelly RM, Kennerley JR, et al. A fluidised-bed process for the recovery of glass fibres from scrap thermoset composites. *Compos Sci Technol* 2000; 60: 509–523.
38. Torres A, de Marco I, Caballero BM, et al. Recycling by pyrolysis of thermo-set composites: Characteristics of the liquid and gaseous fuels obtained. *Fuel* 2000; 79: 897–902.
39. Cunliffe AM, Jones N and Williams PT. Pyrolysis of composite plastic waste. *Environ Technol* 2003; 24: 653–663.
40. Jody BJ, Pomykala JA, Daniels EJ, et al. A process to recover carbon fibres from polymer-matrix composites in end-of-life vehicles. *JOM* 2004; 56: 43–47.
41. Yip HLH, Pickering SJ and Rudd CD. Characterization of carbon fibres recycled from scrap composites using fluidized bed process. *Plast Rubber Compos* 2002; 31: 278–282.
42. Meyer LO, Schulte K and Grove-Nielsen E. CFRP-recycling following a pyrolysis route: Process optimization and potentials. *J Compos Mater* 2009; 43: 1121–1132.
43. Allred RE, Gosau JM and Shoemaker JM. Recycling process for carbon/epoxy composites. In: *SAMPE 2001 symposium and exhibition*. *SAMPE,* Longbeach, CA, USA, 2001.
44. Nakagawa M, Shibata K and Kuriya H. Characterization of CFRP using recovered carbon fibres from waste CFRP. In: *Second international symposium on fibre recycling, the fibre recycling 2009 organizing committee,* Atlanta, Georgia, USA, 2009.
45. Pinero-Hernanz R, Dodds C, Hyde J, et al. Chemical recycling of carbon fibre reinforced composites in near critical and supercritical water. *Compos Part A* 2008; 39: 454–461.
46. Pinero-Hernanz R, Garcia-Serna J, Dodds C, et al. Chemical recycling of carbon fibre composites using alcohols under subcritical and supercritical conditions. *J Supercrit Fluids* 2008; 46: 83–92.
47. Jiang G, Pickering SJ, Lester EH, et al. Characterization of carbon fibres recycled from carbon fibre/epoxy resin

composites using supercritical n-propanol. *Compos Sci Technol* 2009; 69: 192–198.
48. Goto M. Chemical recycling of plastics using sub- and supercritical fluids. *J Supercrit Fluids* 2009; 47: 500–507.
49. Marsh G. Carbon recycling: A soluble problem. *Reinf Plast* 2009; 53: 22–23, 25–27.
50. Pickering SJ. Carbon fibre recycling technologies: What goes in and what comes out? In: *Carbon fibre recycling and reuse 2009 conference,* IntertechPira, Hamburg, Germany, 2009.
51. Warrior NA, Turner TA and Pickering SJ. AFRECAR and HIRECAR project results. In: *Carbon fibre recycling and reuse 2009 conference*, IntertechPira, Hamburg, Germany, 2009.
52. Kasper A. Recycling composites: FAQs. *Reinf Plast* 2008; 52: 39.
53. Hedlund-Astrom A. *Model for end of life treatment of polymer composite materials*. PhD Thesis, Royal Institute of Technology, Stockholm, 2005.
54. Palmer J, Ghita OR, Savage L, et al. Successful closed-loop recycling of thermo-set composites. *Compos Part A* 2009; 40: 490–498.
55. Heil JP, Hall MJ, Litzenberger DR, et al. A comparison of chemical, morphological and mechanical properties of various recycled carbon fibres. In: *SAMPE'09 conference. SAMPE*, Baltimore, MD, USA, 2009.
56. Pickering SJ and Benson M. The recycling of thermo-setting plastics. In: *Second international conference on plastics recycling,* 1991, pp.23/1–10. London, UK: Plastics and Rubber Institute.
57. Nystrom B. Energy recovery from composite materials. In: *Seminar on recycling of composite materials*. IFP SICOMP, MöIndal, Sweden, 2002.
58. Petterson J and Nilsson P. Recycling of SMC and BMC in standard processing equipment. *J Thermoplast Compos Mater* 1994; 7: 56–63.
59. Bledzki AK, Kurek K and Barth C. Development of thermo-set part with SMC reclaim. In: *ANTEC 1992–50 years: Plastics shaping the future society of plastics engineers,* 3–7 May 1992, pp.1558–1560. Detroit, MI: Society of Plastics Engineers.
60. DeRosa R, Telfeyan E and Mayes S. Expanding the use of recycled SMC in BMCs. In: *GPEC 2004 – global plastics environmental conference*, 2004, paper no. 044. Detroit, MI: Society of Plastics Engineers.
61. Job S. Composite recycling-materials KTN report, http://www.compositesuk.co.uk/LinkClick.aspx?fileticket=LXN-MfM0360=& (2010, accessed 20 November 2013).
62. Kouparitsas CE, Kartalis CN, Varelidis PC, et al. Recycling of the fibrous fraction of reinforced thermoset composites. *Polym Compos* 2002; 23: 682–689.
63. Ogi K, Nishikawa T, Okano Y, et al. Mechanical properties of ABS resin reinforced with recycled CFRP. *Adv Compos Mater* 2007; 16: 181–194.
64. Takahashi J, Matsutsuka N, Okazumi T, et al. Mechanical properties of recycled CFRP by injection molding method. In: *ICCM-16, Japan Society for Composite Materials,* Kyoto, Japan, 2007.
65. Reynolds TN, Halliwell S and Conroy A. Markets for FRP recyclate. Institute of wastes management. *Sci Tech Rev* 2004; 5: 29–34.
66. Demura K, Ohama Y and Satoh T. Properties of artificial woods using FRP powder. In: *Proceedings of the international workshop on disposal and recycling of organic and polymeric construction materials*. Rilem, E & FN Spon, London, UK, 1995, pp.169–178.
67. George S and Dillman S. Recycled fibreglass composite as a reinforcing filler in post-consumer recycled HDPE plastic lumber. In: *Proceedings of ANTEC2000 conference materials,* 2000, vol. II, pp.2919–2920. Orlando, FL: Society of Plastics Engineers.
68. Bolin CA and Smith S. Life cycle assessment of ACQ-treated lumber with comparison to wood plastic composite decking. *J Cleaner Prod* 2011; 19: 620–629.
69. BREWEB. *Fibre reinforced plastic as road reinforcement material*. Project Report, Building Research Establishment and University of Ulster. Project Report 044, 2005.
70. Ogi K, Shinoda T and Mizui M. Strength in concrete reinforced with recycled CFRP pieces. *Compos Part A Appl Sci Manuf* 2005; 36: 893–902.
71. Asokan P, Osmani M and Price ADF. Improvement of the mechanical properties of glass fibre reinforced plastic waste powder filled concrete. *Constr Building Mater* 2010; 24: 448–460.
72. Asokan P, Osmani M and Price ADF. Assessing the recycling potential of glass fibre reinforced plastic waste in concrete and cement composites. *J Cleaner Prod* 2009; 179: 824–832.
73. Tittarelli F and Moriconi G. Use of GRP industrial by-products in cement based composites. *Cement Concrete Compos* 2010; 32: 219–225.
74. *Safe handling of fibreglass reinforced plastic (FRP)*. Safety and Health Department, 2004.
75. Gobba F, Cavalleri F, Bontadi D, et al. Peripheral neuropathy in styrene-exposed workers. *Scand J Work Environ Health* 1995; 21: 517–520.
76. Yuasa J, Kishi R, Eguchi T, et al. Study of urinary mandelic acid concentration and peripheral nerve conduction among styrene workers. *Am J Ind Med* 1996; 30: 41–47.
77. Tsai SY and Chen JD. Neurobehavioral effects of occupational exposure to low-level styrene. *Neurotoxicol Teratol* 1996; 18: 463–469.
78. Fallas C, Fallas J, Maslard P, et al. Subclinical impairment of color vision among workers exposed to styrene. *Brit J Ind Med* 1992; 49: 679–682.
79. Campagna D, Mergler D, Huel G, et al. Visual dysfunction among styrene-exposed workers. *Scand J Work Environ Health* 1995; 21: 382–390.
80. Muijiser H, Hoogendijk EM and Hooisma J. The effects of occupational exposure on high-frequency hearing thresholds. *Toxicology* 1988; 49: 331–340.
81. Welp E, Partanen T, Kogevinas M, et al. Exposure to styrene and mortality from nonmalignant respiratory diseases. *Occup Environ Med* 1996; 53: 499–501.
82. Welp E, Partanen T, Kogevinas M, et al. Exposure to styrene and mortality from nonmalignant diseases of

the genitourinary system. *Scand J Work Environ Health* 1996; 22: 223–226.
83. Verplank AJ and Herber RF. Effects on the kidney of occupational exposure to styrene. *Int Arch Occup Environ Health* 1998; 71: 47–52.
84. Galassi C, Kogevinas M, Ferro G, et al. Biological monitoring of styrene in the reinforced plastics industry in Emilia Romagna, Italy. *Int Arch Occup Environ Health* 1993; 65: 89–95.
85. Inaoka T, Nagano M, Kitano T, et al. Biological monitoring of styrene in FRP-making small industries in Kumamoto, Japan—winter-summer difference and effect of protective masks in practical working conditions. *J Occup Health* 2002; 44: 83–88.
86. International Agency for Research on Cancer (IARC). *Monographs on the evaluation of carcinogenic risk to humans: Man-made mineral fibres and radon*, Lyon, France, 1988, p.43.
87. Wardenbach P, Rödelsperger K, Roller M, et al. Classification of man-made vitreous fibres. Comments on the revaluation by an IARC working group. *Regulat Toxicol Pharmacol* 2005; 43: 181–193.
88. Osinubi OYO, Gochfeld M and Kipen HM. Health effects of asbestos and nonasbestos fibres. *Environ Health Perspect* 2000; 108: 665–674.
89. De Vuyst P, Dumortier P, Swaen GMH, et al. Respiratory health effects of man-made vitreous (mineral) fibres. *Eur Respir J* 1995; 8: 2149–2217.
90. International Agency for Research on Cancer (IARC). *Monographs on the evaluation of carcinogenic risk to humans: Man-made vitreous fibres,* Lyon, France 2002, p.81.
91. Hesterberg TW and Hart GA. Health and safety aspects of fibre glass, XV. In: *The fifteenth annual battery conference on applications and advances,* Littleton, 2000.
92. Moulin JJ, Wild P, Mur JM, et al. Respiratory health assessment by questionnaire of 2024 workers involved in man-made mineral fibre production. *Int Arch Occup Environ Health* 1988; 61: 171–178.
93. Tarvainen K, Jolanki R, Forsman-Grönholm L, et al. Exposure, skin protection and occupational skin diseases in the glass-fibre-reinforced plastic industry. *Contact Dermatitis* 1993; 29: 119–127.
94. Jolanki R, Mäkinen I, Suuronen K, et al. Occupational irritant contact dermatitis from synthetic mineral fibres according to Finnish statistics. *Contact Dermatitis* 2002; 47: 329–333.
95. Penpatra S, Nintita S, Wantanee P, et al. Respiratory and skin health among glass microfibre production workers: A cross-sectional study. *Environ Health* 2009; 8: 36.
96. Minamoto K, Nagano M, Inaoka T, et al. Skin problems among fibre glass reinforced plastics factory workers in Japan. *Ind Health* 2002; 40: 42–50.
97. Chen JY, Phillips R, Lewis AT, et al. Irritant contact dermatitis secondary to fibreglass: An unusual presentation. *Int J Dermatol* 2000; 39: 372–374.