DEVELOPING A CIRCULAR ECONOMY IN RECYCLED POLYMER CONSTRUCTION MATERIALS

While numerous studies have focussed on replacing carbon-intensive construction materials like concrete and steel with novel alternatives, few have addressed the feasibility of doing so at a scale that will lead to meaningful reductions in embodied carbon across the construction industry. In this study, prospective construction materials are identified that are derived from polymers reclaimed from municipal and industrial waste streams. The suitability of such materials in construction is shown through a review of mechanical properties and fabrication processes. An analysis of polymer waste sources within the manufacturing sectors is conducted to identify those that can realistically satisfy the volume of material required to replace conventional materials at impactful levels. Projected savings of embodied carbon associated with replacing conventional building materials with recycled polymers are presented, examining the influence of various levels of polymer waste reclamation and industry growth scenarios. It is found that upwards of 16 million tonnes of carbon dioxide emissions can be avoided by adopting these novel materials in construction.

Keywords: circular economy; sustainable construction materials; structural polymers; recycled construction materials; concrete replacement.

1 INTRODUCTION

The looming climate crisis, to which the construction sector has contributed significantly, urgently requires an industrial-scale reconfiguration of the construction supply chain and a reduced dependency on carbon-intensive materials. While the goal of net zero construction has driven numerous research initiatives to develop low carbon construction materials and prefabricated construction methods (Jin et al 2018), the construction sector's characteristic hesitancy to innovate has impeded significant progress on decarbonisation when compared to various manufacturing industries. Likewise, although technologies and methods employed in other sectors have seen progressive advances in precision, speed, operative safety and material efficiency over recent decades, the construction sector has again been slow to exploit such opportunities, with conventional materials, methods of construction and work practices still the norm, with associated implications for speed, safety and carbon.

The UK construction industry consumes over 420 million tonnes of material per annum (AMA Research & BRE 2008) while generating 120 million tonnes of waste (DEFRA 2018). While efforts have been made to reduce construction waste, the sector still contributes enormously to overall waste in the UK (DEFRA, 2018) as can be seen in Figure 1. Of primary concern, while other sectors have seen overall reductions in waste, construction waste continues to grow. This, it should be noted, is in spite of increased awareness across the sector and formidable initiatives instigated by major stakeholders and industry bodies to encourage more sustainable practices.

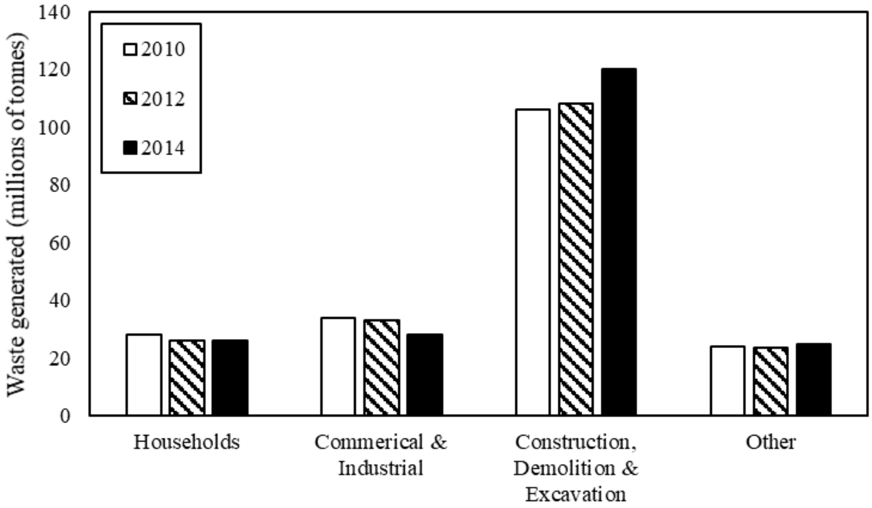

Figure 1: Waste produced by industrial sector (after DEFRA, 2018).

The present study seeks to address how the environmental impact of construction can be reduced not only through low carbon material selection but also through fostering greater circularity in the material supply chain. When considering that construction waste makes up 32% of all landfill waste in the UK (DesigningBuildings 2021), it is clear that there is considerable room for improvement in the sector in both how material use is optimised in the first place and then how waste material is repurposed.

When considering material selection, although innovations in polymer science across the 20th century have led to an enormous array of applications in many different manufacturing industries, the use of polymers in construction is still predominantly limited to non-load bearing applications like pipework and insulation. Fibre-reinforced polymer (FRP) structures have received considerable research focus over the past two decades (Wu et al, 2014), especially given their enhanced mechanical efficiency and their long-term durability in exposed, coastal or highly saline environments (Correia et al, 2015). In addition, the low density and enhanced efficiency of polymers can generate further savings in structural self-weight and the energy required during transport and assembly. While a number of FRP structures and bridges have already been constructed, the collective efforts of numerous research initiatives will soon culminate in a European design standard for fibre-reinforced polymer structures (Ascione et al, 2016). Thus, there is a clear precedent for the use of polymers in construction but as of yet this potential has not been fully exploited across the wide range of polymers available.

Plastics are often identified as a major contributor to environmental damage owing to them being primarily sourced from hydrocarbons and their resistance to degradation. However, when employed sensibly and, crucially, when repurposed effectively, the same material longevity that leads to waste plastic posing such a threat to the natural environment can in fact be used to enhance environmental sustainability by producing products with longer usable lifespans that are easily recycled upon decommissioning. This is especially true in the case of thermoplastic polymers that can be heated and reformed multiple times, albeit with some degradation of material performance.

The present study aims to explore the feasibility of replacing conventional construction materials such as concrete and steel with recycled polymers, thus introducing circularity into the construction material supply chain. Initially, a survey is conducted of the variety of polymers manufactured in the UK, their suitability for recycling and the volumes of waste produced every year. An impact study is presented detailing of the levels of embodied carbon savings that can achieved through various levels of material replacement and growth in the construction and polymers industries.

2 POLYMER USE IN THE UK

In this section, the current extent of polymer use in the UK is surveyed, including polymer types, applications, waste generation and their potential for recycling.

2.1 Types of polymer manufactured in the UK

It is estimated that approximately 5 million tons of polymer material is produced in the UK each year, with over half of this amount used for packaging alone (Smith and Bolton, 2021). Currently, 41 different species of polymer are produced in the UK by 59 major suppliers. These materials represent a wide variety of physical properties, applications and manufacturing techniques across a number of industries from packaging to automotive and beyond. Of these materials, there are only a small number that are commonly recycled (Hsu et al, 2021), which are shown in Table 1.

Table 1: Common recyclable thermoplastic materials (Hsu et al, 2021).

Material	Common applications
Polyethylene terephthalate (PET)	Beverage bottles, kitchenware, food packaging
High-density polyethylene (HDPE)	Waterproofing, cabling, milk bottles, chemical drums
Polyvinyl chloride (PVC)	Packaging, transportation sector, piping
Low-density polyethylene (LDPE)	Toys, bottles, tank linings, water pipes, film packaging
Polypropylene (PP)	Mouldings for cars, structural foams, foam packaging, clothing fibres
Polystyrene (PS)	CD cases, refrigerator trays, cassettes
Polylactic acid (PLA)	Biodegradable substitute in bottles, packaging, health care devices.
Acrylonitrile butadiene styrene (ABS)	Pipe fittings, automobile fittings, electronic housings, helmets

It should be noted that these materials are all thermoplastics, which soften when heated and can be reformed, as opposed to thermosetting polymers like those used in FRP structures that tend to combust instead. Although materials like HDPE and PVC are currently only used in non-load bearing applications in construction, polymers like PP in particular are often used for mechanical protection and electronics housings, while the potential of using PLA in load-bearing contexts has been demonstrated previously by McCann and Rossi (2021).

2.2 Plastic waste

It is estimated (Eunomia, 2018) that 3.5 million tonnes of plastic waste is produced each year in the UK, with plastic packaging alone accounting for 67% of this total. Currently, an estimated 53% of this plastic waste is either sent to landfill or left unrecovered, although the recycling rate of plastic packaging has been rising steadily over the past decade as shown in Figure 1 (DEFRA, 2021). However, it is still the case that at least 1.94 million tons of all plastic waste is being sent to landfill each year. It has also been suggested that UK government figures for recycling rates are actually overestimated since they are based on conservative figures for total waste produced (Eunomia, 2018). Thus, there is a considerable opportunity available to repurpose large amounts of waste plastic each year.

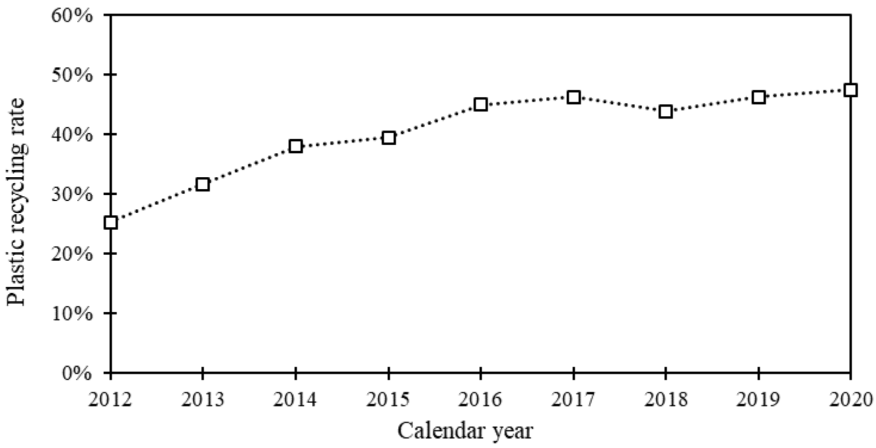

Figure 1: Annual plastic packaging recycling rate in the UK (DEFRA, 2021).

2.3 Polymer recycling processes

In theory, it is possible to recycle all polymer materials, but in practice, the decision to do so is controlled by logistical constraints and environmental factors. The production of virgin polymer materials often carries a heavy carbon cost owing to their provenance from hydrocarbons; this can be considerably reduced through recycling, with savings in carbon emissions as high as 87% achievable in certain scenarios (Campolina et al, 2017). Within the UK, PET and HDPE are the most commonly recycled polymers, while many other polymers must be exported for recycling abroad since the UK possesses neither the capacity nor the correct facilities to process them. For materials that require an onerous amount of energy to reprocess, e.g., thermosetting polymers, greater carbon savings are to be gained from energy recovery via incineration as opposed to recycling. However, true circularity in these materials can be achieved through their use in durable and redeployable structural components, e.g., temporary structural frames, emergency shelters or modular structures.

Mechanical recycling of polymers broadly comprises four main activities: collection, sorting, cleaning and reprocessing. After collection by municipal authorities and waste management operators, plastic waste is transported to material recovery facilities (MRFs). The carbon cost of the collection and transportation stage is largely dependent on the distance travelled by waste collection vehicles, their fuel consumption and the local availability of waste processing facilities. Automated sorting methods are then employed to extract various polymer materials from bulk waste; given that the majority of these processes are conducted by electric-powered machinery, the carbon cost of the sorting stage is largely dependent upon the assumed energy mix powering the facilities.

Once polymer materials have been separated from bulk waste at an MRF, they will be transferred to a plastic recovery facility (PRF) for further sorting into specific polymer types. Infrared sorters are used to separate mixed bottles and further mixed polymer originating at MRFs, which are then washed thoroughly to remove contaminants ahead of mechanical processing. The amount of water required to clean the material thoroughly is a contributor to overall environmental impact.

Once cleaned of contaminants, the polymer materials are shredded and ground into smaller flakes. The final stage of the process involves melting the polymer and extruding it into new pellets, ready for re-use. Herein is where a large proportion of the carbon emissions attributable to the recycling process lie, with more thermally resilient materials requiring larger energy inputs.

3 RECYCLED POLYMERS IN CONSTRUCTION

In this section, the feasibility and impact of replacing conventional materials with recycled polymer products is explored. Although considerable efforts have been made by the construction industry to decarbonise and proliferate the use of low carbon construction methods and materials, conventional materials like concrete and steel still dominate in terms of tonnages used, as shown in Table 2, with implications for carbon and circularity. Although the carbon footprint of steel is reduced through recycling rates as high as 87% (Sansom and Meijer, 2003), the same cannot be said of concrete, although there are numerous research initiatives examining the efficacy of recycled concrete aggregates (Chen et al, 2019). It can be seen in Table 2 that polymers already account for a noticeable share of construction materials but this is largely in non-structural applications like PVC window frames, drainpipes or polystyrene insulation.

Table 2: Materials used in UK construction annually (AMA Research & BRE, 2008).

Material	Thousands of tonnes
Clay	5,752
Concrete products	62,343
Insulation	655
Other cement	18,902
Plastic	771
Raw materials (filler, loose aggregates)	277,300
Rubber	168
Slate	156.5
Steel	3,120
Timber	6,511

3.1 Polymer replacement of conventional construction materials.

A number of precedents exist in the use of waste plastics in construction, including waste PET, HDPE and LDPE as aggregates in concrete (Hama and Hilal, 2017; Ogundairo et al, 2021) and PET fibre-reinforced concrete beams (Khalid et al, 2018). Considering scales, each year in the UK, 3.5 million tonnes of plastic waste is generated but 62 million tonnes of concrete and 3.1 million tonnes of steel are consumed in construction. Thus, it is clear that replacing bulkier structural elements like heavy slabs, walls or deep decking with recycled polymer alternatives is not viable at the industrial scale. Instead, the current study assumes that, in addition to waste plastic being used as aggregates and filler, thin-walled recycled polymer elements will replace light-gauge steel beams, purlins and joists, while recycled polymer lattice decks will replace lightweight concrete or light-gauge steel flooring systems; these replacements are in keeping with current practice regarding FRP structural elements (Correia et al, 2015).

3.2 Carbon emissions equivalents

In Table 3, the mechanical properties and carbon equivalents of various materials are compared. Carbon emission figures are typically calculated per unit mass of material produced, so these have been normalised by strength-to-weight ratio ($\sigma/\rho g$) since less dense, more structurally efficient materials contribute less structural mass and thus less emissions per unit load supported in a structure. In Table 3, values of kg CO_2 emitted per kg load supported per metre are provided for both virgin and recycled polymers based on life-cycle analyses from the literature. It should be noted that these carbon emissions figures relate to the production of raw polymer materials for further processing.

Table 3: Carbon emissions and mechanical properties (sources in footnote).

Material	kg CO_2 / kg material		Density ρ	Strength σ	$\sigma/\rho g$	kg CO_2 / kg load / m	
	Virgin	Recycled	(kg/m^3)	(N/mm^2)	km	Virgin	Recycled
PET	2.15[1]	0.45[2]	1350[3]	50[3]	3.78	0.57	0.12
HDPE	1.93[1]	0.63[2]	960[3]	32[3]	3.40	0.57	0.19
PVC	2.50[4]	1.13[5]	1890[3]	50[3]	2.70	0.93	0.42
LDPE	1.70[6]	0.59[6]	920[3]	23[3]	2.55	0.67	0.23
PP	1.91[1]	0.90[7]	920[3]	33[3]	3.66	0.52	0.25
PS	3.68[1]	2.32[7]	1050[3]	53[3]	5.15	0.72	0.45
PLA	0.50[8]	0.28[9]	1250[3]	55[3]	4.49	0.11	0.06
ABS	3.80[10]	0.41[10]	1210[3]	48[3]	4.04	0.94	0.10
C40 concrete	0.20	-	2400	40	1.70	0.12	-
S355 steel	1.85	-	7850	355	4.61	0.40	-

[1]Mortensen et al (2021); [2]Bataineh (2020); [3]van der Vegt and Govaert (2005); [4]ECVM and PlasticsEurope (2008); [5]Nakem et al (2016); [6]AlMa'adeed et al (2011); [7]Tonini et al (2021); [8]Morão and de Bie (2019); [9]Maga et al (2019); [10]Campolina et al (2017).

As can be seen, most polymers achieve a considerably better strength-to-weight ratio ($\sigma/\rho g$) than C40 concrete, although not quite as much as mild grade S355 steel. When these ratios are calculate carbon emissions per unit structural load supported, it can be seen that most virgin polymers have larger carbon footprints than concrete and steel but when recycled effectively, these figures decrease considerably, with materials like PET, HDPE and ABS having much lower values of kg CO_2 emitted per kg load supported per metre than steel. According to this analysis, PLA performs best in this regard but it should be recognised that nitrate fertilisers sometimes used to assist crop growth for PLA can drastically increase carbon equivalents, and as of yet, large-scale recycling of PLA does not occur (Maga et al, 2019; Morão and de Bie, 2019).

Data on the share of plastic waste by polymer type is not clear from the literature and is thus based on approximate levels of use in the industry as 28% PET, 16% HDPE, 15% PVC, 15% LDPE, 12% PP, 6% PS, 4% ABS and 4% PLA. It is assumed that 80% of the available plastic waste will be used to replace steel with the remainder replacing concrete products. Also, it is assumed that recycled polymers are strengthened by the inclusion of 10% virgin material in order to ensure satisfactory structural performance. The amount of carbon saved through replacing either steel or concrete by a recycled polymer is calculated as follows:

CO_2 saved = (polymer mass)×(polymer $\sigma/\rho g$)×(difference in CO_2 per kg load per m)

By aggregating carbon savings across the eight polymers considered in the study, a weighted average annual carbon savings factor of 0.298 kg CO_2 / kg polymer is found. It should be noted that given the array of polymer manufacturing methods available, this figure does not account for carbon emissions relating to the production of construction components from raw polymer materials. However, it is a quantitative indication of the benefits of replacing steel and concrete with recycled polymers.

3.3 Material replacement

For the purposes of the present study, it is assumed that 1.94 million tonnes of waste plastic is sent to landfill each year with a recycling rate of 48% (Smith & Bolton 2021). Three future waste stream scenarios are modelled whereby it assumed that this waste is repurposed exclusively by the construction industry as load-bearing components to replace concrete and steel:

1. 25% of landfilled plastic + 5% of recycled plastic
2. 50% of landfilled plastic + 10% of recycled plastic
3. 75% of landfilled plastic + 20% of recycled plastic

Next, the model must account for growth in both the construction and polymer manufacturing industries. In spite of recent global challenges, construction is predicted to grow an average of 2.5% per year up to 2025 (Research and Markets 2021). Creating a new market in polymer construction materials will undoubtedly spur further growth in the production of virgin polymers to meet demand, with a commensurate increase in the total amount of waste or recycled polymers available to the construction industry. Two economic scenarios are modelled: 1) production of recycled polymer construction materials matches growth in the construction sector at 2.5%; 2) in response to greater demand created by the new market in construction polymers, the growth rate increases to 5.0% each year. Figures 2 and 3 show cumulative CO_2 savings up to 2040 for these two economic scenarios, respectively, compared to the status quo. It can be seen that, even if growth in polymers merely matches construction output and the most modest waste stream blend is utilised, over 4 million tonnes of CO_2 can be saved by 2040 - this is significant when considering that the construction industry was responsible for 13.5 million tonnes of CO_2 in 2019 (Tiseo, 2020). When larger plastic waste streams are utilised and growth in polymers is increased, the cumulative savings could be as high as 16.4 million tonnes of CO_2. It should be noted that these figures do not account for possible disruptive technologies that may also lead to significant carbon savings, nor do they address regulatory barriers that would inhibit uptake in recycled polymer construction products.

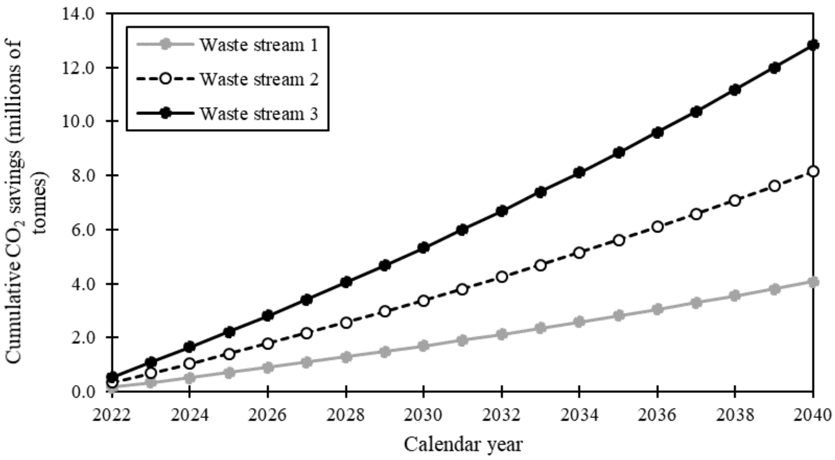

Figure 2: Cumulative carbon savings compared to current construction practice assuming economic scenario 1 (growth in polymers matches construction growth at 2.5% per annum).

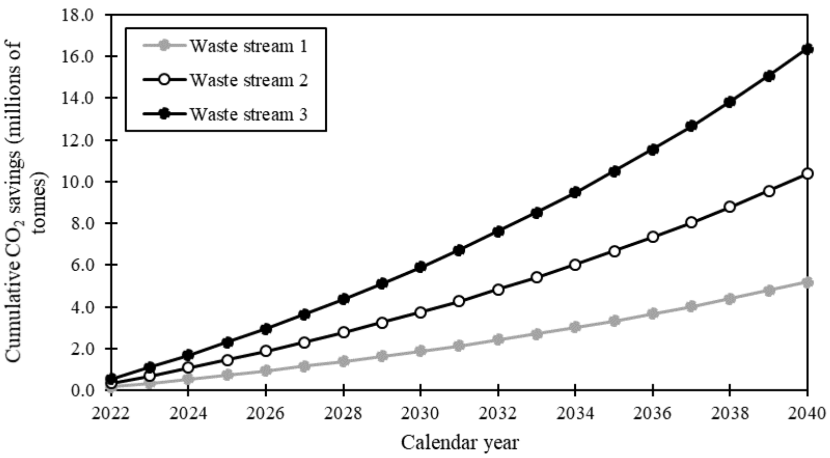

Figure 3: Cumulative carbon savings compared to current construction practice assuming economic scenario 2 (growth in polymers of 5.0% per annum).

4 CONCLUSIONS

The feasibility and impact of replacing load-bearing structural materials with recycled polymer alternatives has been analysed. Suitable polymer materials for recycling and associated volumes of waste have been identified and data on mechanical properties and carbon emissions collected. Two polymer industry growth scenarios and three waste streams reflecting various levels of re-utilisation of landfilled and recycled waste plastics have been considered. It is shown that under the most modest scenario modelled, introducing recycled polymer structural components could save 4 million tonnes of CO_2 by 2040 compared to current construction practices. Projecting further, if growth in the polymer industry were increased and much higher proportions of landfilled and recycled polymers were used exclusively for construction, a total 16.4 million tonnes of CO_2 could be saved up to 2040.

While the findings of the present study are dependent upon a number of assumptions and some modelling uncertainties, and that there are a number of logistical, regulatory and reliability-related barriers yet to be overcome, it appears quite conclusive that the replacement of conventional steel and concrete construction products with alternatives fabricated from recycled polymers is not only viable but has the potential to lead to considerable carbon savings for the construction sector.

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