Carpet Recycling - Improving Reuse and Recycling of Existing Products and Service

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Abstract

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'Carpet Recycling - Improving Reuse and Recycling of Existing Products and Service'

In 2020 467,000 tonnes of carpet and textile flooring waste was generated in the UK, of which only 65,500 tonnes (14%) was sent to destinations other than landfill or combustion. There are many difficulties in finding alternative cheap, scalable, and environmentally friendly end-of-life routes for carpet, as it is a long-lasting, hard-wearing composite material. The aim of this project, working together with Carpet Recycling UK (CRUK), was to explore the feasibility of various end-of-life routes for carpet in the UK. A literature review was conducted, analysing a variety of different routes for waste carpets and the merits and drawbacks of each, concluding that concrete reinforcement, sound insulation, and oil absorption are the three most promising areas, along with the production method of melt/electrospinning. Experimental work has been conducted on the separation of carpet fibres from backing using sink-float separation, the quantifying of these components with FTIR and DSC analysis, and the production of 3D printing filament. The filament produced by this was not of sufficient quality for further testing, potentially due to thermal degradation and/or contamination, and the report suggests ways in which higher quality filament could be produced. CO_2e calculations have been made for a variety of different disposal routes to provide novel information on the CO_2e impact of carpet disposal. This section shows that concrete reinforcement, equestrian surfacing, reuse and recycling are the least CO_2e intensive end-of-life routes (0.063 tCO_2e/tonne of carpet waste). The section also considered the impact of including a projected carbon offset, which reduces the apparent impact of EFW, kiln fuel, and concrete reinforcement (from 2.401 tCO_2e/tonne to 0.548, -0.138, and -0.377 tCO_2e/tonne respectively). Finally, landfill appears in CO_2e impact as effectively neutral in impact, showing it may be a promising option for sequestering carpet waste until recycling technology improves.

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Glossary of Terms

AF – Alternative fuels

BCA – British Cement Association

BEIS – Department for Business, Energy and Industrial Strategy

$CaCO_3$ – Calcium carbonate

CCS – Carbon Capture and Storage

CRUK – Carpet Recycling UK

DECC – Department for Energy and Climate Change

DEFRA – Department for Environment, Food, & Rural Affairs

DSC – Differential Scanning Calorimetry

EA – Environment Agency

EFW – Energy from Waste

ETS – Emissions Trading System

EVA – Ethylene-vinyl acetate

FDM – Fused deposition modelling

FTIR – Fourier Transform Infrared

GWP – Global Warming Potential

LHV – Lower Heating Value

LRWP – Low Risk Waste Position

MDS – Magnetic Density Separation

MFI – Melt Flow Index

NCV – Net Calorific Value

NIRS – Near-Infrared Spectroscopy

OPC – Ordinary Portland cement

PA – Polyamide (Nylon)

PAH – Polycyclic aromatic hydrocarbons

POPs – Persistent Organic Pollutants

PP – Polypropylene

PVC – Polyvinyl chloride

RDF – Refuse derived fuel

RPS – Regulatory Position Statement

SBR – Styrene-butadiene rubber

SRF – Solid recovered fuel

WDF – Waste derived fuel

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Author’s Declaration

I declare that this thesis is my own work and has not been submitted in substantially the same form for the award of a higher degree elsewhere.

Joseph Lawson

1. Introduction

Plastic waste is a global problem of ever-increasing proportions. The mass production of plastics began nearly 70 years ago, and their production rate is expected to double over the next two decades [1]. This presents substantial problems for the environment, as plastics are already responsible for 4.5% of global CO_2 emissions and plastic waste is accumulating in the environment at a rate approaching 400 Mt/year [2] [3].

In 2020 467,000 tonnes of carpet and textile flooring waste was generated in the UK, an increase of 37,000 tonnes from 2019. 30% of this waste was sent to landfill sites. While the remaining 70% of the total was diverted from landfill, over 90% went to energy from waste (EFW) plants [4], where energy is generated by burning residual waste material [5].

Carpet is designed to be hardwearing, long lasting, and take high numbers of footfalls; domestic and commercial carpets are designed to take more than 30,000 and 500,000 footfalls annually respectively [6]. The fundamental problem of recycling post-consumer carpets is that a carpet is a composite material with dirt and other contaminants introduced into the carpet over years of use; each of the components must be recycled in a different manner but cannot be easily separated. This is the problem that any solution must address: some propose a recycling method where no separation is required (e.g. polymer melts), some propose novel methods of separation (e.g. supercritical CO_2 precipitation), but no one method has yet emerged as cheap, clean, and scalable, as demonstrated by the dominance of landfill and energy-from-waste as end of life options in the UK at the current time.

A wide variety of types of carpet and textile flooring exist, made up of a wide variety of material components. 80% of UK carpets are broadloom polypropylene (PP) [7], which are the typical wall-to-wall carpets found in a residential property. These carpets are composed of a primary backing latex glue mixed with calcium carbonate for weight and a secondary backing. The face fibres; the component of the carpet that the consumer interacts with, are in the main made of polypropylene, which is prized for its longevity, chemical resistance, and mechanical strength.

Carpet and textile flooring disposal is therefore clearly a large-scale and difficult environmental problem, and research is essential to explore alternative, more environmentally friendly, recycling and end-of-life treatment options. This report pursued a variety of avenues in search of increasing the recyclability of carpet and textile flooring.

1.1. Legislative Considerations

There are a variety of different government bodies and pieces of legislation that govern the disposal of waste in general in the UK and carpets in particular. The following paragraphs discuss these.

1.1.1. Environment Agency (EA)

The Environment Agency (EA) is a UK government department with the remit of regulating major industry and waste, conservation, and ecology, among other areas [165]. This means that much of the legislation and relevant restrictions pertaining to carpet and textile flooring recycling originate from the EA, so it is a body that is frequently referred to in this document.

1.1.2. General Waste Legislation

There is a legal duty of care applying to anyone who 'imports, produces, carries, keeps, treats, disposes of, or are a dealer or broker that has control of, controlled waste' [166]. Anyone who falls under this umbrella is referred to as a 'waste holder'. A waste holder is legally required to take all reasonable steps to:

- Prevent unauthorised or harmful deposit, treatment or disposal of waste
- Prevent a breach (failure) by any other person to meet the requirement to have an environmental permit, or a breach of a permit condition
- Prevent the escape of waste from your control
- Ensure that any person you transfer the waste to has the correct authorisation
- Provide an accurate description of the waste when it is transferred to another person

Failure to comply with these requirements is a criminal offence and could lead to prosecution [166].

According to a DEFRA document "Guidance on the legal definition of waste and its application", carpet is likely to be considered as non-waste if it is being 're-used for the same purpose for which it was originally conceived' and 'still suitable for the same purpose for which it was conceived' [167]. This is essentially the definition of primary recycling, which is discussed in section 2.5. For any other type of recycling, carpet is likely to be considered as waste. These are important distinctions, as for example the Persistent Organic Pollutants (POPs) legislation discussed below

[168] and the points discussed above, only apply to waste, and so the legislation would not apply if the carpet is never classified as waste.

1.1.3. Regulatory Position Statement (RPS)

A Regulatory Position Statement (RPS) is a position taken by the EA outlining a specific low-risk activity that would normally require a permit under general legislation, but instead does not require a permit under certain circumstances, and therefore the EA 'will not normally take enforcement action' provided that the RPS requirements are met and your activity is not likely to cause pollution or harm [112] [169]. The EA has a regulatory position statement (RPS) issued on the use of shredded carpet waste in equestrian surfacing [112], the implications of which are discussed later in this report.

1.1.4. Persistent Organic Pollutants (POPs)

According to the EA POPs are poisonous chemical substances that break down slowly and enter food chains as a result [170]. The key legislation controlling the manufacture, use, and disposal of POPs is the Stockholm Convention on Persistent Organic Pollutants. Signed in 2001 in Stockholm and entering into force in May 2004 [171], the UK is a signatory to the treaty. POPs were commonly used in carpets in the past primarily for flame retardants and stain resistance, and while CRUK manufacturing members have evidence of current product compliance in the UK and EU with the regulations on POPs. However, the EA still considers the widespread historic use of POPs a concern in the UK. Given that the UK was in compliance with the treaty from 2004 when it was signed and the expected lifespan of carpet is 15 years [6], with most being disposed of before this date, the majority of POPs-containing carpet is expected to have already left the waste stream. However, some old legacy POPs carpet still enters the waste stream, and is subject to stringent EA controls on disposal. The principal disposal method that must be used is incineration on land, of a sufficient temperature that the resulting ash does not itself contain POPs above the allowed threshold [168]. Currently the measures implemented are sufficient that the EA allows certain RPS and Low Risk Waste Positions (LRWPs) for recycled carpet. However, a recent Department for Environment, Food and Rural Affairs (DEFRA) report on POPs in the soft furnishings industry discovered that there are high levels of brominated flame retardants in some discarded sofas and other similar products. In light of this, the EA issued guidance stating that 'If an item of domestic seating waste is upholstered you should assume that it contains POPs, and manage it as a POPs waste, unless you can demonstrate that it does not contain POPs' [172]. This shifts the burden of proof onto the disposer and makes it more likely that all such soft furnishings will be burnt, as the additional cost of widespread POPs testing is likely to remove most, if not all of the profit margin that existed for recycling these items.

The concern of CRUK is that the EA will turn their zeal towards the UK recycled carpet sector. As discussed above, only a small quantity of POPs-containing carpet enters the waste stream each year, but an EA position similar to that taken on soft furnishings has the potential to create problems for the sector.

1.1.5. Extended Producer Responsibility (EPR)

An extended producer responsibility (EPR) is an environmental policy where the producer is held responsible for the waste in its post-use phase of life. Currently there is no EPR in place for the carpet and textile flooring sector, but in 2023 an EPR has been implemented for plastic packaging. It is an attempt to provide incentives for producers to increase the recyclability of the products they produce and reduce the problem of waste, rather than placing the burden on the end user. The problem is summarised well in the executive summary of a government response to a consultation on the implementation of EPRs for plastic packaging:

“The current producer responsibility system for packaging has operated since 1997, but it has never covered the full costs of disposing of packaging waste. Extended Producer Responsibility for packaging (EPR) will move the full cost of dealing with packaging waste from households away from local taxpayers and councils to the packaging producers (applying the ‘polluter pays principle’), giving producers responsibility for the costs of their packaging throughout its life cycle. This will encourage producers to reduce their use of packaging and use packaging which is easier to recycle” [173].

Reporting of data for the EPR for plastic packaging began on 1st January 2023, and fees will be imposed from 2024 [174]. There are no immediate plans to introduce an EPR for carpet and textile flooring, but CRUK has is aware that as part of the Resources Waste Strategy 2018/19 [175], an EPR for Bulky Household Waste was discussed which included carpet waste. Therefore, knowing that is potentially on the horizon, CRUK has been working with its members to help prepare them for such a scheme. Aside from the obvious environmental benefits of EPRs, they should also provide a large influx of data about the waste stream. As will be discussed later in this report, data on carpet and textile flooring throughout its life is lacking, and the implementation of an EPR would help generate better data.

2. Literature Review

2.1. Current UK Waste Treatments

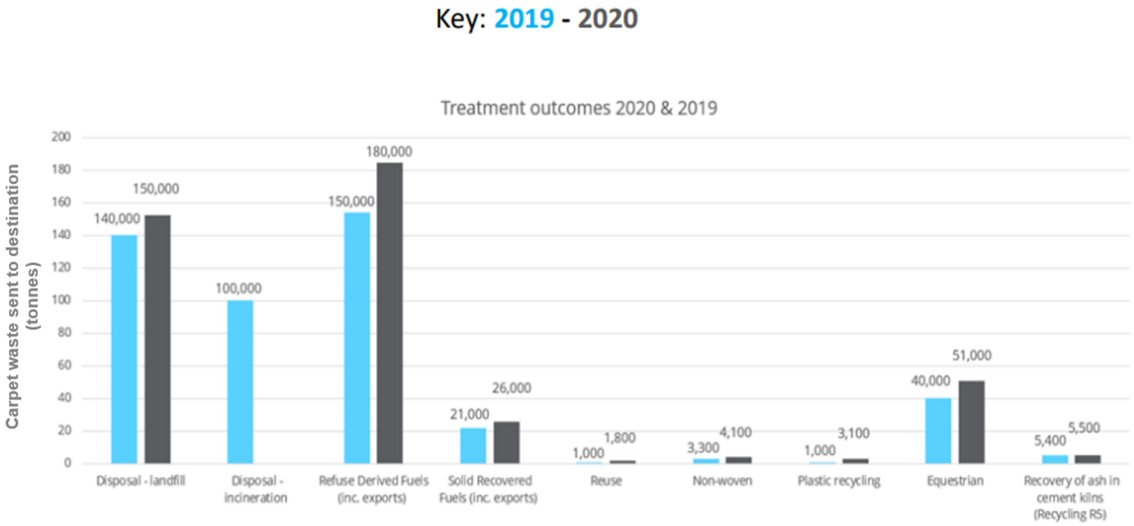


Figure 1: Waste treatment outcomes 2019-20 [5]

Figure 1 shows the distribution of waste treatment outcomes for UK carpet waste in 2019 and 2020. As discussed in earlier sections, it can be clearly seen that the vast majority of carpet and textile flooring waste goes to landfill or EFW, with only a small fraction being recycled or reused.

2.2. Carpet Recycling UK (CRUK)

The industrial partner for this project is CRUK. CRUK's website describes the organisation as a "not-for-profit membership association working to reduce the amount of carpet waste being sent to landfill" [8]. CRUK has 119 members which span the supply chain, including manufacturing, raw material suppliers, distributors, flooring supplier and contractors to recycling and reuse companies.

2.3. Carpet types

Several major varieties of carpet exist: tufted, needle felt/needle punched, and woven. These types have different physical compositions and different typical application environments, with some being almost exclusively residential and some primarily commercial. These two markets are essentially equal in size, as shown in Figure 2.

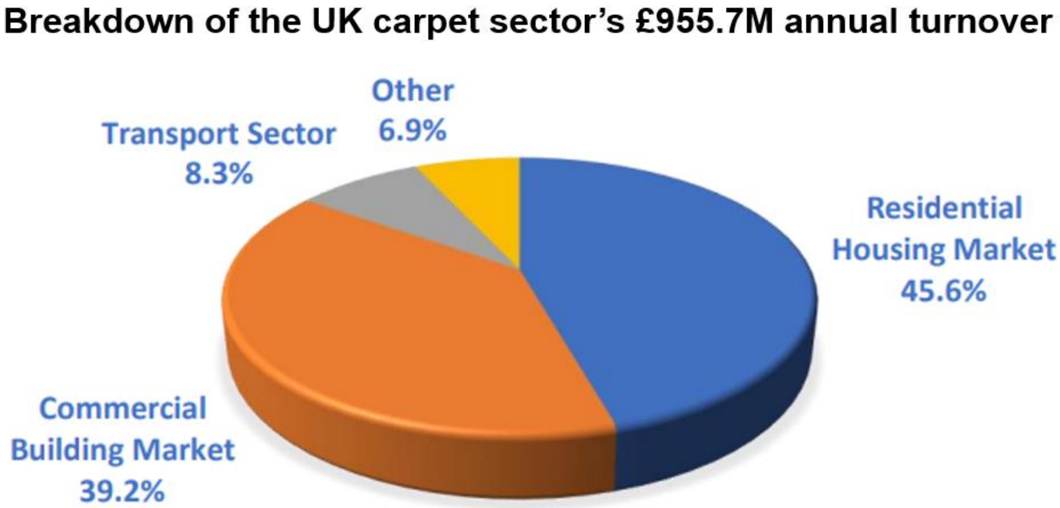


Figure 2: Market segmentation of the UK carpet sector by industry (2017-18) [7]

The wide variety of structures and materials in use in the carpet market provides variety for consumers, but this creates difficulty at the end of life as there is no "one size fits all" recycling solution. Each type of carpet, thanks to its structure and the materials used in it, presents its own unique challenges to recycling. The following section provides an overview of the different types of carpet, their construction, composition, and the different challenges faced at the end of their lifespan.

2.3.1. Tufted

Tufted carpet is composed of three key components: pile fibres, primary backing, and secondary backing, as shown in Figure 3.

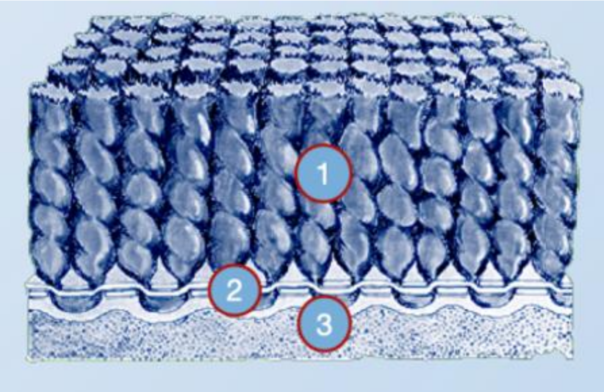


Figure 3: Tufted carpet construction (1 = pile fibres, 2 = primary backing, 3 = bonding material) [4]

Pile fibres are the visible surface of the carpet, and the primary surface that users have contact with; they are typically made of wool, PP, nylon, polyethylene, or a blend of these fibres [7]. The properties of these fibres are discussed in more detail in Section 2.4. Figure 4 shows how the UK tufted carpet market is dominated by broadloom PP, representing 80% of the market [4]. While these figures are only for intra-EU trade, the same report shows that the larger German market is dominated by PA tufted carpets, indicating that this data does not simply reflect an EU-wide preference for PP carpets.

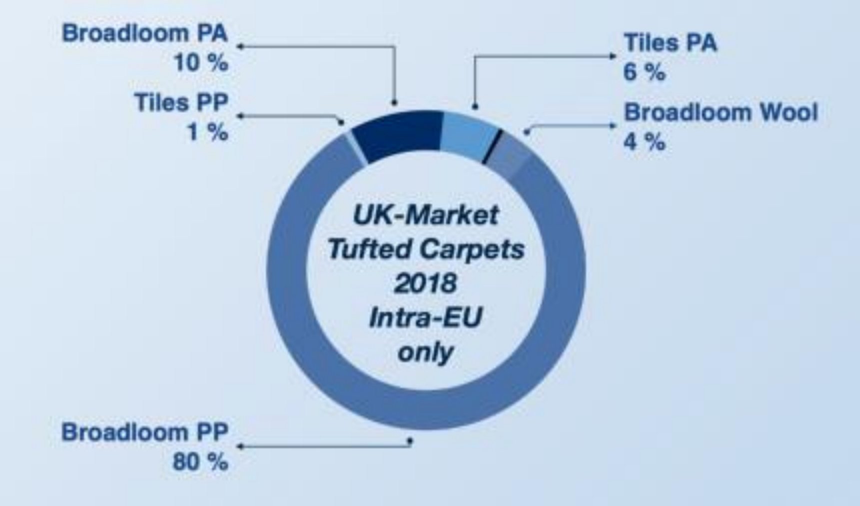


Figure 4: UK Tufted Carpets Intra-EU Market Breakdown [4]

Pile fibres are attached to the primary backing of the carpet, and are either cut or loop pile. The carpet shown in Figure 3 is a cut-pile carpet, where the loops formed in carpet manufacture are cut off, forming the characteristic flat, uniform top surface shown. Loop pile is the alternative, where the loops are left intact.

The backing is composed of PP and is bonded to the pile fibres with a synthetic rubber-based latex adhesive that often contains a large percentage of $CaCO_3$ filler. A secondary backing of jute or PP is added below this to improve strength and dimensional stability.

i. Manufacture

Tufted carpet is manufactured by machines that use needles to punch threads into the primary backing. On a typical machine, a row of several hundred needles will insert the thread, with the backing moving after each stroke to produce carpet in one continuous uniform direction [9]. An example of a carpet tufting machine is shown below in Figure 5.

Figure 5: Carpet tufting machine. Each of the thin lines that can be seen are pile threads, and the thin parallel black lines at the bottom of the image are individual needles [10].

ii. Backing

Carpet backing is a process that makes it less likely a carpet will unravel, improves durability, and increases tuft bind (the force required for fibres to be pulled from the carpet) [11]. The face fibres and backing are typically fixed together by a latex adhesive, typically a styrene butadiene rubber (SBR) or ethylene-vinyl acetate (EVA) latex, often mixed with a calcium carbonate filler to improve mechanical properties and decrease cost [12]. The backing is adhered either by a puddling process, or in a sheet form extruded onto the material. After the backing is applied, the carpet goes through a drying oven where moisture added during the backing process is removed [11].

iii. Composition percentages

To perform some of the later calculations in this report, and for general completeness, an example carpet sample with components listed by percentage is provided below in Table 1. Two sample compositions were sourced from two independent industry members, and the results were averaged into the table below to produce the reference carpet sample. Each column gives mass values for each component for 1kg of carpet for each sample, which are then averaged in the final row. This ‘reference carpet sample’ produced will be useful later in the report for calculating average combustion energies and CO_2e emissions of carpet. It can be seen that PP makes up just under 60% of the carpet by weight, $CaCO_3$ makes up 25%, and the remaining 17% is latex.

Table 1: Reference carpet sample component masses

	Total	Face fibres	Backing cloth	Latex	CaCO3
Carpet 1 (mass fraction)	1.000	0.427	0.070	0.201	0.302
Carpet 2 (mass fraction)	1.000	0.596	0.069	0.134	0.201
Average component mass (average mass fraction)	1.000	0.511	0.070	0.168	0.251

2.3.2. Needlefelt/needle punched

Needlefelt carpet is manufactured by entangling a web of fibres with needles and then bonding the subsequent mesh with a synthetic latex, shown below in Figure 6. Needlefelt tends to be composed of PP, sometimes combined with nylon for added durability [7]. 100% PP needlefelt fibres can be reprocessed for use in plastics, but blended fibres are difficult to separate, typically going to energy from waste [7].

Figure 6: Needlefelt carpet construction [7]

Needlefelt carpet is typically thinner than most other broadloom (residential) carpets, and no separate backing is used as the fibrous mesh and latex form a strong composite. Commercial buildings are the primary users of needlefelt carpet.

2.3.3. Woven carpets

Woven carpets are woven in traditional weaving patterns, with pile yarns secured to a backing and the structure provided by warp and weft yarns, as shown in Figure 7 [7].

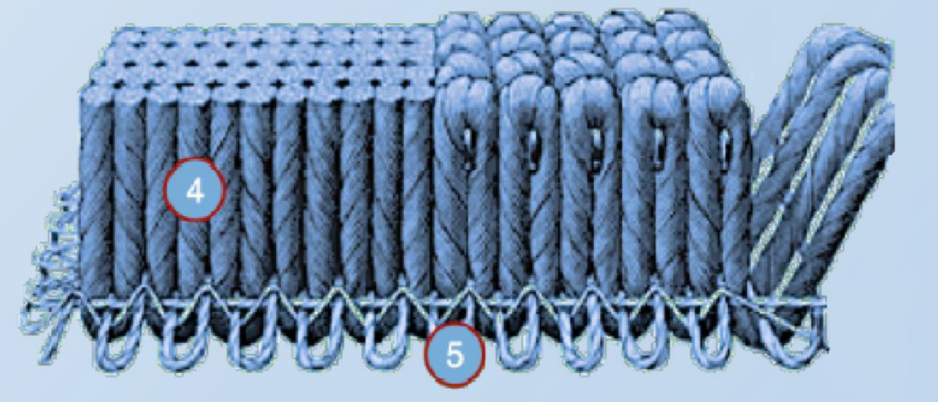


Figure 7: Woven carpet construction [4]

Woven carpets tend to be stronger and harder wearing than other carpet types, but their bespoke nature makes them more expensive. The pile fibres are normally wool, sometimes with a synthetic component, or PP. They are used in both domestic and commercial properties. The strength of woven carpets makes them more difficult to recover fibres from, although it is possible with the correct equipment [7].

2.3.4. Carpet Tiles

Carpet tiles are modular square tiles designed for commercial use. Any of the above techniques can be used for manufacture of the pile yarns, but to ensure tessellation a high level of dimensional stability is required so a woven glass scrim is often incorporated into the backing, which is typically bitumen or PVC. Alternatively, felt or polyurethane backings can be used when higher comfort is required [7]. The modular nature of carpet tiles, coupled with their industrial setting which reduces the fashion considerations, makes carpet tiles ideally suited for reuse. Bitumen also has a high calorific value, making it well suited to EFW, but the low melting point of bitumen means it is unsuited to any process which involves mechanical reduction as the bitumen melts during the size reduction [7].

2.3.5. Underlay

A separate underlay is often used beneath carpet to improve acoustic properties, comfort, and durability; good quality underlay is reported to increase carpet lifespan by 30-50% [7]. Underlay characteristics are governed by BS5808, which provides tests for breaking strength, elongation, reduction in thickness after dynamic and static loading, and compression and recovery characteristics [13]. Underlay can be composed of polyurethane, rubber, felt, or a combination of the above. Post-consumer carpet and underlay streams are often not separated, making precise quantification of the size of the underlay waste stream difficult [7]. Since underlay is in less direct wear than carpet itself, there may be more scope for using recycled materials for its manufacture, although the BS EN14499 now exists for underlays, so any underlay composed of recycled materials would have to satisfy its flammability, noise attenuation, and thermal resistance standards [14]. At least two companies already use recycled underlay, although they are of limited applicability to this report as they are composed of wool and polyurethane. Rushforth et al. have used shredded Nylon carpet tiles mixed with SBR latex to produce an underlay that ‘compared favourably’ to commercial underlays [15].

2.4. Carpet Components

Carpet is made of a wide variety of component materials. A non-exhaustive (but thorough) list is shown in , with the different materials labelled with the carpet components they are commonly a part of.

Table 2: Carpet material composition in Europe, showing the variety of different components that may be included [4]

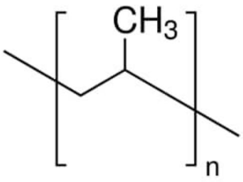
	Tufted Carpets			**Woven Carpets**	
	Face fibres	**Primary backing**	**Other backing**	**Face fibres**	**Backing**
PP	✓	✓	✓	✓	
Nylon 6	✓		✓	✓	
Nylon 6,6	✓		✓	✓	
PET	✓	✓	✓	✓	
PTT (Polyester)	✓			✓	✓
SBR latex		✓	✓		
EVA latex		✓	✓		
TP elastomers			✓		
Bitumen			✓		
PVC	✓		✓		

PU			✓		
Wool	✓			✓	
Jute		✓	✓	✓	✓
Sisal	✓			✓	
$CaCO_3$			✓		
$Al(OH)_3$			✓		
Pigments	✓			✓	
Dyes	✓			✓	
Additives	✓	✓	✓	✓	✓

2.4.1. Polypropylene (PP)

Polypropylene (PP) is a polyolefin, which is a specific type of polymer. It has a high melting point, is tough, chemically inert, and resists most common organic and inorganic chemicals, as well as water, oil and fat [16] [17].

Chemically, PP consists of a carbon backbone with methyl groups (CH_3) on alternate carbon atoms, shown in Figure 8 below, along with the chemical and linear formula.



$$[C_3H_6]_n$$

$$[CH_2CH(CH_3)]_n$$

Figure 8: PP chemical diagram, chemical formula and linear formula [18]

There are three different configurations of PP: isotactic, syndiotactic, and atactic. Their chemical structures are shown below in Figure 9. In isotactic PP (top diagram in Figure 9), the methyl group (represented in Figure 9 by filled black circles) is in a constant position on the backbone for every unit. In syndiotactic PP (middle diagram in Figure 9), its position alternates regularly with each unit. In atactic PP (bottom diagram in Figure 9), the methyl groups position is random for each unit.

Isotactic PP is the most common configuration, making up 90-95% of commercial PP [19]. It is also the most stable structure, since the constant position of the methyl group prevents crystallization in a zig-zag shape and forces a helical crystal structure.

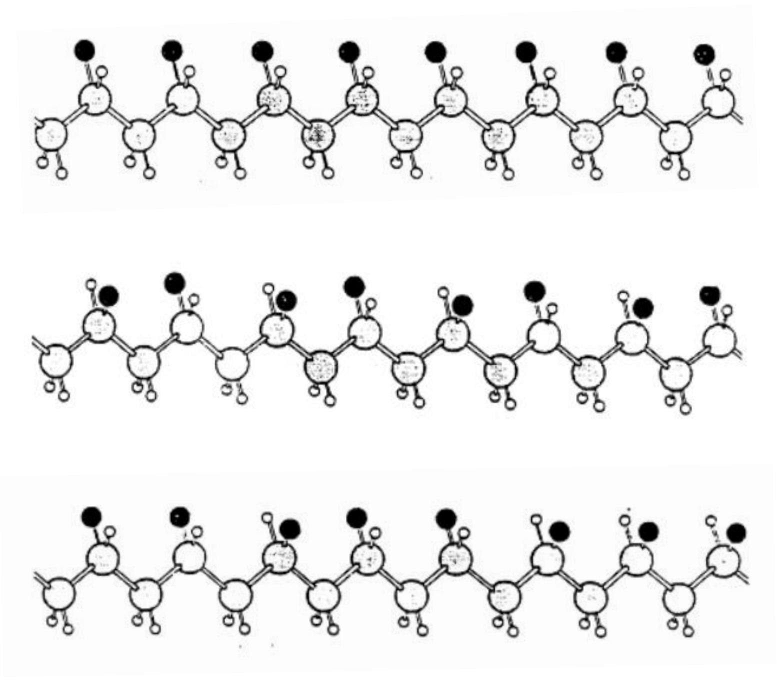


Figure 9: Isotactic, syndiotactic, and atactic PP configurations respectively

As discussed earlier, PP is the primary polymer in approximately 80% of UK carpets, making it the most important material in the ongoing research for a sustainable carpet recycling solution. Unfortunately, the characteristics that make PP a desirable material for products also make it difficult to recycle to its base monomers. When discussing the decomposition of polyolefins into monomers, one paper [17] says that “any monomer recovery at any temperature is remarkable”, thanks to the high exergonicity of polymerisation and high activation energies for thermal decomposition. The implications of this for recycling are discussed in later chapters.

Discussion with industry leaders revealed that the most common PP used in carpets is a homopolymer with a melt flow index (MFI) of 25. Table 3 gives some key mechanical values of polypropylene, taken from a datasheet of PP with an MFI of 24, the closest MFI value that could be found.

Table 3: Polypropylene properties [20] [21] [22]

Property (unit)	**Value**
Melting point (°C)	170
Density (kg/m3)	900
Tensile strength (MPa)	30.3
Young’s Modulus (MPa)	233
Dilute acid resistance	Very good
Dilute alkali resistance	Very good

2.4.2. Nylon (Polyamide, PA)

Nylon (the trade name for polyamide coined by the American chemical company DuPont, which has been genericised to a catch-all term for polyamides) is a group of tough, chemically resistant polymers with a high melting point [23]. The majority of carpets use two specific types of nylon: nylon 6 and nylon 66 [24]. Only around 16% of UK tufted carpets are composed of nylon, but nylon and PP together represent 97% of the UK tufted carpet market. Fortunately, nylon is much easier to depolymerise than PP, with several papers [25] [24] discussing a variety of techniques, some used by industry, that can recover the component monomers. However, since nylon represents only 16% of the UK carpet market [26], the bulk of this thesis will focus on the recycling of PP. Nylon sees much higher usage in other parts of the world, particularly the US, with 65% of carpets worldwide composed of nylon [27]

Table 4: Nylon properties [28] [29]

Unit/Nylon type	6	6,6
Melting point (°C)	214	
Density (kg/m^3)	1140	905
Tensile strength (MPa)	1960-5000	90
Young's Modulus (MPa)		1400

2.4.3. Wool

Wool is a natural fibre [30], and often used in carpets, however the development of cheaper, more durable polymer-based carpets has led to the decline of wool as a carpet material, with approximately just 4% of UK tufted carpets being composed of wool [4][31].

As a natural fibre, wool presents different challenges for recycling compared to the more commonly used synthetic fibres, but also opportunities that are unavailable for synthetics. One paper [32] used woven wool carpet as a fertilizer. The carpet was shredded and left to decompose in the ground for 14 days before Italian ryegrass was sown on it. The grass was harvested at 105 and 169 days, with th e wool-fertilized grass yielding 33% and 95% greater mass respectively than their controls . This demonstrated that wool can effectively act as a slow-release fertilizer, providing a useful end-of life option – however this experiment was conducted with pure wool fibre and not wool mixed with polymer fibres, which would present microplastic release issues. It could also therefore likely be composted, but this would raise the same microplastic issues. The levels of various beneficial minerals and compounds in the soil were raised, although this did include zinc, a heavy metal whose concentration is regulated by many countries, although the advantages of increased zinc intake have been documented, with Zn deficiency claiming 4.4% of the total child deaths in the world [33].

Another difficulty with wool carpet recycling is in the separation from synthetic components. Keratin, one of the primary components of wool [34] is a chemically resistant material, and it is difficult to find a condition which is strong enough to dissolve keratin while also weak enough that the accompanying synthetic polymers are not damaged. One paper proposed a two-step enzymatic process that led to the complete breakdown of wool fibres while having no significant impact on the mechanical properties of the PE mixed with it [35]. This shows that while the typical recovery avenues of depolymerisation may be closed to wool, the natural origin of the fibres opens up novel ways to selectively recover carpet components.

2.4.4. Latex

Latex is a widely-produced material, behind only plastic and synthetic fibre in production volume [36]. Natural latex can be harvested from rubber trees [37], or synthetic latex, the type used in carpets [38] can be produced on a large scale, often for a lower cost [36]. Latex, combined with $CaCO_3$, is the main component in carpet backings [12] [38]. The latex is the component that is bonded to the base of the pile fibres and holds the carpet together, and so is the source of much of the difficulty of disassembly of carpets.

Methods for the recycling of latex exist –Rajan et al. used 2,2’ -dibenzamidodiphenyldisulphide to reclaim natural latex-based rubber and found, with a certain curing method, reductions in the tensile strength and compression set [39](the amount of permanent deformation that occurs when a material is compressed to a specified deformation for a specified time at a specified temperature [40]), but decreases in the rolling resistance when used to construct new tires.

2.4.5. Bitumen

Bitumen is a class of black or dark-coloured cementitious substance, a residue of crude oil distillation [41]. It is widely used in the construction industry, particularly for roads and tarmac [42]. Carpet tile backings are primarily made of bitumen in the UK, but are problematic to recycle as the low melting point of bitumen causes the bitumen to melt during size reprocessing. Some bespoke processes have been created to separate the backing from the pile yarns [43] but the high calorific value of bitumen, the difficulty of these separation processes, and the modular nature of carpet tiles mean that UK carpet tiles naturally lend themselves towards either direct primary recycling as carpet tiles or EFW.

Bitumen has been found to be recyclable; in [44] the authors show that the recycling of bitumen from asphalt back into asphalt, along with a suitable dose of rejuvenators (additives that restore the physicomechanical properties of the aged bitumen, mixed to 6% by mass), can result in a new bitumen material that is less stiff at the end of its own service life than virgin bitumen – a ‘significant benefit’.

2.4.6. Calcium Carbonate

Calcium carbonate is a relatively inert, cheap compound often used as a filler in carpet backings. It is the most widely used filler in polymer formulations, thanks to its cost reduction and improvement in mechanical properties [12]. Some relevant properties are shown in Table 5.

Table 5: $CaCO_3$ properties

Property (unit)	**Value**
Melting point (°C) [45]	825
Density (kg/m3) [45]	2930

2.5. End-Of-Life Options

This section will detail the end-of-life options researched for this report, the advantages and drawbacks of each method, and the overall conclusions as to the most promising products for the sector.

2.5.1. Primary, Secondary, Tertiary, and Quaternary Recycling

Recycling, of plastic waste in particular, is often broken down into four categories: primary, secondary, tertiary, and quaternary [46]. These delineations are often defined only broadly in the literature, so following is the definition that will be used for the purposes of this report. Primary recycling is where the waste is reused as the same product – an example would be the refurbishment, cleaning, and reuse of industrial carpet tiles, or the recovery of the back covers of TVs [47]. Secondary recycling is where the waste goes through some mechanical or chemical process to transform it into a new product, for example converting carpet and textile flooring waste into polymer melt for use in composites. Tertiary recycling is where the polymer waste is broken down into its consistent polymers or monomers for use as a raw material in a comparable manner to virgin material, although sometimes of lower quality – for example the recovery of caprolactam from Nylon 6. Quaternary recycling is where the waste is burnt and the energy from the burning used, for example as SRF, typically burnt in an energy from waste plant, cement kiln, or similar location.

2.5.2. Open-Loop and Closed-Loop Recycling

In addition to the categories of recycling listed above, there is a second dimension of recycling: open-loop and closed-loop. Closed-loop recycling is defined as the recycled material being able to substitute the original virgin material and be used in the same type of products. Open-loop recycling is defined as the properties of the recycled material differing from those of the virgin material, so it is used in other applications as a substitute for other materials [48]. Closed loop recycling is normally the most desirable as it allows the resource cycle to be closed and advances us towards a circular economy. The circular economy concept is in contrast to the current linear economy which uses a ‘make-use-dispose’ lifecycle. A circular economy is all about closing loops in industrial ecosystems, minimising waste, and converting goods at the end of their service life into resources for others [49]. Some types of tertiary recycling fall under the circular economy, for example the ISOPREP project [50] recovers raw PP which could then be used to create the products it was recycled from. Some types of primary recycling, while not producing a material equivalent to the virgin material, could still be considered closed loop recycling as they recycle an old product into a new version of the same product, fulfilling the same end goal. The Furniture Resources Centre’s (FRC) UltraClean machine (discussed in section below) [51] would therefore be an example of closed-loop recycling.

2.5.3. Techniques for facilitation of end-of-life carpet recycling methods

This section will detail the different techniques for dealing with waste that have been researched, such as shredding, 3D printing, and depolymerisation. This is distinct from the next section on end-of-life uses for carpet waste, as the end-of-life uses typically require the use of one or more of the following techniques to transform the end-of-life carpet waste into a suitable form.

i. *Landfill*

The main non-recycling option for end-of-life, and where 56% of the UK's carpet waste [7] currently ends its life, is landfill. Despite the negative connotations generally attached to landfill, there are advantages to it as a disposal process. The average mix of UK residual waste that is sent to landfill generates significant CO_2 emissions over the course of its decomposition [52]. On the other hand, when carpets composed of inert plastics such as PP are disposed of into landfill, the lack of sunlight and high temperatures mean that degradation is expected to take hundreds or thousands of years, and so, for highly stable plastics, landfill can be treated as an effectively zero-emission CO_2e sink [3] [2]. However, due to the more general undesirability of landfill, large landfill taxes are imposed to encourage the use of alternate routes, making it a financially undesirable end-of-life option. In the period from 2007-2016 the landfill tax increased from £24 to £84 per tonne, an increase of 250% [53].

ii. *Reuse*

There are a variety of reuse routes for carpet currently available; the section below details several of them.

a. Spruce Carpets

At the CRUK 2022 conference, the company Spruce Carpets gave a presentation [54] describing how they divert excess post-manufacture carpet that would otherwise go to landfill to low-income housing. The carpet is trimmed and professionally fitted into low-income housing that is often provided to tenants without any floor coverings. This is an extremely desirable route for carpet recycling, taking a large quantity of potential waste and sequestering it from any other landfill options likely for another decade, while reducing the demand for new carpet to be produced, and providing a social good. The drawbacks of the approach are that the quantity is limited – while Spruce carpets perform 3400 fittings per annum, this only amounts to 120 tonnes in a year; approximately 0.026% of the total 467,000 tonnes of textile flooring waste generated in the UK in 2020 [5]. The volume of carpet that could theoretically be reused through this approach is also ultimately limited by the fact that post-industrial carpet represents only a small fraction of the UK carpet waste stream, as discussed above.

b. FRC Group

The FRC group have designed and developed the ‘UltraClean machine’, an automated mattress cleaner that restores mattresses to ‘extremely high cleanliness levels and as good as new’. [51] The machine uses the following seven-stage process to achieve this: [55]

1. Inspection
2. Pre-cleaning
3. Steam cleaning and vacuuming
4. Biocidal ozone immersion
5. UV sanitising
6. Drying
7. Final inspection

FRC group claims that this removes odours, stains, bacteria, viruses, mould, mildew, bedbugs, and fleas [55]. The FRC Group speculates that carpets could be cleaned in the machine, although there would be size restrictions on the broadloom that could be fed through. If a machine such as the UltraClean became commercially viable, cleaned material to legislative standards, and could clean large areas of carpet, it could potentially allow for primary recycling of post-consumer carpet on a wide scale.

c. Carpet Whipping

Whipping is a process where the edge of a carpet is overlocked with yarn for a professional-looking edge that cannot fray, as pictured below in Figure 10 [56]. It is a process suitable for both pre-consumer and post-consumer carpet, and is typically used to make rugs. Given that carpet at the time of its disposal often has several years of life left [57], the use of carpet whipping to give it a second life as a rug is a cheap, environmentally friendly option. The service is offered by various companies across the country [56] [59]. More widespread use of this would potentially reduce the demand for new rugs and save on waste, while delaying waste carpet being sent to landfill or energy from waste and perhaps buying enough time that when the carpet did enter the waste stream better recycling options may have become available.

Figure 10: Whipped carpet edges [56]

d. Carpet Tiles

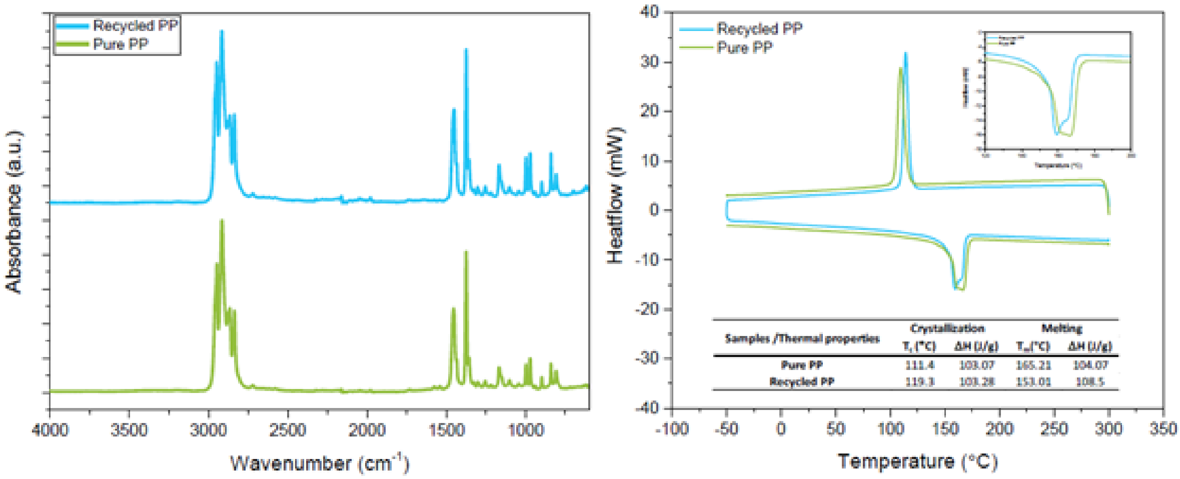
As discussed in 2.3.4, the modular and industrial nature of carpet tiles makes them better suited for reuse than broadloom carpet [7]. Illustrating this fact, several second-hand carpet tile retailers exist, offering a stock of reused carpet tiles for sale, graded by quality [60] [61] [62].

iii. Corporate methods

The methods in the following section, while potentially offering promising recycling options, are currently under development by various companies. Due to this, little information about them is available in the public domain, meaning they could only be subjected to limited scrutiny, and so have been left out of the main conclusions. However, they have been included in this section of the report for the sake of completeness.

a. ISOPREP

ISOPREP is a collaborative European project involving 10 partners across 5 countries, with the aim of developing a cost-effective polypropylene recycling method and a pilot plant to demonstrate the industrial viability of the process. They presented at CRUK’s 2022 conference, discussing their new process, which is now in the stage of pilot plant development. A sorting and mechanical separation process are first completed, involving handheld near-infrared spectroscopy (NIRS) to select PP carpets, followed by a shredding, cleaning, where the PP components are separated in water by density and the PP components are floated off, and drying process. After this ISOPREP use a 'proprietary ionic liquid' stirred at 140°C under reflux to selectively dissolve the PP and separate it from any other contaminants [63][50]. This is a non-peer reviewed publication and proprietary information so it is impossible to verify the claims or discover much more information. ISOPREP claim their polymer is 'virgin quality' [64], and include Fourier transform infrared (FTIR) and Differential Scanning Calorimetry (DSC) as evidence, showing very similar results of recycled compared to virgin PP. These graphs are shown in Figure 11. If ISOPREP's results are reliable and the pilot plant proves economically viable, then the approach could represent a shift for the UK carpet recycling industry, dominated as it is by the need for effective PP recycling techniques. ISOPREP spoke at the conference that they expected results from the pilot plant in the next few years.



Samples /Thermal properties	Crystallization		Melting	
	T_c (°C)	ΔH (J/g)	T_m (°C)	ΔH (J/g)
Pure PP	111.4	103.07	165.21	104.07
Recycled PP	119.3	103.28	153.01	108.5

Figure 11: Fourier transform infrared (FTIR) and Differential Scanning Calorimetry (DSC) analysis of virgin and ISOPREP recycled PP, showing similar properties [50]

b. Innovate Recycle

Innovate Recycle are a company based in Northamptonshire that claim to have developed a 'clean, green and unique, mechanical process to extract high-quality substances from waste carpet' [65]. They claim this process can recover high-quality polypropylene and $CaCO_3$ from waste carpet of a quality suitable for use in a variety of recycled materials. In typical industry fashion, no verifiable information is available to corroborate these claims.

c. Aquafil

Aquafil are a company that have developed ECONYL, a fully recycled nylon obtained through a ‘radical regeneration and purification process’. They claim to recycle nylon to its original purity, and that their product is ‘exactly the same as fossil-based nylon’ [66]. Aquafil use this ECONYL recycled nylon to produce both carpet yarn and clothing, as well as selling it as polymer pellets for use as raw materials by other companies. Aquafil is an exciting idea because it represents a completely circular product; one which can be recycled indefinitely with no loss of quality (if their claims are true), representing an important step towards a circular economy. However, it has limited applicability towards the UK carpet market due to the predominance of PP as a face fibre.

d. Longworth

Longworth are a company that has adapted a process originally developed for the cleaning of industrial stainless-steel filters into a depolymerisation technology called DEECOM LITE. The machine uses superheated, pressurised steam to depolymerise a polymer to monomers, and emits only water as an output [67]. Again, there is no peer-reviewed literature detailing their process, making the specifics of their claims difficult to assess.

iv. Supercritical CO_2 extraction

While not discussed in literature as a method of separating carpet from its backing, supercritical CO_2 separation nevertheless has potential solutions to a different problem of recycling carpets. One of the challenges facing recycled polymers is the contamination that they have been exposed to in their previous applications often places legislative limits on their use as recycled polymers. Supercritical CO_2 has been used in a variety of papers [68] to effectively separate different polymers of carpets, and in this paper, it was used to produce food grade polypropylene from recycled polypropylene by dissolving the contaminants through diffusion and extracting them from the polymer. Under a pressure of 200 bar and 90°C, over 7.5 hours the process achieved a complete extraction of contaminants from the polymer, even for the heaviest contaminant (807g/mol). Trends that were discovered include that the higher the molecular weight, the lower the extraction rate, so the molecular weights of the most common and problematic contaminants in carpet waste would need to be established. Increased pressure positively affected the extraction rate, whereas the effect of temperature depended on the pressure. The paper dealt with the removal of Stearin, Dilaurin, Trilaurin, and Tripalmitin [69].

Another paper dealing with the removal of polycyclic aromatic hydrocarbons (PAH) (such as might be found in tobacco smoke, potentially a common carpet contaminant) from HDPE, and found that, with respect to PAHs, the treated specimens were of a quality complying with the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) EU regulation. This means that within the EU, the polymer derived would be suitable for use in consumer products and children's articles. An NIR analysis of the plastic specimens before and after the process suggested that no degradation was experienced by the plastic samples [70].

While not dealing directly with the types of contamination discovered in carpets, and so potentially not as effective a method, even a moderate level of reduction in recycled carpet polymer contamination would be useful in expanding the applications that these polymers could be used for, making them safer around people and more independent of their past applications. No indication of cost-effectiveness is provided in the paper, so whether this approach is feasible to be applied beyond a laboratory scale remains to be seen.

v. Shredding

Shredding is a very commonly used technique to reduce a continuous piece of carpet into a more manageable size by the application of intense shear forces in a shredder. It is used in a variety of sizes, from the large scale shredders used to reduce carpet to chunks on the scale of an inch [71], to the desktop shredders that produce fibres on the order of several millimetres in length.

vi. Spinning

A variety of techniques exist for producing nanofibers from polymers, which can be used in several of the applications described in Section 2.5.4 Some of the most common in the literature and industry are various spinning techniques. Detailed below is a description of the available techniques and a discussion of their applicability to the project.

a. Melt Spinning

Melt-spinning is a process where molten polymer is extruded through a number of small orifices on a spinneret to produce a large number of thin, continuous fibres that solidify as they pass through the air, before being taken up by a rolling drum [72]. This produces a nonwoven fabric composed of fibres that can be in the tens of µm diameter [73] [74].

b. Solution Electrospinning

Solution electrospinning is a similar method to melt spinning, but instead of melting the polymer, the polymer is dissolved in a solvent. The polymer mix is then drawn through the spinneret by an electric field, shaping the fluid at the opening of the nozzle into a characteristic 'Taylor cone', shown in Figure 12.

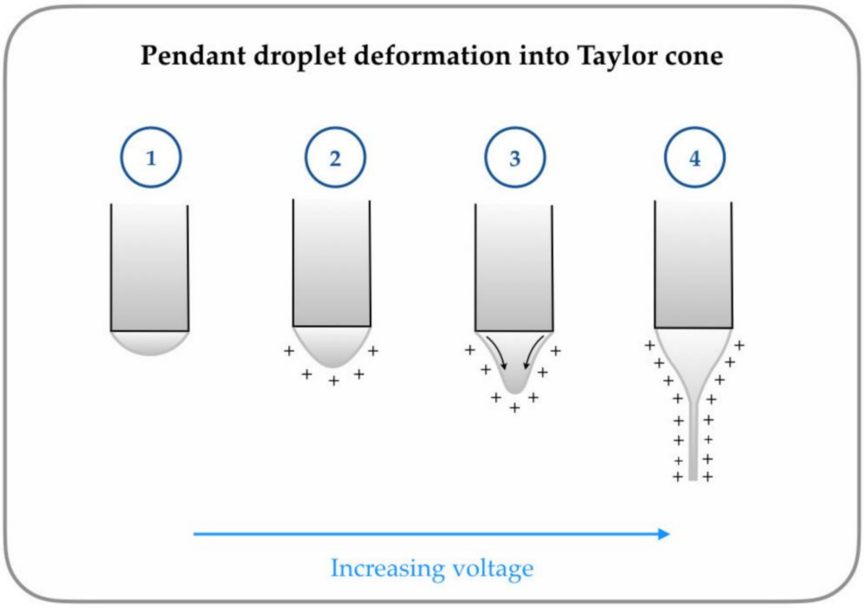


Figure 12: Droplet deformation modes of polymer solution/melt in electrospinning: Mode 1—no droplet deformation appears when there is no voltage. Mode 2—charges accumulate around the droplet on the application of low voltage. Mode 3—Coulombic repulsion overpowers surface tension, and the droplet starts to deform into a Taylor cone. Mode 4—at high voltages, the Taylor cone enters "jetting mode," and a fibre is extruded from the tip [75]

The nanofibre stream is then accelerated by a voltage differential towards a plate or collector, typically a ground plane [76]. The fibres produced by electrospinning can be of the order of tens of nanometres in diameter, significantly smaller than those that can be obtained by melt spinning [77]. Typical solutions used for PP electrospinning are tetrahydrofuran, methyl-cyclohexane, sometimes with the addition of additives such as acetone and dimethylformamide [78] [79] [80].

c. Melt-electrospinning

Most research over the last two decades has focused on solution electrospinning. Melt-electrospinning turns the polymer into a workable fluid by melting them instead of dissolving in a solvent, and is the preferred method for fabricating nanofibres from thermoplastics, due to their typically high solvent resistance. It is a method that particularly lends itself to PP nanofibre production, as it is difficult to find a suitable solvent for PP at room temperature [77]. There is also both a reduced economic and environmental cost associated with melt-electrospinning compared to solution electrospinning, as no solution or expensive solution recycling equipment has to be used. Melt electospinning also favours the production of blends and composites, as in many cases no common solvent for all the components exists [77]. This is an advantage for the use case considered in this report, as tolerance for contamination is a high priority for successfully producing fibres from carpet waste. While giving larger fibre diameters than solution electrospinning, melt-electrospinning still gives significant reductions compared to simple melt spinning, with fibre diameters as small as 0.1µm obtained [74] [81].

d. Needleless Electrospinning

The above electrospinning techniques have been described in the context of conventional needle electrospinning with a small aperture from which the polymer melt/solution is drawn by an electric field. However, an alternative option, aptly named needleless electrospinning, exists. In this type of electrospinning, Taylor cones are still formed by a voltage differential, but they are nucleated by the geometry of various spinneret surfaces rather than a needle. Various geometries and configurations exist, a variety of which are shown in Figure 13.

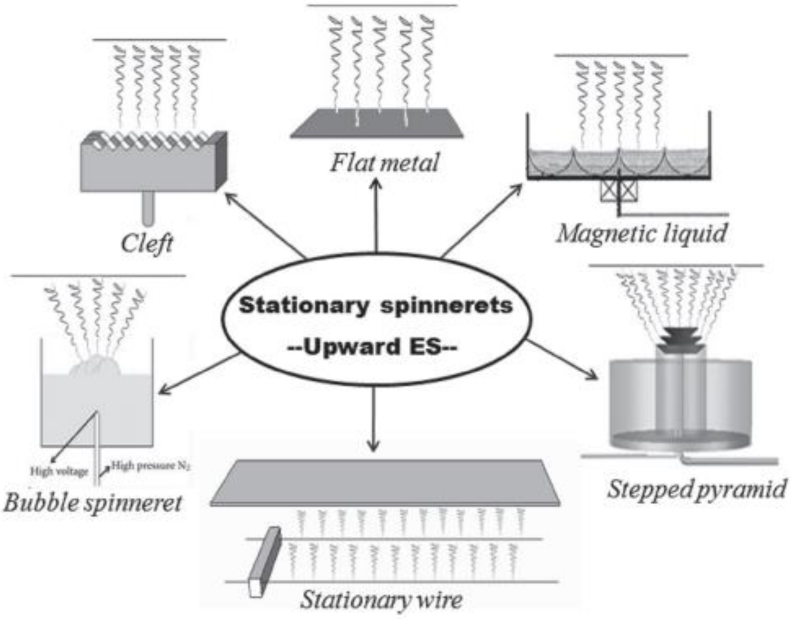


Figure 13: A selection of needleless electrospinning configurations [82]

One of the advantages of a needleless setup is that multiple Taylor cones can be formed, increasing throughput [74]. Another speculated advantage, backed up by conversation with academics, is that a needless setup would be much more resilient to contamination. It is speculated that the larger particles of calcium carbonate would accumulate a large electric charge and be flung towards the collector – the resulting nonwoven would presumably not be as uniform as one using a virgin polymer but there would be no chance of a needle clogging in the process. This could be a vital feature for successfully recycling waste carpet at scale – for any industrial process reliability is key, and needleless electrospinning could allow this.

e. Additives

Typically, the aim of a spinning process is to produce fibres with as small a diameter as possible, to maximise the surface area of the resultant material and therefore the advantageous properties. The principal properties of a polymer melt or solution that determine the diameter of the fibres is (in electrospinning) the electrical conductivity of the solution/melt (the higher the conductivity, the higher the velocity and thinner the fibre), and the viscosity (the lower the viscosity, the thinner the fibre) [77] [74]. Often the properties of a raw polymer such as PP are not ideal in these regards [81], so additives have often been used to improve the spinning properties and therefore the properties of the resultant material. Sodium oleate and sodium chloride at a weight fraction of 7% were used in one melt-electrospinning paper, reducing the average fibre diameter from 3.22µm with pure PP to 0.606µm and 0.78µm respectively [77]. Another paper on melt-electrospinning reduced the fibre diameter from 10-65µm to 2-10µm with the addition of 3% weight of sodium stearate [83].

Another additive that has been used with substantial relevance to this project is calcium carbonate. One paper used small (average size 0.8µm) particles of calcium carbonate as a filler material, showing that coherent fibres could still be obtained even up to 50% $CaCO_3$ content by weight [83]. While the particles in this study were significantly smaller than the average size is expected to be when carpet is mechanically shredded, the result is still encouraging.

f. Application to carpet waste

As shown above, melt spinning and electrospinning are widely studied ways to produce nonwoven materials with a variety of valuable properties from polymers. However, discussions with Milan Proks, an employee at Spintek, revealed that there are difficulties associated with the electrospinning of PP. The literature attests to this, but also suggests that melt-spinning and melt-electrospinning are promising methods that are more compatible with PP and come with a variety of advantages, despite their reduced fibre diameter. The increased fibre diameters given with MS and MES, along with the lack of need to find a solvent that dissolves all components, suggests that these methods will afford a much greater tolerance for contaminants than ES alone.

vii. Depolymerisation

Research on depolymerisation of waste carpet has tended to be US-centric, where the majority of carpets have nylon 6 or 6,6 (also known as polyamide 6 and 6,6, nylon is the commonly used trade name) face fibres [84], unlike the UK where the majority of carpets have PP face fibres [4]. Most US carpets still possess PP backings, but these represent approximately 10% of the mass of the carpet [25] and so the majority of the focus is on the recovery of the nylon; papers often discuss the PP being left as part of the waste stream, and then never discuss the feasibility of recovering it [24]. Separating the PP backing and other carpet components from the face fibres after nylon depolymerisation; the method that minimises separation costs, means that the PP cannot be recovered and recycled [24]. Some papers report attempts to recover the PP however: DuPont, AlliedSignal, and Zimmer have each developed processes involving density separation to recover both nylon and PP from nylon face fibre carpet using shredding and density separation [24], with DuPont claiming a 98% purity for both polymers- however it is not clear how scalable this process is. Another method discussed involves the use of supercritical CO_2, the temperature and pressure of which is gradually increased to sequentially separate the different components, allowing individual recovery of both the PP and nylon, although the paper does not discuss the quality of the PP obtained.

Different polymers have different properties that allow for different commercial depolymerisation potential; while polyamides are relatively easy to depolymerise, for polyolefins (of which polypropylene is one) any monomer recovery at any temperature is extremely difficult [17], thanks to the high exergonicity of polymerisation and high activation energies for thermal decomposition. This suggests that while PP may be able to be recovered in its polymer form from carpet, looking to depolymerise to produce the raw materials to then sell or produce a pure PP product is fruitless. One paper [85] has successfully obtained PP yields of 78% and a purity of 94% from an induction-coupled plasma reactor, but a review paper [17] argues that for this process to be economically viable, a 3000-fold increase in throughput would be required, as well as several other assumptions. The literature studied in this section suggests that while nylon may be effectively recycled to a monomer, PP and as such most UK carpets are not feasible to be recycled with this method.

2.5.4. Uses for end-of-life carpet

This section will detail the different uses for end-of-life carpet waste, typically after it has been subjected to one or more of the end-of-life treatment techniques discussed in the previous section.

i. Concrete Reinforcement

Concrete reinforcement with small, discrete fibres has been discussed in literature since 1975 [86]. Studies tend to involve the mixing of fibres into ordinary Portland cement (OPC). There appears to be a broad consensus among papers on results, as follows:

- The compressive strength of concrete is generally shown to decrease with increasing fibre dosage, with results from several papers falling within the range of a 2.7-21.3% reduction with fibre dosages of 0.25-1.25% respectively [87] [88] [89]. The papers speculate that the reduction in strength may be due to air voids introduced by poorly mixed fibres.

- The tensile and flexural strength of the concrete increases, exceeding a 20% increase in several papers. It is hypothesised this is due to the fibres preventing the formation of macrocracks and reducing stress concentrations. [87] [88] [89] [90]
- The toughness and impact resistance of the concrete are increased, with one study showing an increase in the splitting tensile strength of more than 7% from the non-fibrous control. [87] [88] [89] [90]
- The workability and slump of the concrete are reduced – in one paper the slump shown decreased to 11% of the value of the control sample. [87] [88] [89]
- Chloride penetration depth is reduced, in one paper by 27%. [88] [87] [89]

Although the compressive strength of the concrete reinforced in [87] and [88] decreased early on in the experiments, it was noted that the strength of the samples had experienced a significant rise by the 90-day mark, and in [87] where the concrete was tested again at 180 days, the compressive strength exceeded that of OPC. The authors speculate that this is likely related to the pozzolanic nature of the palm-oil fuel ash (POFA) mix that was used in conjunction with the fibres, so while encouraging that the compressive strength of concrete containing recycled fibres can approach that of OPC, it seems likely that fibre reinforcement in isolation reduces compressive strength.

Pozzolans are 'defined as siliceous or siliceous and aluminous materials that have little or no cementitious properties in themselves but, when finely ground, will chemically react with calcium hydroxide in the presence of water to form compounds that have cementitious properties'. [91] Using pozzolans in concrete gives several advantages: reduced materials cost from substituting cement components with low-cost pozzolans, reduced greenhouse gas emission, and improved cement durability [92]. Various literature has investigated the use of palm oil fuel ash as a pozzolanic additive in concrete, often in conjunction with carpet fibres as both are potential environmentally-friendly additives. [93] [94] [87]

In a similar concept to the use of pozzolans, calcium carbonate ($CaCO_3$) can represent 35% of the mass of a carpet [25], and one paper explored introducing this into industrial concrete mixes as a cheap substitute for cement components. [95] This idea proved ill-founded; the compressive strength of the concrete was at least halved compared to more conventional additives, hypothesised to be due to remnant latex polymers from the backing degrading the performance of the concrete or the particles themselves acting as crack initiators or weak points.

Another factor that fibre reinforcement plays in concrete is in the formation of voids. As can be seen in Figure 14, the size of voids in the concrete decrease with increasing fibre dosage. It is hypothesized by [96] that this is one of the factors that increases the tensile strength of the concrete, by reducing the possible nucleation sites for cracks, as well as bridging action across cracks slowing propagation. It can be seen in Figure 14 that the increase of fibre volume dosage from 0.08% to 0.16% reduced the maximum pore volume size in the image from approximately 250mm^3 to 100mm^3. [96] However, one paper has reported that too high an increase in fibre dosage results in fibre clumping and increased void formation [94], suggesting that there is an upper limit to the fibre dosage before a deterioration in mechanical quality of concrete is experienced.

Difficulties found to exist in composite concrete are how to thoroughly mix the concrete-fibre mix, as the fibres tend to distribute nonuniformly without extended mixing, and the reduced workability of the composite increases time pressure for pouring the concrete [97].

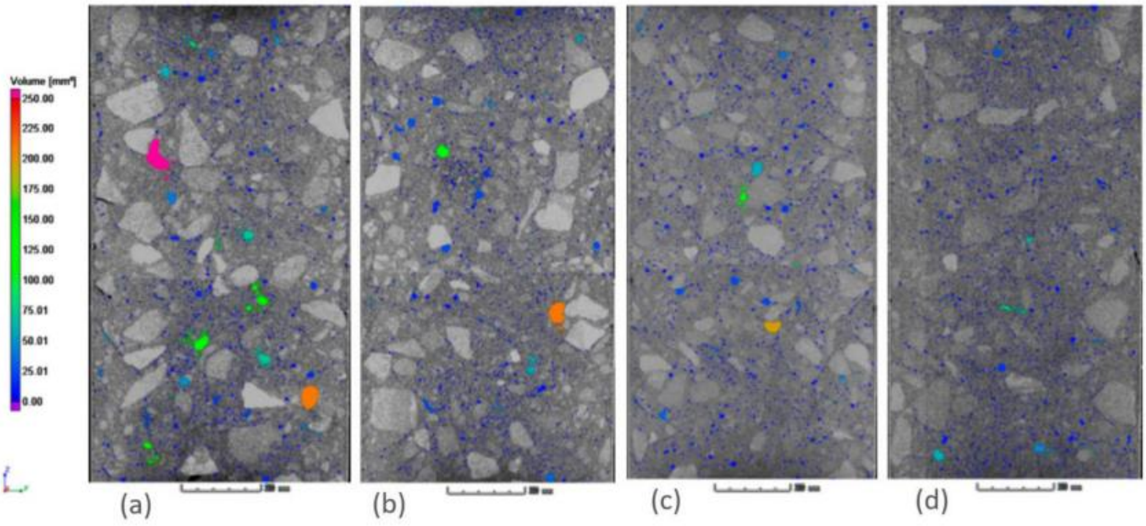


Figure 14: Porosity analysis using X-ray computed tomography: Recycled textile concrete incorporating 19 mm-length carpet fibres: (a) control sample, (b) with 0.08% fibre, (c) with 0.12% fibre, (d) with 0.16% fibre [96]

Concrete reinforcement is one of the most widely studied areas in the literature on recycling carpet. This is likely because concrete is the second most consumed material in the world, behind only water [98]. In 2019, the United States produced 90 million tonnes of Portland cement (not including imports) [99] and in 2019 produced 1.7 million tonnes of carpet waste [26], and therefore any innovation that allowed for easy inclusion of carpet into even a fraction of concrete production internationally would divert a significant fraction of carpet waste away from landfill, and potentially be extremely profitable.

ii. Road surfaces

The concept of using waste plastics as part of road construction is a relatively new one. When added in small amounts (5-10%), plastic has been shown to have positive results on the mechanical properties of the road in laboratory tests [100], improving rutting and fatigue resistance, and reducing thermal susceptibility [101]. However, there has been limited application of the concept in the real world. While roads have been constructed with these techniques and have so far shown good longevity and properties, the oldest were only built 10 years ago, so the long-term behaviour of them is not yet clear. Different polymers have different stabilities within the mix. Polyethylene (PE), low density polyethylene (LDPE), and high-density polyethylene (HDPE), have all demonstrated the capacity to remain stable over long periods in a mixture [101]. Other polymers, such as PP, polyvinylchloride (PVC), and ground tyre rubber (GTR), require a compatibilizer to be added to maintain stability in the mixture over long periods. While a financial drawback, this may be beneficial to the mechanical properties of the resulting road surface. Adding solely polymer to the mixture tends to decrease ductility, which can have a detrimental effect on the aging under load of the mixture. The addition of a compatibilizer may remove this ductility reduction and therefore allow the road surface to age better [101]. This information suggests that the use of waste PP from carpets may be viable in road surfacing. However, a report by the University of Birmingham for the Department for International Development (DFID) provides a list of the types of plastic suitable for road construction [100]. The only types of PP on the list are films of a thickness up to 60 microns, and soft foams of any thickness. Waste carpet does not fall under any of these categories, so its potential to be used in road surfaces may be limited.

iii. Polymer Melts and Composites

Another major form of secondary recycling of carpet waste is the production of polymer melts and composites. This is an appealing form of recycling because the intensive separation stage of the process is removed and the whole carpet including backing and face fibres can be melted down [24]. These advantages also come with drawbacks however, as the non-homogeneous melt that is created contains lumps of calcium carbonate and phase boundaries between the different polymers [102] [24], reducing the mechanical strength of the material. Compatibilizers, defined by [24] as interfacial agents that decrease the surface tension and increase interfacial adhesion between the different phases in a mixture, can be used to greatly improve the quality of the resulting blend. Various papers have studied the mechanical properties of these blends, with the results generally indicating properties similar to or worse than virgin material made from the same polymers, as would be expected [102] [103]. One paper describes a polymer melt which is extruded at 230°C, producing a homogeneous melt exhibiting thermoplastic properties without the need for a compatibilizer, although one may be optionally added which would presumably further improve its properties [24].

One option for improving the mechanical properties and uses of the polymer melts is their use as the primary material in a composite polymer-reinforcement material. Glass fibres, glass fibre matting [103] [102] and carbon nanotubes [104] have been used in this role, the principal advantage being that the properties of a composite depend chiefly on the reinforcement used and not the bulk polymer [103]. The reason recycled carpet waste is so appealing for this role is that it is cheaper than virgin polymers and gives only a slight reduction in mechanical properties when reinforced. One paper also studied the impregnation of waste carpet with epoxy resin and its reinforcement with nanomaterials, showing that it could be a promising candidate for a cheap composite material [104].

With PP making up the majority of polymer content in UK carpets, the ability to effectively reprocess PP is one of the primary concerns in carpet recycling. "Due to the presence of tertiary carbon atoms in the polymer back bone, [PP is] susceptible to pronounced thermo-oxidative degradation during melt processing and/or during use, as well as photo-oxidative degradation during use". [105] Typically, a plastic will contain stabilizers to protect a polymer from the degradation mentioned above. Melt processing leads to the removal of these stabilizers, and so melt processing for PP should only be conducted in the presence of a processing stabilizer, which substantially reduces the degradation experienced in the recycled polymer. This is another consideration and cost that must be considered when recycling PP, making it a less attractive option.

iv. Sound absorption

Much of the automobile industry uses non-recyclable polyurethane foams that are produced using environmentally damaging methods [106]. Some papers have researched whether recycled textile fibres can be used to create an effective sound absorbing material as a more environmentally-friendly substitute for these foams. Two papers managed to achieve sound absorption coefficients of 0.270-0.675 [107] and 0.475-0.523 [106] for 20-40mm thick insulation materials of nonwoven polymer, comparable to conventional glasswool insulation with coefficients of approximately 0.4-

0.6 for the same range [107]. The sound absorbing capability of a material depends on a variety of factors. The thickness of the material is the primary variable, with 1/10th of the wavelength of the sound needed to provide any benefit, and 1/4th of the wavelength required to be effective [106]. The sound absorption coefficient tended to increase with thickness and decreasing fibre diameter, while decreasing with material density [106] [107]. Neither of these papers targeted waste carpet fibres specifically, but they present encouraging results.

v. Thermal Insulation

The UK government has a target of 300,000 new homes a year by the mid-2020s [108]. This means that there is a large demand for home insulation, especially with the current demand for well-insulated housing. Studies have been conducted on using textile waste for thermal insulation – one using post-industrial textile offcuts found that it measured 0.044 Km/W, comparable to conventional home insulation (0.037 Km/W) [109]. Another study found that with melt-spun PP fibres, a thermal insulation value of 0.0277Km/W could be achieved [107]. Melt-spinning is described in Section 2.5.3, and results show the potential for recycled fibre as insulation, although there are some potential problems to acknowledge. One of the papers brings up the problem of the flammability of PP, and suggests that the addition of flame retardants could be necessary for widespread use in construction [107]. Another potential issue is that the tiny orifices required for melt-spinning could be clogged by the impure recycled-carpet feed material. Despite these issues, insulation represents a potentially promising option for future research.

vi. Geotechnical reinforcement

Another common area of research in geotechnical engineering is soil reinforcement, with research undertaken since at least 1991 [108]. Historically this has been achieved with large parallel layers of polymer sheeting, but this method has its drawbacks, such as introducing weak planes and having low applicability in confined spaces [110]. Recently, research has been conducted into the use of randomly distributed fibres in soil reinforcement, an approach which does not result in planes of weakness, is simple to implement in an area of any size, and performs isotropically. Waste carpet lends itself well to this task as a durable synthetic material, and only requires an inexpensive shredding procedure to reduce the carpet to chunks. One paper shows that the inclusion of chunks of PP carpet led to reductions in the coefficient of lateral earth pressure at rest [110]; a measure of the lateral pressure exerted by a body of earth relative to depth when unloaded, an important measure in the design of retaining structures, foundations, and other underground structures which have to resist lateral loading. In another paper [111], cohesion of a soil mass containing randomly distributed PET fibres was increased, and the reinforced soil displayed ductility and gradual failure rather than fragile failure. The principal advantage of this use for waste carpet is the low processing energy required – a simple cleaning followed by a coarse mechanical shredding appears adequate. A concern with this application is the potential release into the ground of microplastics. RPS 248, the Regulatory Position Statement covering the use of shredded carpet waste in equestrian surfacing, states that in order to comply with the RPS and minimise the release of microplastics, a sub-surface membrane, wind break, and retaining boards or kerbing must be installed. [112] The EA would likely insist on similarly stringent controls for geotechnical reinforcement, and so geotechnical reinforcement in the method described above presents a number of issues. Installing a sub-surface membrane around the entire reinforced area would be possible, given the area must be excavated prior to infill with the pre-mixed carpet-soil mixture, but would be expensive and leave the soil component of the mixture contaminated with microplastics, potentially meaning that section of soil must in future be treated as hazardous waste. Individually coating each carpet piece with a contaminant-retaining covering may also be possible, but is likely to mitigate much of the cost savings achieved by using such a ubiquitous and simple material.

vii. Adsorbent material for pollutants

Dyes are a common industrial pollutant. Calcium carbonate has been shown in various papers ([113], [114], [115]) to act as an excellent adsorbent for organic pollutants such as dyes. One paper obtained carpet waste, detached the face fibres, and produced the adsorbent material by pyrolyzing the remaining mixture of nylon, PVC primary and secondary backings, and $CaCO_3$ bonded with epoxy adhesive at temperatures up to 900°C. [116]

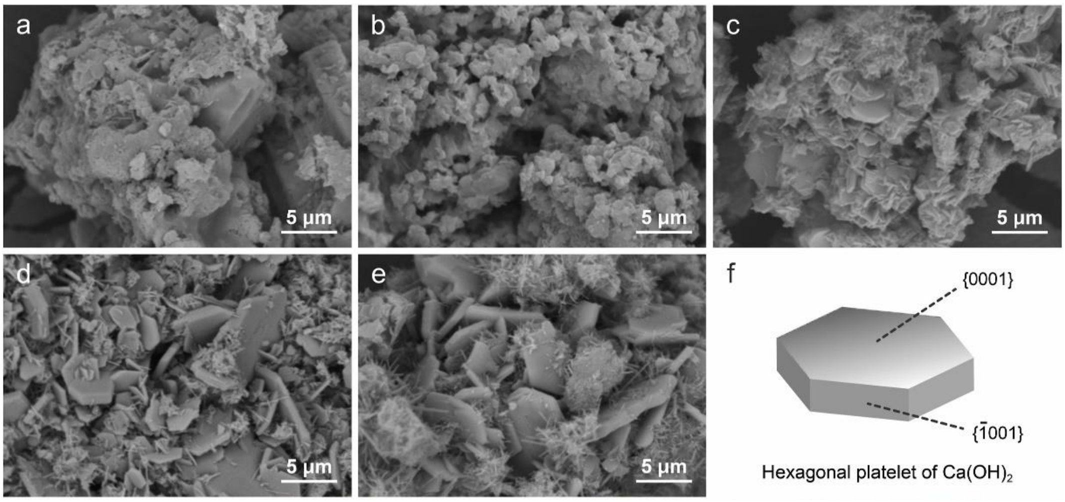


Figure 15: SEM images of pyrolysed carpet waste [116]

This resulted in a material with an adsorption efficiency of approximately 100% for a methylene blue dye and 93-99% with a methyl orange dye, at a dye concentration of 1-20 mg/L. These are promising results, with the added appeal of leaving face fibres which have been cleanly separated from the backing material. Normally the concern with such a method is that it wastes an undue amount of the face fibre which is adhered in the backing material, but that is less of a concern in this case where the backing material is being used for a positive process. The paper performed this study on pre-consumer carpet waste, but given the large variety of material already included in the pyrolisation, it seems possible that the minor contamination left after cleaning of postconsumer carpet would change the effectiveness of the final product only slightly.

viii. *Absorbent material for oil spills*

Oil is a vital energy resource for the world, but large-scale oil spills can cause catastrophic damage to the environment [117]. To mitigate this damage, various chemicals are used to concentrate the oil and reduce spread, but they tend to be expensive, toxic, and thus restricted by legislation [118]. Oil sorbents are used to absorb the oil and allow easier removal from the environment, and can generally be classified into three types: inorganic mineral materials, natural organic materials, and synthetic organic materials [74] [118]. PP is one of the leading synthetic organic materials used; thanks to its inherent hydrophobic-oleophilic nature low density, low water uptake, and excellent physical and chemical resistance, it is 'ideal for spill recovery' [119] [74]. The low density is crucial because, with a specific gravity of 0.91, PP fibres float on top of the water, in the presence of the oil and making them easily recoverable [119].

Nonwoven fabrics of extremely fine PP fibres were produced by melt spinning [117] [119], electrospinning [74], giving fibres of 4µm, 5.25µm, and 4.25µm diameter on average respectively. Another paper gave less details but also used a PP nonwoven fabric [118]. The sorption ratios attained were 7-10 g/g, 11 g/g, and 104.5 g/g respectively (approximate average figures). While the electrospinning figure is an order of magnitude different from the other results, this could be a result of the more exotic production process or an experimental error. The other results are consistent however, and demonstrate the effectiveness of PP as an oil recovery material.

ix. 3D Printing

A variety of papers in the literature have used both virgin and recycled PP as a printing material in additive manufacturing. PP is described as an excellent material for use in 3D printing, and in one paper is compared to acrylonitrile butadiene styrene (ABS), a different polymer which emits toxic fumes when printing, and polylactic acid (PLA), another polymer which has low impact strength and heat resistance. PP, on the other hand, is described as being nontoxic, having excellent stability, toughness, and rigidity.

3D printing interacts in a number of ways with the mechanical properties of the specimens it produces. The process of 3D printing itself degrades the mechanical properties of the 3D-printed specimen substantially, losing 35% and 26% of its stiffness and tensile strength respectively in one paper, compared to the virgin acrylonitrile acrylate (ASA) filament used as feedstock [120]. The method of fused deposition modelling (FDM) itself also gives the specimen anisotropic mechanical properties; 3D printed specimens tend to be substantially weaker to tensile forces in the z-direction (printing direction), as the interlayer bonds are much weaker than the intralayer bonds [121]. Table 6, below, shows the change of the mechanical properties of a specimen with respect to build direction . T_0, the first row, shows the tensile strength when the printed layers are perpendicular to the direction of loading (loaded in the z-direction), and T_{90}, the third row, shows the tensile strength when the layers are printed parallel to the direction of loading (loaded in the x or y direction). It can be seen that the tensile strength in the z-direction is the weakest, at less than half of the strength of the strength of the specimen tested in the x or y direction.

Table 6: Ultimate tensile strength and Young's modulus for different printing angles and layer thicknesses for PLA [121]

UTS(MPa)	0.1 mm layer thickness	0.2 mm layer thickness	0.3 mm layer thickness
T_{0°	26.65 ± 1.50	25.56 ± 0.51	23.78 ± 0.26
T_{45°	32.25 ± 0.25	30.68 ± 0.62	29.16 ± 0.14
T_{90°	55.86 ± 1.17	53.08 ± 1.11	45.26 ± 0.28
E_{0°	1523 ± 118	1963 ± 75	1517 ± 24
E_{45°	1546 ± 109	2086 ± 100	1707 ± 42
E_{90°	1668 ± 119	2226 ± 76	1676 ± 49

One paper conducted a study systematically evaluating the effects of nozzle temperature, printing speed, and layer thickness on the mechanical properties of the specimens, graphs of which are shown below in Figure 16 [120]. They concluded that layer thickness is the most important variable in z-direction mechanical properties, and that an optimum layer height was 0.155mm. When analysing cross-sections of samples, they discovered that 0.155 mm had no bubbles between layers, while samples with layer thicknesses either side of this did, and from this concluded that the weakness in the z direction was due to poor interlayer adhesion and that interlayer bubbles contribute to this.

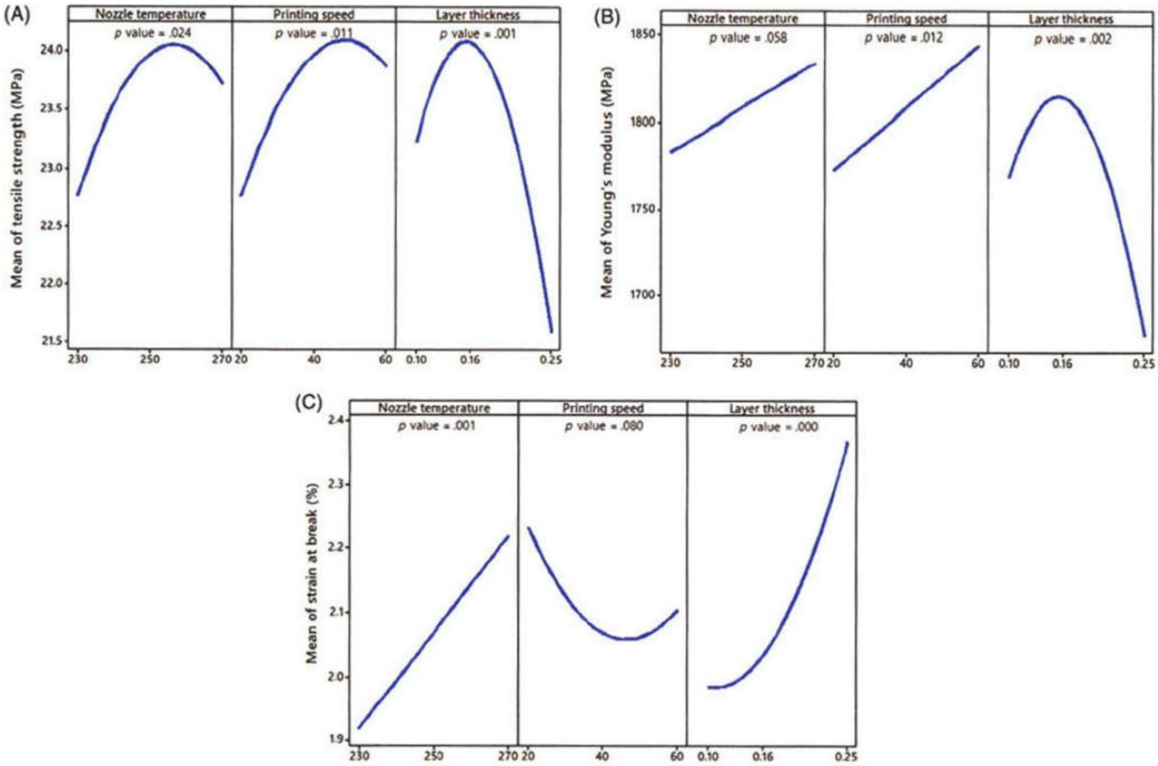


Figure 16: Tensile strength, Young's modulus, and mean of strain break vs nozzle temperature, printing speed, and layer thickness [120]

Several papers [122] [123] looked at using additives with 3D printing to reduce cost, increase strength, or reduce shrinkage. While the exact nature of the additives and their results are not important to this report, it showed that 3D printing with PP is possible with contaminants mixed in, as would undoubtedly be the case for any filament produced from waste carpet.

The papers did provide information that may prove useful when experiments are carried out in this project. For example, the shrinkage rate of PP was calculated in [124] as 1.06-1.10% (dependent on direction of print), and described to decrease with the addition of various fillers, one of which was $CaCO_3$ nanoparticles. It remains to be seen, however, whether macro-scale $CaCO_3$ particles, such as the ones that are likely to be present in waste carpet samples, produce similar effects. Other ways of minimising shrinkage, such as maintaining a moderate atmospheric and bed temperature (45°C and 100°C respectively) were also discussed and will be taken into account in the experimental phase of this project. Another useful innovation was described in [125], where to work around lack of adhesion of the PP to the printer bed, a bed made of PP was used. Finally, another potentially useful production aid was described in [126]. When the filament was being produced, a 30-50g weight was hung from the extruded end to tension-load it and produce a better filament.

Table 7 and Table 8 show sample parameters found in a selection of literature for the production of PP filament and 3D printing using PP filament. These values will provide guidance when experimentally testing PP.

Table 7: Typical literature parameters for filament production using PP.

	[126]	[127]	[125]	[124]	[128]
Bed temp. (°C)					
Nozzle temp. (°C)	220	200	190-250	205-210[2]	
Barrel temp. (°C)	225	100	190-250	205-210[2]	
Ambient temp. (°C)	22		30		
Motor speed (RPM)	7 RPM	40-50			
Stagger angle (°)		30/60			

Table 8: Typical literature parameters for 3D printing using PP.

	[126]	[127]	[125]	[124]	[128]
Bed temp. (°C)		60	20[1]	100	50
Nozzle temp. (°C)		200	165	205-210[2]	210-230
Barrel temp. (°C)				205-210[2]	
Air temp. (°C)			20[1]	45	
Layer height (mm)		0.2	0.2, 0.35	0.3	
Infill (%)		50	20, 60, 100		
Bed material		PP			

From these papers it appears clear that PP is both a desirable and practical material to 3D print with, and the papers provide a number of useful tips to 3D printing with PP to maximise accuracy and quality of print.

x. Equestrian surfaces

Equestrian arenas and racetracks require surfacing to provide a suitable surface for horse-riding. Various surfaces are used, typically composed of silica sand and synthetic fibres [129]. Both post-industrial and post-consumer carpet are used as the fibre component in these, providing a cheap bulk filler material that allows equestrian surfaces companies to advertise as being eco-friendly [130]. Currently this is the dominant form of carpet recycling in the UK, as shown in Figure 1.

The more premium surfacing options tend to eschew post-consumer carpet in favour of post-industrial [130]; although it is not clear that this makes a difference in quality, some manufacturers claim that post-consumer carpet shredding can contain backing and fragments of carpet gripper rods (if true, this would be in direct contravention of RPS 248 where it states the RPS applies to

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[1] Given as room temperature in the papers; it is assumed here that room temperature = 20°C.

[2] For PP mixed with $CaCO_3$ and rubber granules respectively; recycled carpet is expected to act as a mix of the two.

“treated post-consumer waste carpet with all physical contaminants including, but not limited to metal, carpet grippers and non-carpet based plastics removed”) [131] (Environment Agency, 2021). There is potentially research to be done here in more effectively separating out the contaminants from the carpet waste so post-industrial carpet can be used more, but it could also be that this is simply a marketing ploy to sell a ‘more premium’ product for a higher price.

xi. Energy from Waste (EfW)

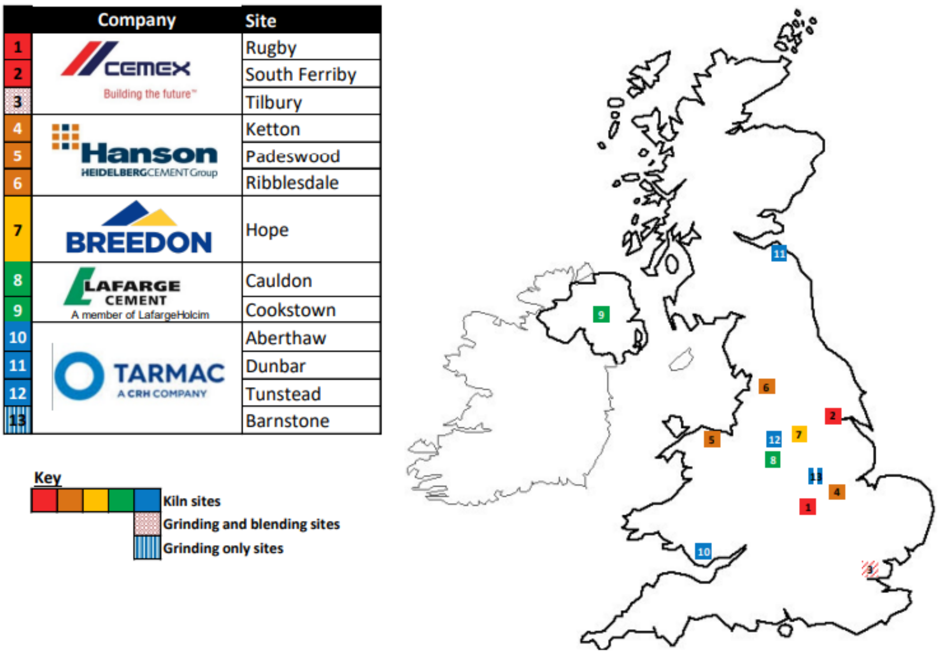
Energy from waste (EfW) is a large and growing industry in the UK, processing more than 13.96 million tonnes of residual waste in 2020, an increase of 10.5% on 2019 [52] DEFRA uses the term EfW as a term ‘to describe a number of treatment processes and technologies used to generate a usable form of energy and which also reduces the solid volume of residual waste’ [132].

These EfW facilities burn both RDF, SRF, and untreated black bag waste, the first two of which often have waste carpet incorporated into them. RDF is a fuel made by combining a variety of types of waste, the quality of which can vary widely from batch to batch depending on the properties of its components [133]. This affects its usage, with some papers critiquing that a good thermal performance cannot be guaranteed from the fuel [134]. Solid recovered fuel (SRF) is a solid fuel obtained from non-hazardous waste that has been processed and refined to a more homogenous, less contaminated, and higher quality fuel than RDF [134]. It is a type of RDF, but not all RDF is necessarily SRF [132].

The distinction in quality and calorific value between RDF and black bag waste can be seen in the difference in power output of the Ferrybridge EfW installation, which only burns RDF, compared to the average annual output; 882kWh/t vs 557kWh/t [52].

xii. Cement Kiln Fuel

The cement industry in the UK produces 10 million tonnes of Portland cement each year, contributing a billion pounds to the economy [135]. There are 11 manufacturing plants in the UK, and 2 focused on grinding and blending. All of these are under the control of 5 major companies, and are shown in Figure 17.



	Company	Site
1	CEMEX Building the future™	Rugby
2		South Ferriby
3		Tilbury
4	Hanson HEIDELBERGCEMENT Group	Ketton
5		Padeswood
6		Ribblesdale
7	BREEDON	Hope
8	LAFARGE CEMENT A member of LafargeHolcim	Cauldon
9		Cookstown
10	TARMAC A CRH COMPANY	Aberthaw
11		Dunbar
12		Tunstead
13		Barnstone

Figure 17: UK cement production sites belonging to the 5 major companies [135]

A cement kiln is the primary method of producing clinker, an intermediate in the creation of ordinary Portland cement (OPC), by far the most commonly used type of cement [136]. The design of a cement kiln is the result of a long evolution of designs for industrial-scale clinker production beginning in the 19th century, culminating in the modern rotary kiln with precalciner (Boateng, 2016). Clinker production is an incredibly energy-intensive process, consuming approximately 2.85GJ per ton of clinker produced, with temperatures inside a cement kiln reaching as high as 1250°C [137], and currently much of this energy is provided by fossil fuels. The substitution of these fossil fuels for high calorific-value waste such as shredded textiles is an appealing concept, reducing fossil fuel usage while providing an avenue for waste disposal.

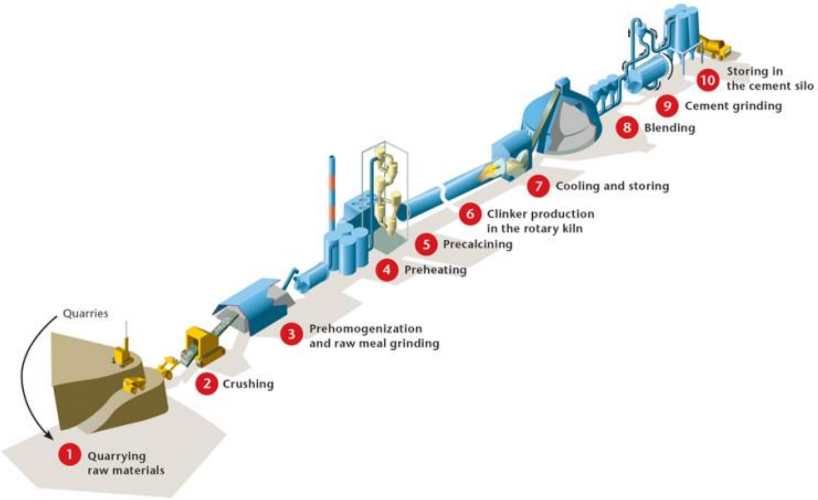


Figure 18: Cement production pipeline [138]

Figure 18 shows the pipeline of cement production from quarrying of the raw materials to the final finished product ready for use. A cement kiln takes 'raw meal', mainly crushed calcium carbonate with small quantities of metals and minerals such as iron oxide, alumina, and silica added, as input and produces small balls of clinker as output. The fuel in a cement kiln is fired in two main places; the main firing chamber, where the heat directly calcinates the clinker, and the suspension preheater, where the incoming meal is preheated through suspension as dust in hot air. In recent years, the efficiency of the preheater has been recognised and precalciners have been widely added. A precalciner is an innovation where a portion of the kiln fuel is burnt in a special chamber at the bottom of the preheater array to use a portion of the fuel in the most efficient manner. In precalciner kilns in the UK, around 65% of the fuel is fired in the precalciner [139], with the remaining 35% of the fuel fired in the main kiln [140]. It is the main kiln burner that requires very precise control of the flame properties, and so the maximum alternative fuel substitution that can be achieved there is 25-30%. The precalciner is a less sensitive component however, and so higher levels of alternative fuel consumption can be tolerated in precalciner burners (the maximum that has been achieved is 80-100%) [141].

Over the past three decades, the UK cement industry has achieved huge emissions reductions, as shown in Figure 19. One reason for the difference between absolute and relative emissions reductions is because of the decline in the quantity of cement manufactured in the UK; the share of the market taken by imports has increased from 10% in 2006 to 22% in 2019 [142].

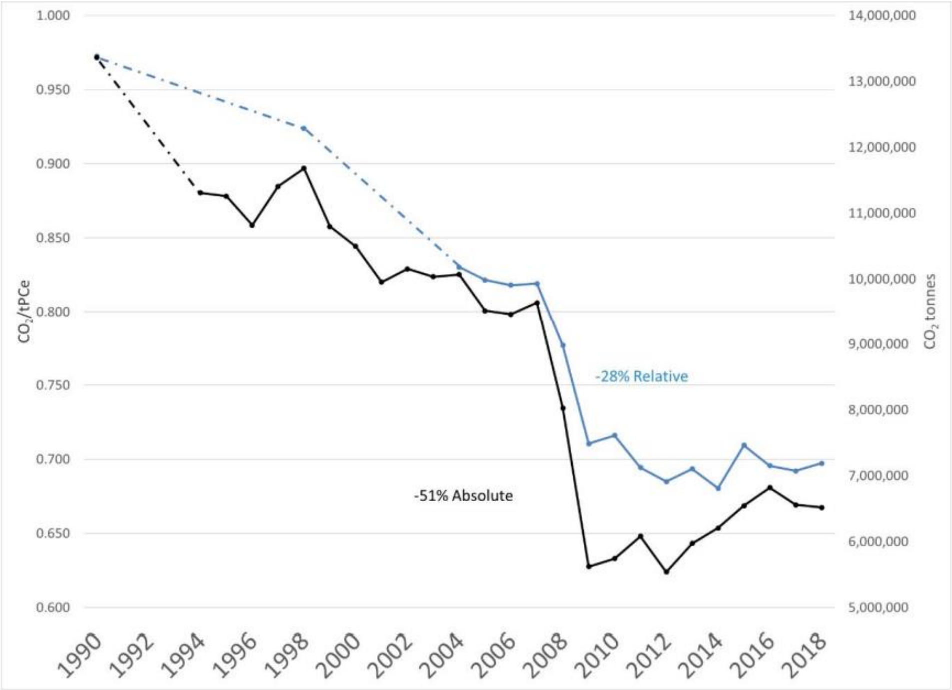


Figure 19: Absolute and relative reductions in UK cement industry emissions [142]

A large part of the CO_2 savings made since 1990 have been due to the industry switching from 'wet process' to 'dry process' cement kilns. This means that the raw meal enters the site as a dust rather than a slurry, and therefore requires far less energy to evaporate the water content. The industry has cautioned that in the near future there is no similar step change expected, and so declines in emissions may be less rapid [139]. Another reason for caution in future emissions changes is the proportion of emissions generated by calcination compared to fuel burning. 70% of the emissions of the industry are generated by the chemical decomposition process of the clinker, compared to 30% generated by the combustion of fuel [142]. While the industry and this report will strive to reduce the CO_2e generated by burning fuel, a full 70% of the emissions cannot be reduced without resorting to carbon capture and storage (CCS), the equipment for which can double the cost of a typical cement plant [139].

Despite these plans, the industry is still optimistic about the changes it can make. One of the primary areas it aims to do this in is fuel substitution; one report states that the benefits of using waste as fuel "clearly outweigh the disadvantages", thanks to the reduction in both cost and CO_2 emissions. The Mineral Products Association, to which all of the 'big five' UK manufacturers belong, aims to have 80% of the thermal input of all plants generated by waste derived fuel (WDF) by 2050 [143].

In 2015 40% of the thermal input consisted of waste derived fuel, while 60% was coal or petcoke (a fuel produced from oil refining), as shown in Figure 20 and Figure 21.

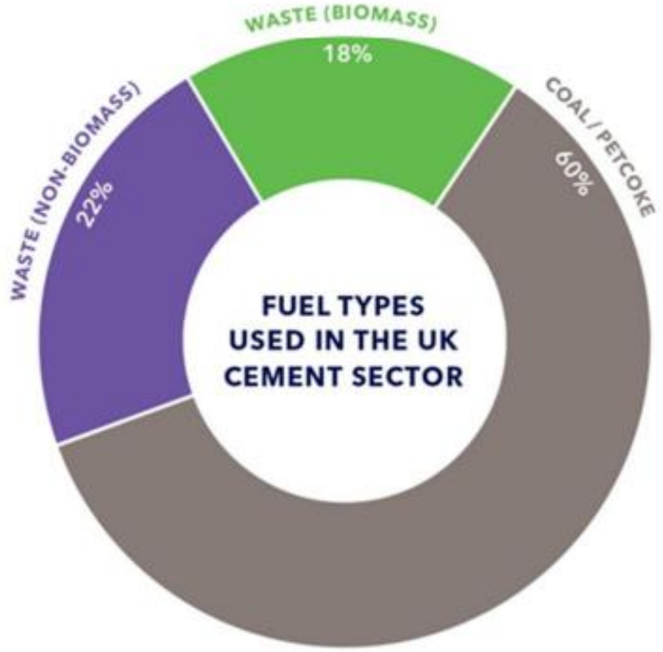


Figure 20: Fuel types used in the UK cement sector, 2015 [139]

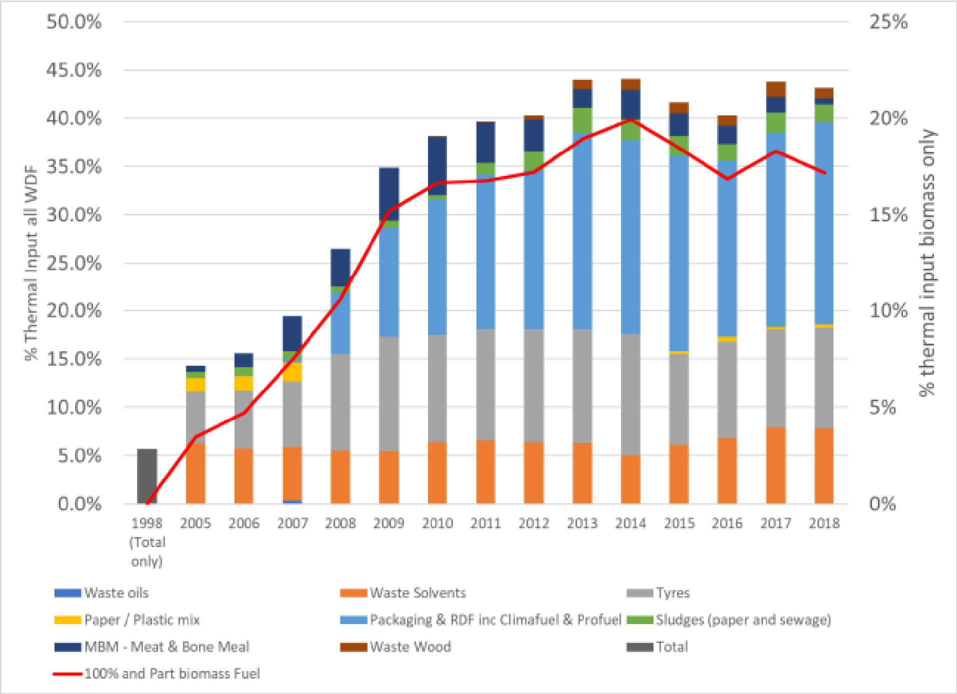
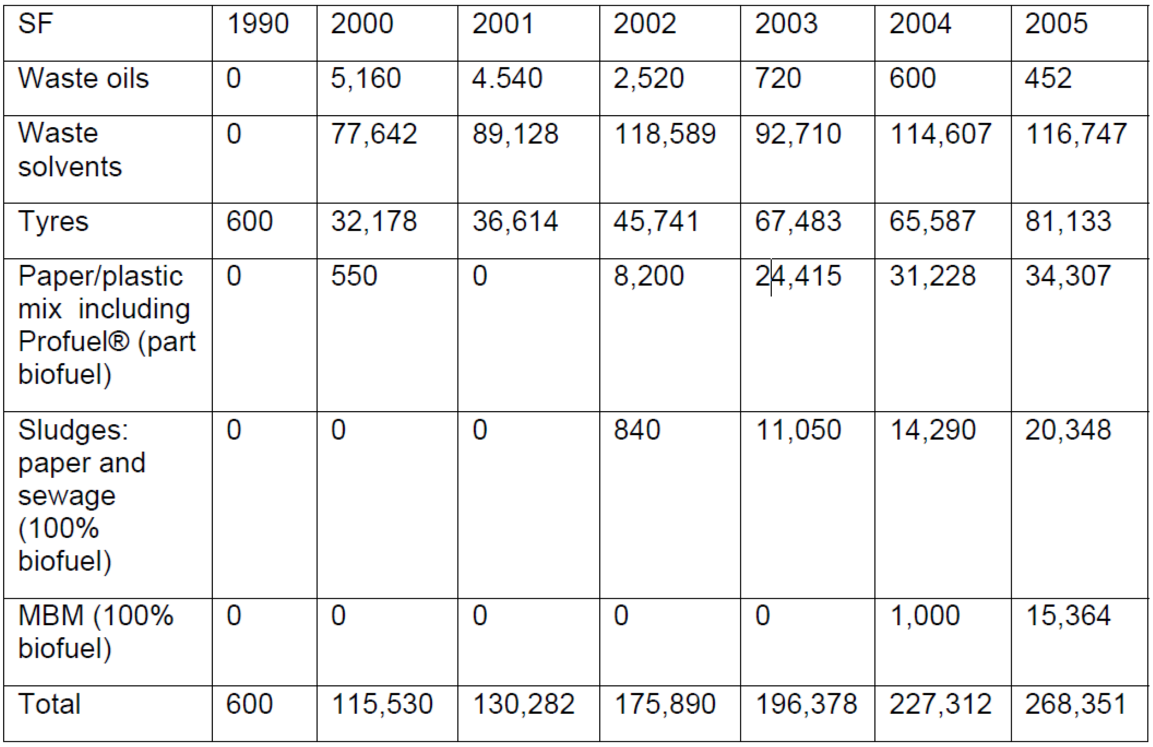


Figure 21: Waste derived fuel use in UK cement manufacture [142]

Table 9: Historic tonnage of substitute fuel used in the cement industry [144]



SF	1990	2000	2001	2002	2003	2004	2005
Waste oils	0	5,160	4.540	2,520	720	600	452
Waste solvents	0	77,642	89,128	118,589	92,710	114,607	116,747
Tyres	600	32,178	36,614	45,741	67,483	65,587	81,133
Paper/plastic mix including Profuel® (part biofuel)	0	550	0	8,200	24,415	31,228	34,307
Sludges: paper and sewage (100% biofuel)	0	0	0	840	11,050	14,290	20,348
MBM (100% biofuel)	0	0	0	0	0	1,000	15,364
Total	600	115,530	130,282	175,890	196,378	227,312	268,351

Table 9 was obtained from an EA report summarising British Cement Association (BCA) data [144], which stated that the thermal substitution rate in 2005 was 14.3%, a figure which matches up well with Figure 21.

a. Obstacles

While appealing for a variety of reasons, there are also various obstacles, both actual and perceived, to the widespread use of Waste Derived Fuel (WDF) in the cement industry. These are discussed in the following paragraphs.

b. Calorific value

A comprehensive review on the usage of substitute fuels in cement kilns was produced by the EA in 2008 (Environment Agency (EA), 2008). Carpet is discussed in the report in the context of being used in Profuel®, a 'highly specified' solid fuel manufactured from dry organic wastes. Originally made just from post-industrial packaging waste, it is now (at the time of the report in 2008) composed of RDF and SRF. If a producer wishes to have their waste included in Profuel, the composition of the waste is analysed, and if found suitable is collected, inspected, then shredded and ground to approximately 20mm and blended to meet the final kiln specification. The calorific value of the final product is approximately equivalent to coal [144]. The calorific value of coal is 25-35 MJ/kg (Dincer, et al., 2018), which fits well with the mean calorific value of Profuel components in Table 10, assuming the more calorific components are used in higher volumes.

Table 10: Calorific value of Profuel ingredients [144]

	Sawdust	Nappies	Medical Rubber	Photopaper	X-ray acetate	Carpet fluff/trimmings	Coffee grounds	Mean
CV (gross, MJ/kg)	14.37	32.71	26.45	23.26	22.93	17.65	23.39	22.97

This calorific value of carpet face fibres is corroborated by [145], where it was measured at approximately 21.141 MJ/kg.

c. Cost

The low cost of alternative fuels compared to more traditional fossil fuels was one of the main drivers that made the UK cement industry an early adopter of alternative fuels. However, the increased competition for alternative fuels has raised the prices for such fuels and is "now proving problematic for the sector" [139]. In the context of this report, however, this could be seen as an opportunity, with substantial demand for cheaper as-yet-untapped alternative fuel resources. Exact figures cannot be given because the economic figures associated with the purchase of fuel are commercially sensitive and not available in the public domain [144]. However, the coal price determines the cost-effectiveness of investment in WDF and other renewable technologies [142], and with the coal price in the UK over the last four years at an all-time high of 1.14 pence/kWh [146] (see Figure 22), the incentive for investment is likely to be high.

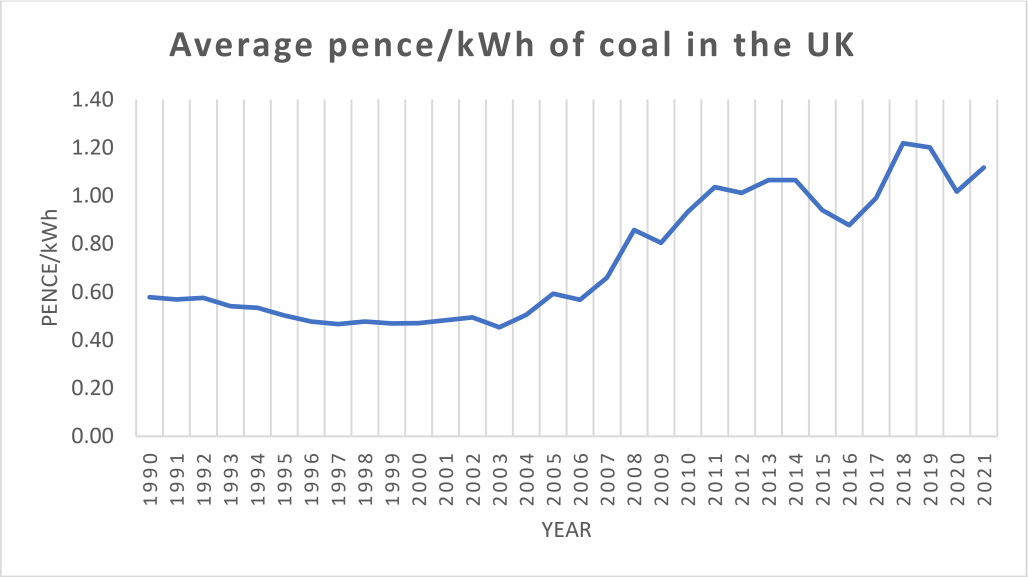


Figure 22: Price of coal in the UK for industry, 1990-2021 [146]

d. Air quality

The Environment Agency has compiled the results of surveys conducted at 5 different cement sites across the UK, and concluded that there were no significant changes in air quality, and no changes that could be unequivocally attributed to the use of substitute fuels [144]. The most comprehensive of these surveys, conducted at a kiln in Ribblesdale, concluded that the area had ‘very good’ air quality.

e. Health

Health is a common concern with regard to the use of substitute fuels, and so again surveys were compiled by the Environment Agency. They concluded that there was a ‘negligible’ risk to human health, and with regards to RDF and Profuel specifically, “any change in health effects would be insignificant”.

2.5.5. Conclusion

This literature review has analysed the production techniques and end-of-life destinations for waste carpet, the results of which are summarised below, ordered into primary, secondary, tertiary, and quaternary end-of-life categories.

Primary recycling is where waste is reused as the same product for which it was originally intended. This is an efficient, desirable route for carpet waste, and if it is being reused as the same product likely avoids the carpet ever being classified as waste, meaning it is not subject to particular legislation (see 1 for further details). CRUK suggest that while carpets have a design life of 15 years, their actual life tends to be dictated by changing fashion trends and is typically more in the region of 7 to 10 years [7]. This suggests significant potential as a recycling method if the fashion angle and contamination can be overcome. Postconsumer carpet often has significant contamination introduced from the years of use it has seen; studies carried out in Europe show that post-consumer carpet is approximately 30% heavier than new carpet [24], and some way of removing this contamination would have to be developed before postconsumer carpet could be widely reused. Supercritical CO_2 extraction and the FRC Group's Ultraclean Machine have been discussed as potential solutions to this, and may well prove useful in secondary recycling too. The alternative is to use only post-industrial carpet, which has not been subject to the same contamination, but which represents only 7000 tonnes (approximately 1.5% [5]) of the UK carpet waste stream. The overview of the primary recycling sector provided above demonstrates that, while a desirable and effective route of carpet recycling, the sector is currently extremely limited in size and requires substantial improvement and development of carpet cleaning and repurposing solutions before any major reuse of postconsumer carpet can be achieved. Since no company has yet occupied the market niche, it is also unclear whether there is a financial argument for widespread primary carpet recycling. Several companies reuse and recycle carpet tiles, although the volume in which they do so is unclear and has no impact on the broadloom carpet waste stream. Overall, the only tractable option in the public domain of the primary recycling sector appears to be supercritical CO_2 extraction. There is a reason carpet is rarely reused, thanks to the dirt inherent in it, so the only option is some form of cleaning, of which all forms apart from CO_2 are proprietary research by companies. Even CO_2 extraction appears to have only ever been performed on a lab scale, and it is unclear if it can be applied to whole samples of carpet.

Secondary recycling of waste carpet is when waste goes through some mechanical or chemical process to transform it into a new product, and is a widely studied area in literature. The studied use of it occupies a variety of areas, which were detailed above.

A wide variety of secondary recycling options for carpet fibres exist and have been thoroughly researched. These have included concrete reinforcement, road surfaces, absorbent materials, and several more. However, apart from equestrian surfacing, none of these options have been exploited widely enough to have a significant impact on the UK carpet waste stream (Figure 1). For truly widespread impact, a secondary recycling option would have to be scalable and financially sustainable, which none of the options discussed above have yet achieved. Concrete reinforcement, while having massive scalability potential due to the volume of concrete produced [147], has been researched since at least 1975 and after almost 50 years has had negligible impact on carpet recycling, suggesting that the cement industry find the trade-offs required unacceptable, or prefer to derive their reinforcement from elsewhere. It does seem though, that less safety-vital concrete components such as kerbs and paving slabs could be perfect targets for carpet fibre reinforcement, especially as the increased impact resistance would be particularly beneficial in these applications. Polymer melts and composites are also not widely used, again suggesting that industry does not consider the trade-offs required in mechanical performance acceptable.

The applications least researched but that could potentially be scalable and financially viable are in thermal insulation, sound insulation, and absorbent materials, none of which have had research conducted in the specific area of recycled carpet, but in all of which other recycled fibres have shown promising results. However, many of these options have substantial drawbacks that would need focused research to overcome. Geotechnical reinforcement would introduce vast quantities of microplastics into soil, while sound and thermal insulation have significant fire risks unless a cost-effective fire retardancy solution is found.

Spinning appears to be a very interesting option, with the potential to enable viable insulation and absorbent materials, but unfortunately Lancaster University does not have access to facilities suitable for this experimentation. The University of Leeds, Surrey, and the Henry Royce Institute at the University of Manchester are several universities that do have access to this, although we were unable to arrange collaboration with them for this project.

3D printing may be a useful technique with which to recycle carpet fibres, as waste carpet could provide low cost, environmentally friendly filament, and it would provide an easy way of testing the mechanical properties of recycled carpet PP thanks to the versatility of 3D printing. The equipment for this was present at Lancaster University, so this was selected as the primary avenue of experimental research.

Tertiary recycling is the decomposition of polymer waste into its constituent monomers for use as a raw material in future products. It has been the focus of much literature research as companies seek to develop a cost-effective method of recycling monomers. While various tertiary recycling methods have been researched and some put into industrial use, the economic recycling of PP to a monomer seems unlikely, and the only promising research is being conducted by industry, from which the details are not publicly available. The fundamental problem is that PP has a very high exergonicity of polymerisation and high activation energies for thermal decomposition – even one paper that obtained PP yields of 78% and a purity of 94% concluded that for this process to be economically viable, a 3000-fold increase in throughput would be required. While nylon recycling to a monomer is possible and potentially economically viable at scale, as has been shown in much US literature, the recycling of the dominant UK carpet polymer of PP does not appear to be tractable through tertiary recycling, at least with information in the public domain at the moment.

Quaternary recycling is the burning of waste to generate heat, for a process or simply for disposal [148]. The fuel for this is typically sorted and processed to some degree, and tends to fall in to one of two categories: RDF and SRF. The use of these fuels for EfW, while better than incineration without energy recovery, is an incredibly wasteful option and should be avoided. The combustion of these fuels in cement kilns may be better since it is replacing mainly coal combustion, and this will be researched further in later sections focusing on CO_2e emissions. Cement kiln fuel seems by far the most promising of these options, as it will be replacing coal and therefore potentially emitting less CO_2e overall than other quaternary routes such as EFW or incineration. Further research will be conducted into this in Section 4 of the report.

The conclusions of this literature review have been summarised and compiled into 11 below. This table provides a concise and intuitive summary of the scalability, cost, sustainability, and technical feasibility of the end-of-life disposal methods and production techniques discussed. The sustainability of the production techniques is not discussed because their sustainability would be more dependent on what their outputs are used for i.e. their end-of-life destination.

Table 11: Summary of literature review findings

Production techniques	**Scalability**	**Cost**	**Sustainability**	**Feasibility**
3D printing	Medium	Low		Mixed
Supercritical CO2 extraction	Low	High		Low
Shredding	High	Low		Live
Spinning	Medium	Medium		Mixed
ISOPREP	Not verifiable; commercial			
Innovate Recycle				
Aquafil				
Longworth				
Depolymerisation	High	High		Low
End-of-life destination	**Scalability**	**Cost**	**Sustainability**	**Feasibility**

Concrete reinforcement	High	Low	Positive	Mixed
Road surfaces	High	Medium	Positive	Mixed
Polymer melts and composites	Medium	Low	Positive	Mixed
Sound absorption	Medium	Medium	Positive	Mixed
Thermal insulation	High	Medium	Positive	Mixed
Geotechnical reinforcement	Medium	Low	Negative	Low
Absorbent material for pollutants	Medium	Medium	Positive	Mixed
Absorbent material for oil spills	Medium	Medium	Positive	High
Equestrian surfaces	Medium	Low	Neutral	Live
Energy from Waste	Medium	Low	Negative	Live
Cement kiln fuel	High	Low	Negative	Live
Landfill	High	Low	Neutral	Live
Reuse	Low	Low	Positive	Live

2.5.6. Future Carpets

While unlikely to be specifically researched in this project, an important question in the sector is what the future carpet market is likely to look like in terms of manufacturing carpets that produce less waste in some way, perhaps being longer lasting and easier to wash, or being more easily recyclable.

Since approximately 80% of UK carpets are composed of polypropylene [4], which is a difficult polymer to break down into its constituent monomers, it seems likely that more easily depolymerised plastics will be used in future carpets. [149] discuss how new methods of recovering polymers are being developed, where rapid depolymerisation is triggered by environmental conditions such as pH.

Another avenue for carpets of the future is the monomaterial carpet. One of the greatest difficulties in carpet recycling currently is the separation of the different components: face fibres, backing material, latex, glue etc. Often processes to break down and recover one material from the carpet require all other materials to be separated or render the other materials unusable in the process of recovering the target material. A monomaterial carpet would drastically reduce the difficulties involved and allow for recovery yields approaching 100%, paving the way for truly circular carpets.

2.6. Separation and Sorting

Separation and sorting of different polymers, fibres, and superfluous waste from the waste stream is a labour-intensive process, and so technology to streamline this process is essential. The primary tool that exists at the moment is the NIR scanner, but further, more complex processes are being developed to automate the process more thoroughly. This section gives a brief overview of these processes.

2.6.1. NIR (Near Infrared) Scanner

Handheld NIR scanners can be used to provide an accurate reading of the material composition of a carpet sample in the order of a few seconds. While not using the same part of the IR spectrum as FTIR, the principles are similar and so an explanation of the science involved is left until section 3.4.1. One paper describes NIR spectroscopy as being able to 'efficiently and accurately recognise all kinds of textile fibres, showing significant superiorities compared with other identification methods' [150]. The technology does require a large dataset to train the statistical models [151], but such a dataset could be easily constructed with the volume of carpet and carpet waste on hand, and indeed presumably already exists in the pre-trained NIR scanners on the market.

2.6.2. CISUFLO POLYSEP

Currently the separation of different fibres is labour-intensive. The CISUFLO POLYSEP technology aims to automate this process for small sections of textile by using a combination of NIR scanners and air jets to identify and direct the textile section [152]. Due to the limited power of the air jets, this process is only suitable for small sections of textile – larger, more unwieldy sections of carpet may be more easily processed through the use of handheld NIR scanners. With this process, CISUFLO claim to achieve an output purity of >90% for polymers such as PA, PVC, and PP [153].

2.6.3. Density Separation

i. 'Sink-float'

'Sink-float' separation is a technique commonly used to separate the lighter polyolefins from the heavier plastics such as PVC and PET [154]. The technique takes advantage of the density difference between the polymers, placing them both in a medium (for the above-mentioned plastics water is ideal) with a density intermediate between the density of the two groups to be separated. The lighter group of polymers then floats, while the denser group sinks to the bottom of the medium.

In this way a clear binary separation can be achieved between two different groups, although it 'becomes difficult if the materials are characterised by [only] a slight [sic] different density' [154].

Figure 23: A sink-float separation of shredded PP carpet from the other carpet components [63]

An example of sink-float separation is shown in Figure 23, performed by the ISOPREP group and used to separate the PP fraction of carpet (floating on the surface) from the other contaminants such as latex and $CaCO_3$. DuPont used a sink-float separation method to separate both nylon and PP from carpet fillers, achieving an output of 98% pure polymer [68].

Sink-float separation appears promising as a simple, cheap, and effective method by which to separate two different polymers from each other, and has been tested and proven effective by several other research teams and companies.

ii. Magnetic Density Separation (MDS)

MDS is a technological progression from sink-float separation. Instead of using a liquid with a single density as the separation medium, nanometre-scale magnetic particles are suspended in water and subjected to a magnetic field varied exponentially over distance in the vertical axis, creating a medium with an artificial density gradient [154] [155]. This can be used to separate plastics of multiple densities simultaneously, unlike sink-float separation. However, this is a much more expensive and complex process than sink-float separation and so is unlikely to be used in this report, despite being of interest as a potential future industrial technique.

3.

3. Sample Characterisation, Separation, and Processing

This section details the experimental portion of the project, covering sample characterisation, separation, and processing. The aims of this section were as follows:

- Obtain samples of used carpet.
- Characterise the samples using various analysis techniques, detailed below.
- Separate the face fibres from the backing material using sink-float separation, as discussed in Section 2.6.3.
- Produce 3D printing filament from the separated fibres.
- 3D print tensile test specimens with the filament produced.
- Perform tensile tests on the specimens to establish material properties of recycled carpet PP.

The overall aim of the section was to provide a small -scale proof of concept of the process of taking waste carpet and processing it into a usable material, while also producing data on the change in properties of the recycled PP throughout the process and the suitability of the various techniques used for separation and processing.

3.1. Analysis Techniques

There are a variety of scientific techniques available to analyse materials. This section discusses the techniques that will be used in this report.

3.1.1. Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared Analysis is a commonly used technique in both industry and academia. It represents the 'simplest, most rapid, and often most reliable means' for identifying organic functional groups [156]. It works by irradiating the sample with infrared (IR) light and recording the wavelengths at which the molecules vibrate. These wavelengths are recorded in an FTIR spectrum.

By convention, the frequency of absorption is expressed in wavenumbers in units of cm^{-1}. The most useful wavelength band for organic chemistry is between 2.5-16μm; more commonly expressed as 4000-625cm^{-1} [156]. Well-defined vibration frequencies exist for a variety of functional groups. The relevant ones for the identification of PP (i.e. bonds containing solely carbon and hydrogen), the key material in this report, are summarised in .

Table 12: C-H bond absorption wavenumber bands [156]

Bond	**Wavenumber range (cm^{-1})**	**Description**
$=CH_2$ $-CH_3$ Unfunctionalised C-H stretching	2960-2850(s)	Stretching vibrations
$=CH_2$ $-CH_3$	1470-1430(m)	Asymmetrical deformations Bending vibration
$-C(CH_3)_3$	1395-1385(m) and 1365(s)	Bending vibrations
$-CH_3$	1390-1370(m)	Symmetrical deformations Bending vibration
$=C(CH_3)_2$	~1380(m)	A roughly symmetrical doublet Bending vibration
$-CH=CH_2$	995-985(s) and 940-900(s)	C-H out of plane deformation Bending vibration
$-CH=CH-$	970-960(s)	C-H out of plane deformation Bending vibration
$=C=CH_2$	895-885(s)	C-H out of plane deformation Bending vibration
$=C=CH-$	840-790(m)	C-H out of plane deformation Bending vibration
$-CH=CH-$	730-675(m)	C-H out of plane deformation Bending vibration
$=CH_2$	~720(w)	Rocking

FTIR analysis may present a useful tool for rapid analysis of any samples obtained in this project and verification of their polymer content. However, due to the wide range of bond vibrations that can appear in an FTIR spectrum, it is unlikely to be useful for any detailed analysis of material composition beyond this.

3.1.2. Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) is a technique where the amount of heat required to heat a sample is compared with the heat required for the same on a reference sample [157]. Typical uses for this are measuring the specific heat capacity as a function of temperature [158] or to measure the crystallinity of the polymer sample, as the degree of crystallinity has a linear relationship to enthalpy of fusion.

The general setup of a DSC apparatus consists of two crucibles, one containing a sample of the material being measured, and a second identical crucible but with no sample contained within. Both crucibles are subject to temperature changes and the differences between the thermodynamic properties of the two are monitored, which provides information on the thermal properties of the sample. The most widespread commercially available DSC method is heat-flow DSC (hf-DSC) [159], where the heat flow from both crucibles is measured to determine their thermal properties. The most common alternative is power-compensated DSC, where the temperature of the samples is kept the same by varying the power flow, and this variation provides the data on their thermal properties [160].

There are a variety of parameters that have to be considered when making DSC measurements, such as sample size, heating pattern, and purge gas. Sample size and heating pattern are closely related; the best way to obtain a strong heat flux signal is to use a heating ramp with a large gradient and a sample with a large mass, but this has issues. Both of these approaches can lead to a temperature gradient within the sample itself, which can cause erroneous measurements as the ideal is for the sample to be a uniform temperature throughout [158]. To avoid this, the general rule is that the sample mass should be inversely proportional to the gradient of the heating ramp, to ensure a uniform temperature throughout the sample.

The purge gas also has an effect on measurements and must be carefully selected. An inert purge gas is circulated past the samples, typically at rates of around 25-50mL/min. These gases serve the dual purpose of providing an inert atmosphere to prevent reactions in the sample and removing any off-gases. The most commonly used purge gases are helium and nitrogen. Helium has a thermal conductivity of $157\,mW/m°C$, 6 times greater than the $26\,mW/m°C$ of nitrogen, giving helium excellent conductive properties and nitrogen good insulating properties. The use of helium as a purge gas has been shown to give lower heat capacity values for samples due to its faster dissipation of heat [158].

One of the main uses for DSC is measuring the crystallinity of polymers. The amount of heat required to melt a given polymer is known as the enthalpy of fusion (ΔH_m) [161]. This is measured using DSC and is divided by the heat required to melt a sample that is known to have a crystallinity of 100%, which is known as the heat of fusion (ΔH_m^{100}). The ratio between the two can be calculated and gives the degree of crystallinity ().

Equation 1: Degree of crystallinity

$$X_c = \frac{\Delta H_m}{\Delta H_m^{100}}$$

DSC may be a useful tool for this project to precisely quantify the behaviour of recycled carpet PP over a large temperature range, information which will be useful as most methods of carpet recycling involve the melting of PP.

3.1.3. Tensile Testing

Tensile testing is a destructive testing process, designed to give information about the tensile strength, yield strength, and ductility of a material [162]. Tensile testing is covered by ISO standards 527-1 and 527-2, which govern the general principles and the test conditions respectively. ASTM D638 also covers tensile testing of plastics, although this report will focus on the ISO standards.

Tensile testing consists of subjecting a dumb-bell shaped specimen of the test material to extension along its major axis at a constant speed until specimen fracture, or until the stress or strain reach a predetermined value [163]. The specimen shape and dimensions are shown below in and respectively. For this report, the type 1A specimen was used as it is the specification for injection and compression moulded plastics.

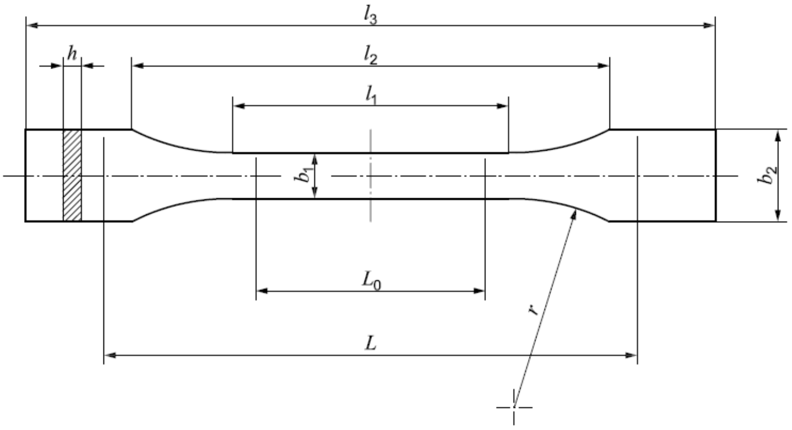


Figure 24: Tensile test specimens type 1A and 1B [163]

Table 13: Tensile test specimen dimensions [163]

	Description	Dimension (mm)
l_3	Overall length	170
l_1	Length of narrow-sided portion	80 ± 2
r	Radius	24 ± 1
l_2	Distance between broad parallel-sided portions	109.3± 3.2
b_2	Width at ends	20.0 ± 0.2
b_1	Width at narrow portion	10.0 ± 0.2
h	Preferred thickness	4.0 ± 0.2
L_0	Gauge length	75.0 ± 0.5
L	Initial distance between grips	115 ± 1

Tensile strength is a key mechanical property of materials, and discovering the value that can be produced in samples made of waste carpet PP will be an important and useful metric for assessing the viability of recycled carpet PP as a material in a variety of other end-of-life uses.

Curiously, no ISO or ASTM standards exist for additively-manufactured plastics [163] [164]. The ISO standard covers injection moulded, compression moulded, and machined plastics, but has no mention of 3D printing. The specifications for compression and injection moulded plastics will be used here, as they should mirror the characteristics of 3D printed plastics more closely than a machined plastic.

i. 3D printing orientation influence on tensile strength

From the research in the literature review section on 3D printing, we can conclude that the parameters of the print, particularly the layer thickness, are important in determining the mechanical properties of the specimen. In order to minimise the effect of the anisotropy of the FDM process on the tensile properties of the specimens, the specimens will be loaded parallel to the layer lines. The test and control (virgin) samples will be printed with identical parameters to ensure comparability of results.

3.2. Samples

To perform experimental work, samples of used carpet were required. However, two other types of samples were acquired as well: a carpet sample with known quantities of materials to calculate yields from the separation process, and a virgin PP for mechanical testing comparison.

3.2.1. Obtaining samples

i. Waste carpet

Contact was established via CRUK with the company Equestrian Surfaces; a family-run company established for over 35 years that provides artificial surfaces for private, professional, and commercial equine enthusiasts [176]. Equestrian Surfaces kindly provided the project with a large quantity of used carpets and pre-shredded carpet waste.

Equestrian Surfaces shred their carpets and mix the resulting fibre with sand and wax to produce their surfaces [176]. From conversations with staff at the company, Equestrian Surfaces remove wool and all other organics from their input stream, but do not perform any identification or selection among the synthetic carpet fibres. This means that their shredded carpet waste contains a variety of polymers, likely mainly PP and nylon as described in 2.3.1, as well as any recycled polymers included in underlay. Since this report is focused on uses for PP, the separation of this mix would have added an unnecessary extra difficulty to the progress and therefore only intact carpet samples sourced from before the shredding process were used for the experimental work.

ii. Quantified carpet

The quantified carpet was obtained from Cormar Carpets. The numbers provided for the composition of the sample are shown below in Table 14.

Table 14: Component quantities in quantified carpet sample

Component	**g/m^2**
PP tufting	1017
Primary PP backing cloth	100
Secondary PP backing cloth	66
Latex	1200
Total weight	2383

iii. Virgin PP

500g of 2.85mm Ultimaker PP filament was obtained from 3DGBIRE. This filament was selected because it has an MFI of 20 g/10 min [177], which is the closest value that could be found to the 25 g/10 min that is most common in carpet yarn.

3.2.2. Organising samples

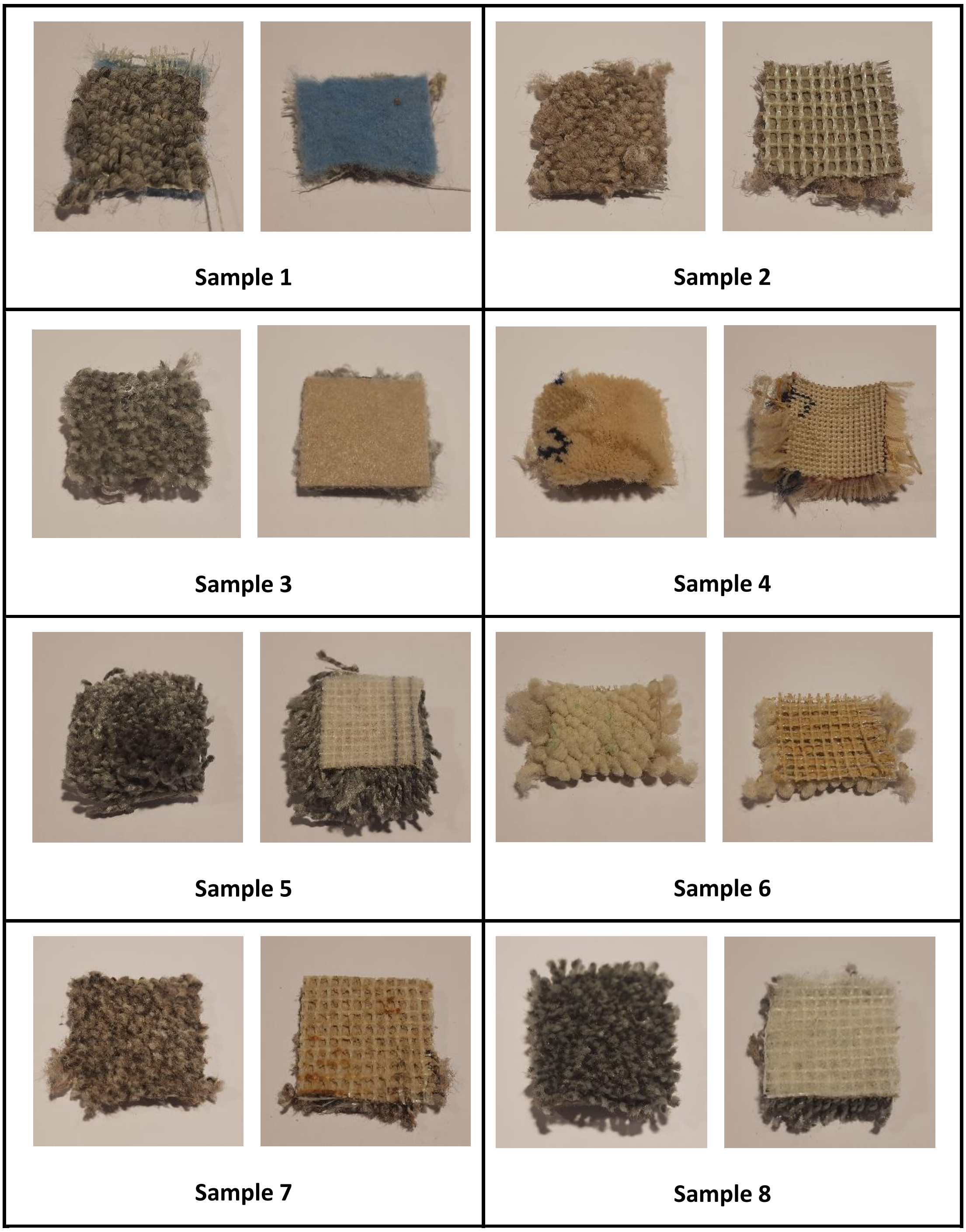
In total, 8 different samples were obtained from Equestrian Surfaces, along with a large bag of pre-shredded carpet fibres. To aid with identification and tracking, the samples were named by a scheme of the colour of their face fibres, the colour of their backing, and whether they had tuft or loop face fibres. The acronyms followed the same schemes with the initial letters of each word. The final names of the samples are listed below in Table 15.

Table 15: Sample names

No.	Name	Acronym
1	GreyBlueLoop	JL_PP_gbl
2	BrownGreyLoop	JL_PP_bgl
3	GreyBeigeTuft	JL_PP_gbt
4	BeigeBeigeTuft	JL_PP_bbt
5	GreyWhiteBlueTuft	JL_PP_gwbt
6	WhiteBeigeLoop	JL_PP_wbl
7	MottledBeigeTuft	JL_PP_mbt
8	GreyWhiteTuft	JL_PP_gwt

GreyWhiteBlueTuft was named with an extra colour as it was indistinguishable from GreyWhiteTuft apart from thin blue stripes on the backing.

A square of approximately 4x4cm was cut from each unique carpet sample and is pictured below in Figure 25 for reference. The sample numbers correlate with Table 15 above.



Sample 1

Sample 2

Sample 3

Sample 4

Sample 5

Sample 6

Sample 7

Sample 8

Figure 25: Carpet samples

3.3. Separation

To perform any experimental work on waste carpet polypropylene, the PP fibres first had to be separated from the backing material. This section details the steps taken to achieve that.

3.3.1. Shredding

Of the samples obtained from Equestrian Surfaces, four were of a suitable size to shred – the others were useful for characterisation but were too small to produce a useful quantity of shredded material after the overhead losses associated with processing. Three of these were chosen initially to shred, with the other put to the side in case more samples were required. For ease of measurement and to ensure that some of each sample was left intact for potential future use, a large rectangular section of each of the selected samples was cut, shown in Table 16.

Table 16: Sample quantities pre-shredding

Sample	**Area (m^2)**	**Mass (g)**	**Density (kg/m^2)**
WhiteBeigeLoop	0.225	418.4	1.860
MottledBeigeTuft	0.225	386.8	1.719
GreyWhiteBlueTuft	0.21175	579.4	2.740

Each sample was processed individually. They were first cut with a Stanley knife into roughly 1x1-inch squares to reduce machine clogging (Figure 26), before being fed into a benchtop 3devo SHR3D IT shredder. The machine was run until all the material was shredded. It was stopped and reversed if too much noise or vibration was produced to reduce clogging, and then run normally. Each sample took approximately 1 hour to shred by this process (the final sample, GreyWhiteBlueTuft, took an hour and a half, which correlates well with the increased mass of this sample compared to the others). After the last intact piece of carpet was taken into the machine, a 3-minute timer was started, at the end of which the machine was stopped and cleaning began. Any material removed from the shredder during cleaning was discarded, as it was in a mixed state of shredding and would have contaminated the relatively homogenous output stream (Figure 26). The final masses of the samples post-shredding and the percentage yield from the inputs into the shredder is shown in Table 17.

Figure 26: Carpet cutting and shredding

Table 17: Sample quantities post-shredding

Sample	**Mass post shredding (g)**	**Yield (%)**
WhiteBeigeLoop	365.6	87.4
MottledBeigeTuft	345.9	89.4
GreyWhiteBlueTuft	508.2	87.7

It is interesting to note from Table 17 the similarity between yields between all of the samples. The similarity, even when the mass significantly increases in the third sample would suggest that it is not an overhead loss of material when shredded but a percentage of the original, and so it may be possible to shred very small amounts of carpet while losing no more material proportionally.

3.3.2. Density Separation

As discussed in 2.6.3, sink-float density separation is a method commonly used in literature to separate plastics of differing densities. It is this method that has been used by the ISOPREP team to separate out purer PP from other contaminants from their process.

The process used to density separate PP fibres from other contaminants in the shredded carpet was as follows:

A handful of shredded carpet was put into a litre beaker of water, which was then thoroughly manually stirred until the fibres formed a homogenous mix and were wet through, with all the fibres mixing throughout the beaker. The hydrophobic nature of PP [178] meant that this stirring had to be thorough. The mix was then left for several minutes until all the visible sediment had settled out. While the water was still slightly murky at this point, none of the suspended material was large enough to make out with the naked eye. The water in the middle of the beaker became clear when left overnight, but with the volume of shreddings to process taking this long to clean out a tiny quantity of material was not feasible. It is likely that $CaCO_3$ was dissolved in this water [179], and with further time it would potentially have been possible to recover it and use titration to determine the mass lost. At this point, there was a band of fibres at the top of the beaker, and an evenly distributed layer of light-coloured sediment at the bottom (Figure 27). The fibres were then gently sieved out to avoid disturbing the sediment layer (giving the separated 'pure' PP), and put on a tray to dry (Figure 26). The remaining water and sediment was then poured through a sieve to filter out any remaining fibres or large pieces of sediment (producing the 'contaminanted PP'), which was put on a separate tray to dry (Figure 26). The beaker was then swilled out again with a small quantity of water, which was poured into a funnel lined with filter paper to remove the last traces of sediment (producing the 'pure sediment' of fine sediment particles)(Figure 27). The process was then repeated. This process was being carried out in parallel in three identical beakers at the same time, with the operations on other beakers being carried out while the first was settling to increase throughput.

Figure 27: Sediment layer in beaker and 'pure sediment' being filtered through filter paper

The end result of the density separation was several trays of 'pure' fibres, with sediment removed, a tray of contaminated fibres consisting of fibres mixed with backing material (likely $CaCO_3$ and latex), which was useless for further processing, and a tray of 'pure sediment' consisting of a silt-like fine mix of backing material. All three are shown in Figure 28. Overall, a yield of almost 52% of the initial mass of shredded carpet was obtained as 'pure' PP (Table 18). However, the process was not perfect – it was apparent that the 'clean' samples still had a noticeable amount of contaminants in them. This was likely because the loose PP fibres had formed a sort of nonwoven material that trapped flakes of contaminant in it. These flakes can be pulled loose with fingers or tweezers with barely perceptible resistance, but more resistance than buoyancy alone can overcome. Some of the flakes were loose in the water but were attached to enough PP fibres to make them buoyant, which meant they were sieved out with the fibres.

The yields and final products of the process are shown below in Table 18 and Figure 28 respectively.

Table 18: Separation yields, corresponding to Figure 28.

Initial mass before separation(grams)	167.88
'Pure' sediment yield (grams)	48.55
Contaminated PP (grams)	19.34
'Pure' PP (grams)	86.9
Total yield (%)	92.2
Total loss (%)	7.80
'Pure' PP yield (%)	51.8

Figure 28: Post separation contaminants, contaminated PP, and separated 'clean' PP

It is likely that passing the 'clean' fibres through this process repeatedly would further reduce contamination, although presumably by diminishing amounts. This extra purity was not required for this report, as it was simply a proof-of-concept. The water left after the process also could have been evaporated to determine whether $CaCO_3$ was dissolved in it.

3.4. Characterisation

3.4.1. Fourier Transform Infrared (FTIR)

The general operation of FTIR analysis is described in Section 1.

i. Analysis

The samples were analysed in an Agilent Technologies Cary 630 FTIR instrument and the spectra exported and processed using Origin Pro. Figure 29 shows one of the FTIR spectra. It can be seen that the baseline of the spectrum is not flat, as highlighted by the red line overlaid, which makes analysis difficult. The red line was plotted using Origin Pro's standard Peak Analyser tool, laying the points on the spectrum baseline and then interpolating the line in between using the Spline method. The baseline was then subtracted using the standard Origin Pro procedure. The resulting flat spectrum is shown in Figure 31.

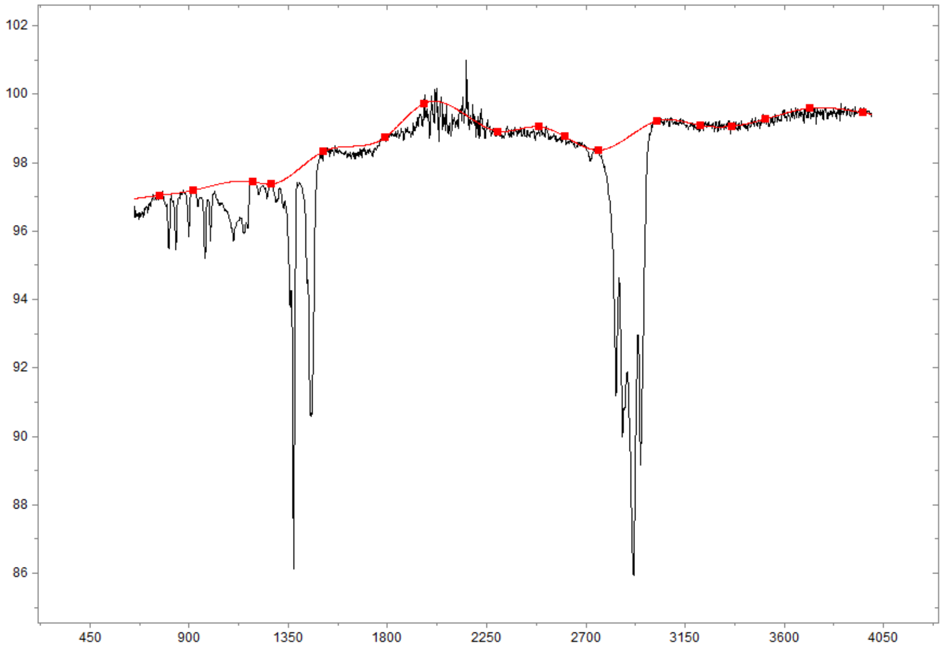


Figure 29: FTIR spectrum before baseline adjustment in Origin Pro

A report by the European Reference Laboratory for Food Contact Materials [180] contained a section identifying the key properties of an FTIR spectrum that are indicative of the presence of PP. Figure 30 shows the example spectrum of PP that was provided in this report. The key characteristics they describe of an FTIR spectrum of PP are summarised in Table 19.

Table 19: FTIR spectrum feature characteristic of PP

Wavenumber (cm^{-1}) (approx.)	Feature
2875	Shoulder
1455	Peak
1358	Shoulder
1376	Peak

These characteristic features correlate well with the expected wavenumbers of the C-H bond peaks taken from [156]. The relevant frequencies are repeated from in Table 20 below.

Table 20: C-H bond absorption frequencies correlating to expected characteristic features

Bond	Wavenumber range (cm^{-1})	Description
CH2 and CH3	2960-2850(w)	
CH2	1470-1430(m)	Asymmetrical deformations
-CH3	1390-1370(m)	Symmetrical deformations

For comparison, the FTIR spectrum of one of the samples is shown below on the same scale in Figure 31. The similarities are immediately apparent, with both spectra presenting similar overall shapes. The expected features from Table 19 are circled in Figure 31 to highlight their appearance. This clearly demonstrates that this sample contains PP.

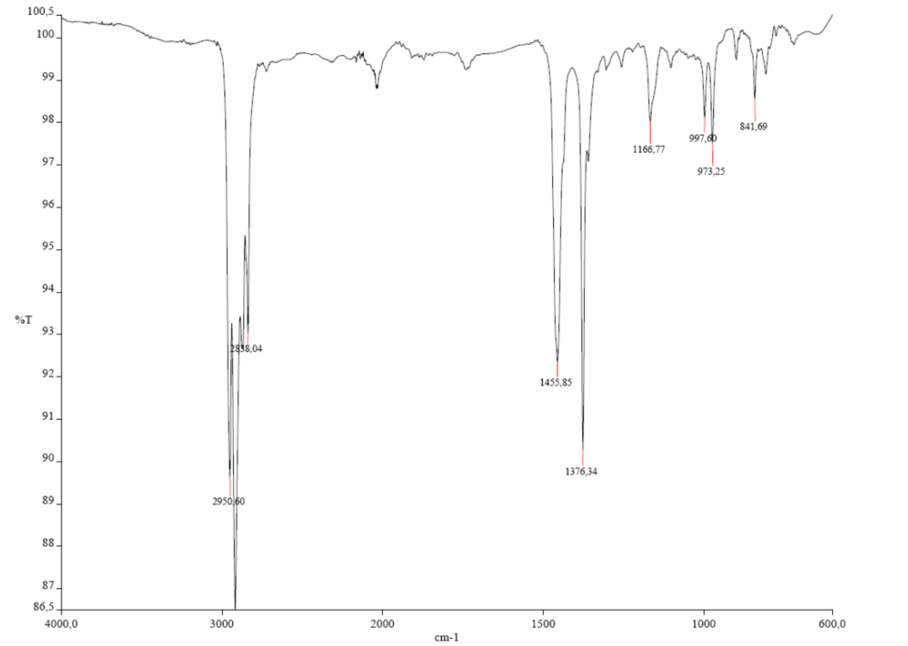


Figure 30: Example FTIR spectrum of PP [180]

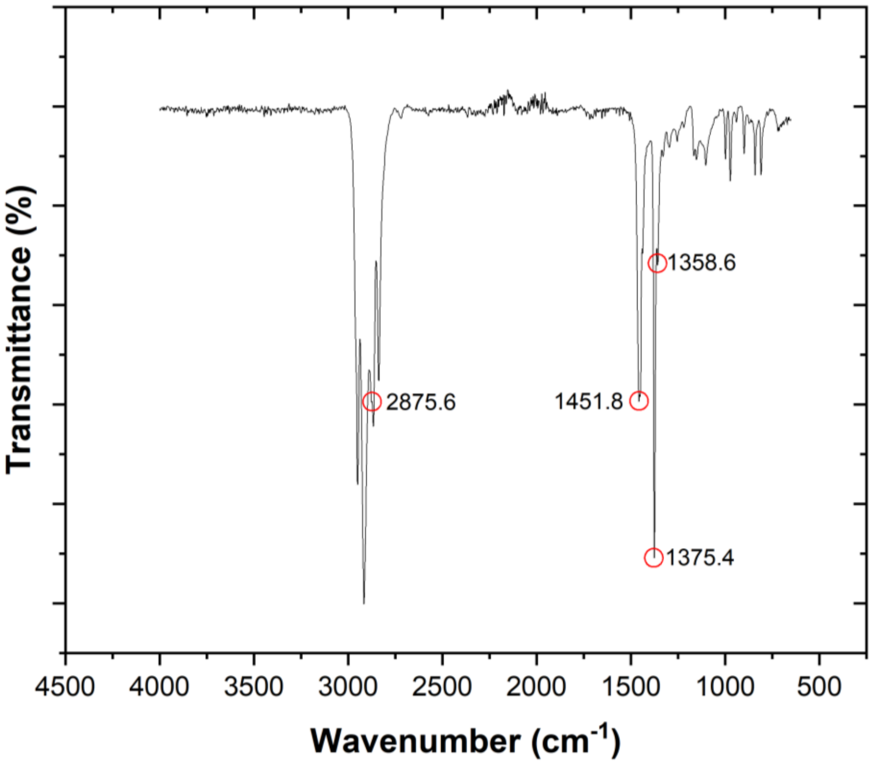


Figure 31: GreyWhiteBlueTuft FTIR spectrum

While it was now certain that the face fibres contained PP, it was not certain that this was the only material present. UK carpets are composed either of PP, PA, or wool. Wool can be eliminated as a possibility, as Equestrian Surfaces separate out all wool and other organics from their stock. Nylon is therefore the only other possibility. An example FTIR spectrum of Nylon 6, taken from the same report as the example PP spectrum, is shown below in Figure 32.

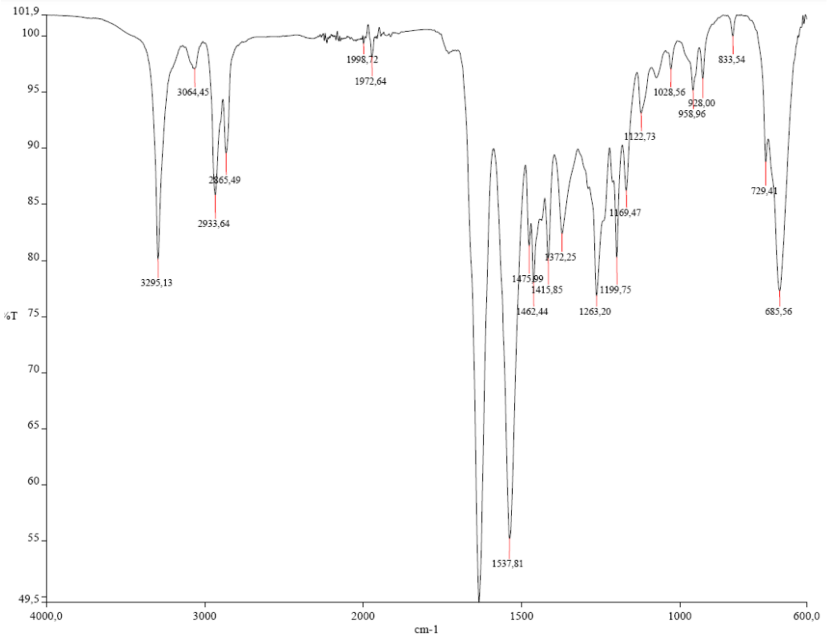


Figure 32: Example FTIR spectrum of Nylon 6 [180]

As can be seen, the nylon spectrum appears distinctly different from the PP spectrum. To verify that nylon is not present in the sample, a set of characteristic wavenumbers that distinguish a nylon spectrum are shown in Table 21, below. The expected peaks at 3295, 3072, 1640, and 1537cm^{-1} are clearly not present in the PP spectrum in Figure 31, demonstrating that the only polymer the face fibres are composed of is PP.

Table 21: FTIR spectrum features characteristic of nylon [180]

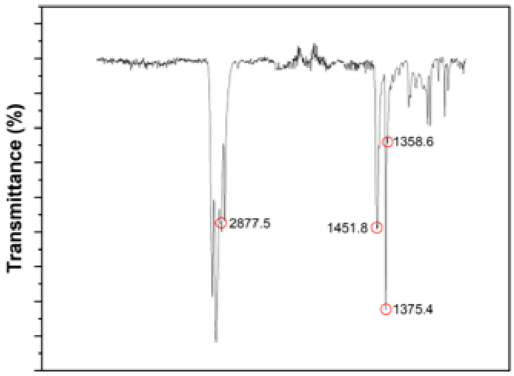
Wavenumber (cm^{-1}) (approx.)	**Bond**
3295	NH stretching
3072	Amide II
2933	CH2 asymmetric stretching
2865	CH2 symmetric stretching
1640	Amide carbonyl stretching
1537	Amide II (NH) in-plane bending +CN stretching

ii. Conclusion

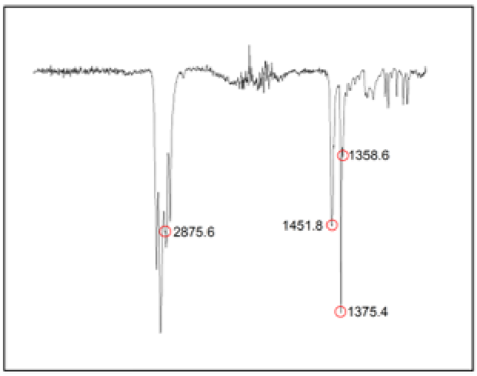
The above section has demonstrated that the sample named ‘GreyWhiteBlueTuft’ had face fibres composed of PP. Pictured in

Figure 33 are the infrared spectra of all 8 samples. As can be seen, all samples shared the same characteristic points of PP and lacked any characteristic points of nylon, so all samples analysed can be assumed to be composed of PP.

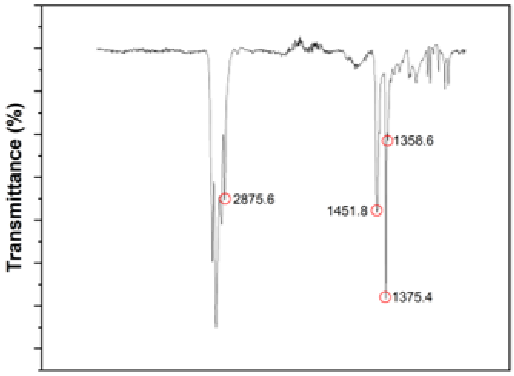
1


Transmittance (%)
1358.6
2877.5
1451.8
1375.4

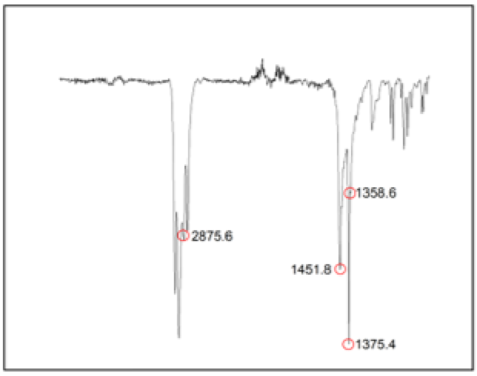
2


1358.6
2875.6
1451.8
1375.4

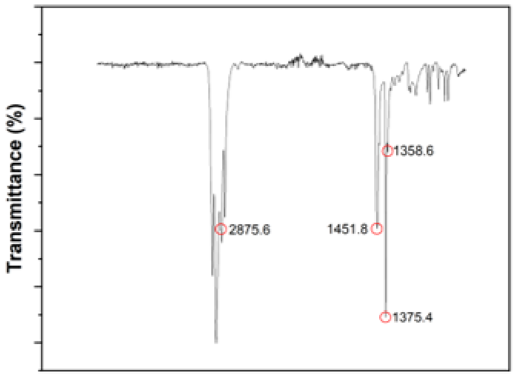
3


Transmittance (%)
1358.6
2875.6
1451.8
1375.4

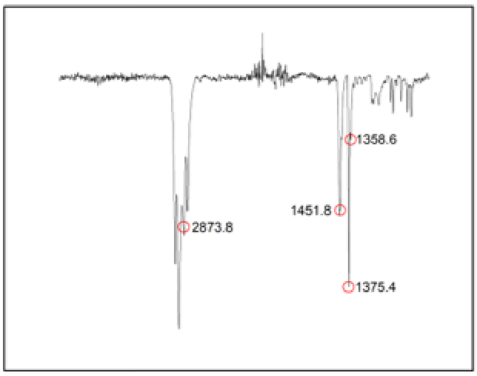
4


1358.6
2875.6
1451.8
1375.4

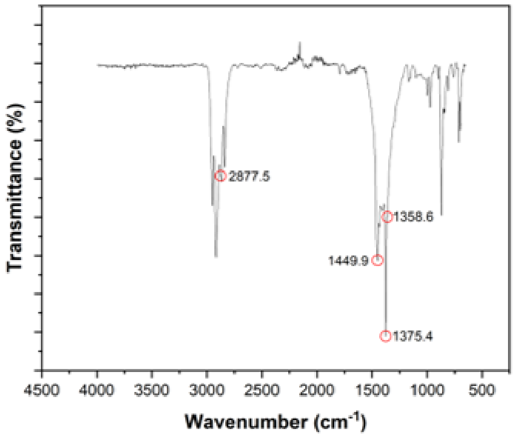
5


Transmittance (%)
1358.6
2875.6
1451.8
1375.4

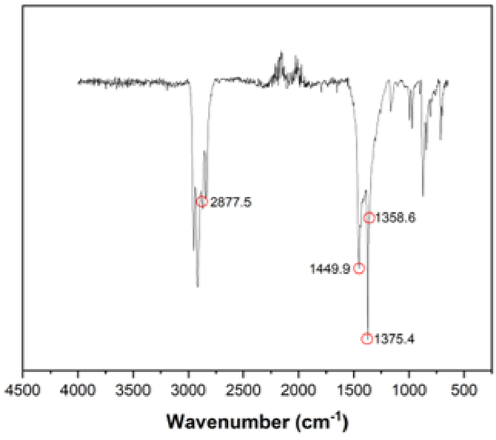
6


1358.6
1451.8
2873.8
1375.4

7


Transmittance (%)
2877.5
1358.6
1449.9
1375.4
4500
4000
3500
3000
2500
2000
1500
1000
500
Wavenumber (cm⁻¹)

8


2877.5
1358.6
1449.9
1375.4
4500
4000
3500
3000
2500
2000
1500
1000
500
Wavenumber (cm⁻¹)

No.	Name	Acronym
1	GreyBlueLoop	JL_PP_gbl
2	BrownGreyLoop	JL_PP_bgl
3	GreyBeigeTuft	JL_PP_gbt
4	BeigeBeigeTuft	JL_PP_bbt
5	GreyWhiteBlueTuft	JL_PP_gwbt
6	WhiteBeigeLoop	JL_PP_wbl
7	MottledBeigeTuft	JL_PP_mbt
8	GreyWhiteTuft	JL_PP_gwt

Figure 33: FTIR spectra of sample face fibres

3.4.2. Differential Scanning Calorimetry (DSC)

To ensure the rates used for the testing were suitable, two academic papers on DSC of PP were consulted for the parameters they used in their DSC process. The results are shown below in Table 22.

Table 22: DSC parameters in literature

Citation	Step size (°C)	Heating rate (°C/min)	Sample mass (mg)	Temperature range (°C)
[181]	2	40	5	-30 to 180
[182]		10	10-20	

A Mettler-Toledo DSC 1 Star was used for this report. Each sample was cut from the face fibres of the relevant carpet sample using a knife, being careful not to incorporate any backing material (apart from the sample specifically for backing material or the samples that were no longer fibrous due to melting). For each sample, the pan was tared on the scales, and then the sample was measured. A list of samples and their weights are shown below in Table 23. The higher sample masses suggested by literature were not reached for most samples, as the PP fibres proved difficult to fit into 40µL pans, having a tendency to spring out. This point is illustrated by the heaviest samples being the backing material ($CaCO_3$_sep) which was a powder, and the post-oven and post-filament samples, which were both solid PP.

Table 23: DSC samples, names, and masses

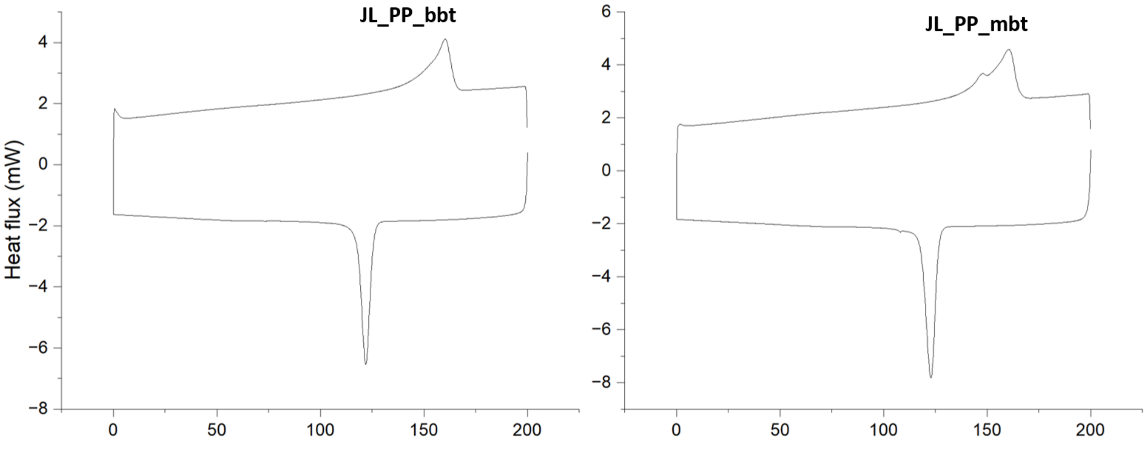
Sample	**Sample name**	**Mass (mg)**
GreyBlueLoop	JL_PP_gbl	2.20
BrownGreyLoop	JL_PP_bgl	2.29
GreyBeigeTuft	JL_PP_gbt	1.70
BeigeBeigeTuft	JL_PP_bbt	1.52
GreyWhiteBlueTuft	JL_PP_gwbt	1.21
WhiteBeigeLoop	JL_PP_wbl	1.09
MottledBeigeTuft	JL_PP_mbt	2.02
GreyWhiteTuft	JL_PP_gwt	2.38
Separated PP	JL_PP_sep	0.97
Separated CaCO3, latex, and contaminants	JL_CaCO3_sep	7.60
Post-oven separated PP	JL_PP_oven	3.15
Post-filament separated PP	JL_PP_fila	3.42

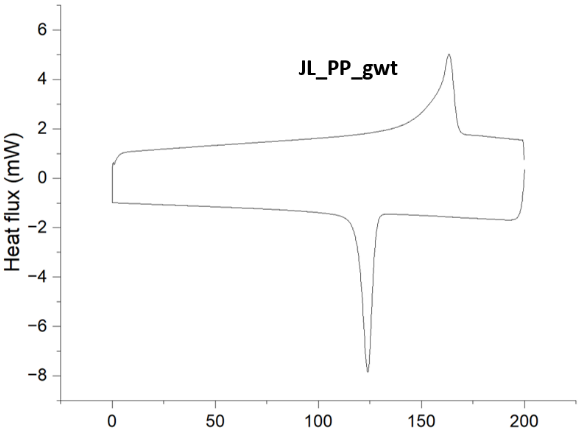
The weighed samples and pans were then placed in a press, where the lid was sealed on. The sealed pans were then transferred to the DSC carousel, and indexed onto the machine. These stages are pictured below in Figure 34.

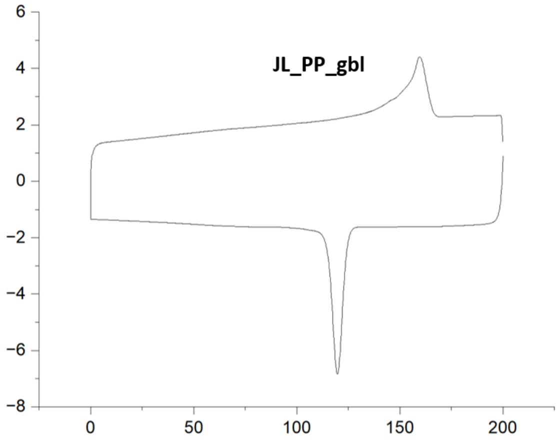
Figure 34: DSC experiment stages. Top left to bottom right: 1- Sample in pan, 2- Sample being weighed, 3- Pan lid pressed on, 4- Sealed pans on carousel

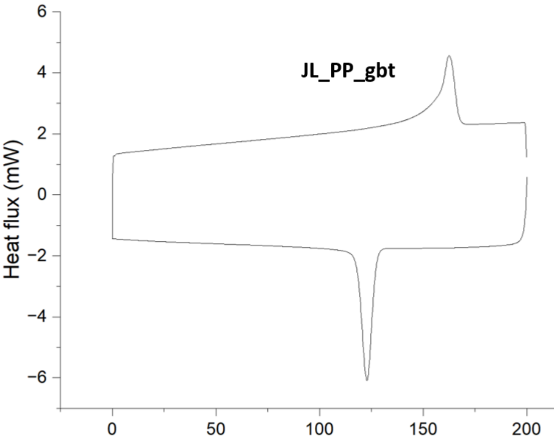
Each PP sample was set for a heating regime of 0-200 °C at 10 °C/min, and the $CaCO_3$ sample was set for 0-300°C at 10°C/min, as it has a much higher melting point and this was the maximum temperature the DSC machine was capable of.

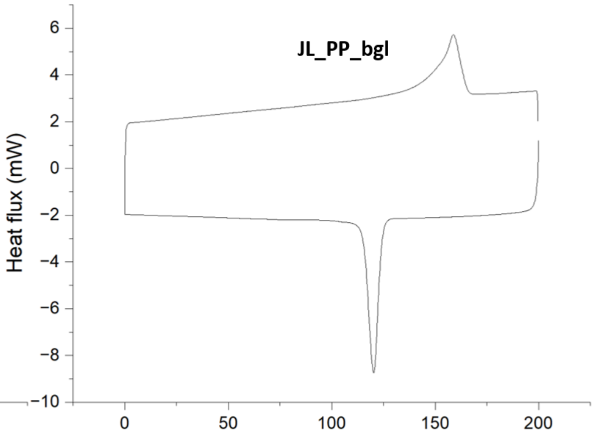
Figure 35, below, shows the DSC curves for all the PP samples. As the first DSC heating cycle is often anomalous and another anomalous result appeared in the second heating curve for PP_sep, the curve for the third heating cycle was selected for display in the graphs below. The DSC run for JL_PP_gwbt appeared to fail halfway through the first heating cycle so the results for this are not included in this section. All raw DSC output data is included in the Figures section at the end of the report for reference.

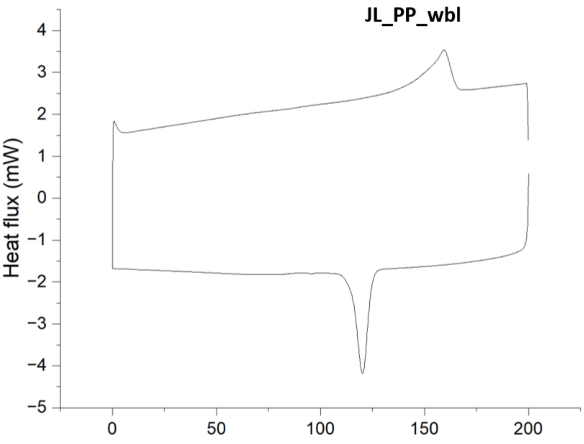


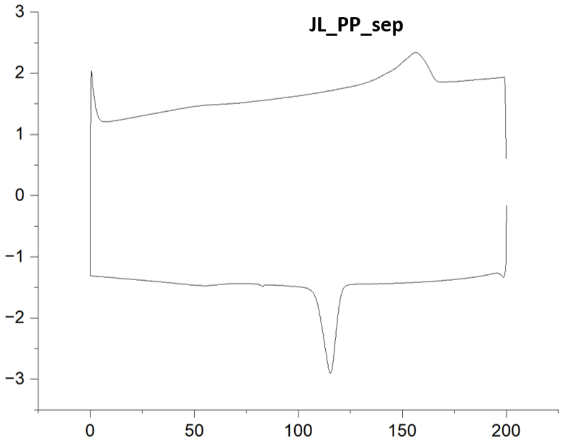

JL_PP_gwt
Heat flux (mW)
6
4
2
0
−2
−4
−6
−8
0
50
100
150
200


JL_PP_gbl
6
4
2
0
−2
−4
−6
−8
0
50
100
150
200


JL_PP_gbt
Heat flux (mW)
6
4
2
0
−2
−4
−6
0
50
100
150
200


JL_PP_bgl
Heat flux (mW)
6
4
2
0
−2
−4
−6
−8
−10
0
50
100
150
200


JL_PP_wbl
Heat flux (mW)
4
3
2
1
0
−1
−2
−3
−4
−5
0
50
100
150
200


JL_PP_sep
3
2
1
0
−1
−2
−3
0
50
100
150
200

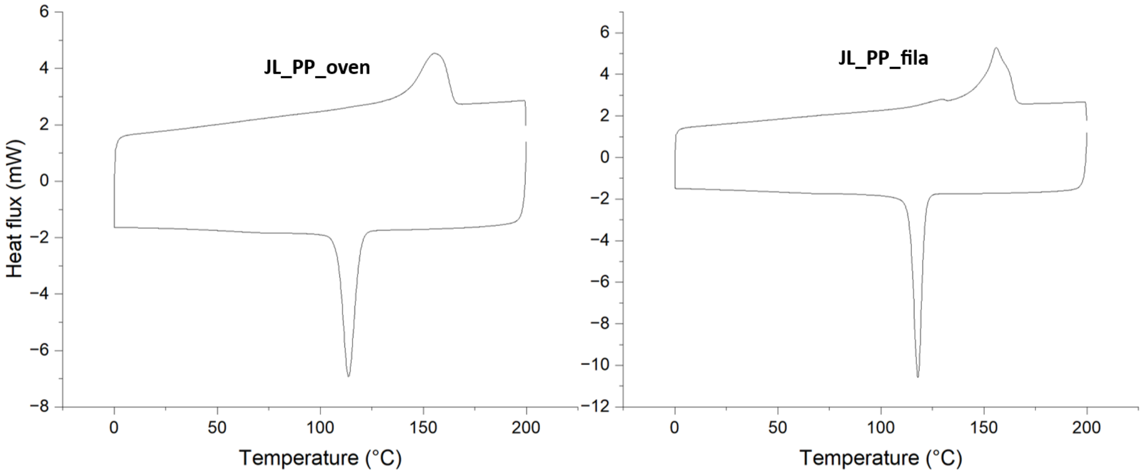


Figure 35: DSC heat flux graphs for PP samples

i. PP spectra

All of the initial carpet fibre samples apart from one produced clear, smooth single peaks, suggesting the samples were composed of a single material (Figure 35). The shape of the peaks; a gentle ramp leading up to a peak followed by a sharper drop, suggests a partially crystalline polymer (such as PP) [183], which is exactly what the samples were expected to show. The presence of two distinct peaks in the PP_mottled sample suggests the presence of two distinct materials. Since the FTIR spectra shown in Figure 35 showed a spectra typical of PP with no sign of other polymers, particularly nylon, it seems likely that this is a different type of PP, or potentially some latex on a fibre that went unnoticed during sample preparation.

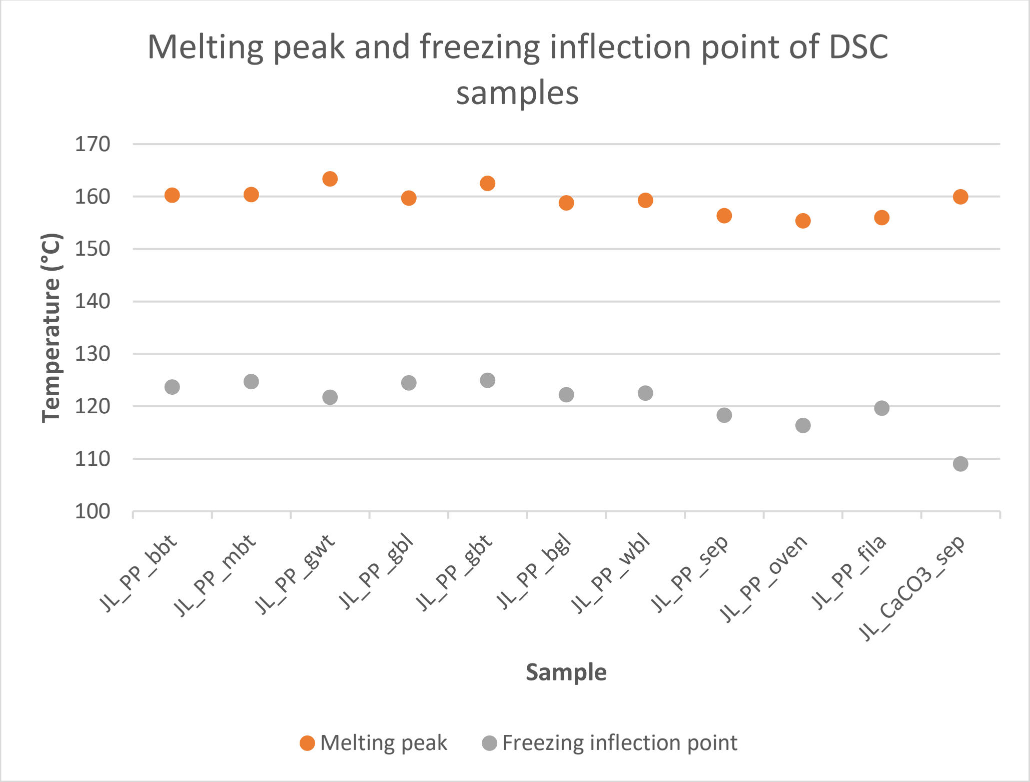


Figure 36: Melting peak and freezing inflection point of DSC samples

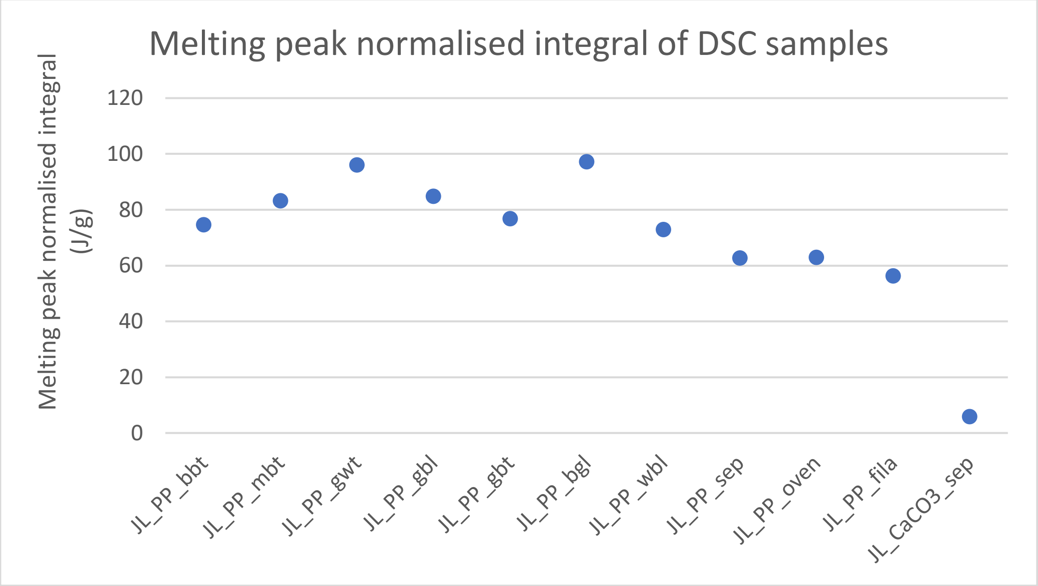


Figure 37: Melting peak normalised integral of DSC samples

Figure 36 and Figure 37, above, show the normalised melting peak integral, peak, and freezing inflection point of all the samples. In all these characteristics the samples are similar, suggesting that they are all composed of PP, which further confirms the expected results from the literature review and FTIR analysis. The results from the $CaCO_3$ sample are different, but that was expected and is further discussed below.

ii. $CaCO_3$

The spectra of the separated backing material sample, labelled as $CaCO_3$_sep, was subject to a different heating regime that took it to 300°C, as discussed above. The DSC curve is shown in Figure 38. As expected with a melting point in excess of 800°C, the bulk of the material did not appear to melt – however a small peak did appear at 160°C, with a normalised integral of 5.32 J/g. This is a much smaller integral than all the other samples, as is obvious in Figure 36, and is indicative of a small quantity of PP or latex contained in the sample. This is unsurprising, given the sample was expected to contain a substantial amount of latex, and PP fibres are likely to be trapped inside some of the larger particles of material.

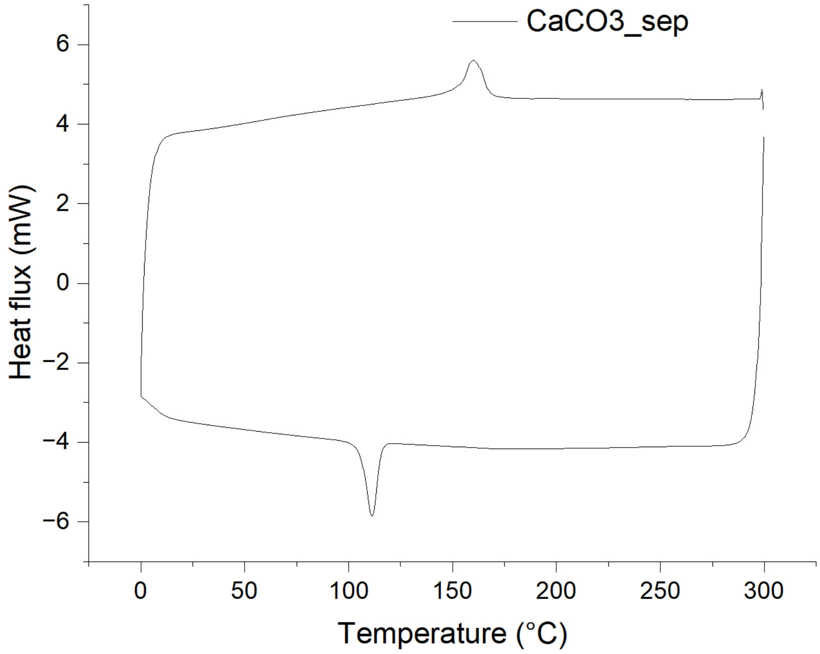


Figure 38: $CaCO_3$_sep DSC curve

iii. PP samples from the different stages of separation and filament production

This section discusses the results of the four samples taken at different stages of the separation and filament production. These are PP_white_loop, which was a tuft of fibres taken from a raw carpet, PP_sep, which was this same carpet fibres shredded and separated from the backing, PP_oven, which was the same material post-melting in the oven, and PP_filament, which was the material post-filament production. As shown in Figure 36 and Figure 37, these sample spectra were all broadly similar in melting integral, peak, and freezing peak, as would be expected.

The PP_filament sample has a much less clearly defined peak than the other PP graphs, with a distinct second section to the peak. This, as well as another minor peak at around 130°C before the main melting peak, imply contamination within the sample, or thermal decomposition of the PP within it. The normalised integral of the peak is substantially lower, implying that the contamination or the degradation products formed are a substance with a lower C_p value than the PP. These hypotheses are consistent with the method of production of the filament – while the PP feedstock was fed into the machine after other material has been fed through there is always some overlap, and clearly some contaminating material was able to mix with the PP, despite the thorough cleaning and selection of the DSC sample from late in the filament production run; this could have been confirmed by further IR or nuclear magnetic resonance (NMR) spectroscopy. The temperature of the filament production was also substantially higher than the melting point of the PP, which could easily lead to thermal degradation.

The crystallisation peaks on the cooling curves of the Filament sample had a higher magnitude than the others, which implies that the contaminants or degradation products were also a crystalline material, potentially a polymer considering the context of the likely materials passing through the filament maker.

Another interesting point is that the WhiteBeigeLoop sample has a higher normalised integral, and therefore energy required to melt it, than the Separated and Oven samples. The WhiteBeigeLoop sample had a normalised integral of around 71-73 J/g, compared to the approximately 63 J/g of the other two samples. Since a sample of WhiteBeigeLoop devoid of visible contaminants like latex and $CaCO_3$ was selected, it seems likely that the difference between this and the other samples is the contamination in the form of dirt and grime introduced into the carpet over the years of its life. This suggests that if carpet PP is being reused for any purpose, a thorough washing of the fibres once shredded could lead to significant energy savings for fibres being thermally reprocessed.

The conclusion reached from this DSC analysis is that it may be helpful in future to further reduce contamination in the samples, and also that the PP used for this application had a lower melting point than expected from the literature data on 3D printing. In future, as was not possible on this project due to logistical constraints from the fire in the department, DSC analysis should be conducted on the samples before 3D printing to ascertain the melting point of the particular PP being dealt with. This excessive temperature was likely a cause of much of the thermal degradation seen in the final filament.

iv. Conclusion

The conclusion of the DSC characterisation carried out on the samples was as follows. The information obtained supported the conclusions reached by FTIR analysis that the samples are composed of PP. There is likely a small quantity of PP contamination present in the separated backing material, which is not surprising but may have implications for the recycling of this material if the quantity is too large. The sequential chain of PP samples that were separated, melted in the oven, and then made into filament did not seem to show appreciable changes in thermal properties until after the filament production stage, which implies that the high temperatures reached during filament production contributed to its mechanical degradation, but also indicates that there was no chemical degradation of the material. The post-filament sample curves also indicated contamination and/or thermal degradation in the filament, which is likely another reason the filament was so weak.

3.5. 3D Printing

3.5.1. Introduction

3D printing has already been discussed in the literature review section of this report, and appeared to present a useful and novel approach to recycling end-of-life carpet fibres. Since it is a novel approach, and since 3D printing is ideal for small-scale low production volume prototypes, it represents an ideal way to experiment with waste carpet fibres while also investigating the viability of 3D printing itself. Section 1 discusses tensile testing, and the production of tensile specimens will be the main use of 3D printing in this project.

Several main conclusions were drawn from the literature review on 3D printing conducted earlier in the report. The importance of preheating the bed and atmosphere of the printer were clear, and this will be taken into account when the experiments are conducted. A variety of temperatures were obtained, both for filament production and printing, shown in Table 7 and Table 8 respectively. These will be useful in reducing the time taken to optimise temperatures with experiments, with an average of these values hopefully providing an appropriate temperature immediately from the beginning of the experiments. Tension loading of the filament as it is being extruded may also prove to be a useful asset in increasing filament quality.

There are issues that are expected when conducting the 3D printing experiments however. The main expected issue is that the flakes of CaCO3 that could not be separated from the carpet fibre mix will clog the printer nozzle and halt the process, requiring time-consuming cleaning of the printer. Calcium carbonate has a melting point of over 800°C, so whilst the approximately 200°C temperature of the printer (from the values obtained in the literature review) will melt latex (approx. 175°C), the calcium carbonate will remain solid and potentially in large enough lumps to cause blockages. One potential solution to this may be to produce filament, which uses a much larger diameter nozzle than printing, and then shred that filament again to hopefully break up the CaCO3 lumps, before producing a second load of filament and printing with that.

3.5.2. Experimental process

In 3D printers, a filament is typically used to feed the 3D printer with material. For this report the filament was produced by the 3devo Precision Series 350 desktop filament maker.

The filament maker is fed with feedstock from a hopper mounted on its top surface. The filament maker must be full of material at all times or it may be damaged, so when a run of filament has finished, cleaning feedstock is fed through it. The cleaning material is abrasive in nature and foams up as it passes through the filament maker, cleaning the internals out and producing a characteristic large diameter foamed thread of waste cleaning filament. Once the output appears clear of contaminants, new feedstock can be fed in simply by layering it on top of the cleaning feedstock in the hopper. The natural mixing action of the machine leads to a region of mixed cleaning and non-cleaning filament being produced before ‘pure’ desired filament is produced, and this mixed section must be discarded.

The first test was to see if the separated fibres would be taken up by the hopper. Unfortunately the fibres were simply too light to properly be taken up by the machine. To solve this, it was decided to melt the fibres into solid lumps of polymer, which could then be shredded and taken up by the machine in the manner normal for filament feedstock. Figure 39, below, shows the process followed to produce the filament.

1: Tray of fibres sat in oven prior to melting

2: Tray of melted fibres, cooled into flakes

3: Example of flake taken from tray

4: Shredding flakes to reduce size

5: Tray of shredded flakes

6: Shredded flakes in hopper of filament maker

7: Example of what filament should look like once extruded from the filament maker

8: Necking and filament separation occurring in 'pure' filament

9: Some of the 'pure' filament produced during the process.

Figure 39: Filament production process

The fibres were laid on a tray in a Gallenkamp 300 Plus Series electric oven, (Figure 39.1) and the temperature was slowly increased. It was set to 100°C initially, and left there for 5 minutes, then set to 150°C and left there for 5 minutes, then finally to 200°C and left there for 30 minutes to fully melt. It was left to cool overnight and taken out of the oven the following morning, and had produced a series of polymer flakes on the tray, shown in Figure 39.2. The melting was performed in two batches to ensure no polymer was spilled from the tray, and once both were complete, the flakes were shredded (Figure 39.4), in the same machine and using the same procedures as were used in 3.3.1. The shredded flakes were then fed into the filament maker (Figure 39.6).

The filament maker has 4 independently controllable heating zones. As shown in Table 7 earlier in the report in the literature section on 3D printing, a variety of potential values for the temperature of these zones was obtained from literature. From these values an appropriate set of temperatures were selected for the filament production and are shown below in Table 24, in the ‘Initial’ column. As the cleaning material had been pushed through and the PP began to be extruded, it was clear that the material had very little strength, and so in an attempt to remedy this the temperature was reduced by 10 degrees in each zone, then by another 10 degrees when this had no noticeable effect after several minutes. The screw RPM was increased when the PP filament was being extruded extremely slowly to increase the speed of the experiment.

Table 24: Filament maker zone heating temperatures

	Initial	**Change 1**	**Change 2**
Temp. 4 (°C)	200	190	180
Temp. 3 (°C)	210	200	190
Temp. 2 (°C)	220	210	200
Temp. 1 (°C)	210	200	190
Screw RPM	5	10	10

Once ‘pure’ filament was being produced Figure 39.8, Figure 39.9), it was clear that the process had not been successful. Instead of producing a long, straight filament of continuous diameter that can hold its own weight hanging from the filament nozzle (Figure 39..7), the filament produced would begin necking (similar in appearance to that seen in tensile testing) and separate under its own weight after a few inches. Cardboard had to be laid down to protect the more sensitive components of the machine from the falling blobs of semi-molten polymer.

3.5.3. Conclusion

It seems likely that there are two causes for the failure of the filament production in these experiments. The first is that, in light of the DSC analysis conducted, the filament was produced at too high a temperature, which severely degraded the PP as it passed through. The papers cited in Table 7 [124] [126] [127] [128] show temperatures recommended by literature for 3D printing as 190-250°C, which may be suitable for virgin PP but is clearly not suitable for recycled carpet PP, which according to the DSC analysis performs melts at around 160°C. The other reason is that contamination appears to have been introduced to the sample through the filament maker, as shown by the split peaks on the DSC. This is not completely surprising, but it was hoped that the effect would be limited to the ends of the filament strand produced, and it was disappointing that it was visible on the DSC graph. In future, further steps would have to be taken to clean the machine even more thoroughly, and a significantly lower temperature should be used. Other variables that could have been changed include adjusting the feed screw rate to ensure the PP spends less time exposed to high temperatures, reducing the degradation, or reducing filament diameter. The ideal way to proceed would be to produce a much larger quantity of separated PP from carpet and conduct a series of experiments varying the temperature and feed rate to determine the optimum speed. However, all carpet PP will likely behave differently, so it may be difficult to find an optimum set of parameters that work ideally for all waste carpet PP.

4. Calculation of CO_2e released from different end-of-life routes

4.1. Introduction

One of the outcomes that CRUK desired from this project was more data on the different methods of disposal discussed in the report. For this section, the CO_2e outputs from various different carpet and textile flooring disposal methods were calculated and graphed. The following sections show the methodologies and calculations used to arrive at these figures.

Throughout the section the unit t_{pp}, t_n, and t_c will be used. This is defined as tonnes of polypropylene carpet, nylon carpet, and general mixed carpet respectively. The use of this unit will make calculations in this section more succinct.

4.2. CO_2e cost units

An important consideration in the decision of how to recycle materials is the average greenhouse gas contribution of the recycling method. Different gases have different global warming potential (GWP), and so a common measure has been established in the unit of carbon dioxide equivalent (CO_2e). For example, nitrous oxide has a GWP of 298, meaning that it contributes to global warming 298 times as much as an equivalent tonnage of CO_2. The calculation for CO_2e is shown below in Equation 2.

Equation 2: Tonnes of carbon dioxide equivalent calculation

$$tCO_2e = tonnes\ of\ greenhouse\ gas\ \times GWP\ of\ the\ gas$$

Most of the sources used in the following section use the unit of CO_2e, and in the absence of LCA software it is difficult to obtain data on other emissions, so for the sources where the units are simply CO_2 it is assumed that this can be approximated to CO_2e.

4.3. UK conversion factor

A figure that will appear repeatedly throughout this section is the UK government conversion factor for electricity. Conversion factors are the values of CO_2e that the government officially assigns to things, from a litre of petrol to a ton of bricks. They are produced annually by DEFRA and the

Department for Energy Security and Net Zero (DESNZ) [184]. The value for the UK energy mix is commonly used here, which is the CO_2e value assigned to the average mix of UK energy production, taking into account the CO_2e outputs of coal fired power stations, wind turbines, nuclear power stations etc., and the differing proportions of grid energy that these supply. The value is given in the 2022 conversion factors (the latest when this report began) as 0.19338 $kgCO_2e/kwh$ [185], which has been converted to 0.69617 tCO_2e/GJ for unit commonality with the rest of the calculations in this report.

4.4. Carbon capture

One potential method of reducing CO_2e emissions that has seen considerable interest is carbon capture. Currently there is no widespread carbon capture program in place in the UK, but it is suggested that the installation of carbon capture technology is 'competitive with other industrial abatement options', assuming the use of an amine solvent scrubbing system [186]. However, the economic viability is highly dependent on application. In a report on reducing CO_2e emissions from cement kilns [139], it was stated that adding carbon capture technology to cement kiln plants would approximately double the cost of a new plant. Regardless of the future potential of the technology, it is not currently implemented on scale in the UK and so will not be factored into the calculations in this section.

4.5. Calculation of CO_2e

To facilitate decision-making in the sector, approximate figures for the CO_2e impact of the most promising recycling methods discussed in this report have been produced. For each disposal method the CO_2ecost of processing, incineration, and transport were added, and the CO_2e cost of the fuel or material displaced by the waste carpet material was subtracted to give the overall projected CO_2e offset of the disposal route per tonne.

The following section will discuss how the figures in each row were calculated. There are three figures that contribute CO_2e to each category: shredding, transport, and combustion, and one that reduces the CO_2e: substitution benefit. Shredding, transport and combustion are calculated in the same way for all categories, and will be discussed first. Substitution benefit is calculated differently for all categories and is discussed afterwards. The calculation of the total CO_2e cost of the recycling method is shown below in Equation 3.

Equation 3: Calculation of CO_2e/t_{pp} cost of disposal method

$$tCO2e/t_{pp} = shredding + transport + combustion - substitution\ benefit$$

4.5.1. Shredding

The shredding costs were calculated using a report from Carpet America Recovery Effort (CARE) stating that "trials indicate that 0.1-0.2 MJ/kg is a reasonable estimate for electrical energy consumption of reducing carpet to squares of 0.25-0.5 inches (6.35-12.7mm) in size" [71]. This was averaged to a value of 0.15 MJ/kg (0.15GJ/t_c), and then multiplied by the UK energy conversion factor of 0.0537 tCO_2e/GJ to give 0.00806 tCO_2e/t_{pp} shredded.

4.5.2. Incineration

To calculate the CO_2e released from carpet in incineration, two figures are required. One is the CO_2e released per tonne of carpet burnt, and the other is the net calorific value (NCV) of carpet; the practical energy contained in a substance which can be released via combustion, which will allow us to calculate the tonnage of carpet that needs to be burnt to replace alternative fuels. The NCV calculations will be performed first, followed by the CO_2e calculations.

i. NCV

To calculate figures for the NCV of carpet, the literature was searched for appropriate sources. While one paper gave values for the combustion of carpet face fibres and the backing material separately, which was a useful demarcation, like much of the literature this carpet contained Nylon 6,6 face fibres since it was written in America [145].

CARE gave a table of NCV values for PP and Nylon 6,6 fibres, giving respective values of 43.6 GJ/t_{pp} and 32.0 GJ/t_n [71]. A way was needed to test the validity of these numbers however, since they were so central to the calculations. Since carbon is the predominant source of energy in the combustion of organic polymers, the ratio of carbon between PP and Nylon was calculated. The paper discussing Nylon 6,6 carpet [145] gave 59.1% as the carbon percentage of Nylon 6,6, and another paper gave the value for PP as 80% [187], correlating with a number of papers that describe PP as the more energetic combustion fuel [188]. The ratio of carbon in nylon 6,6 to PP can be calculated in the following equation:

Equation 4: Ratio of carbon percentage in PP to carbon percentage in Nylon 6,6

$$\frac{0.8}{0.591} = 1.3536$$

The ratio of the combustion value of PP and Nylon 6,6 provided by CARE are shown below:

Equation 5: Ratio of NCV of PP to Nylon 6,6

$$\frac{43.6}{32.0} = 1.3625$$

As can be seen, the two ratios are remarkably similar, which gives validity to both sets of values. The Nylon 6,6 report helpfully provides information on the different combustion values of carpet face fibres (face fibres and a fraction of the backing cloth) compared to carpet fines (shredded backing material, including $CaCO_3$, latex, and a fraction of backing cloth). In order to provide an NCV of PP carpet of both fibres and fines, the decision was made to scale the nylon carpet NCV values according to the ratios calculated in Equation 4 and Equation 5. Initially, though, values were needed for the mass of the different components of carpet compared to each other. For this, the reference carpet sample in Table 1 from the literature review has been used, shown below in Table 25.

Table 25: Reference carpet sample composition

	Total	Face fibres	Backing cloth	Latex	CaCO3
Carpet 1 (kg/m^2)	2.383	1.017	0.166	0.48	0.72
Carpet 1 (mass fraction)	1.000	0.427	0.070	0.201	0.302
Carpet 2 (kg/m^2)	2.39	1.424	0.166	0.32	0.48
Carpet 2 (mass fraction)	1.000	0.596	0.069	0.134	0.201
Average (kg/m^2)	2.387	1.221	0.166	0.400	0.600
Average (mass fraction)	1.000	0.511	0.070	0.168	0.251

Table 25 gives the total weight of the reference carpets. For the next stage, the values for latex and $CaCO_3$ can be summed to give a total non-fibrous backing mass of 0.419 tonnes. Table 26 shows the next calculations; first the mass of each component is shown, then multiplied by the relevant NCV for Nylon 6,6 (29.309 GJ/t for face fibres, 12.973 GJ/t for fines) [145]. Both the face fibres and the carpet fines are assumed to have some of the backing cloth contained within them, and the ratio is not specified in the paper. The decision was therefore made to have the backing cloth scaled with the face fibre NCV rather than the backing NCV as it is a pure polymer – this is likely to slightly overestimate the total NCV of a given mass of carpet, but as can be seen in the final two rows of Table 26, backing cloth only contributes a small fraction of the total NCV of the carpet, so the overestimation is likely to be small.

The face fibres and backing cloth Nylon NCVs are then multiplied by the 1.36 ratio of PP to Nylon 6,6 NCV calculated earlier; the backing material is not scaled with this ratio as it is composed of $CaCO_3$ and latex, the compositions of which are presumably identical in a Nylon or PP carpet. The results are then summed to give the total NCV of PP carpet as 28.591 GJ/t_{pp}. This value tallies well with various values found in literature, including CARE, who suggest 11,100 btu/lb (25.8 GJ/t_{pp}) as the NCV of PP carpet [71].

Table 26: NCV of carpet calculations

	Face fibres	**Backing cloth**	**Backing**
Mass (t_n)	0.511	0.070	0.419
NCV (GJ/t_n of carpet)	14.986	2.039	5.438
Scaling to PP	20.380	2.773	5.438
Total NCV (GJ/t_{pp})	28.591		

ii. tCO_2e/tonne

This section calculates the CO_2e emitted by the combustion of the components of a carpet, which are then summed together to give a total CO_2e output. Table 27 shows the CO_2e emitted by each component; the calculations used to arrive at these figures will be walked through in this section. The face fibres, PP backing, and latex will be calculated first in the same manner, and the calcium carbonate will be calculated later as its reaction is calculated differently.

Table 27: CO_2e emitted from combustion of carpet components

	PP face fibres	**PP backing**	**Latex**	**CaCO3**	**Total**
Carbon fraction	0.800	0.800	0.836		
tCO_2e/t of pure material	2.933	2.933	3.065	0.440	
Mass fraction in carpet	0.511	0.070	0.168	0.251	1.000

tCO_2e/t of carpet	1.499	0.205	0.515	0.110	2.330

For the PP face fibres, PP backing, and latex, the first step was to obtain their respective carbon contents. These were found for PP and latex as 80% and 83.6% respectively [187] [189]. Since carbon has a molar mass of 12, and oxygen 16, then a molecule of CO_2 weighs 44g/mol, which is 3.6667 times more than the mass of a single atom of carbon. Therefore, the next stage in the calculation was to multiply each of the carbon fractions by 3.6667, giving the values on the second row of the table of the tCO_2e that would be emitted by burning a pure tonne of each material. The next row shows the mass fractions of each component in our reference sample of carpet taken from Table 25. Finally, these mass fractions were multiplied by the tCO_2e/tonne of the pure material to give the CO_2e that would be emitted from each component when a tonne of carpet is burnt.

The CO_2e emissions of calcium carbonate are calculated differently, as $CaCO_3$ contains the oxygen atoms used to produce the carbon dioxide upon its thermal decomposition. Calcium carbonate decomposes rapidly into calcium oxide (CaO) and CO_2 beyond 750°C [190], and the target temperature of at least some EFW kilns is 850°C [191]. For this calculation, we will assume the worst-case scenario and assume that calcium carbonate fully decomposes in carpet combustion.

The chemical formula of calcium carbonate is $CaCO_3$. This means each mole of calcium carbonate is composed of a calcium atom, a carbon atom, and an oxygen atom. This information and the molar masses of each atom are shown below in Table 28.

Table 28: Atomic composition of $CaCO_3$

	Ca	**C**	**O**	**$CaCO_3$**
Moles	1	1	3	1
Molar mass	40	12	16	100

Equation 6: Decomposition of calcium carbonate [190]

$$CaCO_3 \rightarrow CaO + CO_2$$

As can be seen from Table 28 and Equation 6, the carbon and oxygen atoms that make up the carbon dioxide released from $CaCO_3$ have a total molar mass of 44, which represents 44% of the total molar mass of calcium carbonate. Therefore, when decomposing in an EFW plant, calcium carbonate will release 44% of its total mass as carbon dioxide to the atmosphere.

This value was used to calculate the tonnage of CO_2e that would be released if a tonne of pure $CaCO_3$ was thermally decomposed, and from there the calcium carbonate figure was treated identically to the other components. The CO_2 figures were summed up to give a total CO_2e release of 2.330 tCO_2/tonne of carpet burnt.

4.5.3. Transport

The transportation costs were calculated using the same report from CARE. Their report used the GREET model of transportation and assumed the following steps in the logistics chain [71]:

- Local transportation of approximately 25 miles of all recovered carpet in loose form.
- Truck or rail transportation.
- Final production transportation of approximately 50% of the material that is brought to the processor.

The report settled on a value of 906.29 MJ required per ton of carpet waste transported. To convert this to a value in terms of tonnes of CO_2e, the CO_2e outputs per unit of energy were looked up in the government conversion factors. Government conversion factors gave the CO_2e cost of fuel as 0.25 $kgCO_2e/kWh$, which was converted to 0.69444 tCO_2e/GJ [184]. This was multiplied together with the above value for carpet transport to give 0.0629 tCO_2e/t_{pp} of carpet waste transported.

4.5.4. Substitution benefit

This section will show the various different calculations performed to arrive at the different substitution benefits assigned to each waste stream. A substitution benefit is, for example, the offset of CO_2e provided by Energy from Waste generating electricity that would instead be generated by a coal-fired power station. These substitution benefits will be used to calculate a projected CO_2e offset for each disposal method.

i. EFW

Discussions with industry members have revealed that UK EFW power generation is set at a fixed level, and typically continues to operate at this level without fluctuations under normal operation.

For these calculations, it is assumed that the power generated by EFW is used to reduce the amount of power required to be generated by the dirtiest UK power source of coal, since it is unlikely that it is instead used to offset a renewable source such as wind.

A key factor when discussing power generation by combustion is the efficiency of power generation. Tolvik have calculated that for each tonne of residual waste burnt in an EFW plant 2.214 GJ of energy is produced [52] . When compared to their stated assumed NCV of residual waste in the UK of 9.78 GJ/t, this gives an efficiency of 22.64%.

The NCV of coal is 27.25 GJ/t and produces 2.41 tCO_2e/t burnt [184]. According to the Digest of UK Energy Statistics (DUKES) spreadsheet for 2022, coal power plants have on average an efficiency of 32% [192]. This means that for every tonne of coal burnt, 2.41 tonnes of CO_2e are produced for 8.688 GJ of power, giving a CO_2e output of 0.2774 tCO_2e/GJ from a coal power plant.

For every GJ of NCV burnt in an EFW plant, 0.2264 GJ are produced. Multiplying this figure by 0.2774 gives 0.0628 GJ/t of CO_2e offset from coal fired power stations per GJ of EFW burnt.

To calculate how much CO_2e each tonne of carpet waste sent to EFW offsets, the NCV of carpet waste (28.591 GJ/t_{pp}) was multiplied by 0.0628 to give a total CO_2e offset of 1.80 $tCO2e/t_{pp}$ of carpet waste.

ii. Kiln fuel

As discussed above, the calorific value and CO_2e output of coal are 27.15 GJ/t and 2.41tCO_2e/t [142] [184]. Unlike for the EFW calculations above, there is no need to calculate the efficiency of combustion since both coal and carpet are fired in the same manner in a cement kiln. To calculate the CO_2e offset from no longer burning a given amount of coal, the 28.591 GJ/t_{pp} of carpet combustion is multiplied by the 0.0888 tCO_2e/GJ of coal combustion to give 2.539 tCO_2e/t_{pp} of CO2e not produced by burning coal.

iii. Concrete reinforcement

The substitution benefit using carpet fibres in concrete reinforcement provides is the displacement of a small volume of concrete to make room for fibres. The most common fibre volume fraction used in the literature was 0.75% [87] [88] [89], so this was used as the standard. PP has a density of 0.910 tonne/m^3 and ordinary Portland cement has a density of 3.150 tonne/m^3 [87].

As shown in Equation 7, the density ratio between concrete and PP is 3.46. This means that for every tonne of PP used in concrete reinforcement, 3.46 tonnes of concrete are displaced.

Equation 7: Density ratio of concrete to PP

$$\frac{3.150}{0.910} = 3.46$$

3.46 can be multiplied by the 0.13175 tCO$_2$e/t of concrete from the UK conversion factors to give a CO$_2$e offset of 0.456 tCO$_2$e/t of fibres that are used to reinforce concrete.

iv. Equestrian

While equestrian surfacing does displace other material that would otherwise have to be used to create it, it is a relatively short-term disposal option with the surfacing only lasting for a few years [193] before it has to be disposed of and re-enters the waste stream. It is still a useful recycling method, and currently the only recycling method for waste carpet operated at scale in the UK, but when compared to the permanent removal of waste by EFW or cement kilns, the indefinite sequestration in landfill, or the decades-long sequestration in concrete reinforcement, it would give an unfair impression of the favourability of equestrian surfacing by giving it a substitution benefit in the same manner as these other, longer term disposal routes, and so one has not been included. This means that only the CO$_2$e costs of equestrian surfaces will be used, and no subtraction will be made from it to account for the CO$_2$e it potentially offsets.

v. Reuse

To calculate the CO$_2$e offset of reuse, the embodied CO$_2$e of the carpet was calculated. For simplicity, and since the properties of latex have not been investigated extensively in this report, the carpet was treated as if it was made of only two components: PP and CaCO$_3$. The mass of the latex was assumed to possess the same embodied CO$_2$e as PP. Two values for the embodied energy of PP were found: 1.58 and 1.6 tCO$_2$e/t [194], and so the value was averaged to 1.59 tCO$_2$e/t. A value for CaCO$_3$ of 0.031 tCO$_2$e/t was found in [195]. These values were then multiplied by the ratios of their respective components in the reference carpet sample decided upon in Table 25, the calculations for which are shown below in Table 29.

Table 29: Embodied CO_2e calculations

Unit	Quantity
PP embodied carbon (tCO_2e/t)	1.590
$CaCO_3$ embodied carbon (tCO_2e/t)	0.031
Embodied PP carbon per t_{pp} (tCO_2e/t_{pp})	1.190
Embodied CaCO3 carbon per t_{pp} (tCO_2e/t_{pp})	0.008
Total embodied carbon per t_{pp} (tCO_2e/t_{pp})	1.198

As can be seen, the total embodied CO_2e per tonne of carpet is 1.198 tCO_2e/tonne. This was used as the potential CO_2e offset for reusing carpet, since it was assumed that the old, reused carpet was displacing a new carpet that would have had to have this CO_2e embodied in it.

vi. Recycle

For recycling, since PP is the highest value component of a carpet, it was assumed that only this would be salvaged. Therefore, just the value of 1.190 tCO_2e/t of embodied CO_2e in PP per tonne of carpet from Table 29 was used as the substitution benefit. Since a large amount of processing is required for any carpet recycling process, but there are so many different potential processes, the shredding CO_2e cost for this waste stream was multiplied by 10 as an arbitrary placeholder for the extra processing required.

4.6. Conclusion

This section has calculated the CO_2e costs for eight different carpet waste disposal and recycling routes, the final figures for which are repeated below in Figure 40 and Table 30. One of the primary discoveries of this section is the lack of CO_2e generated by landfilling carpet waste, and the effectively negative CO_2e generated by using waste carpet for cement kiln fuel and concrete reinforcement, thanks to the displacement of coal and concrete. Reuse and recycling were, unsurprisingly, the most CO_2e-friendly options, and incineration the least. EFW fell, as expected, in between incineration and the rest of the options. When using the assumption that EFW power will solely be used to replace power generated by coal-fired stations, the efficiency difference between an EFW plant and a coal fired power plant (approximately 10%) is the only factor that makes EFW more CO_2e-intensive than kiln fuel, where the carpet and coal are burnt side-by-side, and are therefore assumed to have the same efficiency. In terms of scalability, it is convenient that cement kilns and concrete reinforcement are likely two of the more scalable disposal options discussed in this report, which makes them even more appealing.

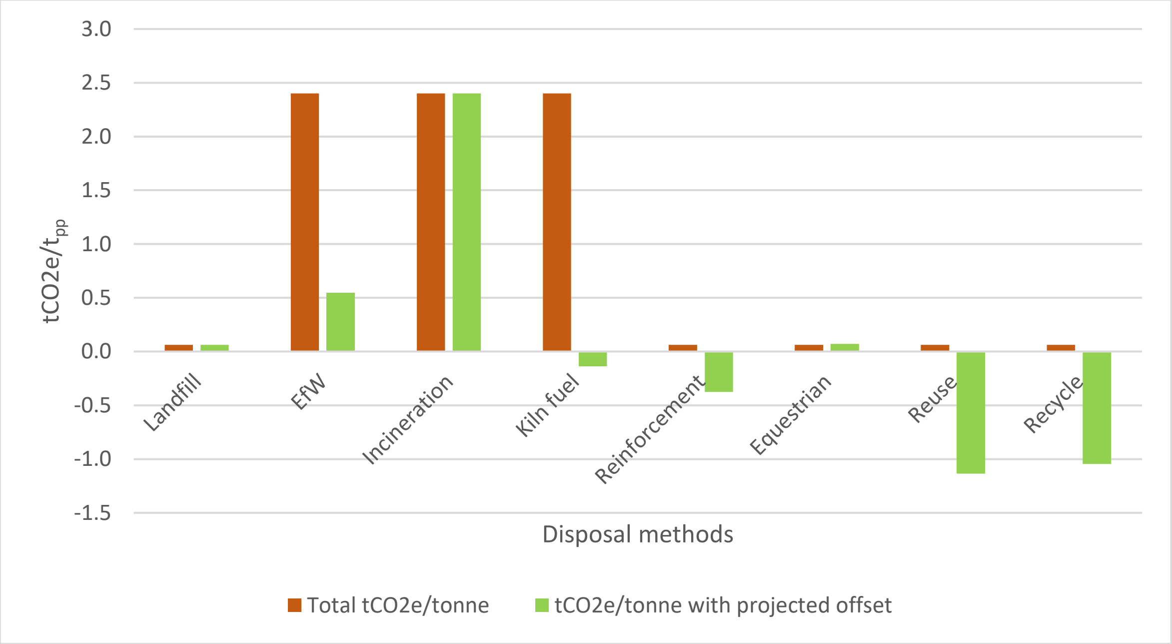


Figure 40: CO_2e emissions per t_{pp} sent to different disposal routes

Table 30: CO_2e calculations for various recycling methods

Metric/Recycling method	**Landfill**	**EfW**	**Incineration**	**Kiln fuel**	**Reinforcement**	**Equestrian**	**Reuse**	**Recycle**
Shredding (tCO_2e/t_{pp})		0.008	0.008	0.008	0.016	0.008		0.081
Incineration (tCO_2e/t_{pp})		2.330	2.330	2.330				
Transport (tCO_2e/t_{pp})	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063
Total (tCO_2e/t_{pp})	**0.063**	**2.401**	**2.401**	**2.401**	**0.063**	**0.063**	**0.063**	**0.063**
Substitution benefit (tCO_2e/t_{pp})		1.853		2.539	0.456		1.198	1.190
Total CO_2e/t_{pp} with predicted offset	**0.063**	**0.548**	**2.401**	**-0.138**	**-0.377**	**0.071**	**-1.135**	**-1.047**

5. Conclusion

This report has covered a wide range of topics, with the overall goal of providing guidance to improve the recyclability of carpet waste in the UK. In the literature review and CO_2e analysis sections, a wide range of potential recycling techniques and applications were analysed from both a feasibility perspective and a CO_2e cost perspective.

Concrete reinforcement, sound insulation, and oil absorption are the three most promising areas of the literature review. Concrete reinforcement presents an option to sequester carpet fibres and slightly reduce concrete usage, providing definite benefits to concrete tensile strength and impact resistance, but reducing compressive strength and workability. Fibre-reinforced concrete appears to be more appropriate for use in relatively low-intensity environments where impact resistance would be useful, such as paving slabs. Sound insulation presents an exciting opportunity to reuse waste in bulk, with low processing costs and high scalability. However, further research must be performed on the flammability of waste carpet fibres, and whether they could be made fire retardant to an appropriate degree in a cost-effective and environmentally friendly manner. Oil absorbent materials appear to be an excellent route for waste PP fibres, as they are cheap, lightweight, and likely a highly effective absorber with little apparent drawback.

The sample characterization, separation, and processing section of the report showed that lab-scale separation of carpet fibres from their backing material is simple, cheap, and effective, and there appear no major obstacles to further scaling the shredding-sink-float separation process performed. Filament production was not successful, possibly due to contamination or thermal degradation, however reducing printing temperature will likely result in better performance.

The CO_2e calculation section showed that the processes involving combustion of fibres (incineration, EFW, and cement kilns) were far more polluting (2.401 tCO_2e/t_{pp}) than other end-of-life disposal options. Concrete reinforcement was, once again, one of the most promising options in this section, with a low CO_2e cost of 0.063 tCO_2e/t_{pp}. Reuse and recycling of waste carpet had the same CO_2e cost, with the major advantage of being circular recycling routes.

One of the recommendations of this report is that there should be a rethinking of our outlook on landfill in the country. Currently, as this report has shown, most carpet waste is either incinerated or burnt for energy, both of which produce large amounts of CO_2e. As an inert material, carpet can be landfilled and have effectively 100% of the carbon and value in the carpet sequestered until a time where better treatment methods become available to deal with it. Incinerating carpet waste should never happen unless there are harmful chemicals such as POPs to be disposed of; there are no advantages to incineration apart from avoiding the landfill tax. EFW, while less CO_2e intensive than incineration, still adds CO_2e to the atmosphere. If EFW was infinitely scalable this might be acceptable, but according to industry specialists the EFW capacity of the nation is effectively fixed, making it a zero-sum game: any carpet sent to EFW simply displaces an equivalent quantity of other waste from being burnt there. There should be a landfill storage scheme set up, where landfills are treated as resources for the future, with inert waste of a high inherent value (such as carpet) stored away in concentrated and organized sections to make recovery easier, inert and requiring no maintenance, until techniques become available to deal with it.

6. Future Work

This section will discuss various topics that, in light of this report, are recommended for future research.

6.1. Use of LCA

LCA software was originally intended to be used in this report, and was only not used for procurement reasons. While the CO_2e figures obtained and calculated in this report are useful and reasonably accurate, there is a limit to the accuracy that can be obtained by manual calculations, and particularly without access to an LCA database, which contains a wealth of data carefully collated by LCA companies. The use of LCA software would refine the figures calculated in this report, enable the CO_2e analysis of other more niche disposal routes where publicly available data is limited, and allow analysis of other indicators other than global warming potential (GWP), which is extremely difficult without LCA software. This report recommends that CRUK obtain access to LCA software, and use it to refine and improve figures in the manner discussed.

6.2. Recycling of other carpet components

As tufted PP carpets make up 80% of the UK market [4], this report has focused on the recycling of tufted PP in order to maximise the effect of the finite amount of effort and time of this report on the industry. However, this is not to say that research in other areas would not be productive and worthwhile. Carpet tiles present a different challenge to tufted carpet with their different composition but increased modularity, and woven carpets are potentially even longer lived than tufted carpets, and so may have even more life left in them when they are disposed of. Nylon has a large amount of literature already dedicated to it thanks to its prevalence as a tuft fibre in the US, and so while it represents a smaller quantity of the UK market a similar effort focused on it could potentially bring even more results thanks to the larger amount of work initially available to build from. Nylon in particular is much easier to depolymerise than PP, and so shows much more potential as a material for circular carpets. Wool carpets, as a much more sustainably-sourced fibre material could be a promising material for future carpets, but little research exists into them at the moment. More research could also be conducted into the recyclability of latex and $CaCO_3$ as carpet backing materials, as they may well experience less degradation than the load-taking face fibres and $CaCO_3$ is an even more inert material that could potentially be reused as carpet backing again if separation is economical.

6.3. Further filament production

Unfortunately time constraints during this report limited the experimental phase to one unsuccessful run of filament production. However, from conversations with industry leaders it appears possible to successfully extrude at least some recycled carpet PP, and so further research into this, perhaps at lower temperatures or incorporating plasticisers, may be promising. DSC analysis has led to the conclusion that the reason the filament production failed was because of the excessive temperature used and likely contamination in the machine. Both of these factors are remediable for future runs as discussed in the Experimental section. It would be particularly useful to know the mechanical properties of recycled carpet PP, obtained by production of tensile specimens, which successful 3D printing would allow.

According to a report by ChemView Consulting, the global 3D printing polymer market is expected to be worth $3.3 billion by 2030 [196]. Data was not available on the market share of PP within this, but the scale of the market gives an idea of the value of cheap recycled feedstock.

6.4. DSC analysis

The DSC apparatus used for this project was excellent for PP analysis, and produced lots of useful data. However, it was not ideal for analysis of the $CaCO_3$ in the backing material, as the crucible in the machine could not exceed a temperature of 300°C, which does not approach the accepted melting point of $CaCO_3$ at 825°C. A higher-temperature DSC or DTA (differential thermal analysis) machine would be useful to explore the behaviour of $CaCO_3$ at these elevated temperatures.

6.5. Fire Retardancy

One of the most promising end-of-life options in the report was to use waste carpet fibres as insulation. However, a crucial piece of data to determine the feasibility of this is the flammability of the carpet, and the extent to which fibres can be made fire retardant in a cheap and environmentally friendly manner. This could be tested in lab scale apparatus and would provide valuable information on what could prove to be an excellent, scalable, and cost-effective end-of-life route for waste carpet.

6.6. Spinning

Melt-spinning and electrospinning, particularly needleless melt-electrospinning, could be very promising uses for recycled carpet fibres in future. The nonwoven materials produced by these techniques would be unlikely to find use in any load-bearing applications, which is normally the limiting factor for recycled plastics, and would provide an excellent low-cost high surface area material for oil absorption. Microplastic release may be a problem, but compared to some of the drawbacks associated with the chemicals and other cleanup methods currently used to combat oil spills, they may be considered relatively minor. The high surface area material may also be a promising low cost insulation material if the flammability issue can be solved economically and environmentally. This would be a promising area of research for a university lab-scale project with fire testing equipment or a suitable area to simulate oil spill absorption, and access to spinning equipment.

Appendix

DSC Sample Data

Each sample was heated and cooled three times, leading to six sets of data. The below tables show the raw data of the heating and cooling peaks for each cycle.

Sample details			Heating											
No.	Sample name	Mass (mg)	Integral 1 (mJ)	Integral 2 (mJ)	Integral 3 (mJ)	Normal 1 (J/g))	Normal 2 (J/g)	Normal 3 (J/g)	Onset 1 (°C)	Onset 2 (°C)	Onset 3 (°C)	Peak 1 (°C)	Peak 2 (°C)	Peak 3 (°C)
1	JL_PP_bbt	1.52	159.4	112.48	113.41	104.87	74	74.61	145.5	151.7	150.4	167.3	160.6	160.2
2	JL_PP_mbt	2.02	252.78	166.98	168.19	125.14	82.66	83.26	150.2	147.5	146.9	167.6	160.7	160.4
3	JL_PP_gwt	2.38	227.11	225.72	228.69	95.42	94.84	96.09	167.9	156.5	155.8	168.2	164.5	163.4
5	JL_PP_gbl	2.2	141.13	187.64	186.66	64.15	85.29	84.85	151	152.1	151.4	165.7	159.9	159.7
6	JL_PP_gbt	1.7	137.64	128.03	130.63	80.97	75.31	76.84	132.1	156.3	156.5	163.8	163.1	162.5
7	JL_PP_bgl	2.29	219.3	222.23	222.58	95.76	97.04	97.19	153.3	150	149.8	165.5	159.1	158.8
8	JL_PP_wbl	1.09	109.95	77.29	79.49	100.87	70.91	72.93	152.2	150.7	147.2	162.6	159.9	159.3
9	JL_PP_sep	0.97	69.43	88.14	60.84	71.58	90.87	62.72	152.5	143.1	136.8	161	158.2	156.4
10	JL_PP_oven	3.15	280.04	197.81	198.32	88.9	62.8	62.96	145.7	140.1	140.1	158.2	155.4	155.4
11	JL_PP_fila	3.42	208.26	191.45	192.48	60.9	55.98	56.28	149.1	149.1	148.2	163.8	156.2	156
12	JL_CaCO3_sep	7.6	-42.42	40.46	44.5	5.58	5.32	5.86	164.7	152.5	152.3	174.1	160	160

Sample details			Cooling											
No.	Sample name	Mass (mg)	Onset 1 (°C)	Onset 2 (°C)	Onset 3 (°C)	Inflection 1 (°C)	Inflection 2 (°C)	Inflection 3 (°C)	Midpoint 1 (°C)	Midpoint 2 (°C)	Midpoint 3 (°C)	Angle midpoint 1 (°C)	Angle midpoint 2 (°C)	Angle midpoint 3 (°C)
1	JL_PP_bbt	1.52	126.1	125.8	125.7	123.96	123.65	123.65	130.36	130.45	130.21	128.4	128.26	128.04
2	JL_PP_mbt	2.02	126.8	126.6	126.6	124.85	124.7	124.7	130.58	130.3	130.34	128.75	128.9	128.68
3	JL_PP_gwt	2.38	128.3	119.1	127.9	125.8	121.72	125.85	132.62	107.35	131.92	129.75	130.04	129.63
5	JL_PP_gbl	2.2	124.8	124.5	124.4	122.79	124.48	124.38	122.14	121.83	128.33	127.07	126.66	126.57
6	JL_PP_gbt	1.7	127.5	127.5	127.4	124.93	124.95	124.96	130.72	130.91	130.81	128.95	129.21	129.06
7	JL_PP_bgl	2.29	124.5	124.4	124.3	122.23	122.24	122.24	128.07	127.96	127.85	126.82	126.72	126.68
8	JL_PP_wbl	1.09	125.8	125	124.8	123.2	122.54	122.38	128.21	127.56	127.36	127.7	127	126.8
9	JL_PP_sep	0.97	123.4	120.8	120.4	120.99	118.32	117.82	126.11	123.93	123.33	125.26	122.57	121.83
10	JL_PP_oven	3.15	119.5	119.4	119.4	116.48	116.33	116.17	124.2	124.06	123.98	123.06	123.49	123.01
11	JL_PP_fila	3.42	121.6	121.5	121.5	119.79	119.64	119.63	126.4	126.13	126.09	124.19	124.31	124.18
12	JL_CaCO3_sep	7.6	105.6	105.4	105.3	109.02	109.02	109.01	98.36	98.35	98.58	98.01	117.83	93.13

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