Post-consumer Waste Streams and the Reworking/recycling of Mattresses

By

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Signed Declaration

Lancaster University

Faculty of Science and Technology

Engineering Department

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Abstract

Over 5 million mattresses go straight to landfill or incineration every year at a significant environmental cost. Mattresses have negative net value, meaning the cost of recycling is greater than the recoverable value. This study identified ways of improving mattress recycling, investigated application of mattress wastes, conducted financial appraisal of mattress deconstruction and recommended actions for recycling body the Reuse Network. Insight was obtained through interviews including four manufacturers and seven mattress recyclers to assess mattress recycling issues, potential improvements and gather statistical and financial data on mattress recycling. In parallel, desk-based literature research was conducted to supplement and support primary findings and give insight into mattress recycling internationally. Experimental research was conducted to determine the properties of building materials incorporated with mattress origin wastes. The research found the value recovered from an average mattress was (£0.5) - £2.8. A manual disassembly plant processing 50,000 mattresses annually, would require a set-up cost of £100,000 based on insight from recyclers and literature, which could save 1400-2200 tCO_2-eq. Experimental research found that incorporating mattress origin waste into building materials has the potential to offer a practical re-utilisation of the waste. At present, the mattress industry has invested very limited resources into improving the recyclability of mattresses in terms of design and processing to help re-utilise waste streams within mattresses. Actions of regional landfill bans, an immediate flat rate sales tax on mattress could help fund collection and infrastructure to recycle mattresses effectively. Further, the Reuse Network should invest resources directly to develop mattress recycling and realise a vision of a nationwide recycling model.

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1 INTRODUCTION

Increasing the utility of finite resources is critical to sustain long term development and stop the degradation of the natural environment in the face of ever rising demand for resources driven by economic development. Business models that rely on the traditional take-make-waste consumption of material resources need to transition rapidly towards a model where the utility of resources can be preserved. This means effectively designing out waste; an underlying principle of what is termed the circular economy [1]. Current infrastructure and business models are geared to encourage the continuous consumption and waste of goods [2]; be it items such as fast moving consumer goods, fast fashion, waste electrical electronic equipment (WEEE) or furniture. In the European Union, legislation is gradually being introduced to encourage, at least in part, the recirculation of resources, such as the WEEE directive [3]. However, due to businesses focusing on driving short term profitability, for many types of goods, the utility of resources is being lost to rot in landfill or burned as a trivial recovery route. One such product type is mattresses.

Mattresses present disposal challenges because they are bulky, of low density, of mixed material composition and are readily contaminated by moisture ingress [4]. The disposal of mattresses is often limited to landfill or incineration due to the high cost of mattress reprocessing, within the context of low material values and limited recycling opportunities. The variable design and heterogeneous nature makes the recycling of mattresses expensive [5], either through manual labour or energy intensive automated disassembly. In the UK, to recycle a mattress is 2-3 times more expensive than disposal via landfill or incineration [6]. Often it is down to the local government (local authorities), who collect mattresses through public disposal sites, to choose whether or not to pay the premium to recycle mattresses. In the UK, over 7.2 million mattresses were estimated to be disposed in 2017, of which 80% were sent to landfill or incineration [6].

The purpose of this study was to identify ways to increase the recycling of mattresses though a collaboration between Lancaster University, local waste specialist Cumbria Recycling Ltd (CRL) and the Reuse Network. CRL, a social enterprise re-processor of WEEE based in Workington, initiated the project along with the Reuse Network. The Reuse Network, represents over 200 charitable reuse organisations across the UK, and aims to reduce waste, particularly through reuse, to support vulnerable people and help alleviate poverty, and to tackle climate change by reducing carbon emissions [7]. The research was primarily funded through the Centre of Global Eco-Innovation (CGE), with the objective to support local SMEs and deliver savings in greenhouse gas emissions through research and development.

2 OBJECTIVES

At the start of the research process, the partners of the research set out a programme of research with the following objectives:

1. To produce a technical report to describe the mattress life-cycle
2. To review currently used mattress deconstruction methods including: i) quantification of the input resources and ii) quantification of predicted recoverable waste streams
3. To review design types of the mattress spring assembly including: i) feasibility studies on burn-off process to remove fabrics and ii) feasibility to increase scrap density to an economic weight/volume ratio
4. To investigate downstream markets for waste streams recoverable from mattress disassembly including: i) feasibility around diversion of waste streams into concrete and/or gypsum building materials and ii) determination of mechanical properties of experimental composites
5. To produce a technical report including recommendations of code of practice for conversion of waste to product

The CGE requirement for the research was to demonstrate that the output of the research project has the potential to lead to significant savings in greenhouse gas emissions. Further, desired commercial and export benefits of the study outlined by the partners were:

I) Identify new downstream markets/application for low value deconstructed materials

II) Reduce disposal costs due to reuse/recycling mattress materials into new product streams

III) Enable CRL in partnership with the Reuse Network to justify investment in a “hub” plant to prevent mattresses going direct to landfill

IV) Become the cornerstone of a recycling service model which can be replicated across England and Scotland

The objectives and desired benefits were broad and ambitious for a 12 month MSc by research project. As a result, some objectives were scaled down with a concentrated focus to address the encompassing objective: to identify ways of increasing the reuse/recycling/recovery of mattresses. As such, the focus of the study was defined by the three research outcomes:

1. Primary and secondary information was sourced from stakeholders across the mattress life cycle, which enabled appraisal of the mattress life cycle of three key issues of sourcing post-consumer mattresses, mattress design and onward markets for arising waste streams. This included quantification of the end of life destination of mattresses, analysis of recoverable waste streams, their composition and value, and recommendations of actions that could be implemented, by policy and industry to improve mattress recycling.
2. Experimental work on the influence on mechanical and thermal properties of building materials with incorporation of mattress origin wastes was identified as a potential new downstream application of low value deconstructed mattress materials. Foam and mixed textiles from a mattress were incorporated into cement-based mortar and gypsum-based plaster.
3. Gathered market insight to help inform how CRL/Reuse Network and members could make a positive impact on mattress recycling in the UK, highlighting the need for increased mattress recycling capacity with analysis of mattress deconstruction, financial appraisal, markets and processing requirements for recoverable waste streams. This also included analysis of environmental

impact of different mattress disposal scenarios, best practices for mattress deconstruction and location factors of determining potential new deconstruction facilities in areas of critical need. Suggestions for potential legislative changes to aid mattress recycling were also proposed.

Noted the research objective to conduct feasibility studies on burn-off process for pocket springs was not addressed as the burning of pocket springs to remove the fabric content was reported to be banned in the UK [8].

Due to the programme of research containing confidential information from the partners (CRL, Reuse Network and members), as well as industry sources who did not want information they provided to be in the public domain, certain information and findings could not be publicly disclosed. However, to maximise the impact of the research programme, there was a desire to make the research public where possible. Consequently, the main body of work has been split into three separate chapters (5,6 and 7), with the view that the Chapter 5 and second Chapter 6 could be published in academic journals, whilst Chapter 7 and the encompassing thesis would have restricted access at the discretion of the industry research partners of CRL and the Reuse Network. Chapters 5 and 6 have co-authors including academic supervisors and the industry partner. The role and contribution of the supervisors was though support as supervisors with guidance during the research and assistance with the written English of the chapters. The role of the industry partner was their contribution of contacts which initiated first contact with some of the different stakeholders. The chapters are defined by the following **research objectives:**

- **Chapter 5:** ***"Life cycle of post-consumer mattresses: waste streams and recycling challenges"***

Investigate challenges within the mattress life cycle of sourcing post-consumer mattresses, mattress design and onward markets for arising waste streams by defining the flows of waste mattresses arising in the UK, the specifics of waste streams recoverable from mattresses and actions that can be implemented by policy and industry to improve mattress recycling.

- **Chapter 6: "*Incorporation of recycled wastes from mattresses into building materials*"**

Investigate the properties of building materials incorporating mattress origin wastes as an alternative for low value mattress wastes going to landfill or incineration.

- **Chapter 7: *"Mattress Recycling Market Insight"***

Investigate mattress recycling issues of deconstruction, recoverable waste streams, processing for onward markets, environmental impact of disposal routes, regional variation in mattress recycling capacity and reuse/recycling opportunities to propose and inform how CRL/Reuse Network and members can positively impact mattress recycling in the UK.

3 LITERATURE REVIEW

The scope of the study was focused on improving mattress recycling in the UK with the view that literature, methods and findings could be applicable to other countries in need of improving the utility of mattresses at end-of-life and other difficult to recycle products.

3.1 MATTRESS LIFE CYCLE

An overview of the mattress life cycle (**Figure 3.1**) was determined from Imperial College London [9]. The report proposed a business model for the Reuse Network to enter the recycling market; through a number of recycling hubs that would feed a central facility to sell recoverable materials. The study listed the main recoverable materials from mattresses to be steels, textiles, foam and wood with information on their possible processing but lacked any significant detail financials or processing requirments.

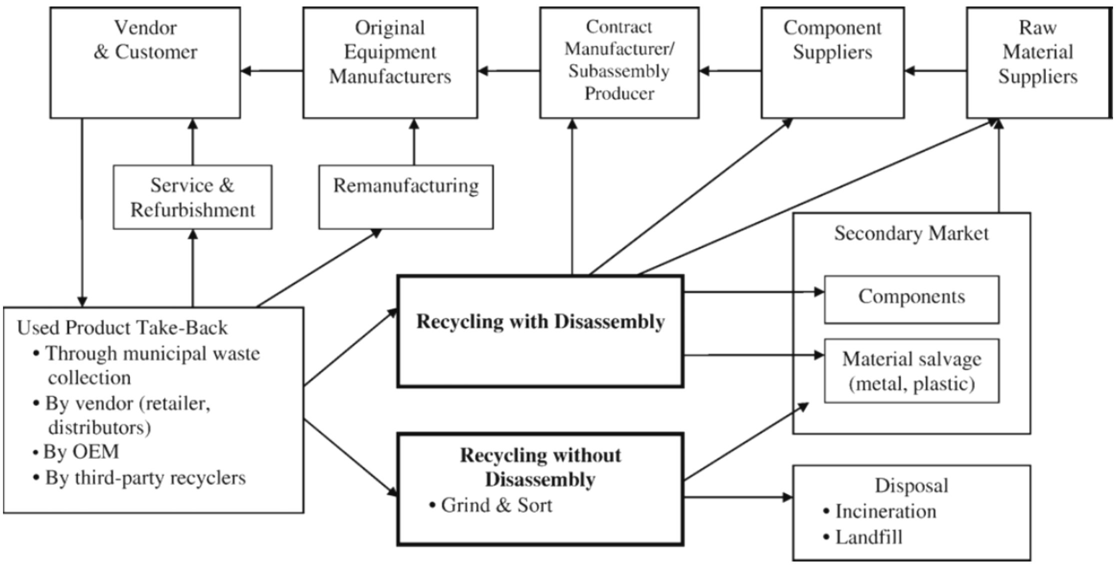

Figure 3.1 Mattress life cycle, Imperial College London [9]

A common mattress design is presented by Ardmel [10], which provided insight into the different mattress layers (**Figure 3.2**), but does not consider other types of mattress design such as foam.

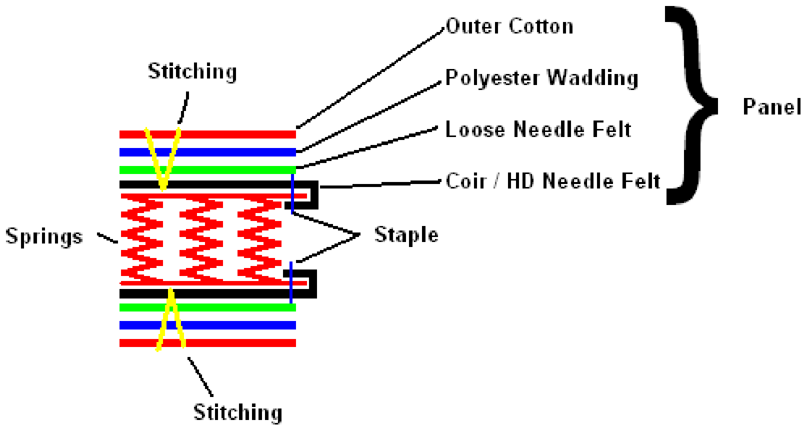

Figure 3.2 Typical spring mattress design, Ardmel [10]

An estimation of the composition of materials recoverable from waste mattresses (waste streams) was presented by Chapman [11], where the composition of an average mattresses was determined using survey data from Dutch and Greek mattress manufacturers, dating back to 1994 [12]; unlikely to be representative of the UK market due to the greater market share of foam mattresses in the EU [13]. Here nine waste streams were defined but limited in detail, with waste streams simplified down to steel, polyurethane (PU) foam, Latex and mixed textiles. Chapman does however provide a comprehensive overview of mattress recycling with information on sourcing end of life mattresses, deconstruction methods, markets for recoverable materials and financials; including price estimates for materials and operational costs. The report used information sourced though interviews with recyclers, mattress manufacturers, waste contractors and local authorities; with findings supplemented by literature. As the research was conducted during 2010, the usefulness of the report was limited, as some of the information on mattress recyclers and financials was now out of date.

More recent analysis of mattress recycling in the UK is available from the NBF, the trade association for mattresses. Reports cover the background and rate of mattress recycling in the UK for the periods 2012-2013 [14], 2014-2015 [13], [15] and 2016-2017 [6]; finding that recycling rates increased by 9% from 2012-2017 (**Table 3.1**). Bell [6] made an important deduction from the recycling statistics, that at the current growth rates, 100% mattress recycling would not be achieved for another 50 years.

Table 3.1 UK mattress recycling rates between 2012-2017, Bell [6]

	1st Survey[2]		2nd Survey[2]		3rd Survey	
	2012	**2013**	**2014**	**2015**	**2016**	**2017**
Number of mattresses recycled	452,000	586,000	924,000	879,000	1,034,000	1,363,000
Number of replacement mattress sales	4,667,000	4,531,000	5,904,000	6,822,000	6,720,000	7,260,000
Mattress recycling rate	**10%**	**13%**	**16%**	**13%**	**15%**	**19%**

The methodology of the NBF reports enabled clear quantified findings to be produced. Information in the reports was obtained from: i) mattresses recyclers, ii) survey data of manufacturers and retailers, iii) statistics on mattresses recycled at local authorities from Waste Data Flows [16] and iv) statistics from the European Commission databases Prodcom [17], from the manufacturers of mattresses in the UK, and Comtext [18], from the import and export value of mattresses.

In the 2019 NBF report [6], it was estimated that 7.2 million mattresses entered the waste stream in 2017, with 19% recycled, 40% sent to incineration with energy recovery and 40% sent to landfill. Although the methodology used to determine the mattress recycling rate was effective and simple, the statistics on landfill and incineration were based on the assumption that mattresses were treated in the same way as general residual waste, meaning further investigation was required to validate the mattress disposal statistics. Across the NBF reports, similar challenges within mattress recycling were raised including: financial insecurities of mattress recycling, lack of transparency and trust, low quality of available data, mattress design restricting recycling and low value application of recoverable waste streams. The NBF reports also made positive suggestions to combat these issues such as mattress redesign and auditing of mattress recyclers, but lacked substantive solutions; stopping short of communicating challenges such as mattress recycler and manufacturer conflicts [19]; possibly due to a desire not to upset the NBF and its members. The NBF has made progress to improve transparency and trust through the establishment of a register of approved mattress recyclers (RAMR) [20], but with the potential benefits yet to be seen.

3.2 MATTRESS DECONSTRUCTION

The deconstruction of a mattresses involves separating materials and components generally into groups of metal, textiles and foams. Deconstruction can be conducted: i) manually by means of using knives and manual force to pull apart different components and layers [21], ii) by shredding where whole mattresses are shredded and constitutes separated by magnets and density separation systems [22], iii) by automation with mattresses fed on a series of conveyer belts to be cut open by machines with different layers separated by spiked rollers and shredders [23], iv) or by some combination of the three [4]. Bell [6] defined the different recycling process as manual, semi-automated and shredding, and found that, though shredding could economically deal with wet mattresses, higher values could be obtained for recovered materials through manual or semi-automated recycling. Bell [6], [13] also discussed the value of waste streams recoverable after deconstruction, with metal and polyester reported to have high values whilst mixed textiles and foams could be more difficult to find markets for. Chapman [11] provided a comprehensive review of deconstruction techniques and required equipment as well as examples of international mattress recycling operators. Griffiths [4] and Coe [24] provided insight into the variability of mattresses received and processed by mattress recycler Amgen Bryn Pica with Coe detailing three types of mattresses (**Figure 3.3**) and the feasibility of a mattress recycling systems in Wales.

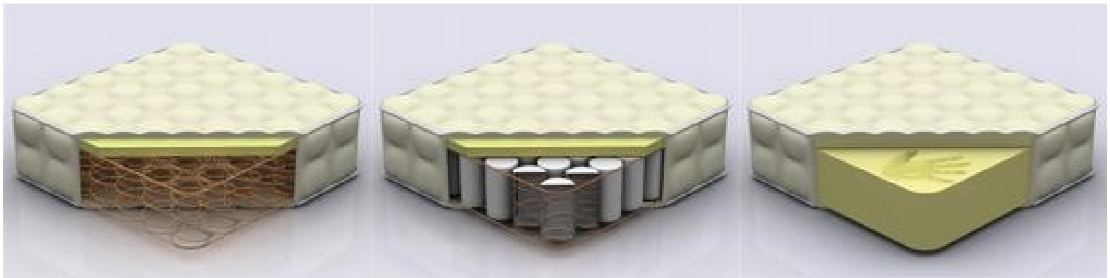

Figure 3.3 Open coil, pocket spring and foam mattress, Coe [24]

The studies on Amgen Bryn Pica gave good insight into operations of deconstruction and processing of waste streams; with deconstruction conducted via a semi-automated system using an excavator to separate mattress layers. A report by circular economy charity Waste & Resources Action Programme (WRAP) [21], into a different recycler, CAD Recycling, gave insight into financials of equipment, such as balers, tables, and deconstruction statistics of processing rates, recycling and cost of transporting baled waste streams. Further information on mattress deconstruction was provided confidentially by mattress manufacturer Sealy [25], who gave information on their deconstruction process and equipment as well a valuable information on onward markets for their industrial waste. Additional insight into mattress deconstruction was identified through Gamester [26], [27], who examined mattress design, deconstruction methods, equipment and financials, but with information requiring updating.

Web based searches on international examples of mattress recyclers provided information on collection schemes and deconstruction processes for France [28]–[30], Belgium [31], the Netherlands [23], [32], [33], the US [34]–[36], Canada [37] and Australia [38], [39]. This provided valuable insight and comparisons of different approaches to mattress recycling. France operate a successful collection and processing scheme for mattresses as a result of legal requirements placed on sellers to assume responsibility for the collection and treatment of their products at end of life. However, legislation has had an insignificant impact on the mattress design, meaning considerations of circular design are not addressed by the manufacturers [40]. Mattress recycling in Belgium has been focused towards energy recover of the materials which has allowed the cost of mattress recycling to be relatively competitive verses landfill [31], but meaning the environmental benefit of the recycling is minimal. The Netherlands has had significant investment into automated mattress recycling facilities which is aided by the geography and population density of the Netherlands reducing transportation and collection costs of mattresses. However, it has not proved cost effect to collect and process mattresses from rural regions meaning total mattress recycling is yet to be cost effective. Future producer responsibility is to be introduced to help increase mattress recycling nationally in the Netherlands [41]. In the US, mattress recycling is support by non-profit organisation the Mattress Recycling Council (MRC) [34], who were originally set up by the ISPA, the trade association for mattresses in the US. The MRC have been successful in supporting state wide legislation on mattress recycling in several states and help support and promote mattress collection and a nationwide recycling network. Despite the successful mattress recycling programs in certain states, recycling rates across the US remain low due high collection costs in rural areas and fragmented legislation created by variations in resources, policy and interest by different state governments. Canada and Australia follows a similar pattern to the US with high recycling rates in certain regions, generally with a higher population density, with mattress recycling in Canada supported by mattress landfill bans in some regions [37]. Australia on the other hand has seen improved mattress recycling in recent years as a result of a partnership between social enterprise Soft Landing and specialist manufacturer of mattress recycling equipment TIC group [39], [42]. The partnership of a profit company with the social enterprise could be a good way to drive efficiencies and cost effectiveness, whilst maximising social and environmental benefit.

3.3 BEST PRACTICES FOR MATTRESS RECYCLING

The NBF has established a code of conduct for the reuse of mattress components [43], outlining what is and is not deemed acceptable. However, the code of conducts was raised by mattresses recyclers to be heavy bias towards the interests of major manufacturers who support the NBF [19]. Further information on best practices and legal requirements were outlined by Oaktree [44] in 2010, which has an overview of specific licences and permits that would be required for mattress deconstruction, where updates to the information could be found from the Environment Agency [45]. The Health and Safety Executive [46] provides current information on legal responsibility for waste management and/or processing sites where some of the key aspects relatable to mattress recycling had been highlighted by Megson [47].

3.4 RECOVERABLE MATTRESS MATERIALS

One of the reasons behind the financial insecurities of mattress recycling are the limited market applications of recoverable materials, with Bell [6] finding that 20-50% of recovered mattress materials were destined for energy recovery. Slater [8] provided insight into mattress component recycling and defined seven different waste streams that are recoverable from a mattress: coil spring, pocket springs, woven textiles, foam pads, synthetic fillings, nonwoven felt and natural filling. The defined waste streams were discussed in more detail for applications, but critical information such as value, specific downstream markets and processing requirements was not provided. Noted a key point from Slater [8] was that the removing of fabric from pocket springs via burning is not permitted in the UK.

Partial information for onward markets was available through WRAP [5], who demonstrated the viability of collecting non-clothing textiles, and provided a useful list of companies that collect and reprocess mattresses and constituent materials. Further literature on applications of recoverable materials have included: i) for textiles, sound insulation [48], dog sun protection canopies [49] and yarn re-spinning [32], [50] and ii) for foam, re-bonded foam [28], [51] and crop growing [52]. Other possible applications were outlined by WRAP [53] who provided information on commercial textile fibre recycling technologies such as mechanical flocking and chemical recycling. Further possibilities outlined and discussed for fibre-to-fibre recycling and chemical recovery were Resyntex [54], Bell [55], Greenblue [56], the University of British Columbia [57], Ellen MacArthur Foundation [58] as well as chemical recycling of PU foam H&S Anlagentechnik [59], Soltysinski [60].

3.5 DIVERSION OF WASTE INTO BUILDING MATERIALS:

The area of modifying building materials through the incorporation of waste has been widely reported on in recent years, due to drives to reduce the environmental impact of construction materials, and find an alternative utility for low value wastes other than landfill or incineration. Wastes that have been tested for application in building materials have included: tyre rubber [61], plastic [62]–[64], textile fibres [65]–[73] and foam [74]–[81]. Similar waste streams to those arising from mattresses have been tested for their possible application in building materials including carpet textiles [82], foam from insulation panels and fillings [62], mixed textiles [65], [68], [83], [84], cotton [68] and other natural fibres [68], [85], [86]. Wastes have been incorporated into different types of building materials including: insulation [68], [83], geotextiles [84], and composites [62], [65], [72], [75], [86]. Applications of mattress waste as insulation would be limited given that insulation manufacturers already have cheap access to industrial waste which is cleaner and purer than post-consumer waste [87]. The testing of the utilisation of waste into geotextiles took several years to understand the impacts on longevity [84], meaning further research of mattress waste into geotextiles may require a long research period. Testing application of wastes in composites can be conducted on a relatively short time period. Common composites used were cementitious or gypsum based with waste modified composites tested for application such as lightweight concretes [61], [80], [81] or mortars [74], [76], thermally insulative enhanced cementitious [77], [79] or plaster [78], [88] materials and or fibre reinforced cementitious [62], [65], [69], [72] or plaster [73], [75] materials. Over 180 million tonnes of cement and gypsum are produced annually in the EU [89] compared with 0.27 million tonnes mattress textiles [55], demonstrating the potential of utilising cementitious and gypsum based composites as a storage vessel for mattress wastes. Generally the mechanical performance of waste induced building materials would decrease with the exception of fibres when utilised as a reinforcement phase. Waste streams of textiles and foam were demonstrated to have a potentially viable application in cementitious and gypsum materials. Non-detrimental mechanical alterations were bound up to certain quantities of wastes added, with modified composites found to have enhanced thermal insulative properties and/or provided reinforcement against bending. Composites were typically tested for their mechanical properties of compressive and flexure strength following either British [90]–[93] and or American [94] testing procedures. Thermal testing would involve experimental analysis [64], [70], [78], [79] and or thermal modelling [64], [70], [79], [88]. The utilisation of mattress wastes in building materials was yet to be tested.

3.6 ENVIRONMENTAL BENEFITS TO MATTRESS RECYCLING

The scale of mattresses going into landfill in the UK is significant. WRAP [95] estimated that 144,000 tonnes of mattresses were sent to landfill in 2010. The embodied greenhouse gas emissions from mattresses in the UK going into landfill was estimated to be 443,000 tCO2e in 2010 [96]. A study conducted on the GHG savings potential on box spring mattresses in the US showed that current material recycling of a mattress offsets approximately 43% of GHG emissions [97]. Other studies on the environmental impact of mattresses included Glew [98], who studied the impact of different disposal scenarios for a luxury mattresses in the UK through the waste hierarchy of: reuse, recycle, incineration with combined heat and power recovery, ethanol conservation and landfill. The methods used by Glew [98] provided useful insight for the estimation of the GHG of different disposal routes. The study found reuse and recycling of a mattresses provided the greatest GHG reduction compared with other disposal routes, but the disposal scenarios considered did not reflect the current available disposal routes [6] and did not consider the environmental credits of energy recovery from incineration. Lanoë [99] compared the environmental impact of a polyurethane foam (PU) mattresses and pocket spring mattresses, finding that the environmental impact of a PU mattresses was 3-4 times higher, but did not quantify this in terms of relatable GHG figures. L'Abbate [100] demonstrated methods to reduce the environmental impact of polyester in mattress ticking in the dying process and yarn production with the best solution the recycling of polyester.

3.7 MATTRESS DESIGN FOR CIRCULARITY

One of the key recommendations from the literature to improve mattress recycling have been around the mattress design, either design for disassembly, design for recyclability or design for the environment. The complex heterogeneity of mattress composition and assembly methods reduces the quality of recoverable materials and increases the cost of recovery and processing [6]. The EU has an official environmental certification scheme (Ecolabel) that manufacturers can apply for. The Ecolabel has requirements to stipulate that a given mattress is environmentally friendly according to set criteria; including restrictions on hazardous substances, longevity and ability for end of life repair/recovery [101]. However, the current Ecolabel has only basic requirements regarding the end of life recovery, the environmental impact of constitute materials and lacks criteria for best practices for assembly methods to ensure design for disassembly and recyclability thereafter. In addition, the complex nature of the application process and assessment criteria may put manufacturers off. The reward of what is essentially a marketing tool label of sustainability (Ecolabel), may not be deemed worth the investment of time and resources for manufacturers to meet the specified criteria. Indeed, currently no UK manufacturer is registered with an Ecolabel. A concentrated set of criteria informing on design for circularity specifically, could be of greater benefit.

Pocket springs have been found to be particularly problematic to recycle due to the metal springs being encased in fabric which requires significant investment into shredding facilities to separate [19]. The recovered fabric is often difficult to recycle due to the glue used in its manufacture [8]. However, one company has recently launched a pocket spring design without glue [102] which could improve the recyclability of the product. Difficulties in separating different materials is a prominent problem when dismantling mattresses, due to the variety of assembly methods and mixture of materials used. A Dutch manufacture offers a fully recyclable mattresses with minimal material variation, with different layers join via a meltable glue [103], meaning mattresses can be easily disassembled and recycled. The fully recyclable mattress is to be offered in a servitisation model, meaning the manufacturer is incentivised to maximise the recoverable value of the mattress at end of life. The approach of using a service model to incentivise manufacturers to design a mattress to be dismantled and recycled could be very successful to improve the quantity and quality of mattress recycling.

An example of a UK manufacture trying to embed circular design in their products is Naturalmat, who select materials which make the mattress easier to dismantle and recycle at their end of life [104]. In other countries, innovation grants are available to encourage ecological design such as in Belgium [31], France [29] and the US [35]. The Netherlands will introduce a proposed EPR in 2019 on a voluntary basis to help improve mattress recycling, which may prove successful given the proactive nature of Dutch companies to the circular economy; such a voluntary initiative may not be as successful in the UK given the current improvident nature of many UK manufacturers.

From the literature it was clear there is a lack of consideration or detail of what design changes can be encouraged. The NBF is currently working on producing a set of guidelines outlining good and bad practices for mattress design[1] which could help have an impact on informing manufacture about circular design principles.

[1] Personal communication Nia Bell, Oakdene Hollins September 2019

3.8 LIMITATIONS OF LITERATURE

From the literature, gaps exist detailing the recoverable waste streams from mattresses with previous determination of the composition of a mattress unlikely to be representative of the UK market. An absence of a comprehensive review of the current mattress deconstruction operators in the UK, means the requirements and effectiveness of different mattress recycling were unclear.

It has also become apparent, that across the literature there was a lack of clear distinction of what the recoverable materials from a mattress (waste streams) were, the technologies available to process them and who the pre-processors/onward markets were. The reported values of waste streams were expected to be outdated meaning updates would be require to accurately inform on mattress deconstruction financials. Further, questionable figures on the current destination of mattresses entering the waste streams required further investigation.

The studies examining the environmental impact of mattresses and disposal routes were either conducted on a specific mattress design [98], [99], or international design [97], meaning figures on the GHG disposal scenarios would not be representative of mattresses being disposed of in the UK due to the far greater market share of foam mattresses in the EU compared with the UK [13].

4 OVERVIEW OF RESULTS

- **Chapter 5: *"Life cycle of post-consumer mattresses: waste streams and recycling challenges"***

Primary information into the mattress life cycle was gained from four manufacturers, two local authorities, four waste contractors and seven mattress recyclers with information and data supplemented with secondary research. Allowing analysis of challenges around sourcing post-consumer mattresses, mattress design and onward markets for arising waste streams. The study estimated that in 2018, 7.6 million mattresses were collected for disposal, of which 5.7 million were disposed of via landfill or incineration with 1.9 million sent to recyclers. Often it was down to the local government (local authorities), who collect mattresses through public disposal sites, to choose whether or not to pay the premium to recycle mattresses. The recoverable value of waste streams from an average mattress ranged from (£0.5) - £2.8. To increase mattress recycling there is a need for collaborative action to address mattress design, fund the collection of post-consumer mattresses to recycling facilities and to develop the capacity to facilitate and increase the quantity and quality of recycling waste streams. Legislative intervention to improve mattress recycling could take several different forms: Intervention in the form of EPR would ideally create a framework to fund the collection and recycling of mattresses whilst creating stimuli to increase the recyclability of mattresses through design for disassembly and design for recycling.

- **Chapter 6: "*Incorporation of recycled wastes from mattresses into building materials"***

Mattress wastes were evaluated as recycled material additions with cement-based mortar incorporating shredded polyurethane or latex foam and with gypsum-based plaster incorporating ticking (mixed fibres). An upper limit of foam additions to mortars without significant detriment to mechanical performance was found with slight positive to negative variation in compressive strength and moderate changes in flexure strength. Further, thermal conductivity of mortars incorporating foam was modelled to decrease. The testing results of plasters suggest an upper limit of gypsum can be substituted for fibres before significant reduction in mechanical performance and workability, below which plasters showed increased flexure strength and energy absorbing properties. The results showed waste from mattresses could be added to building materials either enhancing or maintaining mechanical strength whilst reducing thermal conductivity. Further work is required on a wider variety of mattress waste condition and sourcing to validate the findings that mattress wastes can be effectively utilised as filler/insultion/reinforcement in cementitious/plaster materials.

- **Chapter 7:** ***"Mattress Recycling Market Insight"***

Mattress recycling capacity as of September 2019 was determined to be 2.2 million, meaning over 5 million mattresses would still be destined for landfill or incineration each year. Though Primary insight from mattress recyclers and supplementary secondary literature the study outlined recoverable waste streams, their value through different processing methods and the cost of processing. Further financial appraisal found that a mattress deconstruction facility capable of processing 50,000 mattresses annually would require a £100,000 investment. The recycling of 50,000 mattresses was shown to produce a greenhouse saving of 1400-2000 tCO_2-eq compared with landfill. Analysis on local authorities' mattress recycling rates identified areas in the UK in critical need for mattress recycling capacity including Scotland, Eastern and Southern England. Suggestions were made for CRL/Reuse Network and to expedite improvements in mattress recycling including utilising influence on local and national government to accelerate legislative changes such as regional mattress landfill bans and mattress sales and producer taxes.

5 LIFE CYCLE OF POST-CONSUMER MATTRESSES: WASTE STREAMS AND RECYCLING CHALLENGES

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Abstract – Post-consumer mattresses present disposal challenges internationally because mattresses are bulky, of low density, of mixed material composition and are readily contaminated. In the UK, over 5 million mattresses go straight to landfill or incineration every year at a significant environmental cost with recycling shown to offset emissions from mattress production and landfill by 43%. Mattresses have a negative net value, meaning the cost of recycling is greater than the recoverable value. A greater understanding of the mattress life cycle is needed, so issues around recycling mattresses, recyclability of mattress materials and downstream markets for recovered materials can be identified and evaluated. Using manufacturer, recycler and downstream data collection and analysis from UK stakeholders, this study reports on the waste stream arisings from post-consumer mattresses and discusses challenges that will need to be addressed if mattress recycling rates are to be increased above current levels. The study found that in 2018, 7.6 million mattresses entered the waste stream, where an estimated 1.9 million mattresses were recycled with the remainder sent to landfill or incineration. The market value for recoverable post-consumer materials from the average mattress was found to range from (£0.5)-£2.8. With current values of recoverable materials, and challenges of access to markets, economic viability of mattress recycling remains low. Mattress recycling needs to be encouraged and enabled by both government and industry through collaborative initiatives into mattress redesign, together with increased economic incentives to send mattresses for recycling and investment in capacity and technology for waste stream reprocessing.

5.1 INTRODUCTION

Post-consumer mattresses present disposal challenges to government in the UK and internationally because mattresses are bulky, of low density, of mixed material composition and are readily contaminated by moisture ingress. Examples of the benefits of recycling have been discussed for whole mattresses [97]–[99] and specific materials [58], [100], [105], [106]. Whilst some countries have developed successful mattress recycling programmes with high rates of recycling [30], [31], [34], [41], others such as the UK lag behind. High recycling rates have been achieved through regional and national legislation in the cases of the US and France to fund the collection and processing of mattress recycling as well as through proactive inactivates by NGOs and or significant investment in mattress recycling processing in the case of the Netherlands [23]. Although mattress recycling rates in the UK have been increasing, it would take 50 years to achieve 100% mattress recycling at the current growth rate [6]. The low recycling rates are a pressing issue due to the environmentally detrimental consequences. The embodied greenhouse gas emissions from mattresses in the UK going into landfill was estimated to be 443,000 tCO2e in 2010 [96], with research suggesting that emissions from production and landfill of mattress could be offset by 43% by recycling of the materials [97]. The majority of post-consumer mattresses are non-reusable and have a negative net value, meaning that the cost of dismantling and reprocessing the materials of metal, foam and textiles is greater than their recoverable value. Identifying and securing onward markets for recovered materials is difficult in an often non-transparent, saturated market for post-consumer materials [106]. To address these issues, this study analysed the state of play for post-consumer mattresses in the UK, looking at how recycling rates could be increased. Currently in the UK, the majority of post-consumer mattresses are sent to landfill or incineration [6], and even when mattresses are disassembled for recycling, apart from the metal, the materials are often incinerated for energy recovery rather than recycled or reused. Given the potential environmental benefit of recycling the materials, methods to increase mattress recycling quantities present a significant opportunity to reduce the environmental impact of the mattress industry.

Examining other industries and countries provides insights for possible methods to facilitate increased recycling of mattresses. The WEEE directive [3], which was first introduced into the EU in 2002, puts obligations on producers to take-back and dispose of the products they sell. The directive was designed to internalise the waste treatment costs, and has led to some parts of the sector reprocessing returned products and recycling materials and components [106]. Some countries have introduced similar legislation to facilitate mattress recycling programmes which perhaps may offer a model for the UK to follow. France introduced extended producer responsibility (EPR) schemes for furniture in 2012 and there are legal obligations on furniture sellers to assume responsibility for the collection and treatment of their products at end-of-life [107]. This led to a consortium of mattress recycling sites across France supported by Éco-mobiler, an NGO responsible for collecting, sorting, recycling, and reusing furniture and mattresses, which has a target of zero furniture waste to landfill by 2024 [30]. However, initially most producers opted to fund other organisations, which restricted the impact of the EPR to fund the collection, treatment and disposal only, with few initiatives to impact real design changes at the manufacturers to enable circular products [40]. This has started to change with Éco-mobiler launching Eco-innovation challenges to industry to develop ways to recycle mattresses and bedding and offering financial support to develop recycling processes and re-manufacturing of products from the waste streams [29]. Elsewhere in the EU, the Dutch Government has set a target of recycling 95% of mattresses by 2025 and a target to ensure that 75% of new mattresses produced are designed for disassembly and materials reuse with violently EPR to be introduced in 2019 [41]. In the US, California, Connecticut and Rhode Island have introduced state-wide mattress recycling legislation, requiring retailers and manufacturers to charge a recycling fee for mattresses at the point of sale. The fees are collected by the Mattress Recycling Council, and fund mattress recycling operations in the specific states and wider states nationally [34], as well as funding research grants to improve the efficiency and effectiveness of mattress recycling operations [35]. Future initiatives in other countries to improve mattress recycling could try to incorporate the success of high collection rates of mattress to recycling facilities in France and proactive initiatives taken up by Dutch manufacturers to improve the circularity of mattress design.

There is currently no such directive, legislation or initiatives in the UK relating to mattresses, resulting in a lack of support and investment in mattress recycling. The latest UK government waste strategy [108] states a review on measures, such as EPR on bulky waste including mattresses, will be conducted by 2025. A lack of investment from local and national government and the private sector means recycling facilities are limited. Several organisations in the UK have made significant investment into shredding mattresses [8], [22], but this results in minimal separation of materials with large proportions destined for incineration and energy recovery [6]; generally through solid recovered fuel (SRF) or resource derived fuel (RDF).

On an industry level, there has been progress to improve the state of mattress recycling, led by the National Bed Federation (NBF), the trade association for mattresses. They have undertaken industry research and made efforts to improve the transparency of mattress recycling through the setup of a Register of Approved Mattress Recyclers (RAMR) [20]. Industry reports commissioned by the NBF [6], [8], [13]–[15] were useful for analysis on establishing the flows of post-consumer mattresses from sale to final destination.

A review of literature examining mattress recycling, points to recycling challenges based on mattress design [4], [11], issues with financing the collection and recycling of mattresses [6], [11], [13], [14] and the limited and low value application of recoverable waste streams arising from post-consumer mattresses [8]. However, there was a lack of analysis into the specific nature of the resultant waste streams and lack of exploration into how markets for these waste streams could be developed. To analyse the waste stream further, studies on the textiles and apparel industry were useful to identify emerging technology and trends [106] that could be applied to the recovery of mattress textiles. Research from the Ellen Macarthur Foundation [58] provides a review of the advantages and disadvantages of different textile materials, whilst research from the University of British Columbia [57] reviews technologies and stakeholders within the recycling of polyester, nylon cotton and wool. As for foam, studies from industry [59], [109] and literature [60] on end-of-life application and recycling provide examples of possible recycling methods that could be applied in the UK. These studies were useful in providing information on the environmental impact of mattress materials, possible recycling methods and potential markets for textiles and foam recovered from mattresses.

Through manufacturer, recyclers and down-stream/end user data collection and analysis from stakeholders based in the UK, this study reports on the state of mattress recycling and discusses challenges that will need to be addressed if mattress recycling growth rates are to be increased above current low linear levels.

5.2 METHODS

The purpose of the study was to raise awareness of the current state of play for post-consumer mattresses, and examine how the challenges of mattress recycling can be approached and overcome. Stakeholders across the mattress lifecycle were consulted with a focus on the end-of-life treatment of mattresses and analysis of the recoverable waste streams. The consultations included emails, telephone interview, in person interviews and site visits. Questions were formulated based on building upon the limitations of the literature including how mattresses and constituent wastes (industrial/post-consumer) were dismantled, processed and treated as well as the cost of doing so, the onward market application and their market value. Stakeholders were also consulted for their views on how mattress recycling can be improved, what they were doing to contribute to improving mattress recycling and their perspectives of other stakeholders. Consultations included gathering of quantitate data on mattress recycling statistics, financial information and mattress composition. Data and information was acquired from industry sources, shown below in **Table 5.1**. Site visits enabled the opportunity for in-depth interviews and visual analysis and perspectives from different points across the mattress lifecycle. Broader information was gained through mattress recycler websites in the UK and internationally, mattress sales data from the European Commission, video clips of mattress recycling operations and literature on mattress recycling searched through World Cat and Google Scholar databases, with further information gained from governmental and trade association websites. A wide range of different parties was included in the research to obtain an understanding of the challenges and motivations of increasing mattress recycling rates from the perspectives of different stakeholders across the mattress life cycle. To increase mattress recycling rates, understanding of the mattress life cycle was needed, as from this, downstream markets for recovered materials can be identified and evaluated, ultimately informing where changes are required to improve the value of recoverable waste streams.

Table 5.1 List of sources that contributed to the research

Type of company:	Manufacturer				Local Authority		Waste contractor				Mattress recycler						
Coverage[2]	N	N	N	N	L	L	L	R	N	N	R	R	R	R	R	R	R
Site visit	x	x	x	x	x	x	x				x		x			x	
Interview	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x
Data shared	x	x	x	x	x	x					x	x	x	x	x		

[2] Defined as either national (N) across the country, regional (R) across multiple counties or local (L) within a single county.

Figure 5.1 presents an overview of the basic mattress life cycle to highlight key stakeholders. The main focus area of this study is highlighted in grey whilst the dotted box represents a possible closed loop cycle for mattresses. The arrows represent the transfer of any aspect of a mattress, components or materials and are only indicative of a simplified mattress life cycle. Each box represents a different stage in the life cycle, and there are a multitude of different actors within each box, such as the 170 registered companies that manufacture mattresses in the UK [110]. There are four possible routes that post-consumer mattresses have in the waste hierarchy: reuse (as a whole mattress with or without cleaning or repair), recycling (through disassembling), incineration or landfill.

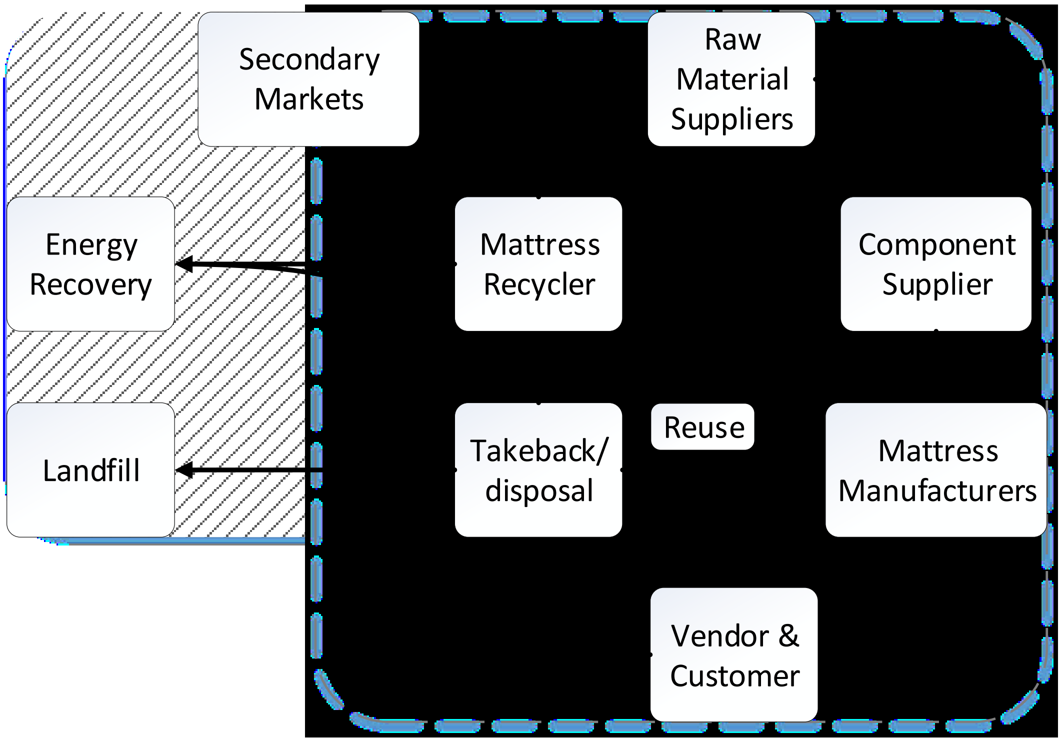

Figure 5.1 Mattress life cycle

5.2.1 COLLECTION OF MATTRESSES AND ROUTES TO DISPOSAL

In order to quantify the scope of the challenge of mattress recycling, the study provided an estimate of the current flows of post-consumer mattresses from collection to end destination for the year 2018, based on methods adopted by previous reports [6], [13]. The number of mattresses sold in the UK in 2018 was estimated by combining statistics from the European Commission databases Prodcom [17], from the manufacture of mattresses in the UK, and Comtext [18], from the import and export value of mattresses. Prodcom provides, for the UK the annual number of mattresses produced and average trade price per unit across four mattress types. The average trade prices were used to estimate the net quantity of imports from the Comtext data, where estimates for net imports were combined with the production data to give a measure of total UK mattress consumption for 2018. From the net consumption figure, it was estimated that 90% of new mattresses purchased will result in a mattress being disposed of, which was in line with previous estimates [6].

The collection routes for post-consumer mattresses were defined as: local authorities, private waste companies (waste contractors) and take-back schemes; either commercial or domestic. Data on mattresses collected by local authorities by tonnage was compiled from the online portal for Waste Data Flows (WDF) [111] with supplementary information from mattress recyclers where there were data gaps. The number of mattresses was calculated by dividing the tonnage collected by the authorities by the average mattress weight, estimated by previous studies to be 20kg [1]. The number of mattresses collected through take-back and waste contractors were estimated based on feedback from mattress manufacturers, mattress recyclers and waste contractors. The final destination of mattresses, defined as either landfill, incineration, recycling or reuse, were based on adjusting recent estimates for 2017 [1] with interviews and data collected from local authorities, mattress recycling companies and waste contractors.

5.2.2 MATTRESS DESIGN AND RECOVERABLE WASTE STREAMS

To provide information on the waste streams that can be recovered from post-consumer mattresses, an overview of the basic mattress design for the different constitute materials and components was given, along with descriptions of the different methods of mattress deconstruction, based on site visits and interviews with mattress manufacturers and recyclers. Recoverable waste streams arising from waste mattresses were determined by information from mattress recyclers, with the categories based on recyclers with a higher degree of separation. Identified waste streams were analysed in more detail looking into the original manufacturing process, disassembling methods, current and potential markets and applications. Information on the waste streams was gathered from primary research into mattress suppliers, manufacturers and recyclers, as well as desk research on recycling companies and applications for the specific materials.

5.2.3 Recoverable waste streams value and composition

To report on values for the identified waste streams, information was used from price points that mattress recyclers reported they would typically receive for the waste streams. Information was sourced during the period January - September 2019 from six mattress recyclers and from published industry prices where available. The value that can be generated from the defined waste streams was important in order to identify the low yielding materials/components and to identify where investment is required to improve their recoverable value.

The quantity of each waste stream per mattress was determined to understand the significance of the waste stream values in relation to an average mattress. The composition of an average mattress was compiled using data and information from six UK mattress recycling facilities with a combined annual throughput of approximately one million post-consumer mattresses. In compiling the composition information from different recyclers and their sources, the information was weighted to reflect the total waste stream of post-consumer mattresses in the UK. This was because mattress recyclers will tend to recycle a higher proportion of mattresses from take-back schemes.

5.3 RESULTS AND DISCUSSION

5.3.1 COLLECTION OF MATTRESSES AND ROUTES TO DISPOSAL

Collection of mattresses and routes to dispose mattresses were collected through retailer, manufacturer or third party take-back schemes as well as by waste contractors, local authorities or charities. Some mattresses that were returned to vendors or manufacturers such as unsold or customer returned mattresses were in certain cases, found to be resold though internal company sales, auctions or charities. Sectors like hospitality and universities, tend to use waste contractors such as local skip companies or have take-back arrangements with mattress suppliers or directly though mattress recyclers. Domestic post-consumer mattresses were disposed of either through local authorities (though drop off at household waste recycling centres and door-to-door bulky waste and fly-tipping) or take-back schemes offered by retailers, manufacturers or third parties. Local authorities generally send mattresses directly to landfill, incineration or mattress recyclers, but a few authorities have reportedly undertaken manual on-site deconstruction in the past [112]. Post-consumer mattresses collected through take-back schemes will largely be sent for recycling [6], with some manufacturers manually deconstructing in-house. Waste contractors, such as skip companies may manually deconstruct mattresses, recovering more valuable materials such as metal or polyester, before incineration/landfill of the rest, or directly send whole mattresses for incineration or landfill.

Table 5.2 presents an overview of the estimates for the flow of post-consumer mattresses in 2018. The total number of mattresses sold in 2018 for UK consumption was estimated to be 8.4 million, a 45% increase from 2013 figures [6]. An estimated additional 0.1 million mattresses which entered the waste stream were recirculated for consumption bringing the total mattress consumption figure for 2018 to 8.5 million. The total number of mattresses disposed of was estimated to be 7.6 million, with most mattresses collected through local authorities and waste contractors.

Table 5.2 Post-consumer mattress flows in 2018

Collection route	Disposal quantity (million)		
	Collected	Landfill/ Incineration	Recycler
Authorities[3]	3.8	2.9	0.9
Waste contractors[4]	3.0	2.6	0.4
Take-back[4]	0.8	0.2	0.6
Total	**7.6**	**5.7**	**1.9**

Local authorities were estimated to collect 3.8 million mattresses annually, based on the calculations from the WDF flows. Not all authorities separate or report mattress collection, so estimates were made for the total number of mattresses collected by authorities across the UK. This was based on the mattress disposal rate of a selection of 66 authorities across the country, representing 27% of the UK's population to give the total mattresses collected which was scaled up to reflect the total UK population. The number of mattresses collected annually though other commercial and domestic take-back schemes was estimated at 0.8 million, with 3 million for waste contractors, based on data and feedback estimates from industry.

The number of mattresses sent for recycling was estimated to be 1.9 million, with 0.6 million originating from take-back schemes, 0.9 million from local authorities and the remainder from waste contractors. For the purpose of the recycling figure, mattresses where only the spring units were recovered have been excluded. Due to the lack of information and data to distinguish between mattresses going to landfill verses incineration the figures have been combined. Feedback from two major energy from waste operators, was that spring mattresses cause problems when passed through their incinerators, meaning that mattresses are often pulled from incineration lines and

[3] Based on data from [111] and information from mattress recyclers assuming an average mattress weight of 20kg
[4] Based on feedback from manufacturers, mattress recyclers, waste contractors and information from Bell [6]

diverted to landfill. The quantity of mattresses going to incineration was considered to be in the region of 2 million mattresses, less than what was previously estimated [6].

The final destination of waste mattresses was heavily dependent on the lower cost of sending mattresses to landfill/incineration versus recycling. In the UK, mattresses are classed as non-hazardous waste at most landfill sites [45], which means a current mattress disposal cost of £91 per tonne [113]. For local authority sourced mattresses with an average weight of around 20 kg, this equates to a disposal cost of £2 per mattress, compared with take-back mattresses with an average weight of around 30 kg [6] costing £3 per mattress. Across the UK, there was limited access to mattress recycling sites, meaning access to these facilities was dependent on being able to fund the transportation of the mattresses. At mattress recycling facilities, a gate-fee was charged, generally between £3-8 per mattress, to cover processing and disassembling costs. The gate-fee amount can depend on sources, mattress condition, location, the recycler's efficiency and the value that can be generated/obtained for the separated waste streams. The lower disposal cost of mattresses to most landfill sites makes it difficult for budget constrained local authorities and profit driven waste contractors to opt for sending mattresses for recycling even when such facilities were available. One interesting point highlighted by the research, was that some councils, even when mattresses recycling facilities were not located in the same region, were opting to pay significant premiums to transport their waste mattress long distances across the country to recycle their mattresses, whilst other councils within the vicinity of mattress recycling plants could opt to send their mattresses for landfill. This counterintuitive scenario was due to discrepancies in council spending power and their motivations to hit recycling targets. The discrepancies could be significant for cost-modelling of future mattress recycling processes.

The recycling rate for take-back mattresses was far higher. The recoverable value of constituent materials and components from take-back mattresses was generally higher than other sources, with mattresses kept dry and containing a greater proportion of valuable recoverable materials such as polyester, reusable spring and foam sets. Further, the mattress recycling premium was being funded directly by the customer when they opt to utilise a take-back service that include mattress recycling; this was not the case for mattresses disposed of via local authorities and waste contractors.

5.3.1.1 Implications of disposal costs

Currently, for local authorities, waste companies and industry, the cheapest and most accessible option to dispose of post-consumer mattresses was commonly through landfill or incineration. A ban on sending mattresses to landfill, would probably not be workable due to the lack of capacity and access to alternatives available nationwide. Where capacity to recycle mattresses does exist, it may be beneficial to ban landfill in those areas, similar to the landfill bans in specific states and provinces in the US and Canada. Policy initiatives to fund and encourage the delivery of post-consumer mattresses to recyclers could be implemented to provide economic incentives whilst recycling capacity grows so that mattress recyclers' gate fees become more competitive versus disposal routes to landfill or incineration. Incentives could be in the form of a deposit scheme as in some US States [34] or an EPR funding scheme as in France [30]. One option raised would be that local authorities would be able to bid for mattress recycling contracts through RAMR [6]. A potential drawback of contract bidding is that the quality of recycling that different recyclers provide could vary significantly in terms of the mass percentage of material recycled versus the percentage sent for calorific recovery though SRF or RDF. This would not be reflected in the gate fee mattress recyclers charge. Further research is required to study the environmental impacts of different recycling options in order to inform the socio-technical cost benefit of recycling routes such as SRF or RDF in comparison to feasible alternatives through maximising material reuse and recovery. Ultimately, the destination of post-consumer mattress and embodied components is determined by the underlying market forces influencing disposal costs and market demand for the resultant materials. To facilitate improved mattress recycling rates and the quality of recycling, value needs to be created from the waste streams.

5.3.2 Mattresses design and recoverable waste streams

There are two principle mattress categories defined by their core component: springs, PU foam, latex foam or other. Sprung mattresses can be subdivided into open coil (fabric free spring set) and pocket springs (individual springs encased by fabric). Beyond the core component, mattresses have a shell and an outer cover. The outer cover, known as tick, ticking, quilting or outer shell, was generally composed of a mix of textiles which were stitched or glued together with an outer woven finish. Foam mattress designs could consist of a single core block of foam with just an outer cover. For spring designs, the shell layer consists of comfort and non-disturbance layers. The comfort layers can consist of a wide variety of materials including different types of foams, synthetics or natural non-woven textiles. The non-disturbance layer, or insulation layer, isolates the mattress from the spring unit, again with a wide variety of different materials used including synthetic felts, shoddy felts (recycled textiles), coir and jute; which were often stapled to the spring unit. The spring unit corners were often insulated with corner pads and in premium mattresses also side pads made from either synthetic, shoddy, natural or foam materials. The different mattress sections and layers can be glued, stitched and stapled together (through tufting) to bind the mattress and prevent layers from dislodging. The variations in mattress design and materials mean that, when dismantled, due to their heterogeneous nature, the separated waste streams were categorised based on the onward application or market.

Mattress recycling facilities either use manual deconstruction or a degree of automation to deconstruct, strip or shred mattresses separating the mattress into different waste streams, predominately of metal, textiles and foam. The majority of waste streams go to a multitude of different secondary markets or incineration for energy recovery. In some cases, mattress components were recovered for reuse in the budget mattress market, for example spring sets and foam, while some textiles were also being recycled through mattress suppliers. Some recyclers only separate down to four difference waste streams whilst others were able to separate up to 20, where specific components/materials were separated based on quality for different applications such as direct reuse, recycling or incineration. All recyclers send a proportion of waste for incineration, termed in this study as mixed/non-separable waste stream, to recover the calorific content through either SRF or RDF.

5.3.2.1 Open coil

The open coil waste stream consists of any fabric free metal spring design. These springs are generally manufactured in the UK from medium to high carbon steel. When separated from the mattress, the resulting scrap is classed as a low value mild steel, the value of which will range depending on market fluctuations, density of the scrap, relationship and proximity to scrap merchant/plant. Some recyclers will sell whole spring sets back into the budget mattress manufacturing industry, with up to 20% of the recovered springs going for reuse at some recycling operators. However, most open coils were generally baled or shredded before being transported to scrap or smelting plants; some recyclers transport uncompressed spring units when such sites were within close proximity. The capacity in the UK to source and process scrap metal means the open coil waste stream has a secure onward market in scrap value. One drawback of the scrap market was the market fluctuations in scrap values which can have a significant effect on a recycler’s profitability.

5.3.2.2 Pocket spring

The pocket spring is composed of hundreds of individually wrapped steel springs predominantly encased in polypropylene with other designs also using polyester or cotton. The pockets are secured together through glue and or metal retainers stapled to the top and bottom of the pocket spring units. Apart from a small reuse percentage, to recycle, most commonly pocket springs were shredded together with whole mattresses, or when separated in industrial tyre or metal shredders; after which magnets will separate the metallic and non-metallic material. The shredded springs were then sold as scrap while the fabric encasing materials were either sent for incineration or reprocessed if the recycler could find markets. The fabric was difficult to recycle due to glue and other contaminates limiting any further applications to energy recovery. Shredding pocket springs was possible at some metal scrap sites and other specialist companies with industrial shredders. Even with specialist equipment, shredders were reportedly temperamental and expensive to purchase and run, costing more to shred the pockets than the value generated from the arising materials [39]. In some cases, the pocket springs were sent directly to metal smelting plants where the non-metallic content was burned off. However, this practice was reportedly banned in the UK and required the non-metallic content to be less than 5% [19]. Separating the individual steel springs from the textile material that encases them has been reported by recyclers not to be financially feasible manually due to the time required to separate the springs from the encasing fabric. If the pocket fabric could be made of a degradable or emission friendly burnable materials, it may make the recycling process easier and improve the value of the waste stream. One UK mattress supplier has recently launched a pocket spring design without glue [102], whilst a Dutch manufacturer is using removable low melting temperature glue to enable easy separation of the materials [103].

5.3.2.3 Shoddy

Shoddy, as was known in the deconstruction industry, was a common waste stream found in mattresses due to its low cost, often produced from shredded post-consumer clothing which is re-manufactured either into a dense felt (hard shoddy) or less dense comfort layer (soft shoddy). Shoddy, commonly dark grey in appearance when made with mixed clothing, contains a mix of cotton, polyester and other fibres. Alternate forms of shoddy could appear in a light grey or blue when manufactured with isolated colours or denim, which was sold at a premium to the manufacturer due to its greater visual appeal [87]. The soft shoddy was generally a distinct waste stream with the hard shoddy going into the mixed/non-separable stream. The variable fibre type and length means secondary application of shoddy was difficult. Shredding shoddy reduces fibre length making the material unsuitable for manufacturing new shoddy textiles. The soft shoddy fibres can be flocked with fibres separated and manufactured either into new felts for applications such as the automotive industry or building insulation. Some recyclers will also shred the shoddy for equestrian surfaces or energy recovery. The mixed fibre content and size limits higher value applications which is unlikely to change, given that shoddy is composed of cheap secondary recycled material popular with mattress manufacturers.

5.3.2.4 Mixed/non-separable

This waste stream was generally comprised of the mixed material ticking, hard shoddy felt, other soiled textiles, and in some cases, all textiles and termed “flock” by the recyclers. The ticking is comprised of multi-layered materials stitched, stapled and or glued together, limiting any feasible material separation, with the textile easily contaminated or soiled from use and transfer to recycling facility, making it very difficult to recycle. The ticking can contain a variety of woven and non-woven material layers including viscose, rayon, silk, polyester, cotton, nylon, polyurethane (PU) foam and polypropylene. The heterogeneous nature of the ticking design and material means separating the materials was generally not feasible. In some cases, where the outer cover has been kept clean, the outer woven fabric can be removed to go into the woven textiles waste stream. The other component of the mixed/non-separable waste stream was the hard shoddy felt, which was used as an insulating layer to ensure the springs do not penetrate other layers. The felt has interlocked fibres which have either been heat treated or supported with polymeric backing to prevent any piercing from the springs, making it difficult to re-flock the material for new applications. In most cases, the hard shoddy has no other markets except for incineration, although some recyclers were able to combine certain hard shoddy felts with the soft shoddy waste stream. In some cases, the shoddy insulation layer was not separated from the spring units if the layer was difficult to separate due to high number of staples used to secure the insulation layer to the spring unit. One application of the mixed/non-separable waste stream included shredding; to produce equestrian surfaces or SRF in the UK or RDF for markets in the EU via Sweden, Belgium or the Netherlands. Due to the high calorific content of the textiles, reported by a research report to be between 19-24 MJ/kg for the ticking [4], RDF plants in the UK generally do not accept this type of waste. As mentioned, for some recyclers this waste stream can consist of up to 60% of the mattress mass, common where mattress were shredded whole with minimal separation thereafter. Looking at other possibilities, a Dutch recycler reportedly ships ticking to Morocco to be shredded to produce new yarns [32], [50], with other research conducted into applications including acoustic panelling [48] and pet accessories [49] as well as research funded by the Welsh Government into processing low value mattress textiles [114], [115].

5.3.2.5 Foam

The foam waste stream generally consists of both polyurethane (PU) and latex foam which were commonly not separated from each other. The majority of the foam waste stream was PU with a low percentage latex foam. Approximately 30% of mattresses consumed in the UK were classed as having a main component of cellular plastic (PU foam) with less than 1% being classed as cellular rubber (latex foam) [17], [18]; with foam also commonly used as a comfort layer in other mattress classes. PU foam is a popular material in mattresses due to its low cost, lightweight nature, produced through a chemical reaction of polyols with isocyanat. Due to its chemical composition, PUs are generally very flammable meaning fire retardants are required to be added to the product to allow its use in mattresses [50]. As fire legislation has changed, previously used fire retardants have been replaced, creating legacy chemicals which can be a problem when considering reuse and recycling of older foam mattresses. Flame retardants can also be harmful to health with increased risk from direct exposure such as during the recycling process [116], [117]. Foam when recovered in blocks from foam mattresses, was in some cases sent for reuse in manufacturing new mattresses, or bedding products including those for animals. Foam has also been reportedly shipped abroad for water retention applications [13], [19] such as crop growing [52]. Otherwise, the foam was generally sent to be mechanically recycled through chipping and disinfectant treatment to produce bonded foam for shock absorbing surfaces and carpet underlay. A few mattress recyclers in Europe have developed their own production line for bonded foam [28], [51]. However, the markets for chipped foam to produce bonded foam were reportedly heavily saturated and recyclers generally do not generate any income from this market [19]. Chemical recycling is a future alternative treatment option for PU foam [109], but due to its higher technical difficulty, it is difficult to realise large-scale industrialised production in the short term, but may in the future be the best recovery solution for PU foam [118]. A German based company has developed a chemical recycling technology, whereby the PU foam is treated though a process called acidolysis back into a raw material polyol, containing approximately half recycled and half virgin polyol which can be used to manufacture new rigid and flexible PU products [59]. A pilot plant for this process has been shown to be economically feasible in producing recycled polyols for new applications [60] with additional plants in Europe said to be launching in the near future. However, the process would require significant investment and is estimated to require a feed-stock of PU foam of over 500 tonnes annually to be economically viable.

5.3.2.6 Polyester

Polyester is the fibre form of the polymer polyethylene terephthalate (PET), which has become the most used fibre in the textile industry with a 55% market share [58] and it is commonly used in mattresses due to polyester's physical properties, price, recyclability and versatility [100]. Polyester used in mattresses takes different forms and could be used as a wadding in the comfort layer, felt in the insulating layer or in the ticking as a component or sole material. In the UK, Polyester fabrics are being produced from a combination of virgin and recycled sources such as PET bottles [87]. Post mattress deconstruction, polyester could be reused where recovered, good quality polyester bales, were carded or flocked into new textiles or stuffing; with lower quality bales send for recycling into the fibre blending industry. High quality pure polyester, generally procured from takeback mattresses, would generate the highest value from these applications with minimal disinfecting or cleaning required. Chemical recycling may be another alternative for contaminated polyester [56], although current sites were limited and not available in the UK. This may in the future prove to be an opportunity to up-cycle contaminated polyester to a new virgin quality PET resin.

5.3.2.7 Woven textiles

From the ticking component, some of the woven materials, made from materials such as viscose, silk, cotton and polyester, can be removed. Where the outer covering of the mattresses has been kept clean and dry, predominantly from mattresses that reach recyclers in plastic film from take-back schemes, the woven outer layer can be separated. Some recyclers send this material back to the original manufacturers or re-processors in countries such as Turkey, Ukraine and Morocco [19].

5.3.2.8 Cotton/wools

This waste stream consists of non-woven natural materials, predominately cotton and various types of wool. For the cotton based non-woven textiles, some recyclers would not distinguish this from the polyester stream and as such, any white non-woven textile was baled together; which generally reduced the value of the bales. The wool based materials were easier to identify as they tend to appear light brown in colour. Where the non-woven natural materials were separated, these cellulose based materials could be sold to onward markets which process them into fibres or yarns for manufacturing paper, textiles and wiping ranges which were generally mixed with virgin fibres [19], [56]. Chemical recycling is also possible for blended or contaminated waste but the majority of process were still in development [57].

5.3.2.9 Jute/coir

This waste stream includes plant derived fibres including jute and hemp, known as bast fibres [58], and coir, derived from coconut husk. These materials were found as woven or non-woven textile layers used more commonly as an insulation layer but also as a comfort layer in traditionally designed mattresses. The use of these materials has become less common but would be problematic to separate due to the high number of staples attaching the layers and the high dust content. These materials can have applications in the horticultural industry but were required to be free of other contaminates such as metal staples. Not all recyclers separate this waste stream as it can be very time consuming to manually separate the insulation layer from spring unit when staples have been used to attach the layers.

5.3.2.10 Plastic film

When mattresses were collected through take-back schemes and some domestic bulky waste collections, mattresses would often be wrapped in plastic covering (film) which enables mattresses to be left outside for kerbside collection and/or to prevent cross contamination of clean and soiled mattresses. The plastic was most commonly classed as low density polyethylene (LDPE) 98:2 film which had a fluctuating market value often between £200-300 per tonne which was sent on to UK plastic merchants for onward processing in locations such Eastern Europe [119], [120]. The quantity of the plastic covering waste stream was heavily dependent on sourcing mattress from take-back or return schemes. Generally, the plastic covering was cut open manually from the mattress, baled and stored before transfer to onward markets.

5.3.2.11 Other

Other waste streams included materials such as wood, LDPE foam, rigid plastic meshing and leather. Wood is less common in UK mattresses than in other countries, predominantly found in box spring designs, a common mattress design in the US and Australia, or as supports in the mattress side panels. Many mattress recyclers will also collect bed-bases and head-boards, predominately wood based, meaning mattress recyclers can process significant volumes of wood which were generally sent to onward markets for chipboard, fibreboard, wood mulch or fuel [11]. The LDPE foam, similar to polystyrene in appearance, was used as a side panelling support in mattresses, but found to have no onward markets other than landfill or energy from waste applications.

5.3.3 IMPLICATIONS OF MATTRESS DESIGN

The nature of mattress design and variability in construction and materials reduces the effectiveness and efficiency of mattress deconstruction and quality of recycling thereafter. This is where the mattress design and material selection need to be changed. Manufacturers should be able to demonstrate that the constituent components within the mattresses they produce can effectively and efficiently contribute to a circular economy. This means designing products to enable easy dismantlement, as demonstrated by Auping, a Dutch manufacturer, [103], whilst ensuring there is onward application and capacity to reuse or recycle the materials. In addition, there is an urgent requirement to understand the health impact of recycling materials containing banned substances and what needs taking into account when considering recycling. Further research is required to provide an in-depth review of best practices for material selection, mattress design and construction, to enable design for disassembling and maximising reuse/recycling of components. The difficulty in improving recyclability of mattresses is beginning to force through change and radical innovation into an industry where traditionally any mattress design modifications to incorporate end-of-life considerations have been largely incremental or non-existent. Design consideration for disassemble and recycling have simply not been a priority of the design process. The lack of significant progress in improving mattress recycling and the quality of the recycling is partly due to manufacturers and suppliers not taking responsibility for the impact of their products on the environment. Manufacturers and suppliers have to be prepared to radically change by investing significant resources into designing products to be circular whilst ensuring there is capacity to actually recycle them. In addition, legislation to ensure recyclability of mattresses must be made a priority; just as past legislation has ensured that mattresses meet strict health and safety requirements [59]. The design and implications of new legalisation need to be supported with understanding of the environmental impacts and benefits of product design, material selection, and end-of-life recovery [31], [36], [97]. Finally, customers and consumers of mattresses need to apply pressure to the mattress industry to change the way mattresses are designed.

5.3.4 RECOVERABLE WASTE STREAMS VALUE AND COMPOSITION

Figure 5.2 presents the average values ranges of the different waste streams. These values were based on the range the recycler would typically receive for the different waste streams. Not all of the recyclers would separate into the defined waste streams, so where the recycler reported a single price range for waste streams which were mixed together, the price was included in the average price for each constituting waste stream. The value from direct reuse of the open coil, pocket springs and foam pads was excluded as prices were reported on a per unit basis, but was thought the value per tonne for direct reuse would be 3-4 times higher than of the highest value listed in **Figure 5.2**.

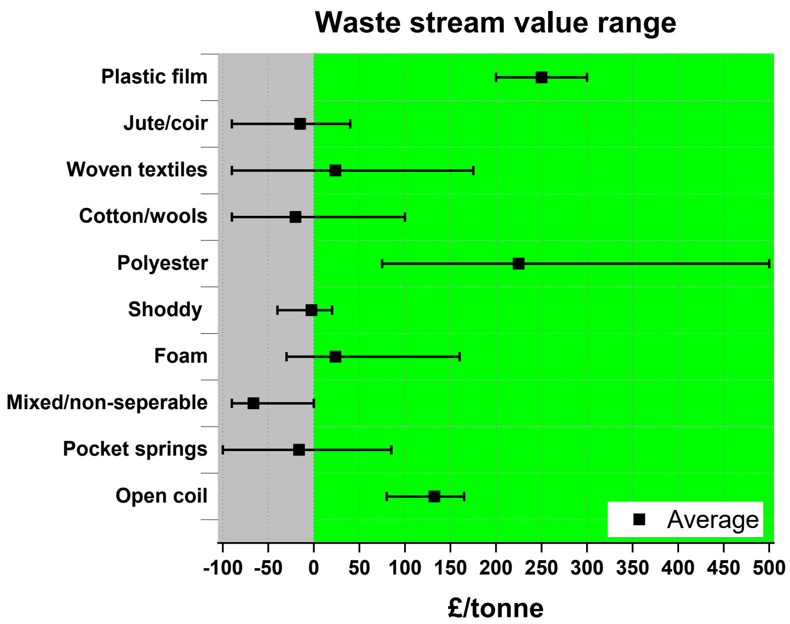

Figure 5.2 Waste stream value per tonne

Large variations in the value received for the waste stream materials was found to be due to factors including the recycler's access to onward markets, on-site reprocessing facilities, quantity and quality of the waste streams. The number of waste streams at different recyclers varies significantly, dictated by the on-site processing facilities and ability to access local and international markets. Recyclers with the highest degree of separation were able to minimise the quantity of materials sent for incineration down to 8%, which increases to over 60% for recyclers with minimal separation.

Figure 5.3 illustrates the findings on the waste stream composition arising from the average post-consumer mattress, with the value range of the waste streams based on the values from **Figure 5.2**. From the UK recyclers, the waste stream composition would vary significantly depending on the sources of mattresses. Mattresses sourced from local authorities would typically be open coil with a greater proportion of shoddy and non-separable textiles, whereas the mattresses from take-back schemes tended to have higher contents of polyester, natural based textiles and pocket spring designs. Generally, the mass fraction of open coil and pocket springs reported by recyclers was in the 50% region, with recyclers reporting growth in the number of pocket spring mattresses. The low recoverable value from the waste streams of shoddy, woven textiles, cotton/wools and jute/coir means there was little incentive for recyclers to separate these waste streams. Waste streams were generally baled and stored until there was sufficient quantity of bales to fill a 40ft. freight container or articulated lorry. For waste streams of cotton/wools and jute/coir, this could require processing over 40,000 mattresses to produce sufficient quantities of the materials.

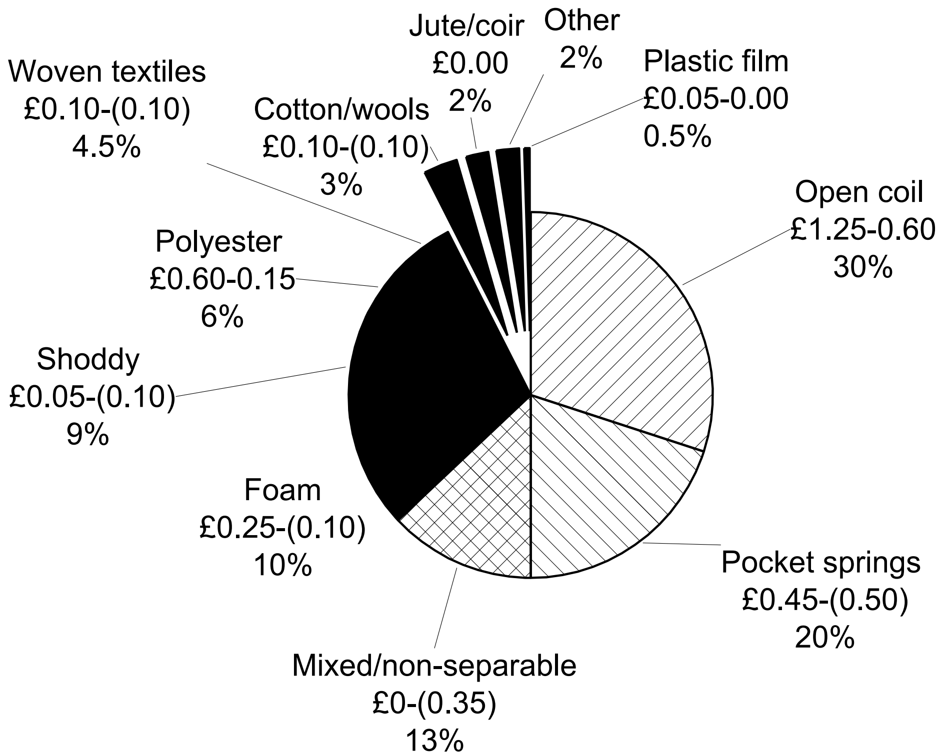

Figure 5.3 Average mattress value range and composition per waste streams

5.3.5 DEVELOPING MARKETS FOR RECOVERABLE MATERIALS

Just as important as increasing the quantity of mattresses going to recycling is maximising quality of recycling. A well as providing economic incentives or legislative policies to divert mattresses away from landfill and incineration, parallel incentives and legislation need to be implemented to grow the capacity and ensure the quality of material recovered from post-consumer mattress, and that it does not saturate current onward markets for waste-stream materials further.

From the price data presented in **Figure 5.2**, there were large discrepancies between obtainable value for separate waste streams due to access, relationship and knowledge of onward markets. Prices were also highly volatility, partially for metals, polyester and plastics. Whilst it is important that mattress recyclers compete by driving efficiency improvements and maximising waste steam values, there is an opportunity for recyclers to work together with industry in developing onward market applications and capacity. Taking scrap metal as an example, markets for scrap metal are accessible across the UK with sites acting as spokes to supply hubs - large smelting plants. Scrap metal sites act as spokes to supply hubs - large smelting plants. The success of this recycling has been driven by retained value of scrap metal and its simple recycling process. The success of this recycling has been driven by retained value of scrap metal and its simple recycling process. However, most materials found within a mattress, especially those readily contaminated, carry low to negative value. For predominant waste streams, technology is available to treat and process components such as ticking, PU foam and other textiles in order to recirculate the resources back into the economy. John Cotton, a major supplier of non-woven textiles to the mattress manufacturing industry, has said they would be able to directly reprocess post-consumer waste streams back into bedding and mattresses, however, this was currently viewed as not financially viable due to the added cost of reprocessing. One option is offering funding opportunities though government or EPR schemes for industry to collaborate in developing technologies and facilities to effectively recycle waste stream materials similar to the US Mattress Recycling Council, or France's Éco-mobilier. One often neglected challenge in developing mattress recycling, is that some mattress recyclers have very negative opinions of each other, due to perceptions of unethical or illegal practices, which also extends to some manufacturers. This is thought to have slowed the development of regulation and any other further collaboration or intervention to expedite the quantity and quality of mattress recycling levels.

5.4 CONCLUSIONS

This study has discussed actions for policy and industry in tackling the three key issues of mattress recycling: sourcing post-consumer mattresses, mattress design and onward markets for arising waste streams. The sources, flows and destinations of post-consumer mattresses have been quantified, with analysis conducted on recoverable waste streams from mattresses. Applications and potential design modifications to increase the recyclability of mattresses have been reviewed. In addition, the research defined the composition of a typical mattress to enable the quantification of different waste streams along with their market value, in order to identify where markets need to be developed further. Potential alternative recycling markets have been discussed, such as chemical recycling for PU foam and textiles. The study has provided examples of industries where legislation and innovation have proven successful in improving the circularity of products and mattresses in countries such as France and in some US states with successful mattress recycling programmes.

In order to increase mattress recycling, beyond its current incremental linear growth rate, as well as the quality of mattress recycling, there is a need for a collaborative and multifaceted approach between industry and government to address mattress design, fund the collection of post-consumer mattresses to recycling facilities and to develop the capacity to facilitate and increase the quantity and quality of recycling waste streams. There was a distinct lack of a coherent and holistic approach to stimulate proactive action between different stakeholder groups across the mattress life-cycle to facilitate widespread quality mattress recycling. Further work is urgently required to inform manufacturers on best practices for material selection, mattress design and construction to enable design for disassembling and maximising the reuse and recyclability of components and materials. Research is required to quantify the socio-economic benefit of different approaches to repurposing waste streams such as energy recovery versus recycling recovery though greater materials separation. Finally, significant additional resources and investment to facilitate increased mattress recycling, whilst maximising the quality of material recovery, must be made a priority for the mattress industry and public policy.

Acknowledgements

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6 INCORPORATION OF RECYCLED WASTES FROM MATTRESSES INTO BUILDING MATERIALS

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Abstract – This study reports on the mechanical and thermal properties of mortar and plasterboard materials that have been modified via the addition of mattress origin waste materials. Mattress wastes were evaluated as recycled material additions with cement based mortar incorporating shredded polyurethane or latex foam and with gypsum based plaster incorporating ticking (mixed fibres). For mortars, foams were substituted for the sand phase with total mass additions from 0-0.75%. For gypsum plaster, mixed fibre was substituted for gypsum powder by mass from 0-3.5%. Compressive and three-point bend flexural test specimens were produced using cube and beam moulds. Thermal modelling was used to predict the thermal conductivity of the modified materials. Mechanical property results were reported for specimens tested at 28 days for the mortars, and for 9 days for the plasters. It was found that compressive and flexural strengths of the cementitious mixtures were detrimentally affected in mortars containing latex above 0.375% and polyurethane above 0.5% by mass. For plaster blends, no statistically significant change in compressive strength was found for mixed fibre additions less than 3% mass, and for all specimens, mixed fibre addition was accompanied by an increase in flexural strength. The thermal modelling showed that incorporation of foams and fibres into the building materials improved their insulative properties, measured by decreases in thermal conductivity (range 2-60% reduction) for both the cementitious and plaster mixes. The study has shown that common building material blends containing mattress material fibres and foams can be produced without significant detriment to the mechanical performance, and modelling showed these additions to improve the thermal insulative properties.

6.1 INTRODUCTION

Mattresses are difficult to recycle as they are bulky, of mixed material composition and readily contaminated by moisture ingest. Mattresses are comprised of a mix of metal, foams and textiles. Although the metal has established onward recycling applications, foams and textiles are often difficult to recycle with much material either landfilled or incinerated to recover calorific content. The landfill of mattresses and components wastes precious resources and has been shown to be the most environmentally detrimental disposal route with incineration through heat and power recovery providing a slight positive offset of greenhouse gas emissions and recycling shown to yield a high positive offset of greenhouse gas emission [97]–[99]. Although recycling has been found to provide the highest environmental benefit, current figures within the EU suggest that mattress recycling rates are low and a large proportion of end of life whole mattresses and mattresses components are being sent to landfill or incineration [6], [55]. One of the main reasons for this has been down to the lack of feasible alternative applications for the mattress and components other than being landfilled or incinerated.

Mattresses are generally comprised of three components: the core (either metal or foam based), the comfort layer (consisting of nonwoven textiles/foams) and the outer cover or ticking (composed of mixed woven and non-woven textiles). Secondary recycling applications are possible where materials are separable and kept clean. Heavily soiled and mixed textiles are inherently difficult to recycle, limiting further onward applications meaning these materials carry low to negative value. The low to negative value of these waste streams reduces the economic incentive to recycle mattresses, and without development of onward applications, is unlikely to change. There have been recent developments to utilising these difficult to recycle waste streams such as mixed textiles [54], [56], [57] and polyurethane foam [59] as feed stock for new applications through chemical recycling, but such processes are currently limited due to lack of investment and the cost effectiveness at a commercial scale.

Furthermore, alternative means of recycling through mechanical and or thermal treatment to clean and process waste streams can be expensive and energy intensive.

As an alternative application, the focus of this paper is to study the transfer of difficult to recycle mattress waste streams into cementitious and gypsum plaster building materials. By minimising the need for sorting and pre-treatment, and targeting direct transfer of shredded waste streams into building materials [65], the cost burden of processing difficult to recycle waste streams from mattresses could be reduced. Therefore, the application of mattress waste streams into building materials needs to be investigated further. In the EU, each year approximately 175 million tonnes of cement and 11 million tonnes of gypsum plaster are produced [89]. The quantity of low value mattress textiles to be landfilled or incinerated annually in the EU, is estimated to be 0.27 million tonnes [55], which relates to a mass three magnitudes lower than that of the production of cement and gypsum plaster, illustrating the potential that these building materials have as storage vessels for the mattress waste. Only a tenth of a percent of the mass of the cement and plaster would need to be replaced to utilise all of the low value waste mattress textiles currently sent to landfill or incineration.

The area of incorporating waste into building materials has been heavily reported on in recent years with a global drive to find applications for a multitude of different waste materials as well as the pressing environmental need to increase the sustainability of construction materials. Research into the addition of waste into cementitious and gypsum materials has been abundant for materials such as tyres [61], rigid plastics [62], [121], foam [74]–[79], [122], and fibres [69]–[73], [75]. The types of cementitious mixture reported vary greatly from mortar based mixes [72], [74], [76], [121], [122] of cement and sand to concrete based mixes with cement, sand and course aggregate [69], [80]. Gypsum mixtures have either incorporated waste as an addition aggregate [73], [75], [77] or substitute for the powered plaster by mass [70], [71], [88] or volume [78]. For the cementitious materials, additions of waste aggregate has replaced either cement [72], sand [74], [76], [121], [122] and or coarse aggregate [80] by either mass [72], [74], [79] or volume [69], [76], [80], [121], [122]. Generally, the compressive strength of materials incorporating waste has been found to decreases and it is thus usually important to employ a mix design, incorporating waste that does not lead to significant reductions in the compressive strength.

The wide variation in mix designs made it difficult to determine mix designs for additions of waste mattress materials. The studies that utilised foam and fibres provided good parallels to that of the mattress waste streams. When foam was incorporated into mortars, higher cement to sand ratios were found to reduce the decrease in mechanical perforce of mortars [76], where it was demonstrated that, with a cement to sand ratio of 1:2, up to 2.5% of cement mass could be substituted for foam without significant detrimental reduction in mechanical performance [79]. For the plasters, studies where fibres were incorporated at mass additions from 0-2%, showed an increase in the compressive strength for [70], and in flexural strength for [73], whilst [70], [75], [78] showed increases in the thermal resistivity of plasters with waste additions.

The findings from previous studies were useful in designing suitable mixes for additions of different mattresses wastes. Studies suggest that a greater quantity of foam can be added to cementitious materials verses platers without significant detriment to the mechanical strength properties, whilst the addition of fibres to plasters suggest that mechanical strength and thermal resistivity can be improved.

The incorporation of waste from mattresses into building materials to our knowledge had not been previously studied. In this context, the present study investigated the mechanical and thermal properties of cementitious and plasterboard materials that have been modified via the addition of mattress origin waste materials. Shredded polyurethane (PU) foam, latex foam and ticking (mixed fibres) mattress material wastes were evaluated as candidate recycled material additions to Portland cement based mortar and to Thistle gypsum based plaster mixes. Waste additions were incorporated into the composites based on their mass due to the waste densities being greatly influenced by their high compressibility and absorption [74], [81]. For the cementitious materials, PU and latex foams were substituted for the sand phase in mortars by mass. To investigate the effect of the waste material additions on mechanical properties, and thereby evaluate the potential design space for the composites in built environment applications, compressive and three-point bend flexural strength test specimens were produced, from which failure strength, toughness and fracture energy were determined. First principles thermal modelling was also used to model the thermal behaviour of the modified materials, which was augmented by experimental thermal analyses conducted on plaster specimens containing recycled material additions.

6.2 MATERIALS AND METHODS

6.2.1 MIXES AND MATERIALS

6.2.1.1 Mortar mixes.

The materials used to prepare mortars were Portland cement (CEM II 32.5R), kiln dried sand with particle size 0-2 mm and apparent density of 1545 kg/m^3, and foam of either polyurethane (PU) or latex which had been hand shredded to particle sizes 5-15mm with apparent densities of 18.25 and 75 kg/m^3. The PU and latex foam was sourced in single blocks from UK mattress manufacturer Silentnight Group Ltd. Nine mortars were prepared with one control mortar and eight with foam additions equal to total mixture mass of (0.25, 0.5, 0.75) % with PU foam and (0.125, 0.25, 0.375, 0.5, 0.75) % for latex foam. The mass of the foams substituted the mass of the sand phase in the mortar mix. The cement was prepared with a mass of 45 % water along with a mass of 1 % superplasticizer (SP) Glenium 51 with the cement to aggregate (sand and foam) mass ratio of 1:2. The composition of mixes is detailed in **Table 6.1** where the mass and volume of the waste material was also given in terms of the total premix waste percentage. To prepare the mortars, cement paste was first mixed by combining the cement, water and superplasticiser for approximately 45 s on low velocity in a 6 litre mixer. The remaining aggregate of sand and foam were pre-mixed by hand and added to the mixing cement paste over the course of 15 s and mixed on a medium velocity for approximately 150 s. Noted PU 0.75 required additional water to combine aggregates.

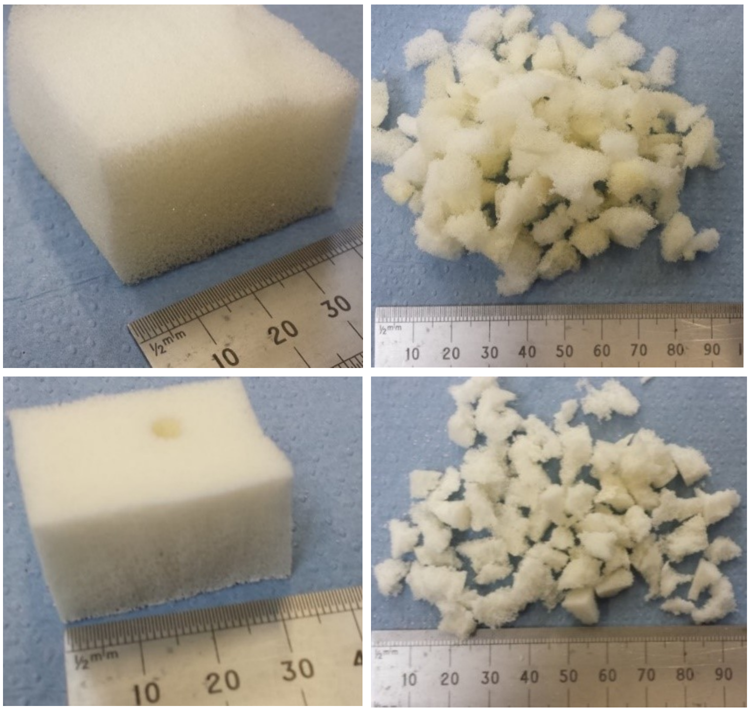


Figure 6.1 PU foam (top), latex foam (bottom)

Table 6.1 Composition of mortars by mass for 1 kg of cement

Mix name	Total mass % foam	Mix proportion Mass (g)						Total premix foam volume %
		Cement	Water	SP	Fine sand	PU foam	Latex foam	
CM	-	1000	450	10	2000	-	-	-
PU 0.25	0.25	1000	450	10	1991	9	-	16
PU 0.5	0.50	1000	450	10	1983	17	-	27
PU 0.75	0.75	1000	600	10	1974	26	-	35
L 0.125	0.12	1000	450	10	1996	-	4	2
L 0.25	0.25	1000	450	10	1991	-	9	4
L 0.375	0.37	1000	450	10	1987	-	13	6
L 0.5	0.50	1000	450	10	1983	-	17	8
L 0.75	0.75	1000	450	10	1947	-	26	12

6.2.1.2 Gypsum plaster mixes

Plaster mixes were composed of commercially available gypsum (Thistle MultiFinish), water and mixed fibre additions which had been shredded from a section of ticking with scissors into mixed fibre clumps of size 5-20 mm with an apparent density of 50 kg/m^3. The ticking was sourced as previous and contained a mix of materials including polyester, polypropylene and cotton. In total, seven plaster designs were prepared consisting of one control and six with additions of mixed fibre substituting gypsum powder by mass for (1, 1.5, 2, 2.5, 3, 3.5) %. Control specimens were mixed following manufacturers instruction with 11.5 litres of water required for 25 kg of gypsum powder with a mass of 46 % water to gypsum which was kept constant to the mass of gypsum and addition of mixed fibres. Dry components of gypsum and mixed fibres were hand mixed for approximately 30 s prior to being added to the water. The mixtures were then combined in a 6 litre mixer at low velocity for approximately 60 s until fully mixed. The composition of the gypsum plaster mixes is found in **Table 6.2** along with the total premix mass and volume proportion of the mixed fibres. Noted GT 3.5 required additional water to combine the aggregates.

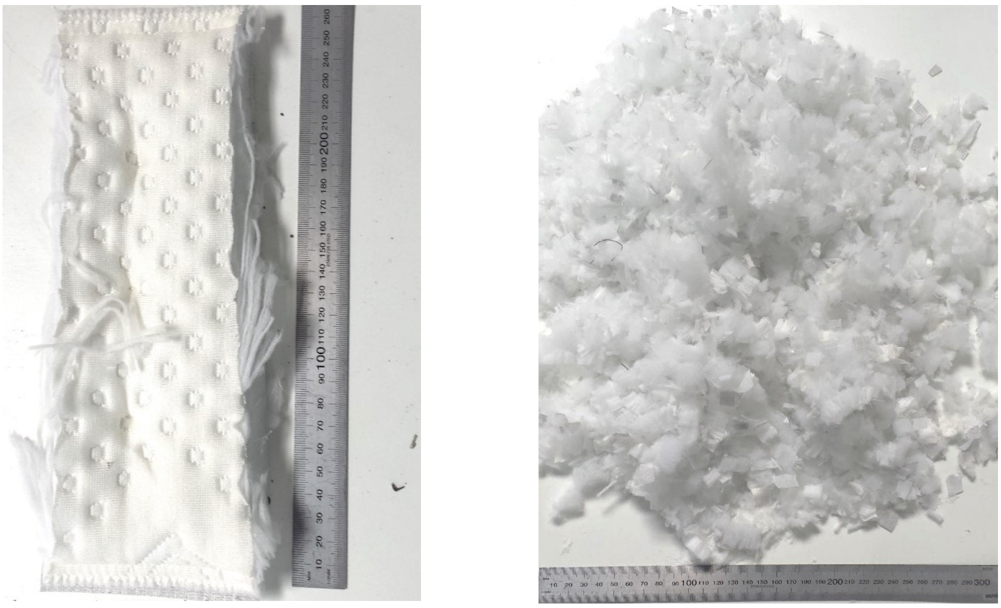


Figure 6.2 30 grams of ticking un-shredded (left) and shredded fibre (right)

Table 6.2 Composition of gypsum plasters

Mix name	Fibre mass % replacing gypsum	Mix proportion Mass (g)			Total mass proportion fibre %	Total premix fibre volume %
		Gypsum	Water	Mixed fibres		
CG	-	1000	460	-	-	-
GT 1	1.0	990	460	10	0.69	14
GT 1.5	1.5	985	460	15	1.03	19
GT 2	2.0	980	460	20	1.37	24
GT 2.5	2.5	975	460	25	1.71	29
GT 3	3.0	970	460	30	2.05	33
GT 3.5	3.5	965	483	35	2.40	36

6.2.2 EXPERIMENTAL

The fresh mortar and gypsum plaster mixes were cast into 50 mm^3 cubic moulds for compressive test specimens and 40 mm x 40 mm x 160 mm beam moulds for three-point bend flexure specimens. For each unique mixture, three specimens were produced for flexure testing and three for compression testing. All specimens were left to cure for 24 hours before demoulding; cementitious specimens were then placed in a temperature-controlled curing tank held at 22 ± 2 °C for 7-28 days where as the gypsum plaster specimens were left to dry at room temperature in ambient laboratory conditions. Mechanical tests on the gypsum plaster specimens were conducted at 9 days post-moulding, the time at which mass loss from the specimens due to water evaporation had become negligible. Additional batches of the gypsum plaster mixes were also produced for workability tests, the mixtures from these tests were cast into the beam specimens for experimental thermal analysis, with dry mixture densities in line with the mixtures for mechanical testing.

6.2.2.1 Compressive properties.

Compressive toughness measurements can be used to evaluate the ability of a specimen to absorb energy and to resist compressive damage [123]. The compressive strength and the compressive toughness of the cementitious and plaster-based specimens was measured. For the mortar specimens, the compressive strength at 7 and 28 days was measured, in accordance with EN 12390-3 [91]. An Instron 8802 with a 250 kN load cell operated with cross-head compression rate of 0.4 MPa/s was used for all cementitious specimens. Gypsum plaster specimens were tested in compression after 9 days, and due to their lower compressive strength verses cementitious materials, were tested with a lowered compression rate of 0.1 MPa/s to accurately capture the plaster failure behaviour. The compressive strength of each mix was calculated from the average of three specimens. **Figure 6.3** shows a specimen prior to compression.

From the load compression data generated for each test, the compressive toughness was calculated for cementitious (from 7 & 28 days) and gypsum plaster materials (from 9 days). The load surface area of specimens was measured prior to testing which was used to generate a stress strain curve (from the load compression data). The toughness was then determined by calculating the area under the stress strain curve using a best fit polynomial (forth-sixth order) up to the maximum stress; with the area defined by the strain point relating to the maximum load.

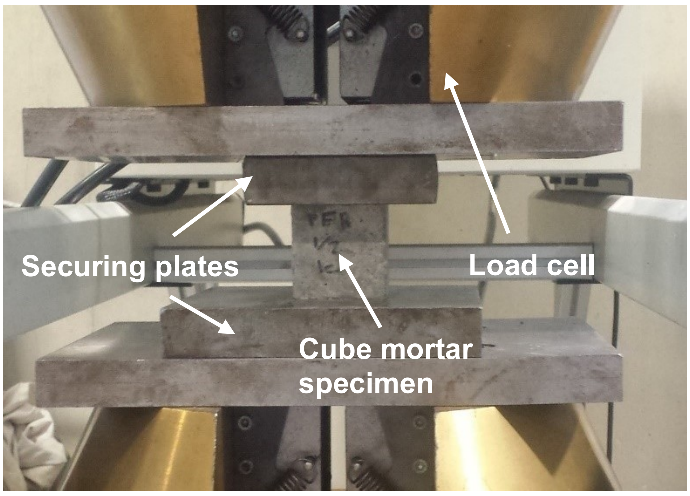


Figure 6.3 Cubic compression test set up

6.2.2.2 Flexural properties

Three-point bending was used to evaluate flexure strength, fracture energy, fracture toughness and flexure toughness index of gypsum plasters. Three-point bending on mortar specimens was tested after 28 days in accordance with EN 12390-5 [124] at a loading rate of 2530 N/min. For the gypsum plaster specimens, tests were conducted after 9 days under displacement control rate of 0.3 mm/min used in order to calculate the flexure toughness index. Flexure properties for all mixes were derived from the average of three specimens.

The flexure strength was used to evaluate the maximum pressure that can be exerted on beams before failure given by **Equation (1)**: where f_{cf} is the flexure strength (MPa), F is the maximum load before failure (N), L is the distance between the roller separation (120mm) and d_1 and d_2 being the lateral dimensions of the specimens cross-section (d_1 = d_2 =40 mm). **Figure 6.4** shows a mortar specimen after failure in three-point bending.

$$f_{cf} = \frac{3 \cdot F \cdot L}{2 \cdot d_1 \cdot d_2^2} \quad (1)$$

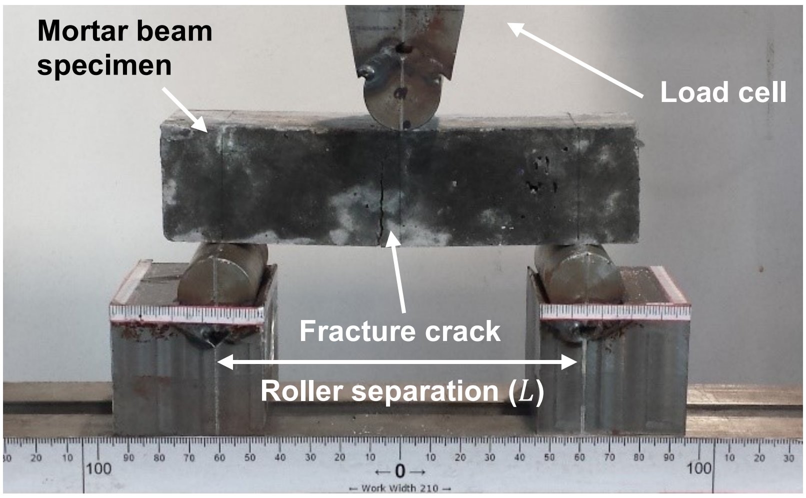
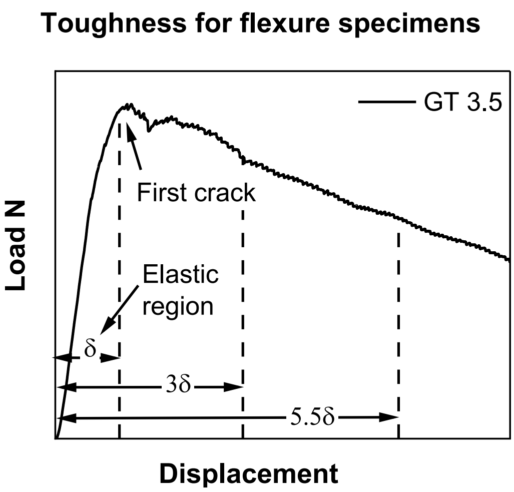


Figure 6.4 Three-point bending post failure

For the gypsum plaster specimens, a constant load displacement rate was used to measure the load-stroke displacement of specimens past failure to estimate the flexure toughness index following the method outlined in [94]. The toughness index allows evaluation of the ratio of the absorbed energy of specimens over the plastic and elastic regions in the three-point bending test [73]. **Figure 6.5** (left) shows the load-stroke displacement of fibrous gypsum specimen where toughness indices were derived through three regions under the load displacement curve; representing different failure regimes. The elastic region was defined by length δ, used to calculate toughness indices (I_5) and (I_{10}) (**Figure 6.5**, right) [94]. The toughness indices of mortars was not possible to measure due to their displacement range being limited to the elastic region.



$$I_5 = \frac{Area\ defined\ by\ length\ 3\delta}{Area\ defined\ by\ length\ \delta}$$

$$I_{10} = \frac{Area\ defined\ by\ length\ 5.5\delta}{Area\ defined\ by\ length\ \delta}$$

Figure 6.5 Load displacement toughness plot (left) and calculation (right)

Fracture energy was used to evaluate the amount of energy necessary to create a crack of unit surface area projected on a plane lying parallel to the crack propagation direction. Using methods adopted by [125], [126], fracture energy was determined by dividing the area under the load displacement curve of specimens by the cross-sectional area of the specimen given by **Equation (2)**: where G_F is the fracture energy (N/m), W_0 is the area under the load displacement curve (Nm), t is the thickness of the beam (40 mm), b is the depth of the beam (40 mm) and a is the initial notch of the beam. In this study beams were un-notched, so the value for a was set to notch/depth ratio of 0.01 (0.4 mm) following the same method adopted by [125]. The artificial 0.4 mm notch would be similar to the sand grain size. An increase in the notch/depth would cause an increase in the computed fracture energy.

$$G_F = \frac{W_0}{t \cdot (b - a)} \tag{2}$$

Fracture toughness, or critical stress intensity factor, was used to evaluate the brittleness of specimens. Fracture toughness was estimated for all specimens based on the failure force and roller separation using an approach adopted by [125] given by **Equation (3)**. Where K_{IC} is the fracture toughness (MPa$\sqrt{\mathrm{m}}$), L is the distance between the supporting rollers, F the maximum load (N), α is the ratio a/b and $g_1(\alpha)$ given by **Equation (4)**. It was reported that the computed fracture toughness on notched beams would be higher than that of the un-notched beams (notch/depth ratio of 0.01), and that computed fracture toughness was over estimated for un-notched beams [125] which suggested the set notch/depth ratio gave a good representation of the fracture toughness.

$$K_{IC} = 3(F)\,\frac{L \cdot \sqrt{\pi} \cdot a \cdot g_1(\alpha)}{2b^2 \cdot t} \tag{3}$$

$$g_1(\alpha) = \frac{1.99 - \alpha(1-\alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)}{\sqrt{\pi(1+2\alpha)(1-\alpha)^{\frac{3}{2}}}} \tag{4}$$

6.2.2.3 Scanning electron microscopy

A FEI Phenom was used for scanning electron microscopy (SEM) to analyse the interfacial transitions zones between the cement paste and foam as well as the gypsum paste and fibres at a magnification in the region of x350. Specimens were prepared from the cross sections of the tested beam specimens. To allow identification of the waste verses normal matrix, SEM on the waste is illustrated below in Figure 6.6. In the figure, the two foam specimens can be seen to contain randomly orientated cells, comprising a matrix of solid struts bridging open pores [127]. The PU cellular structure

(Figure 6.6, left) of pore size 0.2 to 0.5 mm, and the latex (Figure 6.6, centre) of size 0.1 to 0.3 mm. Figure 6.6 (right) shows the typical morphology of a specimen of the mixed fibres, in this showing case polyester fibres of approximate diameter 20 µm.

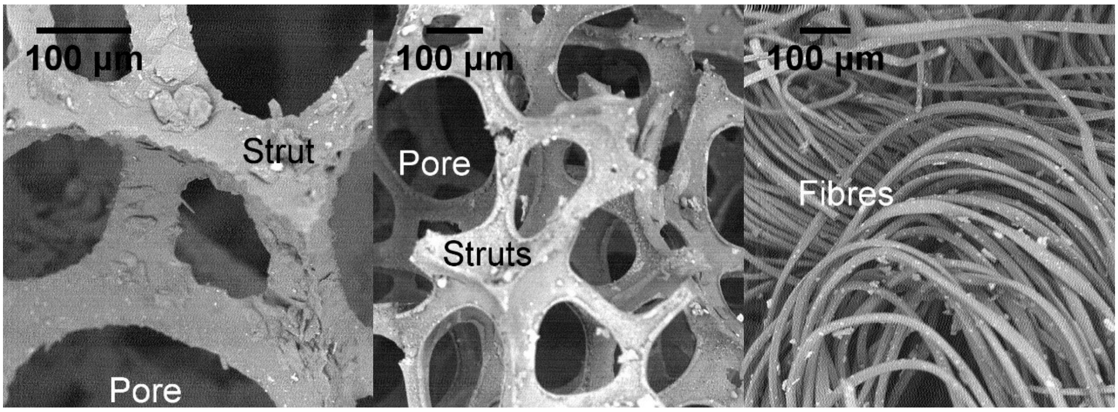


Figure 6.6 SEM images of PU foam (left), latex foam (centre) and mixed fibres (right)

6.2.2.4 Workability

For gypsum plaster mixes, a reaction torque was applied to a paddle mixer during the process of wet mixing as a proxy for workability. Mixing torque was measured using a Heidolph RZR-2102 Benchtop Lab Mixer operated with a paddle mixer of 120 mm diameter and 600 mm, which enabled measurement of the change in workability of the mix with waste fraction addition [128], [129]. The torque required to mix the different plaster mixes was recorded for mixing head speeds of 100, 150, 200 and 250 revolutions per minute (rpm) with the average of three torque readings taken over a 30 s period for each setting. The experimental set-up was capable of recording torques of up to 100N/cm. The no-load torques produced by the mixer and paddle (rotation in air) was subtracted from the measured torques to produce the reported normalised readings.

6.2.2.5 Thermal analysis

Thermal modelling was conducted on mixes using analytical models based on the approach adopted by [79], [88], where the effective thermal conductivity of composites was derived from the volume and thermal conductivity of the two phases of cementitious or plaster matrix and waste matrix. As mentioned, estimating the volume and density of highly compressible and absorbent waste streams is difficult. Previous studies [79], [81] have used the density drop of specimens with different proportions of foam additions to estimate density and volume of foam in the dried specimens; a principle which was applied here.

For each mix configuration, the density of the cementitious or plaster matrix ρ_m, were considered to be equal to the average values measured from the control waste free specimens with the thermal conductivity of the matrix λ_m determined from literature values relating to similar design mixes. The reference thermal conductivity taken for the mortar matrix was 1.79 W/mK [79], which was measured using the same cement to sand mass ratio used in this study. This was in line with industry values for concretes with similar densities [90]. The thermal conductivity of the plane gypsum mix was estimated from the manufacturers' given thermal resistance value (0.004 m^2K/W) [130], assuming this was based on the recommended thickness of plaster (3 mm) to give the thermal conductivity of 0.75 W/mK. This was in line with industry values for gypsum plaster with similar densities [90].

To determine the volume percentage of the waste embedded in the composites $V_{w\%}$, the original waste volume percentage in air $V_{w\%\,(air)}$ was divided by a factor change n given by **Equation(5)**.

$$V_{w\,\%} = \frac{V_{w\,\%\,(in\ air)}}{n} \tag{5}$$

The densities of the waste when suspended in the composites (ρ_w), was estimated from the factor change multiplied by the waste densities in air. Assuming the density of the matrix in the control ($\rho_{control}$) was equal the waste free volume of the composite, then a theoretical density (ρ_{theory}) can be calculated as shown in **Equation (6)**.

$$\rho_{theoretical} = \rho_w V_{w\%} + \rho_{control}(1 - V_{w\%}) \tag{6}$$

The factor n was determined by using Excel Solver to minimising the difference between the measured density and theoretical density of specimens for each waste series, of mortar with PU foam, mortar with latex foam and plaster with mixed fibres (**Equation (7)**).

$$Minimise \sum_{\substack{All\ samples \\ within\ series}} |\rho_{measured} - \rho_{theoretical}| \quad (7)$$

The thermal conductivity of the foam waste volume was based on literature value with similar densities to the foams when suspended in the composite, with thermal conductivity of PU and latex foam taken to be 0.07 W/mK [127] and 0.05 W/mK [131]. The thermal conductivity of the mixed fibre was based on an upper bound by assuming the fibre was pure polyester with thermal conductivity value of 0.03 W/mK [67].

The effective thermal conductivity of specimens incorporating waste additions was modelled using the upper and lower bounds of the Maxwell–Eucken model [132] (**Equation (8)** and **Equation (9)**); where the waste embedded in the composites has volume density ρ_w and thermal conductivity λ_w. The range of the Maxwell–Eucken model was shown to have good agreement with experimental values for gypsums [88] and cementitious materials [64] with values generally found to be closer to the upper bound known as the internal porosity region [132].

$$\lambda_{eff,upper} = \lambda_w \frac{2\lambda_w + \lambda_m - 2(\lambda_w - \lambda_m)V_m}{2\lambda_w + \lambda_m + (\lambda_w - \lambda_m)V_m} \quad (8)$$

$$\lambda_{eff,lower} = \lambda_m \frac{2\lambda_m + \lambda_w - 2(\lambda_m - \lambda_w)V_w}{2\lambda_m + \lambda_w + (\lambda_m - \lambda_w)V_w} \quad (9)$$

For the gypsum plaster specimens, the thermal modelling was supported though experimental analysis on the surface temperature difference of specimens when heated via a Medline 300 hotplate 180 mm x 180 mm set to 100 ºC. This was to give an indication of how incorporating mixed fibres into specimens affected their ability to slow heat loss. Using a FLIR C3 thermal imaging camera, the maximum, minimum and average surface temperature of two specimens, one with fibre additions and one without, was recorded over the course of one hour in five minute intervals. Spot point measurements were also recorded to monitor plate temperature variations over the specimen areas which were found to be limited to 100 ± 5 °C. A dried beam specimen for each design mix was tested alongside a control specimen (fresh specimen for each test) where beam specimens were prepared as previous and cut to approximately 40 mm x 40 mm x 80 mm prior to testing to reduce the effect of temperature gradients on the hotplate. A snapshot of the thermal imaging setup is illustrated in Figure 6.7. In total, six tests were conducted, one for each different fibre addition. From each test, the percentage difference of the temperature readings between the control and fibrous plaster was used to determine a mean temperature difference for the average, maximum and minimum readings.

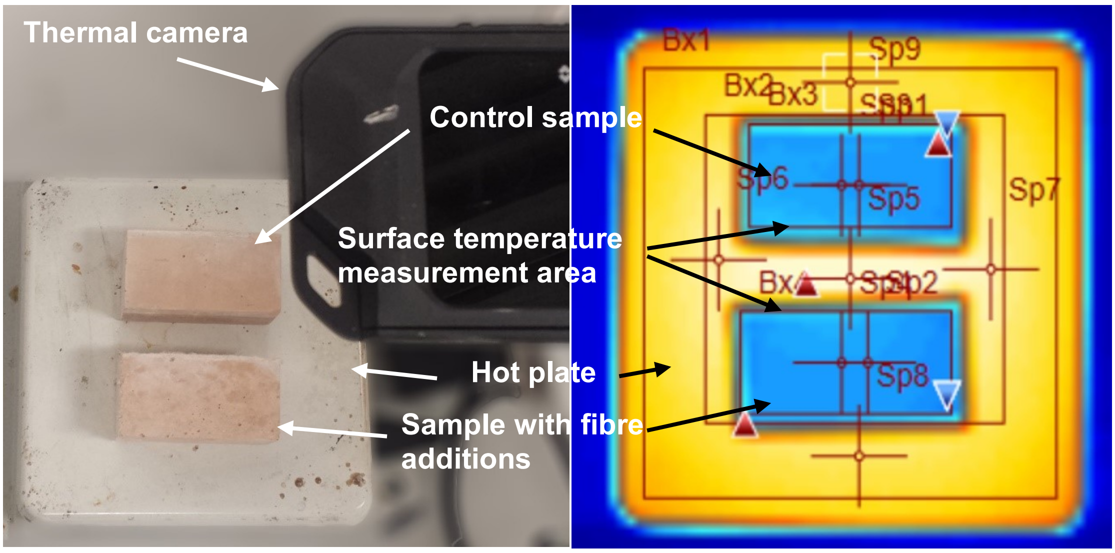


Figure 6.7 Thermal analysis set-up: hot plate and thermal camera (left), thermal imaging (right)

6.3 RESULTS AND DISCUSSION

6.3.1 MORTAR MIX

6.3.1.1 Compression and flexure properties

The mechanical performance of mortar design mixes with mass additions of foam replacing sand are reported below. **Figure 6.8** and **Figure 6.9** gives the results for the 7 and 28 day cube compression and 28 day beam flexure for all mortars. Error bars denote one standard deviation in each direction from the average of three tested specimens for each result. Typical tested specimen graphs of a compression and three-point bend test is given in **Figure 6.10** for L 0.25.

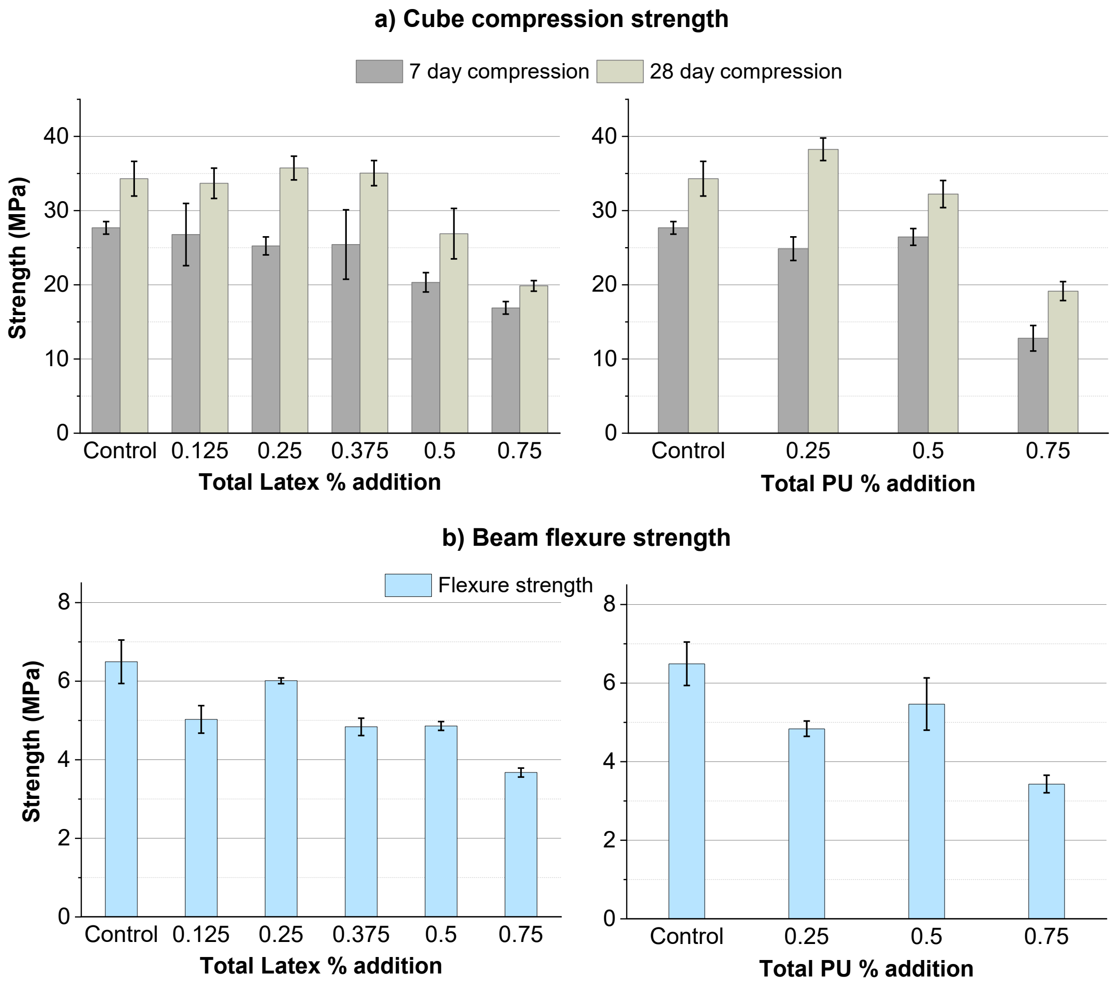


Figure 6.8 Compression (a) and flexure strength (b) of mortar with latex foam (left) and PU foam (right)

For the compression strength, the incorporation of latex foam up to 0.375% and PU foam up to 0.5% showed no significant reduction verses the control mortar. The variation in compressive strength over this range was between 0% to -10% for latex additions and 12% to -10% for PU additions, suggesting that PU additions may have had a lower detrimental effect than latex. Beyond these thresholds, additional foam additions became increasingly detrimental to the mechanical strength. From the data, there was generally a growing difference between the 7 and 28 day compression strength suggesting a delayed hardening process as a result of the additional of foam. For the flexure strength, mortars up to 0.5% foam addition showed moderate reduction in flexure strength in the range of -7% to -26% with significant reduction found for 0.75% additions. The toughness and fracture properties show that the incorporation of additional foam causes a decrease in the ability of mortars to absorb energy; becoming significantly detrimental beyond 0.5% foam additions. A greater decrease in energy absorbing properties verses the mechanical strength, suggests that the addition of foam reduces the deformation range of specimens when under load.

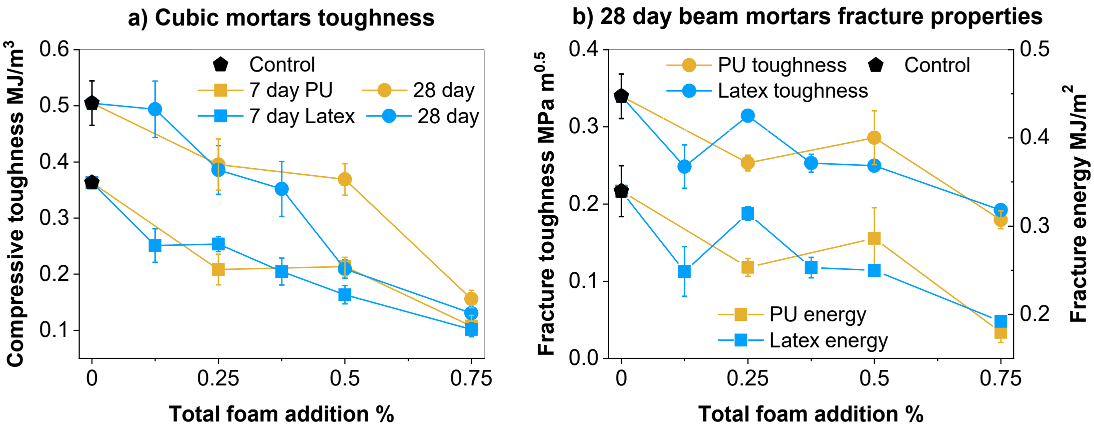


Figure 6.9 a) Cubic mortars compressive toughness at 7 and 28 day; b) Beam mortars fracture toughness and energy at 28 days

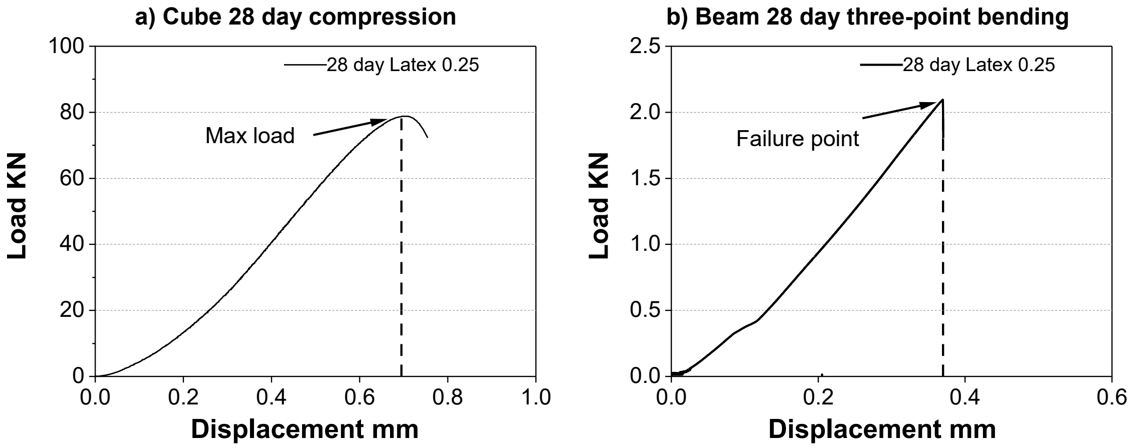


Figure 6.10 Typical compressions (a) and flexure (b) testing results for foam mortified mortars

6.3.1.2 Scanning electron microscopy.

Figure 6.11 shows SEM images of the typical interfacial transition zones observed for control, PU 0.25 and L 0.25 mortars. Noted SEM images of gypsum-plaster samples could not be focused to a high quality and have not been included. In the PU mortar (**Figure 6.11**, centre), the PU foam strut exhibits interlock with the cement paste where open pores in the foam cells have seemingly been filled by the mortar phase. Where as in the latex mortar (**Figure 6.11**, right), the latex foam struts showed a lower degree of interlock with the cement phase with visible pore gaps between the boundary layers and a large open void pore. A noticeable increased porosity of the latex mortar indicates that the latex was less densely compact than the PU in mortar. Noted an additional observation was that the sand grains that are identified in (**Figure 6.11**, left), appear to be close to 0.4mm in length, which helped support assumptions in **Equation (2)** on page 58.

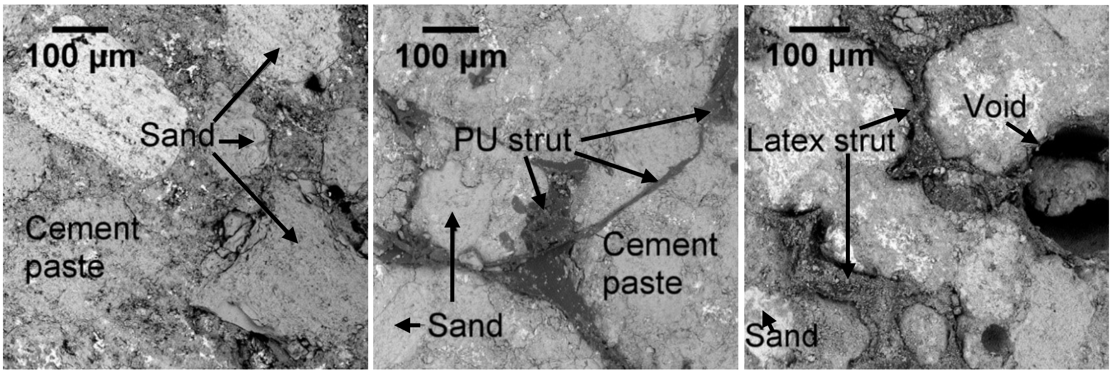


Figure 6.11 SEM of control mortar (left), PU 0.25 (middle) and L 0.25 (right)

6.3.1.3 *Thermal analysis*

Table 6.3 presents the computed volume of mortar and foam phases derived from **Equations (5)**, **(6)** and **(7)** where the reduction factor of the volume of the PU and latex foam when incorporated in the mortars was computed to be 6.1 and 1, which gave final densities of 110 Kg/m^3 and 75 Kg/m^3. **Figure 6.12** presents the computed versus measured density of the mortars and the thermal conductivity bounds for different additions of PU and latex foam. Latex mortars had lower density compared with the PU mortars which was attributed to the lower computed density of the latex resulting in higher porosity; possibly as a result of the smaller pore size of the dry latex reducing the percentage of pores filled by the mortar phase. The lower density of the latex mortars was supported by the SEM observations. As a result, for the same given mass input of foam, the effective volume fraction of latex in the mortars was greater than that of PU in mortars, leading to a greater drop in modelled thermal conductivity of the latex mortars as presented in **Figure 6.12**b). The computed thermal conductivity of mortars decreased by a minimum bound of 4% to 16% with a maximum bound decrease between 19 and 60%.

Table 6.3 Mortar mixes computed volumes and thermal conductivity range

Mix name	Volume %		Thermal conductivity decrease %
	Mortar	Foam	
CM	100		-
PU 0.25	97	3	4-19
PU 0.5	96	4	6-28
PU 0.75	94	6	8-33
L 0.125	98	2	3-19
L 0.25	96	4	6-34
L 0.375	94	6	9-43
L 0.5	92	8	11-50
L 0.75	88	12	16-60

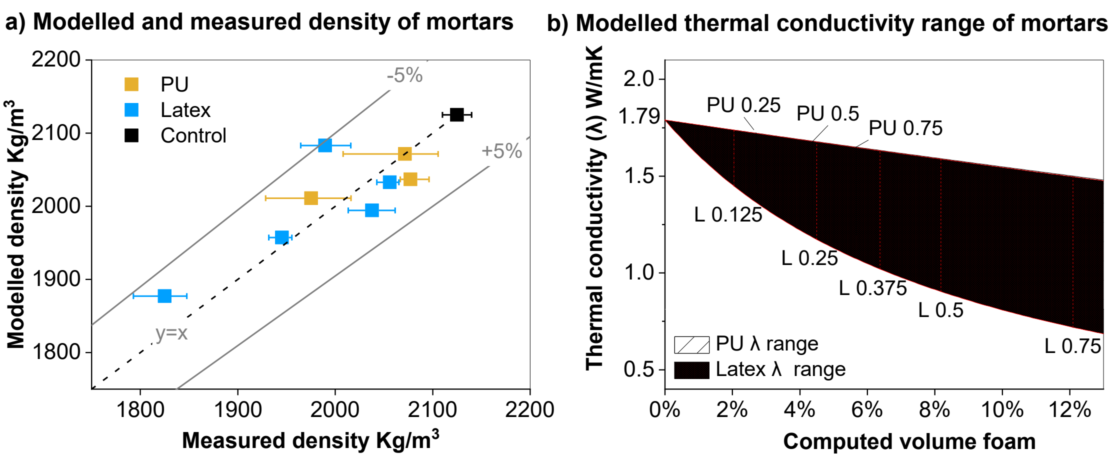


Figure 6.12 a) comparison of measured and modelled mortar density; b) Modelled thermal conductivity of mortars from Equations (8)and (9)

6.3.2 Plaster mix

6.3.2.1 Compression and flexure properties

The mechanical results for the gypsum plaster with mixed fibres replacing gypsum powder by mass are reported below. Figure 6.13 and Figure 6.14 give the cube compression and beam flexure of plaster specimens with error bars as described previous. Typical tested specimen graphs of a compression and three-point bend test is given in Figure 6.15 for GT 2. For mass additions from 1-3%, a slight reduction in compressive strength ranging from 4-8% was found with a significant reduction for 3.5% mass addition at -31%. For specimens with mass additions of 1-2.5% and 3.5%, the flexure strength showed moderate increases in the range of 7-13% with a significant increase for 3% mass addition at 44%; suggesting an optimal range for fibre mass additions to maximise flexure strength. The increase in flexure strength was due to the bridging effect where the mixed fibres cause lateral restraint from the longitudinal compression [123]. For both cube and beam designs, all specimens generally demonstrated increased toughness and fracture energy. The increase in compressive toughness, fracture toughness and fracture energy of plasters shows that the incorporation of fibres leads to an increase in the elastic region of specimens when subject to a force. The toughness index, which considers the ability of the beam specimens to absorb energy beyond failure, shows that specimens with fibres exhibit

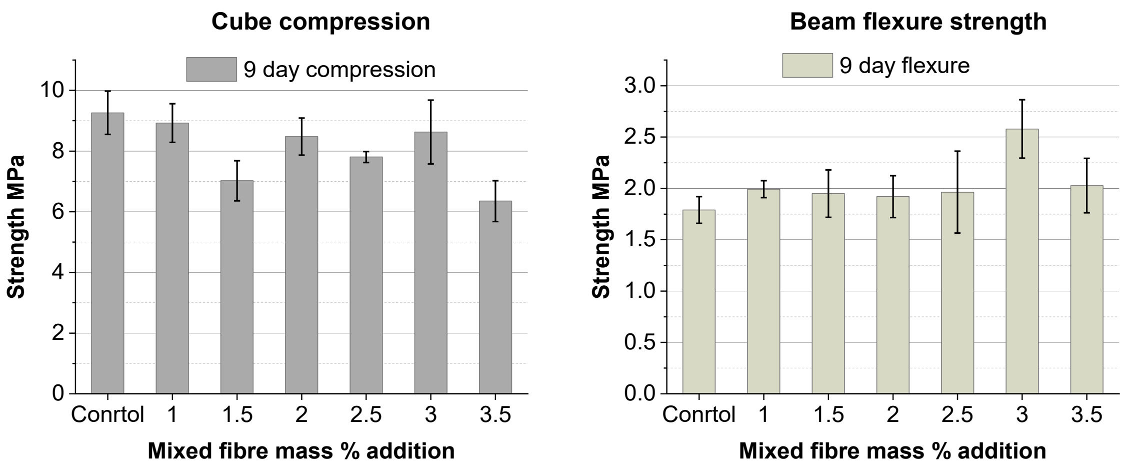


Figure 6.13 Compression and flexure strength of plaster with mixed fibre additions

plastic deformation compared to the pure elastic deformation of control specimens. The toughness index peaked for mixed fibre additions up 1.5% with a slight downward trend thereafter meaning less energy was absorbed for the same post fracture deformation.

The workability of mixes presented in **Figure 6.14**d), shows the torque of the different mixes against the rpm speed. As the rpm increased, there was a linear increase in the measured torque for all specimens where the measured torque of mixes increased for increasing amounts of fibres. The torque for mixing at 100-150 rpm increased in the range of 17% to 35% while mixing at 200-250 rpm caused a torque increase between 21% and 80%. Mixes with 3 and 3.5% additions of fibres were unable to mix below 200 rpm in the set up and produced torque beyond the 100N/cm measurable limit. The torque results show that, although not directly measurable from the test, that the viscosity of the mixtures increased for increasing amounts of fibres with a proportionally greater increase for higher rpm.

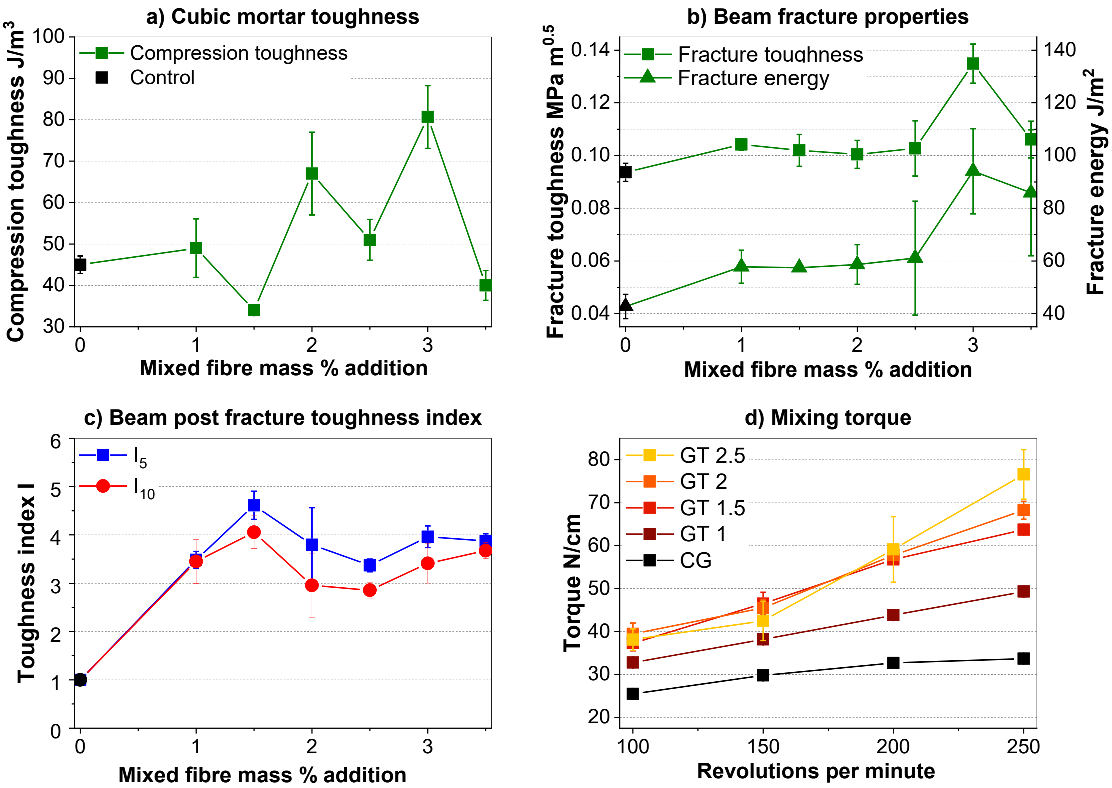


Figure 6.14 a) Compressive toughness of plaster cubic specimens; b) Fracture toughness and energy of plaster beam specimens; c) Toughness index of plaster beam specimens; d) torque of plaster mixes at different rpm

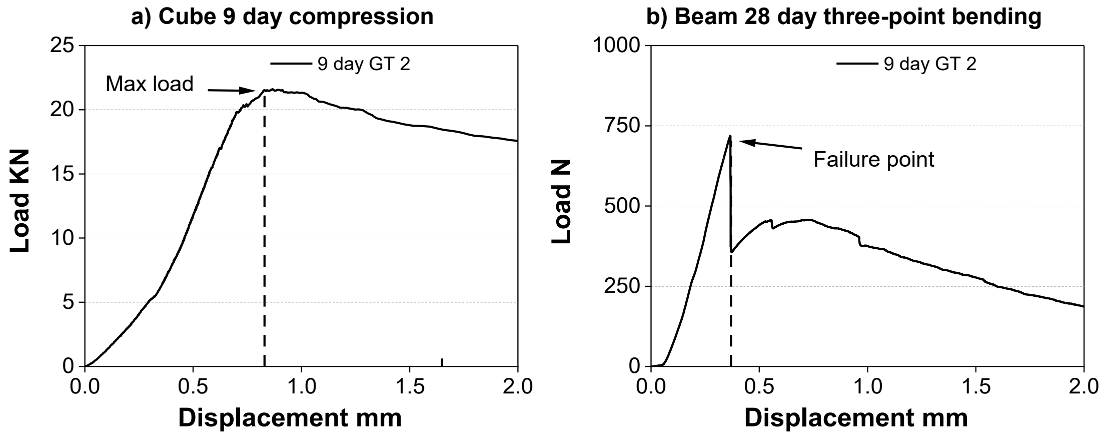


Figure 6.15 Typical compressions (a) and flexure (b) testing results for fibrous plasters

6.3.2.2 Thermal analysis

Table 6.4 gives the computed volume of each phase derived from **Equation (5)**, **Equation (6)** and **Equation (7)** and thermal conductivity decrease range; derived from **Equation(8)** and **Equation (9)**. The reduction factor of the mixed fibre volume that minimised the difference between the measured and computed density of plasters was computed to be 10.2 giving a final density of the mixed fibres of 513 Kg/m^3. **Figure 6.16**a) presents the result of the measured density versus computed density of the plasters with error bars indicating the measured density range of three repeats. All mixes except GT 3.5 show close density parallels with the latter having a measured density near 5% less than computed value; likely due to the mass loss of the additional water added to this particular mix. **Figure 6.16**b) gives the modelled thermal conductivity range of the plaster over increasing volume of mixed fibre with a minimum decreased from 2-5% and maximum decrease from 10-22%. The modelled thermal conductivity range of hot-plate heated control and fibrous plasters was supported by **Figure 6.16**c). As the fibre content went up, the average temperature difference between the fibrous and control specimens became greater from a reduction of 3% for GT 1 down to 13% reduction for GT 3.5. This would suggest that adding fibres to plasters in building materials would either delay and or reduce temperature change.

Table 6.4 Plaster mixes computed volumes and thermal conductivity range

Mix name	Volume %		Thermal conductivity decrease %
	Plaster	Fibre	
CG	100		-
GT 1	98.7	1.3	2-10
GT 1.5	98.1	1.9	3-13
GT 2	97.6	2.4	3-16
GT 2.5	97.2	2.8	4-18
GT 3	96.8	3.2	4-20
GT 3.5	96.5	3.5	5-22

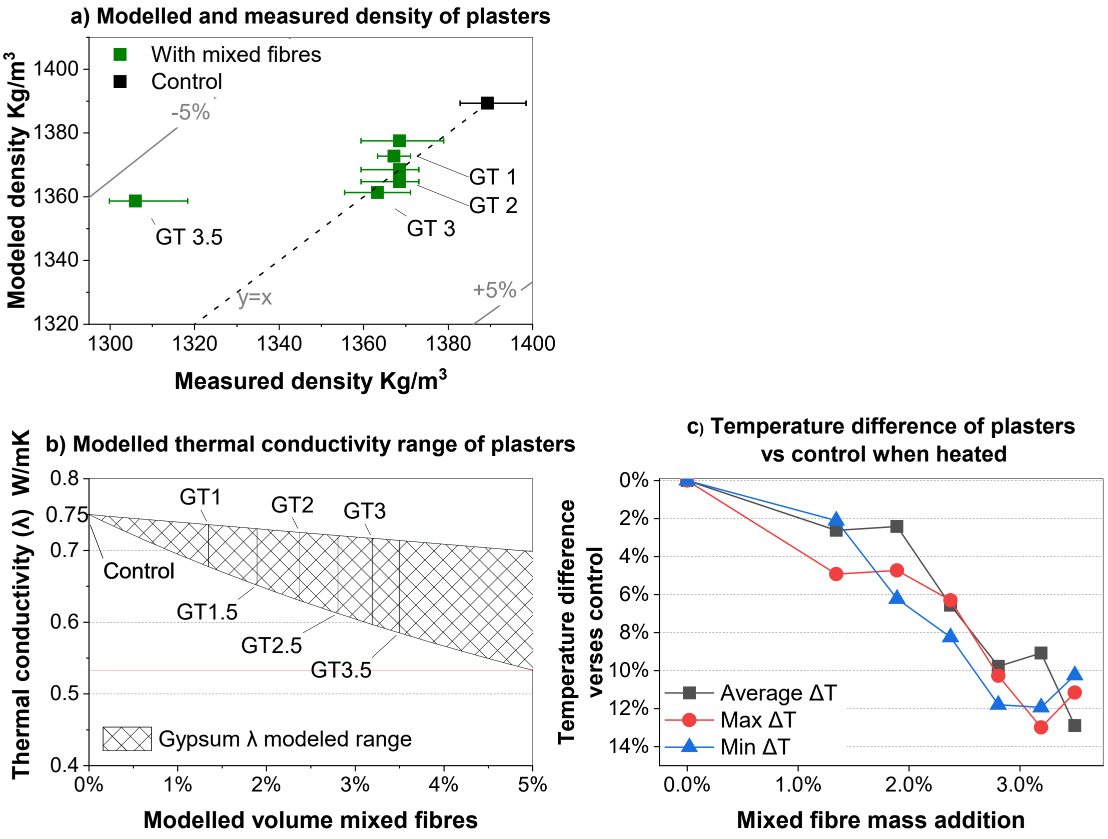


Figure 6.16 a) Comparison of measured and modelled density of plasters with Equation(6); b) modelled thermal conductivity of plaster with Equation (8) & (9); c) Surface temperature difference between control and modified plasters when heated

6.4 CONCLUSIONS

The mechanical and thermal effect of incorporation of mattress origin waste streams of PU foam and latex foam into cement based mortars mixes and mixed fibres in gypsum Thistle based plasters has been studied. An upper limit of foam additions to mortars without significant detriment to mechanical performance was found for total mass additions of latex up to 0.375% and PU up to 0.5%, with variation in compressive strength from 12 to -10% and moderate change in flexure strength down to -26%. Further, thermal conductivity of mortars incorporating foam was modelled to decrease from a minimum bound of 4-16% with a maximum bound decrease between 19-60%. The testing results of plasters suggest an upper limit of 3.5% mass of gypsum can be substituted for fibres before significant reduction in mechanical performance and workability. Below this threshold, plasters showed increased flexure strength and increased energy absorbing properties with slight to moderate increases in workability. The thermal conductivity of the fibrous plasters was modelled to have a minimum decrease from 2-5% and maximum decrease from 10-22% with experimental thermal analysis indicating that materials could either delay and or reduce temperature change.

The results show waste from mattresses can be added to building materials either enhancing or maintaining mechanical strength whilst reducing thermal conductivity. Further work is needed to precisely determine the thermal conductivity and effect of delayed and or reduced temperature change of designs, to evaluate their effectiveness verses industry alternatives. It is recommended additional samples be tested for the specified mixes to improve the validity of the results given only three samples were tested for each design. In addition, specific application(s) of mattress waste-incorporating building materials need to be identified in order for the composites to offer mattress wastes a potential market alternative to incineration or landfill. Further, additional testing would be required on a wider variety of mattress waste condition and sourcing to validate the findings that mattress wastes can be effectively utilised as filler/insultion/reinforcement in cementitious/plaster materials. The end-of-life processing of waste-incorporating building materials would need to be considered.

Acknowledgements

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7 MATTRESS RECYCLING MARKET INSIGHT

Abstract – The purposes of this study were to review existing mattress deconstruction methods and to quantify input resources and the recoverable value of arising waste streams. Further aims were to make recommendations for best practices for mattress deconstruction, identify ways to reduce the quantity of mattress going to landfill, and enable the Reuse Network and partners to evaluate the potential of investing in a disassembly plant. Insight was obtained through primary and secondary research, with interviews conducted across the mattress life cycle including four manufacturers and seven mattress recyclers, in parallel with desk-based research. As of September 2019, annual mattress recycling capacity in the UK was estimated at 2.2 million, so at least 5 million mattresses are still destined for landfill or incineration every year. Three different disassembly methods were reviewed: manual, using an excavator and shredding. A basic manual mattress disassembly process capable of processing 50,000 mattresses annually, would require an initial set-up cost of £100,000 and a deconstruction rate of 35 mattresses per day per employee to break even. The environmental impact of recycling 50,000 mattresses via manual disassembly would be in the range of 1400-2200 tCO_2-eq. Action needs to be taken to facilitate a substantive increase in the quantity of mattress recycling and quality of recycling of recoverable waste streams. The Reuse Network is well positioned to make a significant contribution to improving the state of mattress recycling in a number of ways including: i) Providing expertise to facilitate the setup of mattress deconstruction sites through its members, ii) Expediting reuse possibilities for requilting retailer returned mattresses and remanufacturing products from recovered mattress materials, iii) lobbying local, regional and national governments to accelerate legislative changes such as extended producer responsibilities and regional landfill bans.

7.1 INTRODUCTION

Current estimates suggest that of the 7.5 million mattresses disposed of annually in the UK, only 19% are diverted from landfill or incineration through recycling. Even when mattresses are sent for recycling, it is estimated that 20-50% of the recovered materials are incinerated [6]. Such low rates and low quality of recycling mean precious resources are wasted, which is environmentally detrimental to our society in a time of a climate emergency. The challenges of mattress recycling are well documented [6], [8], [11], [13], [14] and the same issues are raised time and time again, but little action is taken. Issues include the collection of post-consumer mattresses, the lack of onward markets for recycled materials and reports of poor practices in the mattress recycling industry. However, some progress has been made and the rate of mattress recycling has increased in recent years. In addition, steps are being taken by the trade associations – the National Bed Federation (NBF) and Textile Recycling Association - to set up a register of approved mattress recyclers in the UK, to promote good practices and transparency [20]. Despite these efforts there is a lack of proactive collaborative action to radically increase the percentage of mattresses which are recycled and to promote a higher quality of recycling.

The Reuse Network, which represents over 200 charitable reuse organisations across the UK, aims to reduce waste, particularly by diverting landfill, to support vulnerable people and help alleviate poverty and to tackle climate change by reducing carbon emissions [7]. The Network is well positioned to make a significant contribution to improving mattress recycling in the UK. The Reuse Network has an existing sourcing infrastructure for post-consumer mattresses through its members, strong partnerships with retailers such as the John Lewis Partnership (JLP) and IKEA, and the potential to lobby for legislative change. However, despite a successful takeback scheme with IKEA and numerous commissioned reports looking into mattress recycling, the Reuse Network have not been able to utilise their influence effectively and make a substantial impact in reducing the quantity of mattresses being sent to landfill or incineration. A handful of Reuse Network charities operate small scale mattress deconstruction and there have been plans by the Reuse Network to support larger scale mattress deconstruction sites known as “Hubs”. These Hubs would be fed with post-consumer mattresses sourced though “Spokes” consisting of existing members, retail takebacks and household recycling centres (HWRC). Due to a number of issues including a lack of resources, a lack of market knowledge and inconsistency with the Reuse Networks’ core strategy of reuse rather than recycling, the opportunity to significantly impact on the state of mattress recycling in the UK has not yet been realised.

The aims of this study were:

- To review existing mattress deconstruction techniques including financial appraisal:
    - Quantification of the input resources in to mattress deconstruction
    - Quantification of predicted recoverable waste streams from mattresses
- To investigate downstream market solutions for arising waste streams
- To identify ways of reducing carbon emissions from end-of-life mattresses
- To identify ways to reduce the number of mattresses going to landfill
- To make recommendations for a code of practice for mattress deconstruction
- To enable the Reuse Network and partners to evaluate the viability of investing in a mattress recycling plant

7.2 METHODS

The research consisted of desk-based literature reviews and primary information gathering from industry across the mattress lifecycle. Research with industry was conducted over the course of 12 months from October 2018 through to September 2019. Contributing companies are listed in **Table 7.1** with the research type. An example of an interview structure for the different types of companies is found in Appendix I. Secondary industry research was sourced from studies conducted by Waste & Resources Action Programme (WRAP) [5], [21], [95], [96], [120], [133], Oakdene Hollins [6], [8], [11], [13]–[15], [55], government sources [12], [36], [114] as well as unpublished reports by the Reuse Network and partners [9], [26], [44], [47], [134]. The findings of this report are categorised into market insights, and recommendations and developments, with each method discussed below.

Table 7.1 List of companies providing information

Type of company	Name of company	Coverage	Site visit	Interview	Email
Manufacturers	John Cotton Nonwovens	National	X	X	X
	Leggett & Platte (Springs)	National	X	X	X
	Sealy UK	National	X	X	X
	Silentnight Ltd	National	X	X	X
Local Authority	Lancaster CC	Regional	X	X	X
	Kirkless FCC[5]	Regional	X	X	X
Waste Contractor	Pink Skips	Local	X	X	
	FCC Environment	National			X
	SUEZ UK	National		X	X
	Viridor Ltd	National		X	
Mattress recycler	Envirotex/Rematt UK	Regional	X	X	X
	Matt UK	National		X	
	USEL	Regional	X	X	X
	CAD Recycling	Regional			X
	Hamilton Waste	Regional		X	X
	AAT/Textek	Regional	X	X	
	Circom	Regional		X	
Other	Oakdene Hollins	National		X	X
	National Bed Federation	National			X
	Textile Recycling Association	National		X	X

[5] Wigan MBC run by FCC Environment

7.2.1 Market insight into Mattress recycling

Organisations identified that have dedicated mattress deconstruction operations were reviewed based on primary findings from industry, secondary research through literature and web-based searches of mattress recycling operations with analysis of the different UK mattress recycling companies, as well as examples of international mattress recycling schemes.

A figure for the total mattress recycling capacity as of September 2019 was determined by estimates for the size of operations of identified mattress recycling companies based on information obtained from industry. Although most companies were approached for information directly, only the companies listed in **Table 7.1** provided information.

7.2.1.1 Deconstruction financials

Recoverable waste streams from mattresses, markets and processing requirements were reviewed. Identifying markets for recovered materials involved reviewing the literature for identified applications and companies, web-based searches for companies that recycle mattress-based materials and primary insight gained from the mattress industry. The market value of commonly recoverable materials was reported based on information provided by mattress recyclers for direct reuse or recycling of the materials/components. Quantification of input resources and recoverable value of mattress recycling were evaluated by comparing different approaches to mattress disassembly and waste stream processing. Data for input resources was gathered as much as possible from recycler interviews with gaps in the data supplemented by literature and internal reports. To enable a simple comparison of the financials, the following approaches were reviewed: i) manual disassembly, ii) disassembly by use of an excavator and iii) shredding. The basis was to calculate the cost, income and profit range on a per mattress basis for each method. Whilst other disassembly methods exist, such as semi-automated and fully automated, the three disassembly methods reviewed were chosen due to the greater availability of information, methods practiced in the UK and information that was available from the industry. The financials were based on insight from six mattress recyclers, combined with financial estimates sourced from literature for the price of balers, skips, forklifts, disassembly equipment, safety equipment and racking as well insight on operative disassembly rates [5], [9], [11], [21], [26], [44]. For simplicity, costs were consolidated to include disassembly labour, plant running costs, depreciation and interest on finance start-up costs via a loan at an interest rate of 6.5%. Due to the variability of these parameters for different recyclers, high and low rate estimates for labour, material values and gate fees were included. The cost per mattress financials were based on the plant cost for a throughput of 50,000 mattresses for manual and excavator disassembly and 480,000 for shredding. This was due to the availability of information on similar operations. The financials were based only on the disassemble operation, assuming mattresses were delivered to the plant externally and separated materials were collected directly from site. This was done due to the large number of variables to consider when trying to estimate the finances of differing and complex operations.

7.2.1.2 Best practices for mattress deconstruction

Best practices were discussed for mattress deconstruction procedures, i.e. health and safety risks, and legal and ethical implications that are involved in running a mattress recycling plant. Best practices were based on industry observation, feedback from mattress recyclers and government guidelines on waste management operations and health and safety. Detailed analysis on some relevant legal regulations were outlined by internal report [44], of which key aspects to mattress deconstruction were updated.

7.2.1.3 Future development

Future developments were discussed in terms of recent trends identified throughout the research process and possible future legislative changes that could be introduced. Trends identified by [6] and raised by mattress recyclers were discussed. Possible legislative changes were discussed, based on consultations with the product stewardship advisor, David Fitzsimons (who advises the NBF and European Bedding Industries' Association), and on examples of countries that have bought in legislation or cross industry schemes to combat waste mattresses.

7.2.2 ENVIRONMENTAL IMPACT

To highlight the environmental impacts of mattress disposal routes, the greenhouse gas emissions (GHG) of five different disposal scenarios for an average mattress were calculated; namely, landfill, incineration, total recycling, current high-level recycling and current low-level recycling. Here the study adopts a similar method used by Glew [98], on the net GHG emissions arising from different disposal scenarios based on the mass of metal, textiles and plastic within a mattress. Data on the disposal routes of materials is derived from Smith [135] which gives the total effective GHG emissions per kg for metal, textiles and plastic. The data for landfill included, the transport emissions, carbon emissions over 100 years and averages for recovered fuels for energy production. Also included were data on the pollution and energy expended during the process of landfill, recycling, incineration and RDF combustion. Negative emissions were given according to the electricity production from incineration, the avoided use of virgin materials minus the emissions from collection and processing the recycled materials, and the avoided burning of coal in cement kilns with RDF replacements [135].

Using an average mattress weight of 25 kg [6], and an average mattress composition gathered from information from mattress recyclers, the mass of textiles, plastics and metal in an average UK post-consumer mattress was determined. A low-level recycling scenario is based on recycling of the metal and foam with total recovery of textiles though refuse derived fuel (RDF); based on the final destinations reported by mattress recyclers Hamilton and Waste, and Textek. A high-level recycling scenario is based on recycling of the metal, foam and 65% of the textiles, with the reaming textiles producing RDF; based on destination of waste streams reported by Rematt, Matt UK and USEL.

7.2.3 LOCATION CONSIDERATIONS OF DEVELOPING DECONSTRUCTION SITES

Strategy is discussed in terms of identifying appropriate locations for potential mattress deconstruction facilities. Areas in the UK with low mattress recycling statistics were identified through local authority mattress recycling statistics obtained from the Waste Data Flows (WDF) database [111]. For each region, estimates were based on interviews and data gathered from industry, the number of mattress recyclers and their combined capacity for 2019. Other consideration factors included were storage capability to keep mattresses dry and partners of the Reuse Network who would be able to act as spokes within regions to larger hubs; such as partners identified as Approved Reuse Centres (ARCs) (who are members of the Reuse Network with special status as furniture collection points).

7.2.4 STRATEGY FOR THE REUSE NETWORK

Given the importance of legislation as a driver for recycling, lobbying for legislative change is another option for driving improvements in mattress recycling. Possible proactive initiatives the Reuse Network, and/or its partners, was discussed in terms of how resources can best be utilised to improve the capacity of the mattress recycling industry. Recommendations were also made for the changes to public policy. Cases were argued for bans on using landfill, taxing the sales of mattresses and EPR through producer taxes and or other incentives.

7.3 RESULTS AND DISCUSSION

7.3.1 MARKET INSIGHT INTO MATTRESS RECYCLING

Table 7.2 is a compilation of the identified mattress recyclers in the UK, their estimated processing capacity and known operational locations. In the UK, currently there are over a dozen companies with dedicated mattresses recovery operations with a wide variety of deconstruction methods and material recovery rates. In Appendix II a), identified UK mattress recycling operators were discussed for their sources of waste mattresses, deconstruction approach, throughput and material recovery. Examples of international mattress recycling operations are provided in Appendix II b). The approach mattress recyclers took to disassembling and processing mattresses was found to be based on a number of factors, including access to investment, access to onward markets, availability of local or on-site processing facilities, as well as organisational motives; be it purely financial, environmental, social or some combination of the three. The estimated capacity figures were best estimates but believed to be accurate based on similar figures reported by Bell [6].

Table 7.2 Mattress recycling companies, location and estimated capacity

Mattress recycling company	Location	Estimated capacity per year
Matt UK	Chatham	600,000
TFRG[6]	Blackburn	150,000
	Ilkeston	180,000
	Bristol	75,000
AAT/TexTek	Shropshire	400,000
Circom	Coventry	200,000
Mid-Counties UK[6]	Burton	150,000
Rematt/Envirotex	Darwen	50,000
	Accrington	50,000
CAD recycling	Denbigh	100,000
Amgen Cymru[6]	Aberdare	75,000
Hamilton Waste	Edinburgh	50,000
USEL	Belfast	40,000
Carpenters[6]	Glossop	30,000
Mattress Recycling[6]	Batley	20,000
FRC Group	Liverpool	15,000
Mattress Recycling Services	Ripley	Unknown small
SMRC Southwest	Somerset	Unknown small
Total UK estimated recycling capacity as of September 2019:		**2.2 Million**

[6] Based on NBF reports [6], [13], [14]

7.3.1.1 Deconstruction financials

Table 7.3 lists the commonly recoverable waste streams from deconstructed mattresses in the UK with information on typical values that recyclers report they receive for the materials through reuse, recycling or energy from waste applications. The reuse value was generally reported on a per unit basis (e.g. spring unit) by the mattress recyclers since it would not be accurate to report the figure on a per tonne basis. The acquisition cost of machinery to process a waste stream has examples of machinery and suppliers found in **Table 9.2** of Appendix IV along with a list of companies that have been identified that reprocess waste streams recovered from mattresses (**Table 9.3**). The findings only gave partial insight into cost benefits of investments as it proved difficult to source further costing information for in-depth cost benefit analysis of waste stream processing investments. In reality, decision making on whether to invest in machines and further processing should be made on case by case basis determined by: i) proximity to onward markets, ii) difference in price quoted before and after investment and iii) acquisition, transportation, installation and running cost of machinery/further processing.

Table 7.3 Recoverable waste streams, value and acquisition cost of process machinery

Waste stream		£/t	Comment	Machine cost £[7]	Market
Open coil	*Reuse*	5/unit[8]			*Budget matts.*
	Compact	165-120[9]	Shredder cost indicated	40,000	*Scrap*
	Uncompact	100-80[9]			
Pocket spring	*Reuse*	5/unit[8]			*Budget matts.*
	Shredded	165-120[9]	Revenue neutral with running costs	500,000	*Scrap*
	Baled high	120-80[10]	Direct to Smelting plant	60,000	*Europe*
	Baled low	40-80[9]	external shredding facility	60,000	*Scrap*
	uncompact	100[11]			*Landfill*
Foam	*Reuse*	3/unit[12]	Generally uncompressed		*Budget matts.*
	Recycled	30[8]	Chipped and treated with disinfectant	Unknown	*Bonded foam/pet*
		0[8]	Requires chipping	5000	*Bonded foam*
	Other	40-90[11]			*SRF*
Shoddy	*recycled*	0[8]	Baled	6000	*Automotive felt*
	Other	40-90[9]			*SRF*
Polyester	*Recycled*	500[10]	High purity uncontaminated	6000	*Mattresses*
		225[9]	Medium purity	6000	*Upholstery/ pet*
		75[11]	Mixed with all white textiles	6000	*Pet bedding*
Outer woven	*Recycled*	200-100[10]	Reported only by Matt UK	6000	*Yarn*
	Other	40-90[9]		6000	
Jute/ coir	*recycled*	40-0[10]	Must be free of metal and synthetics	Unknown	*Horticultural*
	Other	40-90[9]			*SRF*

[7] Acquisition cost based on personal communication with all mattress recyclers and web-based searches
[8] Personal communication, Ian Jillings, Rematt
[9] Based on personal communication with all mattress recyclers interviewed
[10] Personal communication, Ray Bagnall, Matt UK
[11] Personal communication, Jane McGrath, USEL
[12] Personal communication, Ken Crystal, Hamilton Waste

- **Quantification of input resources and recoverable value**:

The financial variables of the different deconstruction methods are shown in **Table 7.4** with the equivalent cost incurred and revenue generated per mattress processed contained in **Table 7.5** . A full breakdown of the financial data and calculations used to generate the Tables are found in Appendix III. The difference between the high and low net profit per mattress is largely down to the recyclers' ability to generate value from the waste streams and the chargeable gate fee. Larger operators, who tend to have been operating longer, were able to generate higher value for the waste stream due to development of waste stream processing, ability to bulk and knowledge and relationship with onward markets. In the initial months and years of operating a manual mattress deconstruction operation, the income from materials can be expected to be minimal with a lower estimated per average mattresses of (£0.50) expected. The results show that for manual deconstruction, a combination of high disassembly labour costs and low income from recoverable materials and gate fees would result in a loss. The high disassembly labour cost is based on an operative earning minimum wage able to separate 30 mattresses per day, 240 days per year. Even with a higher gate fee of £5 the profitability per mattress would still be negative, showing in the early stages of operating mattress disassembly, the disassembly rate per employee should be maintained above approximately 35 mattresses per day at an absolute minimum to break-even.

Table 7.4 Quantification of different mattress disassembly resources[13]

Variables	Manual		Excavator	Shredding
	High	Low		
Annual mattress unit throughput	50,000		50,000	480,000
Operatives	7	3	2	8
Disassembly salaries and on costs	£115,000	£75,000	£60,000	£190,000
Management and sales salaries and on costs	£30,000		£30,000	£190,000
Other running costs	£60,000		£70,000	£625,000
Start-up costs (Fixed)	£100,000		£185,000	£3,870,000

Table 7.5 Disassembly financials per mattress

Financial variables			Disassembly method financials (£)		
			Manual	Excavator	Shredding
Costs[14]	*Disassemble Labour*	High	2.3	1.2	0.4
		Low	1.5		
	Other running costs		1.8	2.0	1.5
	Deprecation		0.3	0.6	1.4
	Interest		0.1	0.2	0.5
Income[14]	*Materials*	High	2.3	2.1	2.1
		Low	-0.5	0.0	0.0
	Gate fee	High	5.0	5.0	5.0
		Low	4.0	4.0	4.0
Net profit per mattress[15]		**High**	***3.6***	***3.1***	***3.2***
		Low	***-1.1***	***0.0***	***0.1***

[13] Inputs based on cost modelling with insight from mattress recyclers and figures reported in literature. Full breakdown found in Appendix III a)
[14] Inputs based on financial modelling with insight from recyclers outlined in Appendix III a)

[15] Calculation and breakdown found in Appendix III b)

7.3.1.2 Best practices for mattress deconstruction

Findings for best practices for mattress deconstruction are outlined below, in terms of legal requirements to dismantle mattresses, permutation to convert wastes to products, health and safety and transparency.

- **Legal**[16]

Compliance with a number of regulations and various permits are required in order to operate a legally compliant mattress disassembly plant. The exact nature of permits will depend on the quantity and way waste is to be treated, sorted and stored.

Disposed mattresses are classed as a bulky waste under European Waste Catalogue (EWC) code 20-03-07. A mattress disassembly company would need to be registered as a waste carrier/broker/dealer at a one off cost of £154 which should be renewed every 3 years at a cost of £105 [136]. For the storage and treatment of mattresses, there is a requirement for a waste management permit unless a given operation falls within exemption boundaries. Waste exemption T12 [137] for manually treating waste, would permit an operation where the weight of mattress waste at any one time is limited to five tonnes with a maximum storage duration of 12 months. Alternate exception of T4 [138] would not apply given that a mattress is composed of different types of waste through textiles, plastics and metal. To legally operate beyond T12 limits requires a full waste management permit for the treatment and transfer of non-hazardous waste, which incurs a subsistence activity charge of £2,875 per year (for a weight throughput less than 25,000 tonnes annually) in addition to a one off application charge of approximately £1725 [45]. Operating with a full waste management permit requires at least one Certificate of Technical Competence [139] to ensure operators are able prove competency of their staff in the relevant waste activities; the one off cost of an

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[16] Notes that amendments were being made to the legal requirements specifically to mattress deconstruction operations by the Government in October 2019

equivalent level 4 scheme offered by WAMITAB, is around £2,500 and can take 12-18 months to complete[17].

To receive and transfer mattresses and/or separated materials/components requires a waste transfer note for each individual transfer of waste onto and off site. Each transfer note must include the EWC waste code of either mattresses (20-03-07), textiles (19-12-08), foams (19-12-04) or metal (19-12-02).

- **Waste to product conversion**

Further permits would be required for waste streams to be re-classed as a product, which must meet an end of waste test through a quality protocol to assess the following points [140]:

- The waste has been converted into a distinct and marketable product; this means:
  - The waste has been turned into a completely new product
  - The new product is different from the original waste (minor changes to its composition may not be sufficient), for example non packaging plastic recycled material is processed to make new plastic products
  - There is a genuine market for the material so it will definitely be used – if it's stored indefinitely with little prospect for use, the material remains waste
- The processed substance can be used in exactly the same way as a non-waste
- The processed substance can be stored and used with no worse environmental effects when compared to the material it is intended to replace.

Exceptions exist for the recovery of textiles, (T2) as long as textiles were not baled or shredded, and use of textiles to manufacture finished goods (U9) [141] under EWC 19-12-08 and 20-01-11. Arising product(s) would be subject to additional requirements depending on what was being produced. For example, if bedding products were

[17] Personal communication, Ian Jillings, Rematt

produced, they must be compliant with hygiene and cleanliness requirements BS 1425 [142], [143] and or BS EN 12935:2001 [144] as well as the Furniture & Furnishings (Fire) (Safety) Regulations 2010 [145]. Certification is conducted by independent testing companies such as BM TRADA or FIRA; where a batch of a given product must be tested and certified every 6 months. Note that the Furniture & Furnishings (Fire) (Safety) Regulations 2010 would also apply to pet bedding products.

- **Health and safety**

The key aspects of health and safety in operating a mattress deconstruction plant were outlined in terms of recommendations below. Further information could be found from government guidelines for operating in the waste management and recycling industry [46].

The Environment Agency has set health and safety standards that must be adhered too, which would be the responsibility of a site manager. Key responsibilities would include (but were not limited to):

- Health and safety procedures to protect those in the workplace including appropriate signage of health and safety procedures
- First aid and fire evacuation procedures
- Maintaining safe working conditions and ensuring employees were fit for work
- Ensuring employees received induction training on how to work safely including arrangements for first aid, fire and evacuation

A deconstruction site would operate with balers, heavy materials and materials handling equipment such as forklifts, requiring distinct areas for traffic and pedestrian routes.

Specific to mattress deconstructing, dust inhalation was a potentially significant hazard to operatives and anyone else within the vicinity of where mattresses were being deconstructed. In particular, mattresses with coir, hemp or jute materials could produce significant concentrated areas of dust during dismantling. The following recommendations were made to reduce the risks of lung damage from dust inhalation:

- Ensure mattresses are deconstructed in a well-ventilated area and/or with dust extraction systems
- Ensure operatives use respirator masks and eye protection whilst deconstructing mattresses
- Limit dust accumulation on operatives' clothing either by ensuring operatives wear fresh work wear every day or by using hazardous material suits

If mattress deconstruction was to be conducted manually by use of knives, the following recommendations were made to reduce injury risk:

- Ensure operatives are well trained in using and storing cutting equipment
- Ensure operative wear non-cut safety gloves and or arm protection conforming to BS EN 1082-2:2000 [146]

Operatives will also be required to complete training in manual handling and material handling equipment where appropriate. This could be conducted through online assessments and or training workshops conducted internally or externally depending on the experience and qualification of the staff.

- **Transparency**

Reuse of mattress components back into the bedding industry where consumers are unaware they are buying products with second-hand components is ethically wrong. However, one of the issues here is that there is no official method to ensure the quality of components and materials beyond the requirements of BS 2004 [147]; for the specification feather and down filled bedding articles. The argument that mattress recyclers make is that mattress suppliers use recycled components such as in polyester and shoddy, information that is not communicated to the customer, and the NBF who are trying to support mattress recycling and are funded by the mattress manufacturers and suppliers, don't want recycled materials going into the non-member budget mattress market.

Therefore it is important the markets that are utilised by a potential mattress disassembly plant are transparent in terms of the final destination of the materials.

7.3.1.3 Future developments

- **Regulation**

Throughout the research process, it has been found that in the UK, the lack of a regulatory body for mattress recycling has led to a number of rogue operators and poor health and safety at mattress recycling plants past and present. The NBF are currently in the process of establishing a register of approved mattress recyclers (RAMR) whilst talks are ongoing with government to set up extended producer responsibility (EPR) schemes for mattresses. The short-term objective of the RAMR is to enable those wanting to procure mattress recycling services to distinguish the legally compliant mattress recyclers from the rogue operators by means of vetting and auditing. In the long term the NBF would like to see RAMR develop into a trade body for mattress recycling to improve the industry, similar to that of the US Mattress Recycling Council. However, the strong divisions and disputes between existing mattress recycling companies makes this hard to envisage[18]. Some recyclers do not view the RAMR as independent, given that it has been setup by the NBF who are largely funded by the big manufacturers and retailers. Furthermore, there is the view that mattress recyclers who have strong ties to the major retailers who support the NBF can bias the current RAMR auditing process. That being said, in the absence of any other potential regulatory body, the NBF is currently best positioned to head and push for a cross-

[18] E.g.: Circom believes Matt UK are able to undercut them by illegally shipping waste abroad [157]

industry collaboration in tackling mattress recycling. The NBF are reported to have had discussions on potential EPR for mattresses with government, but when any such EPR or legislation would be introduced is unknown[19].

- **Legislative intervention**

Legislative intervention could take several different forms. Intervention in the form of EPR would ideally create a framework to fund the collection and recycling of mattresses whilst creating stimuli to increase the recyclability of mattresses through design for disassembly and design for recycling. A mattress tax has proved successful in countries such as France and some US States by funding collection and recycling programmes but the quality of material recovery remains low. Infrastructure to protect the condition of waste mattresses will help to reduce the number of wet mattress but even clean and dry mattresses are generally difficult to dismantle effectively into the constitute components and materials. Designing mattresses such that the components and materials retain value is crucial in realising effective circularity.

Consumer perception of the issue is critical in catalysing change. Consumer perception and influence has led to significant legislative changes for items such as plastic straws in the UK despite their relatively insignificant waste contribution.

- **Trends**

Local authorities: The number of mattresses deposited at council HWRC has reportedly been dropping, attributed in part to the increase in takeback schemes offered by retailers and third parties. The average mattress weight and size has increased over time as people opt for more premium mattresses. This means mattresses are not as easy for individuals to transport to their local HWRC site, causing the demand for takeback service to grow. The growth in demand for larger premium mattress has meant an increase in the sale of pocket spring mattress, which are generally perceived

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[19] Personal communication, David Fitzsimons

by the consumer to be of higher quality to alternative designs. Continued growth in the market share of pocket spring mattresses is likely to reduce the financial feasibility of manual mattress recycling given the lower recoverable value from pocket springs. The growth of pocket springs is less of a problem to operations where mattresses are shredded or where pocket springs can be directly sent to smelting plants.

Shredding: Shredding whole mattresses has been growing through companies such as Textek, Circom and Rematt UK, and is likely to continue growing. Textek in particular, have the potential to grow rapidly as they can sustain shredding figures of 2000-4,200 mattresses per day. Shredding facilities such as Textek, could help to achieve rapid diversion of mattress away from direct landfill or incineration. However, shredding reduces the quality of materials that can be recovered with a large percentage of constituents destined for SRF. Although shredding may offer a short term solution to economically treat mattresses at scale, in the long term, as the economic outlook for mattress recycling is improved through legislation, shredding should be phased out in favour of deconstruction that maximises quality recycling so that the constituent materials maintain their original value.

Mattress design: Insight from major mattress vendors demonstrates that the design and types of materials being used in mattresses are changing. From interviews with Silentnight and Sealy as well as analysis of IKEA's mattress range, the number of different materials used in the mattress is being reduced in favour of increased polyester based layers[20] such as Airstream developed by John Cotton to replace foam [148]. Replacement of PU foam has also been an area of development for manufacturers. There is ongoing research to produce naturally fire retardant PU foam or replace the use of foam manufactured from non-renewable sources in the case of IKEA [149]. Suppliers have also been increasing the content of materials sourced from other recycled products such as PET waste into polyester. Although investing in

[20] Personal communication with Angela Moran, Silentnight

capacity to reprocess the current stock of post-consumer mattress materials back into mattresses would potentially be of greater environmental benefit, the higher cost of reprocessing post-consumer materials such as polyester [87], means that it is not an attractive option. Developments to change mattress design to increase recyclability have to date been incremental and are unlikely to have any significant effect on mattress recycling.

7.3.2 ENVIRONMENTAL IMPACT OF DISPOSAL ROUTES

Table 7.6 gives, for manual deconstruction, the recoverable waste streams arising and their composition for an average post-consumer mattress[21]. The information from Smith [135] on the emissions of disposal routes for the material types of metal, textile and plastic is given in **Table 7.7**. The PU foam here was defined as plastic.

Table 7.6 Mattress waste streams, average composition and material type

Waste stream	Mass %	Mass Kg[22]	Material type
Open coil	30	7.5	Metal
Pocket spring metal	19	4.8	Metal
Pocket spring fabric	1	0.2	Textile
Mixed/non-separable	13	3.3	Textile
Foam	10	2.5	Plastic
Shoddy	9	2.3	Textile
Polyester	6	1.5	Textile
Woven textiles	4	1.1	Textile
Cotton/wools	3	0.7	Textile
Jute/coir	2	0.5	Textile
Other	3	0.6	-

[21] Average composition based on composition information from Envirotex, CAD Recycling, Hamilton Waste, AAT Recycling, Rhondda Cynon, Matt UK, Circom and USEL
[22] For an average 25kg mattress [13]

Table 7.7 Net GHG emissions arising from disposal scenarios [98]

Material type	kgCO₂-eq/kg			
	Landfill	*Recycling*	*Incineration*	*RDF*
Metal	0.01	-1.49	-1.35	-
Textile	0.02	-3.17	-0.16	-0.53
Plastic	0.01	-1.76	0.31	-0.61

Table 7.8 gives the effective GHG emission arising from disposing of a mattress via the different disposal scenarios. Although the landfill of mattresses does not add a significant amount of emissions, the potential saving through diversion from landfill are substantial. The figures are believed to be a good estimate based on similar reported figures for mattress disposal [80], [81]. Based on the current recycling routes, if the figures were to be scaled up to 50,000 mattresses, the low-level recycling would give a net saving of 1400 tCO2-eq whilst a high level would give a net saving of 2200 tCO2-eq versus landfill. Whilst in comparison to incineration of whole mattresses, the benefit of low level and high-level recycling are 60% and 160% greater. The difference of between current high- and low-level mattress recycling was significant at 16.8 kgCO2-eq per mattress which should be an important factor when comparing different mattress recycling operations. To realise total recycling benefits, all textiles would need to be recyclable, something that could be achievable if mattress textiles were designed to be recyclable and there was sufficient infrastructure to handle and treat the textiles at end of life. It is important to highlight that the GHG savings from incineration were based on the avoided GHG from average EU electricity and heat production for the year 2000, meaning that there would not necessarily be any savings versus energy from renewable sources. Further, the net GHG saving for reuse of metal and foam has been reported by Geyer [80] to be approximately 45% greater than that presented in **Table 7.8**. Further work would be needed to update figures for the effective GHG emissions

of disposal routes through incineration, given the increase in renewable energy alternatives.

Table 7.8 GHG generated by an average mattress from different disposal routes

Material type and mass Kg		Effective net GHG $kgCO_2$-eq				
		Landfill	*Incineration*	*Recycling*		
				Total	*High level*	*Low level*
Metal	12.2	0.10	-16.42	-18.14	-18.14	-18.14
Textile	9.6	0.14	-1.56	-30.42	-21.84	-5.08
Plastic	2.5	0.02	0.78	-4.40	-4.40	-4.40
	Total:	**0.26**	**-17.20**	**-52.97**	**-44.39**	**-27.62**

7.3.3 LOCATION CONSIDERATIONS OF DEVELOPING DECONSTRUCTION SITES

Table 7.9 presents the regional mattress recycling figures from WDF databases reported for up to 2018 along with the estimated capacity of mattress recycling in the region as of September 2019. It would be advisable to open a new mattress deconstruction facility in the areas where there is the highest need and greatest demand for mattress recycling capacity. The disparity between the recycling capacity per region and recycling statistics is due to recyclers targeting mattresses from takeback as well as the capacity growth since 2018. The majority of recycling operations are clustered around the Midlands, so competition for council mattresses and takeback schemes will be high for the surrounding regions. Areas of Scotland, North East, Eastern and Southern England present the greatest need for mattress recycling facilities, based on their population, local authority recycling statistics and current recycling capacity. Further work would be required to identify regions with sufficient demand for mattress recycling (i.e which authorities are willing to pay the premiums to recycle mattresses). Local authorities who have the necessary budgets as well as sufficient waste mattress volumes could be matched to areas where there are Reuse Network partners need for mattress recycling facilities. Information on local authorities with enough budget to afford the premium to pay for mattress recycling could be found through local government finances [150].

Table 7.9 Local authority mattress recycling figures reported by region

Region	*Population (million)*	*Mattresses recycled (tonnes)*[23]	*LA Mattresses recycled per 100 people*[24]	*2019 recycling capacity*
North West	7.3	1,051	0.6	295,000
North East	2.6	247	0.4	-
Yorkshire and Humber	5.5	472	0.3	20,000
West Midlands	2.9	2,671	3.7	750,000
East Midlands	4.8	635	0.5	180,000
Eastern	6.2	-	-	-
London	8.1	11,028	5.4	600,000
South East	9.1	564	0.2	-
South West	5.6	375	0.3	75,000
Wales	3.1	4,840	6.2	175,000
Scotland[25]	5.4	750	0.6	50,000
Northern Ireland	1.9	1,258	2.7	40,000

- **Storage**

Storage of mattresses at HWRC and waste contractors often dictates the condition of mattresses whether they are kept dry and uncontaminated from other waste ion isolated containers or left in the elements in open containers or mix with other general

[23] Figures reported by local authorities by region for up to 2018 [16].
[24] Based on an average local authority mattress of 20 kg [13]
[25] Based on 2018 data from Hamilton Waste for Edinburgh Councils

waste. Wet mattresses sourced from local authorities or waste contractors are more expensive to process and yield lower material recovery. The suppliers feeding mattresses to a potential new disassembly plant would ideally have infrastructure at HWRC or collection sites to keep mattresses dry, through covered or closed containers. Where the sources of waste mattresses do not have such infrastructure, there could be collaboration with councils and waste contractors to invest in facilities to protect waste mattresses, to maximise the recoverable material value. Closed freight containers could be utilised at collection points to keep mattresses dry, maximise container capacity and minimise transfer time by directly loading the container onto a freight truck and off again at a deconstruction plant.

- **ARCs**

May act as spokes feeding a disassembly hub or become hubs themselves. Two ARCs that have been identified of interest, are Newbury Community Recourse Centre [151] in the South East, who have reported spending £32,000 per year disposing of mattresses, and Home Furniture Services Trust [152] in the South West who have a potential 75,000 ft^2 site available for use.

- **Retail partnerships**

Further sources of mattresses could be facilitated through the Reuse Network's relationship with IKEA and the JLP, to serve as a recycling point for their regional sources. Currently, major retailers and manufacturers such as Silentnight[26], Hypnos[27], Dreams[28] and IKEA will have exclusive agreements with a single mattress recycler, increasing the distance the take-back mattress has to travel rather than using potential local recycling facilities.

[26] Through Rematt UK, personal communication, Ian Jillings
[27] Through TFRG, based on communications with other recyclers
[28] Through Circom, personal communication, Richard Allsopp

7.3.4 Strategy for the Reuse Network

For the Reuse Network in approaching mattress recycling and deconstruction, it is important that their approach is though out and links to their core aims and competencies. The following section discusses possible approaches for improving mattresses recycling and discusses possible legislative changes.

- **Planning**

One of the key requirements for taking mattress deconstruction forward is that robust planning and procedures are put in place to avoid economic insecurities and health and safety risks. Mattress recycling can be extremely hazardous and cause serious injuries through the use of knives or long-term damage to lungs though prolonged dust inhalation. For the proposition of a hub to be taken forward, resources should be invested to finance and/or support full-time staff to set up a pilot for a mattress deconstruction operation.

- **Core purpose**

Some members of the Reuse Network do not think that mattress deconstruction should be a priority due to the lack of emphasis on reuse, a core purpose of the network [153]. To avoid disparity between their core aim of reuse and the deconstruction of mattresses, it is important that a potential mattress deconstruction operation should not be directly linked to the Reuse Network, but merely supported through its network and influence. It would be beneficial to identify the necessary personnel who could work together to set up mattress deconstruction in the areas of greatest need. Progress could be made if the Reuse Network's partners were to work with local authorities and industry to tackle the issue of mattresses going to landfill or incineration, while promoting the need for ethical recycling and reuse of the components.

- **Other opportunities**

Although not the focus of this study, there are options to recondition mattresses that are returned to mattress manufacturers and retailers, either from trial periods or general customer returns. Opportunities exist to work with companies such as Sealy, who currently manually deconstruct returned mattresses in-house, and the JLP, who reportedly have stockpiles of returned or unsold mattresses across the country. Through its partners, the Reuse Network would be ideally placed to take advantage of this situation whereby good quality returned mattress could be reconditioned by removing and requilting the outer cover with the agreement of the original manufacturer. The mattresses could be resold under the Reuse or partner brand. As well as the option of reconditioning whole mattresses, there is also the possibility of manufacturing products from mattress origin waste. This has been discussed, and prototypes of bedding products produced from recycled textiles have already been presented to retailers[29].

7.3.4.1 Lobbying for public policy changes

Given the importance of legislation as a driver for recycling, lobbying for legislative change is another option for driving improvements in mattress recycling. This could include bans on using landfill, taxing the sales of mattresses and/or EPR through producer taxes and or subsidies.

- **Landfill**

A total landfill ban would shift disposal to the next cheapest alternative and lead to a surge in demand for alternative disposal routes though incineration, recycling or even potential exporting abroad. Capacity for recycling mattresses was currently 2.2 million meaning per annum in the UK, 5.3 million mattresses would have to be disposed of through other methods whilst recycling capacity grows. A surge in demand for mattress

[29] Personal communication, Martin Gamester

recycling could lead to authorities and waste contractors becoming desperate to dispose of mattress meaning proper due diligence on their disposal is not conducted. This may create an increase of poorly run operators who monetise the collection of mattress before making their disassembly financially viable which has in the past lead to a number of large abandoned warehouse full of mattresses [20]. An alternative solution could be regional bans on mattress recycling where there exists capacity to recycle them. Regional bans could be introduced in phases to assess their effectiveness and rectify any unforeseen challenges. Given the possible unwanted outcomes from banning mattresses from landfill, a more effective approach would be to incentivise their collection and treatment through recycling. Further, key to the feasibility of mattress recycling is that materials/components can be recovered with a positive asset value.

- **Mattress tax**

A flat rate sales tax on mattresses would be a simple and effective way to immediately raise funds to be invested back into mattress recycling. This policy is common in the US mattress recycling schemes [35]. Funds could be used to subsidise mattress recycler gate fees, invest in better storage infrastructure of mattresses at local authority sites and generate funds for grants to improve the capacity to reprocess the recoverable waste streams back into mattresses. However, a flat rate tax would not take into account the variable financial cost of handling and processing different mattresses as well as the recyclability and embodied environmental impact of different mattress designs. A variable mattress sales tax that considered aspects of financial processing costs, recyclability and environmental impact, would require significant resources to initially determine and oversee[30], but could be a good way to capture the

[30] Personal communication, David Fitzsimons

true social-economic cost of different mattresses. Given the glacial pace that legislative changes can take, a simple flat rate sales tax could be most effective in the short term.

- **Extended producer responsibility**

Mattress design needs to enable easy separation of materials/components whilst selecting suitable materials that can either be protected from contamination or be economically feasible to reprocess. Although a sales tax would help fund mattress recycling, it would be unlikely to have much of an impact on manufacturers' design or material selection. The mattress recycling schemes in France introduced EPR on all furniture in 2012, creating legal obligations on furniture sellers to assume responsibility for the collection and treatment of their products at end-of-life [30] . However, this did not affect the mattress design as the responsibility of the producer was routed to simply finance third parties to process the waste mattresses [40]. The ability of manufacturers to pass on responsibility to third parties for the collection and treatment of waste means that the impact of the EPR is severely limited, with the loss of incentives to impact design for circularity; meaning the EPR is not truly the "producer" responsibility, if the reasonability can be avoided by simply paying a fee to a third-party. Improving the circularity of mattress design is integral to maximising recycling potential of mattresses. The producer must be held accountable for the pollution and impact of their products at end of life. Future legislation in the UK could be used to incentivise suppliers to reuse or recycle materials in a closed loop system which could see the mattress design changed to help preserve the original value of materials if suppliers are incentivised to recycle them. A producer tax and/or subsidies could create a stronger incentive for producers to design for reuse/recyclability. Again, such a tax would likely take time and resources to monitor. Further work would be needed to define or quantify the reuse/recyclability of a mattress as well as its environmental impact. It is suggested that in the short term, specific designs and components that are known to cause difficulties in recycling such as using metal staples to secure each layer and pocket springs have a producer levy. Further, specific materials that have high quantities of embodied carbon such as polyurethane foam [99], could also have a levy placed on them, with subsidies for the use of reuse/recycled materials (where it can be proven there is an environmental benefit of doing so). Funding to determine appropriate variable producer taxes and or subsidies could be provided from initial flat rate taxes. The determination of appropriate variable could be conducted through a government task force or RAMR.

7.4 Conclusions

The estimated mattress recycling capacity as of September 2019 was 2.2 million, meaning over 5 million mattresses are still destined for landfill or incineration each year. This was in part due to no financial incentives or legal obligations to prevent mattresses going to landfill. The study reported on recoverable mattress waste streams, their value through different processing methods and the cost of processing. Further financial appraisal has been outlined for mattress deconstruction operations where a modelled manual deconstruction operation with a throughput of 50,000 mattresses was shown to require an initial investment of approximately £100,000. The financially viability of mattress deconstruction in the early stages is dependent on achieving a minimum deconstruction rate of 35 mattresses per day per employee.

There is a significant opportunity to reduce the environmental impact of mattress disposal, with the recycling of 50,000 mattresses shown to produce a 1400-2200 tCO_2-eq net saving in GHG emissions verses disposal via landfill; where the higher range is more representative of manual deconstruction. However, current growth in mattress recycling is being led by an increase in facilities which shred mattresses, reducing the potential environmental benefits of mattress recycling. The recoverable value of mattresses is limited due to insufficient infrastructure to keep mattresses dry at end-of-life and due to the design of mattresses which limits their recoverable value and increases disassembly cost. Potential collaboration between stakeholder across the mattress life cycle to improve infrastructure and mattress recycling could be difficult as most mattress recyclers do not want to work with competitors, making any future collaboration highly complicated.

7.4.1 Recommendations

Investment is critical to improve the quantity and quality of mattress recycling. Ways the Reuse Network could make a proactive impact on the state of mattress recycling:

- Support a mattress recycling facility through members and retailer relationships
- Expedite possibilities for partners in terms of becoming an approved manufacturer/ seller of requilted mattresses and remanufacturing products from mattress wastes

In addition, the Reuse Network could utilise its influence in local, regional and national government to initiate/accelerate legislative changes into:

- **Regional landfill bans** where there is sufficient capacity of alternative disposal routes
- Introduction of an immediate **flat rate sales tax** on mattresses to fund their collection and infrastructure to recycle them effectively; with the a variable sales tax be introduced in the long term
- **Producer tax** to capture the true social-economic cost of different mattress designs with incentive for producers to design for reuse/recyclability.

If the Reuse Network is to realise a vision of a hubs and spokes mattress recycling solution, funding persons full-time to spearhead the development of deconstruction sites is imperative for any future development. Further work is required to identify specific sites where mattress deconstruction would be feasible in the areas of critical need of Scotland, Eastern and Southern England. Where after, further analysis would be required on local onward markets, cost benefit analysis of investing in machinery and further possible waste stream processing.

8 FINAL CONCLUSIONS

Research on the mattress life cycle discussed three key issues of sourcing post-consumer mattresses, mattress design and onward markets for arising waste streams. The study determined that in 2018, 7.6 million mattresses were disposed of with 5.7 million destined for landfill or incineration and 1.9 million sent to recyclers. The recoverable value from an average mattresses ranged from (£0.5) - £2.8. Legislative intervention to improve mattress recycling could take several different forms. Intervention in the form of EPR would ideally create a framework to fund the collection and recycling of mattresses whilst creating stimuli to increase the recyclability of mattresses through design for disassembly and design for recycling. Mattress design needs radical innovation to support and improve the recyclability of mattresses.

The research found that at present there is a distinct lack of a coherent and holistic approach to stimulate proactive action between different stakeholder groups across the mattress life cycle to facilitate widespread quality mattress recycling. A substantive lack of investment by the government and waste contractors has meant mattress recycling and the recoverable value from mattress waste streams remains very low. Further, the absence of any significant change by the mattress manufacturers into design for disassembly and recyclability means mattresses are still inherently difficult to dismantle with a limited utility of recovered materials.

Within the context of this research, Chapter 5 showed waste from mattresses could be added to building materials either enhancing or maintaining mechanical strength whilst reducing thermal conductivity. Although this would not be a high form recycling, the present lack of alternate recycling applications means the incorporation of mattress origin waste into building materials has the potential to offer a viable, practical and performance enhancing re-utilisation of the waste.

From Chapter 7, issues around mattress deconstruction that limited improvements into mattress recycling were:

- No financial incentives or legal obligations to prevent the landfill of mattresses
- Insufficient infrastructure to keep mattresses dry at end-of-life increases disposal costs and limits the majority of their recycling to energy recovery
- Design of mattresses limits their recoverable value increasing disassembly cost
- Lack of infrastructure/investment to recycle waste streams effectively
- Most mattress recyclers do not want to work with competitors, making any future collaboration highly complicated

8.1 RECOMMENDATIONS

To facilitate widespread quality mattress recycling there is a need for a collaborative and multifaceted approach between industry and government to address mattress design, fund the collection of post-consumer mattresses to recycling facilities and to develop the capacity to facilitate and increase the quantity and quality of recycling waste streams. Approaches identified that could be implemented by industry and policy through which the Reuse network could also provide influence to support were:

- Incentives or funding to facilitate investment into recycling mattress origin wastes
- Regional bans on the disposal of mattresses via landfill where there is sufficient capacity provided by alternative disposal routes
- An immediate flat rate sales tax on mattresses to fund their collection and infrastructure to recycle them effectively; with a variable sales tax be introduced in the long-term to take account of different mattresses' true social-economic cost burdens
- Producers' tax to radically alter mattress design to maximise design for reuse/ recyclability and minimise their environmental impact

8.1.1 FURTHER WORK

8.1.1.1 Life cycle of post-consumer mattresses: waste streams and recycling challenges

- Identify best practices for manufacturers on material selection, mattress design and construction to enable design for disassemble and maximise the reuse and recyclability of components and materials.
- Quantification of the socio-economic benefit of different approaches to repurposing waste streams.

8.1.1.2 Incorporation of mattress origin waste into building materials

- Further testing of modified composites to precisely determine the thermal conductivity and effect of delayed and or reduced temperature change of designs.
- Identify specific application(s) of the composites and any requirements or regulations that the waste additions must satisfy.
- Testing on a greater number of samples and wider variety of mattress waste condition and sourcing to validate the findings.
- Consideration of the end-of-life processing of waste-incorporating building materials.

8.1.1.3 Market Insight

- Identification of specific sites where mattress deconstruction would be feasible in the areas of critical need of Scotland, Eastern and Southern England.
- After which, further analysis would be required on local onward markets, cost benefit analysis of investing in machinery and further possible waste stream processing.

9 APPENDICES

APPENDIX I - TYPICAL QUESTIONS ASKED TO STAKEHOLDERS

a) MANUFACTURERS

- What are the components and composition of the products you produce?
    - How do you dispose/treat your waste and returned products and what is the cost of doing so?
- What developments are you working on to improve the reuse/recyclability of the products you produce?
- How do you use recycled materials and or post-consumer mattress materials?
    - How is the recycled content sources and processed?
    - What are the costs and quality implications of sourcing post-consumer feedstock?
    - Who are the specific companies that can reprocess mattress materials for reuse/recycling?
    - What steps are you taking to improve the recycled content of your products?
- What other developments are you aware of in approaches to improve mattress recycling?
    - Are you involved with the NBF discussions to improve mattress recycling, what are your thoughts on their approach and how could it be improved?
    - What are your thought on the current mattress recycling operators?
    - Who are your suppliers and are you aware of how they treat their waste? or their efforts to improve the recyclability of their products?

b) LOCAL AUTHORITIES AND WASTE CONTRACTORS

- How do you collect mattresses and what is the cost of doing so?
- How many mattresses do you receive/collect and from which sources?
    - What is condition of the mattresses you collect and what is the distribution of wet/dry mattresses
- How do you store the mattresses?
    - How often are they collected from site?
    - How are they transferred and how many can be transferred at a time?
- How do you dispose/process the mattresses?
    - What are the disposal/processing costs and how could these be reduced?
    - What is the quantity of the different disposal routes for the mattresses?
- What factors affect your decision on storing/disposing/processing of mattresses
    - What would be the target cost to enable more/all mattresses to go through recycling/disassembly?
    - What are you opinions on the different disposal routes and the companies that recycle mattresses
- What needs to change to enable more mattresses to be recycled by you?
    - What obligations are you under to recycle (more) mattresses?

c) MATTRESS RECYCLERS

- What is the scale of your operations?
    - Who do you source your mattresses from and in what quantities?
    - How do you disassemble the mattresses?
    - How did you start?
    - What are your plans in the future?
- What are the waste streams that you separate from the mattress?
    - What are their proportions and what are their end fates?
    - How are waste streams processed for onward markets and what is the costs of doing so?
- What are the onward markets for recovered waste streams?
    - Who are the companies that reprocess/take the waste streams?
    - What value do you receive for the different waste streams?
    - What other possible markets have you investigated?
- What are your thoughts on the other mattress recycling companies?
    - How many mattresses do you believe they recycle?
    - What do they do with the recovered materials and where are they sent?
- What do you estimate to be the quantity of waste mattresses sourced from take-back, waste contractor and local authorities?
- What are the key barriers limiting the quantity and quality of mattress recycling and what can be done to address them?
    - What are your thoughts on what the NBF is doing to try to improve mattress recycling and how are you involved?

Appendix II – Review of mattress deconstruction

a) UK mattress deconstruction

The Furniture Recycling Group (TFRG) operates through sites in Blackburn, Preston, Ilkeston and Bristol with around 70 employees and is co-owned by mattress manufacturer Hypnos Beds with subsidiaries including a freight transport company [154]. TFRG reportedly focuses on the processing of retail mattresses with known agreements with Ikea, JLP, and Premier Inn. The company claims to process 7000 mattresses per week, a figure which other recyclers say is exaggerated. Mattresses are disassembled via a mix of automation and manual deconstruction into 19 component parts. Springs deemed good quality are sold for direct reuse whilst others are baled with open coil springs sent for scrap and pocket springs reportedly sent for shredding at Endurmetal. Recoverable textiles and foams are put though a sanitisation process, thought to consist of chemical disinfectants and or steam treatments with materials baled and sold on to reprocessors. Their website claims 100% of materials diverted from landfill with 95% of materials recycled and remainder going to energy from waste. Via manual deconstruction, a single operative is said to be set a minimum of 45 mattresses to deconstruct a day with bonuses incentivising deconstruction of up to 100 mattresses per day [47].

CAD Recycling opened a mattress recycling plant in Denbigh North Wales in 2012 in a contractual partnership with TFRG, originally for Denbighshire County Council. Processes 300-400 mattresses per day with potential capacity up to 3,500 mattresses per week with twenty employees. Note CAD recycling also operate other waste service and the twenty employees are not all directly involved in mattress recycling. According to their website, the company previously had a contract with Dreams Beds to process 50,000 mattresses annually (which is thought to have since ended), with data shared by the company also showing that they processed 52,000 mattresses from council sources in the year 2018-2019. From information shared by the company, of mattresses sourced from councils, mattresses were dismantled into the following constitute materials: springs (53%), shoddy (5%), ticking (4%), polyester (8%) and foam (6%) with the reminder (23%) sent for refuse derived fuel (RDF), thought to be shipped abroad. With 15% of the tonnage of springs recovered sent for reuse, with the remainder scrapped.

Matt UK, who operate from Chatham Docks, East London, are the largest UK mattress recycler processing up to 60,000 mattress per month sourcing 80% of mattress from councils and 20% from retail take-back schemes. Operate a manual disassembly process with 17 established material groups with recycling routes. Ray Bagnall, the site manager, claims that mechanical shredding of mattresses is not feasible in the long run and will inevitably lead to machine breakdown. The large scale of operations and location on the dock yard enables the company to ship in bulk to countries all over the world. Materials are separated based on quality and type into, including but not limited to, steels, foam, polyester, mixed (non-separable), woven textiles, cotton, other naturals and jute. For the destination of waste streams, the open coil and pocket springs are sold directly to refineries in the EU, the foam has five different global outlets including markets in Australia, the textiles are separated based on colour and condition and shipped to markets in Turkey and Ukraine, the polyester is graded and generally sold within the UK, whilst the mixed non separable materials is sent for RDF within Sweden or the Netherlands. A minimum of 8-12% of the mattress has to be sent for energy recovery through RDF.

Amgen Bryn Pica, located in South Wales, run by Amgen Cymru in partnership with Rhondda Cyon Taf County Borough Council, has a mattress recycling plant with a throughput of around 35,000 mattresses with a disassembly process consisting of a mix of manual and automated methods [13], [24]. Mattresses are put though a pair of mechanical rollers which strip the outer layers away from the mattress core [4]. The company is currently involved in researching methods to steam clean the recovered textiles along with TFRG who are both part of a £350,000 funding infinitive by the Welsh Government to develop applications for low value textiles recovered from mattresses [114], [115].

Hamilton Waste & Recycling, located in Carberry, Edinburgh, operate a major skips site and opened a mattress recycling plant in 2017, with funding from the Circular Economy Investment Fund, and currently process 2000 mattresses per week, with mattresses sourced only from local councils or waste contractors. Disassembly is a two-person operation involving an excavator used to pin and separate the textiles from the mattress core. The composition of arising waste streams by mass are Steel (30%), foam units (7%), polyester (3%) and mixed non-separable. Spring units are put through an Ulster shredder and sold as scrap, foam units are sold to a local reuse market, polyester is manually separated and sold into the upholstery industry whilst the remaining mixed non-separables are shredded with onsite capabilities to convert the shredded waste to SRF. The company has onsite facilities to transform waste and shredded textiles into solid recovered fuel which required an initial seven figure investment. A gate fee per mattress between £3-4 is charged to cover separation costs, with overhead costs of £70 per hour and net value of £3-3.5 generated per mattress. However, the value generate per mattress is largely due to the revenue created from the sales of SRF which is sold under a long term contractual agreement with an onward buyer (i.e they generated value is as a result of the skips company essentially paying themselves)

AAT Recycling *(textek)*, based in Whitchurch Shropshire, recycle mattresses and carpets from local authorities as well as industrial waste from mattress manufacturers, with a throughput estimated to be in the region of 100-200,000 mattresses per year. Prior to April 2019, mattresses were disassembled by hand with materials separated into open coils, pocket springs and foam, with the remaining materials shredded with waste carpets for equestrian and SRF markets. A single employee was said to be able to process up to 65 mattresses per day. Since then, the company has installed their own shredder which was developed in partnership with a German supplier at a cost of around £3 million. According to the company's website, the shredder is capable of processing 10,000 mattresses per week with materials separated into steel, foam and mixed textiles. The company director claimed that the shredder processed 4,200 mattresses in a single day on a double shift, whilst averaging 2,000 per day in normal operations. The director also said the margin per mattress was around 20-30%, with their average gate fee believed to be around £5.

Envirotex *(Rematt UK)*, who incorporated in September 2017 in partnership with HML Recycling, a metal recycler in Accrington, have capacity to process 2,500 mattresses per week from two sites with capacity also to process bed bases and headboards. They source mattresses from a mix of council and takeback schemes with major clients of Bensons and Silentnight. Dry mattresses are sent to one site for manual deconstruction whilst wet mattresses are sent to a site at the HML recycling plant for shredding. Dry mattresses are separated into reusable and non-reusable spring sets, foam, mixed textiles, polyester, soft shoddy felt, natural textiles, and woven textiles. Reusable springs are sold to the budget mattress manufacturing market with the reminder shredded and scrapped at the metal plant. The shredding of pocket springs would require a specialist machine which, according to the company director would cost more to run than the recoverable value; but was still the economic disposal route. For the other recovered materials, PU foam is chipped and sent on for processing into bonded foam, polyester is sold onto the upholstery industry whilst soft shoddy is collected for re-flocking into automotive felt and mixed non-separables sent for energy recovery.

Circom, a waste management company based in Coventry, have capacity to shred approximately 1000 mattresses per day with a similar shredding set-up to that operated by Envirotex. According to the company director, Circom mainly shred mattresses sources from Dreams take-back schemes but also sources from councils as far away as the South East with Dreams said to have remote CCTV access to the site to ensure transparency. The shredding line separates into three waste streams of metal, foam, polyester and flock. Foam is treated with a domestic equivalent disinfectant and sold for carpet underlay. Polyester goes into the fibre blending industry whilst flock is treated through three magnet stages to remove any metal to be processed externally into equestrian surfaces.

Ulster Social Employment Ltd (USEL), a social enterprise based in Belfast in Northern Ireland, offers recycling services for mattresses, carpets, furniture and manufactures a range of bedding products. It sources waste mattresses from councils and retail takebacks with partners of Dreams and Harvey Norman. Manually deconstruct up to 800 mattresses per week with a single employee able to strip 25-30 mattresses per day. Mattresses are separated into open coil, pocket springs, foam, soft shoddy, coir and remaining mixed textiles. Open coil springs are shredded and scraped, pocket springs are sent to landfill, whilst foam, polyester, soft shoddy, coir and mixed textiles are baled and sold through a broker to markets in England. The mixed textiles are sent for energy recovery whilst other materials are recycled. USEL will charge a gate fee of £5 per mattress or £7-10 including delivery to cover overheads and separation costs. Overall value generate from recovered materials is approximately neutral.

Carpenters, based in Derbyshire, a large foam mattress producer, supply contract foam mattresses to prisons and the MOD with takeback schemes; where the foam is reportedly recycled into carpet underlay [11]. Only foam mattresses are reported to be recycled here and it is thought that the number is below 50,000 per year [6].

SUEZ, a multinational water, recycling and recovery company, have a number of sites across the UK where mattresses are sent for disposal though incineration for energy recovery or landfill. The exact quantity of mattresses processed by SUEZ is unknown but estimated to be over 100,000 mattresses per year. A single processing plant in Devon received 994.2 tonnes of mattress in 2017 from Devon County Council [111], equating to approximately 35,000 mattresses. It is unknown whether the metal is removed from the mattresses prior to incineration.

Other companies operating small scale mattress deconstruction include **Mattress Recycling, Mattress Recycling Services, FRC group** and **SMRC Southwest.** Of the recyclers interviewed, most were open and happy to discuss their operations in detail in the hope to improve the sector. It was clear that there is strong antipathy between certain mattress recyclers due to perceptions of unethical or non-environmentally friendly practices. This presents a major barrier towards collaborative action to improve the industry. In the past there have been meetings between the mattress recyclers which reportedly ended in arguments resulting from larger mattresses recyclers apparently colluding to influence outcomes. As a result there have been no further meetings for the past three years[31].

b) Examples of international mattress deconstruction

- **France**

France disposes of an estimated five million mattresses annually. They introduced extended producer responsibility legislation in 2012 for furniture and bedding through L'Éco-participation [107]. Legal obligations mean that any seller of mattresses into France must take responsibility for the mattress at end-of-life or finance its collection and recycling. Financial contributions are paid to one of two NGO eco-organisations, *Éco-mobilier* and Valdelia, who in turn finance collection, reuse, recycling or energy recovery of end of life furniture and bedding. Éco-mobiler started in 2011 through a consortium of manufacturers and distributors of furniture. The scheme supports seven

[31] Personal communication, Allen Jackson, Textek

preparation and dismantling sites across France in partnership with collection facilities for domestic and commercial disposal in partnership with companies such as ***SUEZ, Recyc-Matelas Europe*** and ***Veolia.*** At a plant in Rennes run by Veolia, mattresses are pre-treated via thermal or chemical sanitisation before being sorted into mattress groups of spring, foam, latex and wool. Springs are separated from other materials using machinery whilst foam and latex have the outer cover mechanically cut and removed before the remaining foam is fed directly through a series of mechanical and thermal process to produce bonded foam. Separated materials are all baled for use for application as mats, cattle mats, thermal and acoustic insulation [30].

- **Belgium**

Belgium disposes of an estimated 1.1 million mattresses per year. A waste management company ***Vanheede***, collects and processes mattress materials largely to produce SRF. This is through an environment group initiative called O-Mat [31]. ***SUEZ*** also operate recycling facilities in Belgium through **Recyc Matelas Belgium**.

- **The Netherlands**

In the Netherlands, around 1.2 million mattresses are disposed of annually with the majority of mattresses (60%) being foam [32]. **RetourMatras,** who are parted owned by UK waste management company Renewi and the Ingka Group (who own IKEA) [155], operate two recycling plants in the Netherlands with the capacity to process a reported 650,000 mattresses annually. Two plants located in Lelystad and Alphen are both highly automated with foam reprocessing lines. Mattresses are collected through municipality sites and retailers in closed storage containers with capacity for an average of 90 mattress per container. The ticking is sorted by colour and shipped to morocco to be processed into yarn [32]. RetourMatras owns the intellectual property for the automated technology and is a joint venture with the Australian based TIC Group. **Matras Recycling Europe BV**, located in the province of Utrecht, recycles 20%

of the Dutch market with 275,000 mattresses per year. This is done through a semi-automated process [31].

- **Australia**

Of Australia's estimated 1.6-1.8 million mattresses disposed of, 900,000 are estimated to be landfilled with the remaining reused (including recycling or energy from waste), stockpiled or illegally dumped. ***Soft Landing Mattresses Recycling*** are a social enterprise formed by a consortium of manufacturers, bedding suppliers, recyclers and retails with 6 recycling sites across Australia diverting around 350,000 mattresses from landfill [42]. The sites include plants operated by TIC Group who formed a partnership with the social enterprise in 2016. TIC Group provide automated technology for mattress recycling adapted from that used by RetourMatras [39].

- **USA**

The US industry for mattress recycling is overseen by the US Mattress Recycling Council (MRC) which identifies over 44 mattress recycling sites across America [34]. MRC estimate that 20 million mattresses are disposed annually in the US. The states of California, Connecticut and Rhode Island have legislation that requires manufacturers to create state-wide recycling programmes which are managed by the MRC. Across MRC state programs approximately 1 million mattresses are collected for recycling each year. Companies include **DR3 Mattress recycling** with facilities in Oakland and Eugene, processing 353,000 mattresses in 2017. DR3, who are typical of mattress recycling operations in the US, predominantly uses manual disassembly methods, bailing separated components for recycling markets for onward application in pet beds, fleeces, carpet underlay, oil filters and energy from waste for the wood.

- **Canada**

Canada has several recyclers, the larger ones being **MattCanada**, **Canadian Mattress Recycling** and **Pacific Mattress** with landfill bans in some provinces. Figures on disposal quantities and recycling rates are unclear, but according to a report for the Canadian Council of Ministers of the Environment [37], generally regions deal with end-of-life mattresses in a similar way. If the materials are not diverted through the existing informal reuse infrastructure, then the materials are disposed of at municipal solid waste disposal facilities (typically landfills). Some large mattress retailers voluntarily collect and recycle end-of-life mattresses when a new mattress is delivered. Mattress recyclers exist in British Columbia, Alberta, Ontario, and Québec. Industry mattress recyclers estimate that only 7% of used mattresses are being recycled in Canada. Some municipalities have started to ban large bulky items like mattresses from landfills. Once local recycling infrastructure was established in 2008, Metro Vancouver implemented a mattress landfill ban in 2012. Québec has included mattresses in its evaluation of potential EPR candidate products.

APPENDIX III – FINANCIAL MODELLING

a) COSTS

i. MANUAL DISASSEMBLY

Disassembly labour cost

- High: One operative processing 30 mattresses per day[32], five days per week, 48 weeks per year working 7.5 hours per day, 240 days per year at an hourly rate of £8.21 with employer's insurance contribution of 13.8%.
- Low: One operative processing 65 mattresses per day, five days per week, 48 weeks per year, with an annual salary including bonuses of £20,000 with employer's insurance contribution of 13.8%[33].

Running cost per year

- Maintenance at 5% of machinery purchase price [156] :£3850
- Building insurance: £5000[34]
- Employee and public liability: £3000[35]
- PPE of boots, gloves, respirators, clothing for four persons: £1000[36]
- Security: £2,000[34]
- Utilities: £6,000[36]
- Rent: £35,000
- Building tax: £4,000[36]
- Site manager and on costs: £30,000[36]

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[32] Based on estimates from mattress recycler USEL
[33] Based on figures reported by mattress recycler Textek [22] and TFRG [47]
[34] Based on Oaktree figure adjusted with 25% inflation over 10 years [44]
[35] Based on estimates from Megson adjusted with 10% inflation over 4 years [47]
[36] Best estimates based on Zero Waste Scotland [11] and WRAP [5] and web searched prices

Fixed start-up cost

- Two balers: £12,000[36]
- Four cutting tables: £1000[36]
- Metal Shredder: £60,000[37]
- Three large Skips/freight containers: £9,000[36]
- Forklift: £5000[36]
- Racking for 120 pallets or approximately 1,000 mattresses: £3000[36]
- Training based on two persons for level 4 WAMITAB: £5000[38]
- IT: £2000[36]
- Permit and operating licences: £5000[38]

ii. EXCAVATOR

Disassembly labour cost

- Based on two operatives processing 20 mattresses per hour, 10 hours per day, five days per week, 48 weeks per year, each earning £25,000 per year with employer's insurance contribution of 13.8%[39].

Running cost per year

- Maintenance at 5% of machinery purchase price [156]: £8,100
- Building insurance: £5000[40]
- Employee and public liability: £3,300[39]
- PPE of boots, gloves, respirators, clothing for two persons: £500[41]
- Security: £2,000[42]

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[37] Based on personal communication with Ken Crystal, Hamilton Waste who have an Ulster shredder and excavator
[38] Based on personal communication with Ian Jillings
[39] Based on personal communication with Ken Crystal, Hamilton Waste who have an Ulster shredder and excavator
[40] Based on Oaktree figure with 25% inflation rate over 10 years [44]
[41] Best estimates based on Zero Waste Scotland [11] and WRAP [5] and web searched prices
[42] Based on figures reported by mattress recycler Textek [22] and TFRG [47]

- Utilities: £10,000[41]
- Rent: £35,000[41]
- Building tax: £4,000[41]
- Site manager and on costs: £25,000[41]

Fixed start-up cost

- Two balers: £12,00[41]
- Excavator: £75,000[39]
- Textile shredder: £10,000[41]
- Metal Shredder: £60,000[39]
- Three large Skips/freight containers: £9,000[41]
- Forklift: £5000[41]
- Racking for 120 pallets or approximately 1,000 mattresses: £3000[41]
- Training based on two persons for level 4 WAMITAB: £5000[43]
- IT: £2000[41]
- Permit and operating licences: £5000[38]

iii. Shredding

Disassembly labour cost:

- Based on requiring eight full time persons to operate a site with a shredder earning £20,000 per year[44].

Running cost per year

- Maintenance at 5% of machinery purchase price [156]: £190,000
- Building insurance: £20000[44]
- Employee and public liability: £4000[44]

[43] Based on personal communication with Ian Jillings

- PPE of boots, gloves, respirators, clothing for eight persons: £2000[44]
- Security: £10,000[44]
- Utilities: £150,000[44]
- Rent: £150,000[44]
- Building tax: £20,000[44]
- Three salespersons and on costs: £75,000[44]
- Site managers and on costs: £115,000[44]

Fixed start-up cost

- Six balers: £36,000[44]
- Excavator: £75,000[45]
- All in one shredder: £3,000,000[46]
- Nine large Skips/freight containers: £18,000[44]
- Two forklifts: £10,000[44]
- Racking for 1200 pallets or approximately 10,000 mattresses: £30,000[44]
- Training based on four persons for level 4 WAMITAB: £10,000[47]
- IT: £10,000[44]
- Permit and operating licences: £5000[37]

[44] Best estimate based on Zero Waste Scotland [11] and WRAP [5] and web searched prices
[45] Based on personal communication with Ken Crystal, Hamilton Waste who have an Ulster shredder and excavator
[46] Based on personal communication with Textek
[47] Based on personal communication Ian Jillings

b) Revenue

Table 9.1 shows the estimated material revenue for waste streams that are separable based on the financials of disassembly setup discussed. The difference between the high and low values will depend on the distance waste streams have to travel for reprocessing, access to local and/or international markets, purity and extent of contamination (such as moisture, discolouration and dirt.). The reduced range of material value for the excavator and shredding methods as a result of a lower separation into metal, foam, polyester and flock.

Table 9.1 Estimate value recoverable from modelled disassembly financials

Waste stream	**Value range of waste streams (£)**			
	Manual		*Excavator/shredding*	
	High	*Low*	*high*	*Low*
Open coil	1.25	0.60	1.25	0.60
Pocket springs	0.00	-0.50	-	-[48]
Non separable	-0.10	-0.35	-	-0.35
Foam	0.20	-0.10	0.20	-0.10
Shoddy (soft)	0.05	-0.10	n/a	n/a
polyester	0.60	0.15	0.6	0.15
Natural	0.15	-0.10	n/a	n/a
Woven textiles	0.10	-0.10	n/a	n/a
Plastic film	0.05	-	0.05	-
Flock[49]	n/a	n/a	-	-0.30
Total	***2.3***	***-0.5***	***2.1***	***0.0***

[48] Processing pocket spring was found to be less in these operational set-ups due to incorporated shredding capabilities
[49] Consisting of Shoddy, natural and woven textiles with prices based on application of SRF or equestrian from personal communication with Circom and Textek

APPENDIX IV – PROCESSING AND MARKETS FOR MATERIALS

a) EXAMPLES OF PROCESSING MACHINERY

Table 9.2 gives examples of machinery required to shred or bale recovered materials with hyperlinks to the suppliers or specific product. Feedback from mattress recyclers and waste contractors was that LinkedIn was often used as a market place to buy and sell machinery. Note that the T250 Metal Spring Baler is specifically designed for mattress springs and has a list price of £75,000 or rental from £195 per week. This is estimated to pay off when processing around 700 mattresses per week assuming that including running cost, the increase value per tonne of baled open coil springs would be £35, with one tonne of springs sourced from 120 mattresses.

Table 9.2 Examples of processing machinery

Waste stream	Machinery	Supplier/link
Foam	Shredder & Granulators	tcmshredder.com alibaba.com
Textiles	Shredder	alibaba.com
General	Rollers/ Shredders/ balers	lidem.com/ing/ ulstershredders.com/ ebay.co.uk ssiworld.com
Open coil	T250 Metal Spring Baler Shredder	clearfuturegroup.com ebay.co.uk

b) COMPANIES THAT PROCESS/RECEIVE MATTRESS ORIGIN WASTE

Table 9.3 lists identified companies that are reported to process mattress origin materials. The table is organised by the type of waste stream along with the identified company, their locations and website. It proved very difficult to identify and confirm companies that reprocess mattress materials, despite attempts to contact the companies below directly. The lack of response from companies reported to recycle the material is likely down to a lack of interest and time the companies had for academic research looking into the area of mattress recycling. A more direct approach where samples of materials could be provided and meeting set-up to discuss financials and material reprocessing methods would have proved a more effective approach. It may have also been the case that some of these companies do not wish to publically disclose that they manufacture products or materials from mattress origin waste.

Table 9.3 Companies that recycle recovered mattress materials

Material component	Company	Location	Comments	Website
Scrap metal	EMR Group	Various		emrgroup.com/
Pocket springs	Endurmeta	Manchester	TFRG have partnership	endurmeta.com/
Foam	Ezifloor	Keighley	LA send here	ezifloor.co.uk/
	Hometex	Blackburn	Partnership with TFRG	hometex.co.uk
Mixed Textiles	James Robinson Fibres	Barnsley	Mixed fibre and Polyester	jrfibres.co.uk/
	Leigh Fibers	US, South Carolina	large scale reprocessor	leighfibers.com/
	Martex fibres	US, South Carolina	Mixed textile recycling	martexfiber.com/
	GeoHay	US, South Carolina	Manufacture geotextiles	geohay.com/
	SOEX	Germany	Current R&D project for chemical recycling	soex.de/en/ resyntex.eu
	HIVESA TEXTIL	Spain	Recycle range of textiles	hivesa.com/

Material component	Company	Location	Comments	Website
Mixed Textiles	Wolkat	Morocco, Tangier	Ticking re-spun into yarn. Partnership with Dutch mattress recycler	wolkat.com/
	Deniz Textile	Turkey	Recycle into shoddy	
	Davy Textiles Ltd	UK, Bradford	Mainly technical fibres	davytextiles.co.uk
	Pennine Blendings	Huddersfield	Make blended fibres	Penninetextilesandrecycling.co.uk
	LMB suppliers	UK, London	Reprocess into wipes	lmb-supplies.co.uk/
Shoddy/textiles	Felt Tec	West Yorkshire, Batley	LAs send here	beaumonts-recycling.co.uk/
Polypropylene	Plumb polymers	Sheffield Carlisle	Bulker for industrial waste	plumbpolymers.co.uk/
	Eco recycling	UK various	Bulk exporter	ecorecyclingltd.co.uk/
LDPE, HDPE	RPC bpi recycling	Various		bpirecycling.co.uk/
PP, PE film	Preston plastics	Preston		prestonplastics.co.uk/
Whole beds	Europa beds/beds4less	WF17 5TD Batley	Budget mattresses	beds4less.net/

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