CIVIL-412

Course project

Recycled plastic in construction

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Abstract

Plastic has become a very important part of modern day to day life. In principle, plastics are sustainable due to their versatility and ability to be recycled, however the current use and disposal methods or plastics generate a large environmental threat. Countries like Great-Britain have set sustainability targets and guidelines to reduce the environmental impact in the short term and even cease it in the long term.

In this report, the following three uses of plastic in construction were reviewed; concrete, road infrastructures and plastic lumber. The focus was laid on the amount of plastic used in the different applications as well as the change in material properties compared to common construction materials. For concrete and asphalt the right amount of plastic additives can show increased structural performance in lab tests.

On this basis an ideal system is proposed, where the plastics that cannot be recycled locally can be used in these applications. The idea would allow to cut emissions due to exportation as well as integrate the waste in a circular system.

Apart from the reduction of pollution, the system shows several benefits such as reduction on carbon emissions from common construction materials, sand replacements for concrete as well as job creation. However, there are also several risks involved, especially with regards to the actual execution of projects with these new materials and plastic pollution in itself. Additionally, one of the main conclusions is that research needs to be conducted in order to guarantee good behaviour of the applications in long and short term.

Overall, with the right guidance and financial support we think that the application of plastic in the construction sector has a high potential. In order to reach it, more research is needed, especially in prototype projects, and the development of guidelines and standards.

Contents

Chapter 1

Introduction

Since the creation of the first fully synthetic polymer in 1907, a very wide range of plastic materials has been developed. Plastics being inexpensive, lightweight and durable are very attractive for a variety of applications such as packaging, electrical and automotive applications. The plastic production industry has become a major factor in the economy, in Europe the plastics industry has a multiplier effect of 2.4 in GDP and around 3 in jobs [32].

As production grew it became clear that the use and disposal of plastic compounds poses many environmental concerns. In fact, the plastic industry consumes about 7-8 % of the world oil and gas production [32]. The production of plastics consume fossil fuels as feedstock and as an energy source for the factories. Another issue is that in the scale of nature plastics have a very slow decomposition rate, therefore littering causes plastics to find themselves compromising ecosystem's health. Additionally, given the extreme surge in demand of plastic products, there is also a growth in waste production. In many instances production kept growing even though the disposal capacity was at a maximum level, forcing industries to ship the waste overseas or putting it in landfills where the risks of it ending up in nature become more important.

Since plastics have been recognised as an environmental threat in 1970, there have been great efforts directed towards transforming plastic waste into a resource. Due to the versatility of plastics, the employed strategies will vary geographically, according to the plastic type and intended use. The outline of the strategy, implying that plastics need to be managed on their full lifespan, is to reduce, reuse, recycle materials and recover energy.

In this paper, we will review the possibilities of reuse of plastics in construction applications and evaluate the impact they have on both the construction industry and the plastic industry. The focus will be set on the United Kingdom and its waste management. Initially, this paper will assess the current solutions for plastic waste disposal and regulations set in the UK to characterise the magnitude of the issue. The focus will then be set on applications of recycled plastics in the construction industry and their benefits, downfalls and risks. Finally, we will advance a suggestion to move towards more sustainable practices.

Chapter 2

Plastic waste management

In today's society, plastics are essential to modern lifestyle. Its versatility allows for a vast range of applications in the construction, manufacturing and retail sectors. As the amount of plastic consumed is growing each year, waste management is becoming increasingly problematic. The inability to properly dispose of plastic waste causes about 4 - 12 million tonnes of plastic per year globally to find their way to the ocean. [8]

This chapter presents the current plastic waste management schemes in the UK as well as the current solutions aiming to mitigate the negative environmental impact of this industry.

2.1 Current waste management routes

2.1.1 Landfill

Landfills are the oldest and most common waste disposal systems. In 2019, landfills accounted for 24.9% of Europe's collected plastic waste, which represents 7.2 Mt of plastics annually. [32]

Sanitary landfills or Landfills are imagined to be able to break down complex compounds into smaller, simpler and hopefully less harmful components. Although such facilities theoretically create limited environmental harm, they are widely unsustainable because none of the energy used to produce the material can be recovered. This amounts to a linear life cycle, whereas sustainability guidelines direct all processes towards cyclic practices.

2.1.2 Recycling

For a plastic item to be considered to be recyclable it has to be collected, sorted, reprocessed and manufactured into a new product at scale and it has to be economically viable. Theoretically, all thermoplastics can be mechanically recycled since they can be melted and reshaped infinitely when pure. However, in practice plastic items are often composed of multiple layers and multiple grades of plastic or other materials which significantly complicate recycling. In fact, most different types of plastics are incompatible upon reprocessing. For example PET pieces in a PVC recycling streams will cause solid PET lumps that will significantly change the properties.

There exist three recycling routes:

- Primary (Closed-loop):
  Recovered plastic is recycled to be used as its initial use or for another application. This method requires to have few contaminants and ideally the recovered plastics should be of similar grades.
- Secondary (Downgrading):
  Recovered plastic used for an application it would not typically be considered for.

- Tertiary (Chemical recycling):
  Recovery of petrochemical components of the polymer to reproduce other plastics or to make sythetic chemicals.

In 2018, 29.1 Mt of post consumer plastic was collected across Europe which shows an increase in plastic waste collection by 19% since 2006. Of the collected mixed plastic waste, 32.5% was recycled, 42.6 % was incinerated and 24.9% was sent to landfills [32]. The general European waste management tendency is to divert waste from landfills towards recycling or energy recovery. This evolution is depicted in Figure 2.1.

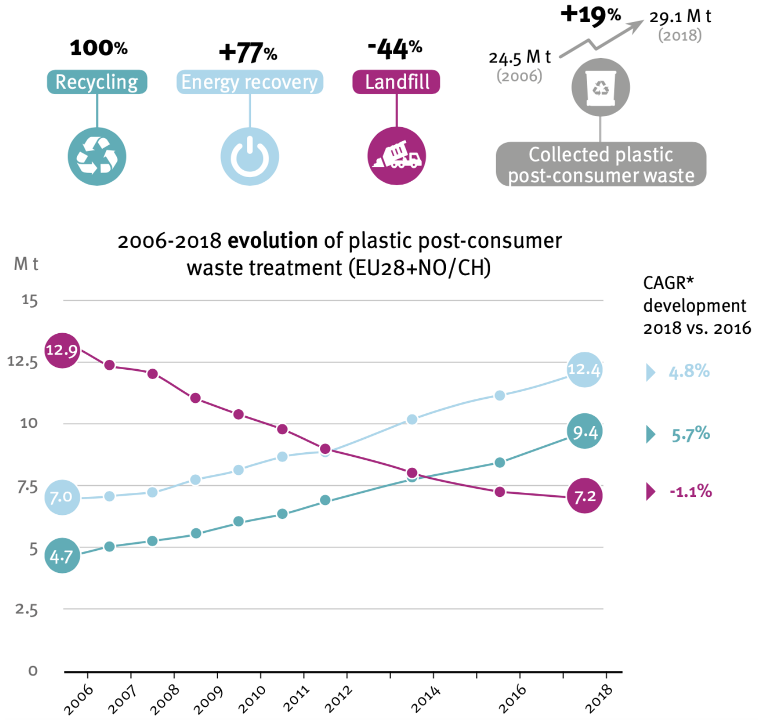


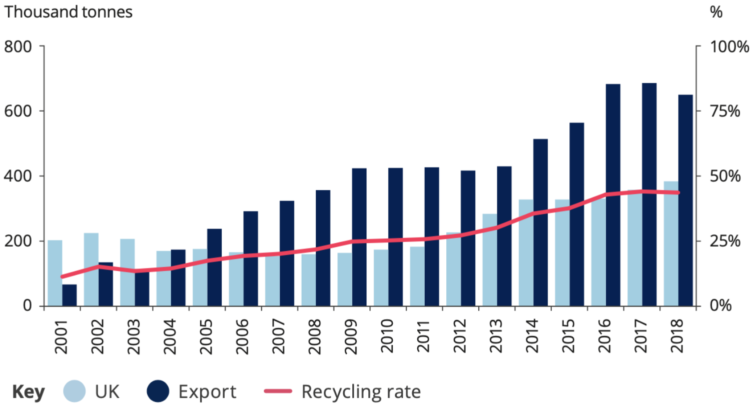
Figure 2.1 – Evolution of plastic post-consumer waste treatment [32]

2.1.3 Energy recovery

Energy recovery consists in burning plastic waste in order to generate heat, electricity or steam. This route is possible because plastics are derived from crude oil that gives plastics a high calorific value. This method of disposal has the advantage of reducing the volume by up to 99% thus reducing the amount of landfill space required and recovering a portion of the energy required to process the material. However, upon incineration, some plastic waste releases hazardous substances. Therefore, even if the method is gaining popularity with a 77% increase over Europe, it is still not very common in most southern countries [32].

2.2 United Kingdom's waste management

The United Kingdom has the fifth biggest plastic converters demand in Europe with 7.3% of the total amount, which represents approximately 3.7 Mt per year. In 2017, 2.36 Mt of plastic packaging waste was produced in the UK as well as approximately 2.5 Mt of non-packaging plastic waste, these quantities differ from the production quantities due to the variable lifespans of plastic products [32]. As of 2018, Britain has three waste management routes; Landfill, energy recovery and recycling. The United Kingdom has approximately 20% of landfill for 30% of recycling and 50% of energy recovery[32]. However, the UK is not currently able to recycle all the plastic waste it produces, it is exported to be recycled in other countries. Currently, the UK has a recycling capacity of 425 kt of plastic waste and 650 kt of plastics being shipped overseas to be recycled [40]. The tendency followed by the UK is shown in Figure 2.2.



Source: NPWD

Figure 2.2 – Plastics packaging reprocessing [40]

Britain is aiming to become a pioneer in environmental protection and a driver for change by setting multiple plastic management targets. Along with the government, the British Plastics Federation (BPF) are striving to prevent plastic from escaping into nature and advocating for responsible use and disposal of plastics. The first important milestone is the UK plastics pact, that sets the following targets for 2025:

- 100% of plastic packaging is to be reusable, recyclable or compostable
- 70% of plastic packaging effectively recycled or composted
- Take action to eliminate problematic or unnecessary single-use packaging
- 30% average recycled content across all plastic packaging

By 2030, there is to be no more plastics directed to landfills and finally the goal is to eliminate all avoidable plastic waste by 2042. In other words, the UK strives for a circular plastics economy. [8] To be able to achieve these targets, the government has developed collection systems as well as guidelines to help industries design for recyclability. The different important steps of the British recycling stream are presented in the following sections.

2.2.1 Collection

Plastic waste collection is governed by local authorities in the UK. The UK has mainly two types of collection strategies; kerbside collection and bring sites. Bring sites commonly have low collection rates unless secondary measures encourage returns such as deposit-refund schemes. In fact, bring sites only account for 7% of all recovered plastic in the UK in 2018 [40]. Through kerbside collection 512'000 tonnes of plastic was collected in 2018 [40].

Local authorities decide on the type of plastic collected based on the recycling possibilities for local companies as well as the economical value of the collected material. In the United Kingdom, almost all authorities collect plastic bottles however only 79% collect plastic pots, tubs and trays (PTT) [40]. Even though collection is widely implemented, only a fraction of plastics are effectively collected as shown in the following table.

Table 2.1 – Plastic collection rates [40]

Plastic Type	Tonnage [kt]	Collection rate [%]
Plastic bottles	380	60
PTT	114	38
Film	18	5

2.2.2 Sorting, size reduction, cleaning and separation

Waste streams enter recycling facilities as mixed waste and undergo pre-sorting to separate plastics from other recyclable materials such as paper, metals or glass. Further sorting of plastic waste is done through Fourier-transform near infrared spectroscopy(FT-NIR) to identify different polymers and colour recognition systems to separate clear and coloured plastics. Currently, flexible plastics are removed from recycling streams due to lack of appropriate equipment to treat such polymers. After being sorted, they are shredded and cleaned to remove traces of residues. Then the flakes undergo further separation that can be done via many methods. Separation between different grades of plastics can be done based on density properties such as float/sink separation in water or based on the colour of the flakes. Current methods have many limitations, for instance sorting dark plastic is complicated and separation for certain polymers such as PVC and PET because of their similar density properties remains challenging. A method used only in a small quantity of European recycling facilities due to it's novelty is laser-sorting. This method identifies the polymer types by scanning every flake of plastic and it allows effective separation of complex mixtures and without being colour sensitive.

2.2.3 Design for recyclability

To be able to reach the goals set out by the government all stages of the life cycle of a plastic product have to be implicated. One of the most important stages is the design of the products because well thought designs lead to eased recycling. Therefore, the BPF and RECOUP have issued guidelines [34] to help product designers have recyclable or more recyclable products and have the least interference with the current recycling processes. The following guidelines should be followed as much as possible without compromising product safety:

- Use the same material
  Products should be made of the same grades of materials or have very different densities to allow for easier separation.
- Minimise colour
  Prefer non-pigmented polymers or avoid strong colours.
- Easily separate closures

- Avoid full sleeves Full sleeves currently prevent proper sorting since they hide the polymer.
- Small, easily removable labels
  Labels should be easy to remove and not cover more than 60% of the area because it will prevent adequate sorting.

Chapter 3

Construction sectors

3.1 Plastic in concrete

3.1.1 Introduction

Concrete is considered to be the world's most-popular man-made building product. Its advantages are numerous; compared to its cost, it delivers the best strength, durability, or resilience, it is easy to cast in different shapes and requires little maintenance. More than 10 billion tons are produced globally each year [29]. In 2019, according to the building materials and components statistics from the Department for Business, Energy, and Industrial Strategy in the UK, the total volume of ready mixed concrete produced in the UK was around 17 million cubic meters. This represents 15.2 million tons of cement, 7.8 million tons of clinker, 23 million tons of sand (Fine Aggregate) and 23 million tons of gravel (Coarse Aggregate).

Concrete mixtures may vary according to the applications. The most important property is the w/c ratio that dictates both strength and workability of the concrete being produced.

3.1.2 Materials and Methods

Since concrete is one of the most popular building materials, it it widely standardised. Therefore, for any concrete mixture it needs to meet the requirements of aforementioned standards. The criteria of acceptability are mainly based on durability and resistance in the hardened state. Additionally, the mixture needs to meet certain properties in the wet state in order to guarantee both proper properties in the hardened state as well as formability.

In the reviewed studies, the plastics used are polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polystyrene (PS). For the scope of this project, mainly applications with PET and HDPE have been reviewed. These two plastics can be integrated into the mixtures as different substitutes such as fine and coarse aggregate replacement, as used in the mixture as PET fibers or used as a resin made of recycled PET in polymer concretes. In order for this type of material to be a realistic solution to reduce plastic pollution, it is essential that the material characteristics are satisfactory enough for it to become applicable as structural concrete. In the following sections, the properties of various studied mixtures are reviewed and compared to evaluate their potential.

3.1.3 Replacement of sand / fine aggregate

The first use of plastic is as sand or fine aggregate replacement. This application answers both the issue of plastic waste as well as the overuse of sand as it is the world's second most consumed natural resource.

In [39], recycled PET and HDPE were used to replace 10% of the volume of sand. The goal of the research was to evaluate whether a 14-day target mean-strength of 53 MPa could be achieved; which represents a realistic structural concrete. In order to evaluate the effect on particle size distribution on the mean strength, different grading of plastic was used. Firstly, PET was graded to match the sand replacement (PET1). Secondly, finer fragments were graded between 0.5 and 2 mm (PET2), and between 2 and 4 mm (PET3). Recycled HDPE carrier bags (HDPE1) shredded into a thin plate (5-500 mm^2) was also used. The variation in compressive and tensile strength compared to the reference mixture used are shown in Figure 3.1.

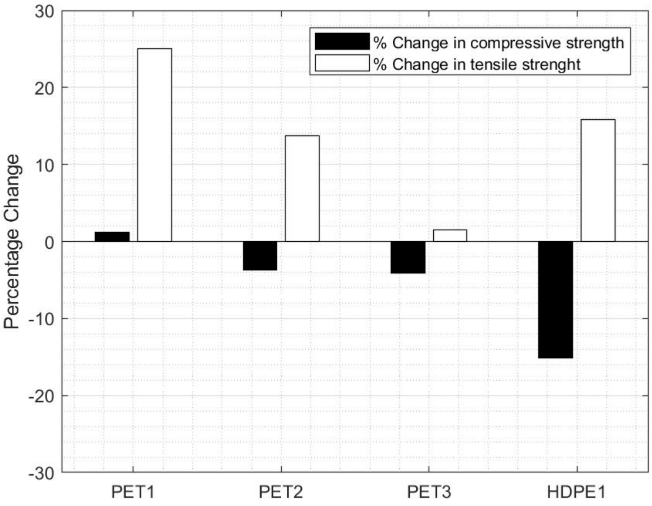


Figure 3.1 – Percentage change in strength of each mixture compared to the reference mixture.[39]

As the compressive strength varies from -4.1% to +1.7% around 53 MPa, respectively for a 2-4 mm PET fragment and sand graded PET. It was shown that the best characteristics were achieved with the sand graded PET. The tensile strength was increased by 25% compared to the reference concrete with a mean value of 3.26 MPa. The recycled HDPE replacement led to a reduction of -15.1% in compressive strength and an increase of +15.8% in tensile strength. As the main problem with plastic use in concrete is the weak bond between the plastic particles and the cement matrix, a test on 2-4mm PET fragments treated with sodium hydroxide and sodium hypochlorite and washed was performed. Compared to the untreated 2-4mm PET fragment there was a slight but not significant reduction in the compressive strength as well as the tensile strength. It was concluded that the most efficient plastic aggregate used in a concrete mixture should have a rough surface, be irregular in shape and be small enough as not to create a significant failure surface but also should be graded as the sand it replaces. Other characteristics as bulk density, slump, air content, workability, modulus of elasticity, time and temperature dependant properties, impact resistance, permeability, and abrasion resistance were not studied as well as other w/c ratios and plastic replacements percentages.

In a second study [6], plastics were grounded to replace the sand. The type of plastics is not indicated and the mixture has a 5% and a 20% replacement of sand by plastic. With this 20% replacement, there is a sharp reduction in compressive strength up to -72%, and with a 5% replacement, the reduction reaches -23%. It shows how important it is to define the type of plastic as well as the particle size distribution to obtain adequate structural concrete properties.

In [28], sand was replaced from 2% to 100% by recycled PET. Three types of maximum particle size were also studied with a range from 1mm to 5mm. It was shown that, with a replacement below 50%, neither the compressive strength nor the flexural strength was decreased. A durability study also shows that for a replacement value below 30%, shrinkage is not influenced by the PET particles. Also, with an increase in the replacement, there is a decrease in the modulus of elasticity.

3.1.4 Use of plastic fibers

It is also possible to use recycled plastic as fibers. Numerous fibers characteristics can dictate how the concrete will respond. For example the fiber length, the shape or the replacement percentage. In [24], fibers were made from thin strands slit in recycled PET sheet. To improve their bond properties with the cement matrix, an embossed shape was chosen, and a maleic anhydride grafted polypropylene coating was applied. The fiber volume fractions are 0.5%, 0.75% and 1%. As the fiber volume increases, the compressive strength showed a slight decrease ranging from 1 to 9% as well as the elastic modulus, compared to a normal concrete specimen, containing no plastic. The free drying shrinkage strain increased. However, ductility and ultimate strength increased substantially, by 1000% and 30% respectively, on reinforced concrete beams. The maximum mid-span deflection increased by 400% and both concrete compression and yielding of the tensile reinforcement simultaneously caused the failure. These changes are presented on the following figure.

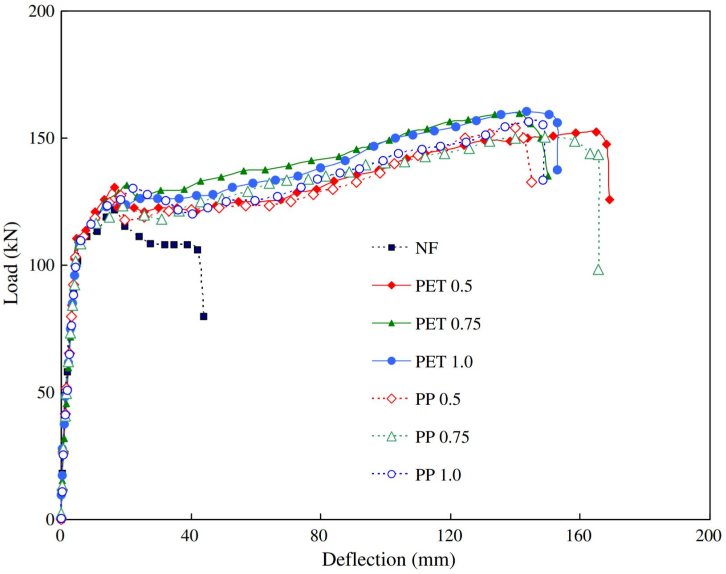


Figure 3.2 – Load–deflection curves of NF, RPET, and PP specimens at the age of 28 days [24]

In [36], different studies are reviewed about the use of polypropylene fibers. As it's not a plastic we chose to study, we'll not go into the details but it's important to notice that, most of the time and according to the length of the fibers, the plastic fibers have either no effect or a slight increase in the compressive strength.

3.1.5 Polymer concrete

The third studied way of using recycled plastic in concrete is by the production of an unsaturated polyester resin based on recycled PET which replaces the use of cement. In [23], the effect on the mechanical properties of different proportions of resin, which is made from 29.1% of PET, is studied. The mixture is made of 11%, 13% or 15% of resin, CaCO3, and coarse and fine aggregates. Results show that very high mechanical properties are achieved. Compared to a high-strength concrete made of cement, with a 58.8 MPa compressive strength, the polymer concrete can achieve compressive strength from 64.6 to 73.7 MPa with a maximum strength from the mixture with 13% resin. Furthermore, flexural and splitting tensile strengths are higher than those of cement concrete; they go up respectively to 23.8 MPa and 7.85 MPa. The mixture made of 13% resin showed the maximum bond strength of resin and showed the highest elastic modulus value of 27.9 GPa. It is concluded that the material is suitable for precast applications.

3.1.6 Others solutions

Another example is the use of recycled plastics as coarse aggregate in cement. However, according to [3] compressive strength reported is much lower than the one without plastic. The reduction in strength was 34%, 51%, and 67% for a replacement of 10%, 30%, and 50%. The main problem being the poor bond between the plastic aggregates and the cement matrix or the low strength of the plastic aggregates. Solutions as applying treatments on the surface or roughening the interface can be done but the characteristics stay too low for the concrete to be used as a structural element.

The effect of rubber in concrete was also studied. According to [37], the reduction in compressive strength observed in concrete containing rubber limits its use in a structural application. Fully replacing coarse aggregates by using coarse crumb rubber reduces compressive strength by 85% and splitting tensile strength by 50%. With fine crumb rubber, this reduction was 65% and 50% respectively. Using pre-treatments on the rubber particles can have a positive impact on these characteristics, but the results are still too poor in order for the material to be used as structural elements. However, better impact resistance, enhanced ductility, lower density, and better sound insulation allow this material to be used in other constructions as for roadway applications.

3.1.7 Solutions to the use of plastics in the concrete industry

Various applications of recycled plastics are possible in concrete. However, to use as much recycled plastics as possible by keeping characteristics good enough for the concrete to be used as structural elements, some solutions appear to be more favourable. These are summarised in Table 3.1.

Table 3.1 – Plastic content for different concrete mixtures

Plastic Type	Process	Content [% in vol.]
PET	Sand graded	10 - 30 (in sand replacement) 5.2 - 15.7 (total)
HDPE	Thin plate	10 (in sand replacement) 5.2 (total)
PET	Fibers	0.5 - 1
PET	Resin	3.2 - 4.3

The first solution is the replacement of sand with sand-graded recycled PET. A range of replacement from 10% to 30% [3,6], showed characteristics as good as normal concrete; the best strengths coming from the 10% replacement [39].The second solution seems to be polymer concrete by using PET as a resin. The fabrication process may be more difficult but the characteristics are the best observed from all the articles studied. However, its application seems to be limited to precast elements which reduce the quantity of plastics that could possibly be reused.

PET used as fibers and HDPE as thin plates give a concrete that could potentially be used structurally. However, it is important to be rigorous with regard to structural calculations as some characteristics are lower compared to regular concrete.

3.2 Plastic in road infrastructures

3.2.1 Introduction

The multiple plastics listed in chapter 2 can also be used in road infrastructures, which are made from asphalt mixtures. In the UK, 95 % of the roads are made of asphalt concrete [22]. Still in the UK, 26 million tons of hot mix asphalt (HMA) were made in 1999, of which the aggregates counted for 90 % of the weight [22]. This last number represents 20 million tons of aggregates. The use of plastics in asphalt binders can reduce its large amount being sent to landfills in thousands of tons as well as potentially improve the performance of asphalt concrete. Two types of waste are cited in literature: polymers and rubber. These materials can be found in waste disposal plastics (bags, bottles) and tyres, respectively. Regarding the plastics in the UK, only 8 thousand tons are currently used as aggregates for road infrastructures, but according to UK WRAP, this number could be raised up to 0.4 million tons [22]. To counteract this waste of potential construction materials, the US, which uses 5.5 % of their scrap tyres in the civil engineering domain [35], have written in 1991 into the Intermodal Surface Transportation Efficiency Act (ISTEA) and the Resource Conservation Recovery Act that the highway projects founded by the country have to contain a certain percentage of waste tyres. Knowing that road infrastructures mainly need to be repaired and that the estimated increase of the plastic wastes generated in 2050 is of 90 % [30], the recycling of waste materials in road infrastructures is a real issue and several reviews already tackled the subject.

3.2.2 Materials and methods

In the tests performed, only crumb rubber has been used regarding the scrap tyres, but regarding the polymers, different grades of polymers have been used: high density polyethylene (HDPE), low density polyethylene (LDPE), polyvinyl chloride (PVC), polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP) and polyester. Two means of incorporation in the asphalt concrete exist: the wet process and the dry process. In the wet process, the plastics are mixed with the asphalt binder, and in the dry process, the plastics replace the fine aggregates of the asphalt concrete. The first one is also known to be more tolerant and the second more sensible to materials selection, mix design and asphalt manufacture. The important parameters of the mixtures are the mixing temperature and the mixing time. These parameters are often changed in the tests that are conducted. Another way to incorporate the plastics in the mixtures is by adding fibers. The best way to add fibers to the mixtures is via the dry process, because it allows a better direction distribution of the fibers and because that way the fibers do not melt. The methodology used in the literature reviews is often the same; the optimum binder content (OBC) is calculated for the reference asphalt concrete and the plastic content is calculated as being a percentage of the OBC weight. Then the Marshall quotient, that is the ratio of stability to flow of the mixture, or in other terms the ratio of load to deformation, and thus the resistance to permanent deformation in service, is calculated to determine the best mixture. The mixing temperature and time are also indicated for some studies.

3.2.3 Results

Rubber

In [35], rubber was used for the analysis. The crumb rubber particles varied in size from 0.075 to 4.75 mm. The wet process was used and showed an increase in the asphalt concrete performance. It was demonstrated that this mixture increases the binder resiliency, the viscosity, the shear strength, the ductility and the resistance to fatigue cracking, while reducing the rutting. Furthermore, it is possible to completely recycle pavements made of crumb-rubber modified (CRM) asphalt into HMA mixtures. But some inconveniences can also be listed as for the larger layer thickness required, the cost and the leachates, that will be discussed in more detail with the following reviews.
However, in this study other drawbacks such as chemical reactions and storage problems were no-

ticed, which is not the case for most other studies.

The first reaction is rubber swelling. It occurs when asphalt is absorbed by the rubber particles that are present in the mixture, which increases the binder viscosity. Then there is the rubber particle dissolution, which occurs when the mixing temperature is too high and the time is too long. In this case the viscosity decreases. Finally, the particles can settle down to the bottom of the binder during the storing and it must be maintained at high temperatures to facilitate the handling.

In [22], tyres were first analysed. The particles size was of 0.15 to 0.6 mm and were blended for 45 minutes with the binder at high temperature in the wet process setting ("asphalt-rubber"). The rubber content was of 18 to 22 % of the reference binder weight without rubber. The viscosity, the durability and the resistance to permanent deformation were increased, whereas the top-down thermal cracking and the resilient modulus were decreased. The noise production is also reduced by at least 50 %. Certain drawbacks can be listed as for example the potential toxic emissions and the fact that 50 % of leachate contaminants were released into surface and ground waters. The initial cost of these infrastructures is also 50 to 100 % higher, but the life cycle cost assessment (LCCA) shows that these solutions can be cost effective.
In the dry process ("rubber-filler"), the particles size was of 0.85 to 6.4 mm and substituted 1 to 3 % of the fine aggregates. The optimum mixture was found to be for 0.95 mm rubber gradation, 10 % for tyre rubber ratio, 5.5 % for binder ratio, 155 °C for mixing temperature, 15 minutes for mixing time and 135 °C for compaction temperature. This composition reduces the resilient modulus, the permanent deformation, the noise and by more than half the nitrate concentration of leachate.

HDPE

In [20], HDPE is used in the wet process and the OBC is of 4.5 %. A decrease in stability for an increasing polymer content was noticed. It is explained by the decrease in adhesion. The increase in the HDPE content also leads to a higher value of flow, which is explained by the weaker interior friction. The conclusion was that the best modified asphalt concrete is the one containing 4 % of OBC weight and prepared during 30 minutes at 165 °C. in this case, the Marshall quotient increases by 50 %. See Figure 3.3

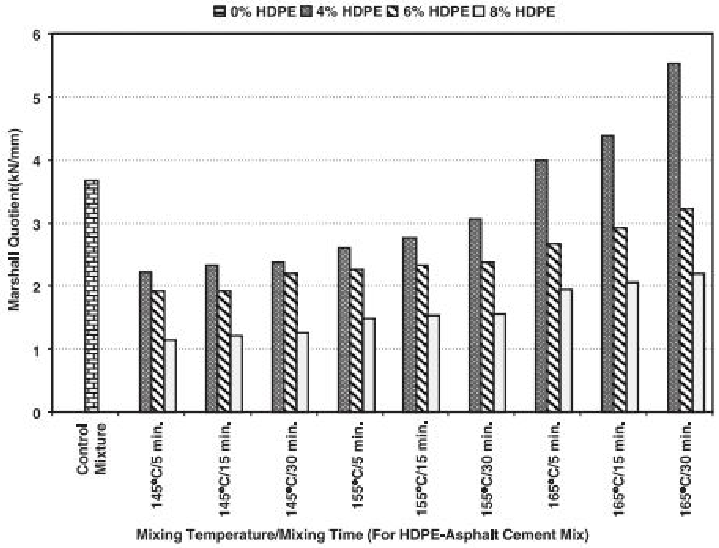


Figure 3.3 – Mixing temperature/mixing time vs. Marshall Quotient [20]

PET

In [30], it was determined that the principal parameters were the mineral aggregates, the asphalt binder and the air voids. In this analysis, the OBC was equal to 5.66 %. In this review, where PET was used, it is explained that the polymers soften between 130 and 140 °C and when mixed with hot binder, the mixture melts and forms an oily cover for the aggregates and is laid on the road surface. Here, the stability is increased by 42.56 %, the flow by 89.91 %, the strength by 13.54 %, and the durability and stability could lead to an increase in the fatigue cracking performance and the permanent deformation performance for a mixture containing 7.43 % of the OBC weight of PET. The intermolecular bonding is the explanation to these improvements.

In [2], PET recycled from plastic bottles was added to stone mastic asphalt (SMA). This type of asphalt concrete is more durable and has a better rutting resistance than normal asphalt concrete. In this research, the PET was blended with the aggregates and mixed with the binder using the dry process. The Marshall Stability was increased thanks to the better adhesion and the Marshall Flow decreases until 4 % of PET and then increases. This leads to an optimal Marshall Quotient when 4 % of the binder weight of PET is added.

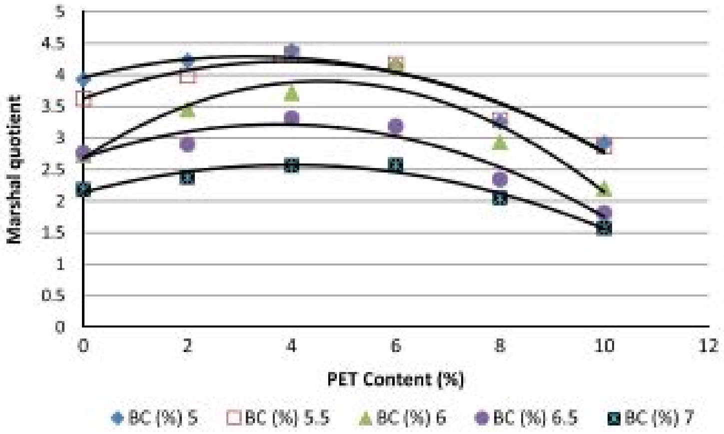


Figure 3.4 – Marshall Quotient value versus PET content for each binder content (BC) [2]

In [1], PET is also added in the fiber format. The OBC was of 6 % and the PET was shredded in fibers of 0.4 x 10 mm and added to the mixture by the dry process. In this review, the Resilient Modulus (RM) was tested. This measure allows to determine the response of dynamic stresses and corresponding strains. The temperature also allows to determine more precise parameters of the mixture. At 25 °C, it measures the fatigue resistance, and at 40 °C, it measures the rutting resistance. The optimum fiber content is 0.7 % of the total weight. It has also been shown that the RM decreases after 1 % of PET fibers because the fibers start to interact between themselves.

3.2.4 Conclusion

The optimum proportions found in the previous studies are summarised in Table 3.2.

Table 3.2 – Processes and content percentages for the three plastics studied

Plastic Type	Process	Content [% of OBC]
Rubber	Wet	18 - 22
Rubber	Dry	5.5
HDPE	Wet	4
PET	Wet	7.43
PET	Dry	4
PET	Fiber	11.67

The use of plastics in road infrastructures has multiple advantages like the improvement in performance of pavements and the reduction of solid material wastes, in this report especially plastics in the form of polymers or tyres, that are dumped in large quantities in landfills. But some disadvantages do exist, especially regarding environmental pollution via tyres. This topic concerns the environmental problems as well as the civil engineering domain, where there is a lot of potential for innovation.

3.2.5 Applications

In this case of road infrastructures, the next step has been done and real life applications have been done. Two examples are presented in the following sections.

PlastiPhalt®

The first example comes from Australia with plastics recycled into asphalt in Adelaide by Fulton Hogan, a New Zealander construction company. For this application, 110 tones of PlastiPhalt® were used to cover roads in South Australia, which allowed to save 140'000 plastic bags from going into landfills [21]. The wet process was used in this case, where the plastics were shredded and incorporated into the asphalt concrete mixture via the asphalt.

PlasticRoad B.V.

The second example comes from the Netherlands. The concept of this company is to produce circular and modular road pieces made of recycled plastic. The elements are composed of the following parts:

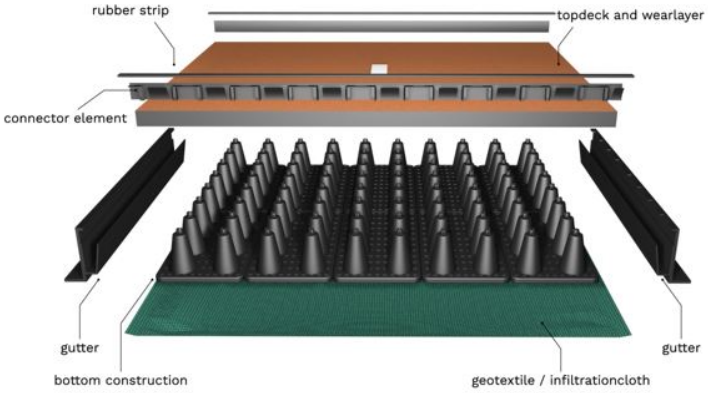


Figure 3.5 – Plastic road element parts [10]

These road elements can last from 30 to 50 years and can be easily removed, as they are clipped together, and recycled into a new element. A road has already been constructed in Zwolle in the Netherlands in 2018, shown in Figure 3.6. The 30-meter-long bike path is made out of 218’000 recycled plastic cups and 500’000 recycled bottle caps [10]

Figure 3.6 – Road in Zwolle [10]

According to PlasticRoad B.V., the advantages are multiple. These roads are first fully circular, which means that they use recycled materials, and that they can be fully recycled themselves. Then, the nuisances due to construction and transportation are reduced as well as the maintenance. Other advantages can be listed like the fact that they are climate-adaptive, lightweight, quick, simple, efficient and multipurpose, but the main ones are that the reduce emissions, and also that they reduce plastic wastes. A second similar project started this year in Giethoorn, also in the Netherlands. These two bike paths stay nevertheless pilot projects in progress.

3.3 Recycled plastic lumber

3.3.1 Production of the material

Recycled plastic lumber (RPL) is a construction material made out of mixed thermoplastics such as PET, PP, LDPE, HDPE and others [18]. It can be produced without additives, but there exists applications where they are used. One of these examples is shown in [11], where the plastic is mixed with sawdust. In many applications, the plastic waste is not separated into the different grades of plastic, but the mixed waste is directly introduced into the process [18]. At first, the plastic scrap is granulated, before it gets melted and processed. When warm, it is forced through a mould which creates the final shape [27]. Finally, the plastic is cooled down. The cooling process creates among other things a inhomogeneous cross section, since the inner parts are taking longer to cool down [12], see Figure 3.7. The other two main reasons for the heterogeneity in the lumber brick is the combination of different plastic types as well as impurities of poorly granulated pieces [27]. The whole manufacturing process of the RPL is less energy intensive than the production of cement or steel elements [33].

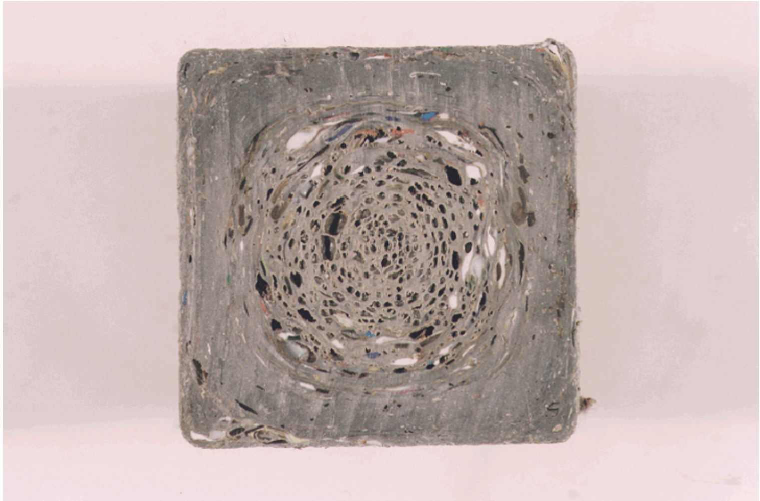


Figure 3.7 – Cross-sectional profile of a plastic lumber made from 100 percent curbside tailings.[26]

3.3.2 Physical properties

RPL typically show a rather low density. The compressive strength of the material can be compared to masonry and timber elements [18]. The stress-strain relationship of the RPL elements is rather complicated [27]. As opposed to more common building materials, RPL does not show a linear elastic stress-strain relationship. This complicates the determination of some of the mechanical properties [27]. In addition to that, the material shows a modulus of elasticity that is by far lower than the one for concrete or steel. It ranges between 350 to 2070 MPa [27]. This is why it is strongly advised against applications where it is subjected to high loads and stresses. Heat can also be an issue, some plastics can become soft very quickly when subjected to high temperatures [27]. The behaviour becomes even worse in contact with fire. Plastic burns hot and fast and would therefore not guarantee any safety in case of a fire [33].

3.3.3 Use cases

In 2009, the first vehicular bridge made out of recycled plastic was opened at Fort Bragg (see Figure 3.8). Almost all components of the bridge were made out of recycled plastics. After that, Fort Eustis decided to replace two old railroad timber bridges with the same material [12]. Up to that point, recycled plastic lumber had only been used in smaller applications, as for urban furniture or low stress outdoor structures. It was often applied as boardwalks or as floating docks, due to its increased marine resistance compared to timber. Nowadays, there exist a fair number of one and two-story buildings built with RPL, but the number of structural applications still stays limited [19].

Figure 3.8 – Fort Bragg plastic bridge, taken the 25.09.2009 by Dawn Elizabeth Pandoliano [31]

When applied in practice, the material cannot be designed according to existing masonry or timber standards, but needs its own design [11]. One of the application challenges is that not two types of plastic are the same. And since the lumber bricks often contain several types of different plastics, each individual brick will be somewhat unique. And this without even mentioning the variation of the brick properties between manufacturers [33]. The variety of properties seems therefore to be an issue that needs to be further developed. ASTM International has developed specifications and test method standards for RPL, but only a few for applications. The standards proposed for structural applications are mostly simple outdoor applications such as decks, boardwalks and platforms [5]. The manufacturers that were looked into in the scope of this project all create their own product and apply it based on their experience with it. [7] [9] [15] [17]

3.3.4 Advantages and limitations

The biggest advantage of RPL with regards to the topic of this paper is of course the great amount of plastic waste that can be re-purposed. Up to 100% of the used material of the brick is plastic waste. If applied in the construction of a small house, at least 30 to 40 thousand kilograms of plastic can be reused [18].

According to [11], RPL can be cut and drilled with the same tools as wood. In some applications, the bricks can also simply be slotted together [17]. Due to this, RPL has a lower construction time compared to concrete or brick buildings [12].

A physical limitation of the material is of course the low stiffness. The material should not be applied in high stress applications. Its applications will therefore be limited to simple structures and non-load-bearing structures. If larger loads should be carried, as for example in the case of the Fort Bragg bridge, large amounts of material will be needed in order to resist to the load [12].

Today, one of the major reasons why RPL is still only little used in structural applications is the lack of knowledge about the mechanical and structural properties of the material, especially with regards to long term performance. So far, the ASTM have played an important role in leading RPL material to the marketplace [25]. In order for RPL finding its place as a frequently used construction material, building standards need to be developed [27].

Chapter 4

Innovation

4.1 Room for innovation

After reporting existing solutions for the use of plastic materials in different construction sectors, a link can be done with the waste management issues described in chapter 2. As we can see in 4.1, a large quantity of plastic is exported to be recycled. Ideally this plastic should be recycled locally to be able to reach sustainability. However, current plastic recycling stations do not have the capacity to do so.

In this light, the goal of this paper is to suggest a waste management system that would help reach the necessary sustainability and circularity. The locally recycled plastics would remain in the recycling stream, however the plastics that are exported should be treated locally. To do so we could use these quantities in the construction applications presented in chapter 3. The tonnages of the PET and HDPE waste in the UK are listed in the following table:

Table 4.1 – Tonnages in the UK

Plastic type	Collected waste [kt/year]	Recycled in the UK [kt/year]	Export [kt/year]
PET	443	110	333
HDPE	270	86	187

The quantity of plastics that is exported will then be divided for the various uses presented previously. The tonnages of plastics that could be used in construction in the UK are explained and presented in the following sections. Only the best solutions regarding durability, strength and plastic usage are selected for the rest of this study to focus only on the most plausible alternatives.

4.1.1 Applications in the construction industry

In order to assess the feasibility of these applications, it is necessary to evaluate the maximal amount of plastic that could be used by the selected methods. The procedure to establish these tonnages is presented in the following.

Concrete

Production of concrete in the UK is high; each year, a total of 17 million cubic meters of ready-mixed concrete is produced. This value was taken from 2019, from the Department for Business, Energy, and Industrial Strategy in the UK. In order to calculate the mass of plastic each alternative could use if all concrete production applied it, densities were defined as following: PET 1380 [kg/m3] and HDPE 950 [kg/m3]. The results are shown in table 4.2.

It is important to notice that only the two best options for the use of plastic in concrete were selected. Good characteristics and a consequent percentage of plastic used in the mix are the two main reasons for this choice.

Road infrastructures

For plastic in road infrastructures, the yearly production is taken at 22.9 million tones of hot and warm mix asphalt (HMA and WMA) in Great Britain [4]. The value taken is from 2018. The tonnage for the different plastics and processes, if they were used exclusively, are derived from the OBC and the values from table 3.2.
Table 4.2 contains the three best combinations for the study, with the best option being the PET used in the wet process. The other solutions with rubber produce too much leachate and have chemical drawbacks like rubber swelling and rubber particle dissolution. As for the dry process, as said before, it is less tolerant and harder to put in place therefore discarded for this study.

Plastic lumber

As seen in the previous chapter, it is recommended to use recycled plastic lumber bricks in non-load bearing structural elements. One suitable application will therefore be as replacement of fired bricks used in non-bearing walls. Of course, there would be many other possible applications for the product as for example the replacement of wooden beams or different types of outdoor furniture and docks. For the sake of simplification these will however not be treated. In 2018, 128 million bricks were used for non-bearing walls in the UK [38]. A small and simple calculation of the brick volumes and the plastic density shows that if all of the non-bearing bricks were replaced by RPL bricks, more than 150 thousand kt of plastic per year could be re-purposed. [16] [19]

Applications: Summary

According to the previous explanations, the choices for the different construction sectors can be summarised in the following table:

Table 4.2 – Summary of the different best solutions to be studied

Plastic Type	Process	Total [kt/year]
Plastic in concrete		
PET	Sand graded	1'219 - 3'683
PET	Resin	751 - 1'009
Plastic in road infrastructures		
HDPE	Wet	41.22
PET	Wet	96.3
PET	Fiber	160.35
Plastic lumber		
Mixed	-	150.5

4.2 Proposed recycling system

In order to actually be able to implement the ideas shown in the previous sections, it is important to asses the current recycling system and see where the construction sector can be integrated. Figure 4.1 shows our idea on how this could be realised.

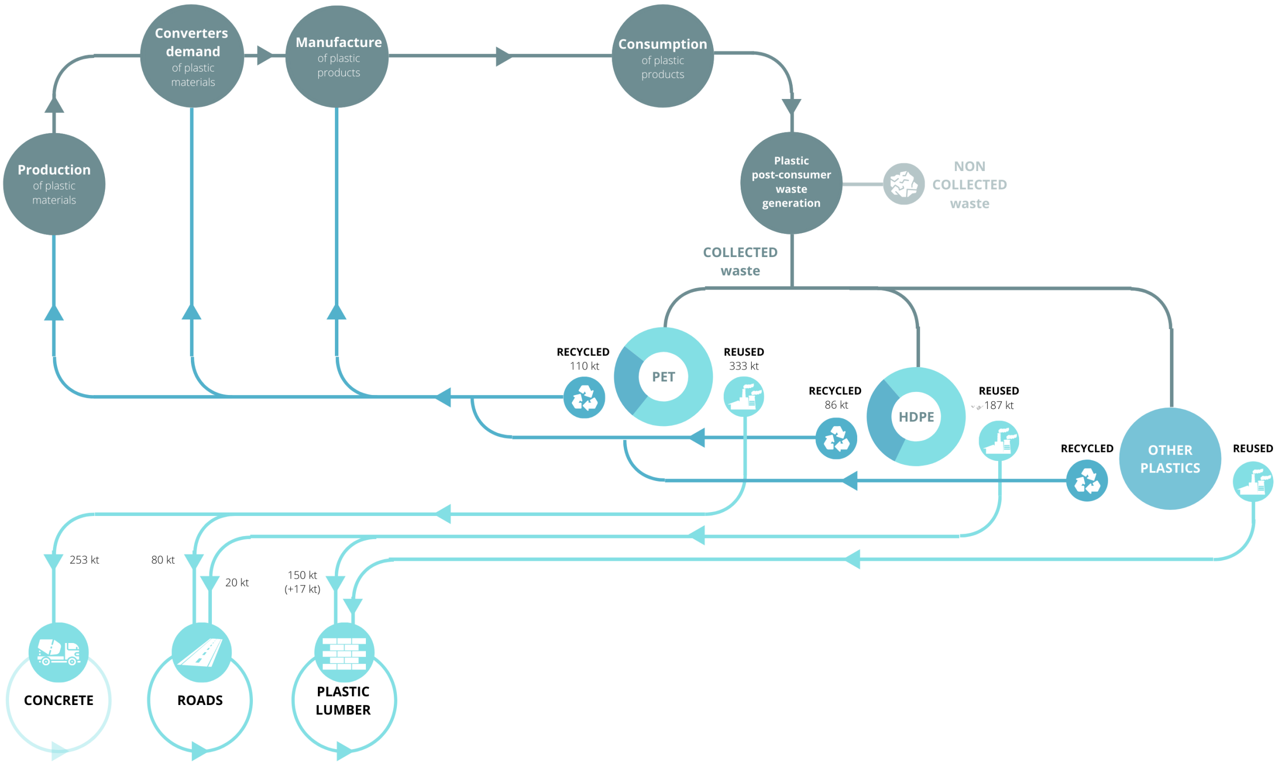


Figure 4.1 – Proposed recycling system

The ocean-green coloured part shows the existing recycling system in the UK including the production, demand, manufacturing as well as the consumption of plastic products. An important step is plastic waste collection, it allows the effective separation of plastic products. Nonetheless, there is always some plastic that is littered for which the quantity is unknown. This is one part of plastic pollution that cannot be solved with the proposed method.

Within the collected plastic waste there are several types of plastic of which PET and HDPE were more closely inspected for this project. It is important to note here however, that a lot of PET and HDPE cannot be recycled as itself because of impurities or because it is inseparable from other types of plastic. If this is the case, it will be sent to the sector of non-recyclable plastics.
For most types of plastic a fraction is already recycled today. Since this plastic does not contribute to any type of pollution and since the final goal is to be able to recycle all of the plastic waste, it will remain within the cycle so it can be reused instead of having to produce new plastics for consumers needs. The other portion of the collected waste, as seen in 4.1 is currently exported. As exportation generates many emissions and often what is done with the materials is fundamentally unknown, we decided to try to use as much as possible of it in the construction sector.

The applications that were previously reviewed where plastic was inserted into concrete mixtures showed that additions of PET had the best behaviour. This is why in the final model, only this type of plastic was proposed as a valid additive. Another element that stands out is that not 100% of the capacity of the plastic incorporation is exhausted.

We think that although concrete is used widely and could use the most plastic, it probably will be harder to have good market penetration due to the current lack of certainty on the properties. In fact, as concrete structures are often high impact high risk structures, it can be difficult to compete with known materials.
In addition to that, we are very unsure about the recyclability of the concrete with the plastic particles. In fact, very few studies pursue the recyclability of such concrete. Indeed, in order to reach the circularity marked as a fading blue arrow in Figure 4.1 studies should be conducted in that direction.

For roads, both HDPE and PET can be used. This is why parts of both types of these plastics can be lead into its manufacturing. Since the application of recycled plastic in roads is already done in some cases (see section 3.2), we were more optimistic and decided to implement the full potential of plastic that can be introduced into roads.
Recycling of regular asphalt is done by crushing the old asphalt into smaller pieces and introducing them into a new asphalt mixture as part of the granulate. The same process could possibly be applied to asphalt mixtures that contains plastic particles. The plastic would therefore stay within the system as recycled asphalt. Further investigations are needed however to actually prove this ideal recyclability.

As it was described in chapter 3.3, any type of thermoplastics can be introduced into recycled plastic lumber. Here, we also assumed that the full potential of plastic storage in the bricks could be exploited due to the many existing applications. In the flowchart describing the process, the main part is taken up by HDPE. If the amount of HDPE directly recycled into their original products could be increased, more of other thermoplastics could be introduced into recycled plastic lumber elements. Furthermore, with the 150 kt only the applications for non-bearing brick walls are considered, while in fact there is a larger range of other products where this material could be introduced, as seen in some of the manufacturers catalogues [7] [9] [15]. However, for other products it is more complicated to quantify the needs which is why their impact was neglected for the sake of preliminary feasibility studies.
We imagined the recyclability of the product as itself as pretty straight forward since it only consists of a mixture of plastics without any additives. If done carefully, the brick could just be extracted from its old location, crushed, melted and reintroduced to a new brick. Nevertheless, if the actual process is as easy as it sounds should still be tested and verified.

4.3 Effects of the innovation

4.3.1 Value creation

The suggestion brought up in the previous section has the potential to mitigate certain issues regarding plastic pollution. The value created by this suggestion is presented in the following.

Giving plastic a second life
The first and probably most important value that is being created is the idea of giving plastic a second life as a construction material instead of sending tons of it into landfills. Plastic pollution should therefore be reduced to a minimum. As seen in chapter 2, a lot of the plastic produced is being exported and sent into other countries. By re-purposing this plastic and using it in the construction sector, this export might also scale down and therefore reduce the pollution emitted by its transportation. If one might want to be very optimistic, it could be suggested that all of the plastic that is being collected might become insufficient for the many construction applications there exist. In that case, plastic waste in existing landfill might become a new source of construction materials.

Reduced construction cost
Since recycled plastic is basically a waste material, the costs for it would be lower than for conventional building materials. Especially for the case of RPL where the entire structural element is made out of recycled plastic, this can reduce construction costs by a considerable amount which makes the product more affordable for everybody.

New regulations and space for innovation
One important thing that the use of plastic in construction depends on is the development of regulations and standards. This would create new space for innovation and development and there is a chance that new materials could be developed with even better structural behaviour and long term performance than the ones presented in chapter 3. This possibly improved structural performance with the right amount of plastic replacements is a positive aspect that should not be failed to mention. For this to have effectiveness it is however essential to strictly follow the guidelines and standards developed.

Reduction in carbon emissions
A further advantage is the reduction of commonly used structural materials needed. The production of both cement and fired bricks emits a lot of carbon emissions. By replacing at least some parts of it in the applications, these emissions could be cut. For the case of concrete, the addition of plastic as sand replacement has yet another interest.

Sand replacement
As sources of sand are running out, alternatives need to be found in order to be able to continue producing notably concrete without having a too large impact on natural ecosystems. Grated plastic particles could be one of those sand replacements.

Job creation
The entire process of applying recycled plastic in the construction sector could create a multitude of jobs in different sectors. To name just a few of them: researchers for the development of standards and guidelines, workplaces for the extended or additional recycling plants, and experts for the application of the new materials.

4.3.2 Risks

Any new and not fully developed product will bring certain risks along. The identified ones for recycled plastic in the construction sector will be described below.

Bringing the material to the market
One of the first and probably most important aspects is actually bringing the recycled plastic construction products to the market. For that, more laboratory and application tests would need to be executed and standards would need to be developed. By acquiring a deeper understanding of the material's properties it would become more fit for application and acceptance.
To make this possible, investors need to be found. Without them, this innovation will fail before even beginning. A next crucial step will be to gain trust and a certain reputation in the construction industry. For that, it would be beneficial if the material can be applied in some interesting and promising projects. To facilitate this process it is therefore important to keep the process of the construction and implementation of the material as simple and cheep as possible which is yet another challenge.

Behaviour in real applications vs. in labs
Another risk of the materials proposed are in the actual application. So far, mostly lab tests have been executed. Only some applications for the RPL and in road infrastructures are known today.

The behaviour of the material in larger scales and over a longer time frame could not yet be investigated. It exists therefore an uncertainty on whether the materials will be pass quality tests in real applications as well as they did in the labs. .

Microplastics
One of the critical dangers with regards to the applications is the possibility of plastic pollution through the material itself, especially in road applications where frictional contact to external elements is abundant. There is a chance that the plastic in the asphalt structure itself might get abraded and end up in the water system. This would therefore counteract all the efforts brought into the process of reducing plastic pollution. If and how much this effect is present can however only be determined through testing.

Dosing
One of the risks of the material itself is the dosing and mixing of the plastic parts with the rest of the material ingredients. As we have seen in chapter 3, the right dosage is crucial and in case this is executed poorly, it can have an significant impact on the material properties. Manufacturers might have a tendency to add a larger amount of plastic in the mixture than what is recommended to reduce costs. It is therefore crucial to instruct the workers properly and introduce them to the respective consequences to reduce this risk.

End of lifetime
Currently the end of life or construction materials containing plastics is quite unknown. Studies would need to be conducted to know whether it can be reused as recycled version of itself as it is partially done in conventional construction materials, as for example partially recycled concrete and asphalt. Or whether it would need to be put in landfills since the plastic and the rest of the mixture will be hard to separate at that state. This is a problem that so far is hard to evaluate due to the development stage of the materials.

No recycled plastic available for construction sector
As seen in chapter 2, the goal of the UK is to make all used plastics will be recyclable. The plastic system should be turned into a closed circle. This however could create a problem for the actual production of the products proposed in this paper. If all plastic is directly recycled and reused in its original applications, none of it will be left for the construction sector. This is why the innovation might only show its value for a short time, which mainly is before 2030. This is one of the possible reasons why investigators might not be interested in the project, since it shows no long term future. Of course, one could argue that there is still a lot of plastic in landfill that could be introduced in these applications and that reducing the plastic waste would actually be a success rather than a problem, but for an investor this might still be an issue.

Littering
The proposed ideas could if well implemented have a positive impact on plastic pollution. However, it cannot account for the plastic that is littered. In order to reduce this part of the plastic pollution, other methods would need to be applied, such as campaigns and milder punishments as for instance fees the way it is done in Singapore.

Chapter 5

Conclusion

Starting from the environmental plastic pollution and choosing to focus on the United Kingdom, solutions to reduce waste ending up in landfills or being exported to other countries have been studied. The use of recycled plastics in construction, more precisely in concrete, road infrastructures and plastic lumber bricks, allows to fulfil this aim. Laboratory experiments have already been executed worldwide to confirm the potential use and performance increase of these materials. It seems possible to go a step further and integrate the available plastics in a circular life cycle and describe their progression in a recycling system process.

This innovation shows many benefits apart from the reduction of plastic pollution. It can reduce construction costs due to the reprocessing of waster materials, create jobs for the treatment and in the construction sector. Furthermore it can reduce the amount of sand needed in construction, which is becoming a critical issue with regards to concrete fabrication.

But with every great idea there are risks coming along, especially regarding the introduction of this new technology into the construction market and the material behaviour in real life applications as opposed to lab tests. Another issue lies with the acquiring of the used plastic for the construction sector. In the future, all plastic should become recyclable in the UK and therefore little to none would be left for construction.

The use of plastics in construction has a promising perspective for the future, but the recycling needs to be boosted and the construction sector needs to be open for these new alternatives. Hopefully some of the ideas shown in this project will be put into action and might partially help to solve the problem of plastic pollution.

Chapter 6

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